EVALUATION OF FORWARD COLLISION MITIGATION BRAKING SAFETY PERFORMANCE FOR COMMERCIAL VEHICLES

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Abstract

The objective of the study was to estimate the safety benefits of a Forward Collision Avoidance and Mitigation (F-CAM) systems comprised of forward collision warning and automated vehicle braking applied to heavy trucks, including single unit and tractor semitrailers. Benefits were estimated for a production "current generation" system, a prototype "next generation" system, as well as for an advanced "future generation" system.

The results (benefits) from the simulation studies were applied to the national crash population. Assuming Collision Mitigation Braking systems were fitted to all tractor semitrailers, the reduction in fatalities relative to the base population for current, next and future generation systems was estimated at 24 percent, 44 percent and 57 percent, respectively. These percentages correspond to an estimated reduction of 55, 99, and 129 fatalities annually, respectively.

1. Introduction

The analysis described in this paper is related to a study Woodrooffe et al. (2012) was conducted by the University of Michigan Transportation Research Institute (UMTRI) under a Cooperative Agreement between the US National Highway Traffic Safety Administration (NHTSA) and Meritor WABCO. The objective of the study was to estimate the safety benefits of Collision Mitigation Braking systems comprised of forward collision warning and automated vehicle braking applied to heavy trucks, including single unit and tractor semitrailers. Benefits were estimated for a production "current generation" system, a prototype "next generation" system, as well as for an advanced "future generation" system. This was accomplished through the following steps:

1. The actual performance of these systems was characterized in various pre-crash scenarios under controlled test track conditions, and then control algorithms for warnings and automatic braking actions were reverse engineered;
2. A comprehensive set of simulated crash events representative of actual truck striking rear-end crashes were developed. This virtual, "reference" crash database was created by analyzing vehicle interactions (or conflicts) from naturalistic studies to create thousands of crashes in a computer simulation environment, and then weighting each simulated crash based on probabilities derived from GES and TIFA crash databases;
3. The Collision Mitigation Braking technology algorithms overlaying (or inserting) into the simulations of each crash event and observing the kinematic impacts (i.e., benefits) from having initiated warnings and/or automatic braking (including reductions in impact speed, or elimination of the crash). The crash population that could likely benefit from the technologies was identified using nationally representative crash databases. The results (benefits) from the simulation studies were applied to the national crash population.

2. System Description

The Forward Collision Avoidance and Mitigation (F-CAM) system described in this paper is designed to be integrated with the antilock braking systems (ABS), and Adaptive Cruise Control (ACC) as well as either a Roll Stability Control (RSC) or Electronic Stability Control (ESC) system. The ACC component of F-CAM systems supplements the normal vehicle cruise control to maintain the vehicle at a driver-selected speed. When it encounters a slower vehicle, it automatically maintains a pre-set distance-based spacing. ACC interacts with the vehicle's engine management system (transmission and throttle) and brake control system to adjust the speed of the vehicle when necessary.

Three different versions of a collision warning and mitigation technology were evaluated. commercially available OnGuard™ system herein referred to as the Current Generation (CG) system.

1. The current generation system is capable of decelerating the vehicle up to a maximum of 0.35 g without any driver intervention. However it cannot act on fixed objects (objects that were stationary before they were in range of the radar). The system can

react to stationary objects that were in motion when first coming into radar range. The radar range for the systems evaluated in this project is nominally 100 m.

2. The second generation was evaluated in prototype for as it was not commercially available at the time of the stud. It is similar to the current generation system except it can act on fixed objects through the use of integrated radar and video system.
3. The third generation system is similar to the second generation system except it has increased braking control authority and can achieve up to 0.6 g of longitudinal deceleration.

A generalized representation of the sequence of warnings and control actions for both the systems is shown in Figure 1.

