STUDY ON STATIC AND QUASI-DYNAMIC EVALUATION METHOD FOR ASSESSING WHIPLASH-ASSOCIATED DISORDERS IN REAR IMPACTS

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ABSTRACT

Studies are underway in JAMA on appropriate static (height of head restraint and backset) and quasi-dynamic (dynamic head rotation angle of Hybrid III dummy and dynamic backset) seat & head restraint evaluation methods for assessing whiplash-associated disorders in rear impacts. For various types of seats, the following items were evaluated for each index: i) road accident & whiplash phenomena, ii) reproducibility and repeatability, iii) correlation with dynamic evaluation results on BioRID II, iv) suitability for various seat types. The results revealed new findings as follows:

1) As for height of head restraint, if the height of head CG + ramping up is secured, a further increase in height does not provide much support for reducing injury.
2) As for backset, due to poor reproducibility in measurements on conventional HRMD, a new measuring method on the basis of SRP is effective. A decrease in backset reduces injury, however, since an excessively small backset impairs comfort, the balance between safety and comfort was examined.
3) As for dynamic head rotation angle of the neck of the Hybrid III dummy, because of poor biofidelity of the dummy, the angle is not considered to be good for a proper dynamic evaluation, however, thanks to good reproducibility and repeatability of the dummy as well as some correlation between head rotation angle and injury criteria, the angle can be used as a tool for alternative evaluation of the backset.
4) The dynamic backset was proposed as an alternative test to the static backset. However, the evaluation uses only the neck behavior of the dummy, and reproducibility and repeatability are still low. Consequently, the backset is not regarded as an appropriate evaluation method at this time.

INTRODUCTION

The death toll in traffic accidents is falling in Japan; however, the number of traffic accidents remains unchanged. Rear-end accidents in particular are significantly increasing (See Figure 1). About 90% of injuries caused by rear-end accidents are light injuries of the neck such as whiplash flagellum and about 90% of victims are the driver or the passenger occupant (See Figure 2). Therefore, the Ministry of Land, Infrastructure and Transport of Japan announced in September 2002 that it would take countermeasures against whiplash-associated disorders (WAD) in rear impacts (WAD reduction seat) as a candidate for the next safety standardization [1].

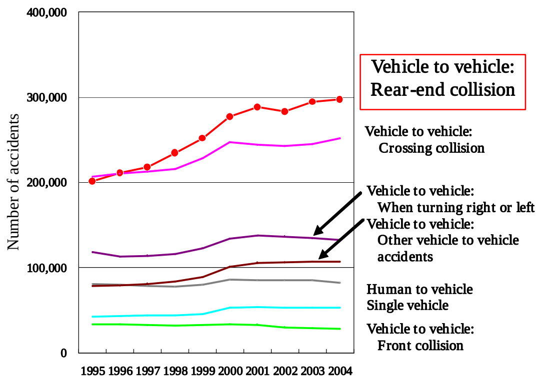

Figure 1. Trends of number of accidents by accident type in Japan (as of end of December of each year).

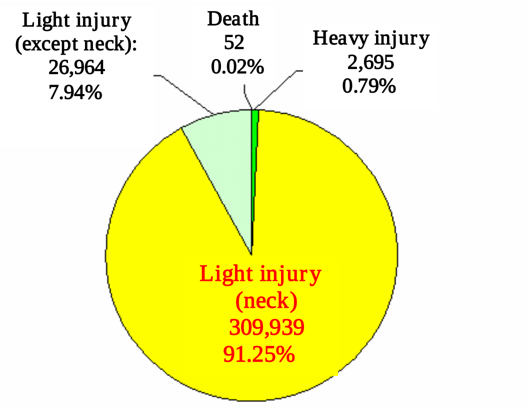

Figure 2. Breakdown of injuries caused by rear-end collisions in Japan.

WAD in rear impacts is attracting global attention. In the World Forum for the Harmonization of Vehicle Regulations (WP.29) held in March 2005, the establishment of global technical regulations (gtr) based on the FMVSS202a head restraint regulation issued that year was approved[2]. In accordance with the MLIT announcement, in June 2003 the Japan Automobile Manufacturers' Association (JAMA) established a working team for examining with MLIT the standardization of whiplash reduction seats. JAMA has also participated in the informal head restraints gtr meeting, which began in February 2005. Moreover, in July 2005, a working group for WAD in rear impacts was established to start studying an appropriate dynamic evaluation method. This paper outlines the static and quasi-dynamic evaluation methods for the seat and head restraint for reducing WAD in rear impacts on the front outboard seats, which were examined by JAMA.

Causes of WAD

To examine an appropriate method for evaluating WAD in rear impacts, it is necessary to understand the mechanism by which whiplash flagellum is generated. However, since the mechanism is not clarified yet, this study employed the following latest hypothesis proposed by Ono[3] to examine the evaluation method.

