MATHEMATICAL SIMULATIONS OF REAL-WORLD PEDESTRIAN-VEHICLE COLLISIONS

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ABSTRACT

Pedestrian-vehicle crashes result in a substantial number of pedestrian fatalities and injuries worldwide. Computer models are powerful tools in understanding how the severity of injuries could have been reduced in the crash. Pedestrian real-world cases serve as an important source of information to evaluate the dynamic performance of pedestrian models and their ability to reconstruct injury-causing events.

The objective of this study was to evaluate the ability of a mathematical pedestrian model to assess the severity of an impact using real-world data. The dynamic performance of the pedestrian model was evaluated by the reconstruction of six real-world pedestrian collisions, which occurred during 1995-2003 in the surroundings of Hanover, Germany. The impact severities were 32-59km/h. Each case contained information about the pre-crash, crash, and post-crash events. This information included hospital reports and detailed description of damages to the vehicle, pedestrian injuries, and the crash environment collected at the scene. The evaluation focused on head injuries since these are the most common cause of severe injuries and fatalities of pedestrians involved in passenger vehicle-pedestrian crashes.

The results showed that the model produced injury measures and readings of the magnitude expected for the highest severity head injuries sustained by the pedestrian in the reconstructed case. Furthermore it highlights the usability of mathematical pedestrian models in evaluating the severity of a vehicle-pedestrian collision.

INTRODUCTION

Road crashes result in a substantial number of pedestrian fatalities and injuries worldwide. Statistics from 35 European countries have shown that pedestrian fatalities represented on average 25% of road users killed throughout Europe (ECMT, 2003). In Japan, pedestrian fatalities accounted for 28% of the road toll (ECMT, 2003), while in Australia approximately 16% of road fatalities were pedestrians (ATSB, 2003). Pedestrian fatalities as a proportion of road fatalities were estimated at 13% in the USA and were as high as 40-50% of the annual road toll in India and Thailand (Mohan and Tiwari, 2000). Head injuries are the most common cause of pedestrian fatalities. Injuries to the chest, spine, abdomen and the lower extremities are also commonly sustained (Anderson and McLean, 2001, Fildes et al., 2004).

Computer simulations provide a powerful tool for studying the loading to the pedestrian in a crash. For the study of overall human kinematics in a crash, computer models based on rigid bodies connected to each other by joints are time efficient. The dynamic and kinematic response of computer models is validated towards biological test results. However, it is important to include evaluation towards real-world cases as part of this process in order to determine the models ability to assess the impact severity in a wide range of scenarios.

The aim of this study was to evaluate the ability of a mathematical pedestrian model to assess the severity of an impact by reconstruction of six real-world passenger vehicle-pedestrian collisions.

MATERIALS AND METHODS

Six real-world vehicle-pedestrian crashes were reconstructed using PC-Crash and MADYMO. The data about the collision and the injuries were compiled from on-site collected data and hospital records coded using AIS (AAAM, 1990) when available. The on-site inspection provided detailed information about the site and circumstances for the crash, such as skid marks and resting positions, in addition to detailed documentation of the damages to the vehicle.

Real-World Cases

The real-world cases were collected around the area of Hanover, Germany in an area with a radius of approximately 70km. An inspection team consisting of 4 members perform an investigation of the collision. Two team members go to the scene, one team member follows the injured person and the 4th team member is the coordinator. The police or fire brigade alert the team and the team normally arrived 30min after the collision.

Case 1 (ID 030816)

A male pedestrian was hit with an estimated impact velocity of 45-50km/h by a VW Golf in an intersection. The intersection consisted of three lanes for forward traffic and one lane for left turning traffic. Vehicles were stationary in the inner forward running lane and the case vehicle was in the forward running lane next to the left turning lane (Figure 1). The driver of the case vehicle saw from a distance the light change from red to green and entered the intersection at a travel speed of 45-50km/h. A pedestrian was walking quickly across the intersection, hidden from the case vehicle by the stationary vehicle. The pedestrian was hit by the right front of the case vehicle, which started to brake at impact.

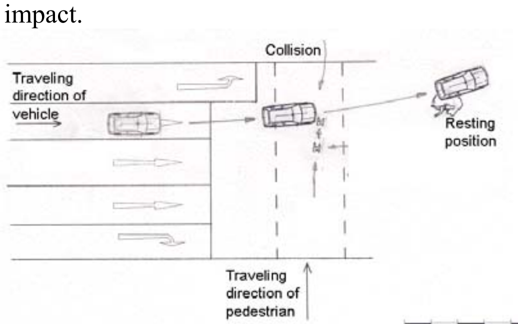

Figure 1. The intersection in Case 1 where a VW Golf struck a pedestrian. The pedestrian was hidden from the view of the driver in the case vehicle by stationary vehicles in the forward running lanes.

The impacting vehicle was a 2000 2-door VW Golf. Marks on the vehicle showed that the pedestrian struck the front right quarter panel, the right side of the windshield and the right side of the roof adjacent to the windshield (Figure 2). The pedestrian was thrown 9.4m from where the impact occurred. The range of thrown distance was estimated to be ± 1m.

