Potential Occupant Injury Reduction in Pre-Crash System Equipped Vehicles in the Striking Vehicle of Rear-end Crashes

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ABSTRACT – To mitigate the severity of rear-end and other collisions, Pre-Crash Systems (PCS) are being developed. These active safety systems utilize radar and/or video cameras to determine when a frontal crash, such as a front-to-back rear-end collisions, is imminent and can brake autonomously, even with no driver input. Of these PCS features, the effects of autonomous pre-crash braking are estimated. To estimate the maximum potential for injury reduction due to autonomous pre-crash braking in the striking vehicle of rear-end crashes, a methodology is presented for determining 1) the reduction in vehicle crash change in velocity ($\Delta V$) due to PCS braking and 2) the number of injuries that could be prevented due to the reduction in collision severity. Injury reduction was only performed for belted drivers, as unbelted drivers have an unknown risk of being thrown out of position. The study was based on 1,406 rear-end striking vehicles from NASS / CDS years 1993 to 2008. PCS parameters were selected from realistic values and varied to examine the effect on system performance. PCS braking authority was varied from 0.5 G’s to 0.8 G’s while time to collision (TTC) was held at 0.45 seconds. TTC was then varied from 0.3 second to 0.6 seconds while braking authority was held constant at 0.6 G’s. A constant braking pulse (step function) and ramp-up braking pulse were used. The study found that automated PCS braking could reduce the crash $\Delta V$ in rear-end striking vehicles by an average of 12% - 50% and avoid 0% - 14% of collisions, depending on PCS parameters. Autonomous PCS braking could potentially reduce the number of injured drivers who are belted by 19% to 57%.

INTRODUCTION

Rear-end crashes, where the front of one vehicle impacts the rear of another vehicle traveling in the same direction as the striking vehicle, are a frequent occurrence on U.S. roadways. Rear-end crashes accounted for 28% of all police reported accidents in the U.S. in the year 2000 [Najm, Sen, Smith, et al, 2003]. In rear-end crashes, distraction or inattention of the striking vehicle driver is often a contributing factor to the accident. It is estimated that inattention (i.e. distraction outside or inside the vehicle) contributed to as many as 65% of rear-end collisions [Campbell, Smith, Najm, 2003].

To mitigate and possibly prevent rear-end collisions and other frontal crash modes, automakers have begun to develop a variety of pre-crash systems (PCS). These active safety systems, which are being developed and already available on some production vehicles, use millimeter-wave radar and/or video cameras to track vehicles and objects in front of the equipped vehicle. When a credible collision threat is identified, the PCS can warn the driver through visual, audible, or tactile means, pre-charge the brakes to prepare for driver braking, and autonomously apply the brakes, even if there is no driver input [Kuroda, 2009; Schoeneburg, 2005; Sugimoto, 2005].

The automated, emergency-braking function of PCS strives to reduce the impact speed of a collision, thus mitigating the severity. The automated braking function of PCS is designed to initiate only when a collision is unavoidable, as determined by a predetermined threshold. Because injuries in frontal collisions are well correlated to vehicle change in velocity ($\Delta V$), reducing the impact speed will decrease injury risk for PCS equipped vehicles [Gabauer and Gabler, 2008; Bahouth, Digges, Bedewi, et al., 2004].

OBJECTIVE

The objective of this study is to determine an upper bound for the effectiveness of automated pre-crash braking in reducing the number of injured drivers in the striking vehicle of rear-end collisions if every vehicle in the U.S. fleet were equipped with a functioning PCS.
METHODS

Reduction in Collision $\Delta V$ due to Pre-Crash Braking using Momentum Method

The vehicle change in velocity during a collision, $\Delta V$, is often used as a metric for crash severity. The $\Delta V$ in a collision is a partial function of impact speed. Thus, for a given crash, if the vehicle had been equipped with a functioning pre-crash brake system the impact speed of that vehicle would be reduced in applicable collisions, reducing the $\Delta V$ of that collision. The reduction in $\Delta V$ due to autonomous pre-crash braking can be estimated using a conservation of linear momentum approach.

Here we make the simplifying assumption that the collisions are collinear, central impacts between two vehicles, as shown in Figure 1. We also assume that the collision is plastic, i.e. there is no restitution. The vehicles have masses of $m$ and impact velocity $V_0$. The front of the striking vehicle (vehicle 1) engages the rear of the struck vehicle (vehicle 2) fully, with the resultant collision force crossing through the center of gravity of both vehicles.

