Safety Benefits of Forward Collision Warning, Brake Assist, and Autonomous Braking Systems in Rear-End Collisions

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***Abstract*—This paper examines the potential effectiveness of the following three precollision system (PCS) algorithms: 1) forward collision warning only; 2) forward collision warning and precrash brake assist; and 3) forward collision warning, precrash brake assist, and autonomous precrash brake. Real-world rear-end crashes were extracted from a nationally representative sample of collisions in the United States. A sample of 1396 collisions, corresponding to 1.1 million crashes, were computationally simulated as if they occurred, with the driver operating a precollision-system-equipped vehicle. A probability-based framework was developed to account for the variable driver reaction to the warning system. As more components were added to the algorithms, greater benefits were realized. The results indicate that the exemplar PCS investigated in this paper could reduce the severity (i.e., ΔV) of the collision between 14% and 34%. The number of moderately to fatally injured drivers who wore their seat belts could have been reduced by 29% to 50%. These collision-mitigating algorithms could have prevented 3.2% to 7.7% of rear-end collisions. This paper shows the dramatic reductions in serious and fatal injuries that a PCS, which is one of the first intelligent vehicle technologies to be deployed in production cars, can bring to highway safety when available throughout the fleet. This paper also presents the framework of an innovative safety benefits methodology that, when adapted to other emerging active safety technologies, can be employed to estimate potential reductions in the frequency and severity of highway crashes.**

***Index Terms*—Crash-imminent braking, intelligent transportation systems (ITSs), precollision system (PCS), rear-end collisions, safety systems.**

I. INTRODUCTION

ACTIVE safety systems that can prevent or mitigate forward crashes are a promising method of reducing crash-related injuries and property damage. Forward collision warning (FCW), precrash brake assist (PBA), and autonomous precrash braking (PB) systems are systems that are implemented in current and near-term passenger vehicles. These systems often depend on the millimeter-wave radar scanning technology to track vehicles and objects in front of the equipped vehicle. These systems can also use input from other sensors or interact with other systems such as speed sensors, steering angle sensors, and airbag control modules. FCW systems warn the driver through visual, audio, and/or tactile means of an impending collision. FCW has been designed to warn the driver close to the last possible moment before a driver corrective action can possibly avoid the collision. With regard to other systems, nuisance or false-positive alarms reduce the acceptance by the driver [1]. PBA is triggered when the vehicle recognizes an emergency-braking scenario and amplifies driver braking input when the driver applies the brake. In systems with multiple precollision system (PCS) components, PBA is designed to activate following the warning. Finally, PB is intended to autonomously add to the vehicle's braking deceleration, even if there is no driver input. In systems with multiple components, PB is triggered last, closest to the collision. Therefore, most PB systems are designed to trigger only when a collision is unavoidable. The main focus of PB is crash mitigation and not necessarily crash prevention.

One of the crash modes that are anticipated to be applicable to PCS is rear-end collision. A rear-end collision is one in which the front of one vehicle (the striking vehicle) impacts another vehicle that travels in the same direction of travel as the first vehicle (the struck vehicle). The struck vehicle can be decelerating, stopped, or moving at a lesser speed than the striking vehicle. Rear-end collisions are one of the most frequent multivehicle crash modes [2]. Although, in general, many of these collisions are low in severity, rear-end collisions can result in serious or fatal injuries. The combination of a high-frequency crash mode and the relative ease with which radar systems can track vehicles that travel in the same direction compared to other crash scenarios makes rear-end collisions a popular subject of study for PCS.

II. RELATED WORK

Significant work has been done to characterize and describe algorithms and hardware configurations for the proposed active safety systems [3]–[8]. Although these previous studies are extremely thorough in describing the implementation and testing of the individual proposed systems, they do not attempt to predict fleetwide benefits of these systems.

Previous studies that have projected benefits for PCS-related components focused on only one feature. However, vehicles both in the production and near-production combine PCS components into integrated systems. Although PCSs that contain FCW, PBA, and PB are currently available on some luxury

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brands, many automakers release systems that have only FCW or FCW in combination with PBA. In these integrated systems, the effectiveness of one PCS component is influenced by the other components. The effectiveness of the integrated PCS components is not simply the linear combination of each individual PCS component.

A review of intelligent transport systems by Bayly *et al.* summarizes the results of studies of expected fleetwide benefits for individual PCS components [9]. FCW systems were the most frequently studied PCS component. Studies that specifically pertain to rear-end collisions reported a range of crashes that were prevented from as low as 7% to as high as 80%. Studies that focus on PBA found a reduction in the number of applicable crashes from 26% to 75%. These PBA studies, however, aggregated several crash modes; rear-end impact was not separately broken out. Benefits in these studies were often implied from an assumed proportion of a target population that would benefit from the PCS component. Although every collision is different, these traditional effectiveness methodologies do not individually treat each collision and cannot predict the effectiveness of PCS on a case-by-case basis.

Driving simulators are also commonly used to assess potential benefits of PCS. For example, Lee *et al.* exposed driving simulator users to a lead vehicle stopped scenario and found that FCW reduced the number of collisions for that scenario by 80.7% [10]. This and other driving-simulator-based studies often only examine a small set of collision scenarios and, thus, cannot be extended to the overall system benefits expected throughout the fleet.

A. Current Study and Objective

This paper examined the effectiveness of the following three integrated PCS algorithms: 1) FCW only; 2) FCW + PBA; and 3) FCW + PBA + PB. This paper uses the unique approach of determining the effectiveness of PCSs on a case-by-case or microscopic basis for thousands of crashes and then aggregating these individual crash outcomes to determine the overall or macroscopic effectiveness of PCSs. The approach that was developed examined a nationally representative sample of moderate to severe collisions and simulated each case as if the vehicle was equipped with a functioning PCS. This paper is unique, because instead of describing a system or an algorithm, it asks how an ideal system, regardless of the implementation, would perform in a set of real-world crashes.