Figure 2. The impact locations of the male pedestrian on the front right quarter panel, windshield and roof on the VW Golf in Case 1.

The pedestrian was a 68-year-old male, 175cm and 85kg. He sustained MAIS 3 injuries. All the injuries were: multiple left side rib fractures AIS 3, left tibia fracture AIS 2, concussion AIS 2, open fracture of nose bone AIS 1.

Case 2 (ID 030945)

Two pedestrians, one male and one female (denoted Case 2a and 2b), were hit with an estimated impact velocity of 43-49km by a BMW when they appeared suddenly from between parked cars in the dark. The male pedestrian was hit by the left front and the female pedestrian was hit by the centre of the case vehicle (Figure 3).

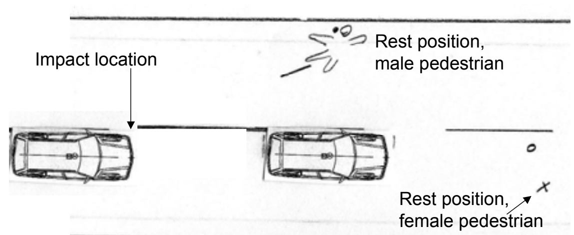

Figure 3. The road where a BMW struck two pedestrians. The pedestrians appeared suddenly from between parked cars and attempted to cross the street in Case 2.

The male pedestrian impacted the left a-pillar; the front left side of the hood and the area above the left side of the head-lamp (Figure 4). The male pedestrian was thrown 8.5m from where the impact occurred. The range of thrown distance was estimated to be ± 1m. The female pedestrian hit the centre of the hood (Figure 4) and was thrown approximately 15m from where the impact occurred. The female pedestrian rose immediately after having landed on the ground and there were no marks that could further verify the orientation of the pedestrian in her rest position. The range of thrown distance was estimated to be ± 2m.

Figure 4. The impact locations of the male pedestrian on the BMW in Case 2.

Figure 5. The impact locations of the female pedestrian on the BMW in Case 2.

The striking vehicle was a 1999 BMW 3 Series Touring Wagon. The more severely injured pedestrian in Case 2 was a 48-year-old male (denoted Case 2a). He sustained MAIS 4 injuries. All the injuries were: head haematoma and oedema AIS 4, subarachnoidal bleeding and fractured base of the skull AIS 3 and skull and fractures to the orbit AIS 2. The other pedestrian in Case 2 was a 23-year-old female (denoted Case 2b). She sustained MAIS 1 injuries. All the injuries were: haematoma of pelvis and lower leg and distortion of cervical spine AIS 1.

Case 3 (ID 17028)

A male pedestrian was hit by a VW Passat with an estimated impact velocity of 59km/h. The case vehicle was driving in the right lane and the traffic light showed a green light for the vehicle. The pedestrian started crossing the street and was hit by the right front of the vehicle (Figure 6). The case vehicle started to brake at impact.

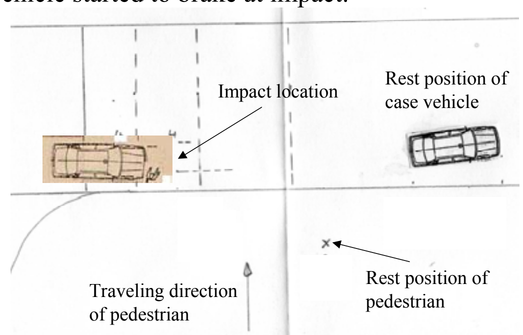

Figure 6. The road where a VW Passat struck a male pedestrian in Case 3. The pedestrian walked out despite having a red light in an attempt to cross the street.

The male pedestrian was hit by the right side of the windscreen, the front right side of the hood and the on the right side of the bumper (Figure 6). The male pedestrian was thrown 10.3m from were the impact with the vehicle occurred. The range of thrown distance was estimated to be ± 1m.

Figure 7. The impact locations of the pedestrian on the VW Passat in Case 3.

The striking vehicle was a 1987 to 1995 VW Passat. The pedestrian was a 35 years old male, 172cm and 70kg. He sustained MAIS 3 injuries. All the injuries were: haematoma frontal thorax and lacerations right forehead AIS 1, fracture right tibia AIS 3 and fracture right fibula AIS 2.

Case 4 (ID 17910)

A female pedestrian was hit by a VW Caravelle with an estimated impact velocity of 32-35km/h. The case vehicle was driving along the road and the pedestrian started crossing the street and was hit by the left front of the vehicle (Figure 8). The case vehicle started to brake prior to impact.

