Study of Human Kinetic Behavior and Injury Mechanism in Pedestrian Accident with Human FE Model

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Abstract: With the development of vehicles, occupant fatalities have decreased steadily over the decades, however, no significant change has been observed in pedestrian fatalities. In Japan, in-vehicle occupant fatalities in accidents were surpassed by pedestrians in 2008.It is believed to be necessary and urgent to decrease the pedestrian fatalities. Although pedestrian protection test procedures such as legform and headform impactor tests have been established, it is still difficult to estimate human injury level in pedestrian accidents, especially with the consideration of human kinetic behavior. In this research, by using human Finite Element model to simulate a pedestrian in an accident, human kinetic behavior is analyzed in detail. Because the head is the most frequently injury-associated region in severe pedestrian accidents, the mechanism of head injuries is also investigated in this research.
Keywords: Ground impact injury, pedestrian, Head injury, Human FE model.

1 Introduction

With the development of vehicles to comply with safety regulations and assessments, occupant fatalities have decreased steadily over the decades, however, no significant change has been observed in pedestrian fatality data. As indicated by traffic fatality data in Japan from 1997 to 2007[1], occupant fatalities decreased over 50%. While, pedestrian fatalities decreased no more than 20%. A common tendency can be observed in traffic accident fatality data from 1994 to 2006 in United States of America.[2] Occupant fatalities decreased slightly, but pedestrian fatalities kept nearly the same. So it is believed to be necessary and urgent to decrease the pedestrian fatalities.

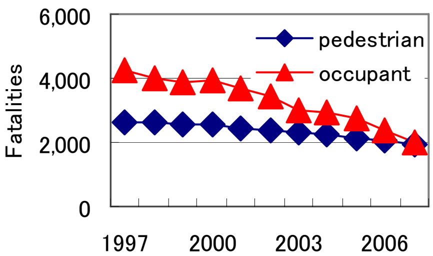

Figure 1 Fatalities of traffic accidents in Japan(Police Survey)

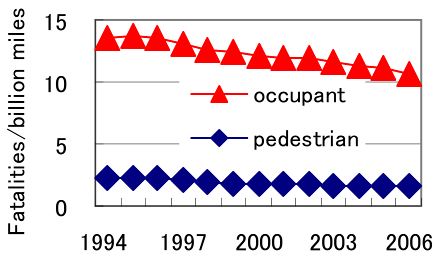

Figure 2 Fatalities of traffic accidents in U.S.A(FARS)

To investigate the injury sources of pedestrian accidents, the pedestrian accident database NASS/PCDS[3] is utilized. By analyzing injury sources of severe accident cases with Max AIS3+, the main injury sources for pedestrians are identified and listed in figure 3. Most of the injury sources are frontal structures such as bumper, bonnet and windshield.

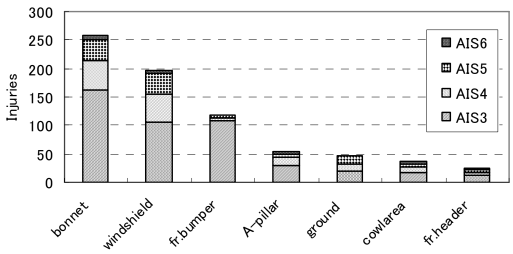

Figure 3 Main injury sources of severe pedestrian injuries(NASS/PCDS)

Recently, with the development of pedestrian protection regulations and assessments, pedestrian protection criteria are established by using headform and legform impactor tests. As a result, more consideration is taken regarding pedestrians in designing vehicle frontal structures such as bumper, bonnet and windshield. However, current regulations and assessments do not cover the main injury sources completely. The A-pillar area and the ground are left out of regulations and assessments. Concerning the A-pillar area, concept of airbags covering the A-pillar area has been proposed[6], as in figure 4. In this research, the ground impact injury in pedestrian accidents is taken into investigation.

