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Experimental Study on Neck Injury in Low Speed Frontal and Rear-End Collisions

Gyu Hyun Kim
Safety Research Laboratory Korea Automobile Testing & Research Inst.
Ouk Sub Lee*
School of Mechanical, Aerospace and Automation Engineering, Inha University
Si Won Hwang
Mechanical Engineering Design Department, Dongyang University

Motor vehicle accidents in rear impacts cause more than fifty percents of drivers to suffer from neck injuries. It is known that most neck injuries are associated with rear-end collisions at a speed lower than 32 km/h and are between the Abbreviated Injury Scale (AIS) 1 and AIS 2. Two different types of low speed crash tests such as the frontal barrier and rear moving barrier crashes have been conducted by following the procedure of the Research Committee for Automobile Repairs (RCAR). The injury for the neck and the Head Injury Criteria (HIC) were measured by using the sensors mounted on dummies. We reviewed neck injuries and the relationship between the neck and head injuries, and examined the deceleration of the body. Using the experimental test data at the neck, we investigated an improved neck injury criterion Nij. Also, the effects of the position of a head restraint on reducing the frequency and severity of the neck injury in rear-end collisions were investigated.

Key Words : Abbreviated Injury Scale (AIS), Head Injury Criteria (HIC), Neck Injury Criteria Nij, Test Dummy, Whiplash, Rear-end Collisions, Crash Tests

1. Introduction

Over the past forty years there have been many studies on the effects of vehicle collisions and the consequential occupant kinematics. However, most of these studies have concentrated on the effects of high collisional speeds, generally above 48 km/h. Little systematic studies have been done for much lower speed impact cases, such as those causing either zero or little (less than a few inches) crush damage to the vehicles. Furthermore, these lower speed cases frequently involve personal injury such as the well-known "whiplash" phenomenon, where one vehicle rearends another at a differential speed, usually below 32 km/h. According to the General Motors, more than one third of all car crash injuries in 1986 occurred in low speed crashes, below 32 km/h. The accident analysis shows that 93% of the injuries classified as an AIS 1 level of neck indicates a cervical rachis strain without any evidence of anatomical lesions during rear-end collisions (Cesarani et al., 1994). "Whiplash" problem occurs when a car is rearended. When a vehicle is suddenly accelerated forward, the body moves forward with the vehicle and the seat. However, the unsupported head moves forward slowly, since forces must be applied via the neck. Thus, although everything (car, seat, torso, and head) is moving forward, the differential motion between the torso and the head causes a backward rotation of the head about a horizontal axis parallel to the

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* Corrsponding Author,
E-mail : leeos@inha.ac.kr
TEL : +82-32-860-7315 ; **FAX** : +82-32-868-1716
School of Mechanical, Aerospace and Automation Engineering Inha University, Inchon 402-751 Korea.
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seat back. For a typical head/neck geometry, the center-of-mass (CM) of the head moves at only about 0.56 times the speed of the torso and shoulders, causing the head to move backward at about 0.44 times the speed of the torso/shoulders (Watts et al., 1996).

The Research Committee for Automobile Repairs (RCAR) has adopted a typical low speed crash test based on the average damage level in crash accidents to estimate the damageability and repairability. In the present work, two different types of low speed crash tests such as the frontal barrier and rear moving barrier crashes have been conducted by following the procedure of the RCAR. To estimate the head and neck injuries, vehicles with a test dummy substituting a driver were crashed on 40% of its front area on the left side against a fixed barrier. The vehicles were also tested by hitting with a moving barrier at a speed of 15 km/h on 40% of its rear area on the right side.

In this study, we have reviewed neck injuries and the relationship between the head and neck injuries in the low speed frontal and rear-end collisions tests for the RCAR. We also looked into the effects of the position of a head restraint on the dynamic response of the front seat occupant in Hyge sled tests. Further, we have investigated an improved neck injury criterion Nij, and a neck injury risk analysis with the aid of resultant data for the neck from the RCAR and dynamic Hyge sled tests.

2. Background

The current Federal Motor Vehicle Safety Standard (FMVSS) No.208 head injury criteria (Nahum, 1993 : Kim, 1997), neck injury criteria for the 50th percentile male using the alternative sled test in the U. S. A., and the Economic Commission for Europe (ECE) Regulation No. 94 for the neck include individual tolerance limits for axial loads, and bending moments as shown in Table 1 (Federal, 1994 : ECE, 1995).

