DEVELOPMENT OF OCCUPANT INJURY PREDICTION ALGORITHMS FOR ADVANCED AUTOMATIC COLLISION NOTIFICATION BY NUMERICAL CRASH RECONSTRUCTIONS

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ABSTRACT

Prediction of injured body regions and injury severity from available accident data can lead to more appropriate and hastier emergency care in automotive accidents. The existing prediction method was based on statistical analysis of a massive amount of real-world accident data. However, numerical crash simulations were also considered to provide a virtual injury database in a relatively short time. Therefore, the purpose of this study was to develop and to evaluate a new method to obtain injury prediction algorithm by utilizing virtual database of numerous computer simulation results.

Occupant and cabin were modeled as multi-bodies. The occupant models have geometries of typical Japanese adult males. The cabin model consists of safety restraint systems and interior panels. Acceleration and intrusion of the door panels during side impact were delivered to the occupant in the simulations. Hundreds of crash simulations were performed where crash parameters were changed systematically. The injury prediction algorithms were developed by logistic regression analysis of the database constructed from the results of the simulations.

The algorithms correctly predicted more than half of the head, thorax, and thigh injuries in 48 accidents. However, this study neglected cabin deformation in frontal crash, break of door-window, as well as occupant's age and gender, which may affect on the occupant responses and injury severities. These limitations might be the cause of the miss predictions of injury severity in the simulations.

In this study, possibility of developing injury prediction algorithms by using numerical crash reconstructions was presented as a different approach from existing method that used real-world accident data. For more accurate predictions, improvement of the simulation models and consideration of occupant characteristics are required.

INTRODUCTION

Advance in active and passive safety technology has contribution on reducing casualties in automotive accidents. For "Zero Death", a multidisciplinary approach at post crash stage is required. Advanced Automatic Collision Notification (AACN), which is a notification system associated with injury prediction based on the accident data, is expected to optimize Emergency Medical Service (EMS) and reduce trauma deaths. In frontal crashes, the ratio of deaths or severe injuries to the number of accidents was siginificant, while in lateral crashes, severe injuries occured under relatively low impact velocity [1]. Therefore, AACN is required in particular for frontal and lateral crashes.

URGENCY Algorithm [2] which was statistically built from a massive amount of field data was proposed to be used in predicting the probability of injury occurrence from several accident parameters. However, it is difficult and costly to collect lots of reliable field accident information which is necessary for developing a valid algorithm. Furthermore, the algorithm does not consider the injury mechanism, because field data can not provide any information regarding injury process during the accidents.

Simulations of various types of accidents using computer models of occupant and vehicle interior can be used to easily develop a huge accident database. In this study, we suggest a new method to develop injury prediction algorithm for frontal and lateral crashes by using multi-body models.

NUMERICAL CRASH SIMULATIONS

Occupant and vehicle interior were modeled as multi-bodies. Only acceleration was delivered to the occupant in frontal crash simulations, while intrusion of the door panels was also simulated in addition to acceleration in near-side impact simulations. MADYMO ver. 7.1 (TASS) was used as an analysis solver.

Occupant Model [3]

The occupant models consist of 15 segments and have geometries of typical Japanese adult males. The body sizes can be divided into three: 5th , 50th , and 95th percentile in body stature and weight. The geometries were based on the database of three dimensional measurement of Japanese subjects. The passive resistance of the joints and contact stiffness of body segments were determined according to references.

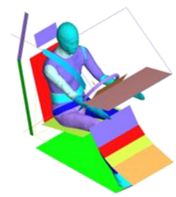
The responses of these occupant models to frontal and side impact had been validated in numerical reconstruction of a volunteer experiment. As a result of numerical reconstruction in frontal impact test [4], the behavior of the model was generally similar to that of the volunteers [5]. In a case of side impact, a volunteer test which simulated side impact on shoulder [6] was numerically reconstructed, and it was found that result of the reconstruction simulation coincided well with the test result [7].

Cabin Model

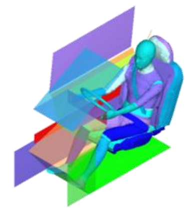
The cabin model for frontal crashes [3] consists of safety restraint systems and simplified interior panels. The airbag and seat-belt were modeled as finite elements. For side impact crashes, the model did not have airbag, and the seat was modeled as finite elements [7].