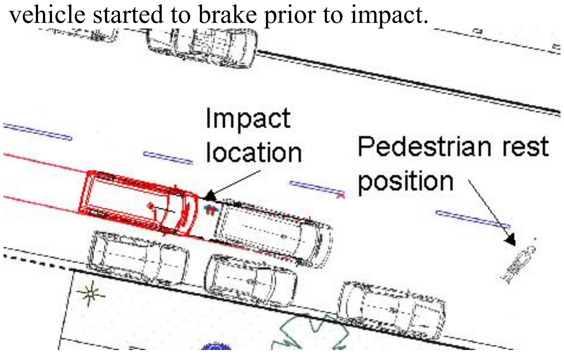

Figure 8. The road where a VW Caravelle struck a female pedestrian in Case 4. The pedestrian walked out in an attempt to cross the street.

Marks on the vehicle showed that the female pedestrian hit the left side of the front (Figure 9). The female pedestrian was thrown approximately 12.5m from where the impact occurred. The pedestrian rose immediately after having landed on the ground and there were no marks that could further verify the orientation of the pedestrian in her rest position. The range of thrown distance was estimated to be ± 2m.

Figure 9. The impact locations of the female pedestrian on the VW Caravelle in Case 4.

The striking vehicle was a 1998 VW Caravelle. The pedestrian was a 77-year-old female. The pedestrian sustained no recorded injuries.

Case 5 (ID 30010020)

A male pedestrian was hit by a Ford Mondeo with an estimated impact velocity of 40-45km/h. The pedestrian crossed the street at night and was struck by the case vehicle (Figure 10).

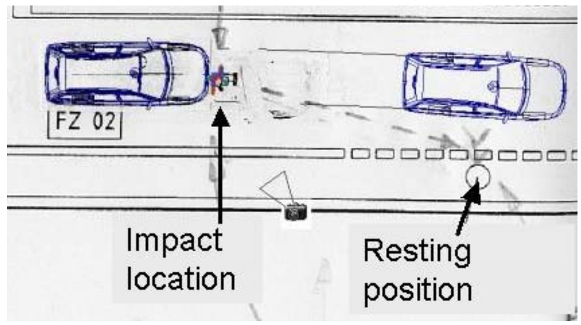

Figure 10. The road where a Ford Mondeo struck a male pedestrian in Case 5. The pedestrian attempted to cross the street.

Marks on the vehicle showed contact with the vehicle at the windshield and the hood. The pedestrian was struck by the centre front of the vehicle, slid to the right along the hood and hit the head on the windshield (Figure 11). The male pedestrian was thrown 7.8m from where the impact occurred. The range of thrown distance was estimated to be ± 2m. According to a witness the pedestrian was seen to run across the street.

Figure 11. The impact locations of the male pedestrian on the Ford Mondeo in Case 5.

The striking vehicle was a 1998 Ford Mondeo. The pedestrian was a 19-year-old male, 182cm, 72kg. The pedestrian sustained deep lacerations forehead, nose and right ear, lacerations to the fingers on the left and right hand and ligament rupture to the right knee.

Case 6 (ID 17946)

A female pedestrian was hit by a Mercedes with an estimated impact velocity of 43km/h. After having reached the middle of the road the pedestrian turned back (Figure 12). The case vehicle braked and struck the pedestrian with the left front. The information about the rest position of the pedestrian was that she ended up within the area where glass splinters from the windshield were found.

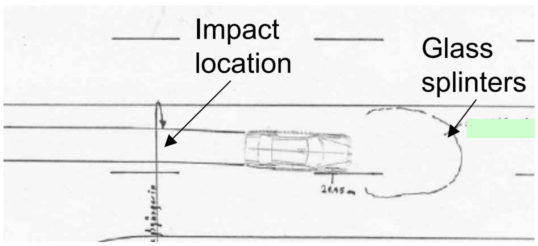

Figure 12. The road where a Mercedes struck a female pedestrian in Case 6. The pedestrian turned back after having reached the middle of the road.

Marks on the vehicle showed that the female pedestrian hit the left side of the windshield (Figure 8). The female pedestrian was thrown approximately 9-14m from where the impact occurred.

Figure 13. The impact location of the female pedestrian on the Mercedes in Case 6.

The striking vehicle was a 1988-9 Mercedes 200E. The pedestrian was a 45 years old female, 170cm and 70kg. She sustained MAIS 2 injuries. All the injuries were: concussion AIS 2, laceration right forehead and nose, haematoma right side of right knee AIS 1.

Reconstruction of Pedestrian Collisions

For some cases the range of the impact velocity was estimated based on thrown distance and braking distance. The pedestrian collisions were then firstly reconstructed with PC-Crash to verify the estimation of impact velocities. Secondly, the collision was reconstructed in MADYMO 5.4.1 (TNO, 1999), using EASI-CRASH and the pedestrian model by Yang et al. (2000).

In the MADYMO simulations, an impact velocity that generated the best match with the thrown distance measured at the scene was used. In the cases where the pedestrian was not regarded as stationary it was given a velocity perpendicular to the vehicle. The velocity of the pedestrian was chosen within the ranges obtained as follows: A healthy male in his 20s performed tests on a treadmill. From these tests, running was established to be ≥ 3m/s and fast walking was established as 1.5 - 3m/s. All cases were initially reconstructed with the 50th percentile male model. In Case 2 where the height and weight of the pedestrians were unknown additional simulations with the 5th percentile female and the 95th male model were performed.

