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# A Demographic Analysis and Reconstruction of Selected Cases from the Pedestrian Crash Data Study

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## ABSTRACT

This study involves two areas of research. The first is the finalization of the Pedestrian Crash Data Study (PCDS) in order to provide detailed information regarding the vehicle/pedestrian accident environment and how it has changed from the interim PCDS information. The pedestrian kinematics, injury contact sources, and injuries were analyzed relative to vehicle geometry.

The second area presented is full-scale attempts at reconstruction of two selected PCDS cases using the Polar II pedestrian dummy to determine if the pre-crash motion of the pedestrian and vehicle could somehow be linked to the injuries and vehicle damage documented in the case.

## INTRODUCTION

In the mid-1970's, pedestrian fatalities in the U.S. reached nearly 8,000 per year [1]. Since then, automakers have incorporated more streamlined, less aggressive front ends into their new vehicle designs. Since then, pedestrian fatalities in the U.S. have steadily declined to less than 5,000 per year [1].

The National Highway Traffic Safety Administration (NHTSA) implemented the Pedestrian Crash Data Study (PCDS) to provide data on vehicle/pedestrian accidents (All acronyms used in this paper are described in the Abbreviations section at the end of this paper). The interim PCDS data was obtained through the National Automotive Sampling System (NASS) database. The interim PCDS analysis, consisting of 292 cases, was conducted by NHTSA from 1994 through 1996 [1]. The PCDS was actually conducted to update the Pedestrian Injury Causation Study (PICS), a similar study conducted in the late 1970's and early 1980's [2]. By 1998, the PCDS was updated to include data from 521 cases acquired at six sites across the United States [3,4]. The first part of this study describes the evaluation and comparison of the results from the interim PCDS dataset consisting of 292 cases and the final dataset of 521 cases (including the 292 from the original PCDS). The pedestrian kinematics, injury contact sources, and injuries documented in the updated PCDS were analyzed relative to vehicle geometric properties.

The second part of this study is full-scale sled testing that attempted to reconstruct two selected PCDS cases using the Polar II pedestrian dummy. Cases were selected based on information such as dummy size, vehicle availability, and conditions relevant to trends present in the PCDS. The objective was to determine if the pre-crash motion of the pedestrian and vehicle could somehow be linked to the injuries and vehicle damage documented in the case.

## UPDATED PCDS ANALYSIS

### BACKGROUND

The PCDS case information included the events of the crash, the vehicle and pedestrian interaction, and the resultant injuries. The PCDS gathered information from investigation teams, police reports, medical records, and interviews with the pedestrian, driver, and any witnesses to the accident. After all of the necessary information was gathered, the final case report was reviewed and recorded in the PCDS database [5].

Analysis of the PCDS database focused on several aspects of pedestrian and vehicle information, including proposals by the International Harmonization Research Activities (IHRA) pedestrian safety working group [1]. Pedestrian injury data was correlated to age, impact speed, vehicle contact regions and parts (injury sources), and other aspects of the pedestrian/vehicle collision environment. A thorough comparison was made between the interim PCDS (292 cases) and final PCDS (521 cases) results to evaluate how changes in vehicle geometry have affected the severity and location of injuries by using Statistical Analysis Software (SAS).

## METHODS

DATA PROCESSING

The PCDS data was obtained from the National Automotive Sampling System (NASS) PCDS database and the data was then manipulated with Statistical Analysis Software (SAS) [4,5]. Numeric results were input into spreadsheets to produce graphs describing the relationship between pedestrian injuries and vehicle parameters.

DEFINITIONS

Bumper height, hood height, bumper lead, hood length, lead angle, and wrap-around distance (WAD) are defined in Figure 1:

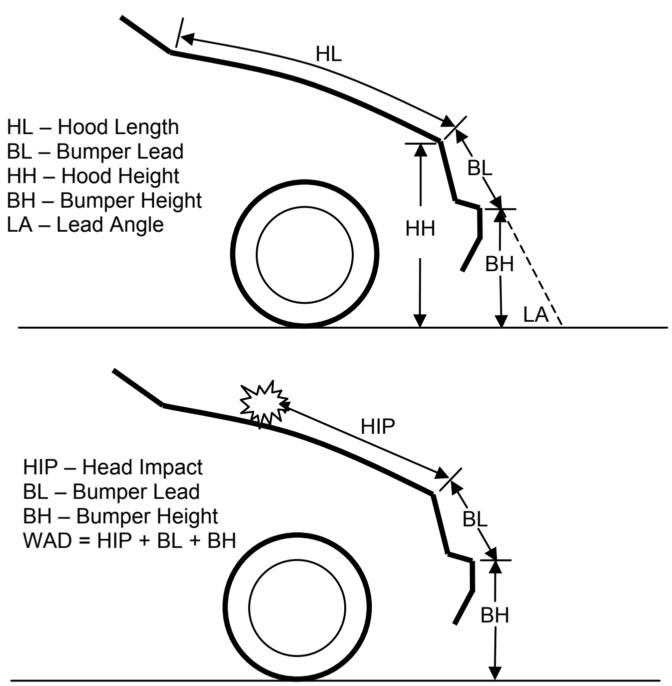


Figure 1: Definitions

VEHICLE AND DRIVER ANALYSIS

Vehicle parameters such as those described in the previous section, as well as vehicle make and category, were calculated and the results of the interim and final PCDS datasets were compared. In addition, collision situation parameters such as vehicle maneuvers prior to impact, number of travel lanes, alcohol involvement and impact speed were compared.

PEDESTRIAN ANALYSIS

Pedestrian characteristics such as gender, height, weight, age, maximum Abbreviated Injury Scale (AIS) injury (Table 1), and Injury Severity Score (ISS) were tallied for the interim and final PCDS and compared. As with the vehicle, collision environment information such as pre-impact motion of the pedestrian, pedestrian avoidance actions, and relative pedestrian orientation to the vehicle was also examined.

| AIS CODE | DESCRIPTION |
|---|---|
| AIS = 0 | No Injury |
| AIS = 1 | Minor Injury |
| AIS = 2 | Moderate Injury |
| AIS = 3 | Serious Injury |
| AIS = 4 | Severe Injury |
| AIS = 5 | Critical Injury |
| AIS = 6 | Maximum Injury |
| AIS = 7 | Injured, Severity Unknown |
| AIS = 9 | Unknown if Injured |

Table 1: AIS Code Description

INTERACTION OF PEDESTRIAN AND VEHICLE

The results of the vehicle and pedestrian analyses were compiled to get a more complete picture of the collision environment. Pedestrian motion in response to the impact, WAD versus reported impact velocity, injury severity/type versus vehicle contact source, and injury severity versus impact velocity were all evaluated for the final PCDS and compared with the interim PCDS.

FATALITY ANALYSIS

The influence of vehicle body type, impact velocity, pedestrian orientation relative to the vehicle, and pre-impact pedestrian motion on the occurrence and nature of pedestrian fatalities was examined and compared with the interim PCDS data.

STATISTICS

Student T-tests (significance level of 0.05) were done to compare mean values in the interim and final PCDS databases.

