POTENTIAL EFFECTIVENESS OF INTEGRATED FORWARD COLLISION WARNING, PRE-COLLISION BRAKE ASSIST, AND AUTOMATED PRE-COLLISION BRAKING SYSTEMS IN REAL-WORLD, REAR-END COLLISIONS

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ABSTRACT

This study examines the potential effectiveness of a Pre-Collision System (PCS) that integrates Forward Collision Warning (FCW), Pre-crash Brake Assist (PBA), and autonomous Pre-crash Braking (PB). Real-world rear-end crashes were extracted from NASS/CDS years 1993 - 2008. The sample of 1,396 collisions, corresponding to 1.1 million crashes, was simulated as if the striking vehicle had been equipped with PCS. A stochastic framework was developed to account for the variability in driver response to the warning system. The result was an estimate of PCS benefits in terms of crash severity (change in velocity during the collision, ΔV), injury reduction for drivers, and prevented collisions. The results indicate that PCS reduced the median ΔV by 34%. The number of moderately to fatally injured drivers wearing their seat belt was reduced by 50%. Finally, 7.7% of collisions were prevented.

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), pre-crash brake assist (PBA), and autonomous pre-crash braking (PB) systems are systems being implemented in current and near-term passenger vehicles. All three of these systems often depend on 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 otherwise 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 driver corrective action can possibly avoid the collision. As with 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 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 being designed to trigger only when a collision is unavoidable. Therefore, the main focus of PB is crash mitigation, not necessarily crash prevention.

One of the crash modes that is anticipated to be applicable to PCS is the rear-end collision. A rear-end collision is one in which the front of one vehicle (the striking vehicle) impacts another vehicle traveling 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 multi-vehicle crash modes. 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 at which radar systems can track vehicles traveling in the same direction compared to other crash scenarios makes rear-end collisions a promising crash mode for PCS application.

A review of Intelligent Transport Systems by Bayly *et al.* summarizes the results of studies of expected fleet-wide benefits for individual PCS components [2]. Forward collision warning systems were the most frequently studied PCS component. Studies pertaining specifically to rear-end collisions reported a range of crashes prevented from as low as 7% to as high as 80%. Studies focusing 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 broken out separately. 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, this traditional effectiveness methodology does not treat each collision individually 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 for that scenario by 80.7% [3]. 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.

Many studies that have examined PCS related components have focused on only one feature. However, vehicles both in production and near-production are combining PCS components into an integrated system. 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.

This study will examine the effectiveness of an integrated PCS containing FCW, PBA, and PB. The study uses the unique approach of determining the effectiveness of PCS 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 PCS. The approach 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.

OBJECTIVE

The objective of this study is to estimate the safety benefits for the striking vehicle in rear-end collisions which are equipped with a pre-collision braking system consisting of forward collision warning, pre-crash brake assist, and pre-crash brake. Benefits will be estimated in terms of reduction in the number of collisions, collision severity (ΔV), and the number of injured drivers.

METHODOLOGY

Case Selection

Real-world collisions were extracted from the National Automotive Sampling System / Crashworthiness Data System (NASS / CDS) from year 1993 to 2008. NASS / CDS is a U.S. Department of Transportation sponsored, representative sample of minor to severe crashes that occurred in the United States. Teams throughout the country investigate approximately 5,000 crashes per year in detail. This investigation includes visiting the scene of the accident, collecting information from police and medical records, photographing and diagraming the scene, conducting interviews with the occupants, and measuring damage to the vehicle(s). In order to be investigated, crashes must feature at least one passenger vehicle and at least one vehicle must have been towed from the scene due to damage. NASS / CDS is released yearly and is publically available for download from the National Highway Safety Administration (NHTSA). Each case in a year of NASS / CDS is assigned a national weight factor. This weight represents the number of similar collisions that occurred annually throughout the entire U.S. In this study 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 adapted from Eigen and Najm [4]. Pre-crash variables in NASS / CDS such as accident type (*ACCTYPE*), critical pre-crash event (*PREEVENT*), and pre-crash movement (*PREMOVE*) were used to classify crashes as a rear-end collision. Furthermore, only collisions involving 2 vehicles (*VEHFORMS* = 2) and involving 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 recorded for total ΔV, vehicle curb weight, and vehicle length. To compute the reduction in injured drivers, a known driver seat belt use was required.