For the MADYMO simulations the position of the pedestrian prior to impact was estimated from the photos of the damaged vehicle. The orientation of the pedestrian prior to the impact was thus estimated individually for all cases. For each case approximately 20 simulations were run to tune the positioning and the velocity of the pedestrian, in the aim of matching the thrown distance, braking distance and impact locations on the vehicle and the ground to the real-world cases.

The reconstruction of the real-world cases in MADYMO is schematically illustrated in Figure 14. The figure shows the flow of data and the loop of iterations of the MADYMO simulations.

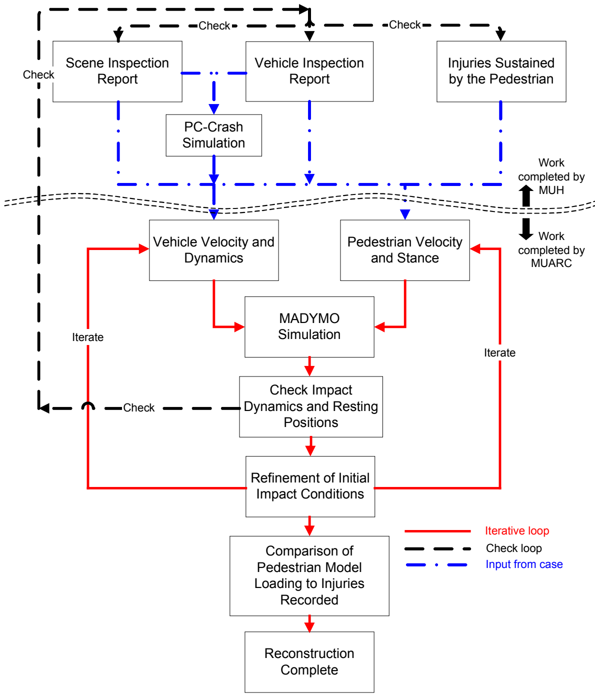

Figure 14. A schematic illustration showing the reconstruction of the real-world cases in MADYMO, the flow of data and the loop of iterations of the simulations.

Mathematical models of the vehicles' structure were constructed using dimensioned drawings obtained from the web page of 3dcenter.ru. These were cross referenced against measurements taken from a vehicle of the same make, year and model as in the cases using straight-edges, tape measures and rulers with particular focus on the pedestrian impact point locations. The force-penetration curves used for the MADYMO vehicle models were approximated from van Rooij et al. (2003) and Mizuno and Kajzer (2000). For the windshield the centre force-penetration curve (Mizuno and Kajzer, 2000) was used. The roof was given a force-penetration loading curve obtained from the average between the hood and hood edge of van Rooij et al. (2003). The hood edge and the quarter panel were given midsection hood edge force-penetration loading curve of van Rooij et al. (2003). The door was given midsection door force-penetration loading curve and the upper and lower bumper the midsection bumper force-penetration loading curve of van Rooij et al. (2003). The a-pillar was given the force-penetration loading curve of the a-pillar as in van Rooij et al. (2003).

The contact interactions between the vehicle and the pedestrian were defined as 'ellipsoid-ellipsoid' using the 'evaluations' keyword where necessary to avoid multiple contact interactions. A friction coefficient was applied to the pedestrian to vehicle contact (0.3) and the pedestrian to ground contact (0.7), as well as a small amount of damping. Where applicable the vehicle was subjected to deceleration and nose-dive due to braking. The amount of braking was chosen so that the final position of the case vehicle being simulated matched as close as possible to that of the case. A 50mm nose-dive and 2 degrees rotation around the front was applied to the models when braking prior to impact was present.

MADYMO Vehicle Model and pedestrian position Case 1

The VW Golf was generated using 15 ellipsoids. The front-right quarter panel, a-pillar and roofline of the vehicle were modelled in detail. Impact velocity of 11.8m/s, braking prior to impact and a braking distance of 13.3m were applied. The pedestrian's initial posture was in a walking stance with the left leg slightly in front of the right. The pedestrian was given an initial velocity of 3m/s.

MADYMO Vehicle Model and pedestrian position Case 2

The BMW was generated using 22 ellipsoids. As a result of the multiple pedestrian impact condition, the curvature of the front of the vehicle was constructed using 3 sections of ellipsoids. As the male pedestrian struck the right hand edge of the vehicle, it was necessary to include an a-pillar, side guard and a door to represent the vehicle being struck. Impact velocity of 12.7m/s and a braking distance of 10.1m were applied. The male pedestrian's initial posture was in a walking stance with the left leg slightly in front of the right. The females pedestrian's initial posture was facing towards the vehicle, right leg slightly in front of the left and using her arms to protect herself from the impact. Both pedestrians were given an initial velocity of 1.5m/s.