Crash Simulation Models

The occupant and cabin models were combined, and impacts were imposed on it as shown in Figure 1. In a frontal crash simulation, posterior-anterior translational acceleration, which was obtained from measured crash acceleration of vehicle during rigid barrier crash, was given to the occupant model. In a side impact crash simulation, left-right translational acceleration was given to occupant model, and enforced displacement was also given to the two inferior panel of the three-segmented door panel model in order to simulate the door intrusion. The top panel represents door window, which was considered to has no significant displacement during a crash.



(a) Frontal



(b) Lateral

Figure 1. Crash simulation models

Validation against JNCAP tests

The crash simulation models had been validated against JNCAP full-wrap frontal and side impact crash tests [5][7] . In the validations, accelerations measured during the tests and estimated door panel displacement were given to the simulation model. The kinematic behavior, the resultant acceleration of head, thorax, and pelvis, as well as the compressive force on thigh matched qualitatively to that of crash dummy. Moreover, The gaps between two responses were not quantitatively significant.

INJURY DATABASE

Injury occurrence was evaluated by relevant injury criteria. Simulations of 324 frontal and 162 near-side impact crashes were performed. Severity of injuries was found to increase along with the increase of crash velocity.

To create an injury database, parametric studies using the crash simulation models were carried out. In an accident, crash parameters, such as collision velocity, collision angle, and driver stature must be varied. Therefore, it should be considered during simulation. Practically, it can be obtained or estimated by in-vehicle devices, such as EDR. Systematically changes on those crash parameters were made during the parametric studies.

Crash Parameters

Frontal Crash The crash parameters for frontal crash simulations, including airbag, seat-belt, driver stature, vehicle type, collision speed, and collision angle, were altered into two or three levels as shown in Table 1. Vehicle accelerations, which depend on the collision speed, collision angle, and vehicle type, were created as an input for simulation. A minivan, a compact-vehicle and a light-vehicle were selected as representatives from JNCAP full-wrap crash tests data respectively. Figure 2 shows the time histories of crash acceleration of each vehicle measured in the tests. The time integration corresponded with rigid barrier collision at speed of 55 km/h. Under an assumption that the waveform features of crash acceleration is independent from collision speed, crash accelerations at 30 and 80 km/h were created by scaling the waveform as presented in Figure 2. In case of oblique crashes, the waveform was resolved into anterior-posterior and lateral components.

Side Crash The crash parameters for side impact crash simulations, including seat-belt, vehicle type, seat height, driver stature, and collision speed were altered into two or three levels as shown in Table 2. Time histories of vehicle acceleration were created depending on the collision speed and vehicle type. A minivan, a compact-vehicle and a light-vehicle were selected from JNCAP side impact tests data respectively. Figure 3 shows the time histories of acceleration of each vehicle measured in the tests. As in frontal crashes, the acceleration waveforms were scaled to create acceleration waveforms for crash simulation at 30 and 70 km/h. Moreover, time histories of the door displacement were created as shown in Figure 4. It was reported that the deformation behavior of door panel is independent of vehicle type [8], and the spring back is less than 25% [9]. Therefore, the maximum displacement was set to be 1.25 times of the residual deformation. The maximum and the residual deformation were assumed to occur at the same time with the maximum acceleration and a time when the relative velocity between the vehicle and the striking barrier became zero respectively. Deformation at Belt Line and H-Point were given to the middle and bottom segment of the door model respectively. Under an assumption that collision speed correlates with the degree of deformation but not with the deformation characteristics, door displacement behavior at 30 and 70 km/h were created based on that at 55 km/h.

Table 1.
Parameters in frontal crash simulations

	Parameter	Level	Value
1	Airbag	2	1: on, 0: off
2	Seat belt	2	1: on, 0: off
3	Driver stature [m]	3	1.58: 5%, 1.71: 50%, 1.85: 95%
4	Vehicle type	3	1: minivan, 2: compact, 3: light
5	Collision speed [km/h]	3	30, 55, 80
6	Collision angle [degree]	3	-30, 0, 30