As shown in Figure 3, the behavior of the passengers when a car is hit at low speed can be roughly categorized into three stages: (1) Straightening of the spine and extending it up to the neck, (2) S-shaped deformation of the neck by the forward displacement of the trunk and subsequent shearing, and (3) Hyperextension of the neck. The mechanism of whiplash flagellum seems to be caused by the S-shape deformation of cervical vertebrae, tucking synovium into the intervertebral joint when extending the cervical vertebrae, and flexure of the articular capsule around the joint. Therefore, an evaluation and indicator that lead to suppression of the S-shape deformation and extension are considered to be appropriate.

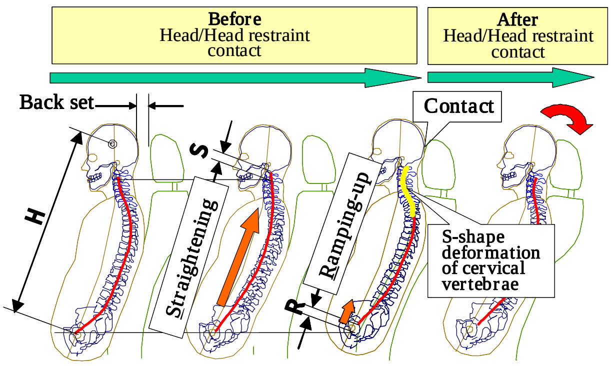

Figure 3. Behavior of passenger's head and neck during a rear impact.

STATIC EVALUATION

To statically evaluate the WAD reduction seat, "Height of head restraint" and "Backset" are considered to be important indexes as the International Insurance Whiplash Prevention Group (IIWPG) is conducting an assessment[4].

Height of Head Restraint

To reduce the S-shaped deformation of passengers with various physical frames, the height of the head restraint must be appropriate for the occupant's head. If the head restraint is too high, it may disturb the field of rear vision and impede an emergency escape since it causes an obstacle to the head when getting in and out of the rear seat of a two-door vehicle. Therefore, the required height should be minimized.

<u>**Maximum Height**</u> - First, JAMA examined the height of the head restraint necessary for properly protecting the head of the passenger from AF5%ile to AM95%ile. As the occupant's behavior in Figure 3 shows, the maximum head restraint height (Hmax) must be higher than the height reached when straightening of the spine in a rear-end collision (S) and ramping up of the trunk (R) are added to the height from the H-point to the center of gravity of the head at the time of seating (H)[5][6]:

$$\text{Hmax} = \text{H+S+R of AM95\%ile} \qquad (1).$$

The length S is 34–38mm and the length R is about 15mm based on experience, however, data that demonstrates the length R is not sufficient. Hmax for US 95%ile male was calculated as 813mm[5][6].

IIWPG also determined their own evaluation threshold by examining the required height of the head restraint obtained from past accident analyses (See Figure 4). The statistics in the figure show that reduction of injury cannot be expected even if the head restraint is higher than the height to the center of gravity of the head, and that taller women tend to be more affected by the height of the head restraint [3].

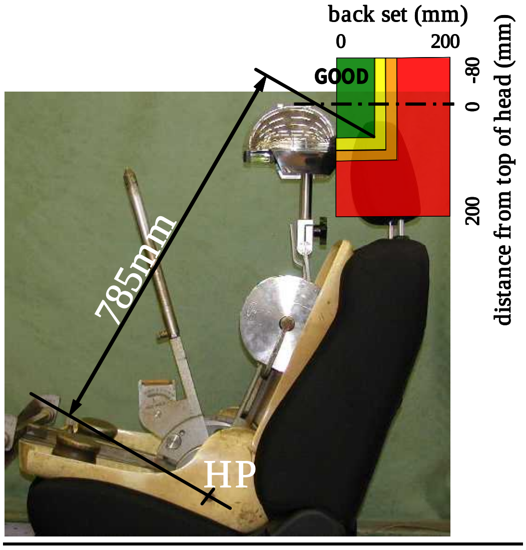

Figure 4. IIWPG head restraint height evaluation.

JAMA examined these hypotheses with an actual car seat in experiments. In the experiments, various changes in injury value were confirmed by changing the height of the head restraint of the existing seat and by IIWPG's dynamic evaluation method. As the results in Figure 5 show, the injury value was not improved even when the height was higher than that proposed by IIWPG. Our test has shown the same tendency as IIWPG accident research. The BioRID II dummy was used for this evaluation. The height of BioRID II is equivalent to the AM50%ile. From these results, an appropriate head restraint height for AM95%ile equivalent passengers is considered to be 820mm, because the height difference to the center of gravity between AM50%ile and AM95%ile is 35mm. The value is almost the same as that calculated from human height.

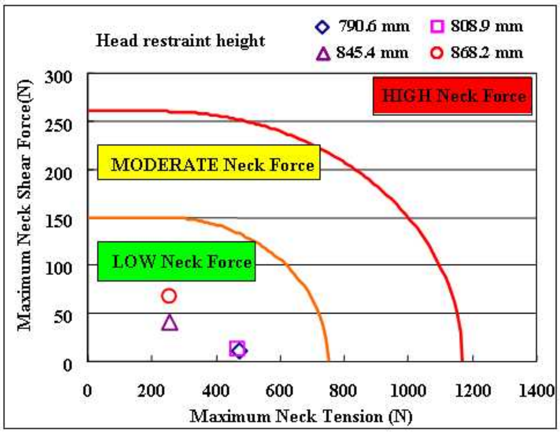

Figure 5-1. Relationship between head restraint height and IIWPG dynamic evaluation.