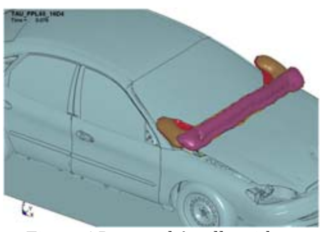
Figure 4 Proposed A-pillar airbag

2 Analysis of Ground Impact Injury

2.1 Data Gathering

The pedestrian accident database NASS/PCDS[3], containing 552 cases gathered from 1994 to 1998 in the United States of America, is utilized. From 552 cases of pedestrian accidents, 13 cases of severe ground impact injuries are separated by using the following criteria:

1 Ground impact is observed, and the severity of injuries from ground impact is AIS3+.
2 Vehicle type, front shape, collision velocity and pedestrian movement are documented.
3 Injury location and its injury source are documented.

All separated cases are listed in table 1.

Table 1 13 Cases of Severe Ground Impact Injury

	Vehicle			pedestrian			
	type	velocity	bonnet height	age	height	injury location	AIS
case1	sedan	56km/h	65cm	39	171cm	head	4
case2	sedan	60km/h	76cm	33	173cm	head	4
case3	sedan	39km/h	64cm	25	160cm	leg	3
case4	sedan	53km/h	70cm	39	183cm	leg	3
case5	sedan	32km/h	76cm	8	121cm	head	4
case6	light truck	29km/h	82cm	12	143cm	head	3
case7	light truck	33km/h	78cm	79	175cm	head	5
case8	light truck	60km/h	106cm	81	168cm	head	3
case9	light truck	47km/h	114cm	79	183cm	head	5
case10	SUV	8km/h	97cm	90	170cm	head	5
case11	sedan	5km/h	70cm	93	170cm	head	3
case12	light truck	16km/h	100cm	33	175cm	torso	4
case13	sedan	39km/h	80cm	77	163cm	leg	3

2.2 Severe Ground Impact Injury Analysis

13 cases of severe ground impact injuries are divided into 2 groups by pedestrian relative movement to the vehicle in an accident: the “forward projection” group and “wrap projection” group[8]. In the wrap projection group, the pedestrian hits the bonnet surface of the vehicle and bounces upward to the rear of the vehicle. In the forward projection group, the pedestrian is pushed forward to the front of vehicle after the first collision.

In a typical pedestrian accident, the pedestrian impacts multiple objects. According to the impact order in an accident, pedestrian vehicle impacts are generally categorized into 3 impacts for convenience:

1 First impact: pedestrian impacts vehicle front-most structure, such as bumper and grill.
2 Second impact: pedestrian falls onto the bonnet and impacts bonnet and windshield.
3 Third impact: pedestrian moves away from the vehicle and impacts the road or other structure in the environment.

2.2.1 Analysis of Wrap projection Group

From the NASS/PCDS database, 4 cases of wrap projection movement are found by data selection.

Table 2 Cases of Wrap projection Scenes

	Vehicle			pedestrian			
	type	velocity	bonnet height	age	height	injury location	AIS
case1	sedan	56km/h	65cm	39	171cm	head	4
case2	sedan	60km/h	76cm	33	173cm	head	4
case3	sedan	39km/h	64cm	25	160cm	leg	3
case4	sedan	53km/h	70cm	39	183cm	leg	3

All four cases are classified into two scenes, and their features are listed in Table 3 below.

Table 3 Features of Wrap projection Scenes

	Ground Injury	Cases No.	Pedestrian	Vehicle type	Vehicle Velocity
Scene1	head	1,2	normal adult	sedan	high
Scene2	leg	3,4	normal adult	sedan	medium high

As head injuries in accident usually lead to severe results, including danger to life, in this research, head injuries of scene1 is analyzed. In scene1, two accident cases are extremely similar. The vehicle types were sedan passenger cars, both colliding with the pedestrian at a velocity of about 60km/h. In both cases, the pedestrians were normal adults with an average height of about 170cm. The head injuries results gathered from the accident are shown in Table 4. The pedestrian’s head impacted the vehicle’s front structure in the second impact, followed by a third impact to the ground. In the collision scene, head impact occurred twice, each impact can result in severe head injuries.

Table 4 Details of Head Injury in Scene1

	1st impact	2nd impact	3rd impact
Case1	none	Hood AIS1	Ground AIS4
Case2	none	Cowl AIS5	Ground AIS4

2.2.2 Analysis of Forward projection Group

From the NASS-PCDS database, 9 cases of forward projection movement are found by the data selection.