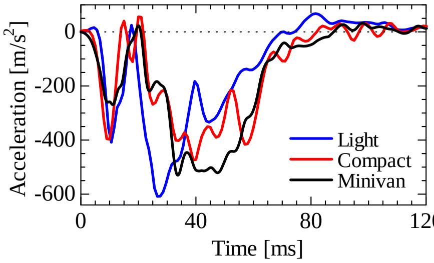


Figure 2. Frontal crash accelerations at 55 km/h

Table 2.
Parameters in side impact crash simulations

	Parameter	Level	Value
1	Seat belt	2	1: on, 2: off
2	Vehicle type	3	1: light, 2: compact, 3: minivan
3	Seat height [mm]	3	230, 255, 280
4	Driver stature [m]	3	1.58: 5%, 1.71: 50%, 1.85: 95%
5	Collision speed [km/h]	3	30, 55, 70

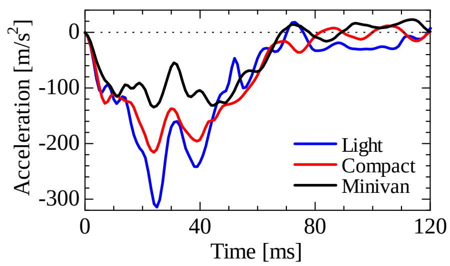


Figure 3. Side impact crash accelerations at 55 km/h

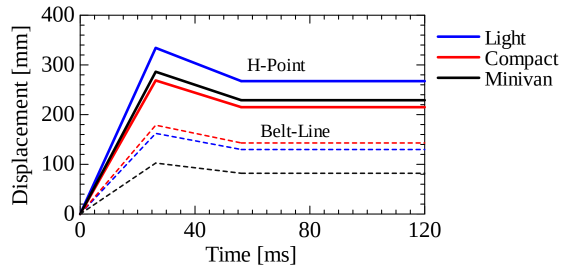


Figure 4. Door panel displacements at 55 km/h

Conversion to Abbreviated Injury Scale

From the occupant model responses, injuries on head, thorax, and thigh were evaluated. Injury criteria for head, thorax, and thigh were Head Injury Criterion (HIC), cumulative maximum resultant acceleration in 3 ms, and maximum compression load on femur respectively.

In EMS, severity of injury is important rather than the value of injury criterion, because this information is required to decide treatment method. Abbreviated Injury Scale (AIS) is an anatomical-based scoring system classifying each injury by body region according to its severity into a six-level ordinal scale (from minor:1 to maximum:6). Proposed injury risk curves [10][11][12], which were developed based on the experiments, provide the relationships between probability of AIS level and value of injury criteria. Under an assumption that 50% of probability was the threshold for injury occurence, the relationships between the value of injury criteria and AIS level were determined as shown in Table 3. According to this relationships, values of injury criteria obtained from the simulations were then converted into injury severities (AIS).

Table 3.
Relationships between Injury Criteria and AIS

AIS	Head	Thorax	Thigh
	HIC	max. res. acc. in 3ms [G]	comp. load [kN]
1+	330 – 585	< 21	< 11
2+	586 – 966	21 – 50	11 – 15
3+	967 – 1435	51 – 69	>16
4+	1436 – 1847	70 – 133	
5+	1848 – 2182	> 133	
6+	> 2182		

INJURY PREDICTION ALGORITHMS

Logistic Regression Analysis

Prediction algorithms for head, thoracic and thigh injury probability were derived from ordinal logistic regression analysis of the injury database where the crash parameters and the injury outcome are related each other. Equation 1 shows the relationships between occurrence probability of over a level of AIS, $P_{\mathrm{AIS}*+}$, and an explanatory variable, Z, whose value was defined by values of crash parameters and their regression coefficients. $P_{\mathrm{AIS}*+}$ become larger along with the increase of Z. Algorithms for frontal and side impact crashes have six and five parameters respectively. Airbag, seat-belt, and vehicle type were categorical, while driver stature, seat height, collision velocity, and collision angle were continuous variables. PASW Statistics ver. 17 (SPSS) was used for the statistical analysis.

$$P_{\mathrm{AIS}*+} = \frac{1}{1+\exp(-Z)} \qquad (1)$$

$$Z_{\mathrm{frontal}} = \beta_0 + \beta_1 + \beta_2 + \beta_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6$$
$$Z_{\mathrm{side}} = \beta_0 + \beta_1 + \beta_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5$$

β_j: regression coefficients, x_j: parameter values

j for frontal crashes
0: intercept, 1: airbag, 2: seat-belt, 3: vehicle type,
4: driver stature, 5: collision velocity,
6: collision angle

j for side impact crashes
0: intercept, 1: seat-belt, 2: vehicle type,
3: seat height, 4: driver stature, 5: collision velocity

Algorithms for Head, Thorax, and Thigh Injury

Generally, in vehicle safety performance evaluations, injury threshold of AIS 3+ was used for head and thorax, while AIS 2+ was used for thigh [13]. In this study, the algorithms for head and thorax AIS 3+ injuries, and for lower limb AIS 2+ injury were developed through the logistic regression analysis.

