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Shape Design of Vehicle Frontal Area for Reducing Pedestrian Injuries

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ABSTRACT: *In a typical vehicle–pedestrian collision, the leading edge or top surface of the hood impacts the pelvis and upper torso, and the hood or windshield strikes the head. The body shell of a vehicle first contacts and injures the body of the pedestrian in a vehicle–pedestrian collision; the shape of the vehicle front determines the location and severity of injuries. Thus, the shape of the vehicle front should be designed in a manner that can minimize casualties. Given this rationale, this study adopted MADYMO to construct a rigid model in which the behaviors of a pedestrian being impacted by a vehicle were simulated, and pedestrian injuries were analyzed. In a vehicle–pedestrian collision, the windshield, hood, bumper, and leading edge of the hood of the car contact the body of the pedestrian. Moreover, the location of the windshield depends on the length of the hood. Thus, the length of the hood, height of the leading edge of the hood above the ground, and bumper lead were used as parameters for the analysis of pedestrian casualties. The criteria for the design of the vehicle front shape that may help to reduce pedestrian casualties in road-traffic accidents were subsequently developed on the basis of the results of pedestrian injury analysis. The proposed design criteria for the vehicle front shape can be used as a reference for automobile manufacturers and researchers to design the vehicle front shape.*

KEYWORDS*: Pedestrian; Vehicle Front; Injury; Hood, Bumper; MADYMO.*

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I. INTRODUCTION

Researchers have extensively studied safety precautions formotor vehicle occupants. However, those for pedestrians are relatively less explored. Casualties among vehicle occupants involved in motor vehicle collisions (MVCs) have declined substantially; however, those among pedestrians in such accidents have shown no evident decrease. Therefore, numerous researchers have investigated vehicle–pedestrian collisions, conducted experiments to improve pedestrian safety, and promoted the formulation of laws that enhance pedestrian safety. Pedestrian casualties are largely caused by front-end MVCs and include injuries predominantly in the legs, pelvis, head, and chest [1, 2]. In a typical vehicle–pedestrian collision, the bumper and the leading edge of the hood of the car contact the lower limbs of the pedestrian. The leading edge or top surface of the hood impacts the pelvis and upper torso, and the hood or windshield strikes the head [3].

Automotive designers focus more on the appearance and performance of road vehicles than on the impact of their design on pedestrian safety. Furthermore, the bumper and hood of a car are typically designed to attenuate impact from its collision with another vehicle. The body shell of a vehicle first contacts and injures the body of the pedestrian in a vehicle–pedestrian collision; the shape of the vehicle front determines the location and severity of injuries. Thus, the shape of the vehicle front should be designed in a manner that can minimize casualties.

Severity of pedestrian casualties from car crashes can be analyzed using impactors [4, 5], crash test dummies [6, 7], and computer-aided engineering [8~11]. In pedestrian-injury tests with impactors, each part of the car structure is subjected to impact forces from different impactors. These tests cannot be used to obtain data on the behaviors and overall injury severity of a pedestrian in a car crash; only the level of impairment of a body region of the pedestrian and that of the car can be measured. In pedestrian-injury tests with crash test dummies, a high-speed camera is used to record a suspended dummy that is being impacted by the vehicle. The dummy is in a walking position, and an accelerometer is mounted on the dummy to examine the behaviors of the test device and the damage to its body parts during collision. Therefore, pedestrian-injury tests with dummies yield more comprehensive data than those with impactors. Pedestrian-injury tests with computer-aided engineering are based on numerous methods and use computational modeling to simulate collision, thus analyzing the behaviors of pedestrians during collision. Computer-aided engineering entails lower costs than the aforementioned test devices; however, the model used in the process must be accurate and validated.