Modeling PCS Function

Activation of each of the PCS components varies by manufacturer and system. A simple metric that many PCS 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}:

$$TTC = \frac{x}{V_{12}} \quad (1).$$

TTC has been shown to directly relate to driver's threat recognition in frontal collisions and is readily measured by radar sensors [5]. A PCS that has the three components described earlier (FCW, PBA, and PB) is presented by Aoki *et al* [6]. The activation times for the PCS components in this system are shown in Table 1..

Table 1.
Activation Timing for PCS Components.

PCS Component	TTC Activation (s)	Effect
Forward Collision Warning (FCW)	1.7	Warns the driver through audio, tactile, and/or visual warning
Pre-crash Brake Assist (PBA)	0.8	Doubles driver braking effort
Pre-crash Brake (PB)	0.45	Increases vehicle deceleration by a level of 0.6 g

To assess the benefit of PCS components in reducing crash severity, crashes were simulated for every striking vehicle involved in rear-end collisions as if they were equipped with FCW, PBA, and PB.

ΔV Estimates in NASS/CDS

The ΔV (delta-V) is defined as the change in velocity of a vehicle during a crash event, i.e. the difference between the velocity at impact and the separation velocity. ΔV is a standard metric of the severity of a collision and has been found to be well correlated to occupant injury risk [7, 8]. The ΔV is reconstructed when possible in cases from NASS / CDS by correlating vehicle damage in a crash to the energy absorbed by the vehicle body. Vehicle crush depth is measured by the NASS / CDS investigator, as shown in Figure 1. Using conservation of momentum the ΔV is computed from the energy absorbed during the collision. This approach is often referred to as the "CRASH3" method for computing ΔV after an algorithm developed by McHenry [9]. A version of the CRASH3 algorithm is used by NASS / CDS investigators to reconstruct collisions. Full derivations of this method can be found elsewhere [9-11].

Figure 1. Photograph of Vehicle Being Measured for Crush Damage.

A schematic representation of the collision is shown in Figure 2. The resultant 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 resultant force with respect to the heading of the vehicle. The moment arm of the resultant collision force, *h*, is found geometrically from the location and direction of the resultant force.

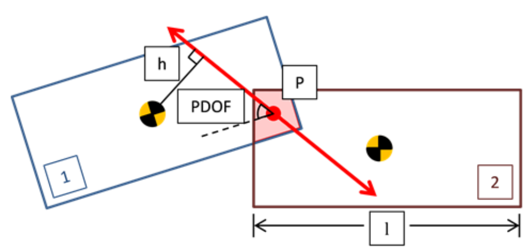

Figure 2. Schematic Representation of Non-central Collision.

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

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

where E_T is the total energy 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:

$$\gamma = \frac{k^2}{k^2+h^2} \quad (3).$$

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 rotational acceleration of the vehicle. The concept holds true when the moment arm of the resultant crash force stays constant during the collision, which is a reasonable assumption for relatively short collisions [12].

Computing Reduced ΔV due to Pre-crash Braking Impulse

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

$$\Delta V_1 = V_{12,0} - V_C \quad (4).$$

where $V_{12,0}$ is the velocity of vehicle 1 with respect to vehicle 2 at impact and V_C is the common velocity 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:

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

Now consider a collision where the driver of vehicle 1 increases the braking magnitude from a_0 to a_1 and again to a_2 prior to the collision. This scenario is akin to how drivers using a PCS experience an increase in braking in response to a warning and again prior to the collision via autonomous pre-crash braking. A diagram of the vehicle deceleration before and after increased braking is shown in Figure 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 time to collision TTC_1 and the second at TTC_2. The first braking pulse has duration of t_1, and the second braking pulse has duration of t_2.

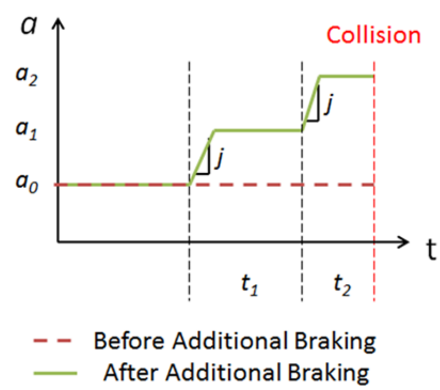

Figure 3. Graph of general, two-pulse braking deceleration. braking deceleration, *a*, increases from a_0 to a_1 and again to a_2 at a jerk authority of *j*.

