Establishment and Analysis on Typical Road Traffic Near-Crash Scenarios Related to Pedestrian in China

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ABSTRACT

Naturalistic driving recorders were installed on 11 passenger cars, running in 5 Chinese cities ranging from first tier to third tier cities to obtain naturalistic driving data. And 65 near-crash cases related to pedestrians are extracted from the database and researched. Based on vehicle’s speed obtained from OBD (On-Board Diagnostic), image process method and kinematic formulas, information of the pedestrian, road environment and vehicle is collected. Firstly, based on the 65 samples, qualitative analysis on the key elements such as pedestrian’s walking direction and road congestion status is conducted to obtain characteristics of near-crash cases related to pedestrians in China. Secondly, typical scenarios at the time of risk start (TRS) are obtained from 39 samples through cluster analysis. Thirdly, the differences between the current study and previous studies are analyzed and discussed further.
INTRODUCTION

Of all traffic participants, pedestrians are the most vulnerable kind. In an accident, the pedestrian usually suffered much severer casualty than the occupants. In 2014, there were 58,523 casualties from road traffic accidents in China, including 15,110 pedestrians, accounting for about 26%\(^1\). Autonomous Emergency Braking System is assumed to be an effective counter measure for this situation. AEB could help to avoid collisions or reduce crash severity through automatic braking. However, in Chinese market, complete evaluation system which is accustomed to Chinese traffic characteristics has not been established to support the development of Pedestrian AEB. Typical scenarios related to pedestrians obtained from Chinese near-crash cases are the essential information for the AEB effectiveness evaluation system in China, and they are the foundation for the R&D of Pedestrian AEB.

CURRENT RESEARCH STATUS

EU project APROSYS (Advanced Protection Systems) obtained three typical scenarios from accidents related to pedestrians based on GIDAS (German In-Depth Accident Study)\(^2\). Another EU project VFSS (Advanced Forward-Looking Safety Systems) designed four testing scenarios for Pedestrian AEB based on four databases\(^3\). In China, Liu Ying obtained four typical scenarios with the corporation of Geely Automobile Research Institute\(^4\).

All the testing scenarios mentioned above include the following factors: vehicle’s speed, pedestrian’s walking direction and driver’s view obstruction. It can be seen that these factors are essential to establish testing scenarios and evaluate function of Pedestrian AEB. Most researches obtain typical scenarios based on accidents instead of near-crash cases. It may result in difference in concrete variables. Besides, all the research mentioned above do not consider about pedestrian’s walking speed or just design testing scenarios utilizing average pedestrian speed, which could not reflect difference on pedestrian’s walking characteristics.

ANALYSIS ON CHARACTERISTICS OF NEAR-CRASH CASES RELATED TO PEDESTRIAN

Near-crash cases refer to events in which drivers take efficient steps under urgent road traffic situations and avoid potential accidents successfully.

Naturalistic driving recorders were installed on 11 passenger cars in 5 Chinese cities to obtain naturalistic driving data. Once the longitudinal or lateral acceleration is higher than 0.3g, or vertical direction is higher than 0.5g, the device is triggered. Videos in that period are then written into memory card. After that, all the video samples during the period in which sudden speed change occurs are judged and sifted manually to get near-crash cases. 65 near-crash cases related to pedestrians from September 2015 to May 2016 are extracted from the database eventually. Based on the 65 samples, qualitative analysis on information such as pedestrian’s walking direction and road congestion status is conducted to obtain characteristics of near-crash cases related to pedestrians in China.

Each near-crash sample can be extracted to the combination of several variables. Through video observation and recording, statistical distribution of each variable, as shown in Table 1, is obtained.

Table 1. Statistical distribution of variables

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Variable value</th>
<th>Sample size</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver’s view</td>
<td>Obstructed</td>
<td>13</td>
<td>20.00%</td>
</tr>
<tr>
<td></td>
<td>Not obstructed</td>
<td>52</td>
<td>80.00%</td>
</tr>
<tr>
<td>Time period</td>
<td>Daytime</td>
<td>55</td>
<td>84.62%</td>
</tr>
<tr>
<td></td>
<td>Night</td>
<td>10</td>
<td>15.38%</td>
</tr>
</tbody>
</table>

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Following conclusions can be drawn from Table 1

1) The condition that the driver is driving under daylight and sunny weather is respectively 5 times and 11 times more than driving under darkness and rainy weather. Presumably, people drive more carefully under darkness and rainy weather. Therefore, accidents are less likely to happen in latter conditions.

2) The location, whether is at intersection or not, does not have effect on occurrence of near-crash. 97% near-crash cases happen on roads which are not congested. By reviewing videos, we find that people drive faster in spacious road and conflicts are more likely to happen.

3) At the time of risk start (TRS), the number of the cases in which pedestrian is crossing the road is about 3 times more than that of the cases in which the pedestrian is walking along the road. The reason why people walking along the road are less likely to have conflicts with vehicle is that they are more likely to be perceived by drivers. Therefore, drivers can take measures in advance to avoid conflicts.

4) Approximately 55% near-crash cases are due to pedestrian’s failure to comply with traffic rules. Therefore, uncertainty of pedestrian’s movement should be fully taken into account when establishing testing scenarios of Pedestrian AEB.

5) People in each life stages may have conflicts with vehicle. People of different ages have different characteristics on factors such as height and walking speed. These differences should be considered about carefully in establishment of testing scenarios of Pedestrian AEB.

6) In near-crash cases, most pedestrians wear dark clothes which are more difficult to detect in poor light condition compared to light-color clothes.

7) Some cases happen between vehicle and several people. Identification of multiple pedestrians is more challenging for AEB system. And research on this situation is very essential.

**OBTAINMENT OF TYPICAL SCENARIOS AT TRS**

Time of risk start (TRS) means the moment when drivers realize emergency and potential risk of crashing with pedestrian. Through vehicle speed obtained from OBD , image process method and kinematic formulas, information of vehicle speed, distance between pedestrian and vehicle and pedestrian’s walking speed at TRS is obtained and quantitative analysis is conducted then. Typical scenarios at TRS can be obtained from the data mentioned above through multivariate statistical method of cluster analysis.

**Analysis of Quantitative Information**

Due to the limitation of image processing algorithm, quantitative information of two kinds of cases cannot
be obtained. In the first kind, distance between vehicle and pedestrian cannot be calculated accurately since the road is uneven. In the second kind, location of pedestrian’s feet cannot be selected if pedestrian’s feet are masked in the image. Therefore, the distance cannot be calculated. Quantitative information of 39 samples is obtained except two kinds of cases mentioned above eventually.

**Vehicle Speed Distribution at TRS** Vehicle speed distribution at TRS is shown in Figure 1. Samples which vehicle speed is in 10-40km/h account for 92.3% of the total; Frequency of vehicle’s traveling at high speed is small among near-crash cases.

**TTC (Time to Collision) Distribution at TRS** TTC distribution at TRS is shown in Figure 2. Cases which TTC is among 1.4s and 4.8s account for 94.9%.

**Relationship between TTC and Vehicle Speed**

Relationship between TTC and vehicle speed is shown in Figure 3. We can draw conclusion that TTC is basically independent of vehicle speed from Figure3

**Introduction of Cluster Analysis**

Cluster analysis classifies individuals or objects so that the similarity between objects in the same group is stronger than the similarity between objects of other groups. The whole process of obtaining typical scenarios includes two steps. First, all samples are classified into several groups. Second, eigenvalues are extracted from these groups as parameters of testing scenarios.

Hierarchical clustering method is used in this research. Firstly, n samples are regarded as n groups, and each group contains a sample. Secondly, two groups with the most familiar sample are combined into a new group. The same process is repeated until all the samples are classified into one group. Thirdly, clustering tree diagram is drawn to describe the whole process and the number of groups and sample size in each group are determined[6].

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**Figure 1.Distribution of Vehicle Speed**

**Figure 2.Distribution of TTC**

**Figure 3.Relationship between TTC and Vehicle Speed**

**Figure 4.Relationship between Vehicle and Pedestrian’s Walking Speed**
Hierarchical clustering method greatly reduces subjective consciousness’s influence on classification compared to classifying manually. Moreover, the classification process is a kind of mathematical calculation, which can be repeated easily.

Steps of Cluster Analysis
39 samples including both qualitative and quantitative information are utilized to do cluster analysis.

Variable Selection
Some variables in qualitative analysis are not applicable in cluster analysis, such as light conditions and pedestrian’s age. In these variables, the proportion of some variable value is less than 15%. The proportion disparity of difference variable values may lead to ignorance of some value. Therefore, this kind of variables is ignored when clustering.

Five variables of three types, as shown in Table 3, are selected to do cluster analysis.

Cluster Process
As described in literature [6], inconsistent coefficient is used to determine final number of groups. In the process of clustering, inconsistent coefficient of certain combination’s higher than that of last combination represents that effect of last combination performs well. Larger increase in inconsistent coefficient means better effect of last combination. The last eight combinations are shown in Figure 6. The increase between 34th and 35th combination’s inconsistent coefficient is the largest of all, indicating that effect of the 34th combination is the best. Therefore, all the 39 samples are divided to 5 groups.

Clustering tree diagram of the whole process is shown in Figure 7.

### Table 2.
Selected variables of cluster analysis

<table>
<thead>
<tr>
<th>Type</th>
<th>Variable value</th>
<th>Variable name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment information</td>
<td>Time period</td>
<td>Daytime, Night</td>
</tr>
<tr>
<td></td>
<td>Intersection or not</td>
<td>Intersection, Non-intersection</td>
</tr>
<tr>
<td>Vehicle information</td>
<td>Vehicle speed</td>
<td>km/h</td>
</tr>
<tr>
<td>Pedestrian information</td>
<td>Pedestrian crossing from</td>
<td>Along the road, Left, Right</td>
</tr>
<tr>
<td></td>
<td>Pedestrian’s walking speed</td>
<td>km/h</td>
</tr>
</tbody>
</table>

**Figure 6. Inconsistent Coefficient**

**Figure 6. Clustering Tree Diagram**

Analysis on Clustering Result
Removing the third group with only three samples, we focus on left four groups and rename them. Clustering result, as shown in Table 4, has obvious characteristics in each group. Variable values of the first group are set to be the main condition. Other groups have some changes in variable.
Table 3. Clustering Result

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Variable value</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian’s speed higher than 4km/h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>Yes</td>
<td>13</td>
<td>5</td>
<td>9</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Proportion (%)</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>81.25</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td></td>
<td>18.75</td>
<td>28.57</td>
<td>0.00</td>
<td>25.00</td>
</tr>
<tr>
<td>Time period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>Daytime</td>
<td>15</td>
<td>6</td>
<td>8</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Night</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Proportion (%)</td>
<td>Daytime</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>93.75</td>
</tr>
<tr>
<td></td>
<td>Night</td>
<td></td>
<td>6.25</td>
<td>14.29</td>
<td>11.11</td>
<td>100.00</td>
</tr>
<tr>
<td>Intersection or not</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>Intersection</td>
<td>16</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Non-intersection</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Proportion (%)</td>
<td>Intersection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>Non-intersection</td>
<td>0.00</td>
<td>0.00</td>
<td>100.00</td>
<td>100.00</td>
<td>33.33</td>
</tr>
<tr>
<td>Pedestrian crossing from</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>Along the road</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>13</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0</td>
<td>7</td>
<td>2</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Proportion (%)</td>
<td>Along the road</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.75</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>81.25</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Number and proportion</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td></td>
<td>16</td>
<td>7</td>
<td>9</td>
<td>4</td>
<td>36</td>
</tr>
<tr>
<td>Proportion (%)</td>
<td></td>
<td>41.03</td>
<td>17.95</td>
<td>23.08</td>
<td>10.26</td>
<td>92.31</td>
</tr>
</tbody>
</table>

Box plots of vehicle speed, pedestrian’s walking speed, distance between vehicle and pedestrian at TRS of four groups are shown respectively in Figure 8, Figure 9, Figure 10 and Figure 11.

Figure 8. Box Plots of Vehicle Speed

Figure 9. Box Plots of Pedestrian’s Walking Speed
According to the result of clustering, 4 typical near-crash scenarios related to pedestrians at TRS are obtained, which cover 92.3% of the total samples. The 4 scenarios are shown in Table 4.

**Table 4. Typical Near-Crash Scenarios**

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Time period</th>
<th>Cross or not</th>
<th>Pedestrian crossing from</th>
<th>Vehicle speed (25 to 75 percentile) km/h</th>
<th>Pedestrian walking speed (25 to 75 percentile) km/h</th>
<th>Distance between pedestrian and vehicle (25 to 75 percentile) m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Daytime</td>
<td>Yes</td>
<td>Left</td>
<td>22-36</td>
<td>5-10</td>
<td>14-29</td>
</tr>
<tr>
<td>2</td>
<td>Daytime</td>
<td>Yes</td>
<td>Right</td>
<td>18-23</td>
<td>4-9</td>
<td>11-17</td>
</tr>
<tr>
<td>3</td>
<td>Daytime</td>
<td>No</td>
<td>Along the road</td>
<td>18-25</td>
<td>6-9</td>
<td>10-19</td>
</tr>
</tbody>
</table>

In the first and second scenarios, the location is at intersection in daytime. The difference between these two kinds is that pedestrians cross roads from different directions. The proportion of crossing road from left side is higher than that of right side. Presumably, Left A pillar hinders driver’s view to perceive pedestrians crossing from left side in advance.

In the third scenario, the location is at normal road in daytime, and the pedestrian is walking along the road. By reviewing videos, we find that roads are usually narrow or sidewalks are occupied in these scenarios, and pedestrians have to walk on motorway and conflicts happen naturally.

In the fourth scenarios, the location is at normal road at night. Pedestrian is walking along the road or crossing the road from right side. Similar with scenario 3, the situation of pedestrian’s walking along the road happens on narrow road.

**CONCLUSIONS AND DISCUSSIONS**

**Conclusions**

1) Through qualitative analysis, the following conclusions could be drawn: at TRS, the number of the cases in which the pedestrian is crossing the road is about 3 times more than that of the cases in which the pedestrian is walking along the road. The condition that the driver is driving under daylight, good lighting and uncongested road is respectively 5 times, 11 times, and 31 times more than driving under darkness, bad lighting and congested road.

2) Aiming at TRS, 4 typical scenarios are obtained including 5 variables: time (day & night), road character (congested & uncongested), pedestrian walking direction (along the road & across the road), car speed and pedestrian’s travel speed. Most vehicle speeds are among 18-37km/h and most pedestrian’s
travel speeds are among 4-12km/h. 4 scenarios cover 92.3% of the total samples.

**Discussions**

1) Obstruction is not included in the cluster analysis as a factor in this study, since drivers have seen the pedestrian at TRS. Meanwhile, it is included in the cluster analysis as a factor in similar studies, which obtain test scenarios based on crash cases since the happening of crash is related to obstruction. This difference can reveal the characteristics of near-crash and crash.

2) Unlike the previous studies, which only bring the average pedestrians’ travel speed into test scenarios, the pedestrians’ travel speed was included in the cluster analysis as a factor in this study, thus allowing more detailed information of pedestrians’ travel speed in the typical scenarios.

**REFERENCES**


POTENTIAL EFFECTS OF AUTOMATIC BRAKING ON ACCIDENT FATALITIES AND SERIOUS INJURIES

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Paper Number 17-0152

ABSTRACT

Automatic Emergency Braking will become a standard feature in light duty vehicles beginning in 2023 due to a voluntary agreement between vehicle manufacturers, NHTSA, and IIHS. The agreed performance criteria will result in a system that reduces the incidence of low-speed crashes and will likely have little effect on severe injuries and fatalities. Opportunities for fatality reduction associated with automatic braking are significant and are based on implementation approaches. Potential fatality reductions resulting from automatic braking activation thresholds in various crash modes and closing speed ranges were considered. The effects of alternative performance requirements on potential fatality reductions were then examined.

INTRODUCTION

The potential benefits associated with Forward Collision Warning (FCW) and Crash Imminent Braking (CIB) features, collectively known as Automatic Emergency Braking (AEB) systems, have been known for over forty years. The technology has been available on production vehicles for over ten years now and in 2016 many vehicle manufacturers, representing 99% of the U.S. auto market, entered into a voluntary agreement with the Insurance Institute for Highway Safety (IIHS) and the National Highway Traffic Safety Administration (NHTSA) to make AEB systems standard equipment. The agreement, documented in a memorandum of understanding (MOU) [1], specifies that AEB be offered as a standard feature in virtually all vehicles with a gross vehicle weight rating (GVWR) of 3,856 kg or less by September 1, 2022 and for vehicles with a GVWR less than 4,536 kg by September 1, 2025.

The MOU identifies the requirements for the FCW and CIB functionalities of the AEB system. The FCW system, as tested according to the NHTSA FCW Tests 2 and 3 [2], must issue an alert when the time to collision (TTC) is at least 2.4 seconds and 2.0 seconds, respectively. The requirements for CIB involve two options as defined by the IIHS test protocol [3]. The first option (A) requires a 5-test average speed reduction of greater than 16 km/h in either the 20 km/h or 40 km/h tests involving a stationary target vehicle. The second option (B) requires a 5-test average speed reduction greater than 8 km/h in both the 20 km/h and 40 km/h tests involving a stationary target vehicle. The IIHS uses a mock foam rear half of a vehicle as the lead target vehicle.

While there may be benefits associated with impacts involving pedestrians, bicyclists and fixed objects the MOU does not address testing for these situations.

