# ESTIMATION OF POTENTIAL SAFETY BENEFITS FOR PEDESTRIAN CRASH AVOIDANCE/MITIGATION SYSTEMS IN LIGHT VEHICLES

**Mikio Yanagisawa**
**Philip Azeredo**
**Wassim Najm**
Volpe National Transportation Systems Center
USA

**Stephen Stasko**
National Highway Traffic Safety Administration
USA

Paper Number 19-0227

## ABSTRACT

This report presents and exercises a methodology to estimate the effectiveness and potential safety benefits of production pedestrian crash avoidance/mitigation systems. The analysis focuses on light vehicles moving forward and striking a pedestrian with the front of the vehicle in the first event of a crash without attempting any avoidance maneuver in two priority scenarios: 1) vehicle going straight and pedestrian crossing the roadway and 2) vehicle going straight and pedestrian in or adjacent to the roadway, stationary or moving with or against traffic. System effectiveness is estimated for crash avoidance and crash severity mitigation. Safety benefits are projected in terms of annual reductions in the number of police-reported vehicle-pedestrian crashes, fatal vehicle-pedestrian crashes, and injured pedestrians at Maximum Abbreviated Injury Scale 2-6 and 3-6 levels. The methodology relies on target baseline crashes obtained from the 2011 and 2012 General Estimates System and Fatality Analysis Reporting System crash databases, system performance data from characterization track tests, and basic kinematic computer simulation of vehicle-pedestrian conflicts.

## INTRODUCTION

From 2007 to 2016, there have been 350,408 fatalities on public roadways according to the National Highway Traffic Safety Administration (NHTSA) Traffic Safety Facts [1]. Over the last few years, the increase in population, licensed drivers, registered vehicles, and vehicle miles travelled has led to a rising trend in police-reported (PR) crashes and fatal crashes [2]. Figure 1 shows the number of pedestrian fatalities during this timeframe, as well as an upward trend in pedestrian fatalities as a percentage of total roadway fatalities. This trend may be caused by a variety of factors. This paper investigates the use of pedestrian crash avoidance/mitigation (PCAM) systems and their potential to ameliorate this trend.

PCAM systems are vehicle-based, forward-looking pedestrian detection systems that alert drivers of potential vehicle-pedestrian crashes and/or apply automatic emergency braking (AEB) to prevent potential vehicle-pedestrian crashes. This paper focuses on crashes that involve light-vehicles (i.e., passenger cars, vans and minivans, sport utility vehicles, and light pickup trucks with gross vehicle weight rating under 10,000 pounds) moving forward, striking a pedestrian in the first event of the crash, and not attempting any avoidance action.

This paper describes and exercises a methodology to estimate potential safety benefits associated with PCAM systems in terms of crash avoidance and crash mitigation measures.

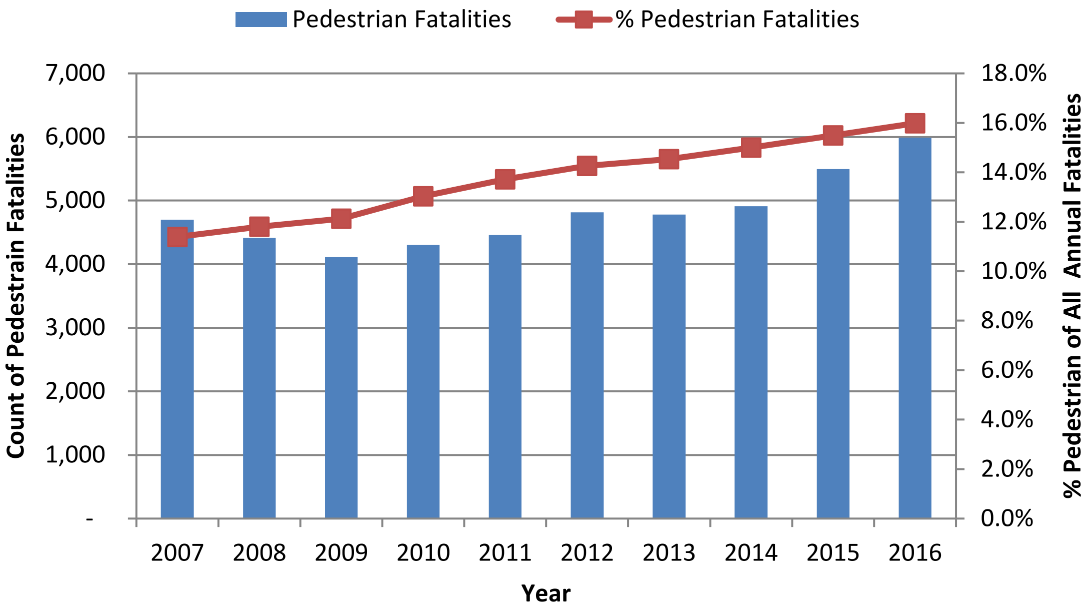
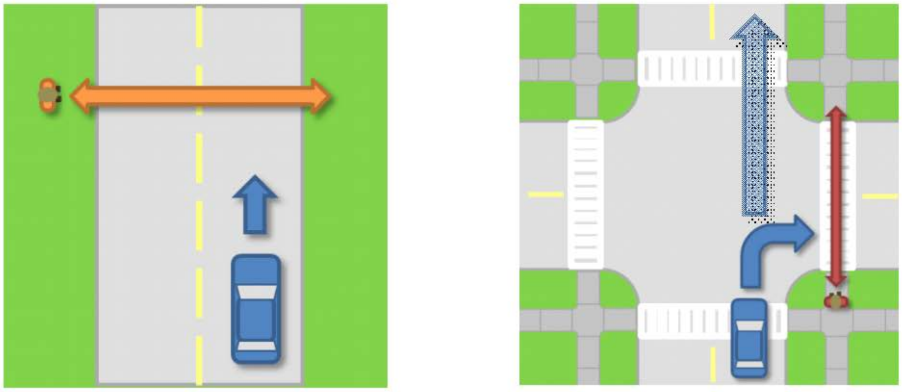


***Figure 1. Annual Traffic-Way Pedestrian Fatalities in the United States.***

**Pedestrian Pre-Crash Scenarios**

Historical research identified and prioritized vehicle-pedestrian pre-crash scenarios that PCAM systems could potentially address, and facilitated the development of test scenarios [3]. Four vehicle-pedestrian pre-crash scenarios were recommended as target scenarios based on the analysis of NHTSA's National Automotive Sampling System (NASS) General Estimates System (GES) and Fatality Analysis Reporting System (FARS) crash databases from 2005 through 2009 [4][5]. These four priority pre-crash scenarios are depicted and described in Figure 2. An updated analysis using 2011 and 2012 GES and FARS data provided similar results, giving evidence that the top priority vehicle-pedestrian pre-crash scenarios remained prominent from 2005 to 2012 [6].

From 2011 to 2012, there was an annual average of 62,917 vehicle-pedestrian PR crashes in the GES data that involved a light-vehicle striking a pedestrian in the first event. Based on similar criteria, FARS data provided an annual average of 3,337 fatal vehicle-pedestrian crashes. However, PCAM systems may only target a subset of these crashes. PCAM-addressable crashes involve the light vehicle moving forward and striking a pedestrian with the front of the vehicle and the driver attempting no avoidance maneuver. These criteria are selected because PCAM systems are considered forward facing vehicle-based sensing systems and driver action may significantly alter vehicle dynamics and system performance after the critical event (e.g., loss of control, unintended secondary events, and system suppression). As a result, the average annual number of all PR PCAM-addressable crashes amounts to about 21,000 crashes based on GES statistics, and about 2,200 annual fatal PCAM-addressable crashes from FARS data. The four priority pre-crash scenarios represent the most common vehicle-pedestrian crashes from 2011 to 2012, in terms of PR and fatal crash frequency as shown in Table 1. These four scenarios account for 90 percent of all GES and 97 percent of all FARS PCAM-addressable vehicle-pedestrian crashes. Thus, this paper focuses on the top four pre-crash scenarios as described by the previously published PCAM research (i.e., S1, S2, S3, and S4 in Figure 2).