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:

$$V_{12,1} = a_0 TTC_1 + \sqrt{(a_0 TTC_1)^2 + (V_{12,0})^2} \quad (6).$$

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, $V_{12,2}$:

$$v(t_1) = V_{12,2} = -a_1 t_1 + \frac{(a_1-a_0)^2}{2j} + V_{12,1} \quad (7).$$

Integrating once more yields the position at t_1:

$$x(t_1) = -\frac{1}{2}a_1 t_1^2 + \left(\frac{(a_1-a_0)^2}{2j} + V_{12,1}\right)t_1 - \left(\frac{(a_1-a_0)^3}{6j^2} + V_{12,1}TTC_1\right) \quad (8).$$

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

$$x_1 = -V_{12,2}TTC_2 \quad (9).$$

Due to symmetry, the kinematics of the vehicle are described similarly 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 be solved algebraically.

The reduction in velocity created by the braking can be found by integrating the deceleration pulse:

$$\mathrm{P_{brake}} = \frac{a_2^2 - a_0^2}{2j} + a_1\left(t_1 - \frac{a_1 - a_0}{j}\right) + a_2\left(t_2 - \frac{a_2 - a_1}{j}\right) \quad (10).$$

Using 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:

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

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

$$a_{12} = a - a_s \quad (12).$$

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.

Modeling Driver Input and Vehicle Dynamics in Response to PCS

The effectiveness of PCS with FCW is dependent upon the response of the driver to the warning. A simplified driver model was developed to describe the reaction time of the driver to the FCW. The time from the issue of the warning to the time that the driver applies the brakes is a 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, shown in Figure 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 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).

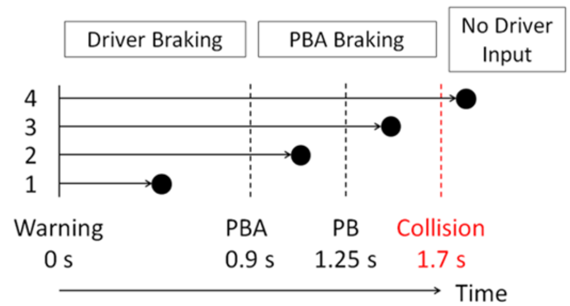

Figure 4. Schematic of PCS component activation based on reaction time for fast (1), normal (2), slow (3), and no response (4). Filled circles indicate the time of driver brake application.

To determine the expected fleet-wide benefits of PCS algorithms, a distribution of driver brake reaction times was used as developed by Sivak *et al* [13]. This study collected reaction times to visual warnings of 1,644 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 lognormal distribution of reaction times, this distribution has been used to investigate PCS warning response [14].

Figure 5 shows the probability distribution 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 were found which corresponded to 20% of the population. The median response time, 1.07 s, was used as the "medium" response time, which was used to characterize the remaining 43% of the population.

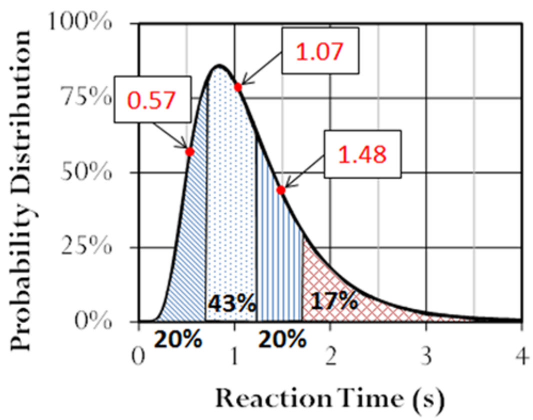

Figure 5. Probability distribution of driver reaction times and characteristic reaction times used for PCS simulations.

From the crash investigation, the speed at impact can be estimated using (Equation 5); however, the maneuvers of the driver prior to the collision without PCS affect the vehicle speeds when PCS components activate. Drivers were separated into 3 groups based on pre-crash 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 two ways: late and hard braking, as a driver who was inattentive and realized a collision risk too late to avoid the collision, or early and weak braking, as a driver who applies the brakes to avoid a collision but misjudges the brake magnitude necessary to avoid the collision. The “braking” group was simulated with both late, hard braking and early, weak braking. The accelerating group was assumed to apply a constant acceleration.

Similarly, braking or acceleration by the struck vehicle was separated into the same three pre-crash maneuver classes. When the MANEUVER variable was missing or unknown for the striking vehicle, the crash was reconstructed using all three pre-crash 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.