MADYMO Vehicle Model and pedestrian position Case 3

The 1993 VW Passat was generated using 11 ellipsoids. The front-right quarter panel was modelled in detail. Impact velocity of 12.7m/s, braking prior to impact and a braking distance of 18.6m were applied. The pedestrian's initial posture was in a walking stance with the right leg in front of the left. The pedestrian was given an initial velocity of 2m/s.

MADYMO Vehicle Model and pedestrian position Case 4

The VW Caravelle was generated using 11 ellipsoids. Impact velocity of 9.5m/s, braking prior to impact and a braking distance of 5.5m were applied. The pedestrian's initial posture was in a walking stance with the left leg slightly in front of the right. The pedestrian was given no initial velocity as it was deemed to be small.

MADYMO Vehicle Model and pedestrian position Case 5

The 1998 Ford Mondeo was generated using 9 ellipsoids. Impact velocity of 9.7m/s, braking prior to impact and a braking distance of 10.4m were applied. The pedestrian's initial posture was in a running stance with the left leg in front of the right. The pedestrian was given an initial velocity of 2m/s.

MADYMO Vehicle Model and pedestrian position Case 6

The 1988-9 Mercedes 200E was generated using 12 ellipsoids. Impact velocity of 12m/s, braking prior to impact and a braking distance of 8.8m were applied. The initial posture of the pedestrian was in a walking stance, turned slightly towards the vehicle with the left leg in front of the right. The pedestrian was given an initial velocity of 1m/s to simulate this walking motion.

RESULTS

The results showed that the kinematics of the pedestrian model in the MADYMO simulations were comparable with that in the real-world cases in terms of impact location, resting position and throw distance. An increased 3ms linear acceleration and HIC_{15} corresponded to an increased severity of the collision in terms of MAIS head injuries for MAIS 2+. This applied to three out of the four cases and for the exception case an unusual initial posture made this impact less severe in terms of injuries compared to what the output from the simulation indicated. Furthermore, both the 3ms linear head acceleration and HIC_{15} showed the highest values for the case where the highest severity of head injuries occurred.

Case 1

Figure 15 shows photos of the impacted vehicle and images from the simulations of Case 1 where the male pedestrian impacted the side of the vehicle. The simulated throw distance was 9.8m forward of the vehicle with the impact velocity of 45km/h. Head impact occurred at similar spot on the vehicle as in the real-world case.

Figure 15. Photos of the impacted VW Golf and images from the simulation of the male pedestrian hit by the vehicle with an impact velocity of 45km/h, Case 1.

Case 2

Figure 16 shows photos of the impacted vehicle and images from the simulations of the male pedestrian Case 2a (simulated with the 95^{th} percentile male model) impacting the front left side of the vehicle. The simulated throw distance was 9.3m from the vehicle and the impact velocity used in the simulation was 46km/h. Head impact occurred at similar spot on the a-pillar as in the real-world case.

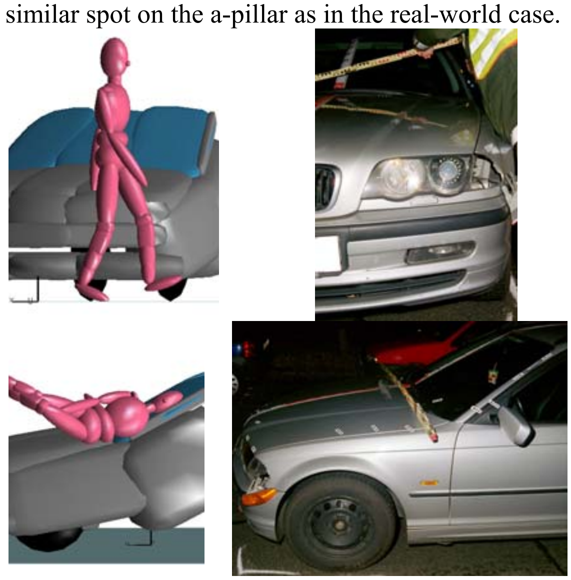

Figure 16. Photos of the impacted BMW and images from the simulation of the male pedestrian hit by the vehicle with an impact velocity of 46km/h, Case 2a.

Figure 17 shows photos of the impacted vehicle and images from the simulation of the female pedestrian Case 2b (simulated with the 5th percentile female model) impacting the centre of the vehicle. The female pedestrian showed no sign of head impact, neither from marks on the vehicle nor from injuries. The simulated throw distance was 14.7m from the vehicle and the impact velocity used in the simulation was 46km/h.

Figure 17. Photos of the impacted BMW and images from the simulation of the female pedestrian hit by the vehicle with an impact velocity of 46km/h, Case 2b.

__Case 3__

Figure 18 shows a photo of the impacted vehicle and images from the simulation of Case 3 where the male pedestrian impacted the front right hand side of the vehicle. The simulated throw distance was 10.3m from the vehicle and the impact velocity used in the simulation was 46km/h. Head impact occurred at similar spot on the windshield as in the real-world case.