Assuming a plastic collision, the vehicles will achieve a common velocity, $V_C$. Applying conservation of linear momentum to the collision yields the common velocity,

$$V_C = \frac{(m_1 + m_2)V_C - m_1V_{1,0} - m_2V_{2,0} + P_{in}}{m_1 + m_2} \tag{1}$$

where $P_{in}$ is the external impulse applied to the crash system. In a crash without pre-crash braking, there is no external impulse on the system ($P_{in} = 0$). Therefore, the common velocity in the crash becomes,

$$V_C = \frac{m_1V_{1,0} + m_2V_{2,0}}{m_1 + m_2} \tag{2}$$

The magnitude of the vehicle change in velocity during the event, $\Delta V$, can be found by taking the difference between the common and impact velocities,

$$\Delta V = V_0 - V_C \tag{3}$$

The $\Delta V$ presented here is the magnitude of the change in velocity, which will be positive in rear-end crashes, because $V_0 > V_C$.

During pre-crash braking, an impulse is applied to the system (via vehicle 1) equal in magnitude to the braking acceleration times the mass integrated over the braking period, $t_b$:

$$P_{brake} = \int_0^{t_b} m_1 a(t) \, dt \tag{4}$$

If the braking pulse is assumed to be of constant magnitude, $a$, over the braking period, the braking impulse is

$$P_{brake} = -m_1 a \, t_b \tag{5}$$

However, because of both limitations to brake application and for occupant safety, a more realistic scenario for braking would be to apply braking gradually to some maximum magnitude. This ramp up period can be modeled by linearly increasing braking deceleration with slope $j$ to a maximum braking deceleration of $a$, shown in Figure 2.
Thus the common velocity achieved by both vehicles during the collision with PCS braking, $V_C^*$, can be expressed as

$$V_C^* = \frac{m_1 V_{1,0} + m_2 V_{2,0} - m_1 a t_b}{m_1 + m_2}$$

or

$$V_C^* = \frac{m_1 a t_b m_1 + m_2}{m_1 + m_2}$$

for constant braking, and

$$V_C^* = \frac{m_1 a t_b m_1 + m_2}{m_1 + m_2}$$

for a ramp-up braking deceleration.

The new impact speed of vehicle 1 after PCS braking is applied, $V_{1,0}^*$, can be expressed as

$$V_{1,0}^* = V_{1,0} - (a t_b)$$

for constant deceleration, and

$$V_{1,0}^* = V_{1,0} - \left(a t_b - \frac{1}{2} \frac{a^2}{j}\right)$$

for ramp-up deceleration.

The change in velocity of the vehicle if PCS braking had occurred can be found by taking the difference between the common velocity and impact velocity,

$$\Delta V^* = V_0^* - V_C^*$$

For constant braking deceleration of vehicle, equation 11 becomes

$$\Delta V_1^* = V_{1,0} - (a t_b) - V_C + \frac{m_1 a t_b}{m_1 + m_2}$$

$$\Delta V_1^* = V_{1,0} - V_C - \frac{m_2}{m_1 + m_2} (a t_b)$$

$$\Delta V_1^* = \Delta V_1 - \frac{m_2}{m_1 + m_2} (a t_b)$$

For ramp-up deceleration, equation 11 becomes:

$$\Delta V_1^* = V_{1,0} - (a t_b - \frac{1}{2} \frac{a^2}{j}) - V_C + \frac{m_1 (a t_b - \frac{1}{2} \frac{a^2}{j})}{m_1 + m_2}$$

$$\Delta V_1^* = V_{1,0} - V_C - \frac{m_2}{m_1 + m_2} (a t_b - \frac{1}{2} \frac{a^2}{j})$$

$$\Delta V_1^* = \Delta V_1 - \frac{m_2}{m_1 + m_2} (a t_b - \frac{1}{2} \frac{a^2}{j})$$

Autonomous pre-crash braking systems are designed to activate at a specified time to collisions (TTC), shown in Figure 3, which is the distance between two vehicles over the instantaneous relative vehicle velocity:

$$TTC = \frac{x_0}{V_{12,0}}$$

where $x_0$ is the distance between the two vehicles at PCS activation, and $V_{12,0}$ is the relative velocity of vehicle 1 with respect to vehicle 2 at the time of activation. The speed of vehicle 2 is assumed to be constant during the braking period. The relative velocity can be found taking the difference of equation 3 for vehicle 2 and vehicle 1.