Table 4 shows the regression coefficients, chi-square value, significance level, and Nagelkerke's coefficient for each prediction algorithm. The injury prediction algorithms showed high goodness-of-fit. The regression coefficients were different among body segments, which means that injury probability has different correlations with the crash parameters according to the body segments. In frontal crashes, β_1 for without airbag deployment was positive and negative for head and thorax respectively, which indicates that airbag was effective to reduce risk of head injury but not for thoracic injury. These correlations were supported by reported injury mechanisms, indicating that the crash simulation models were appropriate to build a virtual accident database.

Table 4.
Coefficients of the injury prediction algorithms

(i) Frontal crash

		Head (AIS3+)	Thorax (AIS3+)	Thigh (AIS2+)
β_1	on: 1	0	0	0
	off: 0	0.069	-0.027	0.173
β_2	on: 1	0	0	0
	off: 0	1.241	1.502	5.026
β_3	3	0	0	0
	2	-0.776	-1.137	-0.883
	1	-0.425	-0.604	-0.630
β_4		4.709	0.798	7.009
β_5		0.123	0.124	0.102
β_6		-0.006	-0.002	0.006
β_0		-14.429	-5.473	-24.659
χ^2		312.730	322.839	253.157
p		<0.001	<0.001	<0.001
Nagelkerke R^2		0.646	0.672	0.664

(ii) Side impact crash

		Head (AIS 3+)	Thorax (AIS 3+)
β_1	on: 1	0	0
	off: 0	4.075	-3.619
β_2	1	5.537	7.165
	2	4.836	6.567
	3	0	0
β_3		0.022	-0.015
β_4		4.998	-10.237
β_5		0.245	0.298
β_0		-29.713	-5.974
χ^2		252.490	231.906
p		<0.001	<0.001
Nagelkerke R^2		0.826	0.869

PREDICTION ACCURACY

Accuracy of each algorithm was evaluated by comparing the prediction results to field accident data. Micro data collected in Japan and USA were used for frontal and side impact crashes respectively.

Real World Accident Data

Frontal Crash From accident analysis reports [14][15], 14 car-to-car accidents (28 cases) including two crash test data reconstructing real world accidents and 12 real world accident data were selected. Table 5(i) shows the detail of each case including crash parameters and injury severity of the driver. Equivalent Barrier Speed (EBS) was adopted as collision velocity during the injury prediction. In the reference [15], driver statures were not mentioned, therefore male and female driver were uniformly assumed to be similar to 50th percentile and 5th percentile Japanese male occupant model respectively.

Side Impact Crash From the CIREN database [16], 20 accidents were selected. Since light vehicle is common only in Japan, this vehicle type was excluded during the accuracy evaluation. Table 5(ii) shows the detail of each case. Seat heights, which were not informed in the database, were assumed as the lowest value, 255 mm. Collision velocities were assumed as the velocity difference between struck and striking vehicles, and were calculated by Equation 2. Vehicle stiffness for striking and struck vehicle were apparent stiffness of Moving Deformable Barrier and the subject vehicle respectively. These values were estimated from the JNCAP test results.

$$V_{\mathrm{B}} = \sqrt{\frac{k_2}{k_1+k_2}\frac{m_2}{m_1+m_2}}|V_1 - V_2| \qquad (2)$$

V_{B}: EBS, V_i: vehicle velocity
k_i: vehicle stiffness, m_i: vehicle mass,
i =1: struck vehicle, 2: striking vehicle

Predicting Injuries in Real World Accidents

Probabilities of injury occurrence in the accidents were calculated by substituting the values of crash parameters into Equation 1, and then compared with the actual injury circumstances. In this study, the threshold for injury was assumed to be 50% of probability. When $P_{\mathrm{AIS3+}}$ for an AIS 3 injury was predicted as over 50% of probability, the prediction was correct. Moreover, the prediction was also correct when $P_{\mathrm{AIS3+}}$ for an AIS 1 injury was predicted as less than 50% of probability.