The shape of the vehicle front determines the severity of injury to the lower limbs, pelvis, and head of pedestrians in car crashes [12]. This underlines the need for designing the vehicle front in a manner that can reduce pedestrian casualties. Given this rationale, this study adopted MADYMO to construct a rigid model in which the behaviors of a pedestrian being impacted by a vehicle were simulated, and pedestrian injuries were analyzed. In a vehicle–pedestrian collision, the windshield, hood, bumper, and leading edge of the hood of the car contact the body of the pedestrian. Moreover, the location of the windshield depends on the length of the hood. Thus, the length of the hood, height of the leading edge of the hood above the ground, and bumper lead (i.e., the extent to which the bumper protrudes in a horizontal position in relation to the leading edge of the hood) were used as parameters for the analysis of pedestrian casualties. The criteria for the design of the vehicle front shape that may help to reduce pedestrian casualties in road-traffic accidents were subsequently developed on the basis of the results of pedestrian injury analysis. In summary, rigid multi-body models of a vehicle and a dummy were established and verified in this study. The proposed design criteria for the vehicle front shape can be used as a reference for automobile manufacturers and researchers to design the vehicle front shape.

II. ANALYSIS OF PEDESTRIAN INJURIES DURING COLLISION WITH VEHICLES

2.1 Vehicle–pedestrian collision model

For the analysis of the vehicle–pedestrian collision, a preprocessing application for creating MADYMO models, XMADgic, was used to construct rigid multi-body vehicle and pedestrian models and to specify environmental parameters.

(1) Pedestrian model

MADYMO includes multiple dummy models. A rigid dummy model of height 175 cm and weight 77 kg was selected as a pedestrian model. To estimate the force sustained by the femurs and tibias of the pedestrian model during collision, the ellipsoids between thighs and calves were replaced with those of equivalent size, and a joint was embedded between the ellipsoids. The model (Fig. 1) comprised 37 ellipsoids of varying sizes and 16 movable joints between the ellipsoids. Twenty-four accelerometers were mounted on the ellipsoids to collect data during simulated vehicle–pedestrian collision.

(2) Vehicle model

The vehicle model was constructed on the basis of data from crash simulations with postmortem human subjects (PMHS) [13]. The front shape of the model and its parameters are presented in Fig. 2, in which BL is the horizontal distance from the bottom of the hood to the front end of the bumper, LEH is the height of the bottom of the hood above the ground, BCH is the height of the front end of the bumper above the ground, HL is the length of the hood, and α is the angle of the hood. The vehicle model comprised multiple ellipsoids: the windshield, hood, hood leading edge, bumper, and tires (Fig. 3).

(3) Conditions of vehicle–pedestrian collision

In a simulated vehicle–pedestrian collision, the vehicle impacted the left side of the pedestrian at 40 km/h (Fig. 4), with the coefficient of friction set as 0.67 (between the pedestrian and the ground), 0.2 (between the pedestrian and the vehicle), and 0.8 (between the vehicle and the ground) and the coefficient of damping as 3000 Ns/m [6].

2.2 Simulation of vehicle–pedestrian collision

(1) Analysis of pedestrian injuries

In the MADYMO simulation of vehicle–pedestrian collision, injuries to the head, pelvis, thighs, and calves of the pedestrian model were analyzed. The head injury criterion (HIC) was 1255, which exceeded the threshold of 1000 and corresponded with Code 4 (severe injury) on the Abbreviated Injury Score (AIS) [14]. An AIS-Code of 4 represents cranial fractures and nerve injuries, which can endanger the life of the victim. The pelvic (the force on the ilium) sustained by the pedestrian model was 623.75 N, which was within the pelvic tolerance of 9921.65 N [15]. The thighs sustained a moment of 94.95 Nm on the x-axis force, with a couple moment of 392.67 Nm, whereas the calves sustained an acceleration of 216.5 g. The thighs and calves might have been fractured because the force that they sustained exceeded their respective acceptable levels of 220 Nm and 150 g, as defined by the European Experimental Vehicles Committee [16].