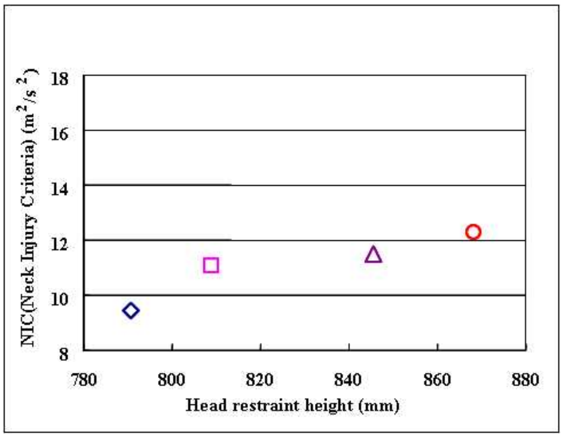

Figure 5-2. Relationship between head restraint height and NIC.

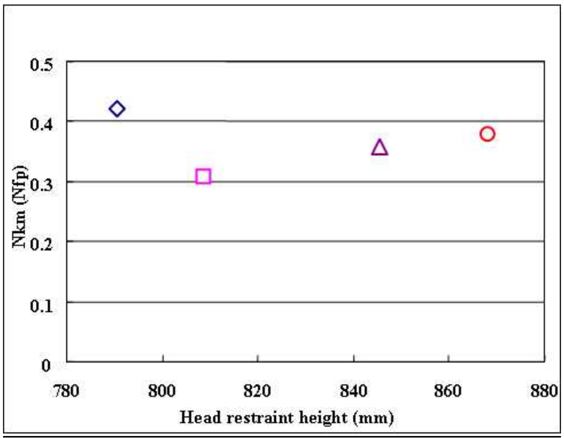

Figure 5-3. Relationship between head restraint height and Nkm.

<u>Rear Visibility Effect</u> - Next, we evaluated the influence of maximum head restraint height on the field of rear vision for a Japanese mini car, which is considered to be significantly affected by head restraint height, because the width of cars in this class must be 1480mm or less, and the distance between driver and passenger seats is almost the smallest in the world. For the evaluation, a vehicle with the head restraint integrated into the seat back was used, as this is common among reasonably priced compact cars, to evaluate the influence of the head restraint height on the direct and indirect field of rear vision and the feelings of passengers. As a result, in the case of such narrow vehicles, it was found that a head restraint height of 850mm or higher might affect the direct rear-diagonal field of vision and the indirect field of vision through the inside rearview mirror (See Figure 6). In the case of 800 to 820mm height, both direct and indirect vision were marginal.

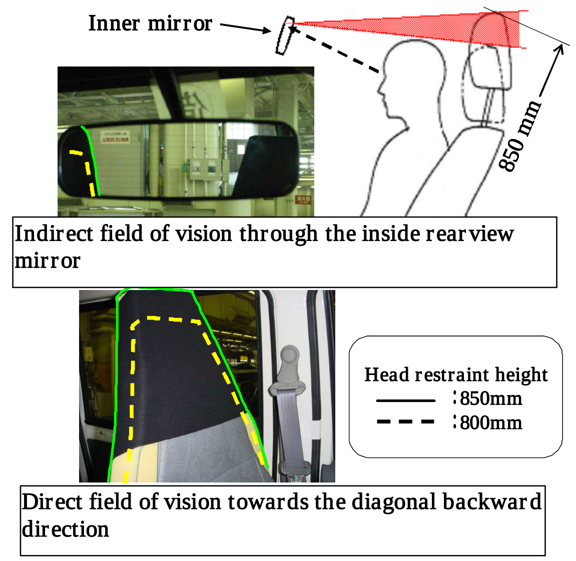

Figure 6. Relationship between the height of head restraint and field of view on the mini car.

Backset

The backset between the head and head restraint was examined as another important requirement. The backset measurement method using HRMD, which was developed by the Research Council for Automobile Repairs (RCAR)(7) and quoted in the assessment of IIWPG and FMVSS202a, has been shown to have problems regarding repeatability and reproducibility during measurement(8). Accordingly, we examined repeatability and reproducibility in order to seek a more precise measurement method, and studied reasonable requirement values for the measurement method.

Repeatability and Reproducibility – Variation measurements of backset using HRMD were evaluated with four typical seats (See Table 1). The repeatability was evaluated from three to five measurements for the fixed seat reclining position by the same evaluator for each seat. The results were evaluated by maximum variation and coefficient of variation (C.V):

$$\text{Repeatability C.V} = \left[\frac{S_d}{\overline{X}}\right] 100\ (\%) \qquad (2).$$

$\overline{X}$ = Average value of each measurement

S_d = Standard deviation of each measurement

Admissible level: C.V $\leq$ 10%

Maximum variation was within ±2mm and C.V was within 1.75%, showing sufficient precision (See Figure 7 and Table 3). The reproducibility was evaluated for two or three measurements with variable seat reclining positions, which could maintain a torso angle of 25 degrees. The result was also evaluated by maximum variation and C.V:

$$\text{Reproducibility C.V} = \left[\frac{S_b}{\overline{X_G}}\right] 100(\%) \qquad (3).$$

$\overline{X_G}$ = Average value of all measurements

$$S_B = \left[\frac{MSB - MSW}{n}\right]^{1/2}$$

MSB: Average square between measurers
MSW: Average square within a measurer
n: Number of repetitions of test
Admissible level: C.V $\leq$ 10%

The maximum variation was up to ±14.5mm and the C.V diverged towards infinity, thus making it uncalculatable (See Figure 7 and Table 3). This was an unacceptable variation.

