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Effectiveness of a Current Commercial Vehicle Forward Collision Avoidance and Mitigation Systems

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ABSTRACT

This paper focuses on the safety performance of Commercial Vehicle Forward Collision Avoidance and Mitigation Systems (F-CAM) that include Forward Collision Warning (FCW) with Collision Mitigation Braking (CMB) technology as applied to heavy trucks, including single unit and tractor semitrailers.

The study estimated the safety benefits of a commercially available F-CAM system considered to be representative of products currently in service. The functional characteristics were evaluated and its performance generically modeled to estimate safety benefits. This was accomplished through the following steps: (1) first characterize the actual performance of these systems in various pre-crash scenarios under controlled test track conditions, and then reverse engineering the algorithms that control warnings and automatic braking actions; (2) developing a comprehensive set of simulated crash events representative of actual truck striking rear-end crashes. This virtual, "reference" crash database was developed by analyzing vehicle interactions (or conflicts) from naturalistic studies to create thousands of crashes in a computer simulation environment; (3) overlaying the F-CAM generic algorithms into the simulations of each crash event and observe the kinematic impacts (i.e., benefits) from having initiated warnings and/or automatic braking (including reduction in impact speed, or crash elimination of the crash).

The crash population that could likely benefit from the technologies was identified using nationally representative crash databases. The results from the simulation studies were applied to the national crash population and are presented in terms of crashes avoided, reductions in fatalities, injuries and property damage.

INTRODUCTION

The material presented in this paper is the subject of a research project [1] funded by the National Highway Traffic Safety Administration (NHTSA) as part of a public private partnership with Meritor WABCO. The research was conducted independently by the University of Michigan Transportation Research Institute (UMTRI). The results and conclusions reported in this paper are not to be interpreted as being approved or endorsed by NHTSA.

Commercial Vehicle Forward Collision Avoidance and Mitigation Systems (F-CAM) include Forward Collision Warning (FCW) with Collision Mitigation Braking (CMB) technology. The current system referred to in this paper used forward-looking radar-based systems that combine Forward Collision Warning (FCW) with automatic Collision Mitigation Braking (CMB) capability. The FCW feature generates visual, audible and/or haptic warnings for the driver when a lead vehicle comes within a predefined distance and closing rate. If the truck driver does not respond to the warning with a braking input, and if the threat continues to worsen, then the F-CAM applies foundation brakes at a point when the collision is determined to be "imminent", (i.e., not avoidable through an evasive steering or lane change maneuver). As this paper will show, the driver warnings and automatic braking actions of current production systems could be effective at helping to mitigate crash severity or to avoid the crash altogether.

The current system does not react to "fixed objects" (defined as objects not in motion when detected by the F-CAM radar.) However if the object was moving within range of the radar and subsequently stopped, then the system will react to the "stopped" object. Throughout the paper, references made to "fixed" and "stopped" objects reflect this convention.

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 [2] and UMTRI's Trucks Involved in Fatal Accidents (TIFA) data [3]. 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.

About the Technology

The version of technology examined is the current commercially available OnGuard™ system herein referred to as the Current Generation (CG) system. The CG 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. At intervention the system gives visual, and haptic warnings to the driver followed by automatic braking as follows:

1. An audible and visual warning is first used to alert the driver to a developing rear-end collision. The timing of the warning is based on proprietary algorithms that use "time to collision" (TTC) and required "deceleration-to-avoid-collision" as primary inputs.

2. If the collision threat progresses, a haptic brake pulse warning (that lasts 0.5 s) is issued, and the engine-retarder is engaged to slow the truck.

3. At the point in which the collision is determined to be "imminent" (as judged so by the system designer), the foundation brakes are automatically applied to mitigate or avoid an impending collision.

Target Crash Population Analyses

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”.

As shown in Tables 1, 2, 3, 4, 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.

Table 1. Estimated Annual Rear-end Striking Crashes, Tractor-Semitrailers, TIFA 2003-2008, GES 2003-2008

	Fatal	Injury	PDO	Total
Crash type	**N**	**N**	**N**	**N**
LV fixed	62	882	2,119	3,078
LV stopped	13	1,244	2,987	4,263
LV slower	90	1,199	1,794	3,082
LV decel.	18	1,502	3,152	4,750
LV cut-in	9	156	649	814
Total	**192**	**4,983**	**10,701**	**15,987***

“PDO” specifies property damage only crashes.
* Total includes 111 crashes of unknown injury severity.