Figure 3. Distance between Vehicles at Autonomous PCS Braking Activation.
\[
V_t = \frac{(V_{12} + \frac{a^2}{2j}) - \sqrt{(V_{12} + \frac{a^2}{2j})^2 - 2a(V_{12}TTC - \frac{a^3}{6j^2})}}{a}
\]

for ramp-up braking. At low impact speeds, the pre-crash braking can completely stop the vehicle. This will be manifested in the actual braking time as an unreal value (i.e. negative value under the radical). For the following analysis the \(\Delta V\) was set to zero for cases where the crash was avoided.

The model presented here for computing a reduced \(\Delta V\) due to pre-crash braking makes several simplifying assumption as it applies to real-world rear-end crashes. First, the model does not include driver braking prior to the activation of the PCS brake. Second, the model does not account for a non-central collision, where the resultant crash force does not pass directly through the center of gravity of the vehicle. Lastly, the model does not model braking during the collision event, which may be a part of some autonomous PCS braking systems.

### Computation of Reduced \(\Delta V\) due to Pre-Crash Braking for Real-World Crashes

Rear-end crashes were extracted from the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS) from years 1993 to 2008. NASS/CDS is a nationwide crash data collection program sponsored by the U.S. Department of Transportation. The data collected includes approximately 5,000 crashes per year which compose a representative, random sample of minor, serious, and fatal crashes. Trained crash investigators collect data from police reports, crash site investigation, interviews, and medical records.

Target vehicles were cars or light trucks and vans (LTV) with an airbag equipped, which impacted another vehicle traveling in the same direction. Pre-crash impact scenario was determined by a methodology adapted from Eigen and Najm [2009], which examines pre-crash events, movements, and accident type as coded in NASS/CDS. Rear-end striking vehicles were involved in collisions with a lead vehicle that was either decelerating, stopped, or moving at a lesser speed in the same travel lane as the striking vehicle. These collisions involved both striking vehicles with no vehicle maneuvers and vehicle maneuvers, such as avoiding another object in the road and then impacting a lead vehicle.

Only cases in which the first harmful event resulted in frontal damage to the striking vehicle were included. Cases involving vehicle rollover, fire, or driver ejection were excluded. Cases with missing computed \(\Delta V\), absorbed energy, or vehicle curb weight were excluded. Only cases involving two vehicles in transport were included. The cases must also include injury information of the driver and driver safety belt use. The curb weight and crash \(\Delta V\) of the struck vehicle was also required for selection, as it is used to compute \(\Delta V\) reduction. Also, cases with serious, self-reported injury, multiple events where the cause of injury was uncertain, or suspicious injury sources were excluded.

For each vehicle identified as rear-end striking vehicle, a new \(\Delta V\) was computed using equations 12 and 13. The range of PCS parameters were selected from reasonable operating values for PCS. The braking deceleration was varied from 0.5 G’s to 0.8 G’s by an increment of 0.1 G while the TTC was held constant at 0.45 seconds. The TTC was varied from 0.3 second to 0.6 seconds by 0.1 seconds while braking deceleration was held constant at 0.6 G’s. For ramp-up braking, the slope (\(j\)) was held constant at 25 m/s².

### Injury Risk for Drivers in Striking Vehicle of Rear-end Crashes

To determine the potential effectiveness of autonomous PCS braking on reducing injury to the driver, a dose-response model was developed to predict driver injury in rear-end striking vehicles. The risk of injury is the probability of injury, defined below:

\[
P(\Delta V, \text{belt use}) = \frac{\# \text{Injured Occupants}}{\# \text{Exposed Occupants}}
\]

Logistic regression was used to correlate safety belt use and \(\Delta V\) to injury outcome. Logistic regression is a statistical technique which is widely used to determine the probability of categorical outcomes, e.g. injury or no injury, as a function of independent variables such as \(\Delta V\). The function form of the resulting relationship is as follows:

\[
P(\Delta V, \text{belt use}) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \Delta V + \beta_2 (\text{belt}))}}
\]

where \(\beta_0\), \(\beta_1\), and \(\beta_2\) are coefficients determined by the regression analysis. For belt use, the quantity belt was equal to 1 for belted drivers, and -1 for unbelted drivers. The resulting relationship leads to an s-shaped function with a minimum value of 0 and a maximum value of 1. Injury risk curves were developed based on the same set of cases identified for \(\Delta V\) reduction analysis. The software package SAS 9.2 was used for the statistical analysis.