Table 1. Conditions of repeatability and reproducibility evaluation by using HRMD

	Seat Type	Seat No.	No. of measur-ers	No. of measure-ments	No. of measurering device	Reclining angle
Repeatability	A	3	3	3	1	Fixed
	B	3	3	3	1	
	C	3	3	3	1	
	D	1	4	1 to 4	1	
Reproducibility	B	3	3	4	1	Variable
	C	3	3	4	1	
	D	1	4	1 to 5	1	

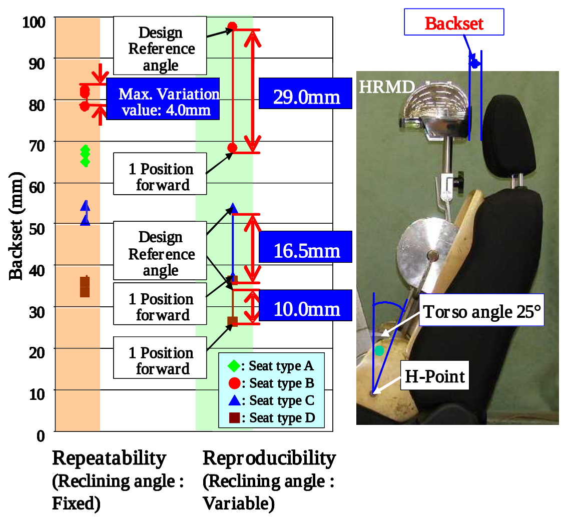

Figure 7. Repeatability and reproducibility for backset by using HRMD.

The three major causes of the deviation are:

(1) Variation of the seatback angle when aligning the seat torso angle to 25 degrees
(2) Variation of H-point when seating the 3DM manikin with HRMD
(3) Variation of vehicle configuration at the time of measurement

The variation, which occurs when mounting the 3DM manikin with multiple joints on a soft seat, has long been a common problem. Therefore, the torso angle of ±5 degrees and H-point of ±25mm have been approved by ECE regulations. In the case of ECE regulation R17, the seating reference point (SRP) and design seat back angle are used as a datum of seat dimensional measurement such as height if the measurement value is within this variation range. Then, we examined applying this idea to the backset measurement. We modified and experimentally manufactured equipment to measure the backset based on SRP and the design seat back angle (See Figure 8), and then evaluated the measurement variation of the backset using the same two types of seats, which were evaluated by the HRMD method, and one new type seat (See Table 2). Since the load by the back pan was applied to the seat back during measurement with the traditional 3DM manikin, we also checked the effect of this. We did not evaluate repeatability because there is almost no potential repeatability variation. The reproducibility was evaluated by using different equipment. The maximum variation was drastically improved from ±14.5mm to ±2.3mm, and C.V from uncalculatable to within 4.41%. The absolute value also became close to the design value (See Figure 9 and Table 3). The value without the back pan was closer to the design value. Similar research conducted by Alliance found that this phenomenon occurred because of excessive back pan load on the seat back due to the difference between SRP and H-point[9]. Within proper load such as back pan load from the normal 3DM manikin, the difference of head restraint position that affects the measurement value of the backset was very minor. Therefore, measurement without the back pan is more appropriate for the new measurement method. On the other hand, some consider that the true value of the vehicle cannot be measured with the new measurement method. Our examination of the difference between SRP and the design standard back angle, and actual measurements on various vehicle seats, showed that the variation is almost even, centered on the reference value (See Figure 10). Therefore, SRP and the design standard back angle are considered to be generally representative of the true value.

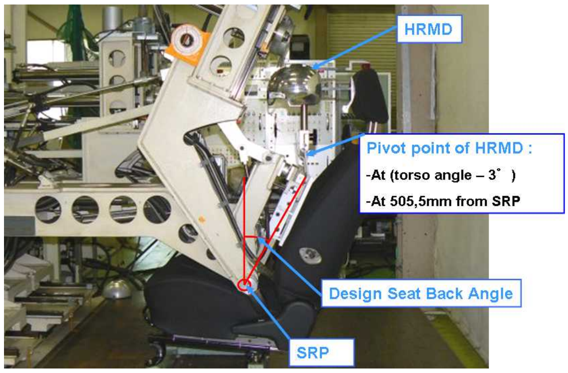

Figure 8. New backset measurement method based on SRP and design seat back angle.