Driver braking magnitude was set at constant levels. Hard braking produced a 0.4 g vehicle deceleration, while 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 they were braking at 0.2 g and PCS equipped vehicle deceleration was found using (12). Simulations with PCS assumed the driver would apply the brakes at the hard level (0.4 g) in response to the warning.

The combination of the four pre-crash 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 pre-crash maneuver and response time is shown for the FCW + PBA + PB system in Figure 6. The large dashed line shows the driver braking without PCS and the solid line shows the vehicle braking with PCS in response to the driver braking input with PCS.

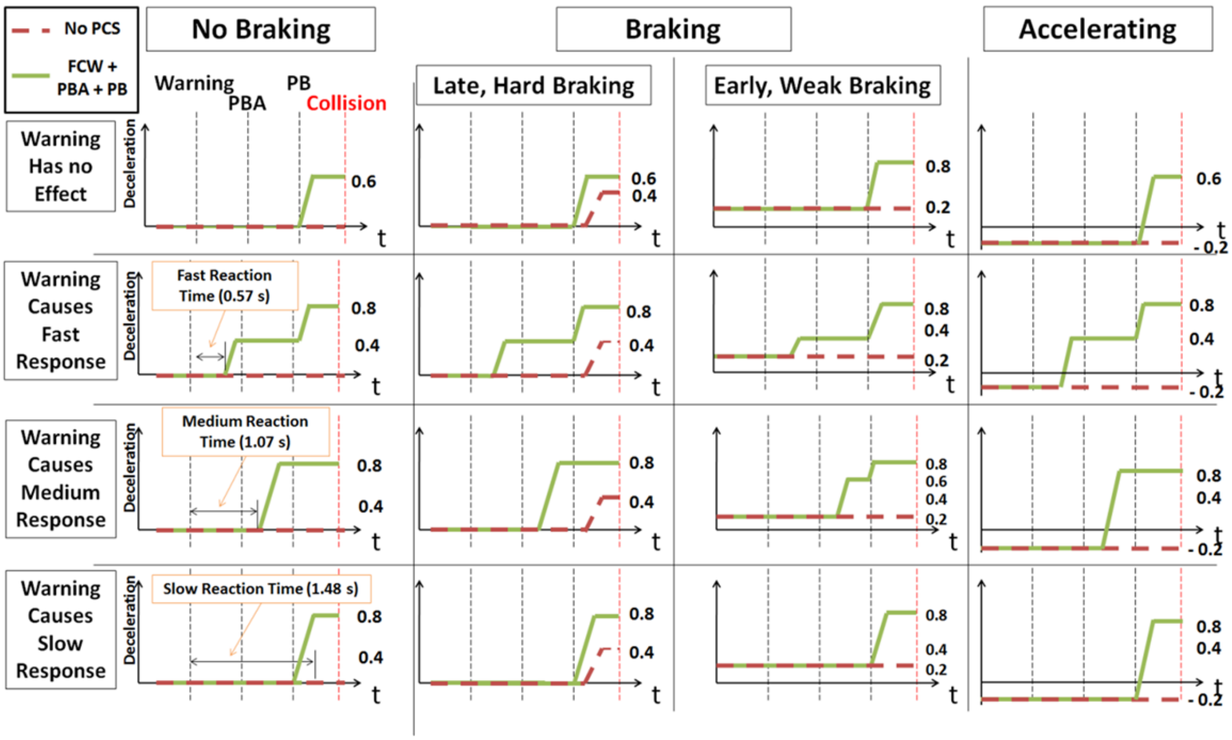

Figure 6. Schematic Representation of PCS Braking Pulses for Pre-crash Maneuver and Response Time for a FCW, PBA, and PB Algorithm. Magnitudes (*g*) and delay times (*s*) are labeled.

Overall System Performance

To estimate 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 and early-weak braking scenarios had equal probability of occurring. Therefore, 8.5% of the case weight was assigned to the no response simulation, 10% to the fast response, 21.5% to the medium response, and 10% to the slow response for each maneuver. Splitting the weighting factor insured that the overall system performance reflected the distribution of driver reaction times.

