PEDESTRIAN HEAD IMPACT TESTING AND PCDS RECONSTRUCTIONS

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ABSTRACT

Pedestrian research and testing at the NHTSA Vehicle Research and Test Center has recently focused on assessment of proposed ISO and EEVC head impact test procedures, and extension of these procedures to additional vehicle frontal surfaces. In addition to test parameter sensitivity evaluation, reconstruction of PCDS (Pedestrian Crash Data Study) cases with laboratory impact tests and computer simulations has been conducted. This paper presents the results of this research.

INTRODUCTION

About 5,000 pedestrians are killed in motor vehicle accidents each year in the United States, and approximately 69,000 others are injured. This accounts for 13% of the nation's total traffic fatalities and 5% of injuries (FARS, NASS, GES). The proportion of pedestrian fatalities is a greater concern in many other countries, such as Japan, where pedestrians account for nearly 27% of total traffic fatalities, and in Europe, where the percentage reaches nearly 30% in the United Kingdom [1]. For AIS 2-6 injuries reported in Japan, Europe, and the United States, the head region constitutes the highest percentage of all injuries (30.5%) [2]. Furthermore, there is a difference between children (ages 15 and lower) and adults (over 15) in terms of impact location distribution (wrap around distance) and relationship between AIS level and impact velocity [2]. This exhibits the need to evaluate head injuries by using both child and adult-sized headforms to measure head decelerations resulting from impacts to vehicle structures.

Many countries and automotive manufacturers have recently been concerned with ways to reduce these numbers. The European Experimental Vehicles Committee (EEVC) has recently proposed regulations that would require all vehicles sold in Europe to pass tests designed to assess the potential for injury to pedestrians [3,4]. These component test procedures include simulated head impacts to the hood, lower leg impacts to the front bumper, and upper leg impacts to the leading edge of the hood. The International Organization of Standardization (ISO) has also proposed similar testing procedures, consisting of head and lower leg tests [5,6]. The International Harmonization Research Activities (IHRA) pedestrian safety working group, with which NHTSA researchers are working, is also developing a testing methodology. It is considering a more comprehensive approach that would not limit head impact testing to the hood, but would also include the windshield and A-pillars.

Testing performed by many researchers in the 1980's and early 1990's, including those at NHTSA, showed that relatively minor changes to the front ends of vehicles could significantly reduce the potential for death and injury to pedestrians [7]. Much of this research focused on head impacts to the hood and fenders; however, vehicle geometry and designs have changed substantially in the intervening years. This has resulted in smaller, more aerodynamic cars with shorter, lower, and more sloped hoods than those that were tested. Light trucks and vans (LTVs) also make up a larger proportion of vehicles on the road today. It is not known how the geometry and ruggedness of these vehicles will affect their interaction with pedestrians.

For these reasons, NHTSA initiated the Pedestrian Safety Issues project in 1995 to evaluate the proposed procedures and investigate the potential to reduce pedestrian fatalities and injuries by modifying the designs of today's vehicles. Initial work focused on developing a lower leg that would meet the requirements of the ISO procedure without the use of frangible knee elements that the proposed EEVC design used at the time. This work has previously been reported [8]. The current report will focus on work that has been performed in the past year to compare and evaluate the head impact testing procedures that have been proposed by both EEVC and ISO, as well as the procedure that NHTSA

proposed in the early 1990's [3-7]. Additionally, reconstructions of PCDS (Pedestrian Crash Data Study) cases were done using both laboratory impacts and computer simulations to more fully evaluate the whole body kinematics of pedestrians in collisions.

ADULT HEAD IMPACT TESTING

This section will summarize the three head impact test procedures. Only the requirements that the researchers judged to be the most important will be presented here. More details on each can be found in its respective report [4,5,7]. All three procedures use the Head Injury Criterion (HIC) as a measure of the potential for injury. A HIC value of 1000 is generally considered the threshold for serious injury, and this is the value used by EEVC [4].