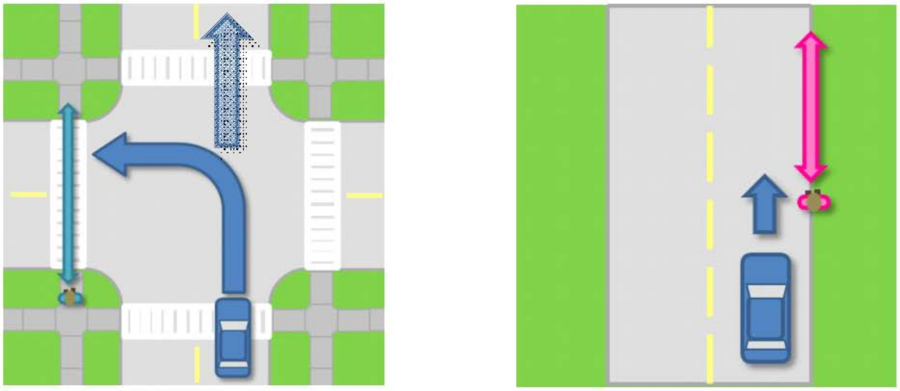


**Scenario 1 (S1)**

S1 - Vehicle going straight and pedestrian crossing the road

**Scenario 2 (S2)**

S2 - Vehicle turning right and pedestrian crossing the road



**Scenario 3 (S3)**

S3 - Vehicle turning left and pedestrian crossing the road

**Scenario 4 (S4)**

S4 - Vehicle going straight and pedestrian walking alongside the road with/or against traffic

*Figure 2. Four Priority PCAM Pre-Crash Scenarios Defined from NHTSA Crash Databases.*

*Table 1.*
*Breakdown of PCAM-Addressable Crashes into Priority Pre-Crash Scenarios from 2011-2012.*

| Scenario | Vehicle Maneuver | Pedestrian Maneuver | GES Frequency | | FARS Frequency | |
|---|---|---|---|---|---|---|
| S1 | Going Straight | Crossing Roadway | 7,481 | 35.5% | 1,396 | 64% |
| S2 | Turning Right | Crossing Roadway | 2,264 | 10.7% | 24 | 1% |
| S3 | Turning Left | Crossing Roadway | 6,200 | 29.4% | 87 | 4% |
| S4 | Going Straight | Walking along Roadway, with/against Traffic | 2,950 | 14.0% | 620 | 28% |
| Other Scenarios (~60 Additional) | | | 2,195 | 10.4% | 66 | 3% |
| **Annual Average Total PCAM-Addressable** | | | **21,090** | | **2,193** | |

*PCAM-addressable crashes are crashes involve a light-vehicle striking a pedestrian with the front of the vehicle in the 1st event of a crash, with no avoidance maneuver

## Previous Research

Previous research studies have employed various methods on available data sources to estimate the efficacy of various advanced pedestrian safety systems, both active and passive. Two studies used the German In-Depth-Accident-Study (GIDAS) to estimate passive, active, and combination safety systems. The first study used GIDAS data to estimate the effectiveness of a 40-degree field of view (FOV) pedestrian AEB system [7]. A total of 243 pedestrian cases within a good FOV and no obstruction from the 1999-2003 GIDAS were identified. This study estimated new impact speeds based on variations in specific parameters to estimate the reduction in fatal and severely injured pedestrians. The duration of the braking event was a critical parameter variation. The average braking duration for drivers was 0.67 second, whereas the AEB system (≤ 0.6 g) had an average braking duration of 1.4 seconds. The results showed that the effectiveness at reducing fatally injured pedestrians in frontal collisions reached 40 percent, with a marginal increase in effectiveness with increased FOV. Nearly 80 percent of the fatality reduction came from cases where the driver had not braked. The second study estimated benefits of using passive (deployable airbag) and active (AEB) countermeasures to mitigate head injuries in pedestrian impacts [8]. This research used 68 GIDAS cases filtered for frontal impacts with pedestrians with severely injured heads. A series of equations and simulations estimated an average impact speed of 48.7 km/h (30.3 mph) in these target cases. Effectiveness estimates were presented for the active, passive, and integrated (active and passive) countermeasure systems. Results showed that the integrated system had an increased potential to reduce pedestrian head injuries as compared to either the active or passive system used alone. Effectiveness values ranged from 11 percent to 64 percent depending on the countermeasure parameters or the type of system modeled: active, passive, or integrated.

A major supplier for video sensing hardware and software used crash data from the Institute for Traffic Accident Research and Data Analysis (Japan) (ITARDA) to estimate the effectiveness of their product in vehicle-pedestrian crashes by identifying specific vehicles and their respective installation rate (none, version 1, or version 2) [9]. This empirical method did not provide explicit results, although basic calculations can provide crash avoidance effectiveness estimates derived from this work ranging from 75 to 88 percent. Furthermore, this study identified common reasons for deactivation based on US survey results, including: low sun angle (80%), followed by heavy precipitation (44%) and fog (17%).

A major car manufacturer used naturalistic driving data to describe pedestrian behavior, conduct track tests, and estimate crash avoidance rates [10]. The naturalistic driving data encompassed 110 vehicles that traveled 1.44 million miles in Indianapolis for one year. There were a total of 1,762 videos of potential conflicts with pedestrians. A distribution of time-to-collision (TTC) versus the number of cases was calculated and cumulative results showed a mean value of 4.43 seconds TTC when a vehicle-pedestrian conflict began. The lateral distances from the left and right side of the vehicle to the pedestrian (at the appearance point) were also calculated, showing means of 6.55 and 5.21 meters, respectively. Track tests of a vehicle equipped with a stereo camera and millimeter-wave radar showed variations in avoidance rate, based on scenario (e.g., pedestrian direction, vehicle motion, light condition, pedestrian size, and pedestrian motion). Preliminary results provided a wide range of effectiveness, including an avoidance rate of 84 percent when the vehicle was turning and an avoidance rate of 35 percent when the mannequin was darting (running).

The review of methods and results proved that a variety of potential data sources and methods may be used to estimate the effectiveness of PCAM systems. Further, as no two analyses are identical (e.g., variations in data sources, modeling, simulation, system algorithms), common elements were identified, including:

- *Crash data*: Understanding of the crash data provides valuable information, including pre-crash scenarios, initial conditions, and baseline measures.
- *Harm curves*: Derived from historical crash data to correlate impact speed to pedestrian injury. These curves help quantify benefits (e.g., crashes, fatalities, and injuries).
- *Operational capabilities*: Understanding the capability of the PCAM system can account for issues that arise when attempting to estimate system effectiveness, such as obstructions, bad weather, speed thresholds, and overall technological capability.
- *Driver and system performance data*: Incorporate driver performance (e.g., reaction time and braking level) and system performance (e.g., activation times, braking levels, driver-system interaction). Warnings systems have different driver-system interactions compared to AEB, thus varying input data and modelling.

- *Simulation or modelling (crash reconstruction or conflicts)*: A method to compare baseline results to treatment results, such as superimposing a PCAM system over historical crashes (reconstructed, probability of baseline crash = 1) or similar crashes in a simulation (probability of a baseline crash ≠ 1). These can use hypothetical systems and conflicts when real-world crash data comparisons are not available.
- *Crash avoidance and/or speed reduction*: Results from baseline to treatment comparison to quantify system effectiveness and safety benefits for crash avoidance and pedestrian injury mitigation.

These elements are identified as core elements for the methodology, each requiring specific data sources and analysis.

## APPROACH

The general methodology for estimating PCAM safety benefits is derived from a method previously used for vehicle-to-vehicle (V2V) based crash warning systems in support of NHTSA research efforts assessing the safety impact of V2V technology [11].

### Basic Equations

A series of basic equations define the methodology, dictating a minimum set of data parameters. These data parameters determine what data sources can be incorporated into the methodology and further identify the need for basic assumptions.

**Crash Avoidance** The general equation of safety benefits and system effectiveness for crash avoidance is presented in Equation **(1)** [12].

$$\boldsymbol{B_A = N_C \times E_A} \qquad \textbf{(1)}$$

The equation provides a potential safety benefit for PCAM systems, in terms of the annual reduction of vehicle-pedestrian crashes avoided, $\mathbf{B_A}$, based on the crash avoidance effectiveness, $\mathbf{E_A}$, and annual number of target crashes addressed by a PCAM system, $\mathbf{N_C}$. The crash avoidance effectiveness is broken down further, into two distinct ratios, as seen in Equation **(2)**.

$$\boldsymbol{E_A = 1 - \frac{EM_{PCAM}}{EM_{Base}} \times \frac{CP_{PCAM}}{CP_{Base}}} \qquad \textbf{(2)}$$

The exposure measure, **EM**, refers to the probability that a vehicle enters into a vehicle-pedestrian conflict. The ratio, comparing with and without ($\mathbf{EM_{PCAM}}$ and $\mathbf{EM_{Base}}$, respectively) will provide a positive safety benefit if vehicles are less likely to enter a vehicle-pedestrian conflict with a PCAM system compared to without any assistance. This measures the ability of a system to reduce the occurrence of conflicts in normal driving, typically derived from long-term naturalistic driving [13]. The crash probability, **CP**, refers to the probability that a collision occurs given that a vehicle-pedestrian conflict has been encountered. The ratio, comparing with and without ($\mathbf{CP_{PCAM}}$ and $\mathbf{CP_{Base}}$, respectively) will provide a positive safety benefit if vehicles are less likely to strike a pedestrian with a PCAM system compared to without. This measures the ability of a PCAM system to reduce the likelihood of a crash, given that the vehicle has entered into a conflict [13]. Given the current state of data, minimal naturalistic driving and vehicle-pedestrian conflict (e.g., non-crash) data is available, making **EM** difficult to quantify. For this reason, it is assumed that vehicles would have the same exposure to vehicle-pedestrian conflicts whether or not a PCAM system is installed, neutralizing the **EM** ratio to 1. Furthermore, based on the state of the crash data, it is appropriate to use a crash reconstruction method, superimposing PCAM system performance on historical crashes. Using this method, the historical baseline crash rate is 1, as all conflicts resulted in a crash ($\mathbf{CP_{Base}}$ = 1). These assumptions simplify Equation **(2)** to Equation **(3)**.

$$\boldsymbol{E_A = 1 - CP_{PCAM}} \qquad \textbf{(3)}$$

Based on the core elements defined earlier and the parameters identified within the equations, data needs have been relegated to crash data to determine target crash populations, $\mathbf{N_C}$, and a baseline set of crashes to reconstruct, along with human behavior and system performance data to determine the likelihood of a crash given system intervention, $\mathbf{CP_{PCAM}}$.

