INJURY RISK ASSESSMENT AT THE TIMING OF A PEDESTRIAN IMPACT WITH A ROAD SURFACE IN A CAR-PEDESTRIAN ACCIDENT

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ABSTRACT

In a car-pedestrian accident, there are two major phases that exist when a pedestrian injury occurs. One is the timing of a pedestrian colliding with a car body (denoted initial collision hereafter). The other is the timing of a pedestrian colliding with a road surface (denoted secondary collision hereafter) which occurs after the initial collision.

Up until now, pedestrian protection has been considered mainly for the initial collision, and several countermeasures have been developed by automobile manufacturers. On the other hand, pedestrian protection issues in a secondary collision have not been considered in depth, therefore, collision phenomenon and pedestrian protection methods in a secondary collision have not been investigated deeply. The purpose of this study is to clarify the risk to a pedestrian in a secondary collision using traffic accident data as well as a computer simulation analysis method.

First, the reality of accidents relevant to a secondary collision was investigated by using car-pedestrian accident data. As a result, it was found that the rate of road surface causing pedestrian injury is twice the rate of injuries caused by a bonnet and fender of a car, both of which are targeted by regulations of pedestrian head protection worldwide.

Next, the phenomenon of car to pedestrian collisions was analyzed by using JARI pedestrian models which are calculated by MADYMO (Tass) and these base models' biofidelity was validated by using Post Mortem Human Subject test data. Computer simulation analyses were carried out in a total of 45 conditions which consisted of combinations of three kinds of vehicle models (sedan type, sports utility type, van type), five kinds of pedestrian models (six-year old child, fifty-year old male and female, seventy-year old male and female, because such ages are frequently involved in car-pedestrian accidents) and three collision velocities of car to pedestrian (20, 30, 40km/h).The results showed that the HIC_{15} value in a secondary collision was higher than that of the initial collision in 38 of the 45 conditions. In addition, the HIC_{15} value in 30 of those 38 conditions was over 2000.

Based on this analysis, it became clear that it is necessary to not only focus on the initial collision but also focus on a secondary collision in car-pedestrian traffic accidents.

For our future plans, we are going to conduct additional analysis by using additional sizes of human models and additional analysis conditions, and also have a plan to develop more effective countermeasures for pedestrian protection in secondary collisions to reduce pedestrian injuries which are generated by secondary collisions in the real-world.

INTRODUCTION

Approximately, 700,000 traffic accidents occur and about 4,500 lives are lost per year in Japan. However, the number of fatalities from traffic accidents has been declining in the last decade, as shown in Figure 1 [1]. In addition, the same set of statistics show that while the number of people riding in a vehicle is declining, the number of pedestrians is increasing. Furthermore, the number of pedestrians is higher than that of those riding in a vehicle in recent years. For this reason, it is important to reduce traffic accident fatalities even further and in particular, to reduce fatalities in pedestrian accidents.

In a car-pedestrian accident, there are two major phases when pedestrian injuries occur. One is the timing of a pedestrian colliding with a car body (denoted initial collision hereafter). The other is the timing of a pedestrian colliding with a road surface or other object (denoted secondary collision hereafter) which successively occurs after the initial collision.

Until now, pedestrian protection has been considered mainly for the initial collision, and several countermeasures have been developed by automobile manufacturers such as head or leg protection countermeasures. On the other hand, pedestrian protection issues in a secondary collision have not been considered in depth, therefore, protection countermeasures for pedestrians in a secondary collision have not been sufficient. Moreover, the collision phenomenon and injury risk in a secondary collision have not been clarified. It is clear that there is a delay of protection countermeasures for pedestrians in a secondary collision, while those in the initial collision have been advancing.

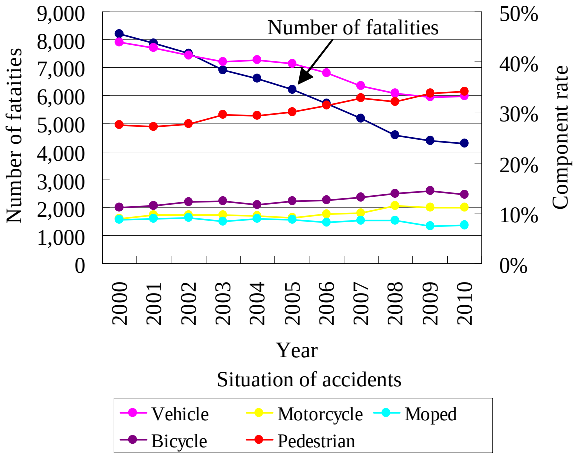


Figure 1. Transition of fatalities from traffic accidents and situation, from 2000 to 2010