## RESULTS & DISCUSSION

VEHICLE ANALYSIS

Table 2 presents vehicle specifications from the interim and final PCDS analysis. The average model year of the vehicle involved did not significantly change ($p>0.05$), which explains why none of the hood and bumper measurements were significantly different than the interim PCDS analysis of 292 cases. Even though the increase was not statistically significant, the hood height increased by 5.9 percent, indicating the presence of more sport utility vehicles as well as minivans in the final database. Similarly, the lead angle was expected to be higher because of the presence of more high profile vehicles, but it did not increase significantly ($p>0.05$) since the interim PCDS data.

| | Interim PCDS (n=292) | | Final PCDS (n=521) | | Variatio |
|---|---|---|---|---|---|
| | **Mean** | **Std Dev** | **Mean** | **Std Dev** | |
| **Model Year** | 1992.8 | 2.1 | 1993.1 | 2.4 | 0.3 years |
| **Bumper Height** | 44.1 cm | 22.2 | 44.6 cm | 22.1 | 1.1% ↑ |
| **Hood Height** | 64.4 cm | 34.0 | 68.2 cm | 51.1 | 5.9% ↑ |
| **Bumper Lead** | 7.8 cm | 7.0 | 8.0 cm | 7.4 | 2.6% ↑ |
| **Hood Length** | 103.5 cm | 17.6 | 103.2 cm | 19.6 | 0.3% ↓ |
| **Lead Angle** | 66.9 deg | 19.3 | 67.2 deg | 17.6 | 0.4% ↑ |

Table 2: Average Vehicle Characteristics

The most common vehicle maneuvers prior to colliding with pedestrians are driving straight and turning left [3,4]. The frequency of accidents is much higher for vehicles turning left than those turning right. This perhaps is due to the driver's side A-pillar, which can more easily impede the driver's frontal view when making a left turn as opposed to a right turn. It may also be due to the considerably longer time it takes to complete a left turn maneuver than a right turn. The pedestrian hazard may not materialize until after the driver has made the decision to initiate the left turn. The driver having made the decision that it is safe to go may no longer be alerted to pedestrian hazards. Conversely, right turns are much shorter from the time the decision is made until the turn is negotiated, and the vehicle is not in the intersection as long as it would be in a left turn situation.

There were significant decreases in the vehicle speed categories of 9-16 km/hr and 25-32 km/hr from the interim PCDS data ($p<0.05$) (Figure 2), but the percentage of unknown vehicle speeds has increased, perhaps hiding instances in these speed categories.

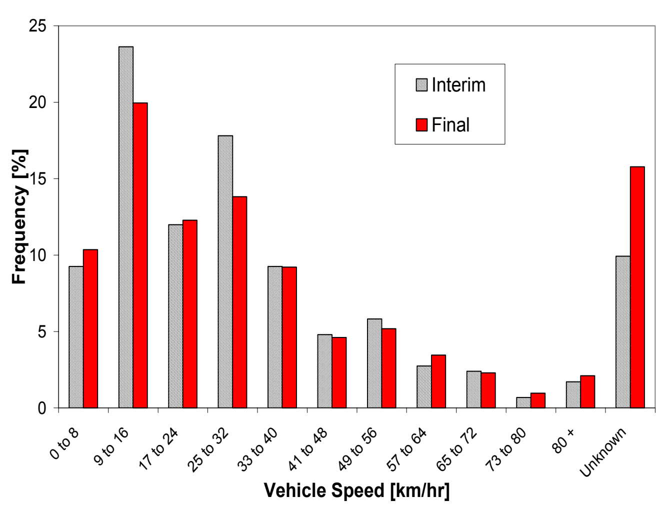


Figure 2: Vehicle Speed Distribution

PEDESTRIAN ANALYSIS

The interim PCDS analysis contained an even distribution between male and female pedestrians. However, the percentage of male involvement (51%) in the final PCDS analysis was slightly higher than the female percentage (49%) [3,4]. The average height (161 cm) and weight (63 kg) of pedestrians involved in the interim PCDS analysis and the final study were nearly identical [3,4]. The final PCDS dataset contained a significantly higher number of pedestrians in the 11-15 year old age group ($p<0.05$), jumping from 2% to 11% of the cases, as shown in Figure 3. It is unknown exactly why this abrupt increase has occurred, but it may be due in part to the paucity of the data in this age group. Additionally, this trend could perhaps reflect an increase in vehicle per person ratio, as individuals of legal driving age are more likely to be inside the vehicle than outside, thus reflecting the percentage decrease in crash involvement for ages 21 to 60. In the span of only a couple of years, however, it seems that this reason is unlikely.

The distributions of pedestrian pre-impact motion in the interim and final PCDS data were not significantly different from each other [3,4], with walking as the most common activity. Over 70% of pedestrians either stopped moving or did not react prior to getting hit as documented in witness and participant statements included in the case information [3,4]. Since the majority of pedestrians did not react much to the oncoming vehicle, testing using a stationary standing pedestrian dummy represents the typical situation in pedestrian collisions.

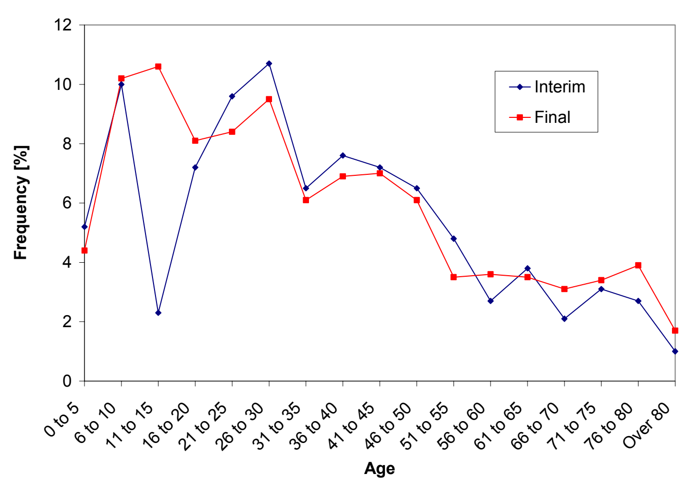


Figure 3: Pedestrian Age Distribution

Figure 4 indicates a large increase in the percentage of pedestrians carried by the vehicle. This number increased significantly from 32.5% to 44.8% ($p<0.05$) [3]. This change is reflected in the noticeable decrease in pedestrians knocked to the pavement (38.6% to 27.7%).

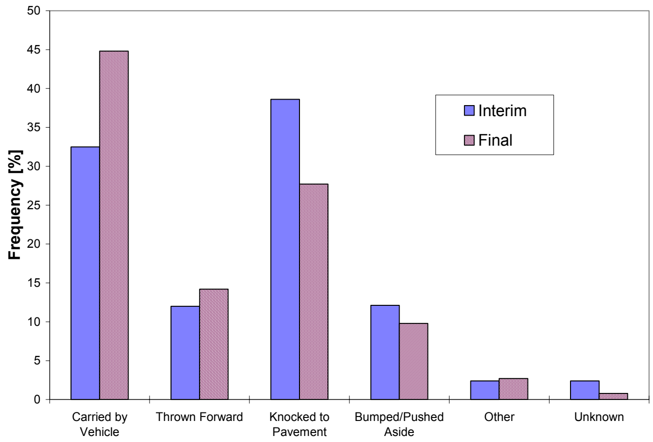


Figure 4: Post-Impact Pedestrian Motion [3,4]

The maximum AIS injuries suffered are shown in Figure 5. In the interim PCDS analysis with 292 cases, over 50% were AIS 1 and 11% were AIS 4 or higher [1]. While the frequency of MAIS 1-2 injuries has decreased by 14% (p>0.05), there has been an 8% increase in MAIS 4 and higher level of injuries (p>0.05). The reason for this increase in injury severity is unclear, but it may have to do with the popularity of sport utility vehicles (SUVs) in the last few years, which are more likely to cause broken ribs and fractured upper legs and hips because of their geometry. These injuries are AIS 3 and higher in many cases. The frequency of upper and lower extremity injuries has in fact increased, especially in the AIS 2 and higher severity ranges [1,3,4].