The resulting crash delta-V is dependent on the mass of the two vehicles involved; smaller vehicles will receive a larger delta-v benefit than larger vehicles for the same observed AEB-produced speed reduction. Additionally, and perhaps more importantly, the real world results will depend on the implementation of the algorithms and sensors. The detection and response thresholds incorporate inputs from sensors that can include radar, cameras, infrared, and/or lidar. Only a small subset of the

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algorithm’s performance can be evaluated in a simple test. On-road performance is likely to vary widely from vehicle to vehicle. Studies of these algorithms have demonstrated that a significant consideration in their design was the philosophy behind the activation criteria. For example, the size of the oncoming vehicle (not based on radar cross-section) could be detected and different activation strategies could be implemented depending on the size of the oncoming vehicle.

It is well known that the optimal safety system performance differs depending on organizational priorities [4] [5]. Manufacturers, suppliers, the insurance industry, and NHTSA all may have differing objectives that would result in different system performance characteristics. For example, these organizational priorities could involve tuning system performance to minimize: a) fatalities, b) moderate-to-serious injuries, c) whiplash injuries, d) low-speed crash costs, and/or e) system cost. The present state of AEB performance testing and the agreements set out in the MOU indicate that low-speed crash costs are the current priority. The NHTSA estimates that the proposed AEB systems will favorable affect approximately 897,000 rear-end crashes; this includes preventing approximately 4,000 serious injuries and 100 fatalities annually [6]. The remainder of those affected include approximately 893,000 minor and property damage only crashes. Thus, there are opportunities for industry, suppliers, and/or governments to pursue regarding improved AEB performance and outcomes.

In this study we examine the maximum number of fatalities that are likely to be addressed with forward-looking AEB systems in passenger vehicles involved in front-to-front, front-to-rear, and front-to-fixed-object crashes. The implications of alternative testing strategies that likely would affect design approaches are discussed. The authors suggest that significant benefits can be achieved by expanding the performance scope and increasing the closing speeds required for AEB performance evaluations.

METHOD

Accident data from the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) from 2008 to 2014 was used in the analysis. NASS-CDS is a stratified sample of approximately 5,000 police-reported tow-away crashes collected annually by trained investigators. Crashes were included in the analysis if they involved only one or two light-duty passenger vehicles. Impact configurations were narrowed to those in which AEB systems would have the opportunity to be effective prior to impact, i.e. front-to-front, front-to-rear, and front-to-fixed-object crashes. Striking vehicles were defined as those that met the above criteria and whose first impact damage was to the front of the vehicle. Thus both vehicles in front-to-front impacts would be considered striking vehicles.

The injury severity, determined from the Maximum Abbreviated Injury Scale (MAIS), was identified for all occupants in each striking vehicle. Occupants coded with MAIS = 6 or that died within 30 days of the crash were coded as fatally injured. The potential benefits to occupants of vehicles impacted in the rear, i.e. the struck vehicle, were not addressed and these occupants are not included in the results below. All values were weighted based on the ratio inflation factor for each case.

The cumulative percentage of occupant casualties by injury severity, as identified from MAIS, was determined for two threshold values of impact closing speed: 20 km/h and 40 km/h. By using this approach the total number of casualties that would be addressed by the AEB systems outlined in the MOU could be determined. The closing velocity for each striking vehicle was derived using the recorded delta-V along with the impact force direction using Equation 1:

$$V_{cf1} = \frac{m_1+m_2}{m_2 \cos \theta} \cdot \Delta V_1,$$  \hspace{1cm} (Equation 1)

where $m_1$ and $m_2$ are the masses of vehicles 1 and 2, $\theta$ is the impact force direction, and $\Delta V$ is the change in velocity for the striking vehicle during the crash.

Finally the effects of alternative testing strategies considering the effects of testing in front-to-front configurations were then determined and compared with those found for the front-to-rear testing paradigm.
RESULTS
Of the occupants identified that were in the striking vehicles involved in front-to-rear impacts, 60% had known injury severity. The cumulative percent of occupants, by injury severity, for the two AEB closing speed thresholds are summarized in Table 1. For impacts with up to a 20 km/h closing speed there were no injuries identified as more severe that AIS 2. The 40 km/h closing speed impacts accounted for only 0.01% of all striking-vehicle fatalities and 0.09% of AIS3 injured occupants in this configuration.

Table 1.
Cumulative percent of striking-vehicle occupants, by injury severity, involved in front-to-rear crashes for AEB threshold closing speeds.

<table>
<thead>
<tr>
<th>Closing speed</th>
<th>Cumulative Percentage of Occupants by MAIS in Front to Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 km/h</td>
<td>0-1  2  3  4  5  Fatal</td>
</tr>
<tr>
<td></td>
<td>1%  0%  0%  0%  0%  0%</td>
</tr>
<tr>
<td>40 km/h</td>
<td>52% 1% 0% 0% 0% 0%</td>
</tr>
</tbody>
</table>

Of the weighted occupants identified in front-to-front crashes, 55% had known MAIS. Table 2 summarizes the cumulative percent of occupants involved in front-to-front crashes by their maximum injury severity. Crashes up to 20 km/h, closing speed of 40 km/h, constitute 3% of all fatalities and 7% of all AIS3 injuries. Crashes in which vehicles were moving at 40 km/h made up approximately 15% of all fatalities and 65% of all AIS 3 injuries.

Table 2.
Cumulative percent of occupants, by MAIS, involved in front-to-front crashes for equivalent AEB threshold closing speeds.

<table>
<thead>
<tr>
<th>Each vehicle impact speed</th>
<th>Cumulative Percentage of Occupants by MAIS in Front-to-Front</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-1  2  3  4  5  Fatal</td>
</tr>
<tr>
<td>20 km/h</td>
<td>46% 21% 7% 0% 0% 3%</td>
</tr>
<tr>
<td>40 km/h</td>
<td>94% 73% 65% 26% 34% 15%</td>
</tr>
</tbody>
</table>

Of the weighted occupants identified as being involved in a forward collision with a fixed object, 55% had known MAIS. Fixed object collisions resulted in greater injury severity than front-to-rear or front-to-front crashes. Table 3 summarizes the proportions of occupants, by MAIS, according to estimated closing speed. A closing speed of 20 km/h represented 5% of all fatalities and 21% of all occupants with AIS 3 injuries in the front-to-fixed object crash mode. At a closing speed of 40 km/h these proportions rose to 27% and 63% respectively.

Table 3.
Cumulative percent of occupants, by MAIS, involved in front-to-fixed object crashes for AEB threshold closing speeds.

<table>
<thead>
<tr>
<th>Closing speed</th>
<th>Cumulative Percentage of Occupants by MAIS in Front-to-Fixed Objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 km/h</td>
<td>43% 28% 21% 3% 41% 5%</td>
</tr>
<tr>
<td>40 km/h</td>
<td>95% 64% 63% 67% 73% 27%</td>
</tr>
</tbody>
</table>

Table 4 lists the relative frequency of MAIS 3+ outcomes and deaths between the front-to-rear and front-to-front or front-to-fixed object impact modes. There are approximately 12 times as many deaths and nearly 3 times as many seriously injured occupants in front-to-front than front-to-rear crashes. Similarly, fixed-object collisions are much more severe than front-to-rear collisions with 21 and 15 times more fatalities and serious injuries, respectively.

Table 4.
Ratios of occupants with MAIS 3+ and fatal injuries in front-to-front and front-to-fixed object vs front-to-rear impacts.

<table>
<thead>
<tr>
<th>Ratio to Front-to-rear</th>
<th>Front-to-front</th>
<th>Front-to-fixed objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIS3+</td>
<td>2.7</td>
<td>15</td>
</tr>
<tr>
<td>Fatal</td>
<td>11.9</td>
<td>20.5</td>
</tr>
</tbody>
</table>

Table 5 summarizes the total estimated benefit to occupants involved each frontal crash mode by injury severity and closing speed.
of serious injuries and fatalities that occur in front-to-front vs front-to-rear crashes, for equivalent closing speeds, suggest that an AEB test configuration should include an oncoming vehicle scenario. This would address far more serious injuries and fatalities.

While it can be understood that the intention associated with limiting testing to low-speed rear impacts is to encourage development, the technology is already beyond what is being tested for, and hence a restructuring of objectives and testing protocols should be accomplished, and, perhaps, is already in process.

How quickly this transition in testing protocols happens is dependent on organizational priorities. The focus on low-speed systems is potentially serving primarily the insurance industry but that industry has also been instrumental in improving overall crashworthiness performance even though their primary costs are associated with low-speed and property damage crashes that dominate the Weibull curve that represents the distribution of their claims frequency. So they are certainly to be commended for taking a lead in this area and hopefully that lead will continue to evolve. Meanwhile other groups like SAE and NHTSA could also follow suit and apply resources to encourage performance under higher closing velocities and using the front-to-front impact mode.

Clearly regulatory mandatory requirements are not required here due to the collaborative nature of the effort to ensure that effective use of the technology is introduced. However, both NHTSA and IIHS have the ability to incorporate performance requirements as part of their NCAP and IIHS rating’s systems quickly. For example, NHTSA could require, for a 5 star rating, greater speed reductions that could be phased in under a timeline such as that presented in Table 6. This would require AEB systems to work in front-to-front crash modes for which 28 km/h speed reductions would be required for each vehicle travelling at 40 km/h. Equivalent requirements could be defined for rear-to-rear impact crashes at 40 km/h into a stationary vehicle. In this way the opportunity to address fatalities will increase with the potential to achieve a reduction of 25% or more of fatalities occurring in frontal impacts with continued

<table>
<thead>
<tr>
<th>Injury Severity</th>
<th>Front-Rear</th>
<th>Front-Front</th>
<th>Front-Fixed Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal</td>
<td>0%</td>
<td>15%</td>
<td>27%</td>
</tr>
<tr>
<td>MAIS 3+</td>
<td>0%</td>
<td>65%</td>
<td>63%</td>
</tr>
</tbody>
</table>
improvements in AEB performance and fleet penetration. The additional side impact collision avoidance could be incorporated as the technology is ready for it which would provide significant benefits to the occupants of the side impact vehicles.

The test conditions could utilize either a representative vehicle that dynamically matches the speed reduction being achieved by the test vehicle, or a representation of the same vehicle as the other vehicle utilize representative cross sections as is currently being done, except representing the frontal cross section presented to the oncoming vehicle.

LIMITATIONS

The NASS-CDS contains a large amount of missing data with regard to both crash conditions and injuries. Thus, estimation techniques are often used to create the missing data, but that was not done here. Also there are large number of cases that are coded as injured extent unknown. Again methods can be used to distribute this data across the know AIS distribution for a given set of conditions; however this was not done here. The need to estimate the closing velocities based on the available information was necessitated by the generally missing closing velocity information in the database. The data in NASS-CDS is also known to have problems with regard to crash severity information; when crash severity algorithms are revised the past data is not corrected for these changes, thus leading further concerns with regard to crash severity data. That said the data is the best available for the United States on a stratified sample basis. The availability of EDR data in the forthcoming, but currently unavailable CISS will be of interest to refine analyses conducted here. However, it is known that there are potential concerns with the EDR data as well. Further, the injury severity counts do not include those occupants that were seated in struck vehicles in front-to-rear impacts.

CONCLUSION

The collision avoidance technology has the potential for significant effects on the number of fatalities and serious injuries occurring in the United States. However, the current AEB performance requirements address only the low-speed, and, consequently low severity, crash conditions. In order to achieve a greater benefit the NHTSA, IIHS and industry should adjust the performance requirements to reflect the conditions that representative of real world front-to-front and front-to-rear crashes that result in serious injury and fatality. Based up our analysis of real-world accident data, a supplemental test protocol is proposed to reduce the likelihood and severity of serious and fatal crashes in addition to minor low-speed crashes and injuries. Specifically, we suggest closing speeds on the order of 40 km/h with required average speed reductions up to 56 km/h for both front-to-front and front-to-rear impact modes.

REFERENCES

ABSTRACT

Research Question/Objective
Advanced Driver Assistance Systems (ADASs) such as Forward Collision Warning (FCW) and Automatic Emergency Braking (AEB) have been developed for light passenger vehicles (LPVs) to avoid and mitigate collisions with other road users and objects. These frontal crash avoidance and mitigation countermeasures have contributed to the reduction in the number of real-world traffic crashes, injuries, and fatalities involving LPVs. However, despite this success, the number of crashes, injuries, and fatalities in the US involving motorcycles has remained relatively constant. As a result, the relative percentage of US traffic fatalities involving a motorcycle has increased from 11% in 2006 to 14% in 2015 (Source: NHTSA 2015 Traffic Safety Facts). Therefore, there is a need for passenger vehicle FCW and AEB systems to also be effective in avoiding collisions with motorcycles. This paper describes the potential application of the Honda-DRI ACAT Safety Impact Methodology (SIM) to the evaluation of passenger vehicle FCW and AEB system effectiveness in avoiding and mitigating collisions with motorcycles, in order to further the objective of improving motorcycle safety and overall traffic safety.

Methods and Data Sources
Extensions to the NHTSA-Honda-DRI ACAT SIM needed to evaluate the effectiveness of LPV FCW and AEB systems in avoiding or mitigating collisions with motorcycles are identified. Potential extensions to the Crash Scenario Database Development Tools (SIM Module 1) to create passenger vehicle pre-crash/crash scenarios involving a motorcycle include a new Automated Motorcycle Accident Reconstruction Tool (AMART) and supporting data sources (e.g., NASS/CDS and MCCS). Potential extensions to the Crash Sequence Simulation Module (SIM Module 3) to simulate the passenger vehicle pre-crash/crash scenarios involving a motorcycle include a refined subject vehicle driver model and supporting data (e.g., driving simulator data) to model the driver glance and control response behavior specific to motorcycle conflicts, refined sensor models for the FCW and AEB systems, a passenger vehicle versus motorcycle collision model, and a motorcyclist equivalent life unit (ELU) injury model. This could also involve the development and refinement of motorcycle specific track tests for the FCW and AEB systems.

Results
Anticipated results of the extended ACAT SIM tool would include the estimated effectiveness and benefits of the LPV FCW and AEB systems in avoiding and mitigating passenger vehicle crashes involving motorcycles.

Discussion and Limitations
The results of the extended ACAT SIM tool would be based on various assumptions, approximations, and limitations that are summarized herein and further documented in the supporting references, such as the representativeness and accuracy of the supporting data and reconstructed accident pre-crash scenarios.

Conclusion and Relevance to session submitted
The proposed extensions to the ACAT SIM methodology to evaluate passenger vehicle-motorcycle safety would provide a valuable tool to help assess the effectiveness and benefits of LPV FCW and AEB systems in avoiding and
mitigating LPV crashes involving motorcycles. This would help to further the objective of improving motorcycle safety and overall traffic safety.

The methods used are directly relevant to the test and evaluation procedures to assess the safety benefits and effectiveness of advanced driver assistance technologies.

**INTRODUCTION**

Advanced Driver Assistance Systems (ADASs) such as Forward Collision Warning (FCW) and Automatic Emergency Braking (AEB) have been developed for light passenger vehicles (LPVs) to avoid and mitigate collisions with other road users and objects. These frontal crash avoidance and mitigation countermeasures have contributed to the reduction in the number of real-world traffic crashes, injuries, and fatalities involving LPVs. However, despite this success the number of crashes, injuries, and fatalities in the US involving motorcycles has remained relatively constant. As a result, the relative percentage of US traffic fatalities involving a motorcycle has increased from 11% in 2006 to 14% in 2015 [1]. Therefore, there is a need for LPV FCW and AEB systems to also be effective in avoiding collisions with motorcycles.

Lenkeit and Smith [2] evaluated the ability of eight 2016 MY US LPVs equipped with FCW to detect an exemplar motorcycle and passenger car using two tests in the NHTSA FCW confirmation test procedures [3]. The results of this preliminary evaluation indicated that only two of the eight subject vehicles (SVs) tested were able to pass the NHTSA test procedure with a stationary motorcycle as the principal other vehicle (POV), compared to all SVs passing the test with a stationary passenger car POV. Therefore these preliminary results tend to confirm the hypothesis that FCW systems may not be as effective in avoiding or mitigating collisions with a motorcycle as they are with a passenger car.

**Background**

Dynamic Research, Inc. (DRI) has been developing and applying safety impact analysis methods for many years (e.g., [4-7]). This included the development of a comprehensive Safety Impact Methodology (SIM) in two NHTSA-Honda-DRI ACAT programs. The ACAT-I program refined and used this methodology to evaluate the effectiveness and benefits of a prototype Honda Advanced Collision Mitigation Braking System (A-CMBS) [5]. The ACAT-II program further refined and used this methodology to evaluate the effectiveness and benefits of pre-production Head-on Crash Avoidance Assist System (H-CAAS) [6, 7]. The comprehensive and general structure of this methodology and accompanying tools are well suited for the potential evaluation of LPV FCW and AEB system effectiveness in avoiding and/or mitigating collisions with motorcycles with the extensions summarized herein.

**Project Aims**

The objective if this paper is to identify the extensions of the NHTSA-Honda-DRI ACAT SIM tools that would be needed to evaluate the effectiveness and benefits of LPV FCW and AEB systems in avoiding and mitigating collisions with a motorcycle.

**SAFETY IMPACT METHODOLOGY**

The NHTSA-Honda-DRI ACAT SIM was developed to correspond to the general framework described in [8]. This framework comprises 22 different functions that are grouped into seven different activities.

**Overview of the SIM**

A top-level block diagram of the Honda-DRI SIM tool is illustrated in Figure 1. The SIM tool comprises four main modules as follows:

1. Crash scenario database development tools, comprising three submodules.
   - Submodule 1.1 assembles a crash scenario dataset with a representative sample of LPVs involved in real-world crashes with a fixed object, 1 or 2 other vehicles, or a pedestrian, as illustrated by the example data in Figure 2. The cases are currently obtained from NASS/GES [9], CDS [10], PCDS [11], and naturalistic driving data [12]. The horizontal axis is the maximum Fatality Equivalents in the crash based on the coded KABCO or MAIS injury according to Appendix A of [5]. The resulting dataset comprises coded information about the accident, subject vehicle, collision partner, and persons, for use in the other SIM tool modules. This includes information for defining technology relevant crash types and effectiveness, and crash outcomes. A subset of this data (e.g., from CDS, PCDS) has more in-depth information that are used to reconstruct and simulate crash scenarios.