The purpose of this study is to clarify the injury risk to a pedestrian in secondary collisions using traffic accident data as well as computer simulation analysis methods. In addition, countermeasures to protect pedestrians in a secondary collision are considered. This study focuses on head injuries because in an analysis of the area of injury responsible for death, head injuries caused 56% of the fatalities, as shown in Figure 2 [2].

RESEARCH RELEVANT TO A SECONDARY COLLISION IN PDEDESTRIAN ACCIDENTS

The reality of accidents relevant to a secondary collision were investigated by using car-pedestrian accident data [3] which was issued by the Institute for Traffic Accident Research and Data Analysis (ITARDA). The report was analyzed by using case examples of accident data for nine years from 1993 to 2001. Pedestrian subjects in this study totaled 104 people.

Figure 3 shows the percentage of parts of the vehicle and such as a road surface causing pedestrian head injuries (AIS2-6). Figure 4 shows the percent of a road surface causing pedestrian head injuries for each vehicle type (AIS2-6). Figure 3 shows that the percentage of a road surface causing pedestrian head injuries is approximately 20% of the total. The

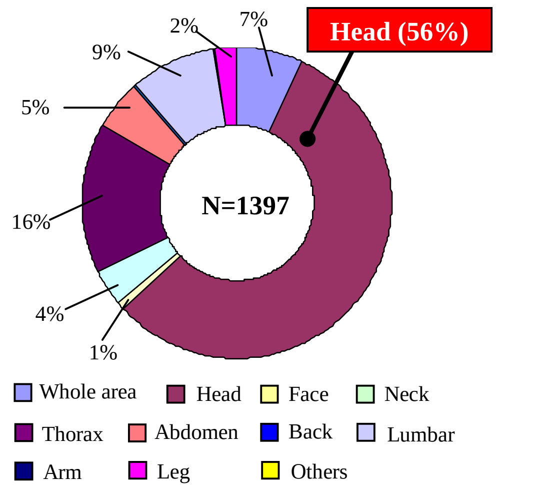
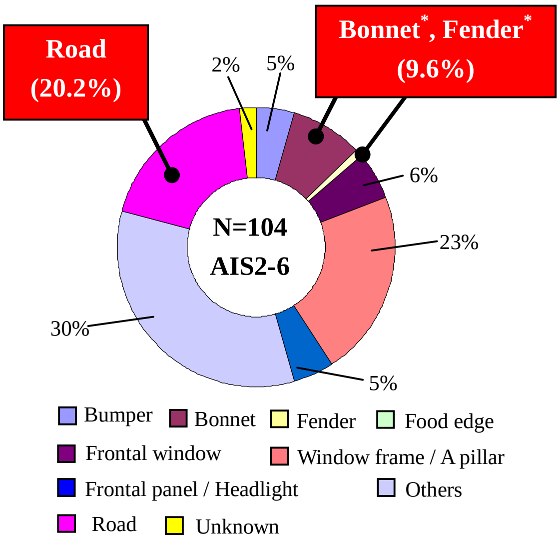


Figure 2. The percent of area of injury responsible for death in traffic accidents in Japan, 2008



*These parts are targeted by regulations of pedestrian head protection worldwide.

Figure 3. The rate of parts of the vehicle, road surface, etc. causing pedestrian head injuries (AIS2-6)

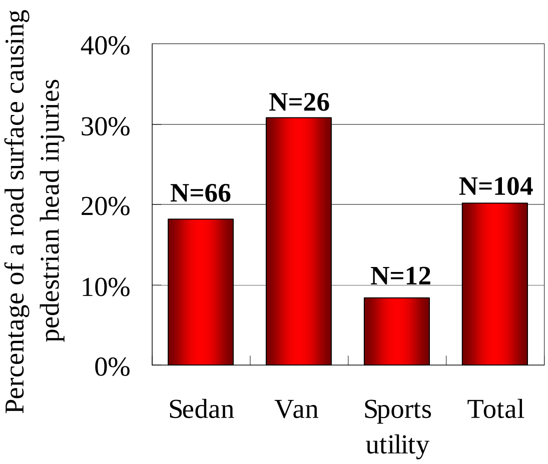


Figure 4. The percentage of a road surface causing pedestrian head injuries for each vehicle type

percentage is approximately twice that of the rate of the bonnet and fender of a car, which are parts targeted by regulations of pedestrian head injury protection worldwide. Figure 4 shows that the percentage of a road surface causing pedestrian head injuries when a pedestrian collides with a van type vehicle is highest of the vehicle models.