The objective of this paper is to estimate the safety benefits for the striking vehicle in rear-end collisions that are equipped with the following three precollision braking systems: 1) FCW; 2) PBA; and 3) PB. The benefits will be estimated in terms of reduction in the number of collisions, collision severity (ΔV), and the number of injured drivers.

III. METHODOLOGY

A. Case Selection

Real-world collisions were extracted from the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) from the years 1993 to 2008. NASS/CDS is a U.S. Department of Transportation–sponsored representative sample of minor to severe crashes that occurred in the U.S. Teams throughout the country investigate approximately 5000 crashes per year in detail. This investigation includes photographing and diagramming the scene of the collision, collecting information from police and medical records, conducting interviews with the occupants, and measuring damage to the vehicle(s). To be investigated, crashes must involve at least one passenger vehicle, and at least one vehicle must have been towed from the scene due to damage. NASS/CDS is annually released and is publically available for download from the National Highway Safety Administration (NHTSA) website [11]. Each case in a year from the NASS/CDS is assigned a national weight factor. This weight represents the number of similar collisions that annually occurred throughout the United States. In this paper, all analyses used the weighted values of cases from NASS/CDS.

Target vehicles were the striking vehicles in rear-end collisions. Rear-end collisions were identified by using a method that was adapted from the work of Eigen and Najm [12]. Precrash variables in NASS/CDS such as accident type ($ACCTYPE$), critical precrash event ($PREEVENT$), and precrash movement ($PREMOVE$) were used to classify crashes as a rear-end collision. Furthermore, only collisions that involve two vehicles ($VEHFORMS = 2$) and a single collision event ($EVENTS = 1$) were included. The crash event must have resulted in frontal damage to the striking vehicle. Both striking and struck vehicles were either a car, light truck, or van. To accommodate reconstruction of each case, both vehicles were required to have values that were recorded for the total ΔV, vehicle curb weight, and vehicle length. To compute the reduction in injured drivers, a known driver seat belt use was required.

B. Modeling the PCS Function

The activation of each of the PCS components varies by manufacturer and system. A simple metric that some PCSs use to judge collision threat is time to collision (TTC). TTC is the ratio of range x to range rate or relative velocity V_{12}, i.e.,

$$\mathrm{TTC} = \frac{x}{V_{12}}. \tag{1}$$

TTC has been shown to directly relate to driver's threat recognition in frontal collisions and is readily measured by radar sensors [13]. A PCS that has the three components (FCW, PBA, and PB) is described in the work of Aoki *et al.* [14]. Fig. 1 shows the activation times and system components in this system, which will be used as the basis for the PCS components in this paper.

To assess the benefits of PCS components in reducing crash severity, three algorithms were simulated for every striking vehicle that was involved in rear-end collisions: 1) equipped with FCW only; 2) equipped with FCW and PBA; and 3) equipped with FCW, PBA, and PB. FCW and PBA are already available on several passenger vehicles, and PB is beginning to become available on luxury vehicles, usually in

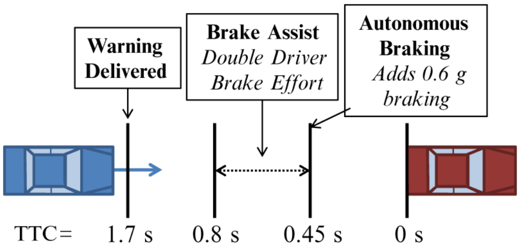

Fig. 1. Activation timing of PCS components leading to a crash.

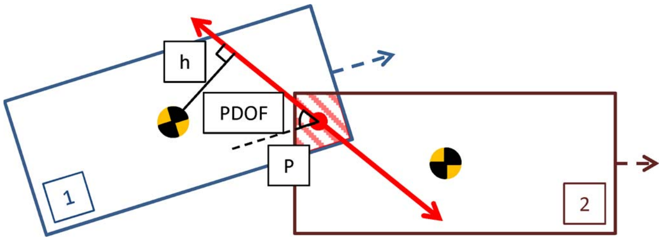

Fig. 2. Schematic of an arbitrary noncentral collision. The damage center location P reaches a common velocity. The change in velocity at the vehicle center of gravity is a function of the PDOF and damage location.

conjunction with FCW and PBA systems. Examining the three algorithms will allow for the comparison of the benefits of each system.

C. ΔV Estimates in NASS/CDS

Delta-V ΔV is defined as the change in velocity of a vehicle during a crash event, i.e., the difference between the velocity at impact and at separation. It is a standard in measuring the severity of a collision and has been found to be well correlated to occupant injury risk [15], [16]. ΔV is reconstructed, when possible, in cases from NASS/CDS by correlating vehicle damage in a crash to the energy that was absorbed by the vehicle body. Vehicle crush depth is measured by an NASS/CDS investigator. Using the conservation of momentum, ΔV is computed from the energy that was absorbed during the collision. This approach is often referred to as the Calspan Reconstruction of Accident Speeds on the Highway 3 (CRASH3) method for computing ΔV after an algorithm that was developed by McHenry [17]. One version of the CRASH3 algorithm is used by NASS/CDS investigators to reconstruct collisions. Full derivations of this method can be found elsewhere [17]–[19].

Fig. 2 shows a schematic of an arbitrary rear-end collision between vehicle 1, the striking vehicle, and vehicle 2, the struck vehicle. The resulting force of the collision is assumed to pass through a common point P. The location of P is found using the crush depth and width of the damage area. The principal direction of force (PDOF) is the direction of the resulting force with respect to the heading of the vehicle. The moment arm of the resulting collision force, h is geometrically found from the location and direction of the resulting force.