A large number of cases (13.5%) had a missing or unknown pre-crash vehicle maneuver. This is coded in NASS / CDS when the investigator is unable to determine the pre-crash maneuver with confidence. For cases with unknown or missing pre-crash vehicle maneuver, simulations for all the maneuvers were performed. To determine overall system performance, the distribution of reaction times was combined with the distribution of pre-crash maneuvers observed in the known population. Of rear-end collisions with known braking status, 29% were not braking and 71% were braking, with almost none (<1%) accelerating. As such, accelerating simulations were not considered for unknown maneuver cases. Multiplying the response time probability with the maneuver probability gave the proportion of the case's weighting factor assigned to each simulation, shown in Table 2.

Table 2.
Distribution of Case Weight for Cases with Unknown Pre-Crash Maneuver prior to PCS.

			Maneuver[b]		
			NB	HEB	WLB
			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, HEB – hard, early braking, WLD – weak, late braking.

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 [15]. 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 to life, with 0 being no injury and 6 fatal injury [16]. 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:

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

where β_0, β_1, and β_2 are coefficients 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 3.

Table 3.
Injury Risk Curve Coefficients from Kusano and Gabler (2010).

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

The total number of injured drivers, N, was estimated as:

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

where w_i and ΔV_i, is the weight and simulated ΔV assigned to each simulation. To compare the PCS outcome to the outcome without PCS, the number of injured drivers without PCS was estimated in the same way. Injury reduction was computed only for belted drivers. Because the relatively high levels of braking involved in PCS, there is possibility of unbelted occupants being 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 airbag deployment. Because of this unknown aspect of potential increase in driver injury, unbelted occupants were excluded.

System Limitations

The maximum vehicle braking deceleration is restricted by the road surface type and conditions. Table 4 lists nominal maximum braking deceleration for different surfaces and conditions [17-19]. Surface type and condition were determined from the variable *SURTYPE* and *SURCOND*, respectively. Vehicles were determined to be sliding based on pre-crash maneuver (*MANEUVER*) and pre-crash impact stability (*PREISTAB*). Unknown surface types were assumed to be pavement / asphalt / concrete and unknown surface condition was assumed to be dry. If vehicle stability was unknown, it was assumed the vehicle was tracking prior to the collision. Because vehicles with PCS would feature an Anti-Lock 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. Furthermore, if striking vehicles were sliding prior to the collision, it was assumed that the ABS would allow them to maintain tracking when PCS activated.

Table 4.
Maximum Braking Deceleration in g for Different Surface Types and Conditions [17-19].

Surface Condition	Braking (no lockup)	Sliding (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

Most PCS do not activate at low vehicle speeds. The FCW and PB systems were assumed to activate at relative vehicle speeds greater than 15 kmph (9.32 mph). The PBA component was assumed to activate at relative vehicle speeds greater than 30 kmph (18.6 mph). 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 adjusted accordingly 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.

RESULTS

Selected Cases

Of all rear-end collisions in NASS / CDS 1993-2008, 1,396 cases met all the requirements of this study. These cases accounted for approximately 1,080,000 rear-end collisions. Table 5 shows pre-crash braking 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 striking vehicles, 13.5% had missing or unknown maneuver status. For struck vehicles, 92% of vehicles were not applying the brakes and 7% of vehicles were braking.

Table 5.
Distribution of Pre-crash 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%
Accel.	1,591	0.1%	10,371	1%
Missing / Unknown	145,877	13.5%	-	-

Almost all cases (99.7%) occurred on concrete, asphalt, or pavement. The remaining occurred on dirt or gravel roads. Table 6 shows the distribution of surface conditions in the selected cases. A majority, 80.5%, of crashes occurred on dry roads, followed by wet roads with 17.6%. Snow and ice combined to account for approximately 2% of cases, with only a fraction of a percent being unknown.

Table 6.
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%

Algorithm Performance

Figure 7 shows the overall distribution of crash severity after PCS activation compared to without PCS. The additional PCS components reduced the distribution of ΔV and the number of collisions prevented.

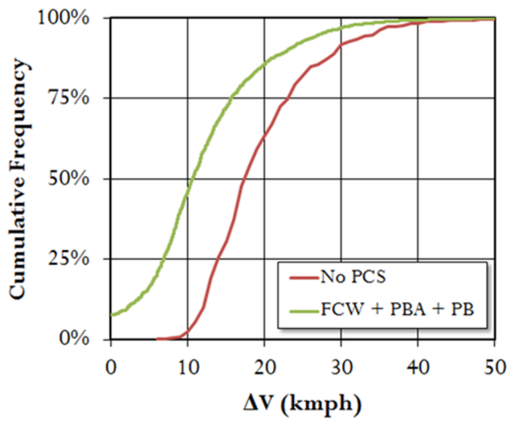

Figure 7. Cumulative Distribution of Crashes after PCS Algorithm Implementation.