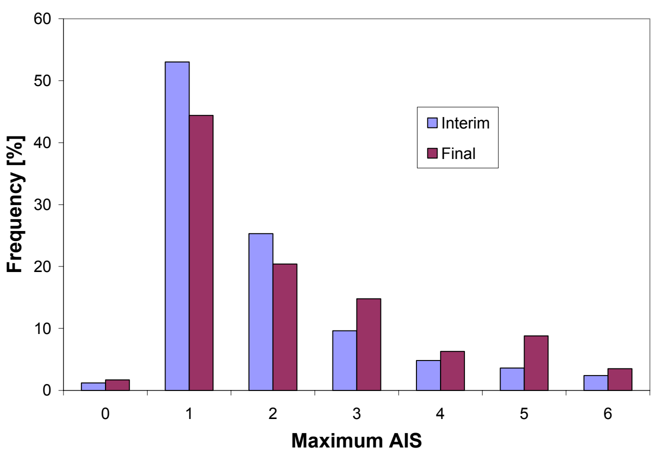


Figure 5: Maximum AIS Injury Suffered by Pedestrian

PEDESTRIAN-VEHICLE INTERACTION

The average 15 year old in the U.S. is 166 cm tall according to CDC growth charts, regardless of gender [6]. The wrap around distance (WAD) is influenced by vehicle impact speed, age, and stature [3]. In Figure 6, the average WAD for adults regardless of using age (>15 years) or stature (>166 cm) as the independent variable is 197 cm. The average WAD for children when using stature as the independent variable is 171 cm, which is larger than when using age (162 cm). This difference in WAD for adults and children reflects the need for concentrating on different areas of the vehicle, depending on whether a child or adult-sized test device is being used. For example, the windshield and A-pillars are important vehicle structures for adults, but not necessarily for children. The bumper and front end of hood are more prevalent injury-causing structures for ages 0-15.

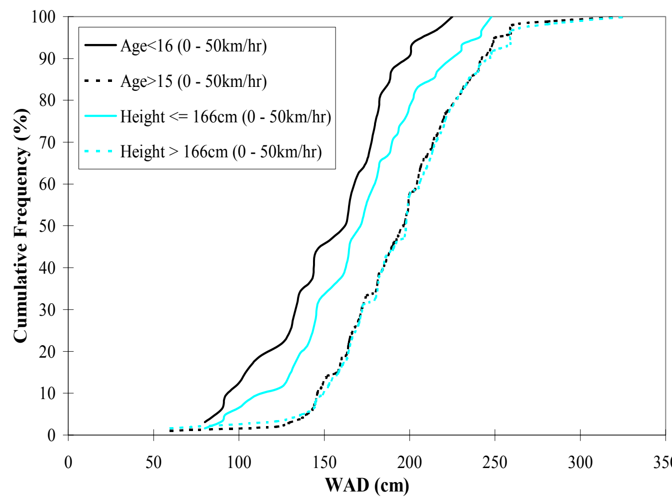


Figure 6: Child and Adult WAD by Age and Stature [7]

There were noticeable changes in the frequency of AIS 2 or greater injuries caused by the bumper and hood areas from the interim PCDS. The frequency of injuries caused by contact with the bumper decreased from 25.5% to 21.5% (p<0.05), while injury frequency due to hood surface contact increased by 4.5% (p<0.05). In the category of "environment" (road surface), the percentage was 20% of all AIS injuries but only 7% of cases with AIS 2 or greater [3]. This trend may have been caused by the lower ride height, cab-forward design, and the lower lead angle of more recent model vehicles resulting in less energy absorption by the leg and pedestrians being carried by the vehicle more frequently, as shown in Figure 4.

As in the interim PCDS, the most frequent injury regions were the head and lower leg (combined 50% of all injuries), most of which were caused by contact with the hood surface, windshield, and bumper areas of the vehicle [1,3,4].

The impact velocity curve of AIS 5-6 injuries for the final PCDS data showed lower percentages of these injuries for the same velocity than in the interim PCDS (Figure 7). As the average vehicle year had not changed significantly from the interim study, it seems that this change is mostly due to sparseness of data for high severity injuries. In fact, there were only 122 AIS 5-6 injuries out of 4,184 total injuries (3%) [3,4].

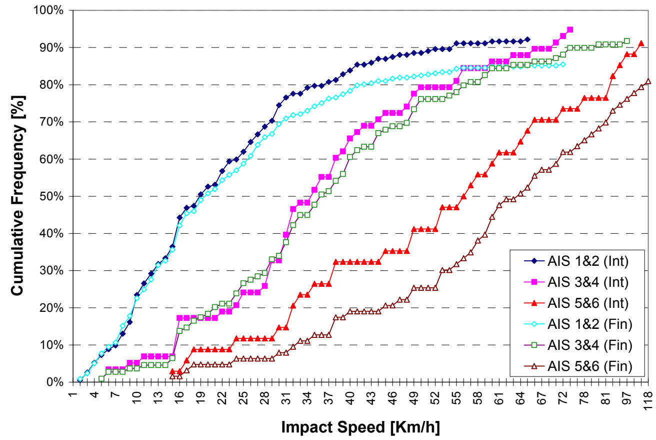


Figure 7: PCDS Impact Speed versus Injury AIS

FATALITY ANALYSIS

The percentage of SUVs involved in fatal cases increased significantly from 11% of the interim cases to 35% of the finalized 521 cases [3], while the percentages of automobiles (sedan and coupe), minivans, and pick-up trucks decreased significantly from the interim PCDS analysis ($p<0.05$) (Figure 8). Even though this change can perhaps be explained again by paucity of data (only 63 fatalities in the final PCDS), this significant increase illustrates the popularity of SUVs in recent years, as well as emphasizing the need to address pedestrian safety concerns with these types of vehicles.

There was a slight increase in the average impact speed of fatalities in the final PCDS analysis, but no significant changes occurred ($p>0.05$).

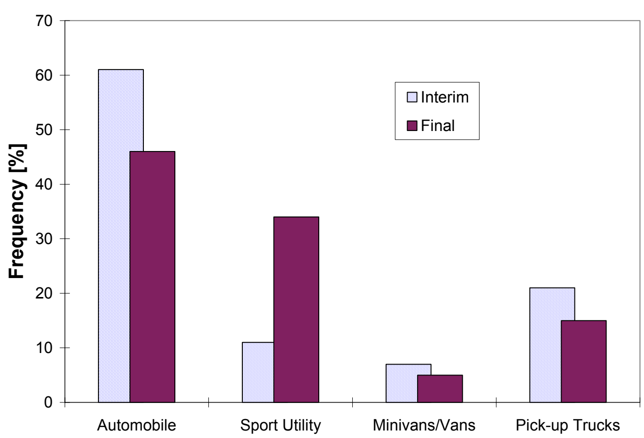


Figure 8: Vehicle Body Type Involvement (Fatalities)

There was a 38% decrease in the percentage of left-side pedestrian impacts in fatal cases (15 out of 28 fatal cases in the interim database but only 21 out of 63 fatal cases in the final database) [3,4], while the increases in the percentage of right side (28%), facing toward the vehicle (46%), and unknown orientations (39%) were also significant ($p<0.05$) (Figure 9). It is difficult to assess whether there really was a substantial decrease in left side impacts because of the eight additional unknown cases. Even with these cases added, there is a significant decrease in fatalities resulting from left side impacts. It is unclear why this trend has changed so much in the past few years.