The change in velocity for vehicle 1 ΔV_1 can be derived as

$$\Delta V_1 = \sqrt{\frac{2E_T\gamma_1}{m_1\left(1+\frac{\gamma_2 m_2}{\gamma_1 m_1}\right)}} \tag{2}$$

where E_T is the total energy that was absorbed in the crash, γ is the effective mass coefficient, and m is the mass of the vehicle. To account for the rotational effects of the vehicle, an effective mass coefficient γ is computed for each vehicle as

$$\gamma = \frac{k^2}{k^2+h^2} \tag{3}$$

where k is the radius of gyration for the vehicle. The effective mass coefficient can fall between zero and unity and is representative of the proportion of the mass that contributes to the change in velocity along the vehicle's heading; the other proportion of the mass contributes to the rotational acceleration of the vehicle. The concept holds true when the moment arm of the resulting crash force stays constant during the collision, which is a reasonable assumption for relatively short collisions [20]. The examination of ΔV between 1993 and 2008 showed no correlation between the case year and the mean ΔV that was computed for each case year over the time period of NASS/CDS cases that were aggregated.

D. Computing the Reduced ΔV due to PB Impulse

To compute the benefits of PCSs, rear-end collisions were reconstructed using the information in NASS/CDS to predict the crash severity that would have occurred if the vehicle had been equipped with a PCS. A momentum approach similar to the CRASH3 method was used so that the ΔV that was recorded in NASS/CDS could directly be modeled. Consider a rear-end collision where the striking vehicle (vehicle 1) collides with a second vehicle (vehicle 2). ΔV for this collision for vehicle 1 is defined as

$$\Delta V_1 = \Delta V_{12,0} - V_C \tag{4}$$

where $\mathrm{V}_{12,0}$ is the velocity of vehicle 1 with respect to vehicle 2 at impact, and V_{C} is the common velocity that was achieved following the collision. The change in velocity of vehicle 2 is simply V_{C}. Therefore, the sum of the two ΔVs yields the impact velocity, i.e.,

$$\Delta V_1 + \Delta V_2 = V_{12,0} - V_C + V_C = V_{12,0}. \tag{5}$$

Now, consider a collision where the driver of vehicle 1 increases the braking magnitude from a_{t0} to a_{t1} and again to a_{t2} prior to the collision. This scenario is akin to how drivers who use a PCS experience an increase in braking in response to a warning and again prior to the collision through autonomous PB. A diagram of the vehicle deceleration before and after increased braking is shown in Fig. 3. The increases in braking level occur at a jerk authority of j. The jerk authority is the maximum rate at which deceleration can be increased by the braking system. The first braking pulse starts at a TTC TTC_1, and the second braking pulse starts at TTC_2. The first braking pulse has a duration of t_1, and the second braking pulse has a duration of t_2.

The speed of vehicle 1 at the time of the first brake activation TTC_1, $V_{12,1}$ can be found using a kinematic relationship as

$$V_{12,1} = a_{t0}\mathrm{TTC}_1 + \sqrt{(a_{t0}\mathrm{TTC}_1)^2 + (V_{12,0})^2}. \tag{6}$$

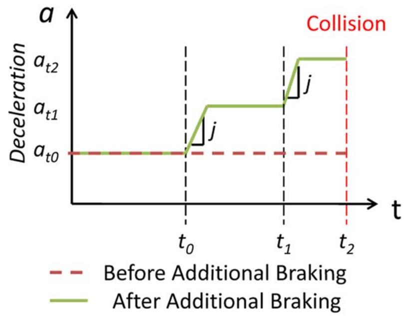

Fig. 3. Graph of general two-pulse braking deceleration. The braking deceleration a increases from a_{t0} to a_{t1} and again to a_{t2} at a jerk authority of j.

Examining the first braking pulse and integrating the acceleration of the vehicle yields the velocity of the vehicle at t_1, which is equal to the vehicle velocity at the start of the second braking pulse $V_{12,2}$, i.e.,

$$v(t_1) = V_{12,2} = -a_{t1}t_1 + \frac{(a_{t1}-a_{t0})^2}{2j} + V_{12,1}. \tag{7}$$

Integrating once more yields the position at t_1, i.e.,

$$x(t_1) = -\frac{1}{2}a_{t1}t_1^2 + \left(\frac{(a_{t1}-a_{t0})2}{2j} + V_{12,1}\right)t_1 - \left(\frac{(a_{t1}-a_{t0})2}{6j^2} + V_{12,1}\mathrm{TTC}_1\right). \tag{8}$$

The second braking pulse starts at an activation time of TTC_2, which corresponds to a position x_1, i.e.,

$$x(t_1) = V_{12,2}\mathrm{TTC}_2. \tag{9}$$

Due to symmetry in the equations, the kinematics of the vehicle is described similar to (7) and (8) for the second braking pulse. The resulting equations are quadratic, allowing for the braking times of the first and second pulses t_1 and t_2 to algebraically be solved.