EEVC Procedure

The procedure specified by Working Group 10 of the European Experimental Vehicle Committee (WG10) was followed in this series of tests [4]. The EEVC Working Group specifies a free flight headform impactor with a mass of 4.8kg. It is unclear why this mass was chosen as both ISO and NHTSA pedestrian procedures proposed 4.5kg headforms, but it has been suggested that the extra mass was included to account for the mass of the neck. The spherical impactor is to be 165mm in diameter, including a 7.5mm thick rubber skin. The draft proposal at the time this research was begun called for the headform to have a semi-rigid polyurethane shell with a steel insert, and this is what was used for this project. The committee more recently proposed an aluminum headform for improved durability, and an increase to a 12.5 mm thickness for the rubber skin covering [3]. The procedure also requires that the center of gravity of the headform and the accelerometer(s) be within 10mm of the center of the sphere [3,4]. The EEVC headform must be certified at specified intervals using the same certification test as Hybrid III headforms. The resultant acceleration must be between 225 and 275g when the headform is dropped from a height of 376mm onto a rigid steel plate [3,4]. The EEVC procedure specifies the velocity of the impactor at the time of impact to be 11.1 m/s at an angle of 65 degrees from a plane parallel to the ground [3,4].

ISO Procedure

The free flight pedestrian headform impactor specified in the ISO procedure has a mass of 4.5kg. Like the EEVC procedure, the spherical headform must be 165mm in diameter with the accelerometer and center of gravity within 10mm of the geometric center of the sphere. The ISO working group does not specify any material or design requirements as long as the headform meets the Hybrid III certification procedure described above for the EEVC headform [5]. The ISO procedure specifies an angle of 53 degrees from a plane parallel to the ground. It was found that this angle was the average angle of the velocity of the head at the time of impact from several cadaver studies. The ISO procedure does not specify a velocity, as it is not intended as a regulation [5].

NHTSA Procedure

The procedure proposed by NHTSA differed from those proposed by EEVC and ISO in that the headform was guided rather than free flight [7]. This means that the headform must be traveling perpendicular to the surface of the hood at the point of impact to reduce the transverse forces that would otherwise be translated to the guide rather than the deceleration of the headform. The 4.5kg headform used in the NHTSA procedure required a spherical contact surface with a diameter of 160mm, which is to be covered by an 11.2 mm thick Hybrid III Head Form Back Plate vinyl skin. A single uniaxial accelerometer measures the acceleration of the headform in the direction of travel. This headform was to meet the same Hybrid III certification procedure as the other two procedures [7].

Since the guided headform device no longer existed, we used the readily available free flight device with the same specified conditions as in the original NHTSA procedure. The hood was impacted perpendicularly by the 4.5 kg adult headform.

Methods

A headform was purchased from TNO (a European contract research organization) that was designed to meet the EEVC WG10 requirements, which specified a polyphenolic resin shell. A second steel insert was fabricated for the headform to reduce the mass from 4.8kg to 4.5kg as required in the ISO procedure while leaving the center of gravity of the assembly at the center of the sphere. The same free flight headform with the second insert was also used as an approximation for the NHTSA procedure since a guided impactor was no longer available. Impact velocity was chosen based on the EEVC procedure specification of 11.1 m/s (24.83 mph). Two vehicles were chosen for testing based on 1997 US sales figures and availability. It was also desired to test vehicles with different designs that might yield

significantly different results, thus a mid-size passenger car and a sport utility vehicle were chosen. The two vehicles were a 1996 Ford Taurus, which is identical to the 1997 model, and a 1997 Chevrolet Blazer.

Impact points for the test matrix were chosen based on the structure of the hood and the amount of clearance to underhood engine components since it was desired to have a wide range of results. Three impact points were chosen for the Taurus. These points are marked with a, b, and c in Figure 1a, and the corresponding points in the engine compartment are shown in Figure 1b. The first point, referred to as the No Reinforcement / Open Area impact point (a), had no hood reinforcement structure and a large amount of clearance to engine components. The second point also had no hood reinforcement but had little clearance to the alternator, and was referred to as the No Reinforcement / Alternator impact point (b). The third point had heavy hood reinforcement and very little clearance to the shock tower, and was called the Reinforcement / Shock Tower impact point (c). Each point was impacted three times with each procedure to evaluate repeatability.
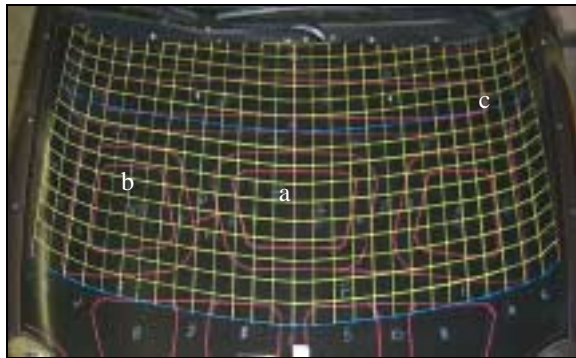