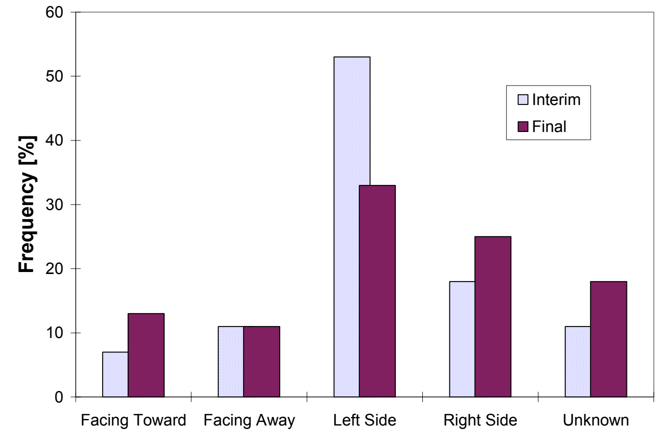


Figure 9: Fatally-Injured Pedestrian Body Orientation Relative to the Vehicle

The percentage of pedestrians walking increased from 39% to 51%, and there was a decrease in those running or jogging prior to being fatally injured ($p<0.05$) (Figure 10) [3,4]. It is unclear why this has changed so much since the interim PCDS, but it seems that the faster the pedestrian is moving laterally across the vehicle front, the less chance there is of receiving a direct fatal injury from one of the vehicle components. As discussed in Part II of this study, an increase in the height of the pedestrian center of gravity and lateral rate of motion relative to the vehicle front is more conducive to the pedestrian sliding across instead of impacting rigid front-end vehicle components.

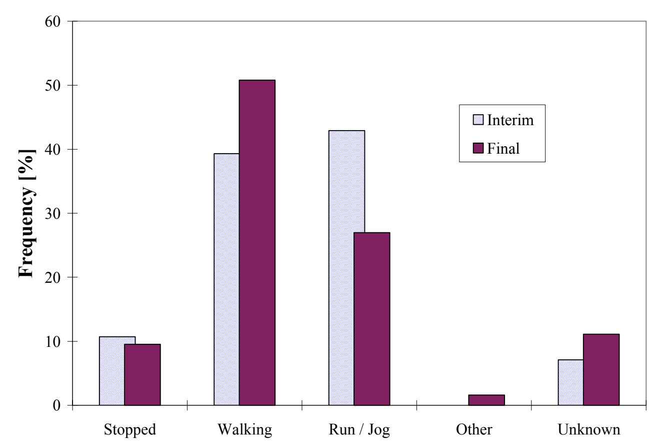


Figure 10: Pedestrian Motion (Fatalities Only)

## CONCLUSIONS

The first part of this study accomplished two major objectives. First, it has shown how vehicles, pedestrians, and their interactions have changed from the interim database (292 cases) to the final database (521 cases). Secondly, the current state of pedestrian collisions has been broken down and quantified. Due to the large number of pedestrian cases and situations, test procedures evaluating the aggressiveness of vehicle front ends should consider the common conditions present in these PCDS accidents. Using computer simulations, test conditions such as head impact speed, angle, and location can be determined based on the vehicle shape in question [7]. The following conditions sum up the present state of pedestrian/vehicle interactions and differences from the interim PCDS [3,4]:

- The average injuring vehicle front had a bumper height of 44.6 cm, hood height of 68.2 cm, bumper lead of 8 cm, hood length of 103.2 cm, and lead angle of 67.2 degrees.

- The most common vehicle motion prior to colliding with pedestrians is driving straight ahead on a two-lane road (one lane going each direction).

- The highest proportion of pedestrian impacts occurred between 9-16 km/hr (6-10 mph), and roughly two-thirds of all accidents occur at or below 40 km/hr (25 mph).

- Males (51%) were involved in slightly more pedestrian accidents than were females (49%).

- The average injured pedestrian regardless of gender was 34.3 years old, with a height of 161 cm and weight of 63.6 kg.

- Most pedestrian stances were walking with their left side facing the front of the vehicle and did not react prior to getting hit.

- New front-end designs are “carrying” instead of “running over” pedestrians, as shown by an increase in AIS 2 and greater upper leg and pelvis fractures.

- For Wrap Around Distance (WAD), stature is a better parameter than age for distinguishing children and adults. The average WAD for adults regardless of using age or stature as the independent variable is 197 cm. The average WAD for children is 171 cm when using stature.

- The most frequent AIS 2 and greater injury regions were head (32%) and lower leg (19%).

- Maximum AIS (MAIS) 1-2 injuries per case have decreased by 14%, while MAIS 3 and greater injuries have increased by that same percentage of total cases.

- The percentage of fatalities has increased from 9.5% to 12% of all cases, likely due to the increase in popularity of sport utility vehicles, which have aggressive front-end profiles toward pedestrians.

These characteristics were taken into account when selecting representative cases from the PCDS for reconstruction in full-scale dummy tests, as described in Part II of this study. These tests were done to demonstrate the experimental application of the collision information contained in the PCDS database.

## CASE RECONSTRUCTIONS

### BACKGROUND

In addition to updating the PCDS database and analyzing the current state of pedestrian/vehicle crashes in the United States, there is a need to apply this information to the improvement of vehicles. Full-scale sled testing provides a realistic view of the entire collision environment, and it can lend information toward the development of more realistic component-based test procedures [7].

Two cases involving low and high profile vehicle fronts were tested by using a 50$^{th}$ percentile size pedestrian dummy (Polar II, Honda R&D) [8]. A series of experimental collisions were conducted at varying impact speeds, angles, and pedestrian stances with vehicles representative of the various front-end profiles present on United States highways. The purpose was to study how these vehicle profiles, speeds, and pedestrian position parameters affect the resultant kinematics of the adult through the use of a post-mortem human subject (PMHS)-validated pedestrian dummy.

## METHODS

### POLAR II DUMMY

The Polar II dummy is a second-generation 50$^{th}$ percentile adult male pedestrian dummy (Figure 11). Table 3 shows the size of the dummy, which is identical to the size of a 50$^{th}$ percentile American male [8].

Figure 11: Polar II Pedestrian Dummy [8]

| | 50th Percentile American Male |
|---|---|
| Weight | 165.3 lb / 75 kg |
| Stature | 69 in / 175 cm |
| Sitting Height | 34.8 in / 88.4 cm |

Table 3: Polar II Dummy Stature [8]

The dummy was designed using THOR, the NHTSA Advanced Frontal Dummy, as a base model for its initial design [8]. The dummy was specified to be durable enough to handle up to a 50-km/hr impact [8], and it possessed the following instrumentation scheme:

| Location | Type | No. of Channels |
|---|---|---|
| Head C. G. | Accelerometer | 3 |
| Upper Neck | Load Cell | 3 |
| Lower Neck | Load Cell | 3 |
| Neck Spring | Load Cell | 2 |
| O.C. | Rotary Pot | 1* |
| Chest C. G. | Accelerometer | 3 |
| Lateral Ribcage | Rotary Pot | 3* |
| Lateral Abdomen | String Pot | 1* |
| Pelvis | Accelerometer | 3 |
| Femur | Load Cell | 4 |
| Femur | Lin. Accelerometer | 1 |
| Femur | Ang. Accelerometer | 1 |
| Upper Tibia | Load Cell | 4 |
| Upper Tibia | Lin. Accelerometer | 1 |
| Upper Tibia | Ang. Accelerometer | 1 |
| Lower Tibia | Load Cell | 3 |

*Not connected to on-board DAS
Total No. of Channels Available for Current Testing = 37
No. of Channels Connected to On-Board DAS = 32

Table 4: POLAR II Instrumentation [8]

## PCDS CASE SELECTION

Test vehicle selections were made based on the available vehicles on-site at the Vehicle Research & Test Center (VRTC) facility. To observe the extremes of pedestrian collisions, two types of vehicle were considered for full-scale sled tests: low profile automobiles and high profile vehicles (SUV, trucks, minivans).