Table 7 summarizes the percentage of crashes avoided and the reduction in median ΔV of non-prevented collisions due to PCS algorithm activation.

Table 7.
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 + PBA + PB	7.7%	11.3	34%

Table 8 shows the predicted reduction in the number of moderately to fatally injured, belted drivers for the three PCS algorithms.

Table 8.
Predicted Number of Moderately to Fatally Injured Drivers for PCS Algorithms.

Algorithm	Predicted Number of Injured Drivers	Percent Reduction
No PCS	12,338	-
FCW + PBA + PB	6,123	50%

Table 9 shows the percentage of all weighted collisions where various PCS components did not activate due to system limitations. Of drivers who braked early enough to activate PCS, 0.1% did not activate FCW because the relative vehicle velocity at FCW activation was below the 15 kmph threshold. This is a reflection of the fact that NASS/CDS only includes cases which at least one vehicle was towed due to damage. Of cases with FCW activation, 12% of all cases did not have PBA activate because the 30 kmph relative velocity condition was not met. Finally, 11% of cases had FCW and PBA activate but not PB due to the 15 kmph relative velocity threshold.

Table 9.
Percentage of Collisions with No PCS Component Activation due to System Limitations.

Component	% Collisions with no Activation
FCW	0.1%
PBA	12%
PB	11%

DISCUSSION

Implication of Results

This study shows the potential effectiveness an integrated PCS algorithm with forward collision warning, pre-crash brake assist, and autonomous pre-crash brake. The simulation takes into account a range of potential driver inputs using population distributions to describe likely results. In this way, this study provides an explicit estimate of the expected fleet-wide PCS algorithm effectiveness for rear-end collisions.

PCS shows large potential effectiveness for mitigating crash severity and injury. PCS reduced the median ΔV 34% and the number of moderately to fatally injured drivers by 50%. Fortunately, most injuries in rear-end collisions are relatively minor. Of drivers in rear-end collisions, 30% sustained minor injuries (e.g. MAIS1, cervical spine injury, abrasions). These occupants would also see benefits from reduced crash severity, which were not estimated here. Also not considered were the economic benefits (e.g. property damage or societal costs of injuries) from prevented and mitigated collisions.

Using real-world data, such as that from 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, since these collisions occur at low impact speeds, it is unlikely that all of the PCS components would activate.

Limitations

Although this study presents a possible range for PCS algorithm performance, it still provides an ideal case. This analysis assumed that the successive stages of PCS would activate successfully. In practice, one or more systems may not activate due to tracking and sensing limitations. Actual field performance of systems may be less effective.

The driver model was greatly simplified due to the limited information available for the driver's state prior to the collision. The simulation process did not include any effect of PCS on driver maneuvers other than braking, such as steering, prior to the collision. Also, 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 simple 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 used to compute the ΔV in each simulation were limited by the information available from crash investigations. The CRASH3 damage method of computing ΔV used by investigators in NASS / CDS was derived out of the need to estimate ΔV without significant knowledge of pre-crash conditions of the vehicles. The CRASH3 method estimates absorbed energy based on an empirical correlation between residual crush and absorbed energy. These correlations are found by obtaining vehicle stiffnesses from crash tests. Although this method has been validated and studied in the past, it relies on vehicle stiffness data from a relatively small number of crash tests extrapolated to the entire vehicle fleet [11]. Therefore, ΔV estimates derived from the CRASH3 method are known to vary depending on the vehicles involved in the collision [20]. The reconstruction methods also assume that the lever arm of the resultant collision force does not change after the application of PCS braking. Although the position of the damage may change slightly after PCS braking, because rear-end collisions feature damage that is often along a majority of the vehicle width and are at shallow angles the change in moment arm will be slight.

CONCLUSIONS

This study identified the potential effectiveness of an integrated PCS algorithm with forward collision warning (FCW), brake assist (PBA), and autonomous pre-crash braking (PB). This unique study used approach of determining the effectiveness of PCS 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 PCS. In this way, the expected fleet wide safety benefits of PCS were estimated. PCS reduced the median ΔV by 34% and prevented 7.7% of crashes. The number of moderately to fatally injured belted drivers was reduced by 50%.

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