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survey logistic procedure (proc surveylogistic) was used to account for variability caused by the complex sample design and weighting of cases in NASS / CDS.

The severity of each injury in NASS / CDS is recorded using the Abbreviated Injury Scale (AIS). AIS is a 1-6 numeric scale for classifying injury severity with 1 being minor injury and 6 being fatal injury [AAAM 2001]. The maximum AIS (MAIS) is defined as the most severe injury suffered by an occupant. MAIS injuries were adjusted for fatalities in NASS / CDS, as occupants can expire without sustaining an AIS6 level injury. MAIS for fatally injured occupants was set to 6 regardless of maximum AIS level. Injury in this study is defined as a MAIS of 2 to 6 (MAIS2+F).

Estimation of Injury Reduction for Drivers in Rear-end Crashes with PCS

Using the developed risk for injury and the reduced $\Delta V$ due to pre-crash braking, the number of injuries prevented can be computed. Injury reduction was computed only for belted occupants. 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 to suffer serious injury due to airbag deployment. Because of this unknown aspect of potential increase in driver injury, unbelted occupants were excluded. The effectiveness of PCS braking in preventing injury, $\varepsilon$, is defined as

$$\varepsilon = \frac{l_{No\,PCS} - l_{PCS}}{l_{No\,PCS}}$$

(19)

where $l_{No\,PCS}$ is the number of injured (MAIS2+F) occupants without PCS and $l_{PCS}$ is the number of injured occupants with PCS. Both of these sums were computed using injury risk curves developed for rear-end crashes. The risk of injury multiplied by the weight of each case summed for all cases gives the number of serious injuries:

$$I = \sum_{i=1}^{N} w_i \cdot P(\Delta V_i, \text{belt use})$$

(20)

Where $N$ is the total number of cases, $w_i$ is the weight of the case, and $P(\Delta V, \text{belt use})$ is the probability of injury for case $i$. The reduction in $\Delta V$ due to pre-crash braking will reduce the risk for injury, thus reducing the predicted number of serious injuries.

RESULTS

Rear-end Injury Risk

In NASS / CDS 1993 – 2008, there were 1,406 applicable rear-end crashes which met the selection criteria as summarized in Table 1. The data set represents 1,100,000 drivers of striking vehicles, of which 16,749 sustained MAIS2+F injuries. Although only 8% of drivers were unbelted, they accounted for 27% of injured drivers.

Table 1. Composition of Applicable Rear-end Crashes from NASS / CDS 1993-2008

<table>
<thead>
<tr>
<th>Category</th>
<th>Raw</th>
<th>Weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cases</td>
<td>1,406</td>
<td>1,097,034</td>
</tr>
<tr>
<td>Belted</td>
<td>1193</td>
<td>999,311</td>
</tr>
<tr>
<td>Unbelted</td>
<td>213</td>
<td>97,724</td>
</tr>
<tr>
<td>MAIS2+F Drivers</td>
<td>120</td>
<td>16,749</td>
</tr>
<tr>
<td>Belted</td>
<td>62</td>
<td>12,209</td>
</tr>
<tr>
<td>Unbelted</td>
<td>30</td>
<td>4,541</td>
</tr>
</tbody>
</table>

Table 2 shows the value of the logistic regression parameters. Risk of injury for unbelted drivers is greater than that for belted drivers. All tests for the global null hypothesis were significant to a level of less than 0.0001. Furthermore, the Wald Chi-Squared tests were significant to a level less than 0.0001 for the intercept and $\Delta V$ parameter and 0.0158 for the belt use parameter. Figure 4 shows the risk for MAIS2+F injury for drivers in rear-end crashes.