The following criteria were used in selecting the cases:

- Adequacy of case documentation (photographs of vehicle damage, injury descriptions, diagrams, etc)
- Approximate pedestrian weight and stature of 50th percentile male
- Impact velocity in the range of 30-50 km/hr

After applying the above criteria, the two cases selected included a low profile vehicle, the Honda Civic coupe, and the Chevrolet Silverado, a pick-up truck with a high profile.

## LOW PROFILE CASE INFORMATION

Table 6 contains the Honda Civic case information:

| | |
|---|---|
| **PSU :** | 82 |
| **Case No. :** | 651P |
| **Accident Year:** | 1996 |
| **Description of Pedestrian:** | |
| **1. Age :** | 34 |
| **2. Gender :** | Male |
| **3. Pedestrian's Height :** | 178 cm (5 ft 10 in) |
| **4. Pedestrian's Weight :** | 75 kg (165 lbs.) |
| **Description of Vehicle :** | |
| 1. Class of Vehicle : | Compact |
| 2. Year / Make / Model : | 1992 / Honda / Civic (2 Dr coupe) |
| **Description of Injury patterns and Vehicle damages :** | |
| 1. AIS : | 1 |
| 2. Injury Source : | Windshield |
| 3. Speed Limit : | 48 kph (30 mph) |
| 4. Impact Speed : | 46 kph (29 mph), [Accuracy range of impact speed ; 2 - 8 kph] |
| 5. Damage Plane : | Front (dents, smears and scuffs as well as smashed holed windshield) |
| 6. Impact Angle : | 17-20 degree |
| **Descriptions of Accident:** | |
| Vehicle one was eastbound in lane one of a 5 lane, two way street, the only lane to travel straight through an intersection. A pedestrian was running in the crosswalk which angle southeasterly across the street. The front of vehicle one impacted the right and backside of the pedestrian. The pedestrian wrapped and struck the windshield and flipped to the right side as vehicle one continued and then stopped in the middle of the intersection. It happened in clear daylight. | |

Table 6: Honda Civic Case Information [9,10]

Figure 12 shows that the longitudinal travel distance of the pedestrian from leg-to-bumper contact to head impact across the vehicle front was 164 cm, and the lateral distance between these two points was 55 cm. The resulting angle is 18.5 degrees [9], and this angle was used as the rotation of the vehicle on the sled buck since the motion of the sled was linear [9]. A tolerance of three degrees rotation was allowed in each direction in case the angle had to be adjusted to facilitate a change in the resulting pedestrian path and vehicle damage. The sled buck was thus fabricated to allow an impact angle between the pedestrian and Honda Civic to be 15.5 to 21.5 degrees [9].

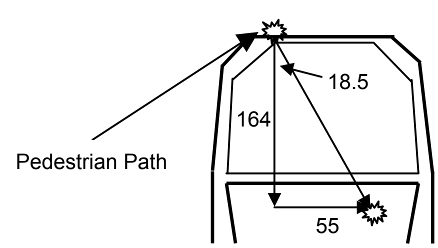


Figure 12: Rotation of Vehicle on Sled

Figure 13 outlines the injuries suffered by the pedestrian in the case:

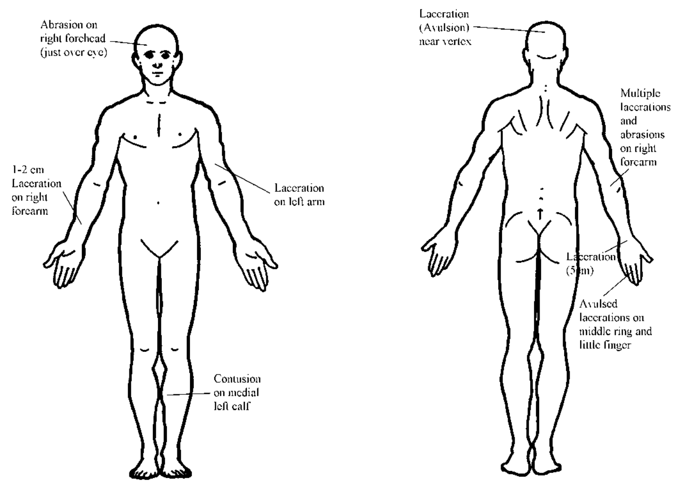


Figure 13: Soft Tissue Injuries [10]

The vehicle contact point descriptions are detailed in Figure 14 and Table 7. These points were marked on the test vehicles so the proximity of test vehicle damage marks could be compared with the case damage [9].

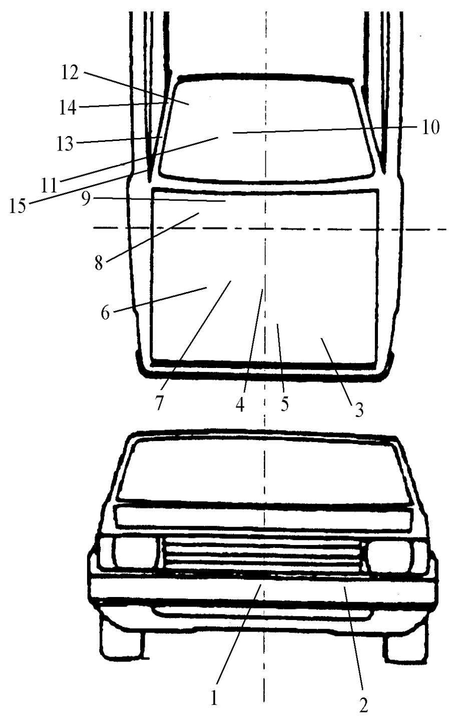


Figure 14: Vehicle Exterior Damage Patterns [10]

| Label | Component Contacted | Longit. Location (X) | Lateral Location (Y) | Crush [cm] | Suspected Body Region | Supporting Physical Evidence |
|---|---|---|---|---|---|---|
| 1 | License Plate | 94 | 0 to -10 | 0 | Left leg | Scuffed at top bumper |
| 2 | Bumper | 94 | -30 | 0 | Right shoe | Scuffed |
| 3 | Hood | 76 | -20 | 0 | Right shoe | Rubber transfer |
| 4 | Hood | 48 | 2 | 0 | Right shoe | Rubber transfer |
| 5 | Hood | 73 | -5 | 0 | Right shoe | Curve rubber transfer |
| 6 | Hood | 30 | 35 | 0 <= 1 | Left knee | Small dent |
| 7 | Hood | 12 | 22 | 0 <= 1 | Hip region | Wide area of scratch |
| 8 | Hood | -6 | 42 | 0 <= 1 | Hip region | Streak & minor dents |
| 9 | Hood | -22 | 38 | 0 | Hip / Legs | Curved scratch marks |
| 10 | Windshield | -70 | 28 | 5 - 10 | Right arm | Skin / Tiny hair |
| 11 | Windshield | -71 | 58 | | Right arm | Blood |
| 12 | Windshield | -103 | 55 | 3 - 5 | Head | Hair / Skin blood |
| 13 | A-pillar | -77 | 70 | 0 | Right arm | Lateral scratch streaks |
| 14 | A-pillar | -116 | 58 | 0 | Head | Lateral scratch streaks |
| 15 | Side mirror | -79 | 88 | 0 | Arm | Scuffed |

Table 7: Vehicle Contact Locations and Descriptions [10]

HIGH PROFILE CASE INFORMATION

As Table 8 describes below, the pedestrian's weight and height varied slightly from the dummy size, but not significantly. Additionally, unlike the Honda Civic case, the high profile vehicle case with the Chevrolet Silverado reported a straight-on impact angle [9].