(2) Validation of the reliability of pedestrian injuries

The accuracy of the rigid multi-body models applied in pedestrian injury analysis was determined on the basis of the findings of Rooij [17]. Similar to the study of Rooij, the present study developed the vehicle model on the basis of data from crash simulations with PMHSs and adopted an adult male dummy model. Moreover, injury data of the vehicle–pedestrian collision model used in this study were virtually identical to those in the study of Rooij (Table 1). Thus, the collision model used in the present study had adequate reliability.

III. EFFECTS OF VEHICLE FRONT SHAPES ON THE SEVERITY OF PEDESTRIAN INJURIES

The aforementioned rigid multibody vehicle and dummy models were also used to study the effects of vehicle front shapes on the severity of pedestrian injuries. In addition, the vehicle model was also based on data from PMHSs. The hood length, height of the hood leading edge above the ground, and bumper lead were set between their respective higher and lower values for a commercially available sedan. The hood leading edge was 653 mm above the ground for the sedan; its effects on the severity of pedestrian injuries were analyzed at 11 levels of height from 590 to 987 mm. The hood length was 511 mm for the sedan; its effects on pedestrian injuries were analyzed at 11 levels of lengths from 340 to 1210 mm. The effects of bumper lead on the severity of pedestrian injuries were analyzed at five values, with a maximum value of 70 mm.

3.1 Effects of the height of the hood leading edge above the ground

Figure 5 depicts the relationship between the height of the hood leading edge above the ground and HIC. Lower HIC levels were observed at the higher and lower levels of the height range of the hood leading edge above the ground. For example, at lower heights of the leading edge, the hood first contacted the upper limbs of the dummy in a 40-km/h collision (Fig. 6), and the limbs absorbed substantial collision impact, thus providing a buffer for injury to the head. Similarly, when the hood leading edge was higher above the ground, the upper body of the dummy swung slightly, contacting the hood directly (Fig. 7) and allowing the trunk above the pelvis to absorb the collision impact, thus reducing the HIC. However, when the height of the hood leading edge above the ground increased, the vehicle collided with the pelvis directly, thus exacerbating the pelvic injury. Table 2 presents the heights of the hood leading edge above the ground in relation to the injuries of head, pelvic, femoral, and tibial. The HIC peaked when the hood leading edge was 786 mm above the ground, and the upper body of the dummy nearly rose into the air following collision, with the head being the first to collide into the hood (Fig. 8). When the hood leading edge was 590 mm above the ground, both the force of pelvic and bending moment of femoral decreased slightly, and the HIC value declined by approximately 250, despite a slight increase in the tibial acceleration. Under this condition, the levels of impairment of all the body regions, except the pelvis, exceeded their respective thresholds.

3.2 Effects of the hood length

The results of the previous analysis suggested that the severity of injury to all bodies was the lowest when the hood leading edge was 590 mm above the ground. Thus, the effects of 11 hood lengths (including a hood length of 511 mm for the sedan) on the severity of pedestrian injuries with a hood leading edge of 590 mm above the ground were analyzed. A comparison of the hood length and severity of pedestrian injuries is presented in Table 3. The hood length positively correlated with the injuries of head, pelvic and femoral. Notably, the HIC value declined substantially with the decrease in the hood length. The tibial acceleration was the highest at a hood length of 511 mm and exhibited only slight changes at the other hood lengths.

Figure 9 illustrates the relationship between the hood length and pelvic injuries. The hood length positively correlated with the force on the ilium. When the dummy was impacted by vehicles with a shorter hood, its wrists contacted the hood to support the body, causing the upper body to hit the windshield head-on and the pelvis to shift with normal force, thus attenuating the impairment of the pelvis (Fig. 10). When the dummy was impacted by vehicles with a longer hood, only the pelvis contacted the vehicle and absorbed the entire collision impact (Fig.11). Moreover, the hood length exerted nonsignificant effects on the impairment of the lower limbs, with the tibial acceleration within the 150-g threshold across all hood lengths, except 511 mm. The hood length positively correlated with HIC value (Fig. 12), indicating that the upper trunk contacted the windshield earlier and sustained less impairment accordingly when the dummy was impacted by vehicles with a shorter hood than with a longer one. Overall, the level of impairment of all body regions, except calves, decreased with the decrease in the hood length.