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1 Additional references are listed in [7].
crashes where the subject LPV was not towed, which tend to be less severe.

Submodule 1.2 is a tool to download or extract scene diagrams for each case in the crash scenario dataset if available.

Submodule 1.3 is an Automated Accident Reconstruction Tool (AART) to reconstruct the pre-crash and crash trajectories of the LPVs for each case in the crash scenario file, provided there is sufficient information available and the case is within the domain-of-validity of the AART (e.g., there is a scene diagram, vehicle velocity, and contact information). These reconstructable cases are denoted by the dark blue symbols in Figure 2. The resulting reconstructions can be used for simulation and testing.

2. Technology relevant case specification and case sampling tools comprise three submodules. Submodule 2.1 is a tool used by the ACAT designer to define the technology relevant crash types. Submodule 2.2 is a tool to select a representative subsample of crash scenario cases for simulation. Submodule 2.3 is a tool to select a subsample of cases for testing.

3. A Crash Sequence Simulation Module (CSSM) to simulate the driver and vehicle with and without the ACAT in crash scenarios in order to estimate the effects of the ACAT in avoiding or mitigating the crash. The CSSM incorporates a Simulink model of the ACAT that was provided by the ACAT designer, and driver behavior data from driving simulator tests. The resulting integrated CSSM simulation was then validated by comparison to driving simulator and track test results.

4. An Overall Safety Effects Estimator (OSEE) to estimate the overall effectiveness and benefits of the ACAT.

The current SIM tool is described in detail in [5, 6].

One of the limitations of the current tool is that it was originally developed primarily to evaluate technologies installed on an LPV to avoid or mitigate crashes with fixed objects, other LPVs or pedestrians. It was not specifically developed to evaluate LPV crashes with motorcycles.

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2 Based on the ACAT-I reconstructable case criteria listed in Tables B-4 and B-5 of [5]. This does not include the more stringent documentation of trajectory data (DOCTR AJ) criterion added for ACAT-II.
Proposed Extensions for Motorcycle Conflicts and Collisions

The following extensions or refinements to the ACAT SIM tools would be needed in order to evaluate the effectiveness and benefits of FCW and AEB systems in avoiding and mitigating crashes between an FCW/AEB equipped LPV and a motorcycle.

Module 1 Refinements

The crash scenario database and development tools would need to be extended and refined to specifically address crashes involving an LPV and a motorcycle. This would fill the data gap for motorcycles shown in Figure 2. This primarily affects the data for submodule 1.1 and the accident reconstruction in submodule 1.3.

The current SIM primarily uses CDS data for more severe and reconstructable crash scenarios involving LPVs. Therefore the first choice would be to also use LPV-MC crash scenario cases from these data as well. There are 138 LPV-MC cases in the 2000 through 2015 CDS data. The main limitation of the CDS data is that motorcycles are not CDS applicable vehicles. Consequently there are no injury outcome data for the motorcycle occupants, which are used by the Overall Safety Effect Estimator (Module 4). It may be possible to link some cases to FARS, GES, or state accident data [13] to obtain the motorcycle occupant injury information.

Another limitation of CDS data is that motorcycles are out of the scope of WinSmash Delta-V reconstructions methods used by CDS. Therefore the Delta-V information currently used by the AART to reconstruct LPV-LPV crash scenarios are not available to reconstruct LPV-MC crash scenarios. Therefore other information about the pre-crash vehicle speeds are needed for the accident reconstruction. One potential source for this information is the EDR data for the subject LPV. EDR data with pre-crash speed information are currently available for 8 of the 138 LPV-MC cases. The pre-crash speeds for the motorcycle would need to be estimated from the posted speed limit (which is known for all of the 8 cases), the CDS coded travel speed, pre-event movement (prior to the critical event), and the attempted avoidance maneuver.

The distribution of potential motorcycle cases from the CDS data is illustrated in Figure 3. The format of this figure is similar to Figure 2. The crash severity in this figure does not include the MC rider and passenger injuries. Therefore this figure illustrates the limited amount of motorcycle crash scenario data potentially available from CDS.

Figure 3. Potential Motorcycle Crash Scenario Cases from the CDS data (LPV injuries only)

NASS National Motor Vehicle Crash Causation Survey (NMVCCS) [14] and Crash Injury Research and Engineering Network (CIREN) [15] data were also investigated for potential LPV-MC crash scenarios. There were 30 two-vehicle cases involving an LPV and a motorcycle in the NMVCCS data. Only two of these NMVCCS cases had pre-crash EDR speed information which could be used in reconstructing the pre-crash scenario. There was only one CIREN case involving a motorcycle.

There are 224 cases in the recently completed Motorcycle Crash Causation Study (MCCS) [16] involving a single LPV and a single L1 or L3 motorcycle and no pedestrians. One potential limitation of the MCCS data is that a large percentage of the cases do not have any injuries coded for the LPV driver. It may be possible to link some fatal cases to FARS data in order to obtain any missing LPV occupant injury information. One could assume that the driver was not injured in the other cases.

It is assumed that the crash can be reconstructed based on the pre-crash travel speeds, impact speeds, and principal direction of forces of the LPV and MC, and other coded information such as the relative heading angle and the VIN or make-model-year decoded vehicle mass and size properties.

The distribution of 116 potentially reconstructable motorcycle cases from the MCCS data is illustrated in Figure 4. The format of this figure is similar to Figure 2 except the different symbol types for the CSSM data. The number of reconstructable MAIS=1 cases is underrepresented compared to the more severe crashes.
Potential Motorcycle Crash Scenario Cases from the MCCS data

The pre-crash trajectory for the motorcycle for the 10 sec prior to impact can be reconstructed using the vehicle dynamics model described in Weir and Zellner (1978) [17]. The LPV-MC crash scenario reconstruction process could then be implemented by a new Automated Motorcycle Accident Reconstruction Tool (AMART) that would use coded data and scene diagrams as inputs.

Module 3 Refinements

The extensions to the crash sequence simulation (CSSM) module and postprocessor would involve: 1) extending the ACAT system sensor models called by the simulation as needed to include motorcycles; 2) incorporating the reconstructed motorcycle trajectories into the CSSM simulation; 3) measuring LPV driver response behavior to motorcycle conflicts using a driving simulator tests (e.g., [18]) and incorporating the results into the CSSM driver model; and 4) adding a new LPV-MC impact simulation and injury severity estimator.

The LPV-MC impact simulation could be based on the simulation described in Kebschull et al. (1998) [19]. This simulation predicts the probability of AIS injury to the head, chest, and abdomen, as well as femur and tibia fractures and knee dislocations. The simulation was also extended to predict neck injuries in [20]. The overall simulation result is an estimated Equivalent Life Units (ELU) [21] or Fatality Equivalent (FE) injury severity index for the motorcycle rider.

Module 2 and 4 Refinements

There would not need to be any extensions to modules 2 and 4 of the ACAT SIM.

Safety Area to Be Addressed by Advanced Technologies

The objective of the ACAT SIM tool with the motorcycle extensions is to evaluate the effectiveness and benefits of LPV technologies such as FCW and AEB in avoiding or mitigating LPC-MC crashes. It is assumed that these technologies would primarily be effective in crashes where the LPV driver inattention is a contributing factor.

Size of the Crash Problem

The potential numbers of crashes, involved vehicles, and fatalities that represent the size of the problem for the entire US motor vehicle fleet are listed in Table 1 in terms of non-technology specific crash types that have been broadly defined in terms of numbers of vehicles involved and vehicle types. Some of these crashes are not expected to be addressable by an FCW or AEB due to either the vehicle application (e.g., not an LPV), the vehicle role (e.g., struck vehicle), or other technology relevant factors. For example, the results in Table 1 include 43,000 single vehicle crashes involving a motorcycle (i.e., did not involve an LPV), with 1,997 rider and non-motorist fatalities. These results indicate that while motorcycles are involved in less than 1% of the crashes, these crashes resulted in 7.5% of the overall crash fatalities and 20% of the fatalities involving two vehicles.

<table>
<thead>
<tr>
<th>Crash Category</th>
<th>Crash Type</th>
<th>Estimated Number of Crashes (1000s)</th>
<th>Estimated Number of Vehicles (1000s)</th>
<th>Estimated Number of Fatalities2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-vehicle</td>
<td>All1</td>
<td>1,817</td>
<td>1,817</td>
<td>19,036</td>
</tr>
<tr>
<td>2-vehicle</td>
<td>Involves a MC</td>
<td>50</td>
<td>51</td>
<td>2,636</td>
</tr>
<tr>
<td></td>
<td>Other1</td>
<td>4,000</td>
<td>8,049</td>
<td>10,506</td>
</tr>
<tr>
<td>3 or more</td>
<td>All1</td>
<td>418</td>
<td>1,336</td>
<td>2,914</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>6,285</td>
<td>11,253</td>
<td>35,092</td>
</tr>
</tbody>
</table>

Sources: GES and FARS data.
1 Includes crashes that do not involve an LPV.
2 Includes parked and working vehicles and non-motorists.

Advanced Technologies

Candidate technologies include FCW and AEB systems. A prototype version of the Honda A-CMBS which included these features is described in [5].

FCW systems use vehicle speed information and forward looking sensors to detect an impending forward collision with another vehicle (POV) or object and alert the driver. FCWs that satisfy the performance criteria specified in [22, 3] for conflicts with “a midsize sedan or a dummy vehicle fixture” have been a recommended by the New Car Assessment Program since the 2011 model year [23, 24].
AEB systems combine FCW with automatic braking that activates if the driver does not react to the alert in order to avoid or mitigate the forward collision. NHTSA has announced plans to add AEB as a NCAP recommended technology beginning with the 2018 model year [25]. Twenty LPV manufacturers have committed to making AEB systems standard equipment on US LPVs by September 2022 [26].

**Objective Tests**

Driving simulator and track tests based on LPV-LPV crash scenarios were conducted for the ACAT evaluation of the Honda A-CMBS [5]. The driving simulator tests were used to determine the driver responses to the conflict and system warnings for a sample of the reconstructed crash scenarios. A subsample of these crash scenarios was also track tested to measure and confirm the responses of the vehicle, sensor, and driver behavior. Similar tests could also be conducted using reconstructed LPV-MC crash scenarios (e.g., [2]).

**Assumptions and Limitations**

The results of the extended ACAT SIM tool would be based on various assumptions, approximations, and limitations, such as the representativeness and accuracy of the supporting data and reconstructed accident pre-crash scenarios. A number of these limitations are described in [5].

**Conclusions**

This paper has summarized the data and extensions to the Honda-DRI-ACAT SIM tool needed to evaluate the effectiveness and benefits of LPV FCW and AEB systems in avoiding or mitigating LPV-MC crashes. One of the key elements of the SIM are real world LPV-MC scenarios, for which several sources were investigated. Approximately 100 LPV-MC scenarios can potentially be reconstructed from MCCS data, with some additional cases potentially from CDS data.

**References**


DEFINITIONS, ACRONYMS, AND ABBREVIATIONS
ACAT Advanced Crash Avoidance Technology
A-CMBS A prototype Honda Advanced Collision Mitigation Braking System
ADAS Advanced Driver Assistance System
AEB Automatic Emergency Braking system
CDS Crashworthiness Data System
ELU Equivalent Life Units (an ISO 13232-5 measure of Injury Severity)
FARS Fatality Analysis System
FE Fatality Equivalents (a NHTSA measure of Injury Severity)
FCW Forward Collision Warning system
GES General Estimates System
H-CAAS A preproduction Honda Head-on Crash Avoidance Assist System
KABCO A police reported injury severity scale
LPV Light Passenger Vehicle (passenger car or light truck or van)
MAIS Maximum Abbreviated Injury Severity
MC Motorcycle
MCCS Motorcycle Crash Causation Study
MY Model Year
NCAP New Car Assessment Program
NHTSA National Highway Traffic Safety Administration, US Department of Transportation
NMVCCS National Motor Vehicle Crash Causation Survey
PCDS Pedestrian Crashworthiness Data System
POV Principal Other Vehicle (e.g., a motorcycle)
SIM Safety Impact Methodology
SV Subject Vehicle (e.g., an LPV equipped with FCW)
HANDS OFF DETECTION REQUIREMENTS FOR UN R79 REGULATED LANE KEEPING ASSIST SYSTEMS

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IEE S.A.
Luxembourg

Paper Number 17-0202

ABSTRACT

Lane Keeping Assist Systems (LKAS) are a key component of (semi-) automated driving functions, allowing for more comfortable driving on highways or in traffic jams. Today, all of those systems are designed to be driven “hands on”. However, one can observe a certain misuse of these types of systems, particularly if they allow for extended “hands off” driving without warning the driver. The United Nations is amending UN regulation 79 on “Steering equipment” to add some technical requirements to LKAS in order to address driver misuse related safety concerns. Entering into force on April 1st 2018 for type approval of new vehicle types, and applicable to all new production vehicles from April 1st 2021 on, R79 will require LKAS-equipped vehicles to provide a means of detecting that the driver is holding the steering control. There are, in principle, two technologies that vehicle manufacturers use today to determine whether the driver is holding the steering wheel: a capacitive sensor in the steering wheel rim for direct information about whether the hands are holding the steering wheel, or a torque sensor for indirect information via steering activity on the steering wheel. So future LKAS will have to evolve and provide an improved hands off detection performance, combined with an appropriate warning sequence starting, at the latest, 15 seconds after the driver removes their hands from the steering wheel. The new requirements are applicable to vehicle categories M and N.

INTRODUCTION

Today, an increasing number of vehicle models are available with Advanced Driver Assistance Systems (ADAS) that can take longitudinal control of the vehicle or support the driver with lateral control. These ADAS are paving the way to Automated Driving (AD), a key trend in the automotive industry. By combining longitudinal and lateral control, a vehicle would meet the AD Level 2 definition of SAE (Society of Automobile Engineers) International’s standard J3016. And while the driverless car (Level 5) may be the ultimate goal, we are not there yet: in the foreseeable future, the driver will remain a key element in the AD concept. But their role is likely to shift away from being a “driver” (up to Level 2) and move towards becoming an “operator” (under Level 3 & 4), and ceding control to the vehicle. This requires a transition of control responsibilities that has to be monitored precisely to avoid any misunderstandings. “Hands on” / “Hands off” detection is going to be one of the key monitoring elements, and additional driver monitoring needs can be expected for those future automated driving functions. In a first phase, the UN regulators have now decided to address system misuse that has been observed with Level 2 systems, and will require monitoring that verifies whether the driver is holding the steering wheel.

WHY “HANDS OFF DETECTION”?

Initial Need For HOD

A frequently quoted key article of the Vienna Convention on Road Traffic says that "the driver shall at all times be able to control his vehicle". Vehicle manufacturers concluded during the development of Traffic Jam Assist or similar functions that drivers might potentially misuse the system by removing their hands from the steering wheel and letting the vehicle do the driving on its own. From the point of view of system safety, and from a liability perspective, this was considered a misuse that should be prevented. After consideration, BMW decided that all vehicles with a Traffic Jam Assist system would have to be supplemented with a reliable “hands off” detection sensor to ensure that the driver keeps their hands on the steering wheel while using this function. Existing steering torque sensors were not considered to be robust enough as they do not provide reliable hands on/off information when the vehicle is at a standstill or is driving on straight,
smooth roads, especially at low speeds. IEE developed a capacitive “Hands Off Detection” (HOD) sensor integrated into the steering wheel rim to overcome those concerns. This HOD sensor allows the vehicle to detect precisely if the driver has his hands on the steering wheel, and if he does not, to initiate an appropriate warning cascade. The IEE HOD sensor has been in production since the end of 2013.

Figure 1. “Hands off” detection scenario

System Misuse – “Hands Off” Driving

LKAS (Lane Keeping Assistance System) on the market today are designed to be operated “hands on”. The vehicle manuals also include corresponding information for and warnings to the vehicle owner. However, an increasing number of drivers are misusing the systems and removing their hands from the steering wheel, particularly for LKAS in combination with Automatic Cruise Control (ACC). Some drivers may only want to test the limits of the systems, while others may have a poor understanding of the system limitations and believe that “hands off” operation is possible under certain circumstances. There are plenty of videos on social media platforms documenting this misuse. The scenarios range from drivers that let the vehicle do the steering while keeping their hands next to the steering wheel, to others who fully rely on the vehicle while having their hands on their lap or even using both hands for eating and drinking. In some extreme cases the driver has even left the driver’s seat, meaning he would no longer have the opportunity to intervene if there is a system error [1]! A fatal crash of a Tesla S operated in Autopilot-mode happened in May 2016. Driver misuse of the system is believed to have played a significant role. NHTSA noted in its investigation report that “The Florida fatal crash appears to have involved a period of extended distraction (at least 7 seconds)” [2]. Some media reports after the crash mentioned that the driver had possibly been watching a video [3], and therefore did not see and did not react to the crossing truck. Regulatory authorities, alerted by the multitude of documented cases of overreliance and system misuse, decided to tackle this issue. As vehicle manual information was apparently not effective enough to prevent those drivers from using their ADAS in a non-authorized way, it was decided to address the issue with a technical solution, by upgrading the UN Regulation 79 (Steering equipment) with a “hands off” detection requirement for LKAS-equipped vehicles. Drivers intending to misuse the systems should be alerted and thus the misuse should be prevented.