Figure 1a. Taurus hood impact points.

Figure 1b. Corresponding impact point locations in the engine compartment.

Three impact points were also chosen for the Blazer, and are shown in Figures 2a and 2b. The Open Area impact point (a) had no hood reinforcement and a large amount of clearance to engine components. The AC Lines point (b) had no hood reinforcement but little clearance to metallic lines from the AC compressor. The third point had hood reinforcement structure and little clearance to the engine air intake cover. This point was impacted a second time for each procedure with the intake cover removed to evaluate the contribution of low clearance to the HIC value of this particular point. This also allowed a comparison of the HIC value at this point with hood reinforcement and no obstructions to that of the point with no hood reinforcement or obstructions. This point was referred to as the Reinforcement with or without Intake Cover point (c). Since repeatability results had been previously obtained for the Taurus series, only one test per location was conducted with each procedure.

Figure 2a. Blazer hood impact points.

Figure 2b. Corresponding impact point locations in the Blazer engine compartment.

The impact point is defined by EEVC as the point of first contact between the headform and the hood.

This is the definition used in this testing for all three procedures. This means that the center of gravity of the headform is actually aimed at a different location for each procedure. The impact test setup is shown in Figure 2c.
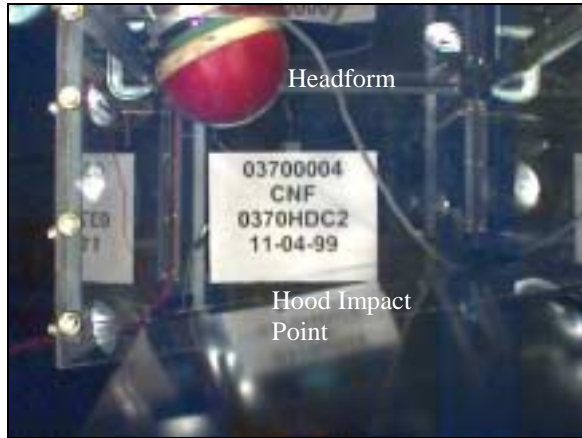

Figure 2c. Head impact test setup.

Taurus Results/Discussion

Figure 3 shows the results of the adult head impact testing performed on the Taurus. This graph shows that in general, impacts that were more perpendicular to the hood resulted in a higher value for the HIC. The only exception to this is for the EEVC and NHTSA impacts to the Reinforcement / Shock Tower impact point, where 65 degree tests resulted in a higher value of HIC than the 90 degree tests. This discrepancy was due to a screw on top of the shock tower that was located slightly rearward of the impact point (see point d in Figure 1b). This effectively resulted in less clearance in the area where the headform was projected during the EEVC tests. Figure 3 also shows good repeatability for all three procedures, particularly for the NHTSA procedure. Also notice that, by comparing the HIC values of the ISO and NHTSA procedures, angle sensitivity of HIC seems to depend on impact location.

Figure 3 shows the effect of underhood clearance on HIC in areas where the hood is not reinforced. It is shown that HIC increases more with impact angle at the low clearance location than at the high clearance area. This indicates that more clearance will lead to a lower HIC for non-reinforced areas.