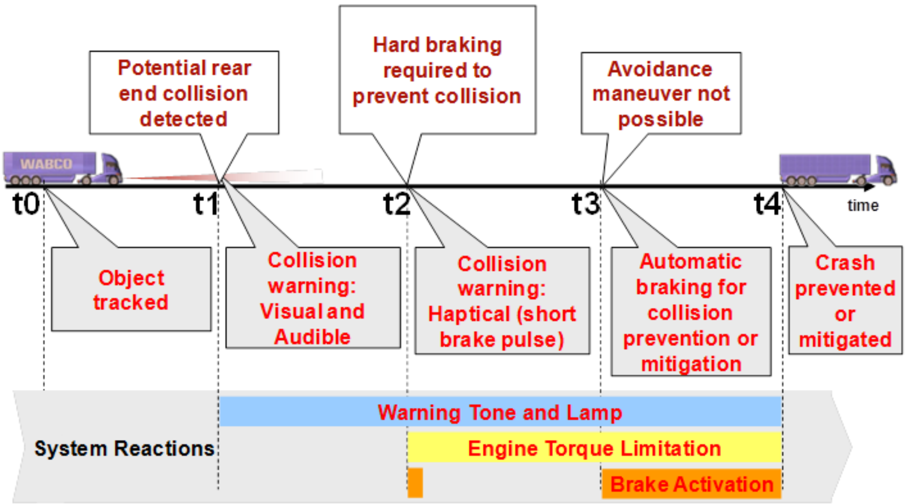

Figure 1. Time Sequence of Warnings and Control Actions

Approach

Estimating the safety benefit for the F-CAM system was accomplished through the following steps.

Step 1: Characterize Technology Performance. The performance of F-CAM technology was characterized in various pre-crash scenarios examined under controlled test track conditions. Actual testing was completed on the current production unit installed on a truck tractor. The algorithms that control warnings and automatic braking were approximated through reverse-engineering based on observed performance. Results of the test track research were also used to help refine target crash population estimates by defining functional and performance limitations.

Step 2: Profile Target Crash Population. Estimates of the annual number of rear-end, truck striking crashes were developed using nationally-representative crash databases, including NHTSA's General Estimate System (GES) data (2008) and UMTRI's Trucks Involved in Fatal Accidents (TIFA) data (2008). This estimate was then narrowed to better identify crashes which could be impacted based on an understanding of performance and technology limitations of F-CAM systems (particularly related to speed, environmental and crash conditions). This narrowing was accomplished by performing a detailed review of a random sample of fatal and nonfatal crash involvements. For the review, fatal crashes were sampled from TIFA, and nonfatal crash data records from two states (California and North Carolina) that maintain particularly detailed reports relevant to this analysis. The product of this step is an estimate of the target crash population for the technology. Delta-V distributions were estimated for key crash types from injury-severity distributions in the struck vehicle, using the TIFA and GES data.

Step 3: Create Simulated "Reference" Crash Database. A comprehensive set of simulated crash events was developed to characterize (or represent) the actual, historical population of truck striking rear-end crashes. A baseline set of approximately 10,000 actual vehicle interactions (i.e. rear-end conflicts involving a truck approaching a lead vehicle) were first identified by leveraging detailed data recorded during naturalistic studies (most notably, NHTSA's Integrated Vehicle Based Safety System Study). Each of these conflict events were then manipulated in a simulation environment by delaying the observed braking of driver. In this manner, a large and diverse number of truck-striking rear-end crashes were created in simulation environment (approximately 172,000 such crashes). Each simulated crash was then weighted using the delta-V weighting profiles developed in Step 2 to reproduce the crash distribution observed in the nationally-representative crash databases.

Step 4: Assess Impact of Countermeasure Technologies in Simulated Environment. The F-CAM technology algorithms (developed in Step 1) were then inserted into the simulations of each crash event, and the change in crash outcome (from having issued the warning and/or applying the brakes) was observed. The outcome could be either a reduction in impact speed, or the crash was avoided altogether. For the simulations, driver behavior (in terms of reaction times to the warnings as well as braking levels) was modeled using data derived from USDOT-sponsored naturalistic field studies, including the Integrated Vehicle-Based Safety System (IVBSS) Field Operational Test.

Step 5: Estimate Safety Benefits for Full Deployment. Effectiveness estimates derived from the simulations in Step 4 were applied to the actual targeted crash population produced in step 2 in order to derive the total number of fatalities avoided, injuries mitigated, and crashes that were avoided. Finally, cost factors for fatal, injury and PDO crashes were applied to the reductions in these types of crashes in order to estimate total economic benefits.

Identification of Relevant Crash Types

The target crash population analysis provides a comprehensive review of the circumstances and consequences for crashes in which the truck was the striking vehicle in a rear-end crash in order to identify the subset of rear-end crash scenarios for which the F-CAM technology could potentially have an impact on crash the outcome of the crash. A variety of filters were applied to the initial truck-striking rear-end crash population that effectively narrowed the target crash population. These filters excluded cases that would likely not have benefited from the technology due to environmental, driver-state (e.g. impairment), infrastructure and other factors.