Table 5 Cases of Forward projection Scenes

	Vehicle type	velocity	bonnet height	pedestrian age	height	injury location	AIS
case5	sedan	32km/h	76cm	8	121cm	head	4
case6	light truck	29km/h	82cm	12	143cm	head	3
case7	light truck	33km/h	78cm	79	175cm	head	5
case8	light truck	60km/h	106cm	81	168cm	head	3
case9	light truck	47km/h	114cm	79	183cm	head	5
case10	SUV	8km/h	97cm	90	170cm	head	5
case11	sedan	5km/h	70cm	93	170cm	head	3
case12	light truck	16km/h	100cm	33	175cm	torso	4
case13	sedan	39km/h	80cm	77	163cm	leg	3

All 9 cases are classified into 5 scenes, and their features are listed in Table 6 below.

Table 6 Features of Forward projection Scenes

	injury by ground	Cases No.	Pedestrian	Vehicle type	Vehicle Velocity
Scene3	head	5,6	Child	sedan ,light truck	Medium
Scene4	head	7,8,9	elderly	light truck	Medium
Scene5	head	10,11	elderly	sedan	Very low
Scene6	torso	12	Normal adult	light truck	low
Scene7	leg	13	elderly	sedan	Medium

In this research, the head injuries of scenes 3,4 and 5 are taken into consideration.

In scene4, elderly pedestrians collided with light trucks. In scene5, elderly pedestrians collided with vehicles at an extremely low velocity. From scene5, it is observed that elderly pedestrian received severe injuries of AIS5, even at an extremely low collision velocity. It can be considered that elderly people have specific reasons to suffer severe injuries, such as degeneration of bone strength and recession of cognition ability. Because these senility specific features are not fully understood now, in this research, the child pedestrian scene3 is taken into investigation.

In scene3, two cases of child pedestrians were involved having severe head injuries of AIS3 and AIS4. The pedestrians were about ten years old, the vehicles were a sedan passenger car and a light truck, both colliding with the pedestrian at a medium velocity of about 30km/h. In scene3, the child pedestrian was hit by the vehicle in upper torso and knocked down to the road. This collision scenario is believed to be caused by relative height between the child and the vehicle[8]. According to the American child body investigation in year 1977 by Virginia University[4], child center of gravity is located at 0.57 of body height. In scene3, vehicle bonnet height in each case is above the height of pedestrian's center of gravity.

Head injury investigations in scene3 indicate that the child pedestrian's head didn't impact the vehicle in the first or second impact. In the subsequent third impact to ground, severe head injuries of AIS4 occurred.

Table 7 Details of Head Injury in Scene3

	1st impact	2nd impact	3rd impact
Case5	none	none	Ground AIS4
Case6	none	none	Ground AIS3

3 Scene Reconstruction By Finite Element Analysis

3.1 Reconstruction of Wrap projection Scene1

The sedan type passenger car in scene1 was simulated by the Ford Taurus FE model. The pedestrian was simulated by a human FE model of the AM50 body build. The collision condition was set as vehicle colliding with the pedestrian from the side at a velocity of 60km/h by referencing the accident record in case1,2.

The Taurus passenger car of 2001 model year type weighs 1500kg with a total height of 1400mm and front edge height of 750mm. The FE model of the Taurus was constructed by NHTSA National Crash Analysis Center[5] in 2007. The Vehicle FE model was constructed by using 900,000 nodes and 850,000 elements. The accuracy of the vehicle was validated against front barrier collision test.

The Human FE model was validated and modified in Toyota Gosei Corporation against multiple impactor and joint bending tests by using THUMS3.0. Because of its high biofidelity the human FE model can be used to predict human movement in an accident with more accuracy than a dummy.

In the collision scene, the ground material in the road is presumed to be concrete or asphalt. A rigid plane was used to simulate the ground in the FE model.

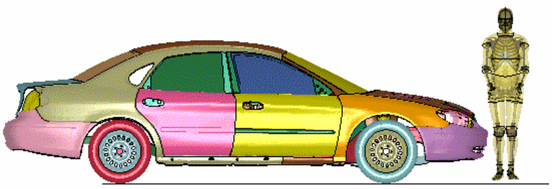

Figure 5 Collision of AM50 human with sedan passenger car

3.2 Reconstruction of Forward projection Scene3

The SUV vehicle in scene3 was simulated by the Ford Explorer FE model, and the child pedestrian was simulated by a scaled human model of 10-year-old body build. The collision condition was set as the vehicle colliding with a child pedestrian from the side at a velocity of 30km/h by referencing accident record case5,6.