The reduction in velocity that was created by the braking can be found by integrating the deceleration pulse as

$$\mathrm{P}_{\mathrm{brake}} = \frac{at_2^2 - at_0^2}{2j} + a_{t1}\left(t_1 - \frac{a_{t1}-a_{t0}}{j}\right) + a_{t2}\left(t_2 - \frac{a_{t2}-a_{t1}}{j}\right). \tag{10}$$

Using the conservation of momentum, the change in velocity after braking ΔV_1^* can be derived in terms of the change in velocity without additional braking ΔV_1 using an approach similar to the CRASH3 algorithm as

$$\Delta V_1^* = \Delta V_1 - \frac{\gamma_1\gamma_2 m_2}{\gamma_1 m_1 + \gamma_2 m_2}P_{\mathrm{brake}}. \tag{11}$$

This method is based on the velocity of vehicle 1 relative to vehicle 2. This method can be used if the struck vehicle accelerates or decelerates at a constant rate. The accelerations (a_0, a_1, and a_2) simply become the relative accelerations, i.e.,

$$a_{12} = a - a_s \tag{12}$$

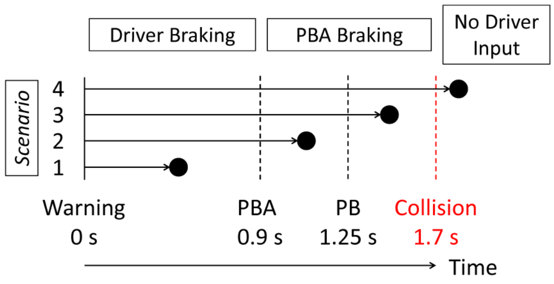

Fig. 4. Schematic of PCS component activation based on reaction time for (1) fast, (2) normal, (3) slow, and (4) no response. Filled circles indicate the time of driver brake application.

where a is the acceleration of vehicle 1, a_s is the acceleration of the struck vehicle, and a_{12} is the acceleration of vehicle 1 with respect to vehicle 2.

E. Modeling Driver Input and Vehicle Dynamics in Response to PCSs

The effectiveness of PCSs with FCW depends on the response of the driver to the warning. A simplified driver model was developed to describe the reaction time of the driver to FCW. The time from the issue of the warning to the time that the driver applies the brakes is the driver's reaction time. Reaction time is important for PCS algorithms, because it determines what systems will activate. For example, consider four scenarios of drivers applying the brakes in response to a warning, as shown in Fig. 4. FCW warns the driver 1.7 s before the collision. A fast reaction time (scenario 1) will cause the driver to apply the brakes before the threshold for PBA, resulting in only driver braking effort. However, a medium reaction time (scenario 2) will cause PBA to activate once the driver starts braking, doubling the driver braking effort. A slow reaction time (scenario 3) will still cause PBA to activate, but the braking time will be shorter. Finally, if the reaction time is greater than 1.7 s, the crash will occur before the driver applies the brake (scenario 4).

To determine the expected fleetwide benefits of PCS algorithms, a distribution of driver brake reaction times was used as developed by Sivak *et al.* [21]. The paper collected reaction times to visual warnings of 1644 drivers on a test track and found a mean reaction time of 1.21 s, with a standard deviation of 0.63 s. Assuming a log-normal distribution of reaction times, this distribution has been used to investigate the PCS warning response [22].

Fig. 5 shows the probability density function of driver response times. For all drivers in the population, 17% would have a reaction time greater than 1.7 s, thus having no response prior to the collision. Characteristic "fast," "medium," and "slow" response times were found from the remaining 83% of drivers. Characteristic "slow" and "fast" responses corresponded to 20% of the population. The median response time, i.e., 1.07 s, was used as the "medium" response time, which was used to characterize the remaining 43% of the population.

Based on the crash investigation, the speed at impact can be estimated using (5); however, the maneuvers of the driver prior to the collision without a PCS affect the vehicle speeds when

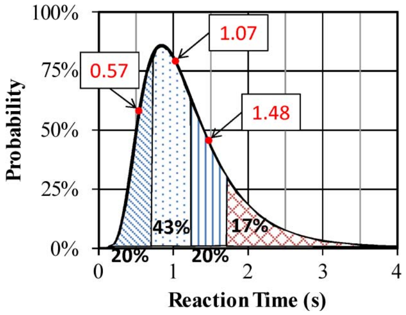

Fig. 5. Probability density function of driver reaction times and characteristic reaction times used for PCS simulations. Of the drivers, 17% have no response prior to the collision. The median response (1.07 s) is characteristic of 43% of the drivers. A fast response of 0.57 s and a slow response of 1.48 s are characteristic of 20% of the drivers, respectively.

PCS components activate. Drivers from striking vehicles were separated into the following three groups based on precrash maneuver ($MANEUVER$): 1) not braking; 2) braking; or 3) accelerating. The "not-braking" group was assumed to not apply the brakes at all prior to the collision. The "braking" group could apply the brakes in the following two ways: 1) late and hard braking, i.e., a driver who was inattentive realized a collision risk too late to avoid the collision, or 2) early and weak braking, i.e., a driver applies the brakes to avoid collision but misjudges the brake magnitude necessary to avoid the collision. The "braking" group was simulated with both late and hard braking, and early and weak braking. In the late and hard-braking scenario, the driver was assumed to apply the brakes at a TTC of 0.4 s, too late to avoid all collision in the data set. The accelerating group was assumed to apply a constant acceleration.

Similarly, braking or acceleration by the struck vehicle was separated into the same three precrash maneuver classes. If the $MANEUVER$ variable was missing for the struck vehicle, $ACCTYPE$ was used in its place. $ACCTYPE$ records the struck vehicle maneuver (moving, decelerating, or accelerating) in rear-end crashes but does not specify the striking vehicle maneuver.

The driver braking magnitude was set at constant levels. Hard braking for the striking vehicle produced a 0.4-g vehicle deceleration, whereas weak braking created 0.2 g of deceleration. The maximum vehicle deceleration possible was limited to 0.8 g. If the struck vehicle was braking, it was assumed that it was braking at 0.2 g, and PCS-equipped vehicle deceleration was found using (12). Simulations with PCS assumed that the driver of the striking vehicle would apply the brakes at the hard level (0.4 g) in response to the warning.

The following three algorithms were simulated: 1) FCW only; 2) FCW + PBA; and 3) FCW + PBA + PB. The combination of the four precrash maneuvers and four response times created 16 possible braking pulses after PCS implementation for each algorithm. A schematic of the 16 possible braking pulses by precrash maneuver and response time is shown for the FCW + PBA + PB system in Fig. 6. The dashed line shows the driver braking without PCS, and the solid line shows the vehicle braking with the PCS in response to the driver braking input with the PCS.