**Crash Mitigation** In addition to crash avoidance, a PCAM system may potentially reduce any resulting harm to the pedestrian by reducing the vehicle's travel speed prior to impact through improved driver response or automatic vehicle control. Similar to Equation **(1)**, the equation to estimate the reduction in pedestrian injury is provided in Equation **(4)**.

$$\boldsymbol{B_M = N_I \times E_M = N_I \times \{E_A + E_W \times (1 - E_A)\}} \tag{4}$$

The equation provides a potential safety benefit for PCAM systems in terms of the annual pedestrian injuries mitigated, $\mathbf{B_M}$, based on the crash mitigation effectiveness, $\mathbf{E_M}$, and annual number of pedestrians injured, $\mathbf{N_I}$. Since any crash avoided would inherently avoid all subsequent pedestrian injuries, crash mitigation effectiveness, $\mathbf{E_M}$, has to account for crash avoidance effectiveness, $\mathbf{E_A}$, and assess the effectiveness of injury reduction, $\mathbf{E_W}$, based on the resulting crash's impact speed. The method to estimate injury reduction effectiveness is shown in Equation **(5)**.

$$\boldsymbol{E_W = 1 - \frac{H(PCAM)}{H(Base)}} \tag{5}$$

The equation uses crash data to correlate impact speed and resulting pedestrian injury in a ratio comparing the pedestrian harm induced given a crash, with and without a PCAM system (**H(PCAM)** and **H(Base)**, respectively). Given the above set of equations, crash data can be used to obtain additional information on the annual number of pedestrians injured, $\mathbf{N_I}$, and to correlate impact speeds to pedestrian injury. Results from the crash reconstruction simulation can be used to determine impact speed with PCAM intervention.

Based on the above data parameters needed within the basic equations and the above core elements, the developed method is broken down into four key steps:

1. Identify and describe PCAM systems. This step identifies current and near-term production PCAM systems and describes their operational boundaries and capabilities. This includes operational design domain, countermeasure profiles, and driver-system interaction algorithms.
2. Identify data needs and data sources. This step uses the core elements to identify the priority data parameters and respective data sources, then performs a query and analyzes the data. This step assesses baseline conditions and treatment data (i.e., driver behavior with warning, system performance). Further, this step is setup to propose and execute a method to collect supplemental data, if feasible and necessary.
3. Run simulation and estimate effectiveness. Based on a preliminary assessment of the available data, it is appropriate that a crash reconstruction simulation, superimposing PCAM systems on historical crash cases, be used to estimate the effectiveness of PCAM systems.

## PCAM SYSTEMS

A technology scan of public literature (e.g., media publications, owner's manuals, publicized testing) was used to understand the functionality and operational conditions of current and near-term production PCAM systems. The dynamics of a vehicle-pedestrian crash offer several intervention or countermeasure opportunities for PCAM systems. Table 2 shows the results of the technology scan of active PCAM systems. Since public literature was used, specific details on system capabilities and limitations were not available (e.g., warning suppression techniques, minimum and maximum thresholds for activation). The PCAM systems identified utilize various forms of technology. However the analysis conducted within this paper is independent of technological implementation.

*Table 2.*
***Number of Active PCAM Systems (Current and Near-Term) Identified and Reviewed from Technology Scan.***

| PCAM System Type (Countermeasure Profile) | Warning Issued To | | |
|---|---|---|---|
| | Driver | Pedestrian | No Warning |
| **Warn Only** | 4 | 1 | |
| **Warn and Brake Assist** | 2 | | |
| **Warn and Automatic Brake** | 3 | | |
| **Brake Assist Only** | | | 1 |
| **Warn, Automatic Brake and/or Steer** | 2 | | |

As noted earlier, the variations in countermeasures may require different data sets. For example, a warning to the driver would require system performance and driver response data, whereas an AEB-only system requires only system performance data. After assessing the various PCAM systems and associated driver-vehicle interactions, this analysis considers the potential safety benefits for the following three[1] PCAM systems:

- AEB only systems,
- Warning + first braking response between AEB or driver, and
- Warning + best braking response between AEB and driver.

Incremental benefits are determined by adding driver response to a warning issued prior to AEB activation. For example, a system would alert the driver, via warning, that a vehicle-pedestrian crash is imminent. This warning would elicit a driver response, but if a driver does not respond appropriately, AEB may initiate. This driver-vehicle interaction requires specific input data for the multiple components of the system. To encompass potential driver-vehicle interaction and system suppression methods, two logic systems are implemented when both driver and AEB are simultaneously activate:

- *First Braking*: Assumes that once braking has been initiated (by driver or AEB), it remains constant for the remainder of the event, regardless of magnitude. This assumes that any initial response suppresses secondary responses (i.e., driver is in control means no AEB is necessary, or AEB activation assumes the driver will never respond).
- *Best Braking*: Assumes that if both braking inputs are active (driver and AEB), the system uses the higher input to maximize braking effectiveness. If only one braking input is active (AEB or driver), then the system uses the active input. This system attempts to maximize effectiveness with the earliest and then the best braking response.

The driver-system interaction variations will provide a system effectiveness range, with the '*AEB Only*' system providing a lower-limit range, while the addition of a warning to the driver may provide incremental benefits (as a driver may react earlier and/or brake harder than AEB).

## DATA SOURCES

The next step of the methodology is to identify potential data sources for the necessary data parameters, then query and analyze these data sources. Within this step, if a data parameter could not be quantified from available data sources, additional data collection methods can be proposed and executed.

---

[1] Minimal information and data was found on the pedestrian warning and automatic steering countermeasure, therefore these countermeasures were excluded from this analysis.

**National Crash Data**

Historical crash data at the national level are available from NHTSA’s GES and FARS crash databases. The GES provides a national representation of police-reported crashes in public traffic-ways, accumulating a sample of police-reports and incorporating associated variables into the data. The FARS provides a complete census of crashes on public roadways that resulted in a fatality within 30 days. These crash databases contain variables, codes, and relevant statistics that help to quantify and characterize the baseline pedestrian crash problem addressed by PCAM safety systems. The crash databases also contain details to specifically characterize each crash, including pre-crash scenario, travel speeds, environmental conditions, driver factors, and attempted avoidance maneuvers. Details surrounding the crash allow for an accurate depiction of the driving conflict, supporting a crash reconstruction simulation. PCAM-addressable crashes only include crashes where a forward moving light-vehicle struck a pedestrian with the front of the vehicle in the first event of the crash and the driver attempted no avoidance maneuver.

The PCAM-addressable criteria aim to encompass the operational capabilities of PCAM systems and their aimed effectiveness. Due to limited information on system performance with driver input (e.g., driver pressing the brake pedal may suppress AEB activation), attempted avoidance maneuvers were not considered. Impaired drivers may not react to a warning but an AEB component (if applicable) may be designed to still activate; therefore, impaired drivers were considered for this analysis. The following definitions were used to obtain the target baseline crashes:

- Light-Vehicle: The use of the vehicle body type variable in the crash databases identifies passenger cars, vans and minivans, sport utility vehicles, and light pickup trucks with gross vehicle weight rating less than 10,000 pounds.
- Pedestrian: Any person on foot, walking, running, jogging, hiking, standing still, sitting, or lying down, excluding any person on a personal conveyance such as personal mobility device or rideable toy.
- First Event: Crash data provide a series of critical events for the crash, regardless of injury or damage sustained (or lack thereof). The first listed critical event of the crash is considered.
- Vehicle Moving Forward: Crash data provide pre-event movement of the vehicle, prior to the driver’s realization of an impending critical event. Movements listed as no driver, stopped, backing, parking related, or unknown are excluded.
- Area of Impact: Crash data provide the area of impact of the vehicle. Only crashes that identified the front of the vehicle to be struck (i.e.., 11, 12, and 1 o’clock values) are considered.
- Avoidance Maneuver: Crash data provide the attempted avoidance maneuver of the vehicle in recognition of the critical pre-crash event. Only crashes with ‘no avoidance maneuver’ attempted by the vehicle are incorporated.

In addition to the statistics provided earlier in Table 1, these PCAM-addressable crashes resulted in approximately 13,000 injured persons at the Maximum Abbreviated Injury Scale (MAIS) $2^+$ levels and 7,000 injured pedestrians at MAIS $3^+$ levels. A conversion matrix was used to convert injury scales, from the GES KABCO injury into a MAIS injury [14]. Further, FARS is used to get the actual count of persons killed in target crashes and included in the KABCO-MAIS conversion. Table 3 shows the breakdown of these injuries into the priority pre-crash scenarios.

***Table 3.***

***Breakdown of PCAM-Addressable Pedestrian Injuries into Priority Pre-Crash Scenarios from 2011-2012.***

| Scenario | Vehicle Maneuver | Pedestrian Maneuver | MAIS 2+ | % of MAIS 2+ | MAIS 3+ | % of MAIS 3+ |
|---|---|---|---|---|---|---|
| S1 | Going Straight | Crossing Roadway | 2,682 | 49.9% | 1,879 | 56.9% |
| S2 | Turning Right | Crossing Roadway | 274 | 5.1% | 92 | 2.8% |
| S3 | Turning Left | Crossing Roadway | 883 | 16.4% | 333 | 10.1% |
| S4 | Going Straight | Walking Along/Against Traffic | 1,207 | 22.4% | 860 | 26.0% |
| Other Scenarios (~60 Additional) | | | 330 | 6.1% | 141 | 4.3% |
| Total Injuries from PCAM-Addressable Crashes | | | 5,376 | | 3,305 | |

**Injury Curves** Injury probability curves aim to predict the probability of a pedestrian injury occurring given an impact speed. These curves are used to measure crash severity by correlating injury levels to impact speeds from historical crashes. Injury probability curves are derived from 2011 and 2012 GES and FARS data. Similar criteria as the above crash data are used, and the vehicle travel speed and resulting pedestrian injury are obtained to determine the injury probability for five-mph incremental speed bins. [2] It is important to note that travel speed information is mostly unavailable in the GES and FARS data where approximately 80 percent of crashes had unknown travel speed information. Results from this query are fed into a regression model to determine functions for the various harm curves. These smoothed curves from developed functions help mitigate anomalies found with smaller data sets and aid in eliminating unusual spikes in data. Figure 3 illustrates the results from the regression model.