Two crash files were used to develop basic crash types (as defined by pre-crash conditions): UMTRI's Trucks Involved in Fatal Accidents (TIFA) survey file and NHTSA's General Estimates System (GES) file. Six years of data (2003-2008). were averaged to provide annual estimates of the target crash population for the F-CAM technology.

A detailed analysis of crash reports from three additional crash databases (specifically, the Large Truck Crash Causation Study (LTCCS) [4, 5, 6] and state crash files from California and North Carolina), were used to help segment those crashes coded in GES as "lead vehicle being stopped" into two distinct categories:

1. those crashes in which the lead vehicle was already stopped at the moment it was first recognized by the subject vehicle's radar; and
2. those crashes in which the lead vehicle was moving at the moment it was first recognized by the subject vehicle's radar, but then slowed to a stop prior to impact.

The former group of crashes (1) was designated a "lead vehicle fixed"; with the latter group (2) designated as "lead vehicle stopped". For tractor semitrailers there are approximately 16,000 rear-end, truck striking crashes each year, with about 192 fatal and 5,000 injury crashes. These truck-striking rear-end crashes result in approximately 231 fatalities and about 8,000 total injuries. For straight trucks involved in such crashes, there are a similar number of total crashes (including property damage only (PDO) crashes) as well as injuries, but much fewer fatalities with approximately 63 fatal crashes resulting in 72 fatalities.

An examination of the operational, environmental, and human factors associated with the targeted crashes suggests that the interventions of F-CAM technology are well-suited to the way rear-end, truck striking crashes occur. For example, there is no significant association with any adverse environmental condition. If anything, the crashes addressed by F-CAM technology are more likely to occur in good weather, on dry roads, in daylight, on a straight section of road, and on the roads (freeways) that are designed to the highest standards. The factors that do seem to be associated with such crashes include driver distraction and a sudden interruption to the flow of traffic. There is an overrepresentation of construction zones and nearby accidents among the targeted crashes. These account for only a small proportion of rear-end striking crashes, but it is notable that they are significantly overrepresented in comparison with other crash types. The other factor of interest is that driver distraction is identified in a very significant proportion of the crashes. In addition, speeding and following too close are also substantially overrepresented.

Track Testing

A vehicle test track program was conducted to document the performance and functional characteristics of the technology in support of the modeling effort. The goals of the test track program were to measure, record, and analyze the timing of driver warnings and automatic brake applications for the current generation F-CAM system in a closed-course test track environment. The experiments were conducted using representative rear-end pre-crash scenarios involving differing kinematic conditions (i.e. range separations, absolute and relative vehicle speeds, closing rates, etc.). For automatic brake applications, measure and record reductions in impact speeds for the scenarios tested, or whether the collision event was avoided altogether.

The data from the test program was used to "reverse engineer" system control algorithms that trigger when warnings and/or brake applications are initiated based on observed relationships and parameters between the lead and following vehicles. The analysis of the test track data showed that "time to collision" and "required deceleration to avoid collision" thresholds to be the best parameters for predicting the timings of warnings and/or braking events for F-CAM technology. Thus, system control algorithms were developed based on these two parameters. Such algorithms were then used in the development of a computer simulation model to estimate crashes avoided as well as crashes mitigated.

The Principal Other Vehicle (POV) was represented by a towed, impact resistant target shown in Figure 2, having the likeness of the rear end of a passenger car, and was designed to sustain repeated vehicle strikes during the test program. In addition pylons were used to represent stationary objects for the second and third generation systems.

Figure 2. Final UMTRI fixed vehicle targets compatible with radar and vision systems

Modeling Safety Performance

Estimating benefits of any crash avoidance system requires identifying the population of crashes that the technology is intended to address, describing the expected change in the outcome of those crashes if the technology were to be fully deployed in the truck population, and estimating the monetary value of the reduction in crashes—including reductions in fatalities, injuries, and property damage. For many crash avoidance technologies (e.g., ESC, RSC) that have previously been investigated by NHTSA, some portion of the targeted crashes are determined (via expert judgment, modeling, and other means) to be completed avoided when the technology is implemented. Benefits are therefore relatively easy to calculate by leveraging GES, FARS and other crash databases to identify the targeted crashes and corresponding injury outcomes, and these can then be multiplied by effectiveness estimates to determine benefits.