A similar schematic is shown for the FCW + PBA and FCW-only algorithms in Fig. 7. The solid lines show the FCW + PBA algorithm, and the small dashed lines show the braking pulse for the FCW-only algorithm. For the "no-response" category, neither algorithm has any benefit. For the "fast-response" category, braking initiates before the threshold for PBA activation; therefore, the two algorithms cause the same braking pulse. Because there is no PB activation, braking starts later for the "slow" response category compared with the FCW + PBA + PB algorithm.

F. Overall Algorithm Effectiveness

To estimate the overall algorithm effectiveness, the NASS/CDS national weighting factor for each case was split between simulations to generate a single distribution of effectiveness after PCS activation. For cases where the driver was not braking or accelerating, 17% of the case weight was assigned to the no-effect simulation, 20% to the fast-response simulation, 43% to the medium response simulation, and 20% to the slow response simulation. For cases that reported driver braking, it was assumed that the late hard-brake and early weak-braking scenarios had an equal probability of occurring. Therefore, 8.5% of the case weight was assigned to the no-response simulation, 10% to the fast-response simulation, 21.5% to the medium-response simulation, and 10% to the slow-response simulation for each maneuver. Splitting the weighting factor ensured that the overall system performance reflected the distribution of driver reaction times.

A large number of cases (13.5%) had a missing or unknown precrash vehicle maneuver. This result is coded in NASS/CDS when the investigator cannot determine with confidence the precrash maneuver. For cases with unknown or missing precrash vehicle maneuver, simulations for all the maneuvers were performed.

To determine the overall system performance, the distribution of reaction times was combined with the distribution of precrash maneuvers observed in the known population. With respect to rear-end collisions with the known braking status, 29% were not braking, and 71% were braking, with almost none ($< 1\%$) accelerating. Because there were almost no crashes with the striking vehicle accelerating prior to the collision, accelerating simulations were not performed for unknown cases with an unknown maneuver. Multiplying the response time probability with the maneuver probability gave the proportion of the case's weighting factor assigned to each simulation, as shown in Table I.

G. Injury Risk After PCS Activation

To estimate the number of injured drivers after PCS activation, an injury risk curve was used to predict the number of injured drivers. An injury risk curve, which relates the probability of injury to crash severity and seatbelt use, was used from a previously published study [23]. Injury was defined as a maximum abbreviated injury score (MAIS) of 2 or greater (MAIS2+), representing moderately to fatally injured drivers. The abbreviated injury score is a measure of an injury's threat

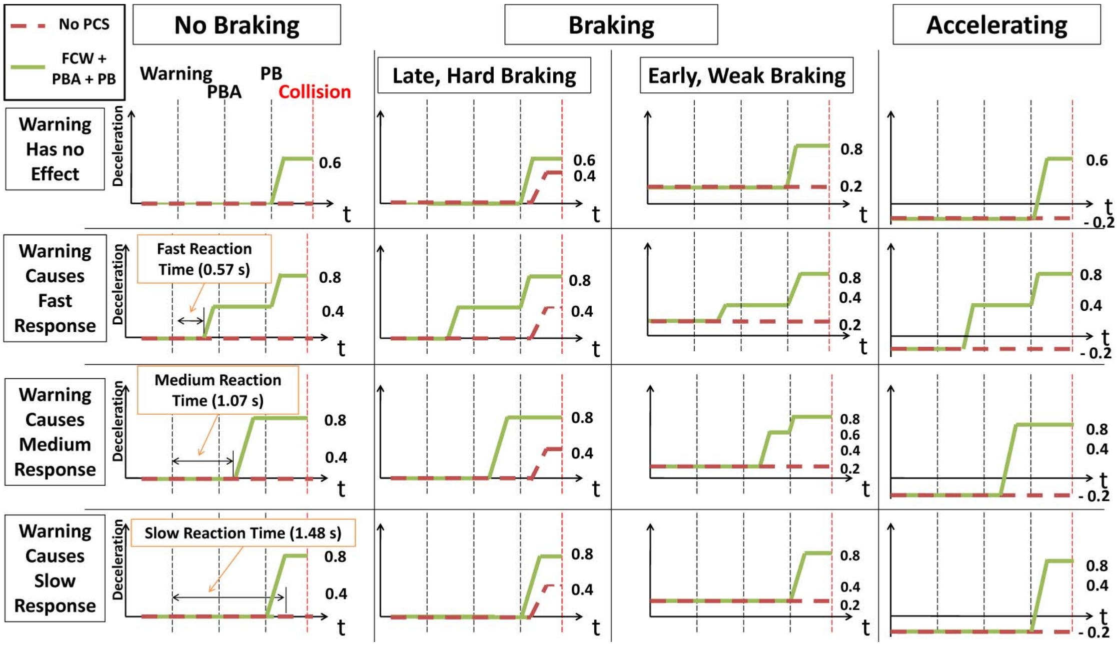

Fig. 6. Schematic of PCS braking pulses for precrash maneuver and response time for the FCW + PBA + PB algorithm. The dashed line shows the estimated braking pulse without PCS activation, and the solid line shows the brake pulse after PCS activation, with the magnitudes g and delay times s labeled.