REGULATION FOR AUTOMATICALLY COMMANDED STEERING FUNCTIONS (ACSF)

Upcoming HOD requirement for LKAS

Today the LKAS systems are still almost unregulated, and that many vehicles “tolerate” the misuse is documented in a multitude of internet videos. The United Nations Informal Group on Automatically Commanded Steering Functions (IG ACSF) is currently reviewing regulation 79 on “steering systems” to define technical requirements for ADAS and AD-related steering functions. Among the new definitions are ACSF category B1 and ACSF category B2. Category B1 basically covers LKAS that must be driven “hands on”, while B2 is aimed at future continuous lane guidance systems that can be operated “hands off”. The UN has recently decided to upgrade the technical requirements that have to be met by B1 “hands on” lane keeping systems.

In countries applying the UN R79, the new requirements will enter into force on April 1st 2018 for type approval of new vehicle types, and will be applicable to all new production vehicles from April 1st 2021 on [4]. The regulation covers vehicles of category M (carriage of passengers) as well as category N (carriage of goods). The regulation requires vehicles fitted with an LKAS to be equipped with a means of detecting that the driver is holding the steering control. The regulation also describes an escalating warning strategy as shown in Figure 2.
Drivers misusing the LKAS function by going “hands off” must be warned by an optical signal after 15 seconds at the latest. Then, at the latest after 30 seconds, parts of the optical signal must turn red, and an acoustic alert must be triggered. After 30 seconds of acoustic warning, an emergency signal of at least 5 seconds must sound as a final warning, and the LKAS must be deactivated. Hence, a reliable “hands on” detection system will be needed in order to meet the regulatory requirement. At the same time, it should avoid false positive warnings for drivers that effectively have their hand on the steering wheel.

**Hands Off Detection Test Method**

The hands off detection and the warning cascade are tested at two different driving speeds. ACSF B1 systems typically have a speed range within which they can operate, from the lowest speed $v_{\text{min}}$ to the maximum speed $v_{\text{max}}$. In a first test, the vehicle shall be driven with an activated LKAS with a vehicle test speed between $v_{\text{min}} + 10\text{ km/h}$ and $v_{\text{min}} + 20\text{ km/h}$ on a track with lane markings at each side of the lane. The driver releases the steering wheel and continues to drive until the LKAS is deactivated automatically. The test is passed if the warning cascade meets the requirements illustrated in Figure 2. A second test must be carried out with a vehicle test speed between $v_{\text{max}} - 20\text{ km/h}$ and $v_{\text{max}} - 10\text{ km/h}$ or $130\text{ km/h}$ whichever is lower.

**From “Hands On” To “Hands Off”**

In a next phase, the IG ACSF will define the technical requirements for ACSF Category B2. A vehicle that will be type-approved in the future and meets those requirements can be continuously operated “hands off”, provided it is done within the system boundaries defined by the regulation and the vehicle manufacturer. One of those regulatory boundaries is limiting the use to road sections with a physical or constructional separation of traffic moving in opposite directions and which has at least two lanes for the direction the vehicle is driving. With regards to the AD Levels, such systems can be a “Hands Off”-Level 2, or Level 3, or Level 4.

Vehicles offering a “hands off” operation will need enhanced driver monitoring capabilities. Under Level 3 & 4, the driver no longer has the task of continuously monitoring the traffic environment. But, in particular for Level 3, the vehicle is not necessarily in a position to handle all traffic situations. And although Level 4 vehicles have some additional fall back capabilities, they will require the driver to take back the control at the end of the defined use case. So the driver will have to remain available to respond to either a possible transition request initiated by the system (e.g. in case of a sensor failure or a too complex traffic situation) or at the end of the use case (e.g. when leaving the highway). The draft regulation text for ACSF B2 requires that the vehicle will have to be equipped with a driver availability recognition system. The vehicle must verify the physical presence of the driver in the seat and, in the absence of any monitored driver activity for more than 3 minutes, the driver must prove his availability by a positive action. For example, by briefly touching the steering wheel the driver can confirm via a capacitive HOD sensor that he has not fallen asleep.

“Hands off” driving functions do not only entail engineering challenges, but also liability questions that have to be addressed. As “hands off” operation is neither allowed nor possible on all roads, there will be a need for transition procedures between manual and automated driving modes. This transition has to be monitored precisely, as a change in liability goes with the change of vehicle control. Obviously, in AD mode the driver is allowed to be “hands off”, but it is crucial to know exactly when he has finally ceded steering control to the vehicle, as well as when he takes back control of the steering or intends to override the automated mode. A reliable HOD can precisely monitor this transition of control. And should there be an incident with a (semi-) automated vehicle, the HOD signal can help to clarify the key question: "Who was in control of the vehicle when the collision happened?".

**IEE’s HOD SOLUTION**

Based on capacitive (electric field) sensing technology, HOD consists of a highly flexible multi-layer sensor mat integrated into the steering wheel, with a miniaturized electronic and the connecting cabling installed in the steering wheel’s
centre hub. The system measures the current flowing from the sensing electrode towards vehicle ground, which is proportional to the capacitance. If a driver touches the steering wheel, the capacitance, and with that the current, increases.

Figure 3. HOD Sensor Mat

By using an IEE-owned ASIC, the electronic can reliably classify and communicate the hands on/off status under all environmental conditions. More advanced classification is enabled by using a multi-zone HOD system, which determines, for example, between a left and/or right hand touch. The HOD sensor mat can be combined with steering wheel heaters.

HOD immediately detects when the driver takes their hands off the steering wheel. So with regards to the Regulation 79 warning requirements, the vehicle manufacturer can initiate the warning with high precision and repeatability, and select any warning time that is within the minimum regulatory requirements. HOD also overcomes the known weaknesses of torque sensors that have limited performance on straight roads with few or no irregularities. In such situations with almost no active steering input by the driver, HOD prevents false positive warnings to “hands on” drivers.

Therefore, HOD is a robust solution to monitor whether the driver has his hands on the steering wheel in any driving scenario. Its field of applications ranges from enabling regulatory compliance for basic LKAS to supporting the HMI concepts of advanced automated driving functions.

CONCLUSION

Regulatory authorities have taken a significant step to prevent drivers from misusing steering assistance systems that are designed for “hands on” use. Vehicles equipped with LKAS and approved under UN Regulation 79 will have to provide a means of detecting that the driver is holding the steering control. The regulation update will become effective for new vehicle types in April 2018 and for all new vehicles in April 2021. So the M and N vehicle categories will no longer be allowed to “tolerate” continuous misuse by drivers that have taken their hands off the steering wheel. Simply providing written information to the driver via the vehicle manual that he has to keep his hands on the steering wheel is no longer sufficient. A technical sensing solution and a defined “hands off” warning strategy have to be implemented.

IEE’s HOD was the first capacitive steering wheel sensor on the market, and there is an increasing need for the technology. HOD is expected to become a key HMI element of vehicles with LKAS and future automated driving functions. Main benefits are reliable hands on/off detection to support the regulatory requirements, improved HMI, safe transition between manual and automated driving modes, as well as the clarification of liability questions.

REFERENCES


ACTIVE SAFETY-COLLISION WARNING PILOT IN WASHINGTON STATE

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Paper Number 17-0218

ABSTRACT
This paper documents a project to test bus collision avoidance warning systems being performed by Pierce Transit under the auspices of the Washington State Transit Insurance Pool (WSTIP) and the University of Washington under a grant from the Innovations Deserving Exploratory Analysis (IDEA) program of the Transportation Research Board. Commercially available collision avoidance warning systems (CAWS) were modified and adapted by a vendor for use on standard transit buses and installed on 38 buses operating at eight transit agencies, including seven buses at Pierce Transit. Each bus also was equipped with a cellular telematics unit and supplemental cameras with video recording. Buses were operated in normal service for several months, including a three month testing and data collection period. The paper discusses the rationale for the project, technology to be tested, operations and data collection, and some of the early findings from the pilot test.

INTRODUCTION TO PIERCE TRANSIT
Pierce Transit (PT) provides public transportation services in the urbanized area of Pierce County, WA, Washington’s second largest county. This area includes the City of Tacoma; and the communities of Edgewood, Fife, Fircrest, Gig Harbor, Lakewood, Milton, Puyallup, Ruston, Steilacoom, Tacoma, University Place; portions of Auburn and Pacific; and some unincorporated portions of Pierce County. The service area population is 557,069.

The service area, located 35 miles south of Seattle, provides critical connections to these employment, education, and commerce epicenters in the region: The Cities of Tacoma, Seattle and Olympia (the State Capitol); SeaTac International Airport; Joint Base Lewis-McChord; and a number of universities and hospitals. We also serve the Puyallup Tribe of Indians, providing service to the tribal healthcare center, youth center, a new business center, and the largest employment center, the Emerald Queen Casino.

PT directly operates local fixed-route service and a portion of its Americans with Disabilities Act (ADA) complementary paratransit service, known as SHUTTLE. Additional SHUTTLE service is operated under contract by First Transit. The SHUTTLE fleet is 100 vehicles, 36 operated by PT and 64 by First Transit. PT has an extensive vanpool program, using about 380 12- and 15-passenger vans and minivans. In addition, PT, acting as a contractor to Sound Transit, the regional transit provider,
operates fixed-route express bus service using Sound Transit vehicles.

The fixed-route fleet is comprised of 204 vehicles of various types, including expansion vehicles due to arrive in the first quarter of 2017. The fleet mix includes these buses: 30- and 40-foot compressed natural gas (CNG), 40-foot diesel-electric hybrid, 40-foot diesel, and 25-foot CNG and gas-powered cutaway vans. PT is the recipient of a 2016 FTA Low or No Emissions grant and will order our first electric buses in 2017. The number of buses required for peak service is 119 at present.

PT operates a network of 36 local fixed routes connecting riders to the Tacoma Dome Station, a multi-modal transit center with direct connections to the City of Seattle, SeaTac International Airport, Link Light Rail, Greyhound bus and the Puget Sound Ferry System, the largest ferry system in the U.S.

Financial and operating statistics for 2015:
Unlinked Passenger Trips: Fixed Route 9,104,337, Paratransit 368,411, Vanpool 849,159.
Revenue Hours: Fixed Route 388,736, Paratransit 166,951, Vanpool 143,234.
Operating Expenses: Fixed Route $56,495,424, Paratransit $17,347,909, Vanpool $4,182,296.

Over ten years, Pierce Transit has experienced 91 incidents resulting in 109 injuries, and incurred $11.1 million in claims. WSTIP data show that 94% of claims are attributable to collisions and sudden stops.

### TABLE 1
Tabulations of Washington State Transit Insurance Pool (WSTIP) Closed Claims Greater Than $10,000 by Type of Claim for Eight Largest Fixed Route Operators – from January 1, 2006 to December 31, 2015 - Run March 31, 2016. – Source: WSTIP

<table>
<thead>
<tr>
<th>Incident Type</th>
<th>Total Claims ($)</th>
<th>% of Total Claims</th>
<th>Average Claim ($)</th>
<th>Fatalities</th>
<th>Injuries</th>
<th>Fatal + Injured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision with Other Vehicle</td>
<td>174</td>
<td>11,834,203</td>
<td>47</td>
<td>68,013</td>
<td>2</td>
<td>212</td>
</tr>
<tr>
<td>Collision with Person</td>
<td>18</td>
<td>6,476,442</td>
<td>26</td>
<td>359,802</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Collision with Bicyclist</td>
<td>2</td>
<td>2,436,701</td>
<td>10</td>
<td>1,218,350</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Non-Collision - Sudden Stop</td>
<td>30</td>
<td>1,645,612</td>
<td>7</td>
<td>54,854</td>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td>Non-Collision - Board/Alighting</td>
<td>36</td>
<td>1,345,139</td>
<td>5</td>
<td>37,365</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>Collision with Fixed Object</td>
<td>8</td>
<td>878,405</td>
<td>4</td>
<td>109,801</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>Non-Collision – Slip/Fall/Trip</td>
<td>9</td>
<td>233,656</td>
<td>&lt;1</td>
<td>25,962</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>90,232</td>
<td>&lt;1</td>
<td>18,046</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Totals</td>
<td>282</td>
<td>24,940,390</td>
<td>100</td>
<td>--</td>
<td>6</td>
<td>335</td>
</tr>
</tbody>
</table>

The IDEA grant and insurance company contributions funded the program to install collision avoidance warning technology on 35 buses at seven participating transit agency members of WSTIP in 2016. Unique claims data for Pierce Transit, Washington State's largest fixed route provider, are provided with data from the previous 10 years. WSTIP data show that 94% of claims are attributable to collisions and sudden stops. The IDEA grant and insurance company contributions funded the program to install collision avoidance warning technology on 35 buses at seven participating transit agency members of WSTIP in 2016.
the state of Washington, and three additional buses at King County Metro, the major transit provider for the Seattle area. The project includes a comprehensive examination of the total costs of the most severe and costly types of collisions, frontal collisions and collisions with pedestrians and cyclists, the potential for collision avoidance technology to reduce the frequency and severity of these types of collisions, and reduce the associated casualty and liability expenses.

**PROJECT OBJECTIVES**
The project was conceived with the following objectives in mind:

- Create a robust demonstration pilot for active/collision avoidance within the State of Washington on a minimum of 35 transit buses at seven WSTIP members
- Determine the ease of retrofit of the existing fleet.
- Develop a methodology for estimating the full costs savings of avoided collisions for each agency.
- Develop a methodology and evaluation process for transit operator feedback
- Provide detailed data and understanding on entrance barriers to this technology (i.e. operational acceptance and rejection issues)

In addition to the stated objectives, the project team was asked by the sponsor to test the effectiveness and accuracy of the CAWS in terms of generating false positive warnings and false negative warnings. Subsequent to the initiation of the project, the vendor provided an additional unanticipated set of data analytics for logging events per mile. That will enable the team to test the hypothesis that as drivers gain experience with the CAWS-equipped buses, they may be better able to anticipate adverse driving conditions, which would be reflected in fewer events per miles logged.

Pierce Transit has been operating seven (7) buses equipped with the Shield+ Collision Avoidance Warning System (CAWS). Five of the systems at Pierce were installed in August-September 2015 and the remaining two were installed in February 2016. A three-month data collection and reporting period was run from April 1, 2016 through June 30, 2016. During that period Pierce buses logged 52,000 miles with CAWS, accumulated an estimated 3,600 hours of video and logged an estimated 2,000 alerts and warnings.

**INSTALLATION AND TESTING OF EQUIPMENT**
The Rosco VQS4560 Mobileye Shield+ System provides coverage of blind zones where vulnerable road users (VRU’s) may be hidden from the driver’s view, and by alerting the driver to avoid potential collisions. The system includes four cameras, one facing forward on the inside of the windshield, one covering the blind spot created by the left front pillar, and one on each side at the rear of the bus to cover blind spots behind the driver.

The Mobileye Shield+ system illuminates one of three indicators located on the windshield to draw the driver’s attention towards a potential pedestrian collision. The indicator shows a yellow light if a pedestrian or bicyclist is calculated to be within 2.5 seconds or less of colliding with the bus. The indicator flashes red and an alarm sounds if a pedestrian or bicyclist are within one second or less of colliding with the bus. An indicator mounted in the center of the windshield also provides forward collision warning, headway monitoring and following time, lane departure warning, and speed limit.

Because buses routinely change lanes in low speed operation while pulling into and out of stops, the lane departure feature was disabled in this pilot to avoid unnecessary distraction for the driver. Figure 1 shows the indicators as they appear to the driver.

![Figure 1. Collision Avoidance Warning System Indicators.][1]

Systems were installed on 38 buses spanning a period from August 28, 2015 to March 17, 2016. Figure 2 is a diagram that illustrates the locations of the system components on a typical bus. Procurement of the collision warning systems was funded locally and was not part of the IDEA contract. Consequently, installation was able to start in advance of the IDEA grant.

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[1]: image
Each system was calibrated and tested in non-revenue operation prior to being placed in revenue service.

**MONITORING AND DATA COLLECTION**

The Mobileye Shield+ system does not include video record/playback. For this pilot, Rosco installs Dual-Vision XC camera systems to record continuous video and Ituran telematics units to record time-stamped events triggering the Mobileye Shield+ system.

Once in service, each bus was continually monitored in real time by an Ituran telematics system which sends a message whenever the collision warning system is triggered by an event. Each event message includes a specific event code, bus identification, heading, miles traveled, speed, and location. Interspersed with the event messages, the Ituran system monitors “G” forces along three axes which provides readings on speed, turning and braking rates.

Each telematics unit communicated directly with a server and uploaded event data in real time. Three of the 38 buses in the project, including one at PT, experienced communications failures due to faults in the telematics units and did not report data during the test period. The following event data for 35 buses were logged from the Shield+ system:

- Exceeded Speed Limits
- HW (Headway Monitoring)
- UFCW (Urban Forward Collision Warning; speed 0 to 19 mph)
- FCW (Forward Collision Warning; speed > 19 mph)
- Mobileye Pedestrian Collision Warning Right (PCWR)
- Mobileye Pedestrian Collision Warning Left (PCWL)
- Mobileye Pedestrian Collision Warning Left Front (PCWLF)
- Mobileye Pedestrian Collision Warning Forward (PCW)
- Total Audible alerts
- Total Audible alerts related to forward facing events
- Total Visual Only - Pedestrian Detections resulting in yellow indicator illumination but no audible alerts (PDZs)

The Ituran telematics system is capable of reporting vehicle/driver performance in terms of numbers of events per miles traveled for each vehicle. Due to agency concerns about driver reactions, Shield+
systems on Spokane Transit buses were set up to collect and transmit data via telematics only and did not issue warnings to drivers. This was called operating in “stealth mode.” Buses operating with systems in stealth mode served as a baseline, or control group, to help determine if installing Shield+ systems with functioning visual and audible alerts and warnings, resulted in changes in driver performance over time. As drivers gain experience with the Shield+ equipped buses, they may be better able to anticipate adverse driving conditions, which would be reflected in fewer events per miles logged. This hypothesis is being tested in the pilot.