Table 2. Logistic Regression Parameters for Injury Risk (MAIS2+F) for Drivers in Striking Vehicles of Rear-end Crashes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>$\beta_0$</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>$\beta_1$</td>
</tr>
<tr>
<td>Belt Use</td>
<td>$\beta_2$</td>
</tr>
</tbody>
</table>

*Edited since first publication – January 2011
Figure 4. Risk of Injury for Drivers of Striking Vehicles in Rear-end Crashes by safety belt use

Figure 5 shows the actual and predicted number of cumulative drivers with injuries by $\Delta V$.

Figure 5. Predicted and Actual Number MAIS2+F of Rear-end Striking Vehicle Drivers from NASS / CDS 1993 – 2008

Reduction in $\Delta V$ and Number of Injuries due to Pre-Crash Braking

Figure 6 shows the reduction in crash $\Delta V$ for varying braking deceleration and TTC with constant deceleration pulse and ramp-up pulse. The introduction of the ramp-up deceleration pulse decreases the shift in $\Delta V$ as well as the difference between braking decelerations. The difference in $\Delta V$ reduction between constant and ramp-up deceleration for varied TTC was not large. Table 3 shows the average reduction in $\Delta V$ due to PCS braking for the parameters evaluated. Collisions that had a lower original $\Delta V$ were reduced more than those with high original $\Delta V$.

Table 3. Average Reduction in $\Delta V$ due to PCS Pre-Crash Braking

<table>
<thead>
<tr>
<th>Authority or TTC</th>
<th>Constant Braking</th>
<th>Ramp-up Braking</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 G</td>
<td>26%</td>
<td>19%</td>
</tr>
<tr>
<td>0.6 G</td>
<td>33%</td>
<td>23%</td>
</tr>
<tr>
<td>0.7 G</td>
<td>41%</td>
<td>25%</td>
</tr>
<tr>
<td>0.8 G</td>
<td>50%</td>
<td>28%</td>
</tr>
<tr>
<td>0.3 s</td>
<td>20%</td>
<td>12%</td>
</tr>
<tr>
<td>0.4 s</td>
<td>28%</td>
<td>19%</td>
</tr>
<tr>
<td>0.5 s</td>
<td>39%</td>
<td>27%</td>
</tr>
<tr>
<td>0.6 s</td>
<td>50%</td>
<td>37%</td>
</tr>
</tbody>
</table>

Figure 7 shows the estimated reduction in the number of drivers suffering injuries due to PCS braking. As the number of drivers suffering MAIS2+F injuries was predicted by assessing the risk for injury at a given $\Delta V$, the cases with the greatest reduction in crash $\Delta V$ experienced the greatest reduction in the number of injured drivers. Again, the addition of the ramp-up braking reduced the effectiveness of pre-crash braking.

At low impact speeds, a number of collisions were avoided due to autonomous PCS braking, shown in Table 4. Avoidance ranged from none up to 14% of collisions. More collisions were avoided for constant braking. The greater the braking authority or TTC, the more collisions were avoided. Because rear-end crashes have a relatively low distribution of $\Delta V$, the estimated number of collisions avoided will be less for other crash modes (i.e. head on collisions).

Table 4. Percentage of Crashes Avoided due to Autonomous PCS Braking

<table>
<thead>
<tr>
<th>Authority or TTC</th>
<th>Constant Braking</th>
<th>Ramp-up Braking</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 G</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>0.6 G</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>0.7 G</td>
<td>5%</td>
<td>0%</td>
</tr>
<tr>
<td>0.8 G</td>
<td>14%</td>
<td>0%</td>
</tr>
<tr>
<td>TTC = 0.45 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 s</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>0.4 s</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>0.5 s</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>0.6 s</td>
<td>14%</td>
<td>2%</td>
</tr>
<tr>
<td>$a = 0.6 G_s$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Edited since first publication – January 2011
0.5 G’s – 0.8 G’s (constant, TTC=0.45 s)  

TTC of 0.3 s – 0.5 s (constant a = 0.6 G’s)

0.5 G’s – 0.8 G’s (ramp-up, TTC = 0.45 s)  

TTC of 0.3 s – 0.5 s (ramp-up a = 0.6 G’s)

Figure 6. Reduction in ΔV for PCS Braking for Varying Braking Authority and Time to Collision (TTC)

*Edited since first publication – January 2011
Figure 7. Predicted Number of Drivers Sustaining Injuries due to PCS Braking as a function of PCS Design

*Edited since first publication – January 2011
Table 5 shows the effectiveness of PCS braking in reducing the number of injured drivers for constant and ramp-up braking deceleration from 0.5 G’s to 0.8 G’s. Effectiveness is computed using equation 19. Effectiveness ranged from 37% to 57% for constant braking and 29% to 39% for ramp-up braking.