However, in the case of the F-CAM system, the expected benefit is often a reduction in the severity of a given crash rather than total elimination of the crash. Although some fraction of crashes will be prevented altogether through the use of F-CAM technology, many others will be mitigated. This situation makes it more difficult to estimate benefits because the effectiveness of the system will depend on initial conditions associated with each crash, and those conditions are largely unknown when crashes are captured after the fact (as they are in Federal and state crash databases such as GES and FARS). In other words, some crash databases generally have good data about the condition of the vehicles and occupants after the crash event (from which delta-V can often be estimated based on injury severity levels), but data on pre-crash kinematic conditions such as speed, range, and deceleration and closure rates are comparatively imprecise and often unknown—yet these are precisely the parameters that can impact the effectiveness and performance of F-CAM systems. Event Data Recorders (EDRs) provide some hope for more accurate pre-crash data in the future, but the availability of EDR data is limited, (and totally absent for heavy vehicle), not present in most crash databases, and not necessarily representative of the overall crash population.

To address the fundamental lack of well-defined pre-crash conditions for the targeted population of rear-end, truck-striking crashes, a significant effort was undertaken to create a "reference" set of virtual, simulated crashes whose type and severity parallel the actual annual average population of truck-striking rear-end crashes as recorded in GES over the last 5 years. The method for generating the simulated, reference crash database begins with two parallel efforts:

First: Focus on leveraging GES crash data and observed injury levels to document the actual, historical distribution of crash severity levels (based on delta-V) in truck-striking rear-end crashes. The profile of target crash populations is evaluated as follows.

1. Identify F-Cam technology relevant crashes,
2. Segment crash population based on crash type (LV slower, LV decelerating, LV cut-in).
3. Reverse-engineer delta-V distributions for each crash type based on injury levels from GES database.
4. Apply delta-V weighting factors.

Second: Focus on leveraging naturalistic driving data to help establish a broad range of initial kinematic starting conditions between two vehicles that could become involved in a rear-end crash. These starting conditions (i.e. varying ranges, speeds and accelerations between the subject and lead vehicle) are used for creating a population of simulated crashes. Referred to as the Simulated Reference, it is derived as follows.

1. Identify rear-end conflicts from naturalistic database (IVBSS) LV slower, LV decelerating, LV cut-in. About 10,000 total conflicts were identified.
2. Re-calculate each conflict in a simulated environment.
3. For each conflict, progressively delay braking in increments of 0.1 sec to create a range of virtual crashes with increasing severity levels.
4. Simulate rear-end crashes (approx., 172,000 crashes of varying type and severity).
5. Reference F-CAM relevant crash database.

At a high level, the analysis involves constructing a delta-V distribution that will reproduce the patterns of injury found in the field (GES) for rear-end, truck striking crashes. In the delta-V estimation process, the relationship between delta-V and injury risk is estimated based on NASS-CDS cases and then used to represent the average crashworthiness of the light vehicle fleet. If injuries tend to be more severe in a given crash scenario, then the estimated delta-V distribution is shifted to the right (i.e. higher delta-Vs) relative to scenarios involving less severe injuries. The parameters defining the delta-v distribution curves for each type of rear-end crash are estimated.

To generate a broad distribution of pre-crash conditions (that will be used to create the virtual, simulated crashes), we start by documenting the initial starting conditions for a large set of rear-end “conflicts” that have been observed in NHTSA-sponsored naturalistic driving studies. For this effort, the IVBSS FOT data were selected. As part of the IVBSS field study, 10 trucks were instrumented to continually collect high resolution data on both the truck and lead vehicle. These data could then be queried to select initial starting conditions (or events) that represented situations in which the lead vehicle was slower than the subject vehicle; was decelerating; was stopped at long range prior to any conflict; or where a cut-in/cut-out lane change maneuver was observed.