| | |
|---|---|
| **PSU :** | 90 |
| **Case No. :** | 628P |
| **Accident Year:** | 1998 |
| **Description of Pedestrian:** | |
| **1. Age :** | 77 |
| **2. Gender :** | Female |
| **3. Pedestrian's Height :** | 169 cm (5 ft 6.5 in) |
| **4. Pedestrian's Weight :** | 71 kg (155 lbs) |
| **Description of Vehicle :** | |
| 1. Class of Vehicle : | Large Pick-up |
| 2. Year / Make / Model : | 1991 / Chevrolet / Silverado (1500 series, regular 2WD) |
| **Description of Injury patterns and Vehicle damages :** | |
| 1. AIS : | 4 |
| 2. Injury Source : | Hood edge (straight path accident) |
| 3. Speed Limit : | 64 kph (40 mph) |
| 4. Impact Speed : | 50 kph (31 mph), [Accuracy range of impact speed ; < 2 kph] |
| 5. Damage Plane : | Front (dents, smudges and scratches on hood surface as well as cracked front hood) |
| 6. Impact Angle : | 90 degree |
| **Descriptions of Accident:** | |
| Vehicle one was eastbound in lane 2. The pedestrian was running across the road in a southerly direction carrying a bag filled with empty aluminum cans. The vehicle struck the pedestrian, who then rotated partly onto the hood and rolled off as the vehicle applied brakes. According to a witness, the pedestrian ran into the path of vehicle one and the vehicle did not have enough time to stop (brake was applied). It happened in clear daylight (11:05 AM) | |

Table 8: Chevrolet Silverado Case Information [11]

Figures 15-17 describe the large number of injuries suffered by the pedestrian in the case. There were numerous injuries both externally and internally, with the most severe (highest AIS) injury being several broken ribs and a bruised lung [11].

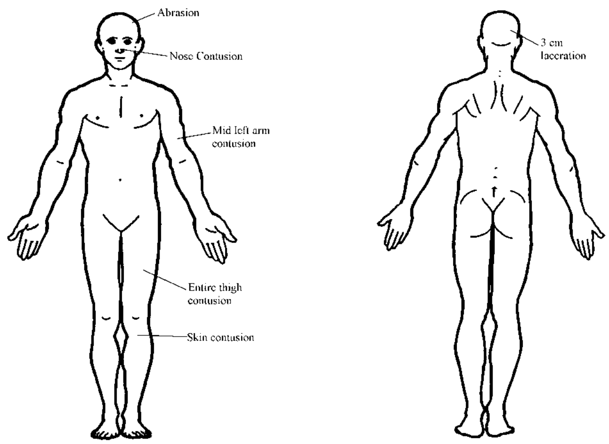


Figure 15: Soft Tissue Injuries [11]

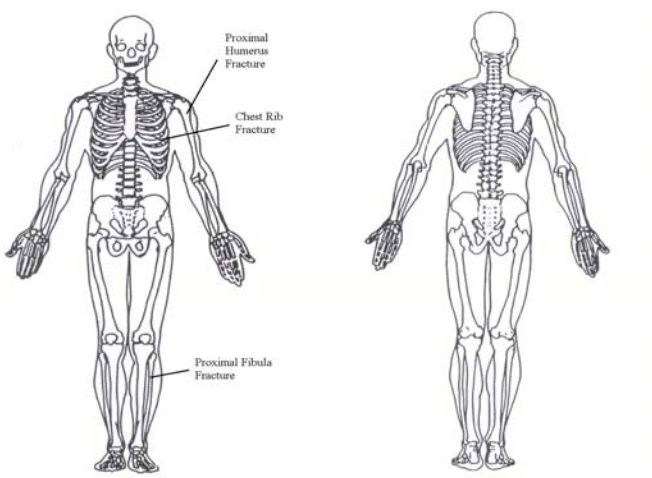


Figure 16: Skeletal Injuries [11]

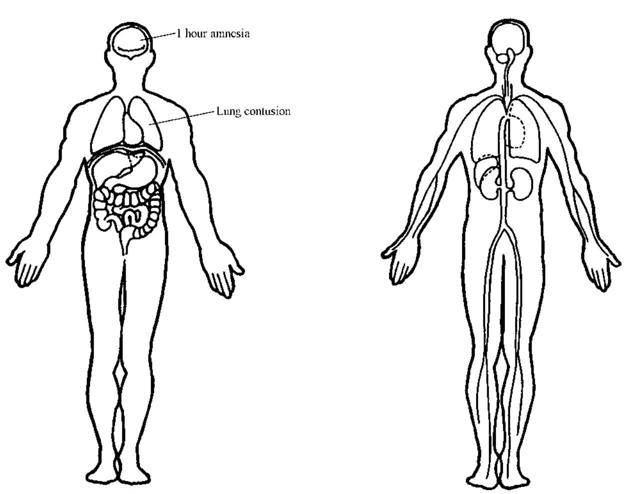


Figure 17: Internal Injuries [11]

Using the same method as for the Honda Civic case, the vehicle contact points were marked on the test vehicle according to the post-accident damage on the vehicle to provide an accurate comparison with data from the sled tests (Figure 18 and Table 9).

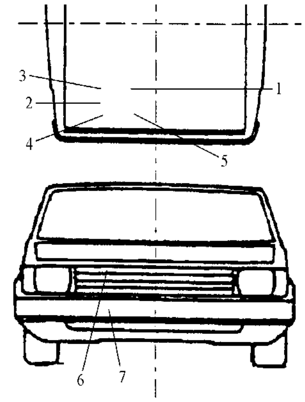


Figure 18: Vehicle Exterior Damage Patterns [11]

| Label | Component Contacted | Longitudinal Location (X) | Lateral Location (Y) | Crush [cm] | Suspected Body Region | Supporting Physical Evidence |
|---|---|---|---|---|---|---|
| 1 | Hood | 21 | 29 | 2 | Shoulder | Dent |
| 2 | Hood | 49 | 55 | 2 | Shoulder | Dent |
| 3 | Hood surface | 20 | 55 | 2 | Chest | Dent |
| 4 | Hood surface | 70 | 51 | 2 | Chest | Dent |
| 5 | Hood surface | 73 | 24 | 2 | Chest | Dent |
| 6 | Grill | 95 | 36 | 0 | Hip | Cracked |
| 7 | Bumper | 137 | 36 | 0 | Left leg | Scuff |

Table 9: Vehicle Contact Descriptions [11]

## 1991 vs. 1999 SILVERADO DESIGN COMPARISON

The actual year of the vehicle involved in the Silverado collision was a 1991 model. The actual testing vehicle available at VRTC was a 1999 Chevrolet Silverado. Therefore, exterior body frame measurements and the location of under-hood components were compared using photographs and measurements to check the feasibility of performing the tests with the 1999 Chevrolet Silverado instead of the 1991 model. There were slight differences between the hood angle and bumper height of the two models, but it was concluded that the differences were not large enough to refrain from using the 1999 model in the test series.

## FULL-SCALE DUMMY HYGE SLED TESTS

The HYGE sled test facility at Transportation Research Center, Inc. (TRC) in East Liberty, OH was used to conduct the tests. Five iterative tests were performed with each vehicle using a 10-g sled pulse to achieve the required impact velocity [9]. The number of five tests was chosen for two reasons. First, the dummy was only available for a short amount of time. Secondly, it was estimated that five iterative attempts to get a close approximation of the accident would be sufficient [9]. Dummy position parameters were changed between tests based on the results of the previous iteration to adjust the path and damage to the vehicle and pedestrian.