Table 5. Effectiveness of PCS Braking from 0.5 G’s to 0.8 G’s, TTC = 0.45 s

<table>
<thead>
<tr>
<th></th>
<th>Constant</th>
<th>Ramp-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 G</td>
<td>37%</td>
<td>29%</td>
</tr>
<tr>
<td>0.6 G</td>
<td>43%</td>
<td>33%</td>
</tr>
<tr>
<td>0.7 G</td>
<td>50%</td>
<td>36%</td>
</tr>
<tr>
<td>0.8 G</td>
<td>57%</td>
<td>39%</td>
</tr>
</tbody>
</table>

Table 6 shows the effectiveness of PCS braking to reduce drivers suffering injuries for TTC of 0.3 seconds to 0.6 seconds with a braking deceleration of 0.6 G’s for constant and ramp-up deceleration. Effectiveness ranged from 30% to 57% for constant braking deceleration and 19% to 46% for ramp-up braking deceleration.

Table 6. Effectiveness of PCS Braking for TTC of 0.3 s to 0.6 s, a = 0.6 G’s

<table>
<thead>
<tr>
<th></th>
<th>Constant</th>
<th>Ramp-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 s</td>
<td>30%</td>
<td>19%</td>
</tr>
<tr>
<td>0.4 s</td>
<td>39%</td>
<td>29%</td>
</tr>
<tr>
<td>0.5 s</td>
<td>48%</td>
<td>38%</td>
</tr>
<tr>
<td>0.6 s</td>
<td>57%</td>
<td>46%</td>
</tr>
</tbody>
</table>

DISCUSSION

The analysis on PCS braking shows the effectiveness of the system to reduce impact speeds and prevent injury as a function of braking authority, activation time (TTC), and braking pulse. Although ideally a PCS would have the maximum possible braking authority and would activate sooner before a collision, there are tradeoffs to these design considerations. Activation must be designed to only trigger during conditions that suggest an imminent collision. Braking systems also have limitations to the maximum amount of braking force that can be exerted, which is dependent on the roadway condition.

A constant braking force is more effective than the ramp-up braking at preventing injuries. However, the case of constant braking, or a step-change in braking at the TTC, is unrealistic for real braking application.

The effect of the ramp-up period in braking deceleration is greater for larger maximum braking authorities because more time is spent reaching peak braking deceleration. Increasing the maximum jerk authority (j) of the system in the case of large braking authorities would increase the effectiveness. Because braking authority was fixed when varying TTC, the ramp-up deceleration had a lesser effect than when varying braking authority. The jerk authority in passenger vehicles is a limitation of the mechanical braking actuator. The ideal jerk authority would be infinite, but again, this is a design tradeoff between cost and performance.

This analysis only considered potential benefits for belted drivers in the striking vehicle of a rear-end collision. Because PCS often incorporates reversible safety belt pre-tensioners, to remove the slack from the belt prior to a collision, belted occupants in the front seat will remain in position for airbag deployment. Unbelted occupants, however, may be displaced significantly due to the potentially large decelerations from the PCS. This may place unbelted occupants at risk for injury resulting from their proximity to the airbag inflator. Thus, computing benefits for unbelted occupants without considering the potential ramifications of the displacement of unbelted occupants may severely overpredict benefits. To potentially mitigate unbelted occupant injury due to out-of-position firing on the airbag, developers of PCS could deactivate and lessen the braking authority of the system if a driver or front passenger is unbelted.

Many pre-crash systems being developed also have warning and pre-crash brake assist components. The warning system will alert the driver through audio or tactile means if a collision is threatening so that he or she can take action to avoid the collision. The pre-crash brake assist will pre-charge the brakes so that a driver’s braking effort will be increased when he or she applies the brake. Both of these components would deploy prior to autonomous pre-crash braking. This study does not account for the additional crash avoidance and mitigation benefits these two PCS components could provide. Future work will include determining possible benefits of warning and pre-crash brake assist systems.