Table 2. Fatalities and Injuries in Rear-end Striking Crashes, Tractor-Semitrailers, TIFA 2003-2008, GES 2003-2008

	Injury severity				Total injuries
Crash type	**Fatal**	**A-injury**	**B-injury**	**C-injury**	
LV fixed	78	139	335	861	1,413
LV stopped	16	158	431	1,179	1,782
LV slower	107	601	865	727	2,300
LV decelerating	22	303	605	1,251	2,180
LV cut-in	9	87	48	115	259
Total	**231**	**1,287**	**2,284**	**4,132**	**7,934**

Table 3. Estimated Annual Rear-end Striking Crashes, Single Unit Trucks, TIFA 2003-2008, GES 2003-2008

Crash type	Fatal	Injury	PDO	Total
	N	**N**	**N**	**N**
LV fixed	20	1,215	2,202	3,438
LV stopped	8	2,228	4,037	6,270
LV slower	26	318	902	1,246
LV decel.	8	1,222	3,815	5,096
LV cut-in	1	134	187	322
Total	**63**	**5,117**	**11,143**	**16,374***

Table 4. Fatalities and Injuries in Rear-end Striking Crashes, Single Unit Trucks, TIFA 2003-2008, GES 2003-2008

	Injury severity				Total injuries
Crash type	**Fatal**	**A-injury**	**B-injury**	**C-injury**	
LV fixed	22	156	278	1,272	1,728
LV stopped	9	277	493	2,306	3,085
LV slower	30	116	154	241	542
LV decelerating	10	189	334	1,426	1,959
LV cut-in	1	2	38	141	182
Total	**72**	**740**	**1,298**	**5,386**	**7,496**

Test Track Evaluations

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 tests were performed at the Ford Michigan Proving Ground (MPG) located in Romeo, Michigan. A total of 282 individual tests were conducted with a fully loaded 5-axle tractor-semi (GVW 80,000 lbs.) on a controlled access vehicle dynamic test area. In general, tests were conducted in good weather, without excessive wind speed, and on a dry surface.

Figure 1. Subject vehicle with fabricated grill guard to protect against impacts with the target.

Testing was based on four scenarios involving the Subject Vehicle Figure 1, (i.e., the test truck equipped with the F-CAM technology; also referred to as the following vehicle), and a single Principal Other Vehicle (POV), which is the lead vehicle. The Principal Other Vehicle 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 all, four test scenarios were conducted:

- Closure From Long Range (lead vehicle moving slower at constant speed; also referred to as Lead Vehicle Slower)
- Lead Vehicle Decelerating
- Lane Change (Cut-in/out)
- Fixed Vehicle (i.e. lead vehicle was not moving when radar of subject vehicle first recognized the lead vehicle)

In the Closure from Long Range, Lead Vehicle Deceleration, and Fixed Vehicle scenarios, the lead vehicle is always in the same lane of travel as the truck. The Lane Change scenarios explore the system's ability to acquire and respond to a vehicle that suddenly appears in the path of the truck.

Figure 2. Final UMTRI towable target compatible with radar and vision systems

Safety Benefits Modeling

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 marketplace, 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 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. 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.

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 Integrated Vehicle Based Safety System (IVBSS) was 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. This 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 is not 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 & 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 delt-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 that 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 [7, 8, 9, 10].

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.

Establish delta-V Distributions for F-CAM-Relevant Crashes

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-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 taken in this study 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 estimation process requires three elements:

1. Relationship between delta-V and Injury for a Specified Damage Location

Delta-V describes the severity of the crash as experienced by a given vehicle, and injury risk is related to crashworthiness. Since crashworthiness differs for different damage areas, this relationship must be modeled for a specific crash direction. In the present context, delta-V is estimated for the lead vehicle in a rear-end crash. Thus, we are interested in the relationship between delta-V and injury for vehicles with rear damage.

2. Injury Distribution for Occupants in Target Crashes

Because GES uses the KABCO injury scale from police reports, the KABCO injury severity curves from CDS were generated to predict KABCO.

3. Distributional Assumption for delta-V

Testing for normality with a stratified, weighted sample is challenging, as standard methods (e.g., Kolmogorov-Smirnoff test) are not available. Instead, graphical methods were used to look at the relationship between the delta-V distribution for crashes in CDS and a variety of candidate distributions. From the set of candidates, the lognormal distribution was selected as it fit the data well, and has a convenient form that is easy to work with because of its relationship to the normal distribution.

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 stopped, slower, decelerating, cut-in).

Assess Impact of F-CAM Countermeasures in a Simulated Environment

The simulated crash conditions were generated and then re-simulated to determine when the safety technologies would act. These simulations used a set of simple technology models for FCW and CMB that were based on combinations of the following well-known components of Time to Collision (TTC, or range divided by closing speed) and Deceleration to Avoid DA), or the constant level of subject vehicle deceleration needed to just avoid impacting the vehicle ahead). The technology trigger models were based on information gained during test track testing. For example, to a very good approximation, the current generation system investigated in the test track study initiated the automatic braking when time to collision (TTC) was less than about 1.3 sec and the deceleration to avoid was less than −0.4 g.