Table 2.
Conditions of repeatability and reproducibility evaluation by using new backset measurement method

	Seat Type	Seat No.	No. of measur-ers	No. of measure-ments	No. of measuring device	Reclining angle
Reproducibility	A	3	1	1	3	Fixed
	C	2	1	1	2	
	E	1	1	1	3	

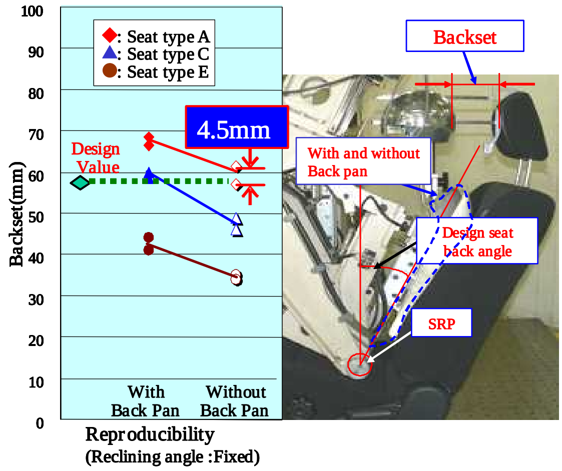

Figure 9. Reproducibility with new backset measurement method.

Table 3.
Comparison of backset repeatability and reproducibility between HRMD method and New method

Seat Type	Repeatability		Reproducibility					
			HRMD Method		New Method with Back pan		New Method w/o Back pan	
	Variation (mm)	C.V.	Variation (mm)	C.V.	Variation (mm)	C.V.	Variation (mm)	C.V.
A	±1.50	0.99	-	-	±1.00	1.70	±2.25	4.41
B	±2.00	1.36	±14.50	∞	-	-	-	-
C	±1.75	1.75	±8.25	∞	±0.75	1.46	±1.50	3.61
E	-	-	-	-	±1.75	4.39	±0.50	1.68

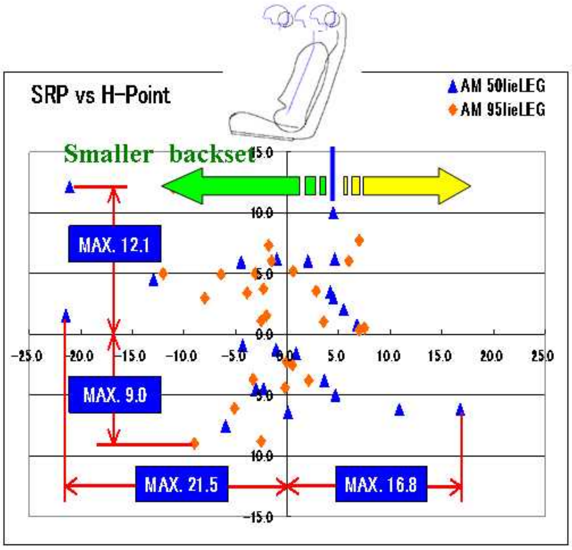

Figure 10-1. Relationship between SRP and H-point.

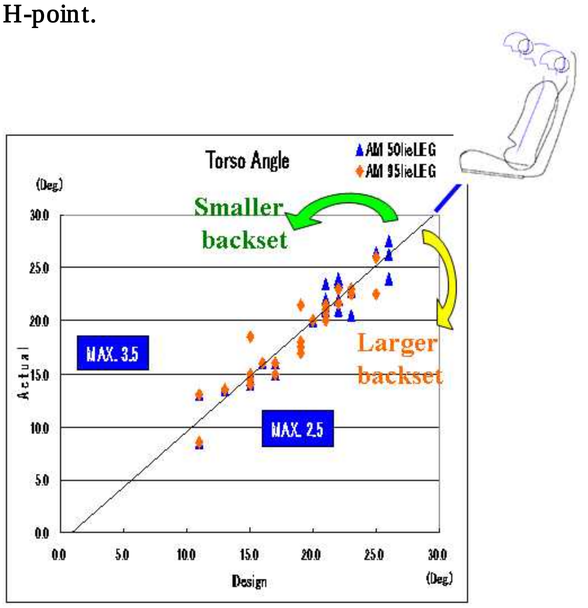

Figure 10-2. Relationship between design torso angle and actual measurement angle.

Comfort - To reduce whiplash flagellum, an effective backset value is 100mm or less and a smaller value produces a larger effect [(3)]. However, it is known that if the backset is too small, it impairs sitting comfort [(10)]. For these reasons, we examined backset values that balance safety and comfort. UMTRI summarized the correlation between backset and comfort, but there was not enough data for values smaller than 70mm (with hair margin). Accordingly, we examined whether correlation data for smaller than 70mm could be a substitute. In the examination, we modified the backset of the head restraint of a typical seat to be variable and then determined the actual backset length that made drivers with various frames feel uncomfortable through a sensory evaluation. We found that the evaluation results of UMTRI could extend to the backset range smaller than 70mm. Hence, the backset value could be 40mm or more to secure about 70% comfort (See Figure 11).