Since the pedestrian dummy was only instrumented on the left side, the low profile case had to be reconstructed as a mirror image because the pedestrian was hit on the right side [9]. Since the exterior body of the vehicle was symmetric laterally, this was not seen as detrimental to the resulting kinematics.

In preparation for the sled attachment, both of the test vehicles were cut behind the B-pillar and the interior compartment was emptied to reduce the weight of the vehicle (the under hood components were kept intact). The vehicle was rigidly attached to a buck via a circular steel interface plate. Because the vehicle was offset from the track, as shown in Figure 19 [9], a ballast equal to the vehicle weight was attached on the opposite side of the track to balance the buck-vehicle assembly and reduce torsion effects. A net was attached to the buck over the sled to prevent the dummy from getting caught in the sled.

Figure 19: Pedestrian Case Reconstruction Test Setup

The damage locations from the actual cases were marked on the test vehicles prior to the tests in order to facilitate comparison of the damage patterns.

Figure 20: Measurement Reference Lines for Civic (above) and Silverado (below) [9]

Prior to each test, detailed measurements of the dummy stance were made to ensure that the dummy positions were the same for each test, except for changes made between tests to get a more accurate reconstruction of the case. Different colors of chalk were applied to the left side of the dummy to distinguish which area of the dummy contacted which portion of the vehicle in post-test analysis. These body areas included the head, arm, lumbar/pelvis, upper leg, and lower leg. Photographic targets were placed on important body landmarks for trajectory analysis (Figure 21).

The dummy was held in a standing position by a magnetic holding device that was triggered to release just prior to impact of the dummy by the vehicle so that the entire weight of the dummy was on the ground and downward acceleration of the dummy was minimal [9].

Figure 21: Target and Dummy Stance [9]

## RESULTS & DISCUSSION

HONDA CIVIC (LOW PROFILE)

In the Honda Civic tests, the third test out of five was most similar to the actual collision in terms of injury measurement levels, vehicle damage patterns, and the trajectory of the dummy. In Figure 22, the dotted white line indicates the region of vehicle damage, while the chalk on the hood and cracks on the windshield show that the test damage falls within this region. The head injury criteria (HIC) value was representative of an AIS 1 injury (688), which was the level suffered by the pedestrian in the case, and the WAD was 239 cm (9 cm short of the case WAD of 248 cm) [9].

Figure 22a: Civic Test

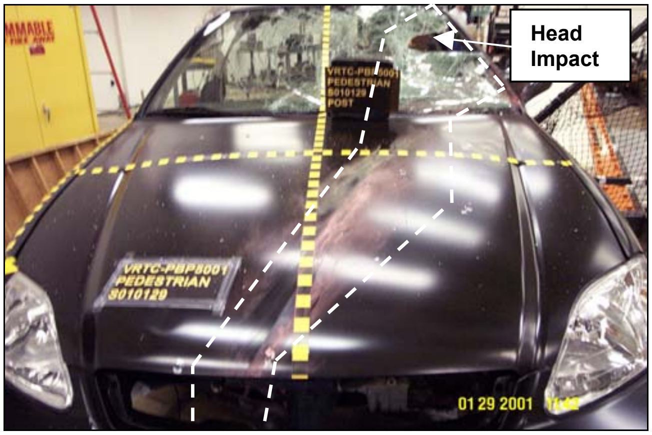


Figure 22b:  Pedestrian Path of Civic Case vs. Test 3 [9]

It was found that the dummy stance was a major factor influencing damage patterns to the vehicle as well as dummy injury severity measurements (Figure 23 and Table 10).  The dummy struck-side leg position controlled the rotation of the dummy following initial impact.  Since the back of the pedestrian's head was injured in this case, it was determined that the dummy's left leg had to be in front of the right to get the proper rotation.  This was accomplished by rotating the dummy so that it was facing slightly away from the vehicle, which could have been the case given the relative angles of travel of the vehicle and pedestrian [9].

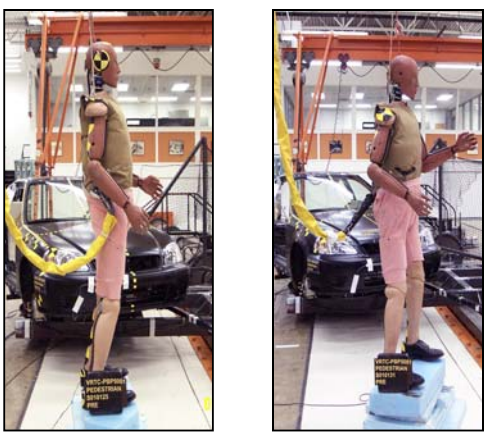

Figure 23: Dummy Stances; Legs Even (Left) and Rotated Away/Increase in Height (Right)

| Test | Stance | Elevation (inches) | Head Injury* | Match Path? | WAD (cm) |
|---|---|---|---|---|---|
| 1 | Legs Even | 10.6** | AIS 5-6 | No | 182 |
| 2 | Legs Even | 17.0 | AIS 3-4 | No | 222 |
| 3 | Rotated Away | 16.0 | AIS 1-2 | Yes | 239 |
| 4 | Rotated Away | 17.0 | AIS 3-4 | No | 216 |
| 5 | Rotated Away | 16.3 | AIS 5-6 | No | 221 |

*Estimated AIS 1-2 corresponds to HIC of 0-800, AIS 3-4 is HIC of 800-1500, and AIS 5-6 is HIC above 1500 [9]
**Calculated ground level in the case

Table 10:  Civic Test Results [9]

The elevation of the dummy off the ground was another major factor in dictating the WAD (impact point of the head) [9].  The initial test was performed with a dummy elevation of 10.6 inches off the ground (the dummy had to be raised because the vehicle was raised).  The height was calculated by the matching the pedestrian height and bumper height of the Honda Civic.  In this initial test, the dummy slammed down upon the hood and made two deep dents, which was very different from the actual Civic case.  The actual case had many scuffmarks instead of dents, indicating that the pedestrian slid over the surface of hood.  The WAD was much too low as well, so the elevation of the dummy was raised about 6 inches to simulate jogging, which includes a portion of the gait cycle when both feet are off the ground. This resulted in WAD measurements very similar to that of the actual case [9].  An increase in relative height of the pedestrian could have also occurred due to pre-impact braking, which was not noted in the case information [9].

It was indicated in Part I of this study that the impact velocity influenced the WAD.  Although the impact speeds for all five tests were the same, the WAD varied between 182 and 239 cm.  This shows that WAD depends not only on the impact speed of actual cases, but can also be affected by the pedestrian stance, elevation off the ground, and pre-impact motion [9].

CHEVROLET SILVERADO (HIGH PROFILE)

The documented impact velocity in this case was about 50 km/hr, but the dummy manufacturer had concerns about the durability of the dummy in high speed, high vehicle profile impacts [9].  Because this prototype dummy was needed for other testing immediately following this test series, lower impact speeds of 20 and 25 km/hr were applied in this test series. Using estimated linear relationships of trajectories and injuries with impact velocity, results were extrapolated to 50 km/hr to get a comparison with the case.  Because of this indirect comparison, more emphasis was put on how changes in stance and velocity affected the kinematics of the dummy [9] than injury replication.  The third test was closest to the case both in terms of damage patterns on the vehicle and the path of the dummy (Figure 24).

Figure 24a: Silverado Test

Figure 24b: Damage of Silverado Case vs. Test 3 [9]

For these tests, three dummy stances were used (Figure 25), incorporating combinations of two different leg positions (legs even, right leg in front of right) and two arm positions (bent in front at elbow, wrists tied in front). The “right leg in front” configuration modeled a walking pedestrian. The reason for tying the wrists together in one arm configuration is to negate the effect the arms would have on the kinematics. The effect of these stances and changing velocity on WAD and estimated injury levels (Tables 11 and 12) was evaluated. The elevation of the dummy was consistent from test to test because the tests were done at lower velocities than the case warranted.