The simulation of the F-CAM technology also employed a driver response model tied to the FCW. This consists of driver requested braking level (the same 0.3g level used in the baseline, or non-F-CAM simulations), which follows a time delay that represents a driver's reaction time in responding to an alert. The response to the FCW alert variable was a combination of data from the literature and observations of drivers in the IVBSS FOT responding to FCW alerts in cases that suggest that immediate braking was required by the driver. The outcome of these simulations determined whether a crash occurred and if it did occur, an estimate of the relative speed at impact.

Benefits Calculations

Cost savings resulting from the reduction in injuries and injury severity levels were estimated per victim injured, using economic estimates of costs of highway crashes involving large trucks [11, 12]. These costs represent the present value, computed at a 4% discount rate, of all costs over the victims' expected life span that result from a crash. They include medically related costs, emergency services costs, property damage costs, lost productivity, and the monetized value of the pain, suffering, and quality of life that the family loses because of a death or injury.

The estimated annual benefit analysis was conducted separately for tractor semitrailers and for straight trucks with no trailer. The results of the analysis are contained in Tables 5 and 6 for tractor semitrailers and Tables 7 and 8 for single unit trucks. The benefits assume that all trucks were fitted with the technology.

Table 5. Reduction in Injury Severity by Device for Tractor Semitrailers

Device	Fatal	Injury	No injury
Subsystem Contribution			
FCW only	24%	24%	9%
CMB only	4%	2%	-1%
Complete System Contribution			
Current Generation	**24%**	**25%**	**9%**

Table 6. Total Annual Economic Benefit in 2013 Dollars for Tractor Semitrailers (in millions of dollars)

Device	Fatal	Injury	No injury	Total
Subsystem Contribution				
FCW only	$396.6	$489.3	$30.0	$915.9
CMB only	$61.1	$54.3	($1.8)	$113.6
Complete System Contribution				
Current Generation	**$412.4**	**$513.0**	**$29.5**	**$954.9**

Table 7. Reduction in Injury Severity by Device for Single Unit Trucks

Device	Fatal	Injury	No injury
Subsystem Contribution			
FCW only	22%	20%	10%
CMB only	3%	2%	-1%
Complete System Contribution			
Current Generation	**22%**	**21%**	**10%**

Table 8. Total Annual Economic Benefit in 2013 Dollars for Single Unit Trucks (in millions of dollars)

Device	Fatal	Injury	No injury	Total
Subsystem Contribution				
FCW only	$109.3	$331.2	$26.2	$466.7
CMB only	$15.8	$36.4	($1.5)	$50.7
Complete System Contribution				
Current Generation	**$112.9**	**$342.8**	**$25.8**	**$481.5**

SUMMARY/CONCLUSIONS

The research described in this paper evaluated the potential effectiveness of and generated benefit estimates a commercially available current generation F-CAM system. The study focused exclusively on truck-striking rear-end crashes using five crash threat scenarios. The F-CAM system benefits were categorized by crashes avoided and crashes mitigated. The most significant research challenge was the estimation of benefits in mitigated crashes. This task required the development of new technical methods based on distribution modeling which used a combination of naturalistic driving data, existing crash data, and human factor brake performance data.

The challenge of forecasting benefits of technologies that have been recently introduced or are in the pre-release planning stages is significant, given that crash populations containing vehicles with the technology are absent or extremely small. Estimating benefits of any crash avoidance system requires identifying the population of crashes that the technology is intended to address, describing the expected outcome of those crashes with the technology implemented, and estimating the monetary value of the reduction in crashes. 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. Chief among them was the creation of a multidisciplinary research team of UMTRI scientists spanning the fields of vehicle testing, vehicle system engineering, complex data analysis, advanced statistics and modeling, and economic analysis. The team used 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 presented in this project 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 study did not examine unintended consequences that may be relevant to this technology although the likelihood of negative unintended consequences for current generation systems appears to be small. Unintended consequences would include things like false alarms and driver adaptation to the technology.

The research effort found that if the F-CAM technology were fitted to all tractor semitrailers the annual reduction in fatalities relative to the base population for current generation systems is 24 percent and the percentage of injury reductions is similar at 25 percent. The value of the combined annual benefit including property damage for current generation systems is $0.9 billion.

The annual reduction in fatalities relative to the base population for straight trucks having current generation systems is similar to the tractor semitrailer result, 22 percent. The percentage of injury reductions is also similar at 21 percent. The value of the combined annual benefit including property damage for current system is about half that of tractor semitrailers, $0.5 billion.

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