The 1997 model year type Explorer weighs 2500kg with a total height of 1700mm and front edge height of 970mm. The FE model was created by NHTSA National Crash Analysis Center[5], containing about 700,000 nodes and 650,000 elements. The accuracy of the vehicle was validated against a front barrier collision test.

The 10-year-old child pedestrian FE model was scaled from AM50 human model by each body part. The scaling factor of each body part was determined by the investigation in 1977 (Anthropometry of infants, children, and youth to age 18 for product safety design)[4]

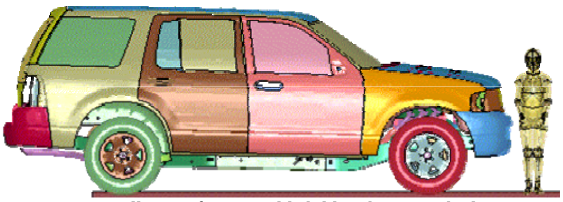

Figure 6 collision of 10year old child with SUV vehicle

3.3 Pedestrian Movement Behavior in Collision

As illustrated in Figure 7, in scene1, the adult pedestrian first impacted the bumper, followed by a second impact to bonnet and windshield. After the first and second impacts the human body was thrown to high position in a rotating movement. Finally, the body crashed into the ground with head. During the collision, the human body rotated 1.5 times in the air with actually no impact to the roof and rear structure of vehicle. The human head impacted twice, once with the windshield and once with the ground, which is consistent with the accident record.

In scene3, because the child's height is relatively close to the vehicle, the child pedestrian was hit by the front structure of vehicle in the torso as illustrated in Figure 8. The pedestrian was knocked down to the ground without a second impact to the vehicle. During the collision process, the child pedestrian head actually didn't impact the bonnet, indicating no conflict with the accident record.

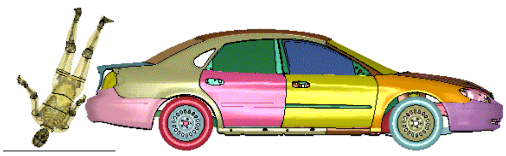

Figure 7 Adult Pedestrian Response in Collision

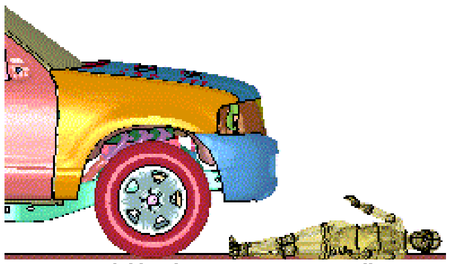

Figure 8 Child Pedestrian Response in Collision

4 Discussions And Pedestrian Protection Concept

When a human impacts the ground with velocity, injuries may occur. Because the ground is stationary and rigid in a collision scene, it is believed that the human injury level determined by the velocity of the pedestrian before impacting the ground.

In the first and second impact the vehicle, kinetic energy is transferred to the pedestrian through the vehicle front structures, accelerating the pedestrian to a high velocity. The final velocity of the pedestrian is determined by the total kinetic energy transferred from the vehicle. In this research, pedestrian protection concept is proposed by inhibiting kinetic energy transfer from the vehicle to the pedestrian using an energy absorbing structure as illustrated in figure 9

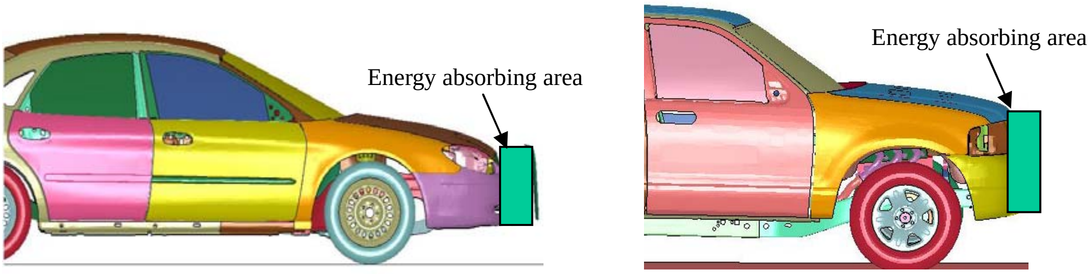

Figure 9 Energy absorbing area equipped on vehicle

4.1 Protection Concept of Wrap projection Movement in Scene1

In scene1, kinetic energy is transferred to the pedestrian in two impacts listed below:

