Accident Analysis and Prevention 79 (2015) 56–69

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

The influence of vehicle front-end design on pedestrian ground impact

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ARTICLE INFO

Article history:
Received 22 October 2014
Received in revised form 7 March 2015
Accepted 8 March 2015
Available online xxx

Keywords:
Vehicle–pedestrian collision
Ground impact
Bonnet leading edge height
Head–ground impact speed
Ground impact mechanism

ABSTRACT

Accident data have shown that in pedestrian accidents with high-fronted vehicles (SUVs and vans) the risk of pedestrian head injuries from the contact with the ground is higher than with low-fronted vehicles (passenger cars). However, the reasons for this remain poorly understood. This paper addresses this question using multibody modelling to investigate the influence of vehicle front height and shape in pedestrian accidents on the mechanism of impact with the ground and on head ground impact speed. To this end, a set of 648 pedestrian/vehicle crash simulations was carried out using the MADYMO multibody simulation software. Impacts were simulated with six vehicle types at three impact speeds (20, 30, 40 km/h) and three pedestrian types (50th % male, 5th % female, and 6-year-old child) at six different initial stance configurations, stationary and walking at 1.4 m/s.

Six different ground impact mechanisms, distinguished from each other by the manner in which the pedestrian impacted the ground, were identified. These configurations have statistically distinct and considerably different distributions of head–ground impact speeds. Pedestrian initial stance configuration (gait and walking speed) introduced a high variability to the head–ground impact speed. Nonetheless, the head–ground impact speed varied significantly between the different ground impact mechanisms identified and the distribution of impact mechanisms was strongly associated with vehicle type. In general, impact mechanisms for adults resulting in a head-first contact with the ground were more severe with high fronted vehicles compared to low fronted vehicles, though there is a speed dependency to these findings. With high fronted vehicles (SUVs and vans) the pedestrian was mainly pushed forward and for children this resulted in high head ground contact speeds.

1. Introduction

The World Bank estimates that each year 1.2 million pedestrians die in road accidents, 35% of which are children (World Bank, 2002; Lopez et al., 2006). The Pedestrian Crash Data Study (PCDS) database in the United States shows that injuries to the lower extremities and head are the most frequent in pedestrian accidents, with head injuries being usually the most severe (Jarrett and Saul, 1998; Chidester and Isenberg, 2001). An epidemiology study showed that pedestrians struck by an SUV are twice as likely to sustain brain injury as pedestrians struck by passenger cars (Ballesteros et al., 2004). The main source of head injuries is the bonnet in SUV accidents but the windscreen dominates in passenger car accidents (Longhitano et al., 2005). Comparing dummy and post mortem human surrogates (PMHS) impact tests with an SUV and a small-sedan at 40 km/h Kerrigan et al. (Kerrigan et al., 2005a,b, 2012) found that the velocity/HIC score at head strike for a sedan was greater than for an SUV and the increased potential for head injuries shown by accident data (Ballesteros et al., 2004) was attributed to the greater stiffness of the bonnet region struck in SUV cases compared to the windscreen struck in car cases. Full scale cadaver tests with a mid-sized sedan and a small city car showed that the whole body kinematics and injury pattern is strongly affected by the kinematics of the pelvis during the vehicle–pedestrian interaction which depends on the pedestrian stature relative to the vehicle front geometry (Subit et al., 2008).

As seen above, most research efforts have focused on minimising injuries arising from the primary impact with the vehicle. Nonetheless, despite uncertainty in attributing injuries to vehicle or ground contact, accident data show that pedestrian ground contact injuries are also significant. Otte and Pohlemann (2001) analysed 293 pedestrian impact cases and found that injuries could be attributed to ground contact in 66% of cases, and in 11% of cases they were the most severe. They also pointed out

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http://dx.doi.org/10.1016/j.aap.2015.03.009
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that head injuries were more frequent and more severe for vehicle bonnet leading edge (BLE) heights above 700 mm and in the vehicle impact speed range between 20 and 40 km/h. Similarly, a study of 522 cases from the US Pedestrian Crash Data Study (Roudsari et al., 2005) found that in 21% of cases injuries could solely be attributed to ground contact, and that ground impact was the main cause (39%) of head injuries for adults struck by light truck vehicles (LTVs).

Pedestrian ground contact mechanisms are highly variable, but in recent years studies have been conducted to investigate the mechanism of injury generation from pedestrian contact with the ground (Kendall et al., 2006,d; Simms and Wood, 2006c,d; Simms et al., 2011). These have focused on head injuries, since these are both frequent and the most severe (Jarrett and Saul, 1998). Simms and Wood (2006a) performed multibody simulations of pedestrian impacts with a saloon car and an SUV. They found that, while head injuries from vehicle impact were strongly dependent on impact velocity, injuries from ground impact were variable but mainly influenced by pedestrian head drop height and not by vehicle speed.