The process relies on the assumption that rear-end crashes generally arise from normal initial vehicle-following conditions, but because the driver fails to react in a timely manner to developing conflict conditions, a crash occurs. This delay by the driver could be due to distraction or inattention, but because crashes are simulated, the cause need not be specified. The approach for creating simulated crashes from the IVBSS data contains the following steps:

1. A large number of vehicle-following events (or “conflicts”) are identified within the IVBSS dataset as described above. A total of about 10,000 such starting conditions were identified including conditions representing lead vehicle decelerating, lead vehicle moving slower, lead vehicle stopped, and cut-in situations. Each scenario had its own selection criteria. For example, criteria used in lead vehicle braking include initial speed greater than 25 mph, deceleration less than -6.0 m/s2, duration more than 5 seconds.
2. Initial conditions for each conflict are “played out” in a simulated environment by delaying driver reaction times incrementally (by 0.1 seconds for each step) until there is no braking at all (thus representing a worse case crash). This process creates a range of crash severities for each one of the starting conditions (i.e., conflicts). As a result, a database of approximately 172,000 simulated rear-end crashes was developed representing a wide range of crash types (lead vehicle slower, decelerating, stopped, cut-in), severity levels (small to large delta-Vs), and initial starting conditions (low and high speeds, closure rates, range settings).
3. To ensure that the simulated database accurately represents the frequency distribution of crashes in the real world in terms of severity levels, weighting factors are developed from the delta-V distributions generated in the crash-data analysis tasks. The weighting factors are applied to each of the simulated crashes (within the 172,000 crash database) so that the delta-V distribution in the reference dataset matches the delta-V distribution from real world crashes.

Driver warnings and automatic braking actions are initiated when specific threshold levels. The algorithms control both the timing of warnings and automatic braking events, as well as the braking deceleration levels.

Once the reference set of crashes is in place, the warning and braking system control algorithms the F-CAM technology can be overlaid within each simulated crash event. An assessment of the impact of the various countermeasures is achieved within a simulated environment using the following steps:

1. Apply countermeasures with each simulated crash. The countermeasures include FCW only, CBM only and FCW+CMB.
2. Apply distribution of driver brake reaction times to each simulated crash
3. Estimate new delta-Vs, based on reductions in impact speeds and the number of crashes eliminated altogether.

Within the computer simulation environment, the effects of driver warnings and/or automatic braking events can be evaluated as to whether a particular crash was prevented, or the degree to which impact speed (delta-V) was reduced. To account for driver variability in responding to warnings, a distribution of reaction times was developed and applied to each of the 172,000 simulated crashes, resulting in over 1.5 million separate simulated crash events. The distribution of reaction times used in the simulation was developed from observations collected during the IVBSS field test, and is in general agreement with reaction time distributions gathered from other studies Johansson (1971), Liebermann (1995), Shutko (1999).

In summary, each single crash scenario in the reference crash set is “played out” both with and without the F-CAM technology configurations in place. There were approximately 172,000 such scenarios representing a broad range of rear-end, truck-striking crash conditions. The model developed within this study utilizes a realistic distribution for driver reaction times to forward collision warnings, representative driver braking effort estimates, as well as established relationships between impact speeds and injury levels, to estimate the safety benefits from a particular F-CAM technology configuration.

Delta-V Distributions

The goal is to generate a good estimate of the delta-V distribution for real-world rear-end crashes. The parameters describing the distribution (function) can then be used to weight the simulated crash cases so as to produce the same mathematical distribution of delta-V crashes. The class of F-CAM-relevant crashes for which delta-V was modeled, included truck-into-light-vehicle rear impacts. Such modeling is required since delta-V estimates for truck-struck involved crashes are not available directly from crash datasets. For example, large trucks are generally not included in NASS-Crashworthiness Data System (CDS), which has delta-V estimates for vehicles involved in crashes. In contrast, NASS-GES includes a broad sample of crashes, including those involving large trucks. However, the only measure of crash severity in GES is the police-reported maximum injury in the vehicle, based on the KABCO scale. The letters of the KABCO scale represent decreasing injury severity including Killed (K), Incapacitating Injury (A), Probable Injury (B), Possible Injury (C), and Property-Damage Only (O).

The general approach to derive delta-V estimations is based on two assumptions:

- First, delta-V distributions can be modeled with a parametric form that will hold for a particular class of crashes (crash types), though different classes of crashes will have different parameters.
- Second, the relationship between delta-V and injury is fixed for a given impact direction and general population of vehicles. In the truck-into-car (light vehicle) rear-end context, the distribution of delta-Vs are estimated for the struck vehicle (i.e., the light-duty vehicle).