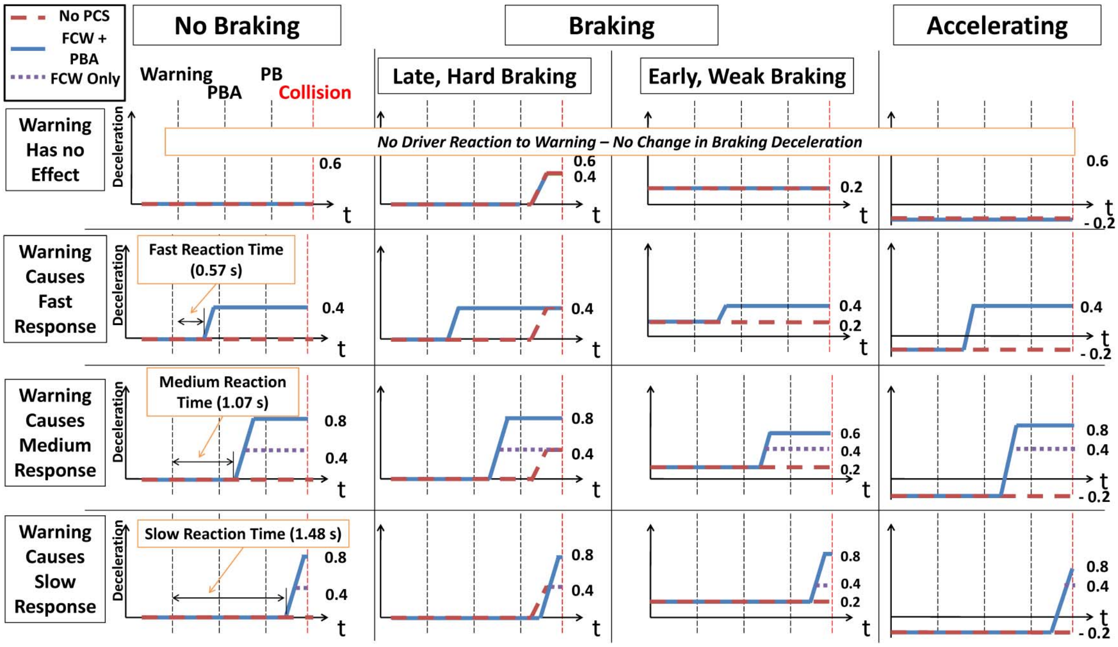

Fig. 7. Schematic of PCS braking pulses for FCW + PBA and FCW-only algorithms. The large dashed line shows the estimated braking pulse without PCS activation, and the solid line shows the brake pulse after PCS activation, with the magnitudes g and delay times s labeled.

to life, with 0 being no injury and 6 being fatal injury [24]. In the previous study, logistic regression was used to fit an injury risk curve to a similar population of rear-end collisions. The resulting risk curve had the form

$$P(\Delta V, belt\ use) = \frac{1}{1+e^{-(\beta_0+\beta_1\Delta V+\beta_2(belt))}} \tag{13}$$

where β_0, β_1, and β_2 are coefficients that were determined by the regression analysis. For belt use, the quantity $belt$ was set to 1 for belted drivers and -1 for unbelted drivers. The coefficients for the injury risk curve are listed in Table II.

The total number of injured drivers N was estimated as

$$N = \sum_{i=1}^{N} w_i\ P(\Delta V_i, belt\ use) \tag{14}$$

where w_i and ΔV_i are the weight and simulated ΔVs assigned to each simulation. Simulation weights w_i are derived from splitting the NASS/CDS sampling weight for each case, as aforementioned. To compare the PCS outcome to the outcome without a PCS, the number of injured drivers without a PCS was estimated in the same way. Injury reduction was computed

TABLE I
DISTRIBUTION OF CASE WEIGHT FOR CASES WITH UNKNOWN PRECRASH MANEUVER PRIOR TO PCSS

			Maneuver[b]		
			NB	HLB	WEB
			29%	35.50%	35.50%
Response Time[a]	NR	17%	5%	6%	6%
	FR	20%	6%	7%	7%
	MR	43%	13%	15%	15%
	SR	20%	6%	7%	7%

[a] NR – no response, FR – fast response, MR – medium response, SR – slow response

[b] NB – no braking, HLB – hard, late braking, WED – weak, early braking.

TABLE II
INJURY RISK CURVE COEFFICIENTS BASED ON THE WORK OF KUSANO AND GABLER [23]

Parameter		Value
Intercept	β_0	-6.068
ΔV	β_1	0.1000
Belt Use	β_2	-0.6234

only for belted drivers. Because the relatively high levels of braking involved a PCS, there is a possibility that unbelted occupants are thrown out of position prior to the collision. Out-of-position front-seat occupants in airbag-equipped vehicles are more likely than belted occupants to suffer serious injury due to being closer to the airbag deployment. Because of this unknown aspect of potential increase in driver injury, injury reduction benefits for unbelted occupants were not computed.

H. System Limitations

The maximum vehicle braking deceleration is restricted by the road surface type and conditions. Table III lists the nominal maximum braking deceleration for different surfaces and conditions [25]–[27]. Surface type and condition were determined from the variables $SURTYPE$ and $SURCOND$, respectively. Vehicles were determined to be sliding based on the precrash maneuver $MANEUVER$ and precrash impact stability $PREISTAB$. Unknown surface types were assumed to be pavement, asphalt, or concrete, and unknown surface conditions were assumed to be dry. If the vehicle stability was unknown, it was assumed that the vehicle was tracking prior to the collision. Because vehicles with a PCS would feature an antilock brake system (ABS), striking vehicles were assumed to achieve the maximum possible braking deceleration with PCS activation. The braking decelerations for each simulation were adjusted to reflect the maximum braking deceleration based on surface type, condition, and stability.

Most PCSs do not activate at low vehicle speeds. The FCW and PB systems were assumed to activate at relative vehicle speeds greater than 15 km/h (9.32 mi/h). The PBA component was assumed to activate at relative vehicle speeds greater than 30 km/h (18.6 mi/h). If the warning threshold was not met at the time of system activation, the case had no system activation and, thus, no benefit. If the PBA threshold was not reached, braking was accordingly adjusted to match the driver's input. If the PB threshold was not reached, the braking level was maintained at its previous level until the collision.