3.3 Effects of the bumper lead

The results of the previous analysis suggested that the level of impairment of all the four body regions was the lowest when the hood was 340 mm long. Accordingly, the effects of six bumper leads (including a bumper lead of 70 mm for the sedan) on the severity of pedestrian injuries were analyzed with the 340-mm-long hood. A comparison of bumper lead and the severity of pedestrian injuries is presented in Table 4. The results indicate that bumper lead positively correlated with the bending moment of femoral and tibial accelerations, but had negligible effects on the pelvic injury. When the bumper faced downwards along the hood leading edge (i.e., exhibited no protrusion), the lower limbs contacted both the bumper and the hood leading edge during collision (indicating the increased contact area of the limbs on the vehicle front), leading to less impairment of the thighs and calves compared with the result with a protruding bumper. Figure 13 presents the relationship between the bumper lead and HIC value. It indicates a negative relationship between the bumper lead and HIC. Moreover, the hood leading edge and the bumper of commercially available sedans typically appear as a unitary structure, thus rendering it difficult to determine the shape and location of the bumper; such design schemes ensure less impairment of the thighs and calves of pedestrians when they collide with vehicles.

IV. DESIGN OF VEHICLE FRONT SHAPE

Given the results of the analysis of the effects of vehicle front shape parameters on the severity of pedestrian injuries, a vehicle front shape was proposed to minimize the impairment of all the four body regions during collision. The aforementioned findings suggest the following: (1) when the hood leading edge was lower above the ground, the injuries of head, pelvic and femoral significantly decreased, whereas the tibialimpairment increased; (2) when impacted with vehicles with a shorter hood, the injuries of head, pelvic and femoral declined, whereas the decrease in the tibialimpairment was within the acceptable level; and (3) the amount of protrusion of the bumper and the angle of the hood leading edge should be adjusted in a manner that can minimize injury to the thighs and calves.

To minimize pedestrian injuries in a car crash, a vehicle front shape was developed on the basis of the vehicle front shape parameters used in previous analyses. The proposed vehicle front shape had a hood length of 300 mm, a bumper lead of 55 mm, and a hood leading edge of 500 mm above the ground. A comparison of the severity of pedestrian injuries between the original and proposed vehicle front shapes is presented in Table 5. The HIC was 659.35 for the proposed vehicle front shape, which is 46% lower than that for the original one (1225) and below the threshold of 1000. Moreover, the proposed vehicle front shape induced head injuries with an AIS-Code of 2 (moderate injury), whereas the original one caused such injuries with an AIS-Code of 4 (severe injury) for the original one. The force on the ilium was 535.87 N for the proposed vehicle front shape, which is 15% lower than that for the original one (623.75 N). The bending moment of femoral and tibial accelerations were 392.67 Nm and 216.5 g, respectively, for the proposed vehicle front shape, which are 35% and 22% lower than those for the original vehicle front shape. In summary, the level of impairment of the head exhibited the highest decrease in impairment in a simulated vehicle–pedestrian collision with the proposed vehicle front shape, whereas that of the other body regions decreased by at least 15%.