Similarly, Kendall et al. (2006) performed impact simulations of the MADYMO multibody pedestrian model with FE models of a small sedan car and an SUV. Overall the vehicle appeared to be more likely to cause injuries than the ground, but the ground was still the main cause of injuries in 25% of cases. In addition, the severity of ground related injuries with respect to vehicle-related injuries was found to be higher with the SUV than with the car. Simms et al. (2011) simulated impacts with pedestrian models of a mid-size male and a small female with six vehicle types at speeds between 25 and 35 km/h. They found that vehicles with high bonnet leading edges such as SUVs were more likely to lead to a direct head impact with the ground compared to lower fronted vehicles. In addition six recurring pedestrian-ground impact mechanisms were observed in 94% of the 72 simulated cases. However, in this preliminary study the vehicle shapes were approximate, the speed range was limited and although the influence of gait on pedestrian kinematics is well established (Elliott et al., 2012), only two gait stances were considered.

Gupta and Yang (2013) simulated impacts of a mid-size male, a small female and a 6-year-old child against FE models of a sedan car and an SUV and found that a lowered car front profile and a raised SUV front profile prevented direct head impact with the ground. In contrast, a raised-front car profile and a lowered-front SUV profile led mainly to head-first impacts with the ground, but it was unclear why this occurred.

In the aforementioned studies (Kendall et al., 2006; Simms and Wood, 2006a; Simms et al., 2011; Gupta and Yang, 2013) the head injury risk evaluation was performed by calculating the HIC scores from impacts with the vehicle and the ground. However, the MADYMO multibody pedestrian model is not yet validated for the prediction of head injuries from the impact with the ground, and results are very sensitive to the contact stiffness in the modelling. A kinematic approach followed by Hamacher et al. (2012) in a multibody computational investigation found that SUVs and vans were associated with higher projection distances, and the authors concluded that high-fronted vehicles therefore pose a higher risk of pedestrian head injuries from the ground contact.

Overall, a biomechanical analysis of the relationship between pedestrian head ground injuries and vehicle type remains incomplete. The objective of the present paper is therefore to use a multibody computational approach to evaluate whether the ground impact mechanisms identified by Simms et al. (2011) could be clearly identified even when a more representative set of vehicle shapes, and a broader range of vehicle impact speeds and pedestrian initial positions is considered. Moreover, this work aimed at assessing whether a relation could be identified between the pedestrian ground impact configuration (head first, pelvis first etc.) and vehicle front shape and height as assessed by bonnet leading edge height.

2. Methods

2.1. Pedestrian models

The 50th % male, 5th % female and the 6-year-old child MADYMO multibody pedestrian models (MADYMO, 2011) were applied in a vehicle pedestrian impact with the initial pedestrian orientation perpendicular to the direction of vehicle travel (i.e. the pedestrian was struck from the left). The main features of the used pedestrian models are shown in Table 1. These three pedestrian models were chosen to have a wider representation of road users. Since the simulations were analysed individually, the number of employed pedestrian models was limited to three in order to attain a reasonable analysis time. The 50th % mid-size male pedestrian model was preferred to the 95th % male pedestrian as it has been extensively validated in (Van Rooij et al., 2003; Anderson et al., 2007) for the reproduction of pedestrian impacts and the analysis of vehicle contact. The model has recently been compared to staged tests and a real collision in terms of head trajectory, longitudinal and transverse head translation relative to the primary contact location of the pedestrian on the vehicle, impact location on the head, head impact time and head impact velocity (Elliott, 2011). The results showed that the model can be used to quantitatively test the influences of pre-impact vehicle speed, pedestrian speed and pedestrian stance on pedestrian kinematics during the interaction with the vehicle (Elliott et al., 2012). Attempts have also been made to validate the pedestrian models in MADYMO by reconstructing real collisions. Linder et al. (2005) used the MADYMO pedestrian model to simulate real accidents and compared the response of simulations to collision data in terms of head impact location and pedestrian throw distances (within 20% of the estimated values from post-collision data). Yao et al. (2008) used the pedestrian model in MADYMO to reconstruct 10 real-world collisions finding a good correspondence with the collision data in terms of pedestrian wrap-around distance (errors of 2–4%) and pedestrian throw distance (errors of 0–16%).

The 5th % female and the 6-year-old child models were obtained by scaling the 50th % male model using MADYMO/SCALER (Happee et al., 1998). No direct validation data of the 5th % female and the 6-year-old child models are available yet.

2.2. Vehicle models

The front shapes of six vehicle types were modelled in MADYMO with 5 extruded cylinders and one ellipsoid. The models, shown in Fig. 1, were based on actual vehicles representative of six

Table 1
MADYMO pedestrian models.

	6-year-old child	5th percentile female	5th percentile male
			
Height (m)	1.17	1.53	1.74
CG height (m)	0.665	0.843	0.958
Weight (kg)	23.0	49.8	75.7