TABLE III
MAXIMUM BRAKING DECELERATION (IN GRAVITATIONAL FORCE, g) FOR DIFFERENT SURFACE TYPES AND CONDITIONS [25]–[27]

Surface Condition	Braking (no lockup)	Sliding (all wheels locked)
Dry Pavement / Asphalt / Concrete	0.8	0.65
Wet Pavement / Asphalt / Concrete	0.7	0.55
Snow	0.4	0.25
Ice	0.15	0.075
Dry Gravel/Dirt	0.7	0.6
Wet Gravel/Dirt	0.6	0.5

TABLE IV
DISTRIBUTION OF PRECRASH MANEUVERS

Braking Type	Strik. Veh.	% Strik. Veh.	Struck Veh.	% Struck Veh.
No Braking	271,259	25.0%	994,505	92%
Braking	468,346	43.2%	78,588	7%
Braking with Lockup	197,453	18.2%	1,062	0%
Accelerating	1,591	0.1%	10,371	1%
Unknown	145,877	13.5%	-	-

TABLE V
DISTRIBUTION OF ROAD SURFACE CONDITIONS

Surface Condition	Number of Crashes	% of Crashes
Dry	872,614	80.5%
Wet	191,267	17.6%
Snow or Slush	16,242	1.5%
Dirt, Mud, Gravel	4,355	0.4%
Missing	50	0.0%

IV. RESULTS

A. Selected Cases

Of all rear-end collisions in NASS/CDS from 1993 to 2008, 1396 cases met all the requirements of this paper. These cases accounted for approximately 1 080 000 rear-end collisions. Table IV shows PB maneuvers for striking and struck vehicles. The most frequent striking vehicle maneuver was applying the brakes (61.4%), followed by not applying the brakes (25%). Of the striking vehicles, 13.5% had a missing or unknown maneuver status. Of the struck vehicles, 92% of the vehicles were not applying the brakes, and 7% of the vehicles were braking.

Almost all cases (99.7%) occurred on concrete, asphalt, or pavement. The remaining cases occurred on dirt or gravel roads. Table V shows the distribution of surface conditions in the selected cases. The majority (80.5%) of crashes occurred on dry roads, followed by wet roads (17.6%). Snow and ice combined to account for approximately 2% of cases, with only a fraction of a percentage being unknown.

B. Algorithm Performance

Fig. 8 shows the overall distribution of crash severity after PCS algorithm activation compared with no a PCS. The

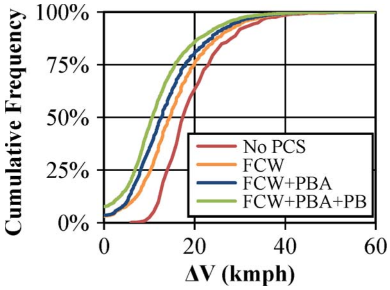

Fig. 8. Cumulative distribution of crashes after PCS algorithm implementation.

TABLE VI
MEDIAN REDUCTION IN ΔV AND PREVENTED COLLISIONS FOR EACH PCS ALGORITHM

Algorithm	Percentage of Crashes Prevented	Median ΔV (kmph)	Percent Reduction of Median ΔV
No PCS	-	17.0	-
FCW	3.2%	14.7	14%
FCW + PBA	3.6%	13.0	24%
FCW + PBA + PB	7.7%	11.3	34%

TABLE VII
PREDICTED NUMBER OF MODERATELY TO FATALLY INJURED DRIVERS FOR PCS ALGORITHMS (NASS/CDS 1993–2008)

Algorithm	Predicted Number of Injured Drivers	Percent Reduction
No PCS	12,338	-
FCW	8,755	29%
FCW + PBA	7,487	39%
FCW + PBA + PB	6,123	50%

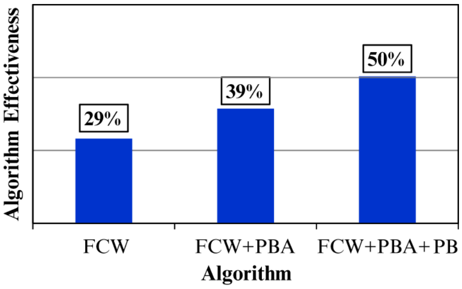

Fig. 9. Effectiveness of pcs algorithms in reducing the number of seriously to fatally injured drivers (MAIS2+).

additional PCS components reduced the distribution of ΔV and the number of collisions prevented. For the FCW + PBA algorithm, at lower severities, the relative velocity threshold for PBA activation was often not met. As a result, low-severity collisions had a similar outcome for the FCW + PBA and FCW-only algorithms.

Table VI summarizes the percentage of crashes avoided and the reduction in median ΔV of nonprevented collisions due to PCS algorithm activation.

Table VII shows the predicted reduction in the number of moderately to fatally injured belted drivers for the three PCS algorithms for NASS/CDS from 1993 to 2008. Fig. 9 shows the number of moderately to fatally injured, belted drivers for the three PCS algorithms in graphical form.

TABLE VIII
PERCENTAGE OF COLLISIONS WITH NO PCS COMPONENT ACTIVATION DUE TO SYSTEM LIMITATIONS

Algorithm	FCW	PBA	PB
FCW	0.1%	-	-
FCW + PBA	0.1%	13%	-
FCW + PBA + PB	0.1%	12%	11%

Table VIII shows the percentage of all weighted collisions where various PCS components did not activate due to system limitations. Of the drivers who braked early enough to activate the PCS, 0.1% did not activate FCW, because the relative vehicle velocity at FCW activation was below the 15-km/h threshold. This case is a reflection of the fact that NASS/CDS includes only cases that occurred at great-enough speed to require a vehicle to be towed due to damage. For the FCW + PBA algorithm, 13% of all collisions had FCW activated, but PBA did not activate, because the 30-km/h relative velocity threshold was not met. For the FCW + PBA + PB algorithm, PBA did not activate in 12% of the cases. This proportion was slightly less than the FCW + PBA algorithm because of earlier braking in the “slow-response” category. Finally, in 11% of the cases, FCW and PBA activated, but PB did not activate, because the relative velocity was below the 15-km/h relative velocity threshold.