Frontal Crash Severe injuries in the 28 cases of frontal crashes were predicted as shown in Table 5(i). The agreement ratios for head, thorax and thigh injuries were 85, 50 and 71% respectively.
$P_{\mathrm{AIS3+}}$ for head injuries were less than 50% except for four cases. This trend matched with the actual injury circumstances where severe injuries did not occur.

Table 5.

Predicted AIS 3+ probability and accident data (wrong predictions are marked: over, under-estimated.)

(i) Frontal

Case	Vehicle	Seat -belt	Air -bag	height [m]	EBS [km/h]	Head		Thorax		Thigh	
						AIS	P_{AIS3+}	AIS	P_{AIS3+}	AIS	P_{AIS2+}
Test 1	V1: minivan	on	off	1.42	35	0	2.3	1	35.0	0	0.00
	V2: light	on	on	1.63	40	0	6.7	0	41.1	3	0.00
No.36	V1: compact	on	on	1.73	60	0	60.9	0	90.5	3	0.06
	V2: compact	on	on	1.60	60	0	45.7	0	89.5	3	0.02
No.40	V1: light	off	on	1.70	40	0	44.9	3	91.4	2	2.42
	V2: light	on	on	1.47	25	0	1.2	3	23.5	1	0.00
Test 2	V1: light	on	on	1.62	45	1	21.0	0	79.9	1	0.02
	V2: compact	on	on	1.70	40	0	13.4	1	56.5	0	0.01
No.41	V1: light	on	off	1.58	25	0	2.0	0	23.9	0	0.00
	V2: light	on	off	1.58	25	0	2.0	1	23.9	0	0.00
No.42	V1: light	on	off	1.71	20	0	1.9	-	15.7	-	0.00
	V2: light	on	off	1.71	20	0	1.9	0	15.7	0	0.00
No.43	V1: light	on	on	1.58	65	0	74.4	0	98.0	3	0.09
	V2: light	on	on	1.58	40	0	10.6	3	67.4	1	0.01
No.47	V1: light	on	on	1.58	35	0	5.5	1	51.8	0	0.01
	V2: minivan	off	off	1.71	35	0	26.8	1	76.1	2	0.93
No.50	V1: light	on	on	1.71	65	0	84.5	4	98.2	3	0.23
	V2: compact	on	on	1.58	45	-	10.2	0	56.2	-	0.00
No.51	V1: compact	on	on	1.58	30	1	1.8	1	16.7	0	0.00
	V2: compact	on	on	1.71	30	0	3.3	1	18.2	1	0.00
No.52	V1: compact	off	on	1.71	45	0	42.6	1	86.5	3	1.85
	V2: minivan	off	on	1.71	50	0	66.1	1	95.3	0	3.88
No.53	V1: compact	on	on	1.71	40	0	9.1	1	42.3	0	0.01
	V2: minivan	on	on	1.58	35	0	3.9	1	37.6	1	0.00
No.54	V1: compact	off	on	1.71	45	1	47.1	1	87.2	1	1.55
	V2: minivan	off	on	1.71	40	1	29.7	1	84.2	1	1.93
No.55	V1: minivan	on	off	1.71	35	0	8.4	1	40.4	0	0.01
	V2: minivan	off	off	1.71	35	1	24.1	0	75.2	0	1.07

(ii) Side impact

Case ID	Vehicle type	Seat belt	Seat [mm]	Driver [m]	EBS [km/h]	Head		Thorax	
						AIS	P_{AIS3+}	AIS	P_{AIS3+}
39868	2	1	255	1.57	26	0	95.6	5	16.0
31170	2	1	255	1.63	71	3	100.0	5	100.0
31159	3	1	255	1.65	84	5	100.0	3	100.0
32031	2	1	255	1.52	33	4	99.9	5	97.3
32297	2	1	255	1.57	19	0	30.6	4	0.2
49229	2	1	255	1.59	36	1	100.0	1	99.3
77797	2	1	255	1.57	34	4	99.9	3	97.7
91657	2	1	255	1.83	19	0	61.7	4	0.0
470047388	2	1	255	1.80	44	5	100.0	4	100.0
426041219	2	0	255	1.65	53	4	100.0	4	100.0
160113410	2	1	255	1.6	38	5	100.0	3	99.8
558007067	2	1	255	1.68	12	0	1.5	2	0.0
558018108	2	1	255	1.68	56	4	100.0	4	100.0
558021392	2	1	255	1.75	27	2	98.9	0	5.6
375026608	3	1	255	1.50	26	1	58.4	0	1.1
551060741	2	0	255	1.63	15	5	79.0	0	0.0
782006238	2	1	255	1.63	40	2	100.0	3	99.9
832075614	2	1	255	1.70	31	4	99.9	0	59.9
851113011	2	1	255	1.60	42	2	100.0	1	100.0
852114778	3	0	255	1.70	19	0	70.1	0	0.0

Two uninjury cases, vehicle 1 in case No.50 and No.43, which have highest collision velocity of 65 km/h, were over estimated.