For these reasons, an effective countermeasure for pedestrian protection is to prevent or absorb impact of a pedestrian's head on a road surface in a secondary collision.

CLARIFICATION OF PHENOMENON OF A SECONDARY COLLISION IN PEDESTRIAN ACCIDENTS USING COMPUTER SIMULATION ANALYSIS METHODS

In the previous section, it became clear that injury risk in a secondary collision is high in pedestrian accidents. However, it is difficult to observe the phenomenon in a secondary collision using car-pedestrian accident data. An additional problem is that the number of cases investigated in the data was low. Therefore, in this section, car to pedestrian collisions are analyzed by MADYMO (Tass), to clarify the phenomenon in a secondary collision in car-pedestrian accidents. The pedestrian models and vehicle models in this study are made on software (AJAK) in which it is possible to automatically adjust parameters such as the pedestrians' weight and height, bonnet leading edge height, bumper skirt height and ground clearance, and so on [4].

Pedestrian models

First, the age of fatalities in pedestrian accidents was investigated to determine subject pedestrians in the model. Figure 5 shows the age distribution of fatalities in car-pedestrian accidents [2]. The figure shows that adults aged fifty and over have the highest fatality rate in car-pedestrian accidents.

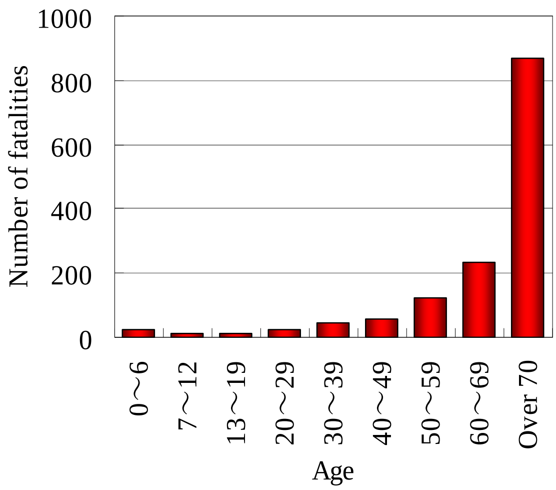


Figure 5. The age distribution of fatalities in car-pedestrian accidents (In Japan, 2008)

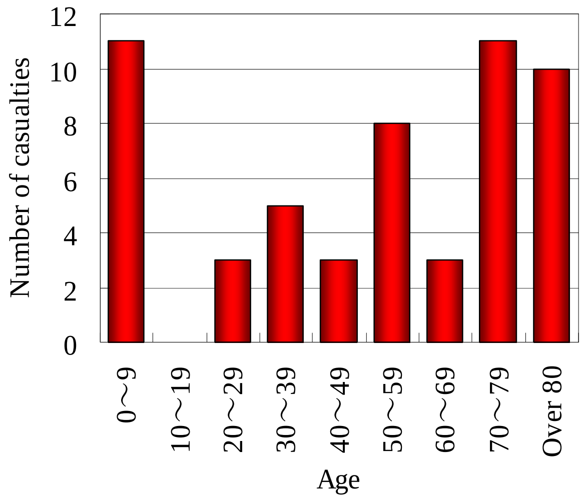


Figure 6. The age distribution of pedestrians who suffered head injuries in car-pedestrian accidents

Moreover, Figure 6 shows the age distribution of pedestrians who suffered head injuries in car-pedestrian accidents [5]. It was analyzed by using case examples of accident data for twelve years from 1994 to 2005. Pedestrian subjects in this study totaled 54 people. The figure shows that head injuries occurred chiefly in children aged nine or younger, and in adults aged fifty or over in pedestrian accidents. From the results, pedestrian models of a child and adults aged fifty or over were chosen for this study.