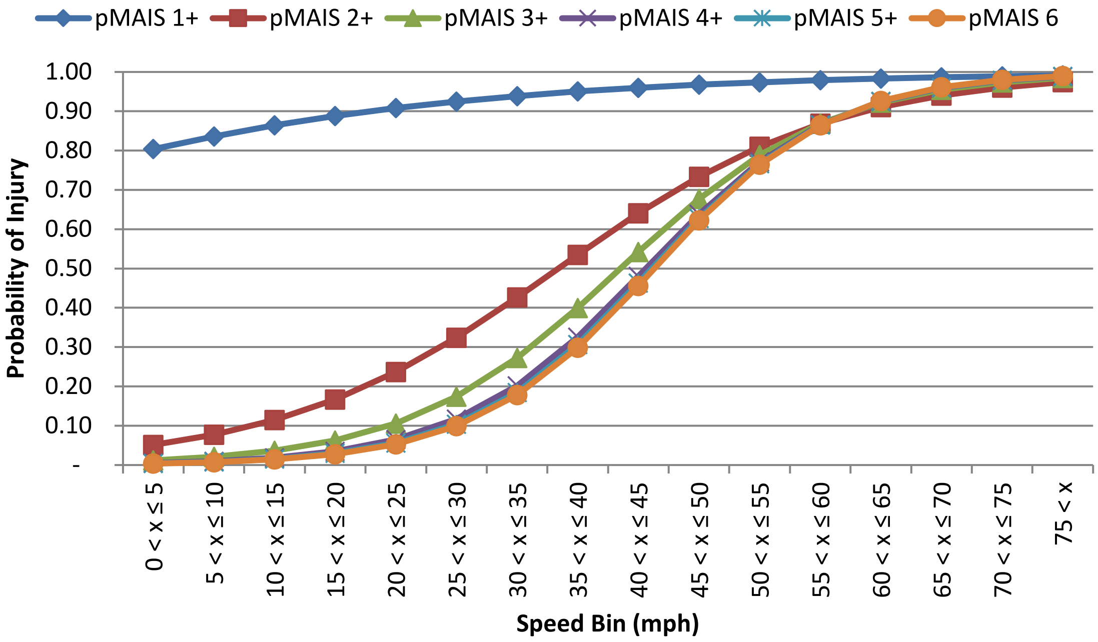


*Figure 3. Plots of Pedestrian Injury Cumulative Probability Functions from Regression Model.*

The probability for a certain injury level is simply the difference of two MAIS+ probabilities. For example, $p_{MAIS1}= p_{MAIS1+} - p_{MAIS2+}$ and $p_{MAIS2}= p_{MAIS2+} - p_{MAIS3+}$. The injury mitigation analysis in this report focuses on the MAIS 2+ and MAIS 3+ injury levels.

## Special Crash Investigation

National crash databases contain an abundance of cases but lack detailed information on the dynamics of the crash. These databases rely on available police reports and witness statements to detail the pre-crash information (e.g., motions, speed, and critical events). Approximately three quarters of GES cases that could be addressed by PCAM systems do not have travel speed information (coded as 'unknown'). Further, detailed information on the pedestrian motion is not readily available (e.g., left-to-right or right-to-left of the vehicle, when crossing the road). From the available information, accurate depictions of the crash become difficult, relying on multiple assumptions. A crucial missing element is the amount of time the pedestrian spent in view of the driver/vehicle, within the roadway, and in the vehicle's intended path. One might assume, for maximum effectiveness, PCAM systems may attempt to maximize accuracy and responsiveness, while minimizing the number of nuisance and false activations. As part of

---

[2] Travel speed may not be equivalent to impact speed; and crash databases do not contain impact speed and have limited availability of travel speed. Travel speed is the vehicle's speed prior to conflict and could be used if no attempt to avoid a crash was made.

the data identification task, a special crash investigation (SCI) team at NHTSA was tasked to investigate the detailed dynamics of an S1 scenario.[3]

The resulting database contains over 50 recorded variables for 43 relevant vehicle-pedestrian crashes where investigators were able to examine the crash in detail and estimate a comprehensive list of details that depict the exact kinematics of the crash. A list of variables obtained can be found in the Appendix. It is important to note that these 43 cases could not be incorporated into this methodology for numerous reasons (e.g., small sample size with wide range of results, bias towards severe injuries, not nationally representative). However, the data obtained provided detailed cases where PCAM systems could provide a benefit. The focus of the investigation was to determine TTC for the vehicle when the pedestrian was revealed to the driver (or would be PCAM system). Figure 4 details the TTC measure in a vehicle-pedestrian conflict.

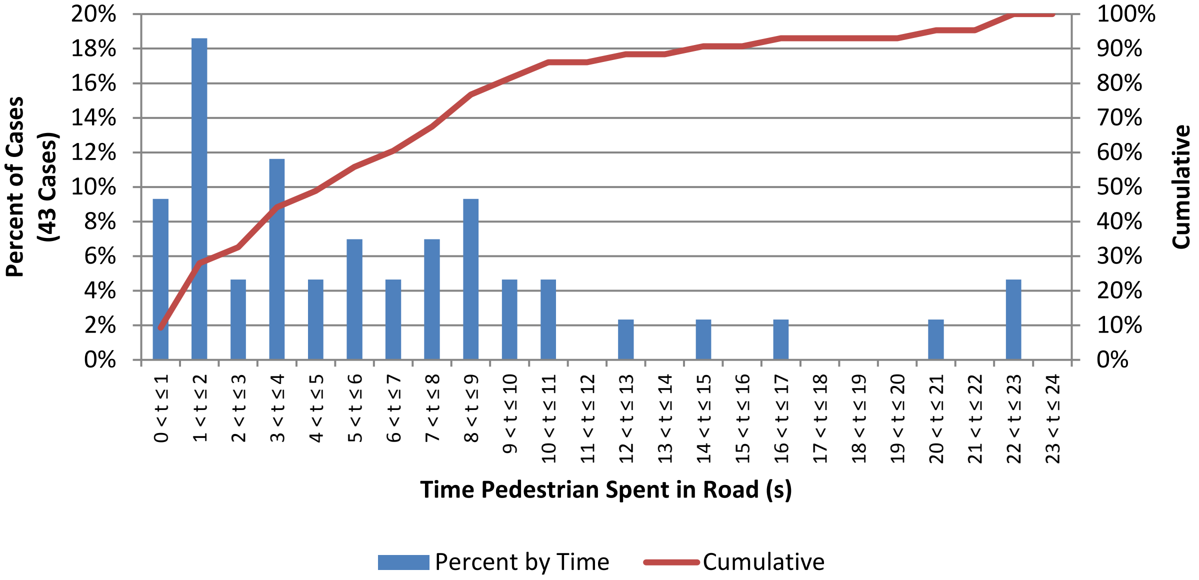


***Figure 4. Distribution of Pedestrian Reveal TTC in S1 from SCI Database.***

The information provides a wide TTC range, estimating a pedestrian being visible from under 1 second to as much as over 20 seconds. The majority of crashes had TTC values under 6 seconds, accounting for 55.8 percent of the crashes. Although the cases could not be used directly in the benefits model, the wide range signifies a potential for PCAM benefit. In cases with low TTC (less than 1 second), PCAM systems may have a difficult time detecting and identifying pedestrians, warning the driver, and/or applying AEB; this accounts for less than 10 percent of the cases. On the other end, in cases with a high TTC (greater than 6 seconds), PCAM systems may have ample time to detect, identify, and/or apply AEB, as this may be well beyond the longitudinal range of the technology used in PCAM systems. Furthermore, these cases identified drivers that were unable to detect, identify, and/or react to the conflict appropriately (e.g., distracted drivers, impaired drivers/pedestrians, or poor lighting conditions, dark pedestrian clothing). These drivers may potentially benefit from a warning, drawing attention to the pedestrian and aiding the driver in reacting appropriately.

## Test Data

A crucial data source for estimating system effectiveness is system performance data. System performance data were obtained from characterization test runs conducted at the Transportation Research Center Inc. (TRC) in East Liberty, Ohio by NHTSA's Vehicle Research and Test Center (VRTC) [15]. Three production vehicles equipped

---

[3] S1 was selected due to its potential variations on circumstances, high frequency, and injury rates. It is assumed in S4 that the pedestrian is already walking or standing in the vehicle's path, and therefore is limited by technological capabilities (e.g., a driver or PCAM system would be able to monitor an S4 situation as long as the pedestrian is within range).

with PCAM systems were tested in S1 and S4 priority pre-crash scenarios, varying multiple parameters (e.g., pedestrian size, pedestrian speed, pedestrian direction/orientation, lighting, obstructions, vehicle speed, and overlap).[4] Vehicle speeds ranged from 15 to 45 mph. Detailed time-history data were collected for each test run and analyzed for 20 variables, including speeds, distances, warning activation time, AEB activation time, and resulting impact. After assessing the testing conditions and correlating respective testing conditions to crash data, the six distinct test scenarios shown in Table 4 were used for the benefits method. For other scenarios, since empirical test data could not be applied to crash data, system effectiveness was conservatively set to 0. This implies that PCAM systems would not have an immediate benefit. Further research, testing, and analysis would be required to revise this assumption.