Figure 25: Silverado Test Dummy Stances for Tests 1 (Left), 2 and 4 (Middle), and 3 and 5 (Right)

| # | Legs | Arms | Velocity (km/hr) | WAD (cm) |
|---|---|---|---|---|
| 1 | Legs Even | Bent 90 Deg at Elbow | 20 | 145 |
| 2 | Right Leg in Front | Bent 90 Deg at Elbow | 20 | 142 |
| 3 | Right Leg in Front | Wrists tied in front of body | 20 | 139 |
| 4 | Right Leg in Front | Bent 90 Deg at Elbow | 25 | 149 |
| 5 | Right Leg in Front | Wrists tied in front of body | 25 | 147 |

Table 11: Silverado Test Results [9]

| Case Injury | Dummy Measurement Extrapolated to 50 km/hr[1] | Estimated Injury |
|---|---|---|
| Proximal Tibia Fracture | 2700 N Tibia Shear, 490 N-m Tibia Bending Moment | AIS 2-3 Heavy Ligament Damage or Fracture[2] |
| 5 Fractured Ribs | 180 g Chest Acceleration | AIS 3-5 Injuries to the Chest Area[3] |
| Bruised Lung | 180 g Chest Acceleration | AIS 4 Internal Organ Contusion or Rupture[3] |
| AIS 2Head Contusion | 4500 HIC | Fatal (AIS 6) Blow to the Head[4] |

[1]Using linear fitting of 20 and 25 km/hr peak data [9]
[2]The bending mode shear damage threshold is 1600 N, and the shear moment threshold is 350-400 N-m according to Kajzer [12]
[3] The chest injury threshold using acceleration is estimated to be approximately 60 g [13]
[4]Anything over 1000 HIC is generally considered to be a serious head injury [9]

Table 12: Estimated Dummy Measured AIS≥2 Injuries

The test results for the head were quite different from the actual case results. The pedestrian received an AIS 2 contusion while extrapolated dummy results indicated a HIC of 4500. While this discrepancy may be partially do to the assumption of linearity between velocity and HIC, the dummy’s upper body may be too stiff causing the dummy to rotate and the head to strike the hood of the Silverado before the shoulder and torso can absorb the majority of energy [9]. Another theory is that pre-impact braking of the vehicle could have increased the amount of time between initial contact with the body and head impact, allowing the upper body to decrease kinetic energy of the head.

There was good agreement between the case and estimated test injury levels for the tibia and chest, indicating that the dummy responded to the high profile impact in a human-like manner. A linear relationship between injury levels and impact velocity provided an estimation of these injuries. Regardless of whether a linear or non-linear approximation was used, the measurements at low velocity were close enough to published injury thresholds to assume injury at 50 km/hr. Figure 26 gives an example of how the tests at two velocities were used to estimate the measurements at the case impact velocity of roughly 50 km/hr.

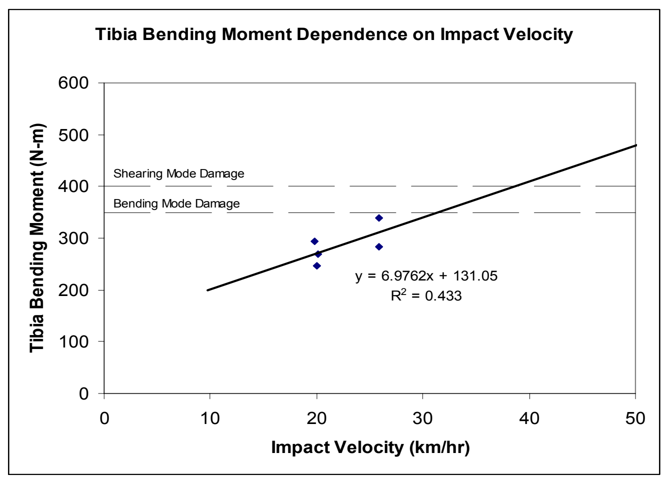


Figure 26: Extrapolation of test results to 50-km/hr

As was expected with the minimal change in velocity and constant pedestrian height relative to the vehicle, the WAD was very consistent. The WAD of the Chevrolet Silverado remained between 139 and 149 cm [9]. There was a slight increase in WAD with increasing velocity, and there was also a slight decrease in WAD when the wrists were tied together for both velocities, although the small number of samples prevents a statistical conclusion. It is not clear why this change occurred, but a possible reason for this small decrease in WAD may be that free arms would reduce the effective mass and allow the dummy to travel a bit further [9]. The wrists separated almost immediately from the force of impact, however, and it is doubtful that in that short of time the arms could make a substantial difference in WAD.

## CONCLUSIONS

It was very difficult to reconstruct the two pedestrian cases for two main reasons. First, the case information is only an estimation of the impact situation. A large amount of uncertainty is contained in the collision documentation, and approximation is required to evaluate the accuracy of the reconstruction in terms of pedestrian motion and injuries. Secondly, while the Polar II dummy trajectories have been validated with human cadaver corridors in the Civic case, uncertainties in its durability in high front-end profile vehicles such as the Silverado prevented an exact replication of the impact speed. Even though these difficulties existed, there were some good results that reflected and supported information contained in the PCDS database.

The relative position of the right and left legs and orientation of the pedestrian relative to the vehicle dictates the rotation of the pedestrian and location of body contact with the vehicle. The relative positions of initial contact (usually bumper) and pedestrian center of gravity dictate the wrap-around-distance (WAD), and subsequent vehicle structures that are impacted. Lower bumper height by design or from pre-impact braking, as well as pedestrian activity such as jogging (when the pedestrian is elevated off the ground) are conducive to sliding onto and being carried by the vehicle. In this situation, impact energy is dissipated due to sliding, and by the time the head reaches the windshield, the relative velocity of the pedestrian to the vehicle is low, thereby decreasing injury severity. The occurrence of this situation has increased in the finalized PCDS (Figure 4), which shows that a combination of lower bumpers and possibly more responsive braking systems have been developed in newer automobiles.

WAD increased slightly with increasing velocity in high front-end profile vehicle tests and the occurrence of an AIS 2-3 level leg injury was caused by the high profile impact. This situation reflected the trend in the final PCDS database toward more severe leg injuries. There was also a hint of arm position affecting WAD (increasing WAD when the wrists were tied), but the small sample size prevented any firm conclusion.

The relationships of pre-impact conditions with resulting impact parameters such as pedestrian reaction, motion, and injuries are vital because they can be applied directly to the design of less aggressive vehicle fronts. From an efficiency standpoint, use of a mathematical model would be ideal for reconstructing a large number of accidents. However, full-scale sled tests give the most realistic view for determining these relationships, and the method presented here allows the application of many pedestrian stances and a large number of vehicle shapes and sizes.


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## ABBREVIATIONS

| | |
|---|---|
| PCDS | Pedestrian Crash Data Study |
| NHTSA | National Highway Traffic Safety Administration |
| NASS | National Automotive Sampling System |
| PICS | Pedestrian Injury Causation Study |
| IHRA | International Harmonization Research Activities |
| SAS | Statistical Analysis Software |
| WAD | Wrap Around Distance |
| AIS | Abbreviated Injury Scale |
| ISS | Injury Severity Score |
| MAIS | Maximum AIS |
| SUV | Sport Utility Vehicle |
| CDC | Centers for Disease Control |
| PMHS | Post Mortem Human Subject |
| VRTC | Vehicle Research and Test Center |
| HIC | Head Injury Criteria |

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