The National Highway Traffic Safety Administration (NHTSA), U. S. A. has recently developed an improved neck injury criterion called the Nij, and reanalyzed the neck injury risk analysis. The purpose of adding a new set of requirements is to prevent airbag from causing injuries and to expand the existing set of requirements intended to ensure that airbags cushion and protect occupants in frontal crashes.

The primary sources of biomechanical data concerning the airbag related neck injury conditions are a series of tests on pigs conducted by the General Motors and the Ford Motor Company in the 1980's. Recently the biomechanical basis for

Table 1 Test method and requirements of occupant crash protection for head and neck

Regulation			KMVSS No. 102 (Korea)	FMVSS No. 208(U. S. A.)		ECE Reg. No. 94 (Europe)
				Current	Proposed	
Impact speed(km/h)			48.3			56.0
Impact method			A fixed collision barrier full frontal			A deformable barrier 40% overlap
Injury criteria	Head Injury Crieria(HIC)		1,000			1,000
	Upper neck	Extension bending moment(M_E)	-	57 N · m	Nij≤1.4	57 N · m
		Flexion bending moment(M_F)	-	190 N · m		-
		Axial tension force(F_z)	-	3300 N		3300 N
		Axial comp. force($-F_z$)	-	4000 N		-
		Fore/After shear force(F_x)	-	3100 N		3100 N

neck injury criteria was reassessed. Neck tension continued to exhibit the closest correlation with injury. The addition of neck extension (rearward) bending moment did not improve predictive capabilities. However, engineering experience with stresses in structures leads to the prediction that neck failure is most likely a function of both tension and bending moment. In consistency with this concept, available data were reanalyzed to determine the best combination of tension and extension moment which predict the injury outcomes very well (Kleinberger et al., 1998). The NHTSA believes that a disadvantage associated with specifying separate limits for flexion, extension, tension, compression, and shear is that it does not account for the superposition of loads and moments, and the additive effects on the injury risk. The NHTSA attempted to take these effects into account. The resulting neck injury criteria, called the "*Nij*", propose critical limits for all four possible modes of neck loading: tension or compression combined with either flexion (forward) or extension (rearward) bending moment. The Nij is defined as the sum of the normalized loads and moments, i. e.,

$$Nij = F_z/f_{int} + M_y/M_{int} \tag{1}$$

where F_z is the axial load, Fint is the critical intercept value of load used for normalization, M_y is the flexion/extension bending moment, and M_{int} is the critical intercept value for moment used for normalization.

Neck injury risk curves previously presented by Mertz (Mertz et al., 1997) were calculated based on the Mertz and Weber modified Median Rank method using the experimental data from porcine subjects (Mertz, 1982). An *Nij* value of 1.0 on this curve corresponds to an approximately 30% risk of an AIS≦3 injury. In order to establish the corresponding risk curve for a live human subject, a comparison was made between the injury rates predicted by using the *Nij* calculations from the experimental dummy test data and the real word injury rates estimated from the National Automotive Sampling System (NASS) database. To take into account the differences between the NASS-based injury risk estimates and the experimental test data, the original porcine risk curve was shifted to the right so that an *Nij* value of 1.4 corresponds to a 30% risk of an AIS≥3 injury. This shifted risk curve shows a 15% injury risk for an *Nij* value of 1.0 and represents the best estimate for the probability of human injury. Since the *Nij* criteria are defined as normalized injury measures, an *Nij* value of 1.0 represents a 15% risk of injury for all occupant sizes. The probability of neck injury risk for AIS≥3 and AIS≥5 is calculated, respectively, as

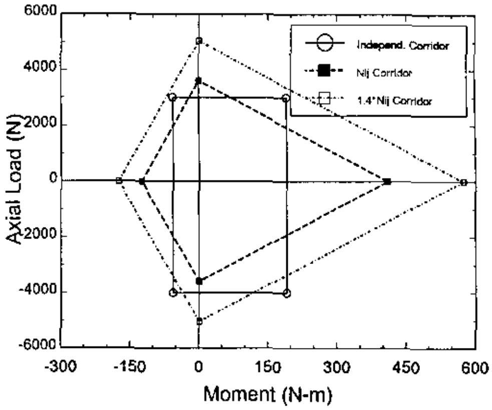

Fig. 1 Typical plot comparing *Nij* with independent injury criteria

$$p(AIS \geq 3) = 1/(1 + e^{3.906 - 2.185Nij}) \tag{2}$$

$$p(AIS \geq 5) = 1/(1 + e^{4.310 - 1.36Nij}) \tag{3}$$

Comparison between the *Nij* combined neck injury criteria and current FMVSS No. 208 alternative sled test criteria is shown for different types of data, Fig. 1 (NHTSA, 1998). The solid rectangle represents the current FMVSS 208 alternative sled test neck injury criteria for axial load and bending moment. The solid "kite" shape represents the *Nij*=1.0 criteria, corresponding to a 15% risk of injury. Data points lying within either the box or kite are considered to pass the corresponding criteria.