***Table 4.***
***Priority PCAM Testing Setups that Correlate to Crash Data and Associated Number of Test Runs and No Impact Results (All Vehicle Speeds* and Vehicles).***

| Name | Scenario | Pedestrian Size | Pedestrian Speed | Pedestrian Direction | Lighting | Obstruction | Number of Tests | ‘No Impact’ Results |
|---|---|---|---|---|---|---|---|---|
| S1-A | S1 | Adult | 3.1 mph | Right-Left | Day | No | 497 | 397 |
| S1-B | S1 | Adult | 4.9 mph | Right-Left | Day | No | 265 | 90 |
| S1-C | S1 | Child | 3.1 mph | Right-Left | Day | No | 194 | 167 |
| S1-D | S1 | Child | 3.1 mph | Right-Left | Day | Yes | 108 | 42 |
| S4-A | S4 | Adult | Stationary | Stationary | Day | No | 403 | 325 |
| S4-B | S4 | Adult | 3.1 mph | Away | Day | No | 202 | 183 |

*Speeds ranged from 15 to 45 mph

Analysis of the resulting data provides characteristics of the various PCAM systems. Various parameters were analyzed, including correlating AEB activation time to vehicle speed and average AEB level to vehicle speed, as seen in Figure 5 and Figure 6, respectively. Each production vehicle was analyzed anonymously, labeled as original equipment manufacturer (OEM) 1 to 3. Additional parameters were analyzed for each of the six test scenarios and production vehicles to help in characterizing the system.

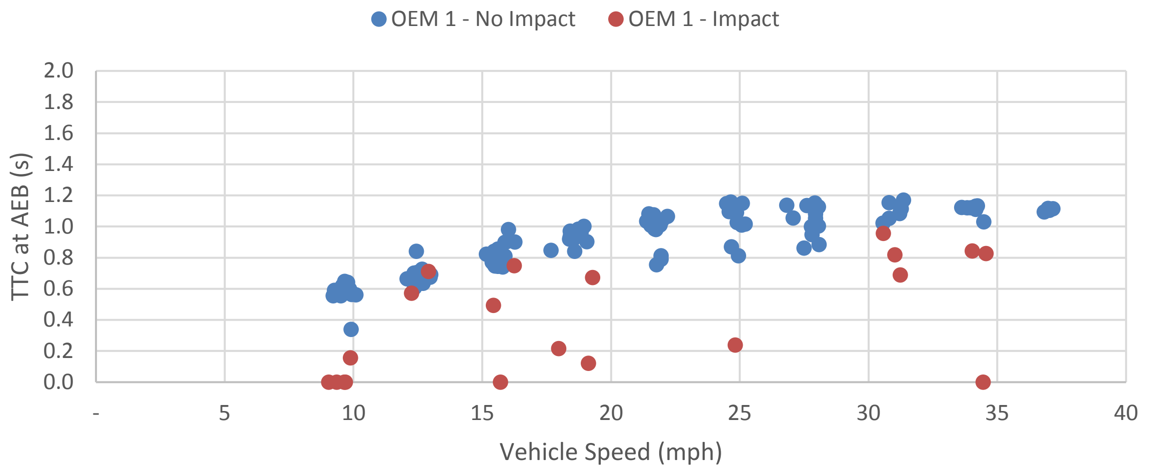


***Figure 5. Test Run Results for Production Vehicle 1, Comparing AEB Activation Time to Vehicle Speed in S1-A.***

---

[4] Overlap refers to point on the front bumper where the pedestrian is projected to impact, given no PCAM intervention.

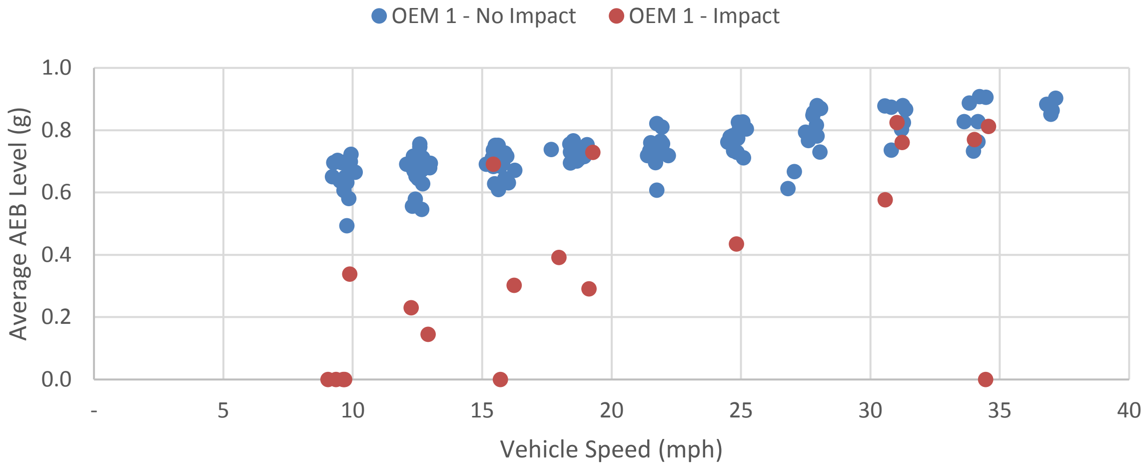


***Figure 6. Test Run Results for Production Vehicle 1, Comparing Average AEB Level to Vehicle Speed in S1-A.***

Test results show that there is a relationship between AEB activation time and level to vehicle travel speed. This intuitively makes sense, as more time and braking power are needed for the vehicle to come to a complete stop within the finite detection range of the system. Further, it can be seen that although AEB timing and braking varied, there is an overlap in AEB performance and vehicle travel speed and the end result (impact or no impact). In the S1 test setup, the various combinations of conditions allow for the vehicle to stop after the pedestrian's travel path and still avoid the impact (i.e., vehicle slowed enough to allow pedestrian to finish crossing). Even if an impact occurred (potentially due to insufficient AEB) vehicle speed reductions were observed, resulting in lower impact speeds with the pedestrian. Finally, as shown in the figures, in some instances the PCAM system did fail to activate, resulting in an impact at full speed. The test data provided empirical data that were used to estimate system effectiveness.

### Human Behavior

Information on driver behavior was obtained from previous research studies, determining driver responses in conflicts with the presence of a warning. Driver performance is incorporated into the treatment data to determine incremental benefits when a warning is issued, along with AEB. As seen in Table 5, based on earlier studies, driver reaction time was estimated as a lognormal distribution with a mean of 1.1 seconds and standard deviation of 0.3 [16]. Also in Table 5, driver braking level was estimated as a normal distribution curve with a mean of 0.5 g and a standard deviation of 0.1 [17]. Only treatment data are necessary, as the benefits method uses a crash reconstruction method. This assumes that all baseline conflicts resulted in a crash regardless of driver response. These parameters are incorporated into the Monte Carlo simulation independently.

***Table 5.***
***Driver Performance Measures in Response to a Warning***

| Inputs: | Min | Max | Mean* | Std. Dev.* | Distribution Type |
|---|---|---|---|---|---|
| **Host Driver Reaction Time In Control (s)** | 0 | 5 | 1.1 | 0.3 | Log Normal |
| **Host Driver Deceleration In Control (g)** | 0.25 | 0.75 | 0.5 | 0.1 | Normal |

*Mean and standard deviation are based on sample data not population

## RESULTS

Results from the benefits model provided information on a PCAM's potential ability to avoid pedestrian crashes and mitigate pedestrian injury through impact speed reduction in unavoidable crashes. The results were derived from crash probability in Equation **(**3**)** and the resulting impact speed to determine pedestrian injury in Equation **(**5**)**. The parameters in these equations were obtained from a crash reconstruction simulation, superimposing empirical PCAM system performance data onto historical vehicle-pedestrian crash cases.

## Simulation

A Monte Carlo simulation model exercises general kinematic equations in conjunction with driver and system performance data to determine the probability of a crash and the resulting impact speeds given a crash. Kinematic equations were derived from previous research for the four priority pre-crash scenarios [6]. This simulation reconstructed historical 2011 and 2012 PCAM-addressable GES and FARS crashes and superimposed PCAM system test data and driver performance distribution data to determine the outcome with PCAM intervention.

Initial conditions for the simulation are described by vehicle location, size and speed, pedestrian location, size, and speed, and environmental conditions (e.g., lighting and obstructions). Driver and system performance data are described by driver reaction time, driver braking level, system activation time, and system braking level. The simulation was run for 100,000 iterations.[5] Each iteration cycles through historical crashes and superimposes PCAM system performance data directly from the test data. PCAM system performance data were tied to historical crashes by correlating the initial conditions (e.g., vehicle speed, pedestrian speed). For example, a crash reporting vehicle travel speeds of 25 mph with a pedestrian walking across the road in the daylight with no obstruction was superimposed with S1-A test data (vehicle speeds of 25 mph), as this scenario is representative of this crash case.