Figure 3 also shows the effect of hood reinforcement on HIC in areas with low underhood clearance. It is shown that HIC increases more with impact angle at the non-reinforced location (Alternator) than at the reinforced area (Shock Tower). This does not

indicate that reinforced areas cause lower HIC, however, with HIC being around double that of non-reinforced areas. The low R-squared value for the reinforced location is a result of the impact with the screw at 65°.
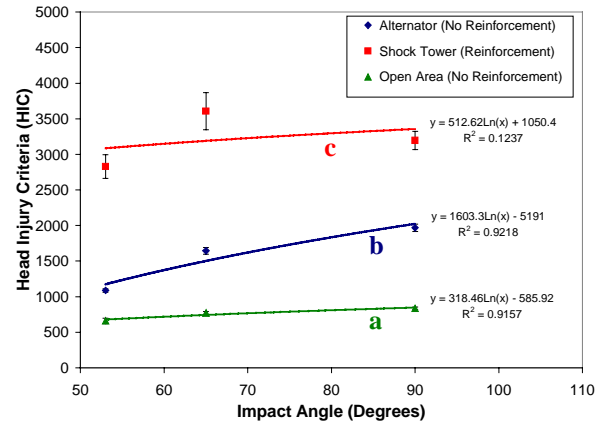

Figure 3. HIC results for Taurus hood locations with different underhood clearance and hood reinforcement.

Blazer Results/Discussion

Figure 4 shows the results of the adult head impact testing performed on the Blazer. This figure follows the trend of higher HIC values for more perpendicular impacts at all impact points. A higher HIC value resulted from impacts to the non-reinforced open area than from the reinforced area with no intake cover. This is attributed to the relative shape of the hood at these points. The hood is flat at the open area impact point, which means that the steel must stretch to allow deformation, whereas the hood is slightly crested at the reinforced impact point with the intake cover removed. The HIC at this reinforced area without the underhood obstruction was the lowest value in this test matrix.

Figure 4 shows the effect of underhood clearance on HIC for reinforced and non-reinforced locations. As was observed for the Taurus, low clearance impacts result in a greater increase in HIC with impact angle. Notice that the trends for both are similar.

Figure 4 also shows the same data, this time comparing the effect of hood reinforcement on HIC for low and high clearance locations. As stated previously, the HIC magnitude is greater for non-reinforced locations, which is a result of the relative shapes of the hood impact locations. Results from the Taurus, where hood shape was not an issue, indicated that hood reinforcement significantly increases HIC, which makes physical sense because

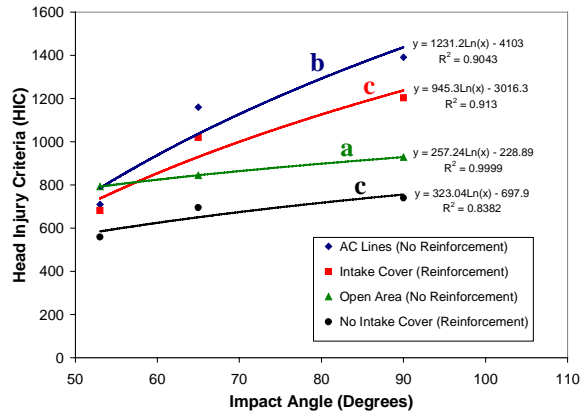reinforcement adds a structure that limits deformation.

Figure 4. HIC results for Blazer hood locations with different underhood clearance and hood reinforcement.

Conclusions

In general, more perpendicular impacts result in higher HIC. All procedures showed good repeatability, particularly the NHTSA procedure. For the Taurus, less underhood clearance and more hood reinforcement resulted in higher HIC for the adult headform. For the Blazer, less underhood clearance resulted in higher HIC, but more hood reinforcement resulted in lower HIC for these tests, most likely because the crested hood contour at these particular reinforced points allowed for more deformation prior to stretching of the steel. It is possible that this trend would not occur at other, more flat locations on the hood. Headform showed good durability, as it did not need to be replaced over the course of testing. By comparing the HIC values of the ISO and NHTSA procedures for both the Taurus and Blazer, angle sensitivity of HIC seems to depend on impact location.