3. Structure of Neck

The spine consists of 7 cervical vertebrae, 12 thoracic vertebrae and 5 lumbar vertebrae. The vertebrae are numbered from top (superior) to bottom (inferior), starting with the atlas (C1) directly under the skull and the axis (C2) below. The cervical vertebrae are thus labeled C1 through C7 as shown in Fig. 2. If the cervical and lumbar curvatures become excessive, the condition of lordosis applies. As a result of neck trauma such as a whiplash, muscle spasms and/or displacement of cervical vertebrae (spondylolisthesis) can cause the loss of lodosis (the neck straightens). This is frequently considered as an indicator of poor future improvements. Spasm is the condition where a muscle locks into a rigid condition. A swelling of the vertebrae (spondylitis) usually involves stiffness and pain; if only stiffening occurs, this is called spondylosis, while a freezing of a joint is called ankylosis (Backaitis, 1993).

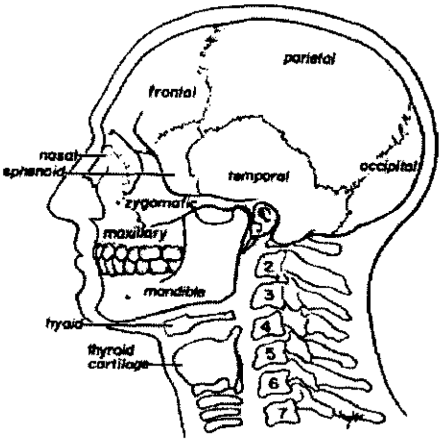

Fig. 2 Lateral anatomical view of skull

4. Experiments

We conducted five frontal barrier crash tests and five rear moving barrier crash tests with five different models (called Cars E, F, G, H, and I) of passenger vehicle, and also conducted five frontal barrier tests for one model of Truck J. Passenger cars and Truck J1 were tested according to the RCAR standard, and Trucks J4 and J5 were tested according to the FMVSS No. 208, full frontal barrier crash shown in Table 2. As to the restraint system, Cars E, F, G, H, I and Truck J5 have a 3-point manual seat belt and a airbag, and Trucks J2, J3 and J4 have a 3-point manual seat belt only.

The Hybrid III 50th percentile male test dummy specified in subpart E Part 572 49 CFR in USA, was instrumented with accelerometers for the head and load cells for the upper neck. The instrumentation was conducted according to the SAE J211 convention. The Hybrid III dummy was consistently placed in the normal seating position for each type of seat.

Table 2 Test conditions for frontal crash test

Vehicle		Standard	Restraint system
Passenger Car	Car E	15km/h 40% offset frontal barrier crash and rear moving barrier crash	3-point seat belt and airbag
	Car F		
	Car G		
	Car H		
	Car I		
Truck	Truck J1	15km/h 40% offset frontal barrier crash	3-point seat belt
	Truck J2	15km/h full frontal barrier crash	
	Truck J3	27km/h full frontal barrier crash	
	Truck J4	49km/h full frontal barrier crash	
	Truck J5		3-point seat belt and airbag

Table 3 Data from frontal crash tests

Vehicle		Normalization of FMVSS 208 sled test criteria(%)							Body Acceleration(g)	
		HIC	Upper neck						LH	RH
			Fx		*My*		*Fz*			
			Positive	Negative	Extension	Flexion	Tension	Compression		
Passen-ger car	E*	1.1	8.2	2.2	7.0	17.9	9.0	0.4	8.6	9.4
	F	1.5	13.6	2.8	12.0	15.8	7.0	0.7	9.0	8.4
	G	1.0	12.2	2.3	10.1	24.0	7.8	0.7	10.8	8.5
	H	1.0	11.7	2.7	10.9	15.3	6.5	0.6	10.4	10.3
	I	1.1	12.5	2.5	11.3	24.6	6.4	0.6	13.3	9.7
Truck	J1	3.2	19.4	2.2	17.6	66.7	56.4	0.9	-	18.8
	J2	2.1	16.9	3.2	11.5	38.6	10.6	2.3	20.7	22.7
	J3	7.9	25.5	3.9	23.4	97.2	20.6	2.4	37.3	47.5
	J4	166.3	58.7	4.3	5.5	226.5	73.3	8.0	81.7	83.6
	J5*	61.8	32.6	9.2	35.9	169.8	55.2	15.2	56.2	77.1