GATHER OPERATOR, STAFF, AND PUBLIC REACTIONS TO THE WARNING SYSTEMS

During field testing in revenue service, it was determined that passengers did not interact with the collision warning systems. Indicators are not very visible to passengers and audible warnings may not be distinguishable by passengers from other normal bus sounds such as stop requests and fare card validators. On some runs, depending on conditions, there may be no noticeable activations. Consequently, it was decided not to conduct a survey to obtain passenger feedback, but to rely on reports from the drivers.

Operator survey instruments were developed for administration through distribution of paper questionnaires and for direct entry via computer. The survey was administered three times, to determine if driver reactions would change over time. We did not see a discernable pattern of change in responses over time. The following numbers of responses were received: April – 115, May – 85, and June – 75. Because their Shield+ systems operated in stealth mode, Spokane Transit did not administer the survey to its drivers.

Two of the questions that were asked of operators about Shield+ deserve note: 1) was it helpful, and 2) would they prefer to drive with it. Overall, 37 percent of the responses indicated that the system was helpful, and 63 percent indicated the system was distracting. Thirty three percent of the responses were affirmative when drivers were asked if they preferred to drive with it and 67 percent were negative. Operators were encouraged to provide comments on the questionnaires. One hundred seventy eight (178) comments were received.

ISSUES NOTED IN OPERATOR COMMENTS

- False positive pedestrian Indications – Warnings and alerts frequently sounded
- Inaccurate speed limit warnings – The system inoperative
- System inoperative – Some operators commented that they received no alerts or warnings from the system during a run. In some instances maintenance was required to restore systems to operation.
- False speed limit violations – Some operators commented that they received false speed limit violations.
- Headway warnings – Some operators commented that headway warnings appeared when they pulled behind parked cars or when cars pulled into their lane.
- Inaccurate speed limit warnings – Some operators commented that they received speed warnings that differed from the readings on the bus speedometer.

VIDEO DATA SPECIFICATION AND CAPTURE

Videos collected by the Rosco Dual-Vision system are in .asd format. Rosco provided a converter to convert all videos in one SD card all at once from “.asd” to “.avi”. The final .avi files are composed of videos from three channels. As shown in Figure 3,
Channel 1 videos are taken by the front-facing camera; channel 2 videos are taken by the windshield-mounted rear-facing camera; and channel 3 videos are split-screen images taken by the external rear left and right side-mounted forward-facing cameras.

![Figure 3. Left to Right - Images captured by Rosco Dual-Vision: Channel 1 forward-facing, Channel 2 interior rear-facing, Channel 3 split screen left and right external side cameras.](image)

Video data is downloaded from each Dual Vision camera using 32GB SD cards, which are sent to UW for processing. Video from each channel is 640 × 480 pixels (width × height). One SD card can normally hold up to 2,799 video clips. Video clip duration varies from about 45 seconds to 75 seconds. One video clip is about 10 MB. During the data collection period, 717 SD cards were processed capturing about 10,000 events totaling 16,600 hours and requiring about 19TB of storage.

**Video Processing Framework**

`UW developed a framework for automatically processing the front-facing videos and filtering out most of the frames without events. Another round of manual checking is conducted to further verify the detection results. The proposed detection framework excludes complex background information and attempts to locate the pedestrian directly. Distance calculation to the pedestrian is calculated in 3D real-world coordinates. Our framework has four main stages: 1) pedestrian detection in onboard video, 2) motion estimation in image coordinates, 3) relative position and speed calculation in real-world coordinates, and 4) near-miss detection.

Figure 4 illustrates the process. In the first stage, a Histogram of Oriented Gradients (HOG) pedestrian detector is used to detect pedestrians within the camera vision. In the second stage, interest points inside the detected rectangle representing the pedestrian are tracked with a Kanade-Lucas-Tomasi (KLT) tracker to estimate pedestrian motion in image coordinates. In stage three, a camera model is used to find the correspondence between image coordinates and real-world coordinates. The pedestrian’s position and speed relative to the bus are calculated in 3D real-world coordinates. In stage four, several thresholds such as time to collision (TTC) are calculated to detect near-miss events which can be extracted from video clips.
FIGURE 4. Proposed processing method for vehicle-pedestrian near-miss detection through onboard monocular vision. Four stages are pedestrian detection, motion estimation, relative position and speed estimation, and near-miss detection.
Validation
More than 30 hours of onboard video data was used to test the performance of the proposed near-miss detection method. Figure 5 shows some sample frames identified as near-misses. In (a), the vehicle is approaching a stop sign when two pedestrians are crossing the street. One of the pedestrians is detected as having the potential to collide with the bus if no evasive action is taken. In (b), a pedestrian standing at a bus stop is detected when the bus approaches the stop and changes lanes. In (c), an event is detected when the bus approaches a non-signalized intersection and a pedestrian is running to cross the street. In (d), the system demonstrates the ability to detect multiple conflicts at the same time.

CONCLUSIONS AND RECOMMENDATIONS
As mentioned earlier in the section on data collection and monitoring, the rate of warning per 1000 miles was recorded for each bus. It was therefore possible to compare the performance of buses that broadcast the warnings to drivers with buses that did not. Table 2 shows the comparison for each type of warning.

For each type of warning, there is a discernable reduction in warnings per 1000 miles for the active fleet. Although the data was not recorded for individual drivers, it appears that drivers of buses in the active fleet triggered fewer warnings than those who drive buses in “stealth mode.”

It is possible that the CAWS equipped buses made the drivers more sensitive to conditions that triggered warnings, and they may have been able to anticipate those conditions and avoid triggering the CAWS indicators. Thus the CAWS may be able to reduce collisions by increasing driver awareness of potential conditions that might lead to a crash.
### Table 2. Comparison of Control Group with Active Fleet for Warnings per 1000 miles

<table>
<thead>
<tr>
<th>Warning Type</th>
<th>Control Group (2 buses 17K mi)</th>
<th>Active Fleet (33 buses, 344K mi)</th>
<th>Active Fleet Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed Limit</td>
<td>16.74</td>
<td>15.39</td>
<td>-8%</td>
</tr>
<tr>
<td>Headway (HW)</td>
<td>185.84</td>
<td>50.31</td>
<td>-73%</td>
</tr>
<tr>
<td>Forward Collision &lt;19 mph (UFCW)</td>
<td>317.74</td>
<td>96.04</td>
<td>-25%</td>
</tr>
<tr>
<td>Forward Collision &gt;19 mph (FCW)</td>
<td>10.99</td>
<td>6.27</td>
<td>-43%</td>
</tr>
<tr>
<td>Pedestrian Collision</td>
<td>27.67</td>
<td>18.00</td>
<td>-35%</td>
</tr>
</tbody>
</table>

In summary, key findings from the pilot test are as follows:

- None of Pierce’s CAWS equipped buses were involved in any collisions with vehicles, pedestrians or cyclists during the test period.
- Telematics data provided by the vendor indicated that CAWS-equipped buses may have a positive impact on driver performance.
- The initial version of the CAWS received mixed reactions in driver surveys, but demonstrated a clear path for product improvements.
- Based on evidence from the pilot test, WSTIP has committed to provide insurance and support for loss prevention activities for continued development and a full-scale deployment of CAWS on all Pierce Transit fixed-route buses.

The findings from the pilot study led Pierce Transit to apply for a competitive research and development grant from the Federal Transit Administration (FTA) to equip all 176 of its 40 foot transit buses with CAWS and to run extended testing and data collection for a full year. The expectation is that PT would be able conduct a full-year of testing, data collection, analysis, and evaluation during an estimated 4.4 million miles of revenue service for our entire fixed-route fleet. PT received notice that the FTA awarded $1.66 million to PT for the project and we are currently working with our partners to complete and submit the necessary documents to initiate the work.

**REFERENCES**


The National Transportation Safety Board (NTSB) is an independent federal agency charged by Congress to investigate every civil aviation accident and significant accidents in all other modes of transportation, including highway, railroad, marine, pipeline and hazardous materials. The NTSB is not part of the Department of Transportation. The NTSB uses a similar investigative process for all the transportation modes, regardless of the complexity of the accident or the vehicle systems involved. The objective of this paper is to document the NTSB’s process for investigating all crashes with a focus on vehicle and system automation, particularly in the highway mode where the transition to automated control systems is occurring in the current vehicle fleet.

The NTSB follows a systematic investigative process for all modes of transportation, with modal specialists leveraging support from in-house research and engineering laboratories. The paper explains each step of the investigative process from start to finish, including the initial crash notification, launch selection, the on-scene phase, the party process, recorded data, laboratory capabilities, investigative hearings, factual reports, technical reviews, analysis reports, safety recommendations, and the final NTSB products. The paper will highlight the breadth and diversity of the NTSB disciplines covered throughout the investigation: biomechanical engineers, survival factors specialists, human factors experts, meteorologists, structural engineers, materials scientists, recorder engineers, medical and toxicological specialists, and vehicle dynamics engineers. Examples from NTSB investigations are highlighted to elucidate the investigative process and its application to vehicle and system technologies. Measures of NTSB effectiveness are discussed, including recommendation acceptance rates and outreach efforts.

The goal of the NTSB investigation is to determine the probable cause of the crash and to issue safety recommendations to prevent future crashes or reduce the severity of future crashes; the goal is not to assign blame or determine fault. Through a formal system involving designated parties to the investigation, the NTSB leverages the technical knowledge of organizations associated with a crash, such as the operators, manufacturers, unions, maintenance operators, and regulatory agencies. The party system ensures that all factual information is collected, agreed to, and reported correctly. This process enables the party members to obtain knowledge of critical aspects of a crash investigation in a timely manner. The NTSB takes full responsibility for determining the probable cause and making recommendations; this unbiased reporting fosters public trust that safety is being properly addressed. The NTSB’s investigative process has successfully documented the probable cause and issued safety recommendations for complex investigations in all transportation modes. Case examples from recent investigations will serve as examples of the investigative process: the crash during landing of Asiana Flight 314, the Washington Metro Area Transit Authority red line crash, and the high-speed derailment of the Amtrak train in Philadelphia, PA.
INTRODUCTION

In 1967, Congress consolidated all transportation agencies into a new U.S. Department of Transportation (DOT) and established the NTSB as an independent agency placed within the DOT for administrative purposes. In creating the NTSB, Congress envisioned that a single organization with a clearly defined mission could more effectively promote a higher level of safety in the transportation system than the individual modal agencies working separately. An aviation predecessor of the NTSB originated in the Air Commerce Act in 1926, which in turn evolved into the Civil Aeronautics Board in 1940. Since 1967, the NTSB has investigated accidents in the aviation, highway, marine, pipeline, and railroad modes, as well as accidents related to the transportation of hazardous materials.

In 1974, Congress reestablished the NTSB as a completely separate entity, outside the DOT, reasoning that "...No federal agency can properly perform such (investigatory) functions unless it is totally separate and independent from any other ... agency of the United States." Because the DOT has broad operational and regulatory responsibilities that affect the safety, adequacy, and efficiency of the transportation system, and transportation accidents may suggest deficiencies in that system, the NTSB's independence was deemed necessary for proper oversight. The NTSB, which has no authority to regulate, fund, or be directly involved in the operation of any mode of transportation, conducts investigations and makes recommendations from an objective viewpoint.

The NTSB is comprised of five Board members who are nominated by the president and confirmed by the Senate to serve five-year terms. One member is designated as the Chairman and another as the Vice Chairman, with each serving a two-year term. The NTSB staff of about 400 individuals includes technical experts in all transportation modes including aviation, railroad, highway, marine, pipeline, and hazardous materials. Supporting the modal offices are the Office of Research and Engineering, which includes laboratories dedicated to recorded information, materials investigations, simulation, data analysis, and animation, along with other administrative offices.

In 1996, Congress assigned the NTSB the additional responsibility of coordinating Federal assistance to families of aviation accident victims. While originally legislated to provide assistance following major aviation accidents, the program has expanded to provide assistance in all modes of transportation on a case-by-case basis.

To date, the NTSB has issued over 14,400 safety recommendations to more than 2,300 recipients. [1] Because the NTSB has no formal authority to regulate the transportation industry, our effectiveness depends on our reputation for conducting thorough, accurate, and independent investigations and for producing timely, well-considered recommendations to enhance transportation safety. The objective of this paper is to document the NTSB's process for investigating all crashes with a particular focus on vehicle and system automation, particularly in the highway mode where the transition to automated control systems is occurring in the current vehicle fleet.

METHODS

The NTSB process for investigating a crash begins with the initial notification. Early notification is critical to an organized investigation and the notification process is defined by procedures in each mode. For highway crashes, this notification typically comes from the NTSB 24-hour Response Operations Center, which monitors the news reporting systems watching for events that match an active list of crash types of interest. The NTSB may also be notified by our industry and government partners. Initial information concerning the circumstances of the crash are communicated to a modal duty officer who makes initial contact with the local law enforcement personnel on-scene to confirm the nature of the crash. Based on the circumstances of the crash, a management decision to launch to a crash site is determined and a go-team is formed.

Launch Selection

The launch selection process is established by each transportation mode at the NTSB. In highway crash investigations, the NTSB has the ability to select crashes that have national importance, represent a significant loss of life, address emerging technologies or threats, or contribute knowledge to areas of special investigation. Recent crash investigations have focused on infrastructure failures, large school buses, railroad grade crossing collisions, multi-vehicle crashes involving commercial vehicles, catastrophic motorcoach crashes, pedestrian collisions, and collisions involving vehicles with advanced technologies.
Go-Team

A highway investigation go-team consists of NTSB specialists in human factors, survival factors, vehicle performance, crashworthiness, highway factors, motor carrier factors, data- and video-recorders, biomechanics, medical factors, and crash reconstruction. The composition of the team is based on the nature of the crash. The go-team is led by an investigator-in-charge (IIC), who is a senior investigator with years of NTSB investigative experience. On major investigations, those involving a full go-team with national interest, an NTSB Board member accompanies the go-team to serve as the primary spokesperson for the investigation. The go-team typically departs for the crash scene within several hours of the initial notification in order to initiate the investigative process to capture perishable forensic evidence.

Investigative Process

The investigative process begins with the on-scene phase of the investigation. This phase usually continues for approximately one week, depending on the location of the crash and the complexity of the investigation.

On-scene investigation

During the on-scene phase, NTSB specialists are responsible for a clearly defined portion of the investigation. Working groups are formed with each NTSB specialist serving as the group chair. These specialized working groups are staffed by technical experts from the parties (see the party system in the next section) to the investigation. While most working groups operate on-scene, some groups such as the recorders group may operate at the NTSB headquarters to ensure the security of the recorded data.

The party system

The NTSB designates participating organizations to be parties associated with the crash investigation. Party members bring a technical or specialized expertise to contribute to a specific working group. For example, in a highway investigation, party status may be offered to an equipment manufacturer, a union representative, the vehicle manufacturer, the local law enforcement agency and the branch or branches of the DOT responsible for oversight of the situation. This designation as a party enables the NTSB to work with those involved in a crash to ensure that a complete and technically correct factual documentation of the circumstances and evidence are gathered and documented for each crash. The party members participate in the working groups where they have technical expertise and are responsible for reviewing and validating the documentation of factual evidence. This process further enables the party members to obtain knowledge of critical aspects of a crash investigation in a timely manner. Persons in legal or litigation positions are not allowed to be assigned as party members to the investigation. All party members report to the NTSB, and agree that the NTSB will be the sole source of information about the investigation for the media.

Factual Phase

Once the on-scene phase of the investigation is complete, the NTSB technical specialists, working with their party group members, finalize the factual reports. During this period, the IIC, working with management and the engineering labs, plans the additional work required for the investigation, which may include additional tests and documentation of equipment or examination of exemplar vehicles and systems. Medical records may be subpoenaed and autopsy reports are requested to fully document the injuries sustained by those involved in the crash. Toxicology tests may be processed on vehicle operators to better understand their fitness to operate the vehicle at the time of the crash. Design drawings, equipment specifications, maintenance records, and business records may be needed to understand vehicle operations. Simulations representing the crash dynamics may also be performed during this phase of the investigation. Party members assigned to each working group are responsible for reviewing the factual reports to ensure their accuracy and completeness.

Recorded data

In commercial aviation, flight data recorders (FDR) and cockpit voice recorders (CVR) are common and NTSB’s experience with them has developed an expertise that is applied to locomotive recorders, marine voyage recorders, and event data recorders from all modes. Highway vehicles may also be equipped with electronic data recorders, airbag modules, engine control modules, and other devices that can document event and crash related information. Commercial highway vehicles may also be equipped with recording devices such as event-based and continuous video recording systems. Further, additional recorded data in all modes of transportation may be available from non-traditional devices such as surveillance...
cameras, smart phones, tablet computers, and medical devices.

**Laboratory capabilities**

The NTSB laboratories are located in the headquarters facility in Washington, DC and include laboratories focusing on recorders, vehicle and infrastructure materials, simulation, animation, and data analysis. The recorders laboratory is a state-of-the-art facility originally designed to enable downloads of aviation flight data recorders and cockpit voice recorders, both intact and after damage and fire sustained during a crash. The laboratory supports all modes with a capability to recover, download, and document recorded data from trains, ships, pipelines, highway vehicles, and all other forms of video, audio, and personal electronic devices. This laboratory also supports foreign investigations.

The materials laboratory staff of multi-disciplinary engineers examine vehicle components and infrastructure wreckage from crashes in all transportation modes. Staff performs expert scientific analyses to determine if the performance of materials and structures in the crash conditions were related to the cause or severity of the event.

The simulation lab consists of a cab-based commercial vehicle driving simulator used to recreate crash related circumstances in a laboratory environment. The simulation lab also uses three-dimensional (3D) laser scanning technologies to document crash related evidence including the crash scene, damaged vehicles, and exemplar vehicles. The 3D laser scanning data enables review of the crash environment and vehicles virtually.

An animation laboratory combines all of the factual data from the other laboratories, along with additional pertinent investigative information, into animations depicting the crash scenarios to highlight key information that aids in understanding a complex sequence of events.