## System Effectiveness

System effectiveness is estimated as a range of values, in terms of crash avoidance and injury mitigation, for the three systems types defined earlier, three production vehicles, and six testing scenarios. A refined target crash population is presented in Table 6 representing the historical crashes that may be addressed by PCAM systems in the six distinct testing scenarios, as effectiveness cannot be accurately assessed for other conditions. Costs are calculated from NHTSA economic analyses and are based on 2010 economic costs [14].

***Table 6.***
***Annual Average Number (2011 to 2012) of Target Crashes, Injuries, and Costs (2010$).***

| Scenario Name | GES Crashes | FARS Crashes | Costs (2010 $M) | MAIS 2+ | | MAIS 3+ | |
|---|---|---|---|---|---|---|---|
| | | | | Pedestrians Injured | Costs (2010 $M) | Pedestrians Injured | Costs (2010 $M) |
| S1-A | 4,582 | 838 | $ 8,393 | 1,576 | $ 8,269 | 1,111 | $ 8,083 |
| S1-B | - | 1 | $ 5 | 1 | $ 5 | 1 | $ 5 |
| S1-C | 796 | 35 | $ 433 | 150 | $ 408 | 72 | $ 377 |
| S1-D | 279 | 9 | $ 124 | 52 | $ 115 | 24 | $ 104 |
| **% PCAM-Addressable S1** | **76%** | **63%** | **64%** | **66%** | **63%** | **64%** | **63%** |
| S4-A | 300 | 100 | $ 967 | 160 | $ 959 | 125 | $ 945 |
| S4-B | 471 | 72 | $ 763 | 187 | $ 750 | 120 | $ 723 |
| **% PCAM-Addressable S4** | **26%** | **28%** | **28%** | **29%** | **28%** | **28%** | **28%** |

From these target crashes, a subset of crashes are identified with enough data to allow for a suitable crash reconstruction. The main factors in eliminating crashes included missing information about vehicle travel speed and pedestrian motion and speed. These specific crashes were then used to determine a baseline harm curve, as described earlier (National Crash Data), for use in Equation **(5)**.

**Crash Avoidance** The results for crash avoidance system effectiveness are presented in Table 7, based on 100,000 iterations within the Monte Carlo simulation. Results are presented for the various production vehicles using the AEB system logic (i.e., only AEB activates without any driver warning). It is important to note that this system logic is presented because it was determined from the test data that the difference between driver warning and AEB activation was minimal (average less than 1 second) and a driver would not be able to react to the warning prior to the AEB activation. Simulation results confirmed this, as there was minimal crash avoidance effectiveness differences between the three system logic variations.

---

[5] A sensitivity analysis was performed to determine the number of iterations for the simulation to enter a stable state. After 2,500 iterations, this analysis entered a steady state within a ± 0.2 percent range.

*Table 7.*
***Crash Avoidance Effectiveness of PCAM Systems for Three Production Vehicles (AEB Only) and Two Crash Databases.***

| Scenario Name | GES | | | FARS | | |
|---|---|---|---|---|---|---|
| | OEM 1 | OEM 2 | OEM 3 | OEM 1 | OEM 2 | OEM 3 |
| S1-A | 76% | 75% | 40% | 52% | 49% | 7% |
| S1-B | N/A* | N/A* | N/A* | 10% | 68% | 0% |
| S1-C | 90% | 70% | 64% | 37% | 36% | 12% |
| S1-D | 20% | 22% | 39% | 0% | 0% | 9% |
| S4-A | 49% | 64% | 53% | 39% | 51% | 34% |
| S4-B | 70% | 100% | 95% | 22% | 59% | 46% |

*No GES crashes met conditions to be reconstructed

Based on the initial conditions and system performance data, the various production vehicles were successful in avoiding many crashes, although they demonstrate lower performance with faster pedestrian speeds and obstructions. Further, results prove that not all crashes are avoidable but a reduction in impact speeds may provide an additional safety benefit.

**Crash Mitigation** An output of the Monte Carlo simulation is to report the impact speed of the resulting vehicle-pedestrian crash. A distribution of these impact speeds is compared to the baseline impact speeds to determine the potential for reduced pedestrian harm. Figure 7 illustrates an output of the simulation, showing the various distributions of impact speeds for a production vehicle in the S1-A testing scenario within the GES crash reconstructions. Distributions of impact speeds were smoothed using regression modelling to account for data anomalies.

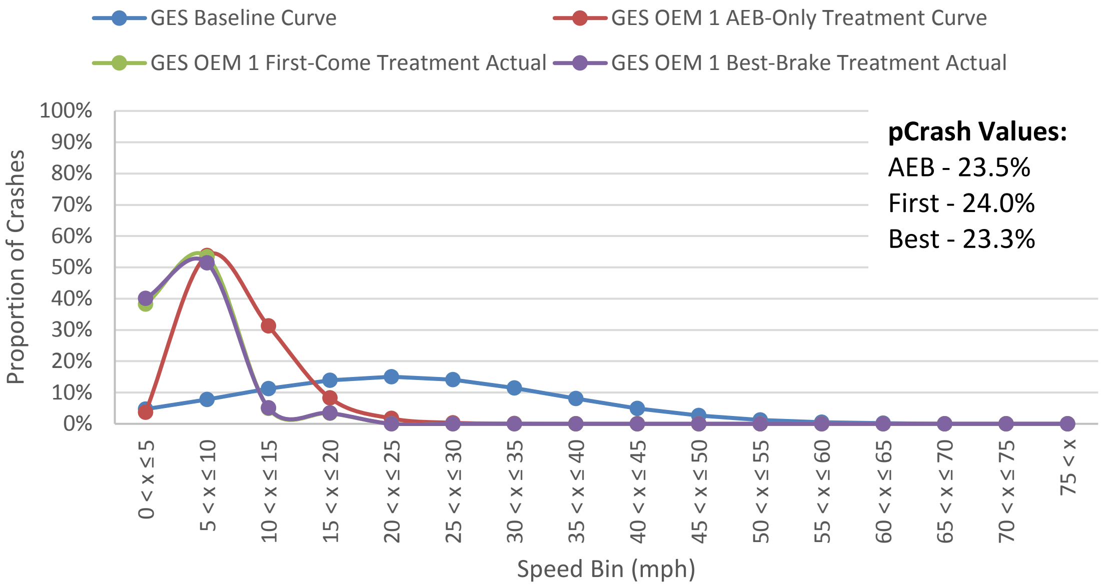


***Figure 7. Plots of Functions Comparing Baseline and Treatment Impact Speeds for Production Vehicle 1 in a S1-A Test with GES Crashes.***

Results show a distinct shift in the average impact speed, reducing speed from 20-25 mph to 5-10 mph. An impact speed reduction of 15 mph can have a profound effect on mitigating injuries, dropping potential pedestrian injuries from severe to minor. Further, as shown in Figure 7, crash mitigation effectiveness accounts for the crashes avoided, including the 24 percent of crashes avoided, effectively eliminating all subsequent pedestrian injuries (Equation (4)).

Crash mitigation effectiveness for the three production vehicles using the AEB system logic (i.e., only AEB activates without any driver warning) is shown in Table 8. Similar to crash avoidance, the minimal difference in AEB activation and driver warning provided small variations in effectiveness.

***Table 8.***
***Crash Mitigation Effectiveness of PCAM Systems for Three Production Vehicles (AEB Only) and Two Crash Databases.***

| PCAM Scenario | Harm Measure | GES | | | FARS | | |
|---|---|---|---|---|---|---|---|
| | | OEM 1 | OEM 2 | OEM 3 | OEM 1 | OEM 2 | OEM 3 |
| S1-A | MAIS 2+ | 92% | 91% | 72% | 91% | 88% | 67% |
| | MAIS 3+ | 96% | 96% | 83% | 96% | 94% | 79% |
| S1-B | MAIS 2+ | N/A* | N/A* | N/A* | 65% | 88% | 46% |
| | MAIS 3+ | N/A* | N/A* | N/A* | 77% | 92% | 54% |
| S1-C | MAIS 2+ | 89% | 79% | 46% | 83% | 79% | 64% |
| | MAIS 3+ | 90% | 83% | 38% | 91% | 87% | 76% |
| S1-D | MAIS 2+ | 54% | 65% | 73% | 41% | 68% | 73% |
| | MAIS 3+ | 65% | 77% | 82% | 52% | 84% | 87% |
| S4-A | MAIS 2+ | 84% | 88% | 87% | 83% | 86% | 80% |
| | MAIS 3+ | 89% | 92% | 93% | 89% | 91% | 87% |
| S4-B | MAIS 2+ | 92% | 100% | 98% | 78% | 89% | 85% |
| | MAIS 3+ | 96% | 100% | 99% | 86% | 93% | 91% |

* No GES crashes met conditions to be reconstructed

**Safety Benefits**

PCAM systems can potentially provide a wide range of safety benefits, depending on the initial conditions and the system algorithms. Table 9 presents the crash avoidance effectiveness for the six scenarios tested. The range is defined by the three production vehicles and the two sets of crash reconstruction databases; however as noted earlier, only AEB is used for this effectiveness (i.e., no driver warning). The resulting benefits are determined from Equation **(1)** using the values from Table 6 and Table 7. These crashes translate to savings in billions of dollars and hundreds of equivalent lives saved (i.e., a metric that translates comprehensive costs into a reduction in pedestrian fatalities).