Note) * : The airbag was deployed.

5. Discussion

5.1 Frontal crash tests

Test data for the head and neck of the test dummy and the acceleration at the side lower sill of left (LH) and right (RH) side B-pillar are shown in Table 3. The airbag was inflated in Car E and Truck J5. The values at the head and neck for the truck were higher than those for passenger cars in the RCAR tests because the body of truck was stiffer than those of passenger cars (Lee, 1999).

The real world cervical injuries resulting from airbag interaction are often classified as tension-extension injuries. A tensile load applied to the neck results in the stretching of both the anterior (front) and posterior (rear) soft tissues of the neck. If an extension (rearward) bending moment is superimposed upon the tensile load, the anterior soft tissues will be further stretched while the posterior tissues will become less stretched. Under this loading scenario, a tension-extension injury (N_{TE}) is more likely to occur than a tension-flexion (N_{TF}), compression-extension (N_{CE}), or compression-flexion injury (N_{CF}). Accordingly, the value for NTE would be expected to be the maximum of the four Nij values.

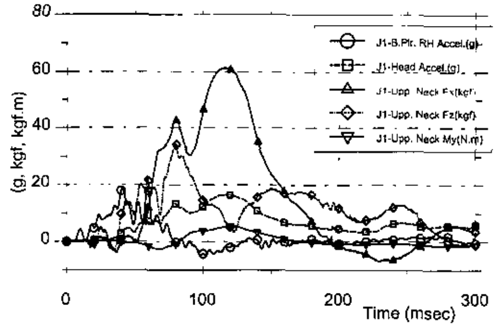

Fig. 3 Time variations of test data for driver in Truck J1 in frontal crash

In case of Truck J1, the time of maximum flexion bending moment *My* and shear force Fx for the upper neck coincides with that of peak resultant acceleration for the head as shown in Fig. 3. The maximum tension *Fz* for the upper neck occurred 40 milliseconds earlier than the peak acceleration for the head.

In case of Car E whose airbag was inflated, as shown in Fig. 4, the time of maximum flexion bending moment *My* for the upper neck coincides

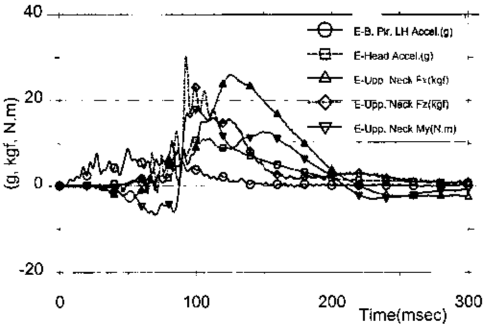

Fig. 4 Time variations of test data for driver in Car E in frontal crash

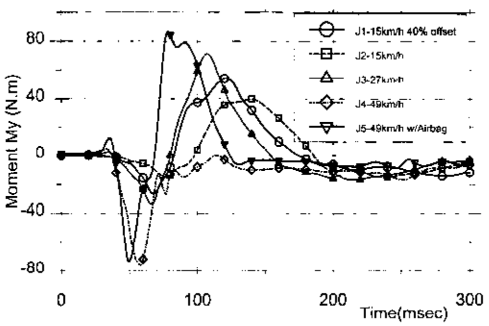

Fig. 5 Time variations of upper neck *My* for driver in Trucks J in frontal crash

with that of peak acceleration for the head. The high tension Fz and the maximum extension moment *My* for the upper neck occurred between 10～15 milliseconds ealier than the peak acceleration for the head, and the maximum shear force Fx occurred 25 milliseconds later than that due to the contact with the deployed airbag. The values of HIC and NTE for the upper neck in the case where the head contacts with the deployed airbag were similar to those in the case where the head does not contact with the airbag.