Next, height and weight of the chosen ages were investigated using literature (shown in Table 1) [6]. From the results, gender-segregated data of height and weight from one-year old to nine-year old children was inserted. From that data, it was found that the height and weight differences of gender are not so large in children of the same age, but differences between ages are significant. Therefore, data for the average height and weight of a six-year old male and female was used for the child model because it is a median in the intended age and gender difference is not large. For adults aged fifty and over, gender-segregated data of height and weight of adults in their fifties, sixties and aged seventy or over was inserted. From the data, it was found that age difference was not so large but gender difference is significant. Therefore, a total of four adult models were made which were based on height and weight data for males and females in their fifties and males and females aged seventy or over.

Hence, a total of five pedestrian models were made in this study: one child model (based on six-year olds' data, denoted CH06 hereafter) and four adult models (based on data of males and females in their fifties, denoted AM50 and AF50 hereafter, and based on data of males and females in their seventies, denoted AM70 and AF70 hereafter). Table 2 shows the data of height and weight of each pedestrian model and Figure 7 shows each model.

These models were created using a scaling method with the JARI pedestrian model in which these base models' biofidelity was validated using Post Mortem Human Subject test data. The scaling method used in this study followed the method stated in the user manual of MADYMO version 5.4 as a reference.

Table 1. Height and weight data by age (abridgment)

Age	Male Height [m]	Male Weight [kg]	Female Height [m]	Female Weight [kg]
1	0.807	10.9	0.782	10.1
2	0.894	12.5	0.879	12.0
3	0.961	14.6	0.971	14.3
4	1.051	16.9	1.035	16.8
5	1.098	18.7	1.097	18.7
6	1.172	21.2	1.156	20.7
7	1.214	24.5	1.226	23.9
8	1.267	27.6	1.280	26.0
9	1.329	29.3	1.341	31.8
⋮	⋮	⋮	⋮	⋮
50-59	1.673	66.6	1.545	55.0
60-69	1.640	64.2	1.514	53.6
Over 70	1.605	59.3	1.468	49.8

Table 2. Height and weight data of each pedestrian model

Model	Height [m]	Weight [kg]
Child（CH06）	1.164	21.0
Fifties Female（AF50）	1.545	55.0
Seventies Female（AF70）	1.468	49.8
Fifties Male（AM50）	1.673	66.6
Seventies Male（AM70）	1.605	59.3

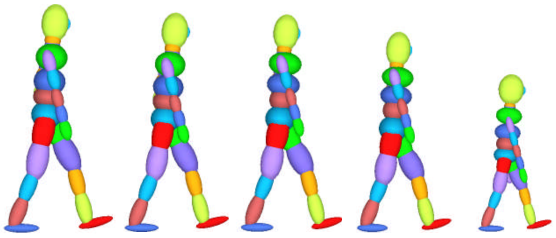


Figure 7. Pedestrian models

Vehicle models

A total of three vehicle models were made in this study which were sedan type, sports utility type and van type, to clarify collision phenomenon for all kinds of vehicle type. Figure 8 shows the construction of a vehicle model's front parts as used in this study. The model consists of some plane elements and some cylindrical elements. Each element is given stiffness which is shown in Figure 9. Figure 10 shows vehicle models used in this study. These models were made based on the data of the average shape of each vehicle from IHRA WG researched results [7].

Collision conditions

The vehicle models collided with the pedestrian

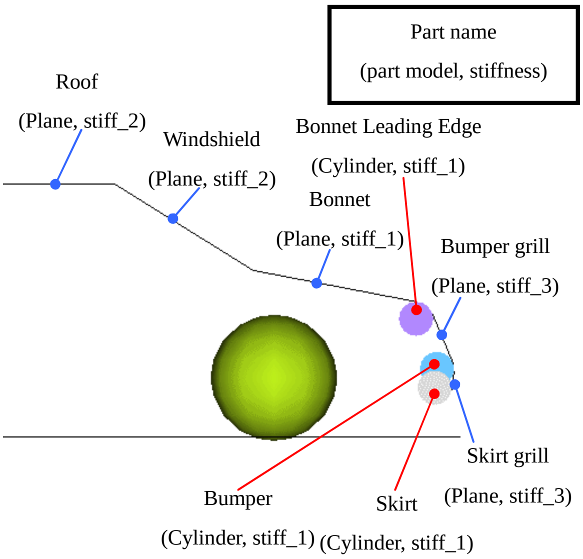


Figure 8. Construction of a vehicle model's front section

models at three collision velocities which were 20km/h, 30km/h and 40km/h. Thereafter, the vehicle models slowed down with deceleration of 0.5G. The stance of pedestrian models was set up as shown in Figure 11 and Table 3. The pedestrian's standing position was made the center of the vehicle models. The pedestrian model was set up for each contact condition to be able to impact the vehicle models and the road surface model.