The laboratories, resident within the Office of Research and Engineering, also include a statistical and data analysis division. Research staff prepare safety reports based on analyses of transportation accident data which are used to determine factors common to a series of events and to identify safety improvements or evaluate the value of transportation-related devices or policy. The laboratory also provides statistical expertise to support the analytical projects of the NTSB. Also within the Office of Research and Engineering are medical officers, biomechanical engineers, and fire/explosion specialists.

**Investigative hearing**

The Board may choose to hold an investigative hearing to gather additional factual information in support of a major investigation. During an investigative hearing, sworn testimony is gathered from subpoenaed witnesses addressing specific aspects of the investigation. The investigative hearing also serves to allow the public to observe the factual portion of the investigative process. Typically, an investigative hearing is held within the first six months after a crash has occurred but may be held after that time for more complex investigations.

**Technical review**

During the technical review, the party members are provided draft factual reports from all the investigative working groups, including groups on which they may not have technical representation. During the technical review, the party members review the factual reports and provide technical information to support any substantive changes that are proposed. Once the factual information has been reviewed and finalized, the groups’ factual reports and any associated factual information are archived in the NTSB’s public docket management system, which is available on the NTSB’s web page.

**Analysis Phase**

Following completion of the factual reports, the NTSB technical specialists then analyze the factual information to identify safety deficiencies that need to be addressed in order to mitigate the severity or to prevent the occurrence of a similar crash in the future. The party members do not participate in the analysis of the factual information or in writing the analytical reports but may still contribute key information to group leaders during this phase. Analytical reports are not available in the docket management system because those reports are viewed as staff opinions concerning the investigation, whereas the analysis and conclusions from the investigation are considered to be the opinion of the NTSB.

**Final Board Report**

The final Board report is a compilation of the relevant factual and analytical information gathered and developed during the investigative process. The Board report includes the Board’s statement of probable cause, investigative conclusions and recommendations.
issued to prevent or mitigate the severity of a future crash. Parties to the investigation are permitted to submit their proposed findings of cause and proposed safety recommendations, which are made part of the public docket.

The investigative staff presents their work to the Board Members that deliberate over the final report in a public Board meeting in Washington, D.C. The Board Members debate all aspects of the draft report and conduct separate votes on the probable cause, the conclusions, and the recommendations, and may file an assenting and/or dissenting opinion. The final report and presentations shown during the public meeting are available on the NTSB web page shortly after the conclusion of the Board meeting.

RESULTS

The results section of this paper presents a summary of several on-going and completed NTSB investigations.

Williston, Florida

The Williston, Florida crash involves the first known fatality in a vehicle operating using automated control systems. As of April 2017, the crash remains under investigation by the NTSB. A final report is expected during the 2017 calendar year. The NTSB’s preliminary report detailed the collision involving a 53-foot semitrailer in combination with a 2014 Freightliner Cascadia truck tractor and a 2015 Tesla Model S, which occurred on May 7, 2016. [2] The vehicle’s system performance data revealed the driver was using the advanced driver assistance features Traffic-Aware Cruise Control and Autosteer lane keeping assistance to tactically control the vehicle. Used in combination, these systems are referred to by Tesla Motors as an Autopilot system. The semitrailer and passenger vehicle were scanned using a 3-dimensional (3D) laser scanner. Figure 1 and Figure 2 shows images from the laser scanner of semitrailer and vehicle, respectively.

Collision of Two Washington Metropolitan Area Transit Authority Metrorail Trains near Fort Totten Station, Washington, D.C.

On June 22, 2009, inbound Washington Metropolitan Area Transit Authority (WMATA) Metrorail train 112 struck the rear of stopped inbound Metrorail train 214. The accident occurred on the aboveground track on the Metrorail Red Line near the Fort Totten station in Washington, DC. As shown in Figure 3, the lead car of train 112 struck the rear car of train 214, which resulted in a loss of occupant survival space in the lead car of about 63 feet (about 84 percent of its total length). Nine people aboard train 112, including the train operator, were killed. Emergency response agencies reported transporting 52 people to local hospitals. Damage to train equipment was estimated to be $12 million. [3]
The NTSB determined that the probable cause of the accident was (1) a failure of the track circuit modules, built by GRS/Alstom Signaling, Inc., which caused the automatic train control system to lose detection of train 214 (the struck train) and thus transmit speed commands to train 112 (the striking train) up to the point of impact and (2) WMATA’s failure to ensure that the enhanced track circuit verification test (developed following the 2005 Rosslyn near-collisions) was institutionalized and used systemwide, which would have identified the faulty track circuit before the accident.

Contributing to the accident were (1) WMATA’s lack of a safety culture, (2) WMATA’s failure to effectively maintain and monitor the performance of its automatic train control system, (3) General Railway Signal/Alstom Signaling, Inc.’s failure to provide a maintenance plan to detect spurious signals that could cause its track circuit modules to malfunction, (4) ineffective safety oversight by WMATA’s Board of Directors, (5) the Tri-State Oversight Committee’s ineffective oversight and lack of safety oversight authority, and (6) the Federal Transit Administration’s lack of statutory authority to provide Federal safety oversight.

Contributing to the severity of passenger injuries and the number of fatalities was WMATA’s failure to replace or retrofit the 1000-series railcars after these cars were shown in a previous accident to exhibit poor crashworthiness. The NTSB issued multiple recommendations as a result of this investigation. The WMATA Metrorail system has still not fully returned to the automatic train control system.
monitoring/instructor pilot’s inadequate supervision of the pilot flying; and (5) flight crew fatigue, which likely degraded their performance.

As a result of this investigation, the NTSB made safety recommendations to the FAA, Asiana Airlines, Boeing, the Aircraft Rescue and Firefighting Working Group, and the City and County of San Francisco.

**Derailment of Amtrak Passenger Train 188**

**Philadelphia, Pennsylvania**

At 9:21 p.m. eastern daylight time on May 12, 2015, eastbound Amtrak passenger train 188 derailed in Philadelphia, Pennsylvania, with 245 passengers and 8 Amtrak employees on board. The train had just entered the Frankford Junction curve—where the speed is restricted to 50 mph—at 106 mph. As the train entered the curve, the locomotive engineer applied the emergency brakes. Seconds later, the train derailed, as shown in Figure 5. Eight passengers died, and 185 others were transported to area hospitals. [5]

![Figure 5: The Philadelphia Amtrak derailment scene.](image)

The NTSB determined that the probable cause of the accident was the engineer’s acceleration to 106 mph as he entered a curve with a 50-mph speed restriction, due to his loss of situational awareness likely because his attention was diverted to an emergency situation with another train. Contributing to the accident was the lack of a positive train control system, which is a system that can monitor and control train movements specifically to avoid train to train collisions and derailments resulting from overspeed conditions. Contributing to the severity of the injuries were the inadequate requirements for occupant protection in the event of a train overturning.

As a result of the investigation of this accident, the NTSB made recommendations to Amtrak, the Federal Railroad Administration, the American Public Transportation Association, the Association of American Railroads, the Philadelphia Police Department, the Philadelphia Fire Department, the Philadelphia Office of Emergency Management, the mayor of the city of Philadelphia, the National Association of State EMS (Emergency Medical Services) Officials, the National Volunteer Fire Council, the National Emergency Management Association, the National Association of EMS Physicians, the International Association of Chiefs of Police, and the International Association of Fire Chiefs.

**Orland, California**

Although not a crash dealing with automated vehicles, this crash highlights the need for crash-survivable recorders. On April 10, 2014, a 2007 Volvo truck-tractor in combination with double trailers, operated by FedEx Freight, Inc., was traveling southbound in the right lane of Interstate 5 (I-5) in Orland, California. At the same time, a 2014 Setra motorcoach, operated by Silverado Stages, Inc., was traveling northbound on I-5 in the right lane. In the vicinity of milepost 26, the combination vehicle moved into the left lane, entered the 58-foot-wide center median, and traveled into the northbound traffic lanes of I-5. [6]

The truck-tractor collided with a 2013 Nissan Altima four-door passenger car, which then rotated counterclockwise and departed the highway to the east. The truck-tractor continued moving south in the northbound lanes and collided with the front of the motorcoach, before both vehicles partially departed the highway to the east.

![Figure 6: Postcrash fire engulfing FedEx Freight truck double trailers and Setra motorcoach in Orland, California.](image)
A postcrash fire ensued, as shown in Figure 6. Both the truck and the motorcoach drivers died, along with eight motorcoach passengers. The remaining 37 motorcoach passengers received injuries of varying degrees. The two occupants of the passenger car received minor injuries.

The safety issues identified in the investigation included fire performance standards for commercial passenger vehicle interiors and difficulties in motorcoach egress. The investigation also dealt with the need for event data recorder survivability for crash reconstruction and safety improvements.

The NTSB determined that the probable cause of the Orland, California crash was the inability of the FedEx Freight truck driver to maintain control of the vehicle due to his unresponsiveness for reasons that could not be established from available information. Contributing to the severity of some motorcoach occupant injuries were high impact forces; the release of combustible fluids, leading to a fast-spreading postcrash fire; difficulties in motorcoach egress; and lack of restraint use.

As a result of this investigation, the NTSB issued safety recommendations to the National Highway Traffic Safety Administration (NHTSA) and to the Federal Motor Carrier Safety Administration (FMCSA). The NTSB also reiterated safety recommendations to NHTSA and reclassified a recommendation to FMCSA.

Safety Report: Commercial Vehicle Onboard Video Systems

The NTSB has investigated many highway accidents where onboard video systems recorded critical crash-related information. This commercial vehicle onboard video systems report discussed two crashes where continuous video systems were installed on commercial vehicles. [7] In a 2012 school bus crash in Port St. Lucie, Florida, the video recording system captured all three phases of the crash, including precrash driver and passenger behaviors and vehicle motion; vehicle and occupant motion during the crash; and postcrash events, such as passenger evacuation, short-term injury outcomes, and emergency response. The school bus at final rest is shown in Figure 7.

Figure 7. Right side of the school bus involved in the Port St. Lucie, crash.

In a 2011 motorcoach crash in Kearney, Nebraska, the video recording system captured critical precrash information but had certain limitations that negated the potential benefits of crash and postcrash event data. The safety report summarized the analysis of the onboard video systems from these two crashes. Further, to advance biomechanical and pediatric trauma-based research, it presented the video analysis and subsequent extensive injury documentation from the Port St. Lucie investigation.

As a result of the safety report, the NTSB issued safety recommendations to NHTSA; to the American Bus Association, United Motorcoach Association, American Trucking Associations, American Public Transportation Association, National Association for Pupil Transportation, National Association of State Directors of Pupil Transportation Services, and National School Transportation Association; and to 15 manufacturers of onboard video systems.

Special Investigation Report: The Use of Forward Collision Avoidance Systems to Prevent and Mitigate Rear-End Crashes

Over a three-year period, the NTSB investigated nine rear-end crashes involving passenger or commercial vehicles striking the rear of another vehicle—the result of which was 28 fatalities and 90 injured people. This special investigation report reviewed the previous recommendations made by the NTSB pertaining to the reduction of rear-end crashes and examined collision avoidance technologies that would aid in their prevention. [8]

The report concluded that collision warning systems, particularly when paired with active braking, could significantly reduce the frequency and severity of rear-
end crashes. As a result of this report, The NTSB issued safety recommendations to NHTSA and to vehicle manufacturers, both passenger and commercial.

**DISCUSSION**

The use of automated vehicles and systems is increasing in all modes of transportation. In some cases, automation is implemented to assist the operator in complex environments. In many other circumstances, automation is included in the vehicle design to increase safety, to reduce the consequences of human error, and to aid in the detection of risks that might not be recognized by a human.

In the Asiana crash, the pilots were confused by the aircraft’s automation system and as a result of a misconfiguration and a lack of awareness of their airspeed, the aircraft slowed and descended below its desired flight path and crashed into the seawall at San Francisco’s airport.

Common to many investigations involving automated vehicles and control systems is the operator’s misunderstanding of the systems—examples include mode confusion, false assumptions, and system limitations. In many train crashes and high-speed derailments, positive train control has been documented as an automated system that can prevent or mitigate the consequences. In the Amtrak derailment in Philadelphia, the NTSB concluded that a fully implemented positive train control system would have enforced the 50-mph speed restriction and prevented the accident. The NTSB went further, including positive train control in the probable cause by stating that the lack of a positive train control system contributed to the accident.

In highway vehicles, despite the introduction of systems such as electronic stability control, advanced restraint systems, collision warning systems, and automatic emergency braking, the number of fatalities has been increasing significantly in recent years. [9] These increases may result from the improved economy, lower fuel costs, and additional miles traveled but the increases may also result from driver error including driver distraction. [10] Many vehicle manufacturers are looking toward automated systems to increase safety, reduce driver error, and to provide transportation for individuals that may not be able to drive themselves. NHTSA recently issued a Federal Automated Vehicles Policy addressing highly automated vehicles. [11]

Further, the NTSB has long advocated for more recorded data to monitor both systems and operators in order to better understand the causes of crashes. Both video and data based recording systems have provided critical information in understanding the crash causation and in developing persuasive recommendations to mitigate or prevent future crashes. Importantly, the recorded information must survive the crash and postcrash environment.

Through all of these past investigations and looking into the future, the NTSB has a unique multi-modal perspective on crash investigation, recorded data, vehicle automation, human performance, survival factors, and injury prevention. Further, the NTSB does not work in isolation but instead, leverages the technical knowledge and abilities of the party members in the investigation. Ultimately, this investigative process yields a comprehensive factual and analytical report of the circumstances surrounding an accident and the steps that need to be taken in order to prevent or mitigate the effects of a future accident.

**CONCLUSIONS**

The NTSB has issued more than 14,400 safety recommendations to more than 2,300 recipients in all transportation modes as a result of our investigations. Although the NTSB is a non-regulatory agency and does not have the power to enforce its recommendations, due to our reputation for objectivity, accuracy and effectiveness, the NTSB has an overall positive acceptance rate of more than 72 percent over the last 5 years. In addition, since 1990, the NTSB has also published a “Most Wanted List” of transportation safety improvements, highlighting safety-critical actions that the DOT modal administrations and others should take to help prevent accidents and save lives.

**REFERENCES**


ROAD VEHICLES PASSIVE SAFETY RATING METHOD

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ABSTRACT

Models, procedures, validation tests of vehicle and crash tests generally aim exclusively to assess ADAS (Advanced Driver Assistance Systems) devices performances in terms of their correct behavior or reaction of the driver, but do not refer to the new scenario (residual impact). An analytical procedure aimed to analyze experimental and numerical tests for the evaluation of vehicle – driver – ADAS system performances, in terms of road safety, is proposed. If there is a collision, the procedure considers typical impact severity and configuration related to the new scenario consequent to the activation of an ADAS system and/or driver operation.

The procedure proposed does not require the use of a software for accidents reconstruction, but it is based on two parameters: the Crash Momentum Index (CMI), which expresses impact configuration and impact severity, and the relative speed combined into a single diagram CMI–Vr. The CMI–Vr diagram allows to compare different vehicles and accidents occurred at different impact configurations, considering only kinematic parameters, without considering variables related to the vehicle’s occupants (gender, age, position occupied in the passenger compartment, etc.).

In a given accident, a vehicle is characterized by a CMI and a relative speed values, therefore the vehicle is indicated by a point of coordinates (CMI; Vr). The corresponding point position, on the CMI–Vr plane, identifies both the potential severity and the potential injury. To find the two points coordinates, it is necessary to identify the relative impact speed and CMI in the two impacts, potential and residual. On that plane, the iGLAD data analysis carried out (in a previous analysis) shows two different areas to which two different accident classes correspond: the former is the area regarding kinematic impact conditions of intrinsically safe accidents, for which the maximum injury level results to be MAIS 1 and the latter area is the one in which all injury levels can be found, from the lighter one up to the fatal one.

The procedure is illustrated by taking as an example an AEB system in different accident situations between two vehicles. On the CMI–Vr plane both the ADAS activation and the corrective maneuver of the driver can be verified. In particular, it is interesting to verify how and how much the point related to residual impact (post activation ADAS system) moves towards the intrinsically safe area, or towards lower injury risk. The proposed procedure can be used as a post processing of experimental tests or numerical simulations, for example aiming at: analysing the effectiveness of an ADAS system, comparing different systems, optimizing the ADAS logic or, moreover, comparing different experimental test conditions.
INTRODUCTION

European Commission announced, in the "White Paper" on European transport policy, a program of actions aimed to improve the vehicles safety, both in terms of passive and active safety, by the introduction of new technologies for driver assistance [1]. Today a large number of driver assistance systems is available for almost all vehicles. Automated driving will contribute to a new quality of mobility.

These technologies, in continuous progress, aim to ensure a better prevention of the risks faced by the occupants and are becoming established and evolving towards autonomous driving. The path to high and full automation is, however, not only one of technology, but it will also require amendments to both national and international legislation. Six levels have been defined from 0 to 5 for national and international use to classify the degree of automation of the individual systems (SAE Level [2]). This technical classification describes which tasks the system carries out, and which tasks/requirements the driver has to fulfill. At Level 0 there are no automated driving functions and there are no systems that intervene: this level can be defined as "conventional driving". If the implementation of advanced assistance technologies is carried out, the driver can be assisted, or even substituted as in Level 5 where the vehicle can completely independently perform the task of driving in full on all types of roads, in all speed ranges and in all environmental conditions. In intermediate level the responsibility of operation remain to the driver. The environment provides the stimuli (input) both to the driver and to the ADAS system, thus it's important to know the interaction between environment, driver and ADAS. These interactions can be evaluated by different approaches, as reported in [3–5]. In case of detected danger, the ADAS can alert the driver through stimuli (tactile, audible or visual), after which, if the reaction time to these exceeds established limits, the system may activate autonomously and act on the controls [6,7]. For this reason it is important to establish the requirements and test methods for the drivers alert mode [8,9], and the quality of information provided to the driver [10–14].