A comparison of the upper neck My of the driver for trucks J showed that the flexion My for the upper neck was increased due to the increasing impact speed, as shown in Fig. 5, except for Truck J4 where the head contacted with the steering wheel. When the head contacted with the steering wheel and the deployed airbag for Trucks J4 and J5 at the impact speed of 49km/h, severe extension bending moment for the upper neck was generated. The value of shear force Fx for the the upper neck decreased by 44.4% when the head was hit on the deployed airbag in Truck J4, and the negative value of shear force was generated 35 milliseconds earlier than the maximum shear force as shown in Fig. 6.

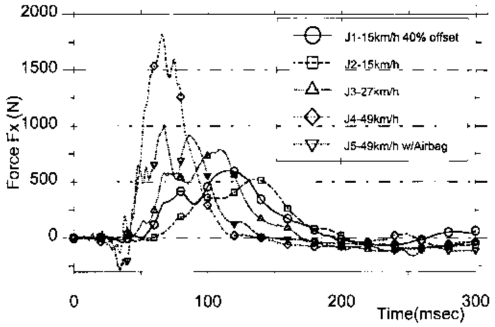

Fig. 6 Time variation of upper neck *Fx* for driver in Trucks J in frontal crash

As shown in Table 3, the values of acceleration of body for the passenger cars were between 8.4g and 13.3g and that for Turck J1 was 18.8g in the RCAR frontal crash tests, which was 41% higher than the highest acceleration of body for the passenger cars. Table 3 and 4 reveal that the highest values of the normalized criteria for the upper neck was the extension bending moment *My*, among the values of shear load *Fx*, bending moment *My*, and axial load Fz for both the passenger cars and trucks in frontal crash tests, and the value of tension-extension injury NTE was the highest among the four *Nij* values, N_{TF}, N_{TE}, N_{CF} and N_{CE}. The values of N_{TE} for passenger cars in the RCAR frontal crash tests were between 0.08 and 0.13, and the values of p(AIS≥ 3) corresponding to a risk of AIS≦3 injury were between 2.3% and 2.6% (see Table 4).

Table 5 indicates that the average value of the normalized extension bending moment My criteria for the upper neck in passenger cars was 19.5%. The average value of the normalized N_{TE} was 7.6%, and the value of NTE compared to the value of extension bending moment *My* was 39.0% for the passenger cars in the RCAR tests as shown in Table 5. Similarly, the value of NTE compared to the value of My for Truck J1 was 32.1%, and those for Trucks J4 and J5 were 36.6% and 34.9%, respectively. We found that the value

Table 4 Data for upper neck from frontal crash tests

Vehicle		Nij(Upper neck)				Neck injury risk(%)	
		N_{TF}	N_{TE}	N_{CF}	N_{CE}	P(AIS≦3)	P(AIS≦5)
Passenger car	E*	0.08	0.09	0.00	0.05	2.4	1.5
	F	0.08	0.10	0.08	0.02	2.4	1.5
	G	0.06	0.13	0.06	0.02	2.6	1.6
	H	0.07	0.08	0.07	0.04	2.3	1.5
	I	0.07	0.13	0.07	0.00	2.6	1.6
Truck	J1	0.11	0.30	0.02	0.12	3.7	2.0
	J2	0.07	0.19	0.08	0.02	3.0	1.7
	J3	0.12	0.49	0.16	0.00	5.5	2.6
	J4	0.19	1.16	0.07	0.13	20.2	6.1
	J5*	0.37	0.83	0.16	0.02	11.0	4.0

Note) ＊ : The airbag was deployed.

Table 5 Analysis of upper neck injury in frontal crash tests

Item		Normalization of criteria(%)		N_{TE}/ My(%)
		My**	N_{TE}***	
Passenger car	E*	17.9	6.4	35.8
	F	15.8	7.1	44.9
	G	24.0	9.3	38.8
	H	15.3	5.7	37.3
	I	24.6	9.3	37.8
Average over Passenger cars		19.5	7.6	39.0
Truck	J1	66.7	21.4	32.1
	J4	226.5	82.9	36.6
	J5*	169.8	59.3	34.9

Note) ＊ : The airbag was deployed.
＊＊ : FMVSS 208 sled test criteria
＊＊＊ : Proposed Nij criteria

of extension bending moment My for the FMVSS 208 sled test criteria might have a strong relationship with the N_{TE} of Nij criteria in the RCAR frontal crash tests.