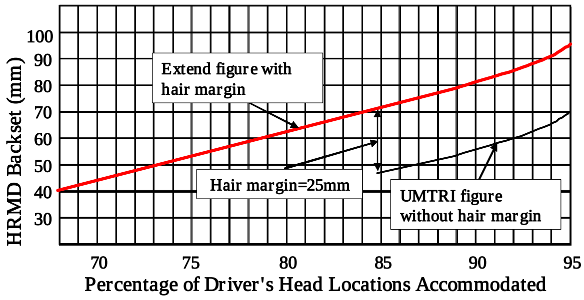

Figure 11. Relationship between comfort and backset.

QUASI-DYNAMIC EVALUATION METHOD

Normally, WAD must be evaluated by the dynamic test, which represents typical rear crash accident conditions. The test must take into consideration the vehicle crash pulse of an actual accident, a dummy with high biofidelity, and injury indicators. However, there was no standardized dynamic evaluation method for regulatory use. On the other hand, it is difficult to measure the static backset value of an active head restraint, in which the seat moves the head restraint forward using the pushing force of the passenger or another drive force at the time of a rear-end collision. The active seat has been increasingly adopted recently to reduce WAD. Therefore, a quasi-dynamic evaluation method with the Hybrid-III dummy was proposed in FMVSS202a as an alternative method of evaluating static backset. We examined the validity and possibility of this method and alternative test methods.

Assessment Dummy

BioRID II, which was developed for evaluating rear-end collisions, is considered to be suitable since it can simulate the behavior aforementioned (knocking up by straightening of the entire spine, S-shaped deformation, etc.) and has high biofidelity, however, it is incomplete as measurement equipment. Therefore, we confirmed a comparison test with Hybrid-III, which has been proven in many proposed collision tests. K. Ono et al. examined the repeatability and reproducibility of two types of dummies [(11)].

Test Conditions – The evaluation method was as follows (See Figures 12 and 13).

Figure 12. Sled test using BioRID II.

Figure 13. Sled test using Hybrid-III.

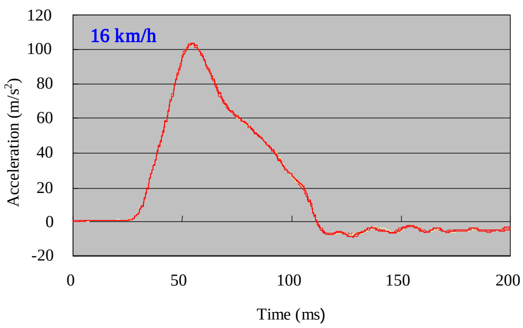

Figure 14. Sled pulse.

- HYGE sled test that simulates the rear-end collision
- Pulse wavelength is △V = 16km/h (See Figure 14)
- Rigid seat
- Test conducted five times under the same conditions
- Dummy: BioRID II (A, B, C), Hybrid-III (A, B, C)
- Features of the dummy, standard calibration description, and measurement items are as follows.

BioRID-II Level F
Dummy A: Owner A (With standard calibration)
Dummy B: Owner B (Without calibration)
Dummy C: Owner C (With standard calibration)

Hybrid-III
Dummy A: Owner A (With standard calibration)
Dummy B: Owner D (With standard calibration)
Dummy C: Owner E (With standard calibration)

Evaluation Indicators
BioRID-II
- Acceleration of the first thoracic vertebra (T1) (T1_Acc)
- Shearing load to the neck (Fx)
- Axial load to the neck (Fz) (Reference evaluation)
- Acceleration of the head (Head_Acc)
- Neck moment (My)
- Rearward rotation angle of the head (HA-TA)

Hybrid-III
- Rearward rotation angle of the head (HA-TA) (Reference evaluation)
- Acceleration of the first thoracic vertebra (T1) (T1_Acc)
- Shearing load to the neck (Fx)
- Axial load to the neck (Fz)
- Acceleration of the head (Head_Acc)
- Neck moment (My)

Method and Criteria for Evaluating Repeatability – The definition of the C.V value used as an evaluation indicator was as follows:

$$\text{Repeatability C.V} = \left[\frac{S_d}{\overline{X}} \right] 100\ (\%) \qquad (4).$$

$\overline{X}$ = Average value of each dummy
S_d = Standard deviation of each dummy
Admissible level: C.V $\leq$ 10%

For both BioRID II and Hybrid-III, the repeatability of the evaluation indicators was within the limit of tolerance (See Figures 15 and 16).

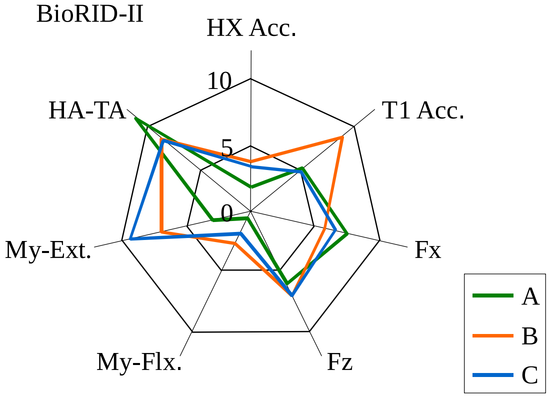

Figure 15. Repeatability C.V for BioRID II.