Generally, the correction of vehicles dynamics is related both to the driver and ADAS intervention, and as a result of these actions, the initial impact scenario changes. In case of rear–end collisions, in which only a braking action intervenes, previous researches have shown that the AEB (Autonomous Emergency Braking) carries benefits in terms of degree of injury decrease [15–20]. However, when the ADAS system makes a corrective maneuver, or the driver intervenes, a change in the impact configuration happens and the reduction of injury may not be directly proportional to the speed decrease. Usually models, procedures, validation tests of vehicle and crash tests do not refer to the new scenario of residual impact. The standards procedures, as the tests conducted by organizations such as EuroNCAP [21], or by NHTSA (National Highway Traffic Safety Administration) [22], generally aim to evaluate only the ADAS instrumental performance with standardized test procedures or virtual simulations in several impact configurations.

The purpose of this paper is to present a procedure for analyzing the performance of ADAS systems, which takes into account, in case of residual impact, also the new scenario and the new impact severity generated after the activation of that system or after a possible corrective measures put in place by the driver. Inputs for the definition of the new scenario derive from the instrumental functioning of the considered ADAS, which can be derived also from the EuroNCAP test and from hypothetical maneuver by the driver, which can be derived from an opportune driver model. The procedure proposed does not require the use of a software for accidents reconstruction, but it is based on two parameters: the Crash Momentum Index (CMI), which expresses impact configuration and impact severity, and the relative speed combined into a single diagram CMI–Vr. The procedure is illustrated by taking as an example an AEB system in different accident situations between two vehicles. On the CMI–Vr plane both the ADAS activation and the corrective maneuver of the driver can be verified.

MATERIAL AND METHOD

Crash Momentum Index (CMI) assessment - The CMI, as shown in [23], expresses the "potential" impact severity and can be formulated "a priori" in function of parameters that define the impact configuration and the inertial characteristics of the vehicles, as follows:

$$CMI = \frac{\gamma_1 \gamma_2 (1 + \epsilon_1)}{\gamma_2 + \gamma_1 R_m}$$

(Equation 1)

where $\gamma_1$ and $\gamma_2$ are the factors of mass reduction [23, 24], $\epsilon_1$ is the coefficient of restitution, and $R_m$ is the masses ratio of the vehicles involved in the crash. The value of the coefficient of restitution depends on the relative speed of impact in a normal direction n, $V_{Rn}$ and can, with a good approximation, be deduced...
from experimental correlations [25]. While and are connected exclusively to the vehicles’ typology (mass and stiffness), provides information about the crash configuration, being expressed as a function of the distance (h) between the vehicle’s centre of mass and the straight line of pulse action. For this reason it is necessary to know the direction of the principal direction of force (PDOF). To determine the PDOF, the results reported in [26] can be referred to, assuming an impact plane t or tangential direction and a normal direction n. The impact plane is generally assumed as the plane containing the deformed profile of the vehicle [27–29], as shown in figure 1, or described in [30].

Figure 1. Diagram of the vehicles planar impact: normal, n, and tangential, t, direction [30].

Referring to these directions, the following definitions can be given:

- the speed ratio Sr, expressed as the ratio between the relative deformation speed VRt, along the tangential direction, and the relative slipping speed, along the normal direction, VRn [26]:

\[ Sr = \frac{V_{Rt}}{V_{Rn}} \]  
(Equation 2)

- the coefficient of friction \( \mu \), expressed as the ratio between the component of impulse, tangential and normal, during the impact:

\[ \mu = \left( \frac{l_t}{l_n} \right) \]  
(Equation 3)

\[ \text{PDOF} = \tan^{-1}(\mu) \]  
(Equation 4)

Figure 2 shows an empirical relationship between \( \mu \) and Sr [26] from which, once known the relative speed of impact between the two vehicles, and calculated the ratio between its tangential and normal components, \( \mu \) can obtained and then, using equation 4, the desired value of PDOF.

Figure 2. Equivalent coefficient of friction at impact surface [26].

Here, the expressions derived for accidents with related Sr comprised in a range between 0 and 2.50 (equation 5) and for those with Sr comprised in a range between 2.50 and 6 (equation 6) are reported.

\[ \mu = 0.3287 \, \text{Sr} + 0.0659 \]  
(Equation 5)

\[ \mu = -0.1136 \, \text{Sr} + 1.2991 \]  
(Equation 6)

The scatter of experimental data results showed uncertainties on the PDOF in the range of ± 15°. Other analysis of literature [31] confirm that the PDOF, for each vehicle, can vary by ±20° in relation to the subjective assessment of the impact plane. Using these as typical uncertainties, in [31] a degree of uncertainty in \( \Delta V \) of about 15–17% for front to side impacts is found. This reduces to around 9–12% for front to front or front to rear impacts. The largest individual contribution is that due to uncertainty in PDOF.

CMI can also be expressed “a posteriori” [23], on the basis of the kinematic parameters obtained by reconstructing the accident (usually available in accident databases), such as the speed variation undergone by the vehicle for relative speed units:

\[ \text{CMI} = \frac{\Delta V}{V_{r-pdof}} \]  
(Equation 7)

where \( V_{r-pdof} \) is the component of relative impact speed along the PDOF (Principal Direction of Force) during the impact, which coincides with the direction of Delta V (\( \Delta V \)) [27]. According to this last definition, CMI takes the meaning of "potential severity" of an impact; in fact, to higher values of this parameter correspond higher values of \( \Delta V \) for relative speed units. In potential impact the relative speed between the two vehicles depends exclusively from testing or simulation conditions used.
CMI can be calculated with equation (7), if numerical simulations of the impact phase are available, for both the residual and potential impact. Numerical simulation can be carried on using FEM models (i.e. LS Dyna [32], etc.), which provide accurate results but require the specific vehicle models and a long simulation time. Alternatively for the impact simulation, impulsive models (PC Crash [33], Pro impact [34], etc.) can be used, which allow to obtain solution with a detail level lower than the FEM, but they need a very low simulation time.

**CMI–Vr plane application** - The ΔV is the parameter most closely related to the injury risk IR [35–37]. Figure 3 shows that each ΔV value can be associate to different value of IR [36], and the injury risk can be evaluate in different impact condition (frontal–near side/far side impact with compartment involved/not involved and rear–end).

![Injury Risk Function for car occupants: Seriously injured +](image)

**Figure 3. Injury risk function for car occupants: Seriously injured + [36].**

Considering a specific value of ΔV, in the CMI–Vr plane, the iso injury risk function [36] can be represented as iso–ΔV curves by equilateral hyperbolas with centre in the origin (0:0). Thus, considering the CMI, an high level of detail in terms of impact configuration can be obtained through the factor of mass reduction γ which allows to consider the impact eccentricity. So, in the CMI–Vr plane a different classification of impact is possible in respect to principal impact configurations considered in [38], because the CMI varies in a wide range. In this plane, each vehicle is characterized by a point of coordinates (CMI; Vr) [38].

A previous analysis conducted in [38] showed that in the area below the iso–ΔV=20 km/h curve only low injury degrees are present, and therefore it may be considered an intrinsically "safe area". Figure 4 shows that over this curve the injuries are characterized by the whole range of values of MAIS [39], up to MAIS 6.

![Figure 4. CMI–Vr plane: MAIS under changing iso–ΔV curves [ RIF 38].](image)

Given an impact suffered by the vehicle, the position of the corresponding point in the CMI–Vr plane therefore identifies both the potential severity and the potential injury. Considering identical vehicles (R = 1), figure 5 shows the points regarding the same impact configuration (front–side, with compartment involved), with different impact relative speed. As shown in figure 5, the IR is greater for the vehicle that undergoes the side impact than the vehicle which impacts on the front.

![Figure 5. CMI–Vr plane: IR change in case of a frontal-side impact for the vehicles.](image)

The position of the vehicles toward the low injury potential area, and thus the decrease of IR, can be obtained both by decreasing the relative speed Vr and by changing the impact configuration. The CMI variation, deriving from the relative speed, is due exclusively to the change of coefficient of restitution, which decreases with the increase of relative speed.

Instead, a different impact configuration due a drivers or ADAS intervention to such as to move the initial point toward areas characterized by high severity will be less effective in terms of IR reduction, if the impact configuration switch from frontal to side impact.
Procedure - The proposed procedure is based on the use of CMI–Vr plane that allow to verify, following the ADAS activation or the driver intervention, how the point corresponding to the potential impact moves, respect to the point regarding the residual impact. This procedure can be used as a post processing of experimental tests or numerical simulations, for example aiming at: analyzing the effectiveness of an ADAS system, comparing different systems, optimizing the ADAS logic or, moreover, comparing different experimental test conditions. In particular, it is interesting to verify how and in what way the point moves towards the intrinsically safe area, or towards lower IR. To find the coordinates of the two points, it is necessary to identify the relative impact speed and CMI in the two impacts, potential and residual.

RESULTS AND DISCUSSION

Real accidents analysis have shown that the scenario 'Collision with another vehicle that is turning into or crossing a road at an intersection' is the most frequent, with a percentage of 58% of the total accidents between two vehicles collected in the iGLAD database [40]. By using the software Proimpact 6.0 [34] for this scenario and considering the all the time equal vehicles, were analyzed different impact configurations. CMI have been calculated with equation (2). The analysis carried out assuming no driver intervention.

For example, for tests on AEB City version, the EuroNCAP standards require speed between 10 and 50 km/h for the bullet vehicle while the target vehicle is standing. In case of rear-end impact the AEB system benefits are reported in [41,42]. This study is conducted referring to orthogonal impact configuration, in which the ADAS activation can to get a benefits. Previous analysis [42] showed that in case two vehicles collide in an orthogonal configuration, where the vehicle A is stopped and the vehicle B is moving with velocities in increase (20–40 km/h), the low speed of impact allow to collocate the two vehicles in low injury potential area.

Considerating, instead, the vehicles A and B are initially moving at a speed of 35 km/h on orthogonal directions in conflict with each other. For this scenario were analyzed two different impact configurations, α and β, shown in table 1 (Appendix), comparable to situation resulting from the possible activation of a system AEB for the vehicle B. If the AEB system or the driver do not intervene, the vehicles will collide in the α configuration.

One second before (time to collision=1 s) the AEB system of vehicle B applies a deceleration of 8 m/s² and the vehicle arrives to impact in configuration β. Table 1 (Appendix) shows the results obtained assuming, for each vehicle, different impact speed and in figure 6 are shown the results of the analysis on the CMI–Vr plane. For both vehicles, the activation of the ADAS system determines a shift of the point towards lower potential severity areas. Vehicle B switches the impact configuration from eccentric frontal impact to frontal impact, with IR decreasing from 6% to 2%, whereas vehicle A switches from eccentric frontal impact to side impact (compartment involved), with an IR increase from 6% to 7.5%. Thus, in this case the ADAS activation of the vehicle B resulted in only modest benefits for vehicle B and a worsening for vehicle A.

![Figure 6. CMI–Vr plane: results of simulation.](image)

In addition to this, the use of this plane allow also to lead an analysis aiming to optimize the ADAS operation, since it can be verify and identify the best maneuver strategy aiming to reduce in an effective way the injury risk, which is not guaranteed 'tout court' by applying the maximum braking action allowed be tires. In fact the injury risk reduction depends not only on the decrease of the relative speed between the vehicles, but also on the new impact configuration that is outlining. It is illustrated how braking modulation can lead to impact configuration potentially less severe, configuration to be found for an optimal performance of the ADAS.

Considering a different pair of vehicles that collide in four different impact configuration, but with the same Rm (Rm = 1) showed in table 2 (Appendix), is possible to observe the different situation following the activation of AEB system for the vehicle B, as a function of slowdown intensity, gradually increasing, for the vehicle B. Figure 7 shows the results on the CMI–Vr plane.

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Vangi, 5
CONCLUSIONS

This study presented an analysis of ADAS performance based on the CMI–Vr plane, in case of impact vehicles-to-vehicles. This plane represents a useful tool that allow to evaluate the relationship between kinematic parameters, as Vr between two vehicles and the ΔV undergone by the vehicles. Each vehicle is characterized, on that plane, by a point of coordinates (CMI; Vr), where the abscissa represents the potential severity of the impact and the ordinate represents Vr. To define a point on the plane means to define the potential severity and the potential injury of the impact. Previous analysis have been found, on that plane, two different areas to which two different accident classes correspond: the former is the area regarding kinematic impact conditions of intrinsically safe accidents, for which the maximum injury level results to be MAIS 1 and the latter area is the one in which all injury levels can be found, from the lighter one up to the fatal one.

The action of an ADAS system or a corrective maneuver of the driver entails a change of impact configuration and relative speed, if the collision cannot be avoided. By comparison between the new scenario and the initial scenario is possible to evaluate the effectiveness of the performance of this device, ADAS, in term of injury risk reduction. This plane summarizes in a single tool all information necessary for an analysis of experimental tests or numerical simulations about the ADAS. In addition to this, that plane allows also to lead an analysis aiming to optimize the ADAS operation, since it can verify and identify the best maneuver strategy aiming to reduce in an effective way the injury risk, which is not guaranteed ‘tout court’ by applying the maximum braking action allowed by tires – pavement adherence condition. Knowing two characteristics parameters of the accidents can be verified, on the CMI - Vr plane, where the point corresponding to the two vehicles are located and how is the distance of the latter to area low injury potential. In fact, the injury risk and its reduction depends both the decrease of relative speed at the crash and the new impact configuration.

Let us consider the case number 1, in which the two vehicles collide without any slowing of vehicle B: this impact condition, as a result of an eccentric frontal impact for both vehicles, is characterized by an IR equal to 4.8% for the vehicle A and equal to 6.8% for the vehicle B.

Following a deceleration of vehicle B, in the case number 2, the two vehicles collide with the same impact speed in configuration γ, rather than α, with a potential residual impact less severe for vehicle B. For the latter the reduction of relative speed is such that its IR decreases by 2%. Conversely, for the vehicle A, since it passes from a frontal impact to side impact without compartment involved, it is observed an increase of the IR equal to about 4.2%, so that the impact is potentially more severe.

Assuming a greater intensity of deceleration, in the case number 3, the initial configuration α modifies to β, with a potential residual impact less severe also in this case for the vehicle B, because the reduction of the relative speed is such that the IR decreases by 2.3%. For the vehicle A, instead, the impact results significantly more severe, because it suffers a side impact with compartment involved and the IR increases of 4.2%.

Let us consider a slowdown of even greater intensity in the case number 4, where the impact configuration switches from α to δ and for which the speed reduction is such that the residual impact is potentially less severe both for vehicle B, for which the IR decreases by 4.7%, and for vehicle A, for which the reduction is equal to 0.8%.

If the collision is inevitable, the analysis of the evolution of the kinematic situation in real time between the two vehicles, will allow to select the best strategy of intervention to reduce the possible injury.
REFERENCES


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[33] www.pc-crash.com

[34] www.atenaingegneria.it


[40] http://iglad.net/


APPENDIX

Table 1. Results of Pro impact 6.0 simulation, for front-to-side impact.

<table>
<thead>
<tr>
<th>Case number</th>
<th>Configuration</th>
<th>Mass [Kg]</th>
<th>Vehicle</th>
<th>$V_i$ [km/h]</th>
<th>$\Delta V$ [km/h]</th>
<th>$V_r$ [km/h]</th>
<th>PDOF$^*$ (Pro impact)</th>
<th>PDOF$^*$ (Procedure)</th>
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<td>45</td>
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Table 2. Vehicles' positions resulting to an intervention of an optimized AEB system.

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<th>Configuration $\beta$</th>
<th>Configuration $\delta$</th>
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<table>
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<th>$V_i$ [km/h]</th>
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SELECTION OF NHTSA’S SOUND ANALYSIS CODE

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ABSTRACT

The Pedestrian Safety Enhancement Act of 2010 requires the National Highway Traffic Safety Administration (NHTSA) to establish a Federal Motor Vehicle Safety Standard (FMVSS 141) mandating minimum sound requirements for electric vehicles (EVs), and hybrid electric vehicles (HEVs). As part of FMVSS 141 development, NHTSA needed to select one sound analysis code (a software program) for sound data processing so that methods used to evaluate vehicle sounds for compliance testing or other purposes would be consistent. Two candidate sound analysis codes, the B&K Code and the Volpe Code, have been used by NHTSA. This paper documents NHTSA’s selection of one of these two for its future use.

Criteria for selecting a sound analysis code were that the code: (1) must give correct results for mathematically-generated test cases, (2) must meet all filter requirements for one-third octave band Class 1 filters contained in ANSI S1.11-2004: Specification of Octave, Half-Octave, and Third-Octave Band Filter Sets, [1], and (3) could be made available outside the Federal government to allow others to perform sound data analyses using NHTSA’s software.

The B&K and Volpe Codes both did an excellent job of calculating one-third octave band levels when pure tones were input. Both sound analysis codes correctly performed A-weighting. When a composite signal consisting of superimposed pure tones, one at the mid-band frequency of each of 13 one-third octave bands, was input, calculated levels exceeded input amplitudes by a small but acceptable amount.

The one-third octave band filters used by the B&K Code did not fully comply with one-third octave band Class 1 filter specifications contained in ANSI S1.11-2004. S1.11-2004 specifies that Class 1 filters asymptote to an attenuation of 70 dB for both high and low frequencies. For low frequencies, the B&K Code is asymptotic to between 55- and 60-dB attenuation for all one-third octave bands. For some one-third octave bands, there was also a region above the specified one-third octave pass band but below the high frequency region that also did not meet S1.11-2004 specifications. The Volpe Code filters complied with all S1.11-2004 Class 1 filter specifications for all one-third octave bands. For this, and other reasons, the Volpe code has been selected for future NHTSA analyses of vehicle-emitted sound.