Three out of four AIS 3+ thoracic injuries were correctly predicted. The algorithm was more likely to predict injuries severer than actuals, thus 13 cases were over estimated. The over estimated cases included minor injuries in vehicle 2 of case No.52 and No.54 in spite of non-seatbelted, and minor injury in vehicle 1 of case No.36 in spite of high collision velocity. Furthermore, the driver of the under estimated case, vehicle 2 of case No.40, was 58 years old elderly occupant.

P_{AIS2+} for thigh injuries were less than 5%, and all of eight AIS 2+ injuries were under estimated. Especially, severe injuries in high velocity accidents including vehicle 1 of case No.43 and No.50, and both vehicles of case No.36 were miss predicted as minor injuries.

Side Impact Crash Severe injuries in the 20 cases of near-side impact crashes were predicted as shown in Table 5(ii). The agreement ratios for head and thoracic injuries were 60 and 70% respectively.

All of ten AIS 3+ head injuries were correctly predicted, while eight minor injuries were wrongly predicted as severe (over estimated). These minor injury cases were peculiar, since their collision velocities were not as high as in the severe injury cases.

Thoracic injuries of 14 cases were correctly predicted. In the three over-estimated cases, minor injuries occurred in spite of high collision velocities. On the other hand, in the three under-estimated cases, all of the occupants were over 59 years old.

DISCUSSIONS

The agreement ratios of the injury prediction algorithms against real world accidents were in comparable to the URGENCY Algorithm, whose agreement ratio against 30 frontal crashes was reported to be 70% [2]. Furthermore, the algorithms could predict head and thigh injuries well, indicating that the development method of the algorithms using computer models can be an alternative to the present way using statistical analysis of real world accident database, though more accident cases were required for further evaluation.

Over estimations of minor head injuries in frontal crashes occurred in particular cases of high collision velocity and light vehicle. To overcome this problem, more accurate geometry and contact stiffness of cabin model is required in correspondence with vehicle type. In side impact crashes, over estimations also occurred, though the accident cases were not peculiar. Disregard of deformation and break of door window might cause this miss predictions. In the side impact tests, the door window leaned outward and broke, so the occupant head did not receive significant impact.

Thoracic injuries in frontal crashes were predicted severer than actuals. It could be caused by the condition that the seat-belt and airbag models did not adequately protect occupant models. Despite this fact, several under estimations occurred in cases of elderly occupants. Age and gender affect on injury tolerance, especially on thoracic injury [17][18]. To consider it in the simulation models is difficult because of the huge individual variations. A realistic approach was extracting the effects by statistical analysis of real world accident database, and then introducing it into the algorithm [19]. Furthermore, the occupant model did not consider chest deflection, which strongly relates to thoracic injury as reported by another [20]studies.

Thigh injuries in frontal crashes were predicted less severe than actuals. Disregard of interior panel intrusion might cause this result. In the accident analysis reports [14][15], deformation of interior panels was regarded as dominant cause of injuries. In high velocity frontal crash, the effect become more significant, and may cause under estimation in injury prediction.

CONCLUSIONS

This study suggested a method to develop injury prediction algorithms by statistical analysis of results of hundreds numerical crash reconstructions using multi-body models of occupants and vehicle cabin.

The conclusions obtained from this study were as follows.

- Injury prediction algorithms for AIS 3+ or AIS 2+ injuries of head, thorax and thigh have comparable accuracy to the URGENCY Algorithm.
- Numerical crash simulation was a good alternative to develop reliable injury prediction algorithms for frontal and side impact crashes.
- For improving the accuracy of the algorithms, cabin deformation, age effects, and chest deflection are required to be considered, and the geometry and the properties of the cabin models, especially the restraint system are need to be validated more precisely.

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