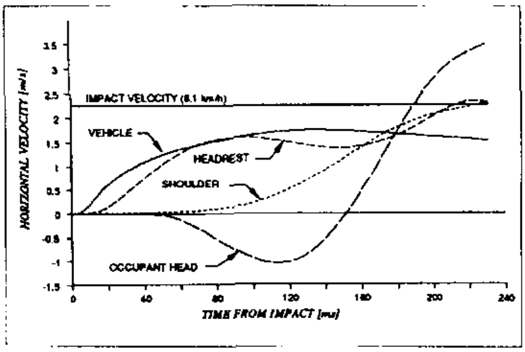

Fig. 7 Occupant's and vehicle's responses in low speed rear-end collision(Thomson et al., 1993)

5.2 Rear-end collision tests

Typical data showing the response of an occupant during a rear impact are shown in Fig. 7 (Thomson et al., 1993). It shows the time variations of horizontal velocities for parts of the occupant and vehicle. These data show that the inertia of the occupant delays the occupant's motion from the initial impact by 50 milliseconds. At the instant when the occupant began to move, the vehicle has achieved 60% of its maximum speed. This causes a subsequent impact when the occupant strikes the seatback. The geometry of most seatbacks affects the striking moment of the occupant's torso to the seatback before the head strikes the head restraint. These nonsimultaneous rebounds of the head and torso increase the potential for neck injury.

The head restraint was hit in the RCAR rear moving barrier crash tests. The maximum values of *Fz* and *My* for the upper neck occurred 100 ~130 milliseconds later than the peak body acceleration, as shown in Fig. 8. In the case of Car H, the time for the maximum negative shear force Fx and tension Fz coincides with that for the peak head acceleration. The extension bending moment My occurred 20 milliseconds later than the peak head acceleration.

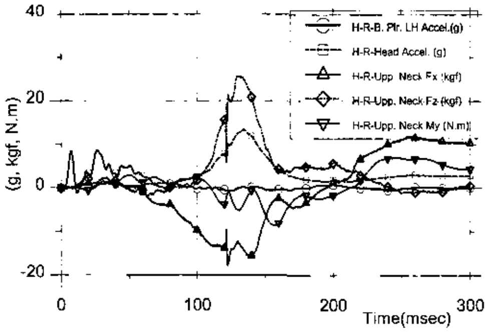

Fig. 8 Time variations of test data for driver in Car H in rear-end collision

Table 6 shows that the values of body acceleration for the passenger cars in the RCAR rear crash tests were found to be between 2.6g and 16.5g, which is a large variation compared with the RCAR frontal crash tests. The highest values of the normalized criteria for the upper neck was the extension bending moment My among those of shear load *Fx*, bending moment *My*, and axial load *Fz* in the RCAR rear crash tests. And the value of tension-extension injury N_{TE} was the highest among the four *Nij* values, N_{TF}, N_{TE}, N_{CF} and N_{CE}, as shown in Table 7. The values of NTE for passenger cars in the RCAR rear collision tests were found to be between 0.06 and 0.12, and

Table 6 Data from rear-end collision tests

Vehicle		Normalization of criteria(%)							Body Acceleration(g)	
		HIC	Upper neck							
			Fx		*My*		*Fz*		LH	RH
			Positive	Negative	Flexion	Extension	Tension	Compression		
Passenger car	E	1.4	3.6	4.2	2.8	10.9	7.3	0.6	5.6	2.6
	F	0.7	3.7	4.5	4.3	19.3	7.2	1.0	7.0	10.9
	G	1.0	3.2	4.8	3.1	12.1	7.0	1.1	5.8	4.8
	H	1.2	3.7	5.5	2.7	14.4	7.6	0.5	8.5	8.9
	I	0.9	3.3	3.7	3.8	20.9	7.8	0.7	12.3	16.5

Table 7 Data for upper neck from rear-end collision tests

Vehicle		*Nij*(Upper neck)				Neck injury risk(%)	
		N_{TF}	N_{TE}	N_{CF}	N_{CE}	P(AIS≥3)	P(AIS≥5)
Passenger car	E	0.04	0.06	0.02	0.01	2.2	1.4
	F	0.02	0.12	0.03	0.00	2.5	1.6
	G	0.04	0.06	0.02	0.00	2.2	1.4
	H	0.04	0.07	0.02	0.01	2.3	1.5
	I	0.03	0.12	0.02	0.01	2.5	1.6

the value of $p(AIS \geq 3)$ were between 2.2% and 2.5%.