The road surface model was given stiffness of a real road which was determined by analysis using MADYMO. The data used for analysis was obtained

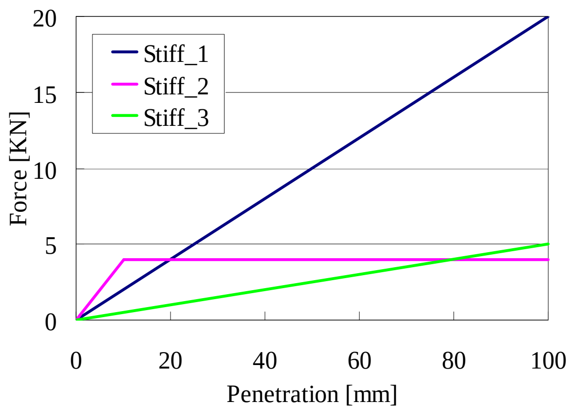


Figure 9. Stiffness of vehicle model

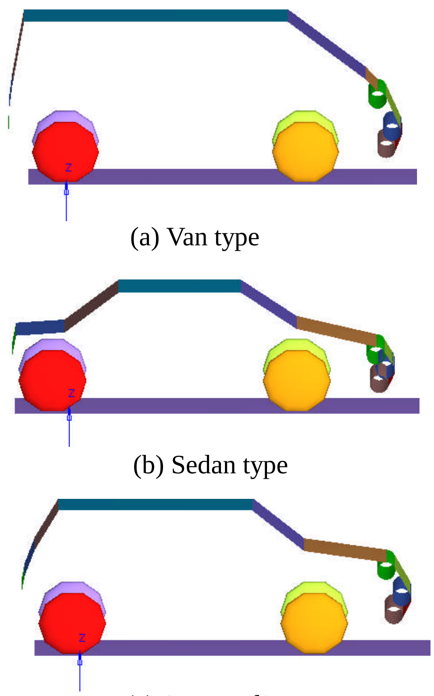


Figure 10. Vehicle models

from an experiment in which a head impactor fell to a real road surface. From those results, the stiffness of the road surface model was shown by the following, Equation 1.

$$F = 1 \times 10^5 x \quad (1)$$

Here F is the force [kN], x is the penetration [m].

All conditions were calculated by using MADYMO version 7.1 in this study.