***Table 9.***
***Annual PCAM-Addressable Crash Mitigation Safety Benefits (AEB Only).***

| PCAM Scenario | Crash Avoidance Effectiveness | GES Crashes Reduced | FARS Crashes Reduced | Costs Reduced (2010 $M) | Equivalent Lives Saved |
|---|---|---|---|---|---|
| S1-A | 7% - 76% | 318 - 3,503 | 58 - 641 | $ 582 - 6,417 | 64 - 702 |
| S1-B | 0% - 68% | N/A* | N/A* | $ 3* | N/A* |
| S1-C | 12% - 90% | 93 - 713 | 4 - 31 | $ 51 - 388 | 6 - 42 |
| S1-D | 0% - 39% | 0 - 108 | 0 - 3 | $ 48 | 5 |
| **Total Effectiveness of PCAM Addressable S1** | **7% - 77%** | **411 - 4,324** | **62 - 675** | **$ 633 - 6,856** | **69 - 750** |
| **S4-A** | 34% - 64% | 103 - 192 | 34 - 64 | $ 332 - 618 | 36 - 68 |
| **S4-B** | 22% - 100% | 105 - 471 | 16 - 72 | $ 170 – 763 | 19 - 83 |
| **Total Effectiveness of PCAM Addressable S4** | **27% - 86%** | **208 - 663** | **50 - 135** | **$ 501 - 1,380** | **55 - 151** |

*Only 1 FARS case was identified over two years, this benefit is simply the effectiveness multiplied by the average annual comprehensive cost (one half comprehensive cost of one fatality).

Table 10 presents the injury mitigation effectiveness for the six scenarios tested. Similar to crash avoidance effectiveness estimates, the wide range of crash mitigation effectiveness is obtained from the three production vehicles and two crash reconstruction databases. Further, crash mitigation effectiveness estimates incorporate the crash mitigation effectiveness. Again, results are only provided for AEB only. Metrics used to estimate injury mitigation benefit are annual reduction of pedestrians injured at MAIS $2^+$, MAIS $3^+$, comprehensive costs, and the number of equivalent lives saved.

***Table 10.***
***Annual PCAM-Addressable Crash Mitigation Safety Benefits (AEB Only).***

| PCAM Scenario | Harm Measure | Crash Mitigation Effectiveness | Injuries Reduced | Costs Reduced (2010 $M) | Equivalent Lives Saved |
|---|---|---|---|---|---|
| S1-A | MAIS 2+ | 67% - 92% | 1,051 - 1,448 | $ 5,514 - 7,594 | 603 - 830 |
| | MAIS 3+ | 79% - 96% | 873 - 1,068 | $ 6,347 - 7,767 | 694 - 849 |
| S1-B | MAIS 2+ | 46% - 88% | N/A* | $ 2 – 4* | N/A* |
| | MAIS 3+ | 54% - 92% | N/A* | $ 2 – 4* | N/A* |
| S1-C | MAIS 2+ | 46% - 89% | 69 - 133 | $ 188 - 364 | 21 - 40 |
| | MAIS 3+ | 38% - 91% | 27 - 65 | $ 143 - 344 | 16 - 38 |
| S1-D | MAIS 2+ | 41% - 73% | 21 - 38 | $ 47 - 84 | 5 - 9 |
| | MAIS 3+ | 52% - 87% | 12 - 21 | $ 54 - 91 | 6 - 10 |
| **Total Effectiveness of PCAM Addressable Total S1** | **MAIS 2+** | **64% - 91%** | **1,142 - 1,620** | **$ 5,751 - 8,046** | **629 - 880** |
| | **MAIS 3+** | **76% - 96%** | **912 - 1,154** | **$ 6,547 - 8,206** | **716 - 897** |
| S4-A | MAIS 2+ | 80% - 88% | 128 - 141 | $ 764 - 844 | 84 - 92 |
| | MAIS 3+ | 87% - 93% | 109 - 116 | $ 822 - 881 | 90 - 96 |
| S4-B | MAIS 2+ | 78% - 100% | 145 - 187 | $ 581 - 750 | 64 - 82 |
| | MAIS 3+ | 86% - 100% | 103 - 120 | $ 621 - 723 | 68 - 79 |
| **Total Effectiveness of PCAM Addressable Total S4** | **MAIS 2+** | **79% - 94%** | **273 - 329** | **$ 1,346 - 1,594** | **147 - 174** |
| | **MAIS 3+** | **86% - 97%** | **212 - 236** | **$ 1,443 - 1,604** | **158 - 175** |

*Only 1 FARS case was identified over two years, this is benefit is simply the effectiveness multiplied by the average annual comprehensive cost (one half comprehensive cost of one fatality).

Overall PCAM systems could provide a crash avoidance effectiveness of 78 percent, as shown in Table 11. Further, the table shows if a crash occurs, PCAM systems may provide injury mitigation effectiveness of 92 and 96 percent for pedestrians injured at MAIS $2^+$ and MAIS $3^+$, respectively. The table only shows the highest crash avoidance and crash mitigation effectiveness observed from the simulation and the correlating benefit.

*Table 11.*
*Best Observed Effectiveness and Safety Benefits for PCAM-Addressable Crashes.*

| Scenario | Crash Avoidance Effectiveness | GES Crashes Reduced | FARS Crashes Reduced | Costs Reduced (2010 $M) | Equivalent Lives Saved |
|---|---|---|---|---|---|
| S1 | 76.4% | 4,324 | 675 | $ 6,857 | 750 |
| S4 | 85.9% | 663 | 135 | $ 1,380 | 151 |
| **Total System** | **77.6%** | **4,987** | **810** | **$ 8,237** | **901** |

| Scenario | Harm Measure | Crash Mitigation Effectiveness | Pedestrian Injuries Reduced | Costs Reduced (2010 $M) | Equivalent Lives Saved |
|---|---|---|---|---|---|
| S1 | MAIS 2+ | 91.0% | 1,620 | $ 8,046 | 880 |
| | MAIS 3+ | 95.6% | 1,154 | $ 8,206 | 897 |
| S4 | MAIS 2+ | 94.5% | 329 | $ 1,594 | 174 |
| | MAIS 3+ | 96.5% | 236 | $ 1,604 | 175 |
| **Total System** | **MAIS 2+** | **91.6%** | **1,948** | **$ 9,640** | **1,054** |
| | **MAIS 3+** | **95.8%** | **1,391** | **$ 9,810** | **1,073** |

## CONCLUSION

This paper developed and applied a methodology to estimate potential safety benefits for existing and near-term production PCAM systems. These systems are vehicle-based pedestrian detection systems that can warn drivers and/or automatically apply the vehicle brakes to avoid a collision or reduce the impact speed. This paper addressed current and near-term production PCAM systems with driver warning and AEB. Safety benefits were estimated in terms of reductions in the number of all annual vehicle-pedestrian crashes, annual vehicle-pedestrian fatal crashes, and annual injured pedestrians at MAIS $2^+$ and MAIS $3^+$ levels, annual comprehensive costs, and annual equivalent lives.

Data sources available at the time of this analysis included national crash databases, test track data, and human behavior information. Additional data were collected using a NHTSA SCI team to detail the dynamics of historical pedestrian crashes, specifically the amount of time the pedestrian was visible to the driver. A crash reconstruction simulation superimposed with empirical PCAM system data was conducted to determine crash avoidance effectiveness and any reduction in impact speed if a crash occurred.

Overall, the methodology presented in this paper relied on the availability and accuracy of real-world data. Ideally, safety benefits would be estimated from empirical crash data over the course of multiple years, comparing crash statistics of vehicle-pedestrian crashes without a PCAM system to crashes with a PCAM system. However, with the current state of crash data and collection methods, information is unavailable to estimate PCAM safety benefits in this method. Future considerations may be made to amend the data collection method to address any deficiencies in the crash data. Therefore, this methodology supplemented historical crash data with objective testing of production vehicle systems and previous literature/research. This information was input into a Monte Carlo simulation to compare historical vehicle-pedestrian crashes with synthetic crashes, superimposing PCAM system performance on these historical crashes. Using this method and the limited data available, safety benefits estimates are presented at a high level.

For this study, objective testing was limited to only three production vehicle systems under six specific conditions. The performance of these three systems was not indicative of system performance for other vehicle systems using other technology. Furthermore, as the technology within PCAM systems continues to improve over time, these three systems may not be representative of all current or future technology. Moreover, the limited objective testing conditions may not take advantage of the full operational capabilities of these PCAM systems. Due to the unknown performance of PCAM systems in other scenarios (i.e., S2 and S3) and other conditions (e.g., adverse weather or minimal lighting conditions), it could not be assumed that PCAM systems will have a positive (or negative) safety benefit. Not being able to correlate testing conditions to historical crashes required this analysis to take a conservative approach and assume that a significant amount of crashes may not be addressed by a PCAM system (e.g., no safety benefit for crashes in the dark). Additionally, limited information on driver-vehicle interaction of these PCAM systems required this analysis to generalize the interaction with three simplified system logic approaches.

This paper summarizes a multi-year effort of data collection and analysis, as such this paper only describes the methodology and presents a portion of the entire data analysis [18]. The full report with data and analysis can be found at: https://www.nhtsa.gov/document/estimation-potential-safety-benefits-pedestrian-crash-avoidance-mitigation-systems

## REFERENCES

[1] National Center for Statistics and Analysis. (2018, March). Traffic Safety Facts: Pedestrians (Report No. DOT HS 812 493).Washington, DC: National Highway Traffic Safety Administration.

[2] National Center for Statistics and Analysis. (2018, September). Traffic Safety Facts: Summary of Motor Vehicle Crashes (Report No. DOT HS 812 580).Washington, DC: National Highway Traffic Safety Administration.