CHILD HEAD IMPACT TESTING

Approximately 35% of pedestrian cases involve children ages 15 and younger based on data collected from the United States, Europe, and Japan. This age group represents the largest proportion of accident victims for AIS 1-6 injury classifications. Children account for roughly 20% of AIS 2-6 head injuries, and 18% of AIS 4-6 severe head injuries [2]. Fifty percent of child head injuries (AIS 2-6) occur at or less than 40 kmph (25 mph), which corresponds closely with the EEVC requirement of 11.1 ± 0.2 m/s (24.83 mph) [2]. In response to this problem, both EEVC and ISO have developed child head impact

procedures [3,4,6]. ISO specifies a headform mass of 3.5 kg, diameter of 165 mm, and impact angle of 54 ± 2° [6]. EEVC specifies a mass of 2.50 ± 0.05 kg, diameter of 165 mm, and impact angle of 50 ± 2° [3]. There is disagreement between the procedures in terms of headform mass and impact angle. Because of this contradiction, it was decided to investigate the influence of impact angle on child HIC by using the EEVC headform, which was more readily available than the ISO version, and conduct tests at various angles within the tolerance of the two procedures.

Methods

A headform was purchased from TNO that was designed to meet the EEVC WG10 requirements, which specified a polyphenolic resin shell. The specified triaxial accelerometer (Endevco 7267a) was mounted at the center of gravity in a stainless steel insert. Impact velocity was 11.1 m/s, as it was in the adult head testing.

The impact point chosen for this study was the No Reinforcement / Alternator location on the Ford Taurus (same as the point used in the adult head impact testing). Angle sensitivity testing involved child head impacts at angles of 48, 51.5, and 55 degrees. Six tests were done at each angle over the alternator to ensure repeatability. HIC values were calculated and clay cones were attached to the top of the underhood structure for measurement of maximum dynamic hood deflection resulting from impact.

Data anomalies (poor repeatability) resulting from the angle sensitivity tests prompted a second identical test matrix using a damped triaxial accelerometer (Entran EGE3-73).

Results/Discussion

Table 1 summarizes the initial set of angle sensitivity tests (n = 6 for each angle) with standard deviations. Notice the large variation in HIC for each angle, especially the 48 and 51.5-degree impacts.

Table 1.
HIC Values for Various Impact Angles on Taurus

Impact Angle	HIC
48°	1169 ± 167
51.5°	1322 ± 231
55°	1695 ± 56

These large standard deviations led to an investigation into why good repeatability for identical impact angles, locations, and velocities was not achieved. A number of parameters were checked. The accelerometer may have been damaged, throwing off its calibration during operation. It was sent back to the manufacturer for recalibration. Once received, it was calibrated in-house as well. The accelerometer was found to be working correctly, with no changes in sensitivity.

Changes in the rigidity of the headform would change its ability to absorb energy during impact with the hood. If the headform were damaged, the response of the accelerometer could have changed. The headform was examined and found to be intact, and the calibrations done in-house were in agreement with those reported by the manufacturer.

The point on the hood directly above the alternator was not horizontal in the lateral direction. The impact point was marked on a slight curve on the hood surface, making it possible for the head form to impact the hood at an angle, which would skew acceleration measurements. The impact point was marked in the identical spot on every hood tested. Furthermore, analysis of high-speed video indicated no noticeable differences in headform motion for lower and higher HIC value tests at the same angles.

It was questioned whether the accelerometer chosen had the optimal natural frequency for the headform impact test application. This was a valid argument considering the proximity of the testing frequencies and the natural frequency of the accelerometer (5-25 kHz vs. 14 kHz), which is shown in the Fast Fourier Transform (FFT) plot (Figure 5). When these frequency ranges coincide, there is an increased chance that resonance can occur, which could lead to saturation of the amplifiers in the signal conditioning stage of the data acquisition system. This can cause corruption of the data, giving inconsistent or unreliable results [9]. To investigate this potential problem, a damped accelerometer was purchased, and an identical test matrix was repeated to evaluate the effect on HIC. The HIC values became less varied and the resonant frequency content was eliminated, an improvement in instrumentation was made. It should be noted that no resonance was present in FFT plots of adult head impacts on the same alternator location.