Table 8 indicates that the average value of the normalized extension bending moment My criteria for the upper neck was 15.5%, and the average value of normalized NTE of *Nij* criteria was 6.2%. And, the value of N_{TE} compared to the value of the extension bending moment My was 40.0% for the RCAR tests as shown in Table 8. The value of NTE compared to the value of extension bending moment My for passenger cars were found to be between 34.7% and 44.6%. We found that the value of the extension bending moment My for the FMVSS 208 sled test criteria relates strongly with the N_{TE} of *Nij* criteria in the RCAR rear-end collision tests.

5.3 Dynamic Hyge sled tests

To determine the effects of the position of a head restraint on the response of the occupant's neck, three positions of the head restraint were considered in dynamic Hyge sled tests simulating rear impacts. A total of three series of Hyge sled tests were conducted to determine the effects of the headrest's position on the occupant's kinematics and head/neck responses in rear impacts. As shown in Table 9, in the first two test series (S-LM, S-H), adjustable head restraints were positioned in the lower-most and upper-most vertical settings, respectively. In the third series (S-WO), the headrest was removed. For all the three series, the seat was installed on a rigid platform buck, eliminating any performance differences due to structural characteristics or floor deformation. The seat was placed in the mid-seat track position and the seat back was fixed at an angle of 17° to achieve a torso angle of 25° from the vertical. The Hyge sled acceleration pulses used were derived from a 15 km/h 40% offset car-to-moving barrier rear-end collision. The seat was tested at a ΔV of 16 km/h in a rigid environment with a restrained Hybrid III dummy.

Table 8 Analysis of upper neck injury in rear-end collision tests

Item		Normalization of criteria(%)		N_{TE}/My(%)
		My^{**}	N_{TE}^{***}	
Passenger car	E	10.9	4.3	39.4
	F	19.3	8.6	44.6
	G	12.1	4.3	35.5
	H	14.4	5.0	34.7
	I	20.9	8.6	41.1
Average		15.5	6.2	40.0

Note) * : FMVSS 208 sled test criteria
* * : Proposed *Nij* criteria

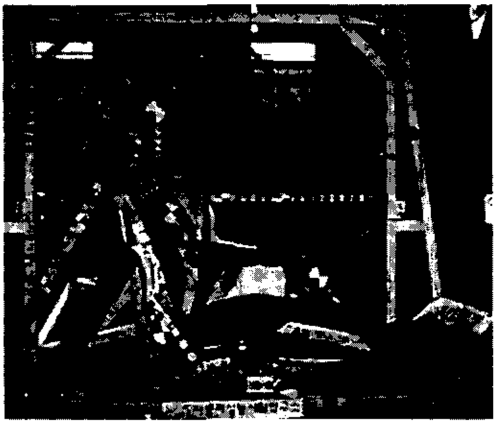

Fig. 9 Positioning of test dummy for Hyge sled tests

Table 9 Test conditions for rear impact in sled tests

Test No.	Vel. ΔV (km/h)	Head restraint				Torso angle of dummy
		Position	Hight from H-Point(mm)	Distance from top of head(mm)	Distance from Back of head(mm)	
S-LM	16	Lowest	601	133	52	25°
S-H		Highest	659	75	48	
S-WO		Without	436	298	-	

Table 10 Data from rear impact in sled tests

Vehicle		Normalization of criteria(%)							Sled	
		HIC	Upper neck							
			Fx		*My*		*Fz*		accel. (g)	ΔV (km/h)
			Positive	Negative	Flexion	Extension	Tension	Compression		
Sled test	S-LM	3.8	5.6	7.8	7.9	36.7	21.3	1.8	6.5	16.3
	S-H	3.4	4.4	7.9	7.9	30.7	13.5	2.2	6.5	16.4
	S-WO	1.1	6.9	8.2	8.8	38.2	10.2	2.5	6.3	16.1

Table 11 Data for upper neck injury from rear impart in sled tests

Vehicle		*Nij*(Upper neck)				Neck injury risk(%)	
		N_{TF}	N_{TE}	N_{CF}	N_{CE}	P(AIS≥3)	P(AIS≥5)
Sled test	S-LM	0.05	0.17	0.05	0.00	2.8	1.7
	S-H	0.07	0.14	0.05	0.12	2.7	1.6
	S-WO	0.07	0.19	0.07	0.00	3.0	1.7