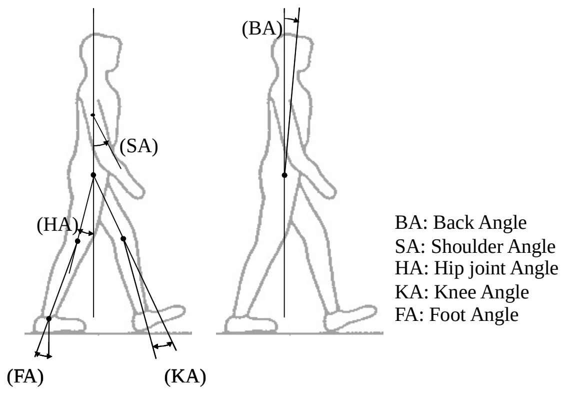


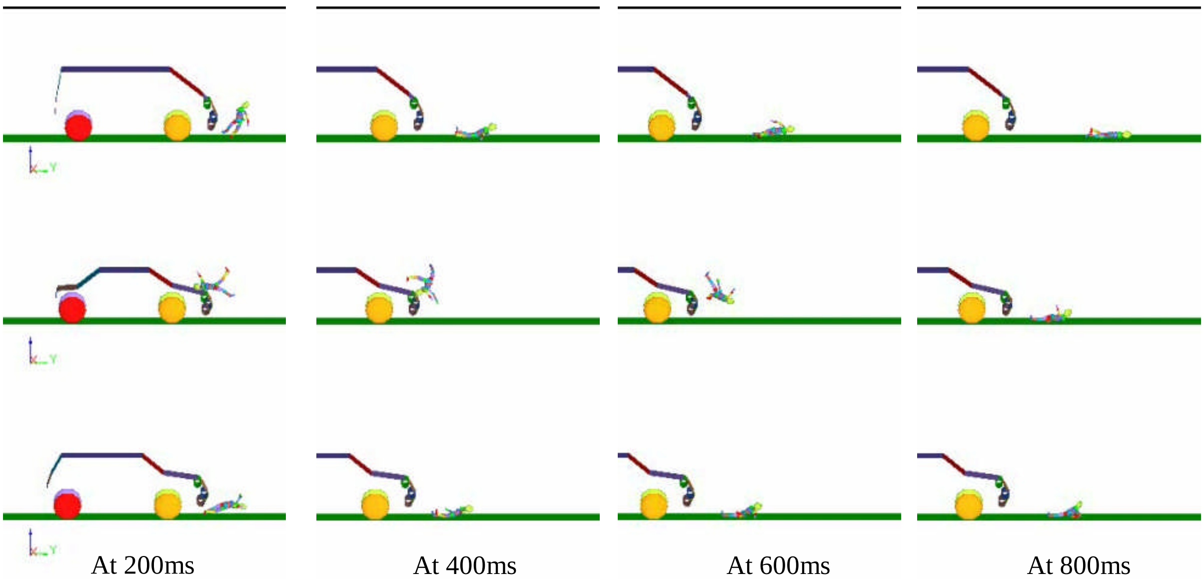
Figure 11. The stance of pedestrian model definition angle

Table 3. The value of the stance of pedestrian model definition angle

	Left	Right
BA (deg.)	+5	
SA (deg.)	-15	+15
HA (deg.)	+29	-12
KA (deg.)	-14	-10
FA (deg.)	0	+22

Results and Discussion

Behavior in collision Figure 12 shows an example of collision behaviors when each vehicle model collides with the child model (CH06) at 40 km/h. The figure shows that the timing of the pedestrian's head impact with the road surface is different according to vehicle model. Specifically, the pedestrian impacts with the road surface at 200ms in the sports utility type, at 400ms in the van type and at 800ms in the sedan type. In addition, behaviors until the pedestrian's head impacts with the road surface vary greatly. Moreover, behaviors of the pedestrian model after colliding with the vehicle models vary greatly as an overall trend when one condition is changed among the pedestrian models, vehicle models and collision velocities.



At 200ms At 400ms At 600ms At 800ms

Figure 12. The collision behavior when each vehicle model collided with the child model (CH06) at 40 km/h. Upper: van type, Middle: sedan type, Lower: sport utility type

Comparison of HIC of the initial collision with the secondary collision Table 4 shows the HIC_{15} value in each analysis condition to compare injury risk between the initial collision and the secondary collision. In the table, the cases are highlighted in yellow when the HIC_{15} value is higher in the secondary collision. (That is, the HIC_{15} values which are highlighted are for the secondary collision). The cases which are not highlighted are when the HIC_{15} value is higher in the initial collision (That is, HIC_{15} un-highlighted values are for the initial collision). For the values that are higher in the initial collision, the HIC_{15} value of the secondary collision is given in parenthesis.

The table shows that the HIC_{15} value in the secondary collision is higher than that of the initial collision in 38 of the 45 conditions. Additionally, the HIC_{15} value in the secondary collision exceeds 1000 in three cases when the HIC_{15} value in the initial collision is higher than that of the secondary collision. (When the HIC_{15} value exceeds 1000, head injuries generally occur). The HIC_{15} value in those 38 cases was over 2000 in 30 of the conditions.

Comparison of injury risk in vehicle models Table 5 shows the average of the HIC_{15} value for each vehicle model. The results shown in the table are calculated by maximum HIC_{15} value for each case. The table shows that risk increases in order of sedan type, van type, and sports utility type when comparing the average of the HIC_{15} value for each vehicle model.

Behavior in collision with the road surface It was found that a pedestrian's head impacted with the road surface in all conditions in this study. When focusing on behavior of a pedestrian's head impact with a road surface, two major patterns exist. One is the case of a pedestrian's head impacting with a road surface first (shown in Figure 13 a), and the other is the case of any part of a pedestrian, except the head, impacting with the road surface first. Moreover, this second pattern may be further categorized into cases where one pedestrian part (except the head) impacts first, followed by head impact as seen in Figure 13b, and in cases where two or more parts of the body impact first, followed by head impact, Figure 13c. Thus behavior of pedestrian head impact with a road surface can be categorized by order of impact.