Additional details about this research are contained in the NHTSA Technical Report “Selecting a Sound Analysis Code for use with NHTSA Test Procedures to Characterize Vehicle Sounds,” [2].
BACKGROUND AND OBJECTIVES

As directed by Pedestrian Safety Enhancement Act of 2010, NHTSA established FMVSS 141 setting minimum sound requirements for EVs, and HEVs. (In addition to EVs and HEVs, FMVSS 141 also applies to low speed electric vehicles (LSVs).) The sounds required by FMVSS 141 are ones that pedestrians should be able to hear in a range of ambient environments and contain acoustic signal content that pedestrians should recognize as being emitted from a vehicle. FMVSS 141 will ensure that visually-impaired and other pedestrians can detect and recognize nearby HEVs, EVs, and LSVs by hearing those vehicles.

As part of its effort to develop a FMVSS 141 compliance test procedure, NHTSA measured and characterized sounds emitted by a selection of existing vehicles. NHTSA measured sounds produced by vehicles using a slightly modified version of the test methodology contained in the September 2011 version of SAE Surface Vehicle Recommended Practice J2889-1, “Measurement of Minimum Noise Emitted by Road Vehicles” [3].

After the measured vehicle sound data was recorded, each sound file was analyzed using a sound analysis code (a software program to process measured sound data). A sound analysis code calculates such quantities as Overall Sound Pressure Level (SPL) as a function of time, the Maximum and Minimum Overall SPLs during a test, one-third octave band levels as a function of time for each one-third octave band of interest, and the maximum and minimum one-third octave band levels during a test from sound data. NHTSA uses the output of a sound analysis code to characterize the sounds produced by a vehicle during a test and to determine if a vehicle complies with minimum requirements.

Two sound analysis codes1, Brüel & Kjær’s PULSE Reflex software (the “B&K Code”) and a code developed by the Volpe National Transportation Systems Center (the “Volpe Code”) have been used by NHTSA to analyze vehicle sound data. Sound data recorded during some test runs was analyzed using both the B&K Code and the Volpe Code. Analysts examining results from these runs noted that there were slightly different overall SPLs and one-third octave band levels for the exact same recorded sound data depending upon the sound analysis code used. While the differences that were seen were not large, they were not acceptable for a prospective NHTSA compliance test.

To resolve discrepancies in results from the B&K Code versus the Volpe Code, NHTSA undertook the work described in this paper. The objective of this research was to select one sound analysis code that NHTSA would use to process and analyze future vehicle sound data. Selection criteria for choosing one sound analysis code were:

- Must generate correct results for mathematically-generated test cases.
- Must meet all filter requirements for one-third octave band Class 1 filters that are contained in ANSI S1.11-2004 over the entire range of frequencies.

1 Although NHTSA has not used them, there are other commercially-available sound analysis codes. The goal of this research was not to examine every available sound analysis code; instead, it was to examine the two sound analysis codes NHTSA had previous experience with and select one for future NHTSA use.
Could be made available to other individuals or organizations that wish to perform sound data analysis using the same software used by NHTSA.

One-Third Octave Bands of Interest to NHTSA

NHTSA is focusing its FMVSS 141 compliance testing on 13 one-third octave bands having nominal mid-band frequencies ranging from 315 to 5,000 Hz. Additional details about these one-third octave bands can be found in ANSI S1.11-2004.

DESCRIPTION OF THE B&K AND VOLPE SOUND ANALYSIS CODES

The purpose of a sound analysis code, from a NHTSA perspective, is to process measured sound data to calculate Overall SPL and sound levels in the 13 one-third octave bands of interest to NHTSA. For vehicle pass-by testing or stationary vehicle sounds, the maximums during the test of these values are determined. For analysis of ambient sounds, minimums of these values are determined.

The B&K sound analysis code is commercially-available software licensed from Brüel & Kjær. The B&K Code performs A-weighting, exponential averaging, and filtering while processing sound recordings to obtain Overall SPL and the 13 one-third octave band sound levels.

The Volpe Code was developed for the United States Government by the Volpe National Transportation Systems Center. Since this sound analysis code is the property of the United States Government, it can be shared with interested parties. The Volpe Code performs A-weighting, exponential averaging, and filtering while processing sound recordings to obtain Overall SPL and the 13 one-third octave band sound levels.

TEST CASES FOR VALIDITY CHECKING

Both sound analysis codes were tested to ensure that they provide correct results. This was done through Test Cases. Test Cases were computer-generated sound pressure data files developed to test specific aspects of sound analysis codes. They were not generated through vehicle testing; they were completely artificial simulations. Once Test Cases had been developed, they were processed using both sound analysis codes.

The Test Cases NHTSA developed were sound pressure data files for which outputs expected from sound analysis codes were known in advance. To ensure that expected results from Test Cases were known a priori, very simple sound pressure functions (pure tones) were used. Test Case sound data files do not have the complexity of actual, measured, sound data; this is what makes it possible to determine a priori what the correct output from the analysis code should be.

Test Case 1: Single Frequency, Constant-Amplitude, Pure Tones

For Test Case 1, the pressure associated with a sound as a function of time was given by a single, constant-amplitude, constant-frequency, sine wave (i.e., a pure tone). Both the constant-amplitude and the constant-frequency were varied from test run to test run. Two constant-amplitudes, 40- and 60-dB, which are typical of sounds made by vehicles, were used.

The pure tones for Test Case 1 were generated at 201 individual frequencies every 1/8th of a one-third octave band (i.e., every 1/24th of a full octave) over the covered frequency range. The covered frequency range was approximately 70 Hz to 22,300 Hz. This frequency range encompasses an
additional six one-third octave bands on either side of the 13 one-third octave bands of interest to NHTSA. This range was chosen to ensure a full profile of how each code responds to known inputs.

The following aspects of sound analysis code correctness were checked using Test Case 1:

- Correctness of calculated amplitudes, when A-weighting was not applied, for pure tones at frequencies corresponding to the exact mid-band of each of 13 one-third octave bands.
- Correctness of calculated amplitudes, when A-weighting was applied, for pure tones at frequencies corresponding to the exact mid-band of each of 13 one-third octave bands.
- The band-pass filters that split frequency weighted sound pressure level data into 13 one-third octave bands. NHTSA requires these band-pass filters to meet all filter requirements for Class 1 one-third octave band filters contained in ANSI S1.11-2004.

Test Case 2: Multiple Frequency, Constant-Amplitude, Pure Tones

For Test Case 2, the sound pressures from 13 pure tones were superimposed to form one sound pressure signal. These 13 pure tones were at the exact mid-band frequencies of each one-third octave band.

Only two variations were developed for Test Case 2. The first had a 40-dB pure tone at the exact mid-band frequency of each of the 13 one-third octave bands (giving an Overall SPL of 51.1394 dB). The second had a 60-dB pure tone at the exact mid-band frequency of each of the 13 one-third octave bands (giving an Overall SPL of 71.1394 dB).

The following aspects of sound analysis code correctness were checked using Test Case 2 data files:

- Correctness of calculated amplitudes, when A-weighting was not applied, for a multi-tone sound waveform.
- Correctness of calculated amplitudes, when A-weighting was applied, for a multi-tone sound waveform.

CORRECTNESS OF AMPLITUDES

Using a Single Pure Tone without A-Weighting

The first test for both sound analysis codes was correctness of their calculated one-third octave band levels for individual pure tones when A-weighting was not applied. This was accomplished by running 26 variations of Test Case 1, comprising two amplitudes (40-dB and 60-dB input signals) for each of 13 pure-tone frequencies, one at the exact mid-band frequency of each one-third octave band with A-weighting disabled.

To match the specifications of Table B1, “Limits on Relative Attenuation for One-Third Octave Band Filters,” in ANSI S1.11-2004, for Class 1 filters, each calculated one-third octave band level, at the exact mid-band frequency of each 13 one-third octave bands must match the nominal input level within a tolerance of ±0.30 dB.

As shown by Table 1, for both sound analysis codes, for both amplitudes of input signals, and for all 13 one-third octave bands, the calculated levels were within ±0.01 dB of the input amplitude. This was well within the ±0.30 dB tolerance permitted by ANSI S1.11-2004.

Using Multiple Tones without A-Weighting

The next thing checked was correctness of calculated amplitudes for the multi-tone sound input of Test Case 2. For Test Case 2, sound pressures from 13 pure tones were superimposed to form one
sound pressure signal. Only two test runs were made using Test Case 2. The first had a 40-dB pure tone at the exact mid-band frequency of each one-third octave band. The second had a 60-dB pure tone at the exact mid-band frequency of each one-third octave band. Table 2 summarizes Test Case 2 results.

For the B&K Code, for both amplitudes of input signals, and for all 13 one-third octave bands of interest to NHTSA, calculated band levels were within (+0.04, +0.08) dB of input amplitude. For the Volpe Code, calculated band levels were within (+0.06, +0.13) dB of input amplitude.

Calculated band levels for Test Case 2 always exceeded the input amplitudes by a small amount (up to 0.13 dB). This was as expected since ANSI S1.11-2004 does not require, and neither the B&K Code nor the Volpe Code have, infinitely fast filter roll-offs at the edges of one-third octave bands. Due to finite filter roll-offs, a small amount of energy leaks through into each one-third octave band from other, nearby one-third octave bands. The 315 Hz and 5,000 Hz one-third octave bands have calculated band levels that are closer to the input amplitude than the other 11 bands. This was because, for these two bands, there were only bands containing acoustic energy on one side and not on both sides as was the case for the other 11 bands. Although ANSI S1.11-2004 does not apply to composites of pure tones, the composite multi-tone results were within the permitted ±0.30 dB pure tone tolerance.

Comparison of 40-dB and 60-dB Input Amplitude Results

Both for individual pure tones and more complex, 13 superimposed pure tones, no differences were seen between the 40-dB and 60-dB input amplitude results. Therefore, to reduce the number of analyses that had to be performed, the remainder of this paper will be based only on results from 40-dB input amplitude test cases.

Using a Single Pure Tone with A-Weighting

The correctness of calculated amplitudes when A-weighting was applied was checked for both sound codes both when a single pure tone was input (Test Case 1) and when a composite signal composed of multiple pure tones was input (Test Case 2).

To check correctness of A-weighting when a single pure tone was input, 13 Test Case 1 runs were made. A single 40-dB amplitude pure tone was input at the exact mid-band frequency of each of 13 one-third octave bands.

Table 3 shows calculated, A-weighted, band levels and the effects of A-weighting for both sound analysis codes for all 13 one-third octave bands. Table 3 also shows the theoretical effects of applying A-weighting. For both the B&K and Volpe Codes, the actual effects of A-weighting were very close to the theoretical effects. For the B&K Code, there was a maximum difference between the actual and theoretical effects of A-weighting of 0.05 dB at 5,000 Hz. For the Volpe Code, there was a maximum difference between the actual and theoretical effects of A-weighting of 0.05 dB at 4,000 Hz.

Using Multiple Tones with A-Weighting

To check the correctness of A-weighting when multiple pure tones were simultaneously input, one Test Case 2 run was made. Multiple 40-dB amplitude pure tones were input at the exact mid-band frequency of each of 13 one-third octave bands.

The Table 4 shows calculated band levels after applying A-weighting and differences due to A-weighting for both sound analysis codes for all 13
one-third octave bands. For both the B&K and Volpe Codes, the actual effects of A-weighting were very close to the theoretical effects. For the B&K Code, there was a maximum difference between the actual and theoretical effects of A-weighting of 0.05 dB at 5,000 Hz. For the Volpe Code, there was a maximum difference between actual and theoretical effects of A-weighting of 0.05 dB at 4,000 Hz.

**COMPARISONS TO ANSI S1.11-204 CLASS 1 FILTER SPECIFICATIONS**

SAE J2889-1, specifies that “the corresponding 1/3 octave results per ANSI S1.11, Class 1”\(^2\) shall be reported. ANSI S1.11-2004: “Specification of Octave, Half-Octave, and Third-Octave Band Filter Sets,” contains specifications for Class 1 filters. For its work, NHTSA is using the base-ten system for calculating frequencies. The base-ten system has been chosen because ANSI S1.11-2004 states that while the base-two system for determining frequencies is acceptable, the “base-ten system is preferred.”\(^3\)

In the figure that follows, linear interpolation between data points in ANSI S1.11-204 were used to develop the Minimum and Maximum Attenuation Limit lines shown.

All 201 Test Case 1 single-frequency, constant (40-dB) amplitude pure tones were processed using both sound analysis codes. A-weighting was **not** used for these runs. Results were used to check correctness of filters used by the B&K and Volpe Codes to calculate one-third octave bands.

Figure 1 shows performance of the B&K Code’s and Volpe Code’s filters for a typical one-third octave band, the 1,000 Hz band, over the entire frequency range from 80 to 20,000 Hz. For a filter to comply with the ANSI S1.11-2004 Class 1 filter specifications, its attenuation must fall between the “Minimum Attenuation Limit” and the “Maximum Attenuation Limit” curves over the entire frequency range.

As shown by Figure 1, the filters used by the B&K Code did not comply with Class 1 filter specifications contained in ANSI S1.11-2004 over the entire frequency range. Note: In documentation for the B&K Code, B&K does not claim that their filters meet the Class 1 filter specifications contained in ANSI S1.11-2004. B&K states “Fulfills ICE225-1966, DIN45651, and ANSI S1.11-1986, Order 3, Type I-D” filter specifications.

For frequencies around the pass band, the B&K Code filters complied with the Class 1 filter specifications contained in ANSI S1.11-2004. For low frequencies, the B&K Code filters were asymptotic to an attenuation of 55- to 60-dB while ANSI S1.11-2004 Class 1 specifications require an asymptotic attenuation of at least 70 dB. The B&K Code filters were closer to ANSI S1.11-2004 Class 1 filter specifications in frequencies substantially above the pass band. The asymptotic behavior of the B&K Code filters for high frequencies met the ANSI S1.11-2004 Class 1 filter specified attenuation of 70 dB. However, for the 1,600 Hz and lower frequency one-third octave bands, there is a mid-frequency region between the pass band and the high frequency range for which B&K Code filters did not meet ANSI S1.11-2004 filter specifications.

The filters used by the Volpe Code complied with Class 1 filter specifications contained in ANSI S1.11-2004. For frequencies around the pass band, the Volpe Code filters fully comply with pass band

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\(^2\) Quote from SAE J2889-1.
\(^3\) Quote from Section 3.2 of ANSI S1.11-2004.
Class 1 filter specifications contained in ANSI S1.11-2004 for all 13 one-third octave bands. For frequencies substantially above or below the pass band, its attenuations substantially exceeded the minimum 70 dB filter attenuation specified in ANSI S1.11-2004.

CONCLUSIONS

Both the B&K and Volpe Codes did an excellent job of calculating one-third octave band levels when one or more pure tones were input at the exact mid-band frequencies of the 13 one-third octave bands. Calculated band levels were well within the ±0.30 dB tolerance permitted by ANSI S1.11-2004.

A-weighting is correctly performed by both the B&K and Volpe Codes.

One of the objectives of this work was to select one sound analysis code that met all of the filter requirements for one-third octave band Class 1 filters that are contained in the standard ANSI S1.11-2004 for future use by NHTSA. The one-third octave band filters used by the B&K Code did not fully comply with one-third octave band Class 1 filter specifications contained in ANSI S1.11-2004. The Volpe Code filters complied with all S1.11-2004 Class 1 filter specifications for all one-third octave bands. For this, and other reasons, the Volpe code has been selected for future NHTSA analyses of vehicle-emitted sound.

NHTSA will be making an executable image (so that parties without a MATLAB license can still run the Volpe Code if they wish) of the Volpe Code available to interested parties. The Volpe National Transportation Systems Center is currently adding an easy-to-use graphical user interface to the Volpe Code. The Volpe Code with the graphical user interface will not only calculate overall sound pressure levels and one-third octave band levels for a set of measured vehicle sound data but will also determine whether the vehicle complies with the sound requirements contained in the final version of FMVSS 141. When completed and tested, this software will either be placed in the appropriate docket at www.regulations.gov and/or made accessible on the NHTSA website.

REFERENCES


### Table 1: Calculated Band Levels for 40- and 60-dB Input Signals without A-Weighting for Test Case 1

<table>
<thead>
<tr>
<th>Nominal One-Third Octave Midband Frequency (Hz)</th>
<th>40-dB Input Signal</th>
<th>60-dB Input Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated Band Level (dB)</td>
<td>Difference from 40-dB (dB)</td>
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<tr>
<td>315</td>
<td>40.01</td>
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<tr>
<td>400</td>
<td>40.01</td>
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<tr>
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<tr>
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### Table 2: Calculated Band Levels for 40- and 60-dB Input Signals without A-Weighting for Test Case 2

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<tr>
<th>Nominal One-Third Octave Midband Frequency (Hz)</th>
<th>40-dB Input Signal</th>
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</thead>
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<td>Difference from 40-dB (dB)</td>
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Table 3: A-Weighted Calculated Band Levels for 40-dB Input Signals for Test Case 1

<table>
<thead>
<tr>
<th>Nominal One-Third Octave Midband Frequency (Hz)</th>
<th>Exact A-Weighting Correction (dB)</th>
<th>B &amp; K Code</th>
<th>Volpe Code</th>
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<tr>
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<td>A-weighting Effect (dB)</td>
<td>Calculated Band Level (dB)</td>
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Table 4: A-Weighted Calculated Band Levels for 40-dB Input Signals for Test Case 2

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<th>Nominal One-Third Octave Midband Frequency (Hz)</th>
<th>Exact A-Weighting Correction (dB)</th>
<th>B &amp; K Code</th>
<th>Volpe Code</th>
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<td>Effect of A-weighting (dB)</td>
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Figure 1: Filter Performance for the 1,000 Hz One-Third Octave Band