V. DISCUSSION

A. *Implication of Results*

This paper shows the potential effectiveness of three PCS algorithms that represent increasingly advanced braking systems. The simulation takes into account a range of potential driver inputs using population distributions to estimate likely results. This way, this paper provides an explicit estimate of the expected fleetwide PCS algorithm effectiveness.

Additional PCS components increased effectiveness in mitigating collisions. FCW alone decreased the median ΔV by 14%. The FCW + PBA and FCW + PBA + PB algorithms decreased the median ΔV by 24% and 34%, respectively. The addition of PCS components also prevented the number of collisions. Although PB is thought of as a collision-mitigating countermeasure, PB in combination with FCW and PBA can help a driver avoid collisions when he/she applies the brakes in response to a last-second warning. PBA only activates at high relative vehicles speeds (greater than 30 km/h). As such, in low-severity rear-end impacts that could be avoided, PBA may not activate. The result is that the FCW-only and FCW + PBA algorithms prevented a similar number of collisions. Changes in the activation threshold for PBA could serve to prevent more collisions for the FCW + PBA algorithm.

The PCS algorithms show large potential effectiveness for reducing the number of moderately to fatally injured drivers. Fortunately, most injuries in rear-end collisions are relatively minor. Of the drivers in rear-end collisions, 30% sustained minor injuries (e.g., minor cervical spine injury and abrasions). These occupants would also see benefits from reduced crash severity, which were not estimated here. In addition, the economic benefits (e.g., property damage) from prevented and mitigated collisions were not considered.

Using real-world data, e.g., based on NASS/CDS, is advantageous to predicting safety benefits. The crashes simulated here are a nationally representative set of rear-end collisions that all resulted in a collision without PCS implementation. The impact severities are a distribution of minor to severe collisions that have historically been experienced in the field. By accounting for the distribution of possible driver responses, the results estimate the expected overall system benefits for each algorithm. Because crashes in NASS/CDS must involve at least one vehicle towed due to damage, very minor collisions are not included. However, because these collisions occur at low-impact speeds, it is unlikely that all of the PCS components would activate. This paper aids in the understanding of potential benefits of PCSs in systems with multiple components.

B. Limitations

Although this paper presents a possible range for PCS algorithm performance, it still provides an ideal case. This analysis assumed that the successive stages of PCSs would successfully activate. In practice, one or more systems may not activate due to tracking and sensing limitations. Actual field performance of systems may be less effective. In real-world applications, limitations in the sensors and algorithms may cause difficulty in accurately sensing TTC. Furthermore, real-world PCS may use more complex algorithms to determine collision risk instead of or in addition to TTC [28]–[31]. Different algorithms will have different effectiveness. PCS algorithms will be manufacturer specific, but published reports suggest that they share many similarities, including their use of TTC. This paper has evaluated three algorithms that are believed to be characteristic of the current and proposed PCS systems. The methods that were presented here can readily be tailored to model the manufacturer-specific variables in PCS algorithms.

The driver model was greatly simplified due to the limited information available for the driver's state prior to the collision. The simulation did not include any effect of PCSs on driver maneuvers other than braking, such as steering, prior to the collision. Of the cases examined, only 8% had a recorded avoidance maneuver of steering alone. In addition, the driver model assumed that driver's braking increased at a constant rate and remained constant at a specified magnitude. In practice, driver deceleration can change in magnitude during a braking period. Without instrumentation in real-world collisions, further simulation of driver braking deceleration was not feasible beyond constant magnitudes. Although the driver model included a range of possible driver reactions, it did not capture all possible driver braking inputs.

The reconstruction techniques that were used to compute ΔV in each simulation were limited by the information available from crash investigations. The CRASH3 damage method of computing ΔV that was used by investigators in NASS/CDS was derived out of the need to estimate ΔV without significant knowledge of precrash conditions of the vehicles. The correlation between damage and absorbed energy is found by obtaining vehicle stiffness from crash tests. Although this method has been validated and studied, it relies on vehicle stiffness data from a relatively small number of crash tests extrapolated to the entire vehicle fleet [19]. Therefore, ΔV estimates that were derived from the CRASH3 method are known to vary, depending on the vehicles involved in the collision [32].

VI. CONCLUSION

This paper has identified the potential effectiveness of the following three PCS algorithms: 1) FCW only; 2) FCW + PBA; and 3) FCW + PBA + PB. For the FCW algorithm, the median ΔV was reduced by 14% compared to crashes with no PCS. The FCW + PBA and FCW + PBA + PB algorithms decreased the median ΔV by 24% and 34%, respectively. For the FCW-only algorithm, 3.2% of the collisions could have been avoided. For the FCW + PBA and FCW + PBA + PB algorithms, 3.6% and 7.7% of the crashes could have been prevented, respectively. The FCW-only algorithm reduced the number of belted moderately to fatally injured drivers by 29%, the FCW + PBA algorithm by 39%, and the FCW + PBA + PB algorithm by 50%. This paper has shown the dramatic reductions in serious and fatal injuries that PCSs, one of the first intelligent vehicle technologies to be deployed in the production of cars, can bring to highway safety, when available, throughout the fleet. This paper has also presented the framework of an innovative safety benefits methodology that, when adapted to other emerging active safety technologies, can be employed to estimate potential reductions in the frequency and severity of highway crashes.

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