V. CONCLUSION

In this study, MADYMO was used to construct rigid multi-body models of vehicle–pedestrian collision, the behaviors and injuries of the dummy in the models were compared, and the applicability of the models was examined. Moreover, the effects of the vehicle front shape parameters on the severity of pedestrian injuries in the vehicle–pedestrian collision models were analyzed to propose criteria for the design of a vehicle front shape that can minimize such injuries. This study has the following conclusions:

1. The simulation of vehicle–pedestrian collisions based on MADYMO rigid multi-body models and the pedestrian injury analyses conducted using the models yielded results similar to those of crash simulations. Thus, the rigid multi-body theory can be used to simulate vehicle–pedestrian collision simulation and analyze pedestrian injuries.
2. In a vehicle–pedestrian collision, a hood leading edge closer to the ground is associated with less impairment of the head, pelvis, and thighs, whereas that farther from the ground is associated with less impairment of only the lower limbs.
3. Shortening the hood length can attenuate the impairment of the head, pelvis, and thighs; reduce the severity of tibial injury to acceptable levels; and neutralize the increases in the level of impairment of the lower limbs due to the adjustment of the height of the hood leading edge above the ground.
4. Protrusion is essential to the design of the front bumper, and bumper lead must be aligned with the height of the hood leading edge above the ground. Generally, front bumpers with slight protrusion contribute to less severe pedestrian injuries than those without any protrusion or hood leading edges higher above the ground.

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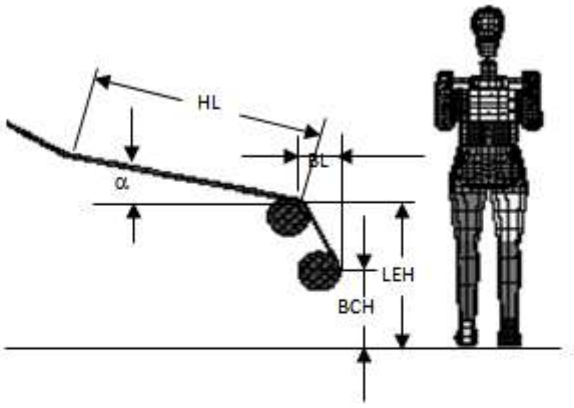
Fig. 1 Pedestrian model

BL	LEH	BCH	HL	α
145mm	763mm	383mm	1120mm	12°

Fig. 2 The parameters of vehicle front



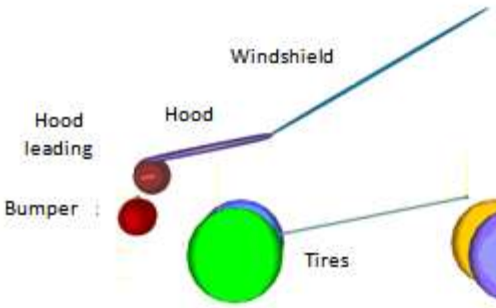


Fig.3 Vehicle model

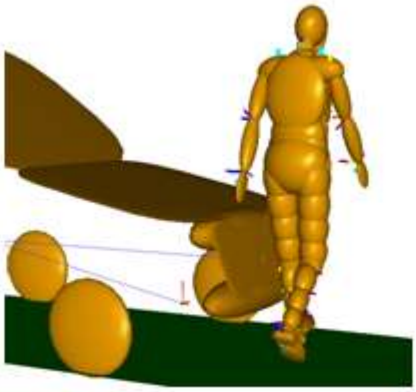


Fig. 4 Vehicle–pedestrian collision model

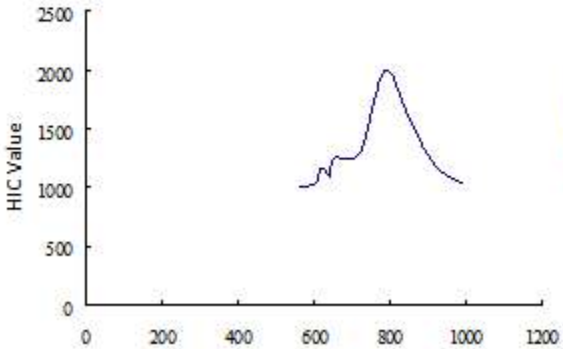


Fig. 5 The relationship between the height of the hood leading edge above the ground and HIC