Table 4. HIC_{15} value in each analysis condition to compare injury risk between initial collision and secondary collision

(a) CH06

	Vehicle speed [km/h] 20	30	40
Van	3048	4401	4434
Sedan	2708	3446	7758
Sports utility	4924	7655	4463

(b) AM50

	Vehicle speed [km/h] 20	30	40
Van	3766	3669	5868
Sedan	1023	1469	19729
Sports utility	4399	4554	3374

(c) AM70

	Vehicle speed [km/h] 20	30	40
Van	7687	4626	961 (125)
Sedan	497 (115)	1361 (1255)	3663
Sports utility	736	3549	2019

(d) AF50

	Vehicle speed [km/h] 20	30	40
Van	2655	6665	2717 (669)
Sedan	400	8751	3630 (2894)
Sports utility	786	35580	13870

(e) AF70

	Vehicle speed [km/h] 20	30	40
Van	1199	910 (317)	10524
Sedan	809	1992	3424 (1852)
Sports utility	5295	2556	10468

Table 5. Average of HIC value in each vehicle model

	Van	Sedan	Sport utility
CH06	3961	4637	5681
AM50	4434	7407	4109
AM70	6157	3663	2101
AF50	4660	4576	16745
AF70	5862	1401	6106
Average	5015	4337	6949

Table 6 shows the relationship between behaviors of impact as categorized above and HIC_{15} values at that time. The table shows that the HIC_{15} value becomes low when there is more impact frequency of pedestrian parts except the head with the road surface before the pedestrian's head impacts. This is because the velocities and energy in the pedestrian's head impact with the road surface is decreased when pedestrian parts impact before the head.

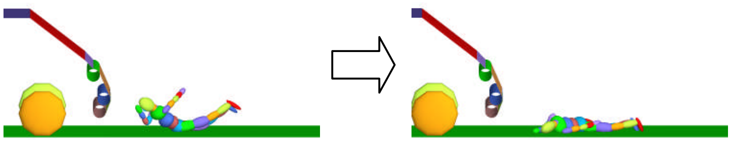
Table 6. The relationship between behaviors of impact categorized as above and HIC values at that time

	Pattern (shows the fig. 13)		
	a	b	c
HIC_{15} Ave.	9449	3817	2407

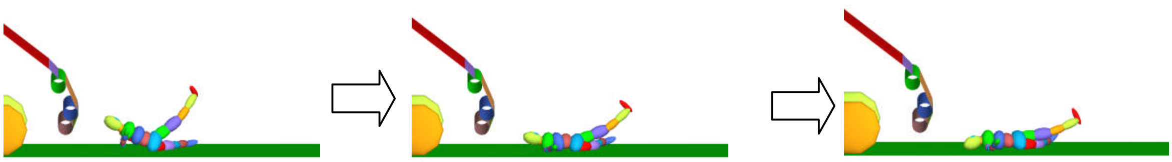
STUDY ON COUNTERMEASURES FOR PEDESTRIAN PROTECTION IN SECONDARY COLLISIONS

From the results of accident data research and computer simulation analysis, it was clarified that a secondary collision has a high risk in pedestrian accidents. However, pedestrian protection countermeasures in a secondary collision have not been developed. Therefore, in this section, road characteristics influencing the secondary collision were investigated using computer simulation methods for pedestrian protection.

(a) The case of a pedestrian's head impacting with the road surface first



(b) The case of one pedestrian part, except the head, impacting with the road surface then followed by head impact



(c) The case of more than two pedestrian parts, except the head, impacting first followed by the head

Figure 13. Patterns of pedestrian impact with a road surface

Influence of road characteristics on a pedestrian in a secondary collision

Road stiffness The material was rubber sheet (thickness: 6mm, rubber hardness: A45) which was applied to the road surface in this study. Computer simulation analysis was carried out for two conditions of road surface characteristics which were one layer of rubber, and three layers of rubber. Each characteristic was given the stiffness of a real road which was determined by analysis using MADYMO. The data used for analysis was obtained from an experiment in which a head impactor fell to the road surface for each condition. From those results, the stiffness of one layer of rubber is shown by the following, Equation 2, and three layers of rubber is shown in Equation 3.

$$F = 4 \times 10^3 x \quad (2)$$

$$F = 1 \times 10^3 x \quad (3)$$

Here F is the force [kN], x is the penetration [m].