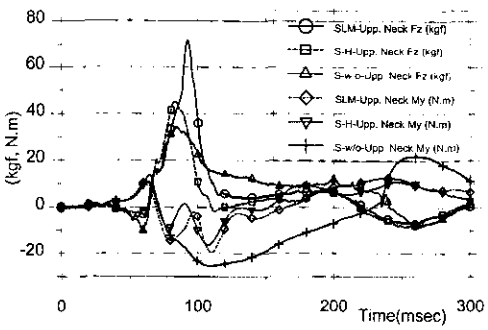

Fig. 10 Time variations of upper neck Fz and My for various positions of head restraint in sled tests

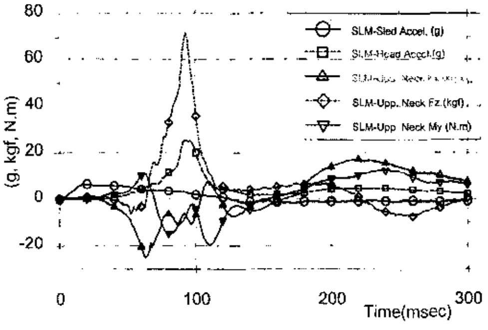

Fig. 11 Time variations test data for lowest position of head restraint in sled tests

The position of the head restraint and dummy head are shown in Table 9. Figure 9 is a photograph of the test dummy set up for the Hyge sled tests.

For the three series of tests, as shown in Figs. 10 and 11, the time of extension for the upper neck was between 50 and 80 milliseconds with the head restraint. And the times of extension and tension for the upper neck without the head restraint were about 140 and 160 milliseconds, respectively.

Table 10 indicates that the highest value of normalized criteria for the upper neck was the extension bending moment My among those of shear load *Fx*, bending moment *My*, and axial load Fz in sled rear impact tests. And the value of the tension-extension injury N_{TE} was found to be the highest among the four Nij values, N_{TF}, N_{TE}, N_{CF} and N_{CE}, as shown in Table 11. It turned out that the probability for a neck injury risk AIS≥ 3 was 2.7% with the upper-most vertical setting, and it was 2.8% and 3.0%, respectively, with the lower most setting and without the head restraint. The values of *Fx*, *My* and N_{TE} were the highest in the case of no head restraint, but the value of tension *Fz* was the lowest.

The value of NTE compared to the value of extension bending moment *My* for the upper neck at the lower most setting of the head restraint was

Table 12 Analysis of upper neck injury from rear impact in sled tests

Item		Normalization of criteria(%)		N_{TE}/ My(%)
		My	N_{TE}	
Sled test	S-LM	36.7	12.1	33.0
	S-H	30.7	10.0	32.6
	S-WO	38.2	13.6	35.6
Average		35.2	11.9	33.7

33.0%, and those for the upper most setting and for no head restraint were 32.6% and 35.6%, respectively (see Table 12). We found that the value of the extension bending moment My for the FMVSS 208 sled test criteria might have a strong relationship with the NTE of Nij criteria in sled rear impact tests. The value of HIC with a head restraint was higher than that without one. The value of the extension bending moment My and N_{TE} at the lower-most setting of the head restraint were higher by 19.5% and 21.4%, respectively, than those with the upper most setting of the head restraint.

6. Conclusions

Through the low speed frontal crash and rear-end collision tests, and dynamic Hyge sled tests for the passenger cars, the following results have been obtained.

(1) The values of head and neck injury for trucks were higher than those of passenger cars in the RCAR tests because the velocity of the driver's movement in trucks was higher than those in passenger cars.

(2) The values of Nij for passenger cars in the RCAR frontal crash tests were found to be between 0.08 and 0.13, and the values of p(AIS$\geq$3) corresponding to a risk of AIS$\geq$3 injury were between 2.3% and 2.6%. The values of Nij for passenger cars in the RCAR rear-end collision tests were between 0.06 and 0.12, and the values of p(AIS$\geq$3) were between 2.2% and 2.5%.

(3) The tension-extension injury was the maximum among the four Nij values for five passenger cars and truck in the RCAR frontal crash and rear-end collision tests.

(4) The nonsimultaneous rebounds between the head and torso increases the neck injury as the occupant's torso strikes the seatback before the head strikes the head restraint in the RCAR rear-end collision tests.

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