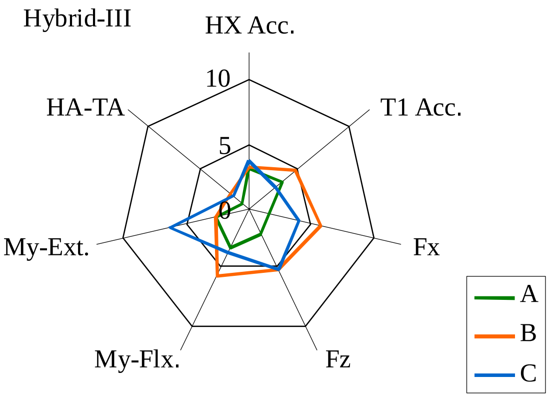

Figure 16. Repeatability C.V for Hybrid-III.

Method and Criteria for Evaluating Reproducibility – The respective three dummies of BioRID II and Hybrid-III of different owners were used and the C.V value to evaluate the reproducibility was calculated as follows:

$$\text{Reproducibility C.V} = \left[\frac{S_b}{\overline{X}_G}\right] 100(\%) \qquad (5).$$

$\overline{X}_G$ = Average value of 3 dummies

$$S_B = \left[\frac{MSB - MSW}{n}\right]^{1/2}$$

MSB: Average square between dummies
MSW: Average square within a dummy
n: Number of repetitions of test
Admissible level: C.V $\leq$ 10%

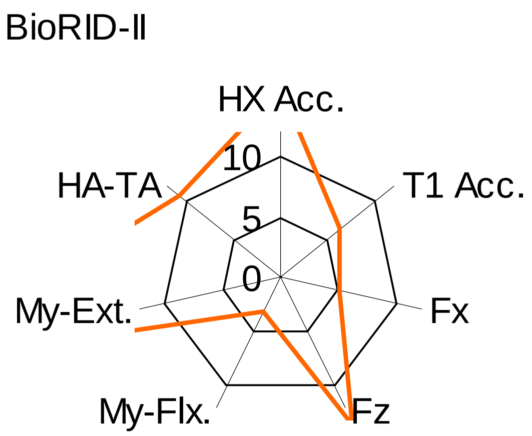

Figure 17. Reproducibility C.V for BioRID II.

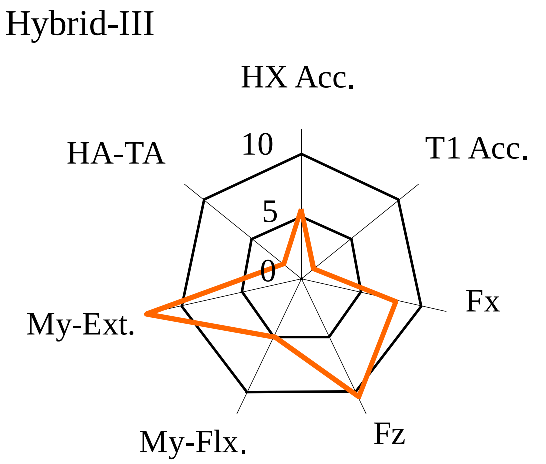

Figure 18. Reproducibility C.V for Hybrid-III.

For Hybrid-III, the reproducibility of the evaluation indicators was within the limit of tolerance (See Figure 17). On the other hand, some of the indicators of BioRID II exceeded the evaluation reference value of the reproducibility (See Figure 18). This occurred because the calibration method for the dummies differed.

Criterion

The backward rotation angle of the head was proposed as an evaluation criterion for Hybrid-III for head restraint gtr, the same as FMVSS202a. The threshold of the rotation angle was also proposed as 12 degrees or less [(12)]. JAMA conducted a comparison sled test between BioRID II and Hybrid-III to evaluate the validity of the indicators aforementioned.

Test Condition – The test was conducted under certain conditions (using Hybrid-III dummy, thread test, △V=16km/h, measurement of backward rotation angle of the head) proposed in gtr with the same type of seat as tested by IIWPG that has already been evaluated with BioRID II. The results of the test and IIWPG were then compared

Test Result – As shown in Figure 19, the results are roughly correlated. However, since even the seat with a "Good" evaluation in IIWPG is slightly above the proposed criterion, 12 degrees, the proposed criterion is slightly too severe to compare IIWPG criteria.

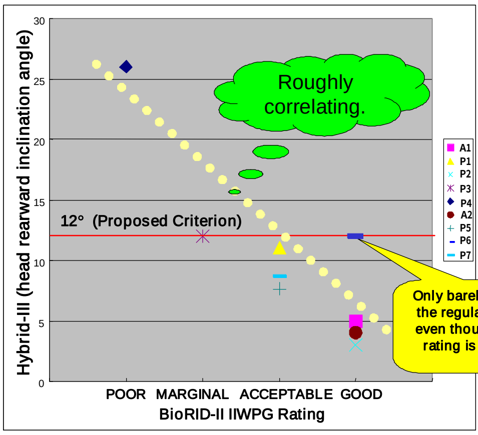

Figure 19. Correlation between IIWPG (BioRID II) and FMVSS 202a (Hybrid-III) evaluations.