Analysis conditions Computer simulation analyses were carried out in a total of 90 conditions which consisted of combinations of three kinds of vehicle models (sedan type, sports utility type, van type), five kinds of pedestrian models (CH06, AM50, AM70, AF50, AF70), three collision velocities of car to pedestrian (20, 30, 40km/h) and two kinds of road surface characteristic (one layer of rubber, three layers of rubber). The pedestrian models and vehicle models were those used in the previous sections.

Result and Discussion Figure 14 shows the HIC_{15} value for each road model. Table 7 shows the number of HIC_{15} values that exceed 1000 in the secondary collision for each road model.

Figure 14 shows that the HIC_{15} value is low in all pedestrian models when the road model is changed from characteristics of a real road to characteristics using a buffer such as rubber. In addition, the HIC_{15} value becomes lower if three layers of rubber are used, compared to one layer of rubber. Table 6 shows that the number of HIC_{15} values exceeding 1000 in the secondary collision is lower when a buffer is applied.

Therefore, it was found that the rate of a pedestrian's head injury occurring in the secondary collision was favorably influenced by the application a buffer such as rubber and expanded polystyrene to the characteristic of the road surface. Therefore, a buffer is an effective countermeasure to protect a pedestrian's head in a secondary collision. However, decreasing road stiffness greatly decreases the durability of a road surface and travelling performance. Therefore, it is necessary to consider other effective countermeasures including those developed by automobile manufactures for protecting pedestrians from head injuries. In particular, controlling pedestrian behavior after colliding with a vehicle, aimed at reducing injuries when they are knocked to the road in a secondary collision.

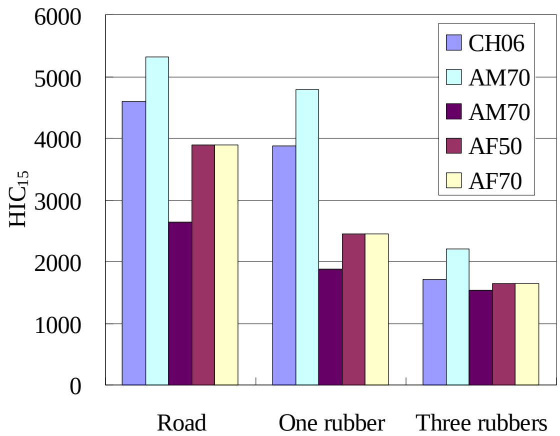


Figure 14. HIC value in each road model

Table 7. The number of HIC values exceeding 1000 in a secondary collision for each road model

	Road	One rubber	Three rubbers
CH06 (9)	9/9	9/9	6/9
AM50 (9)	9/9	8/9	5/9
AM70 (9)	6/9	5/9	4/9
AF50 (9)	7/9	5/9	4/9
AF70 (9)	7/9	7/9	7/9
Total (45)	38/45	34/45	26/45
Probability	84%	76%	58%

CONCLUSSION

In this study, the risk to a pedestrian in a secondary collision was investigated using traffic accident data as well as computer simulation analysis methods. From the results of researched traffic accident data, the rate of a road surface or construction causing pedestrian injury is twice the rate of the bonnet and fender of a car, both of which are targeted by regulations of pedestrian head protection worldwide. From the results of computer analysis methods, the HIC_{15} value in a secondary collision was almost always higher than that of the initial collision. In addition, the HIC_{15} of the higher value cases was over 2000 in 30 of the 38 conditions. From these results, it became clear that the secondary collision has a high risk of causing injury. It is necessary to not only focus on the initial collision but also focus on a secondary collision in car-pedestrian traffic accidents.

From the modeled results, countermeasures for pedestrian protection in a secondary collision were considered. It was found that one effective countermeasure to protect a pedestrian from head injury is to apply a characteristic of a buffer such as rubber and expanded polystyrene to the road surface. However, such a countermeasure would affect road durability and performance. Therefore, in the future it is necessary to consider other effective countermeasures for protecting pedestrians from head injuries. In particular, controlling pedestrian behavior after colliding with a vehicle, aimed at reducing injuries when they are knocked to the road in a secondary collision.

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