While the analysis presented here predicted a number of collisions avoided, the aim of autonomous PCS braking is crash mitigation. The intent of autonomous braking is to activate only when a collision in unavoidable. The definition of the point of an unavoidable collision will depend on brake performance, vehicle speed, and roadway conditions.
and will be reflected by the PCS design parameters. Also, some proposed autonomous braking systems do not activate under very low impact speeds. Because this analysis was performed on crashes from NASS / CDS, which are required to involve damage requiring at least one vehicle to be towed from the scene, the crashes are biased toward impact speeds where PCS would be likely to activate.

This study presents an upper bound on autonomous PCS braking effectiveness and has several limitations. First, our methodology for determining \( \Delta V \) reduction assumes collinear crashes with no restitution. In cases where the resultant crash force does not pass through the center of gravity of the vehicle, rotational effects will decrease the observed \( \Delta V \) [Rose, Fenton, Ziernicki 2004]. Although the \( \Delta V \) computed in NASS / CDS does account for vehicle rotation to some extent, the momentum methodology that is presented in this study does not. Thus, \( \Delta V \) reduction will be overestimated in cases where there is significant offset and vehicle rotation during the crash event. However, because our dataset was composed of rear-end crashes, the effects of rotation should be minimal (98.3% of cases have a principal direction of force, PDOF, within 10 degrees of front). After the vehicles reach a common velocity in a collision, there is almost always rebound, or restitution, in the vehicle body which is not accounted for in this method. The approach presented here is consistent to the approach used to estimate \( \Delta V \) in NASS/CDS and has been shown to under-predict \( \Delta V \) [Hampton and Gabler 2008].

Second, the methodology assumes there is no driver braking prior to impact. If a driver applied the brakes, the PCS brake assist function could boost his or her effort. This boost may reduce the amount of autonomous braking that PCS can apply in addition to the brake assist. In this case, our methodology would overpredict the benefit of the autonomous braking. In this case, our methodology would overpredict benefit. Due to the limited information available in NASS / CDS, it is difficult to predict what level of braking, if any, the driver applied before a collision. Furthermore, this methodology assumes that PCS braking stops after the initiation of impact. This assumption is also made when computing the \( \Delta V \) in NASS / CDS. The momentum method could be extended to include a braking impulse during the collision, but the length of the collision would need to be estimated. In some frontal collisions, the braking systems are destroyed during the frontal structural deformation, but the extent and timing of this brake damage is difficult to determine.

Lastly, this study only considers drivers. NASS / CDS did not have a large enough data set to develop robust risk curves for passengers. There are also benefits for the collision partner, or struck vehicle, occupants that are not estimated. Struck vehicle driver injury information was limited, thus risk could not be robustly analyzed. Furthermore, in evaluating benefits for striking vehicle drivers, injury reduction benefits were assumed to only be derived from reduction in \( \Delta V \). Injury risk is known to vary by body region and with the occupant’s physical nature (i.e. age and sex), which is not addressed in this approach. Other outcomes of the collision, namely intrusion into the occupant compartment, can also play a role in occupant injury risk. Because the majority of collisions in the dataset analyzed here were low severity collisions with minimal offset, the effects of intrusion were small.

**CONCLUSION**

This study presents a methodology for determining the reduction in crash \( \Delta V \) if all striking vehicles in rear-end collisions were equipped with a functioning, autonomous pre-crash braking system. Injury risk was determined as a function of crash severity (\( \Delta V \)) and belt use. The reduction in crash \( \Delta V \) was used to determine the reduction in the number of injured drivers. Maximum braking authority, time to collision, and braking pulse were varied over the expected range of PCS design parameters to determine the effect of PCS parameters on system effectiveness.

We conclude that autonomous PCS braking has a maximum potential to reduce the crash \( \Delta V \) of the striking vehicle on average between 12% - 50% and avoided 0% to 14% of collisions. The number of injured drivers was reduced by 19% to 57% from the reduction in \( \Delta V \) from autonomous pre-crash braking. Braking authority and shape of the braking pulse (i.e. ramp-up period) had the greatest effect on system effectiveness.

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**REFERENCES**


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Eigen A, Najm W. Problem Definition for Pre-Crash Sensing Advanced Restraints. DOT HS 811 114, Department of Transportation, Washington, D.C., 2009.


*Edited since first publication – January 2011