[3] Yanagisawa, M., Swanson, E., & Najm, W. G. (2014, April). Target Crashes and Safety Benefits Estimation Methodology for Pedestrian Crash Avoidance/Mitigation Systems (Report No. DOT HS 811 998). Washington, DC: National Highway Traffic Safety Administration.

[4] National Center for Statistics and Analysis. (2014, December). National Automotive Sampling System (NASS) General Estimates System (GES) Analytical User's Manual 1988-2013 (Report No. DOT HS 812 091). Washington, DC: National Highway Traffic Safety Administration.

[5] National Center for Statistics and Analysis. (2015, April). Fatality Analysis Reporting System (FARS) Analytical User’s Manual 1975-2013 (Report No. DOT HS 812 092). Washington, DC: National Highway Traffic Safety Administration.

[6] Swanson, E., Yanagisawa, M., Najm, W. G., Foderaro, F. & Azeredo, P. (2016, August). Crash Avoidance Needs and Countermeasure Profiles for Safety Applications Based on Light Vehicle-to Pedestrian Communications (Report No. DOT HS 812 312). Washington, DC: National Highway Traffic Safety Administration.

[7] Rosén, E., Källhammer, J.-E., Eriksson, D., Nentwich, M., Fredriksson, R., & Smith, K. (2010). Pedestrian Injury Mitigation by Autonomous Braking. Accident Analysis and Prevention, 42, 1949–1957.

[8] Fredriksson, R. (2015, January). Potential Head Injury Reducing Benefit of Combining Passive and Active Pedestrian Protection Systems [presentation]. 2015 SAE Government-Industry Meeting. Washington, DC.

[9] Shibata, E. (2015, January). Next Generation EyeSight® and Future Strategy [presentation]. Subaru. 2015 SAE Government-Industry Meeting. Washington, DC.

[10] Sherony, R. (2015, January). Pedestrian Pre-Collision System (PCS) Test Mannequin and Test Method Development [presentation]. Toyota. 2015 SAE Government-Industry Meeting. Washington, DC.

[11] Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., Lukuc, M., Simons, J., & Wang, J. (2014, August). Vehicle-to-Vehicle (V2V) Communications: Readiness of V2V Technology for Application (DOT HS 812 014). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

[12] Najm, W.G., and daSilva, M.P. (2000, May). Benefits Estimation Methodology for Intelligent Vehicle Safety Systems Based on Encounters with Critical Driving Conflicts. ITS America 10th Annual Meeting and Exposition. Boston, MA.

[13] McMillan, N.J., Christiaen, A.-C., & Stark, G.V. (2001, November). Estimating Safety Benefits for the IVI Generation 0 Field Operational Tests. Paper No. 01TB-59. 2001 SAE International Truck & Bus Meeting & Exposition. Chicago, IL.

[14] Blincoe, L., Miller, T.R., Zaloshnja, E., & Lawrence, B.A. (2015, May). The Economic and Societal Impact of Motor Vehicle Crashes, 2010 (Revised) (DOT HS 812 013). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

[15] Albrecht, H. (2017, January). Objective Test Procedures for Pedestrian Automatic Emergency Braking Systems [presentation]. 2017 SAE Government-Industry Meeting. Washington, DC.

[16] Olson, P.L., Cleveland, D.E., Fancher, P.S., Kostyniuk, L.P., & Schneider, L.W. (1984, June). Parameters Affecting Stopping Sight Distance. NCHRP Report No. 270. Washington, DC: Transportation Research Board (TRB).
[17] Kiefer, R.J., Cassar, M.T., Flannagan, C.A., Jerome, C.J., & Palmer, M.D. (2005, August). Surprise Braking Trials, Time-to-Collision Judgments, and "First Look" Maneuvers Under Realistic Rear-End Crash Scenarios (DOT HS 809 902). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.
[18] Yanagisawa, M., Swanson, E., Azeredo, P., and Najm, W.G. (2017, April). Estimation of Potential Safety Benefits for Pedestrian Crash Avoidance/Mitigation System (Report No. DOT HS 812 400). Washington, DC: National Highway Traffic Safety Administration

## ACRONYMS

| | |
|---|---|
| **AEB** | automatic emergency braking |
| **CP** | crash probability |
| **EM** | exposure measure |
| **FARS** | Fatality Analysis Reporting System |
| **FOV** | field of view |
| **GES** | General Estimates System |
| **GIDAS** | German In-Depth-Accident-Study |
| **ITARDA** | Institute for Traffic Accident Research and Data Analysis |
| **MAIS** | maximum abbreviated injury scale |
| **NASS** | National Automotive Sampling System |
| **NHTSA** | National Highway Traffic Safety Administration |
| **OEM** | original equipment manufacturer |
| **PCAM** | pedestrian crash avoidance/mitigation |
| **PR** | police-reported |
| **SCI** | Special Crash Investigation |
| **TRC** | Transportation Research Center |
| **TTC** | time-to-collision |
| **V2V** | vehicle-to-vehicle |
| **VRTC** | Vehicle Research and Test Center |

## APPENDIX

***Figure 8. Detailed List of Variables Obtained from NHTSA'S SCI Team for 43 Vehicle-Pedestrian Crashes***

| Variable | Description |
|---|---|
| **Year** | Year of the crash |
| **State** | U.S. state of the crash |
| **# Ped. Involved** | Number of pedestrians hit by the vehicle |
| **Ped. Age Group(s)** | Age of the first pedestrian hit (years) – if multiple pedestrians, another field |
| **Ped. Injuries** | Pedestrian injury level on KABCO scale |
| **Weather** | Current weather at the time of the crash |
| **Lighting** | Lighting at time of crash (e.g., daylight, dark, dark w/ lighting) |
| **Road Surface Condition** | Coefficient of friction on road at the time of crash |
| **Speed Limit** | Posted speed limit on the road of the crash (km/h) |
| **Intersection?** | Did the crash occur at an intersection? (Y/N) |
| **Roadway Alignment** | Road alignment (e.g., straight, curve) |
| **Roadway Grade** | Roadway grade |
| **Traffic Control** | Traffic control at the crash location (e.g., lights, stop sign, none) |
| **Veh. Pre-Crash Man.** | Vehicle maneuver in the pre-crash scenario |
| **Veh. Avoidance Man.** | Vehicle attempted avoidance maneuver (e.g., brake, steer, brake and steer) |
| **Travel Lane #** | The vehicle travel lane (numbered left to right of driver) |
| **Veh. Speed** | Vehicle pre-crash speed (km/h) |
| **Veh. Speed Range** | Potential error range on the pre-crash vehicle speed (km/h) |
| **Distance from Ped.** | Vehicle distance from pedestrian when the pedestrian entered the road (m) |
| **Veh. Dist. Range** | Potential error range on vehicle distance from pedestrian (m) |
| **Driver Vision Obstructed?** | Was the driver's vision obstructed? |
| **Vision Obstruction** | What obstructed the driver's vision? |
| **Driver Eyes Off Road?** | Were the driver's eyes off the road? |
| **What Driver Looked At** | What was the driver looking at if the eyes were off the road? |
| **Ped. Man. Pre-Crash** | Pedestrian's pre-crash maneuver (e.g., crossing road, walking, jogging, standing) |
| **Ped. Avoidance Man.** | Pedestrian avoidance maneuver (e.g., walk, run, yell, none) |
| **Ped. Location Pre-Crash** | Pedestrian's pre-crash location |
| **Ped. Speed** | Pedestrian's movement speed (km/h) |
| **Ped. Direction** | Direction of pedestrian movement (left-right or right-left of vehicle) |
| **Ped. Vision Obscured?** | Was the pedestrian's vision obscured? |
| **Ped. Vision Obscured by?** | What obscured the pedestrian's vision? |
| **Ped. Impaired?** | Was the pedestrian impaired? (include description of impairment) |
| **Ped. Inattention?** | Was the pedestrian inattentive? |
| **Ped. Inattentive Because?** | Why was the pedestrian inattentive? |
| **Distance Away from Roadway** OR **Line of Sight of Car** | Vehicle distance from pedestrian when the pedestrian entered the road or was first visible (m) |
| **Location of impact** | Where the impact happened (e.g., roadway, crosswalk) |
| **Travel Lane Location of Impact** | The lane of impact (numbered from left to right of vehicle) |
| **Distance From Curb** | How far from the curb the impact happened (m) |
| **Before, Middle, After Int.?** | Did the impact occur before, inside of, or after the intersection? |
| **Area of Impact on Veh** | Part of the vehicle that made contact with pedestrian |
| **Distance Traveled by Veh.** | Vehicle distance from pedestrian when the pedestrian entered the road (m) |
| **Time Ped. Spends in Roadway** | Time the pedestrian spent in the roadway visible and in path of vehicle (s) |
| **Related Factors/Causal Factors** | Any related factors that may have contributed to the crash? |
| **PCAM Warning Helpful?** | Would a PCAM warning have been helpful for this crash? |
| **PCAM Automatic Braking Helpful?** | Would AEB have been helpful for this crash? |
| **PCAM Automatic Steer Helpful?** | Would automatic steering have been helpful for this crash? |
| **Summary** | Written description of the entire crash scenario |
| **Scene Diagram and photos** | Diagram of crash scene and picture of vehicle (contact area, damage) and scene (location) |
| **GPS Coord.** | GPS coordinates of the scene of the crash |
| **Impact Speed** | Vehicle impact speed (km/h) |
| **Final Rest v1 and p1** | How far the vehicle and pedestrian moved after impact until it came to a stop (m) |