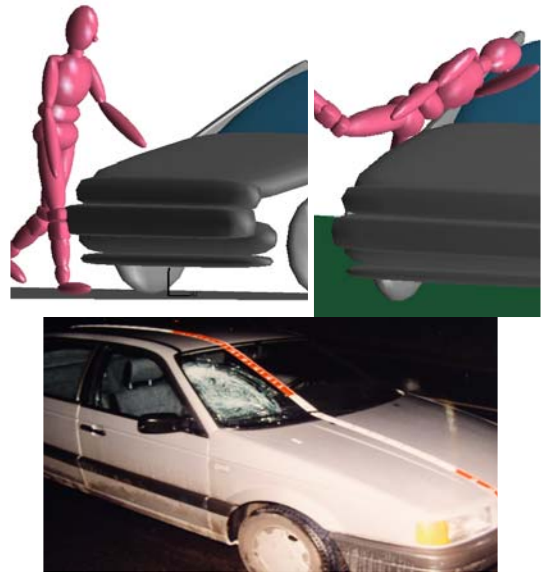

Figure 18. A photo of the impacted VW Passat and images from the simulation of the male pedestrian hit by the vehicle with an impact velocity of 47km/h, Case 3.

__Case 4__

Figure 19 shows a photo of the impacted vehicle and images from the simulation of Case 4 where the female pedestrian impacted the front side of the vehicle. The simulated throw distance was 12m from the vehicle and the impact velocity used in the simulation was 34km/h. The impact occurred at similar spot on the hood as in the real-world case.

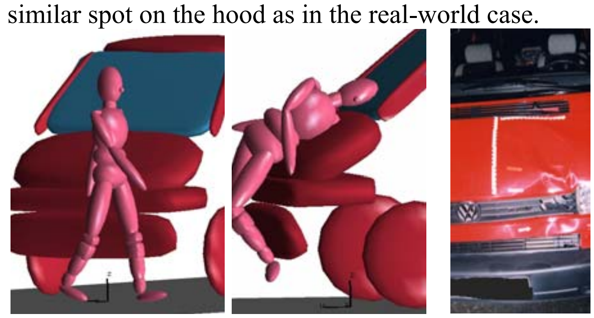

Figure 19. A photo of the impacted VW Caravelle and images from the simulation of the female pedestrian hit by the vehicle with an impact velocity of 34km/h, Case 4.

__Case 5__

Figure 20 shows photos of the impacted vehicle and images from the simulation of Case 5 where the male pedestrian was impacted while running across the road. The simulated throw distance was 8.2m, with an impact velocity of 35km/h. Head impact occurred at similar spot on the windshield as in the real-world case.

Figure 20. Photos of the impacted vehicle end images from the simulation of the male pedestrian struck by a Ford Mondeo with an impact velocity of 35km/h, Case 5.

__Case 6__

Figure 21 shows photos of the impacted vehicle and images from the simulation of Case 6 where the male pedestrian impacted the front of the vehicle. The simulated throw distance was 10.1m from the vehicle and the impact velocity used in the simulation was 36km/h. Head impact occurred at similar spot on the windshield as in the real-world case.

Figure 21. Photos of the impacted vehicle and images from the simulation of the female pedestrian struck by a Mercedes with an impact velocity of 36km/h, Case 6.

Figure 22 shows the thrown distance from the real-world cases and those generated in the simulations of the cases. The impact velocities used in the simulations are shown in Figure 23 together with the calculated range of the impact velocity based on thrown and braking distance and velocities used in the PC-Crash simulations.

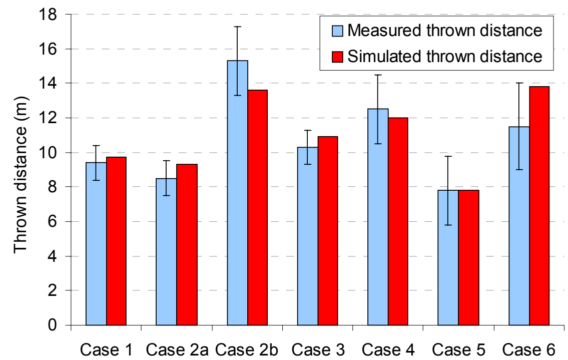

Figure 22. The thrown distance measured at the crash scene and from the simulation of the six cases. The bars on the measured data represent the range of thrown distances.

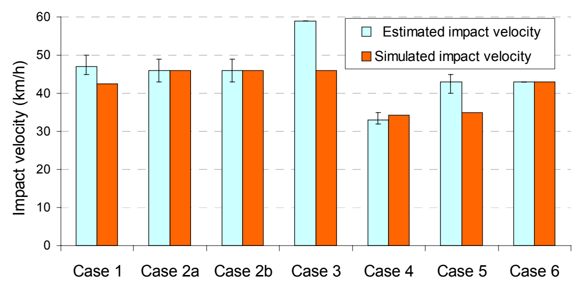

Figure 23. The impact velocity estimated from the crash scene data and the impact velocity in the simulation of the six cases. The bars on the estimated data represent the calculated range of impact velocities based on thrown distance and braking distance.