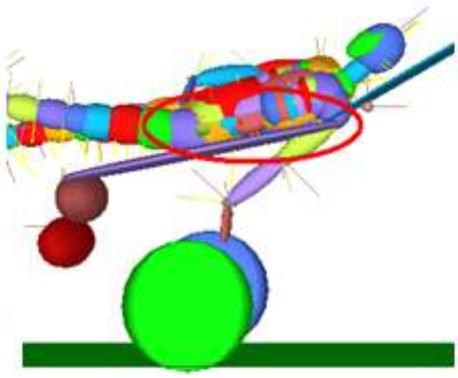


Fig.6 Kinematic response for the car with a lower heights of the leading edge

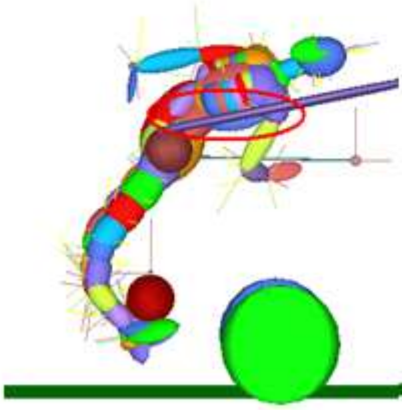


Fig. 7 Kinematic response for the car with a higher heights of the leading edge

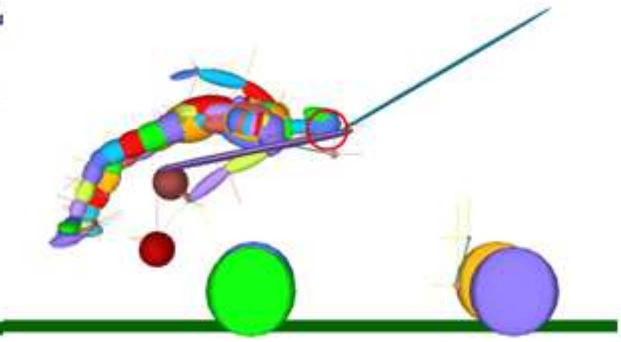
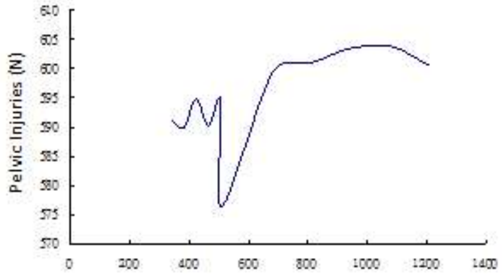


Fig. 8 Kinematic response for a 786 mm height of the hood leading edge above the ground



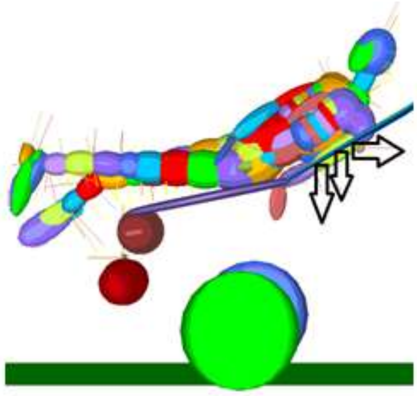


Fig. 9 The relationship between the hood Fig. 10 Kinematic response for the car with a length and pelvic injuriesshorter hood length

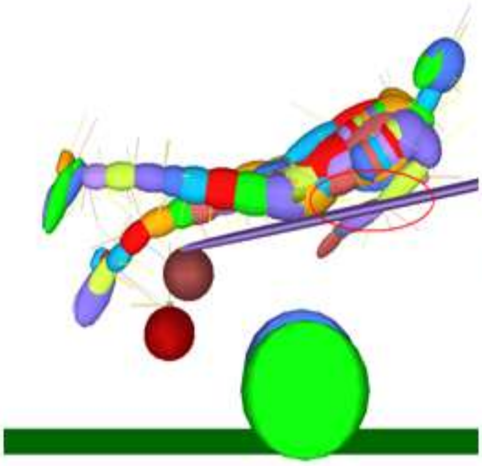
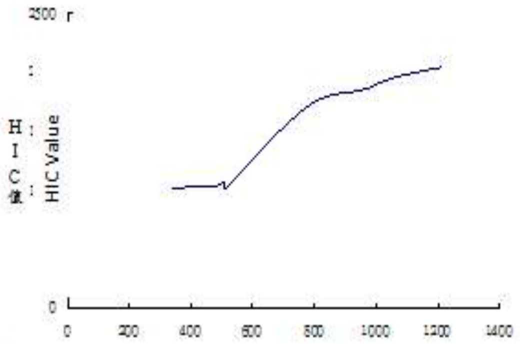