1 In the first impact, kinetic energy is transferred to the pedestrian's leg through the bumper

2 In the second impact, kinetic energy is transferred to the pedestrian's torso and head through the bonnet and windshield According to the finite element analysis result, after first impact, the lower leg velocity of the pedestrian was accelerated far above the vehicle velocity. A protection method is proposed by absorbing leg kinetic energy to decrease pedestrian kinetic energy.

By creating the energy absorbing structure between the leg and vehicle, rebounded leg velocity decreased by 10% as shown in figure 10. The subsequent second impact velocity of the head decreased by 15%, as shown in figure 11.

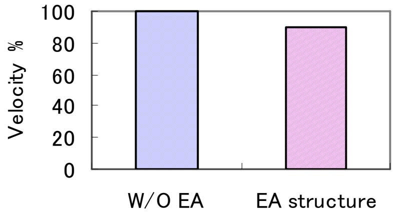

Figure 10 leg velocity after first impact

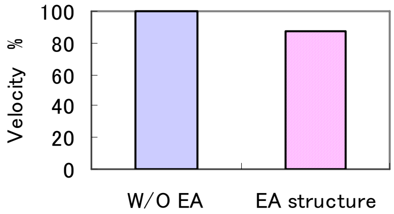

Figure 11 head velocity at second impact

Without the energy absorbing structure, the pedestrian was thrown up above the roof, finally impacting the ground by head. After the second impact to the windshield of vehicle, pedestrian movement behavior changed significantly by equipping the vehicle with the energy absorbing structure, direct head-ground impact was avoided. The relationship between energy absorption and the change of human body movement behavior hasn't been confirmed yet. Further research is needed.

4.2 Protection Concept of Forward projection Movement in Scene3

In scene3, kinetic energy is transferred during the first impact from the vehicle frontal structure to the torso of the child pedestrian. According to the finite element analysis, the pedestrian torso velocity measured at the 10th thoracic vertebra was higher than the vehicle collision velocity. The protection method is proposed by equipping the vehicle with an energy absorbing structure at the first impact position between the pedestrian's chest and the grill of the vehicle.

After equipping the energy absorbing structure, the movement behavior of the human model did not change fundamentally. However, the pedestrian torso velocity decreased 8% after first impact to the grill of the vehicle, as shown in figure12. As a result, the pedestrian head velocity at collision with the ground decreased 10%, as shown in figure 13. It indicates that the head injuries from ground impact may be mitigated by utilizing the energy absorbing structures.

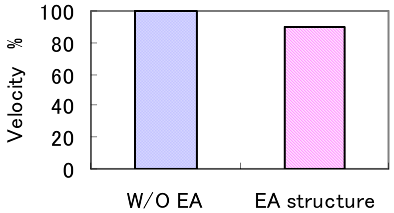

Figure 12 torso velocity after first impact

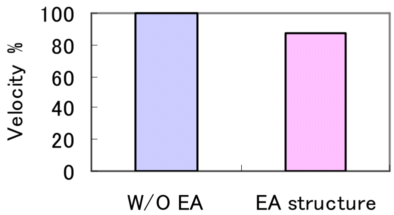

Figure 13 head velocity at ground impact

5 Conclusion

Ground impact injuries in pedestrian accident were investigated through accident records. From all 13 cases of accidents, ground impact cases are categorized into several scenes, and the features of each scene were investigated.

Two typical scenes – an adult impacting a sedan passenger car and a child impacting an SUV vehicle - are reconstructed by using the finite element analysis. Human kinetic response in each collision scene is analyzed.

By equipping energy absorbing structure to the frontal area of the vehicle, the velocity of the human body after impact is decreased, indicating the possibility of reducing injuries.

Reference

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