The HIC 15 and 3ms head linear and rotational acceleration from the simulations of the six cases is shown in Figures 24-26.

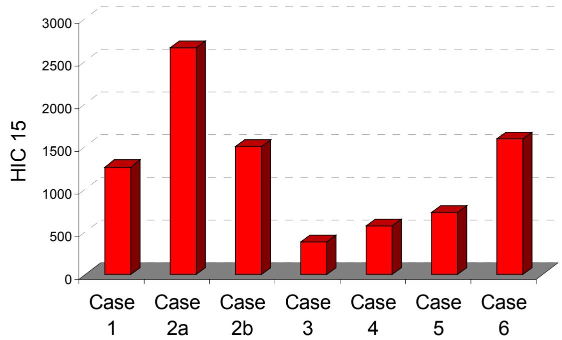

Figure 24. The HIC 15 from the simulations of the six cases.

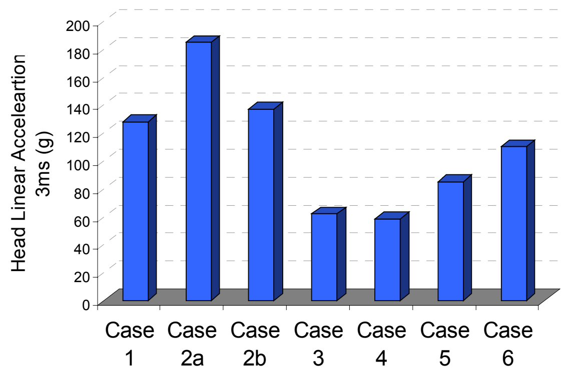

Figure 25. The 3 ms head linear acceleration from the simulations of the six cases.

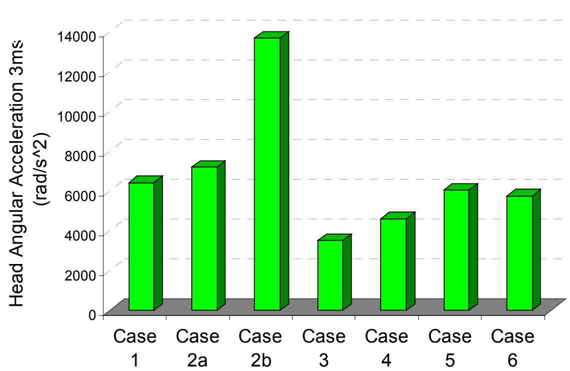

Figure 26. The 3ms head angular acceleration from the simulations of the six cases.

DISCUSSIONS

Through simulating six real-world pedestrian vehicle crashes, it was observed that in general, the kinematics of the pedestrian model of Yang et al. (2000) corresponded well with crash scene data in terms of impact location, thrown distance and resting position. Even though the model was used for various impact conditions in terms of pedestrian posture, orientation and velocity prior to impact, the pedestrian model was able to generate a close match to the on–scene collected data. Also head loading was compared to the real-world injury outcome without any internal modifications of the model needed.

The head injuries MAIS from the six cases is shown in Figure 27. The simulation of the case with the highest MAIS head injury, MAIS 4, produced a HIC 15 of 2660. A HIC of 2660 correspond to 85% risk of skull fracture according to the relation determined by Hertz (1993) and in this case the pedestrian sustained skull fractures.

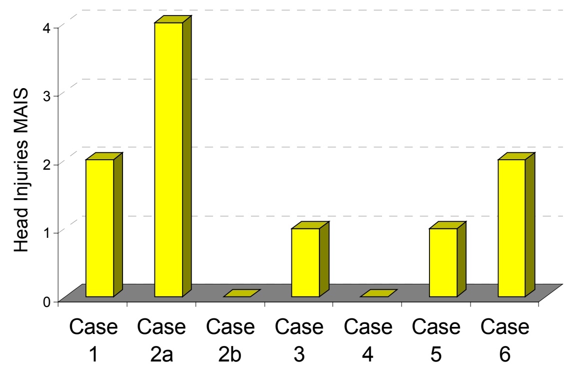

Figure 27. The head injuries MAIS from the six real-world cases.

Of the dynamic responses investigated, it was found that both 3ms Linear Head Acceleration and HIC_{15} displayed the same trend as did the severity of head injuries. An increase in either of these parameters corresponded with an increased severity of the collision, with respect to MAIS 2+ head injuries (Figures 24, 25 and 27). The exception being case 2b, where the pedestrian had an unusual initial posture, due to her awareness of the approaching vehicle. This consequently led to her having a very different kinematic response to the other cases. Specifically, for this case, the pedestrian managed to avoid any noticeable head contact with the vehicle. This event was unable to be replicated through simulations.

It was also observed that both 3ms Linear Head Acceleration and HIC_{15} showed the lowest values for cases 3, 4 and 5. For these cases, head impact severity was limited to AIS 0 or 1. For Case 4, an AIS 0 was estimated as no official injuries were recorded as the pedestrian had left the hospital prior to meeting with the investigation team. If the pedestrian in this case sustained any head injuries it was most likely a low AIS head injury.