The tests were repeated (n = 3 at each angle), and it was determined that the results were much more consistent (Table 2). Notice the repeatability and smaller variation for the damped accelerometer, as well as the prevention of resonance in Figure 6.
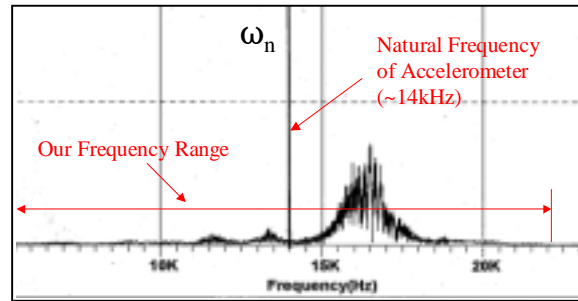

Figure 5. Resonance seen in the frequency response of the undamped accelerometer.

Table 2.
HIC for Undamped and Damped Accelerometers

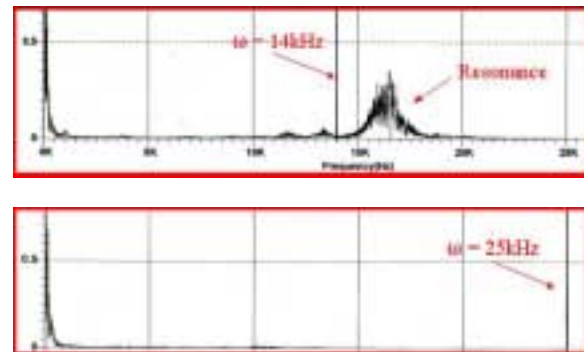| Impact Angle	Undamped	Damped
48°	1169 ± 167	1556 ± 31
51.5°	1322 ± 231	1614 ± 23
55°	1695 ± 56	1681 ± 32

Figure 6. Resonance is prevented by the use of a damped accelerometer.

Figure 7 shows the clay cone arrangement on the alternator. Table 3 summarizes the average clay cone heights and shows that hood deflection, which is inversely proportional to clay cone height, increases with impact angle.

From a Student's t-test, it was determined that the damped and undamped clay cone height values were not significantly different for each angle (p > 0.05), but there was a small variation of 1-2 mm between test sets. This small difference was attributed to variations in the initial impact point (i.e., slight

changes in contour) and not a more severe impact for damped cases. This consistency in impact severity further supports the use of damped accelerometers because the deformations caused by impact were equal for undamped and damped cases.

Figure 7. Clay Cone Configuration on Alternator

Table 3.
Hood deflection increased with impact angle

Impact Angle	Average Clay Cone Height (mm)	
	Undamped	Damped
48°	18.7 ± 3.1	17.1 ± 3.1
51.5°	17.2 ± 3.0	15.7 ± 2.7
55°	16.5 ± 3.1	14.4 ± 2.6

Conclusions

Utilization of the undamped accelerometer specified for child headform testing resulted in unreliable accelerations and HIC response due to resonant frequency and subsequent signal conditioning overloads. Incorporation of a damped accelerometer into the child headform is preferred because it eliminates resonance and gives more reliable HIC results. It is concluded that for the 1996 Ford Taurus, HIC and hood deflection increase slightly with an increase in impact angle for the child headform.

PCDS RECONSTRUCTIONS

After establishing a procedure for head component testing, it becomes necessary to use that procedure and other methods to simulate whole-body kinematics that occur in pedestrian collisions with vehicles. The way to validate the accuracy of these methods is to reconstruct real-world cases with each of the methods and compare the resulting trajectories

and forces with each other and with injuries incurred by the pedestrian in the accident.

The Pedestrian Crash Data Study (PCDS) was conducted by NHTSA from 1994-1998. During that time, detailed crash data was collected from 521 cases at six sites across the United States. The following case reconstruction was selected from this information.