Fig. 11 Kinematic response for the car withFig. 12 The relationship between the hood length a longer hood lengthand head injuries

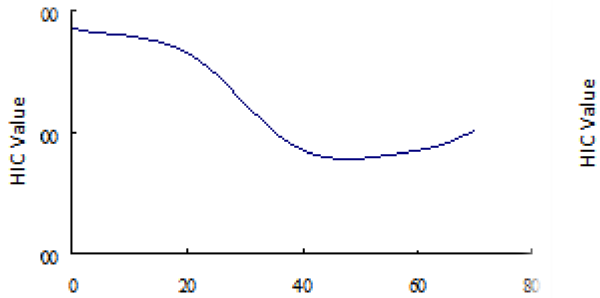


Fig. 13 The relationship between the bumperlead and HIC value

Table 1 injury data of the vehicle–pedestrian collision

	Rooij[17]	Present study
Head Injury (HIC)	1420	1255
Pelvic Injury (N)	675	623.75
Thighs Injury (N.m)	99.56	94.95
Calves Injury (g)	237	216.5

Table 2 A comparison of the heights of the hood leading edge above the ground and severity of pedestrian injuries

Injuries Height	Head (HIC)	Pelvic (N)	Thighs (N.m)	Calves (g)
987.30mm	1038.1	13167	245.70	208.14
920.44mm	1178.7	10627	214.81	203.94
853.58mm	1558.0	670.31	238.90	208.00
786.72mm	1994.7	670.51	281.57	204.55
719.86mm	1283.9	660.77	345.80	257.56
653.00mm	1255.0	623.75	392.67	216.50
640.42mm	1096.5	613.91	390.50	222.62
627.84mm	1160.1	604.69	390.41	236.70
615.26mm	1156.9	605.45	280.25	241.29
602.69mm	1031.7	590.31	271.70	240.62
590.12mm	1014.9	576.38	307.34	243.00

Table 3 A comparison of the hood length and severity of pedestrian injuries

Injuries Hood Length	Head (HIC)	Pelvic (N)	Thighs (N.m)	Calves (g)
1210 mm	2041.4	600.66	334.54	148.81
1078.2 mm	1970.6	603.92	328.85	148.86
946.4 mm	1843.6	603.44	333.04	148.78
814.6 mm	1774.3	601.07	337.53	148.82
682.8 mm	1488.2	599.31	336.91	148.89
511 mm	1014.9	576.38	307.34	243.00
508.8 mm	1064.3	594.65	314.68	149.02
466.6 mm	1021.4	590.28	310.30	149.02
424.4 mm	1033.8	594.74	313.38	149.02
382.2 mm	1021.0	589.73	309.82	149.02
340 mm	1001.2	591.32	310.68	149.02

Table 4 A comparison of the bumper lead and severity of pedestrian injuries

Injuries Bumper Lead	Head (HIC)	Pelvic (N)	Thighs (N.m)	Calves (g)
0mm - 90°	1085.0	593.66	271.43	126.41
20mm - 80°	1065.60	598.43	269.07	141.89
40mm - 75°	984.70	587.51	344.50	149.64
60mm - 70°	985.10	589.92	326.21	151.44
70mm - 67°	1001.20	591.32	310.68	149.02

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