The thrown distances observed in the MADYMO simulations were shown to be within the range given from the real-world cases (Figure 22). To generate the match between simulated and measured thrown distance, in combination with vehicle impact location and braking distance, the impact velocities were in some cases somewhat lower than those estimated from the crash scene data (Figure 23).

All cases were initially simulated using the 50th percentile male pedestrian model. For Cases 1,3,5 and 6 the height and weight of the pedestrian was similar to that of the 50th percentile male model. Whereas the height and weight of the pedestrians in Case 2 and 4 were unknown. In Case 4 a reasonable match between simulated, measured and estimated values of kinematics, impact locations and rest positions were obtained using the 50th percentile male model. However this was not the situation for Case 2, thus models other than the 50th percentile male were necessary to be used. For both pedestrians in Case 2, the 50th percentile male was not able to generate the kinematics, impact locations and rest positions expected from the crash scene data. In the case of the male, the 50th percentile male model predicted a lower impact location on the a-pillar to what occurred in Figure 4. For the female's impact, the 50th percentile male model struck his head on the windshield. This is thought to be unlikely, as if this was the case, windshield damage would be expected. This led to the choice of using the 5th percentile female and 95th percentile male models for the female and male in this case. When simulating the case with the large male and the small female pedestrian models, the impact locations, thrown distance and kinematics were closer to that observed in the real-world case. The head impact location from the simulations with the various models is shown in Figures 28-29.

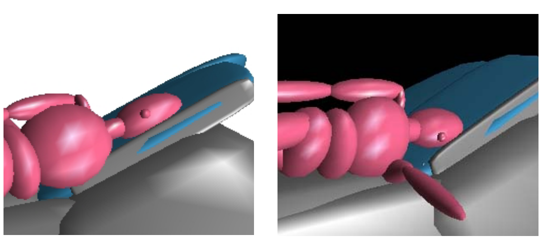

Figure 28. The simulation of the 95th percentile (left) and the 50th percentile (right) male pedestrian model impacting the BMW with the simulated impact velocity of 46 km/h, Case 2a.

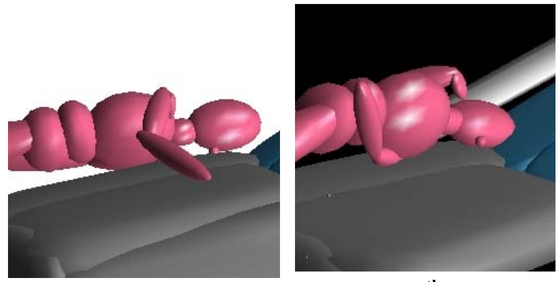

Figure 29. The simulation of the 5th percentile (left) female and the 50th percentile (right) male pedestrian model impacting the BMW with the simulated impact velocity of 46km/h, Case 2a.

In Case 2 there were remarkable differences between the injury outcomes for the two pedestrians. The male pedestrian struck the a-pillar and suffered severe head injuries, whereas the female pedestrian only sustained minor injuries. The pedestrians were struck by the same vehicle and by the same impact velocity. This case highlights the importance of preventing pedestrians from hitting high stiffness structures and the large difference that can occur for a given impact velocity.

The stiffness of various vehicles parts was generated from component tests at 40 km/h (van Rooij et al., 2003 and Mizuno and Kajzer 2000). The range of impact velocities used in these simulations was 40 ± 6 km/h. The simulations were thus carried out at a range of impact severities close to that for which the force-penetration curves were defined.

It has previously been highlighted by among others van Rooij et al. (2003) that generating a vehicle model with the correct geometry largely determines where on the vehicle various parts of body impact. In addition, localized contact stiffness characteristics have a great influence on the injury outcome. Therefore great care was taken to ensure that for each case vehicle, profiles and appropriate stiffnesses were used in the simulations. Furthermore, the initial position of the pedestrian, braking distance and impact velocity from the real-world case were important factors in the reconstruction of the real-world pedestrian collisions. These all played an important role in order to generate the match between measured and simulated thrown distance (Figure 22) and the impact locations of the pedestrian on the vehicle (Figures 15-21).

In depth analysis and reconstruction of real-world collisions are important to link simulation responses to real-world outcomes. In this study, the pedestrian model was used to identify two head loading measurements that corresponded in increased magnitude to increased severity of MAIS 2+ head injuries. Further study of higher severity head injuries sustained in real-world pedestrian-vehicle crashes may enable a stronger link to be generated between these simulated dynamic responses and actual head injury.

CONCLUSIONS

In the reconstruction of six real-world pedestrian-passenger vehicle crashes in the range of impact velocities around 40km/h it was found that an increased 3ms linear acceleration and HIC_{15} corresponded to an increased severity of the collision in terms of MAIS head injuries for MAIS 2+.

The results of this study showed that the kinematics of the pedestrian model in the MADYMO simulations of the six real-world cases were comparable with that in corresponding collisions in terms of impact location and throw distance.

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