<u>Test Variation</u> – The results of backward rotation angle of the head when the thread test was conducted five times under the same conditions with three types of Hybrid-III dummies are shown in Table 4. The difference between the maximum and minimum value is about 4 degrees. Therefore, the criterion should have this ±2 degrees variation margin.

Table 4.
Head rear rotation angle variation

	Dummy	Speed (km/h)	Value					Value	
			1st	2nd	3rd	4th	5th	max	min
HA-TA (deg)	Hybrid-III A	16	48.6	48.9	48.0	48.4	48.4	48.9	48.4
	Hybrid-III B		50.3	48.1	49.4	48.7	48.4	50.3	48.1
	Hybrid-III C		48.3	46.5	47.2	47.4	46.8	48.3	46.5

DISCUSSION

We have examined the static and quasi-dynamic evaluation methods and requirements concerning the effects of head restraints and seats for WAD in rear impacts. These static requirements mainly affect only the part of first stage of the whiplash phenomenon (the stage before the head contacts the head restraint) as shown in Figure 3. To evaluate the S-shaped deformation of cervical vertebrae, which is a major factor of whiplash flagellum, the difference of behavior between the trunk and head before and after contacting the head restraint and the degree of load applied to the neck must be evaluated. To do so, a dynamic evaluation using a dummy for the rear-end accident simulation is effective, and many studies and assessments have already been conducted. In fact, the correlation between the IIWPG backset value and result of the dynamic evaluation in terms of only the seats with sufficient head restraint heights is extremely low (See Figure 20). Therefore, to properly evaluate the seat and head restraint performance for WAD, it is essential to introduce the dynamic evaluation.

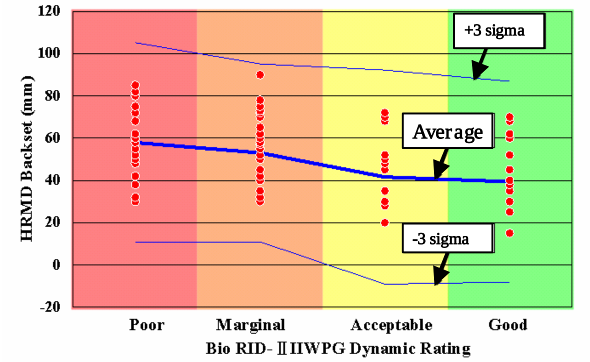

Figure 20. Correlation between IIWPG backset and dynamic evaluation score for proper height of non active seat.

<u>Proposal from JAMA</u> – A new workgroup must be established to examine the proper dynamic test and evaluation method. The results of the tests and method must be fed back to the head restraint gtr as phase two which was agreed in GRSP held in December 2006. This workgroup should clarify the following items.
Agenda Items for WG

- Sled pulse conditions:
  Reflecting accident realities
- Assessment dummy:
  Biofidelity level, Test method, Seating method, etc.
- Assessment criteria:
  Reflecting injury phenomena; Assessed in terms of injury values
- Limit value:
  An appropriate value based on injury risk analyses and feasibility studies
- Effect assessment:
  Determining the injury-reducing effect on real-world accidents

CONCLUSIONS

From the evaluation results described in this paper, JAMA recommends the following description as the static and quasi-dynamic evaluation method and the evaluation standard on the front outer seat and head restraint.

Height

The appropriate required maximum height (Hmax) is 820mm for both protection and visibility.
We could not find any further benefit of setting the head restraint higher than 820mm for up to AM95%ile.
We also found by our internal review that most of the current head restraints, complying with the 800mm

requirement regulated in ECE R17, are already higher than 820mm; therefore, the current regulation requirement, Hmax = 800mm, virtually already covers the required height.

Backset

To achieve a good balance between competing requirements, WAD reduction performance and comfort, the backset value should be made as small as possible without sacrificing comfort. To achieve this, the variation of the evaluation method should be minimized. In this regard, our study showed that the new backset evaluation method is the most appropriate method. Since even this test method cannot eliminate manufacturing variations of the seat itself (±10mm), we propose that the limit of the backset requirement value with the new measurement method be as follows:

Backset requirement =Comfort boarder [40mm]
+ Measurement variation [4.5]
+ Manufacturing variation [10mm]
=[54.5mm] (6).

QUASI-DYNAMIC

This test method is an alternative to the backset evaluation for the active head restraint in which the head part moves at the time of a rear-end collision. As well as the active head restraint, the test method that measures the backward rotation angle of the neck of the Hybrid-III dummy was also considered to be effective since the variation is smaller than that of the traditional HRMD backset measurement method. However, since Hybrid-III has less biofidelity during a rear-end collision, it was found that they were evaluated differently from the BioRID II dummy having high biofidelity on some seats. Therefore, it is difficult to introduce the dynamic evaluation with severer criterion unless a highly reproducible method that can properly reproduce the actual phenomenon with a dummy with high biofidelity is established. For these reasons, for the time being, a Hybrid-III dynamic test with slightly less severe criterion or the new backset measurement method incorporating the activation margin of the active headrest are considered to be effective in the case of the active head restraint.

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