Methods

A pedestrian accident case was selected from the PCDS database for reconstruction with computer simulations and laboratory testing. The vehicle used for the reconstruction was a 1996 Ford Taurus Sedan. The recorded speed of the vehicle at impact was 27 km/h, and the pedestrian was a 48-yr old male (height 178 cm, weight 82 kg). The victim sustained AIS 1-2 head injuries from the collision due to windshield impact. Vehicle hood and windshield stiffness were determined from headform impacts to the structures by calculating force and deflection. These pedestrian and vehicle properties were entered into a pedestrian accident simulation model shown in Figure 8 (TNO-MADYMO) that had been validated with biomechanical corridors created from cadaver tests.
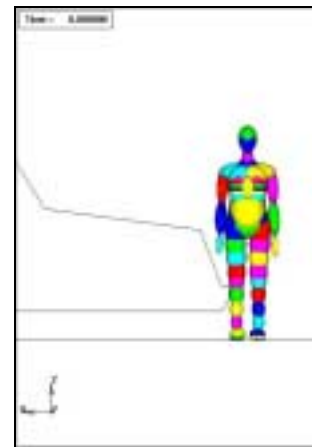

Figure 8. Pedestrian accident simulation model

A simulation was then performed and four important parameters were determined. The relative impact velocity of the head was the first parameter, which was essentially the speed of the vehicle plus the reaction speed of the head in the opposite direction. Another was the relative impact angle of the head with the windshield. The last two parameters were the head injury criterion and windshield contact force. After these parameters were determined, a laboratory reconstruction with an adult headform was

done at the same impact velocity and angle as the computer simulation on a 1996 Taurus. The headform was instrumented with a damped triaxial accelerometer (Model EGE-373, Entran Devices). The head was impacted at the same location on the windshield as was documented in the case, and the resulting HIC and windshield contact force (effective mass multiplied by impact acceleration) were recorded and compared with the computer simulation results. Two impact tests were done to achieve repeatability.

Results/Discussion

Table 4 shows the results of the pedestrian simulation, and Figure 9 defines the head impact angle.

Table 4.
Pedestrian simulation results

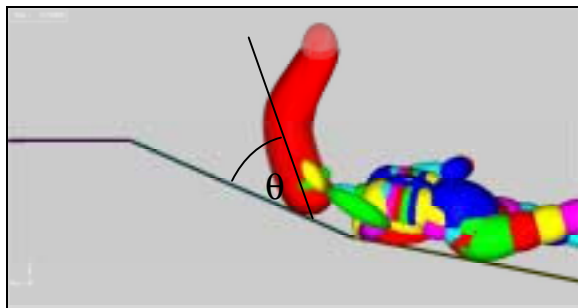| Parameter	Result
Relative Impact Velocity	44.21 km/h
Relative Impact Angle	49°
Head Injury Criteria (HIC)	256.7
Windshield Contact Force	5960 N @ 197 ms

Figure 9. Relative impact angle

The wrapping of the torso and lower body around the front end of the vehicle caused the neck to rotate past vertical prior to contact with the windshield, forcing the head to impact at an angle less than 90 degrees with the windshield. Also, the relative impact velocity was much greater than the vehicle impact velocity at contact with the legs of the pedestrian. The HIC was lower than in hood impacts due to the greater dynamic deformation characteristics of the windshield. Table 5 outlines the results of the laboratory reconstructions:

Table 5.
Laboratory reconstruction results

Parameter	Result
Relative Impact Velocity	44.5 ± 1.0 km/h
Relative Impact Angle	49°
Head Injury Criteria (HIC)	257 ± 6.0
Windshield Contact Force	5080 ± 732 N

The resulting HIC and windshield contact forces were very close to the values found in the simulation. The HIC values for both simulation and laboratory tests were typical of AIS 1-2 injury levels, as they were in the case [10, 11]. The windshield damage patterns were similar for the accident case and laboratory test (Figure 10).

Figure 10. Accident case (top) and test (bottom)

Conclusions

We were able to replicate an actual case by using a computer model simulation and laboratory impact with an adult headform. The similarity of the results for the two methods encourages the use of these techniques to make a connection between injuries

incurred in an accident and acceleration/force measurements in reconstructions.

FUTURE DIRECTIONS

Another step in creating the bridge between real-world accident cases and laboratory testing will be the use of a full-scale pedestrian dummy in HYGE sled tests. This will give a whole-body perspective for comparison with computer simulations. While component testing will focus on the impact mechanics of a head or leg collision, dummy tests will additionally offer body region trajectories in response to impact. Testing is currently being done at VRTC with one such dummy. Knowledge gained from computer simulations and full-scale dummy tests will help to strengthen the linkage between accident cases and IHRA component test procedures.

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