The primary outcome of each simulated crash case is the delta-V experienced by the lead vehicle, calculated as 95% of the speed difference between truck and car at impact, to reflect typical heavy truck-light vehicle mass ratios. However the distribution of delta-V's in the simulated crash dataset did not match (exactly) the delta-V distribution from real world crashes. Therefore, once the simulated-crash dataset was constructed, the cases had to be weighted to reflect the real world delta-V distributions for each crash type category (i.e., lead vehicle fixed, slower, decelerating, cut-in).

Estimated Safety Benefits

The estimated annual benefit analysis was computed separately for tractor semitrailers and for straight trucks with no trailer. The results of the analysis are contained in Table 1 assume that all trucks were fitted with the F-CAM technology.

Table 1: Reduction in Injury Severity F-CAM System and Sub-Elements

Reduction in Injury Severity by Device
For Tractor Semitrailers

Device	Fatal	Injury	No injury
Subsystem Contribution			
FCW only	31%	27%	11%
CMB only 2nd gen.	26%	32%	10%
CMB only 3rd gen.	44%	42%	19%
Complete System Contribution			
Current Generation	**24%**	**25%**	**9%**
Second Generation	**44%**	**47%**	**20%**
Third Generation	**57%**	**54%**	**29%**

Reduction in Injury Severity by Device
For Single Unit Trucks

Device	Fatal	Injury	No injury
Subsystem Contribution			
FCW only	28%	25%	11%
CMB only 2ND Gen.	27%	33%	13%
CMB only 3rd Gen.	42%	46%	23%
Complete System Contribution			
Current Generation	**22%**	**21%**	**10%**
Second Generation	**43%**	**46%**	**24%**
Third Generation	**55%**	**57%**	**34%**

The research effort found that the current generation system offers significant safety improvements across all severities for both the tractor semitrailer and single unit trucks. The second and third generation systems were found to provide substantive additional benefits.

The difference in safety performance outcome between the current generation system and the second generation system is attributed to the ability of the second generation system to respond to fixed vehicles, that is, vehicles that were not moving at the time that the system engaged them. The data strongly suggest that development of systems that can reliably respond to fixed vehicles and objects in the travel lane will result is very significant safety benefits.

The difference in safety performance outcome between the second and third generation systems is attributed to the higher foundation brake deceleration. The maximum foundation brake deceleration for the current and second generation systems is -0.35g while the third generation deceleration limit is -0.6 g. Therefore the influence of greater braking levels at the stage of "imminent collision" on safety outcome is significant but not as powerful as the safety improvements associated with fixed vehicle detection.

Conclusions

The challenge of forecasting benefits of technologies that have not been introduced or have limited market penetration is significant, given that crash populations containing vehicles with the technology are absent. Estimating benefits of any crash avoidance system requires identifying the population of crashes that the technology is intended to address and describing the expected outcome of those crashes with the technology implemented. In the case of collision-mitigation braking and forward-collision warning, the expected benefit is often a reduction in the severity of a given crash rather than total elimination of the crash. This is more difficult to estimate because the effectiveness of the system will depend on initial conditions associated with each crash and those conditions are largely unknown when crashes are captured after the fact.

To overcome this challenge several innovative elements were required in order to estimate the effectiveness of the technology in reducing or mitigating crash severity. Example of such innovative elements include the use of naturalistic driving data together with detailed crash records to infer a distribution of impact speeds of truck striking rear-end crashes, and developed a model to predict the effectiveness of variations in the technology at avoiding or mitigating crash severity.

The new approach described in this paper used the pattern of injury outcome from GES and a distributional assumption for delta-V to calculate parameters that reproduce the injury pattern for each crash scenario. This method was used first to estimate the delta-V distribution for each scenario, and then to weight the cases in the simulated crash dataset so that their outcomes (delta-V) are distributed like those of real-world crashes.

The research effort found that the current generation system offers significant safety improvements across all severities for both the tractor semitrailer and single unit trucks. The improved safety performance of the second generation system over the current system is attributed to the ability of the second generation system to respond to fixed vehicles. The difference in safety performance outcome between the second and third generation systems is attributed to the higher foundation brake deceleration. The influence of greater braking levels at the stage of "imminent collision" on safety outcome is significant but not as powerful as the safety improvements associated with fixed vehicle detection.

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