# PERFORMANCE OF SEATS WITH ACTIVE HEAD RESTRAINTS IN REAR IMPACTS

**Liming Voo**
**Bethany McGee**
**Andrew Merkle**
**Michael Kleinberger**
Johns Hopkins University Applied Physics Laboratory
United States of America
**Shashi Kuppa**
National Highway Traffic Safety Administration
United States of America
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## ABSTRACT

Seats with active head restraints may perform better dynamically than their static geometric characteristics would indicate. Farmer *et al.* found that active head restraints which moved higher and closer to the occupant's head during rear-end collisions reduced injury claim rates by 14-26 percent. The National Highway Traffic Safety Administration (NHTSA) recently upgraded their FMVSS No. 202 standard on head restraints in December 2004 to help reduce whiplash injury risk in rear impact collisions. This upgraded standard provides an optional dynamic test to encourage continued development of innovative technologies to mitigate whiplash injuries, including those that incorporate dynamic occupant-seat interactions. This study evaluates four original equipment manufacturer (OEM) seats with active head restraints in the FMVSS 202a dynamic test environment. The rear impact tests were conducted using a deceleration sled system with an instrumented $50^{th}$ percentile Hybrid III male dummy. Seat performance was evaluated based on the FMVSS 202a neck injury criterion in addition to other biomechanical measures, and compared to the respective ratings by the Insurance Institute for Highway Safety (IIHS). Three of the four OEM seats tested were easily within the allowable FMVSS 202a optional dynamic test limits. The seat that was outside one of the allowable limits also received only an "acceptable" rating by IIHS while the other three seats were rated as "good." Results also suggest that the stiffness properties of the seat back and recliner influence the dynamic performance of the head restraint.

## INTRODUCTION

Serious injuries and fatalities in low speed rear impacts are relatively few. However, the societal cost of whiplash injuries as a result of these collisions is quite high: the National Highway Traffic Safety Administration (NHTSA) estimates that the annual cost of these whiplash injuries is approximately $8.0 billion (NHTSA, 2004). Numerous scientific studies reported connection between the neck injury risk and seat design parameters during a rear impact (Olsson 1990, Svensson 1993, Eichberger 1996, Tencer 2002 and Kleinberger 2003). When sufficient height was achieved, the head restraint backset had the largest influence on the neck injury risk. In addition to its static position relative to the occupant head, the structural rigidity of the head restraint and its attachment to the seat back can have a significant impact on the neck injury risk in a rear impact (Voo 2004). Farmer et al. (2003) and IIHS (2005) examined automobile insurance claims and personal injury protection claims for passenger cars struck in the rear to determine the effects of changes in head restraint geometry and some new head restraint designs. Results from these studies indicated that cars with improved head restraint geometry reduced injury claims by 11-22 percent, while active head restraints that are designed to move higher and closer to occupants' heads during rear-end crashes were estimated to reduce claim rates by 14-26 percent.

In response to new evidence from epidemiological data and scientific research, NHTSA published the final rule that upgrades the FMVSS 202 head restraint standard (49 CFR Part 571) in 2004, and is participating in a Global Technical Regulation on head restraints. The new standard (FMVSS No. 202a) provides requirements that would make head restraints higher and closer to the head so as to engage the head early in the event of a rear impact. The rule also has provisions for a dynamic option to evaluate vehicle seats with a Hybrid III dummy in rear impact sled test that is intended in particular for active head restraints that may not meet the static head restraint position requirements such as height and backset. However, the dynamic option is not limited to active head restraints. By active head restraints we mean head restraints that move or deploy with respect to the seat back. These active head restraints might perform better in rear impact collisions than their static geometric measures may indicate. The neck injury criterion in this dynamic option uses the limit value of 12 degrees in the posterior head rotation relative to the torso of the dummy within the first 200 milliseconds of the rear impact event.

The Insurance Institute for Highway Safety (IIHS) has been publishing ratings of head restraint geometry since 1995 (IIHS, 2001). IIHS along with the International Insurance Whiplash Prevention Group (IIWPG) developed a dynamic test procedure (IIHS, 2006) to evaluate head restraints and have been rating head restraint systems since 2004 using a combination of their static measurement procedure and the newly developed dynamic test procedure. In this combined procedure, seat systems that obtain a “good” or “acceptable” rating according to the IIHS static head restraint measurement procedure, are put through a dynamic rear impact sled test with the BioRID II dummy, simulating a rear crash with a velocity change of 16 km/h. The dynamic evaluation is based on the time to head restraint contact, maximum forward T1 acceleration, and a vector sum of maximum upper neck tension and upper neck rearward shear force. This evaluation results in a dynamic rating of the seat ranging from “good” to “poor”. As a consequence of this evaluation procedure by IIHS, head restraints that obtained a good or acceptable rating from the static head restraint measurements may obtain an overall poor rating from the dynamic test procedure. In addition, some active head restraint systems that obtain a marginal or poor static measurement rating are not even tested dynamically although their dynamic performance may actually be good.

This study evaluates the performance of a select group of automotive seats with active head restraints from original equipment manufacturers (OEM) under the environment of the optional FMVSS 202a dynamic test.

## MATERIALS AND METHODS

Driver seats from four different passenger cars were evaluated: Saab 9-3, Honda Civic, Nissan Altima and Subaru Outback. The OEM driver seats were 2006 model year production stock, ordered directly from either the vehicle manufacturers or their suppliers, and included the seatbelt restraints. The seats were not modified in any way. Custom-designed rigid base brackets for each seat were used to anchor the seats to the impact sled such that the height and relative position of the seat to the B-pillar and floor pan would be similar to its position in the car. For each seat model, the corresponding OEM seatbelt was used as the restraining device during each test.

The seats were positioned nominally in accordance with sections S5.1 and S5.3 of FMVSS 202a. However, some aspects of the IIHS procedure (IIHS 2001) were implemented regarding the set up of the SAE J826 manikin and the seat back position. The procedure is briefly described below. Once fixed to the sled with its back toward the impact direction, the seat was positioned at the mid-track setting between the most forward and most rearward positions. Then the seat pan angle was set such that its front edge was at the lowest position relative to its rear edge. The vertical position of the seat was placed at the lowest position if a dedicated height adjustment mechanism existed independent of the seat pan incline adjustment. Once the seat pan angle and height were fixed, the seat back was reclined to a position such that the torso line of SAE J826 manikin (H-point machine) was at 25 degrees from the vertical, following a procedure similar to that used by IIHS (IIHS 2001). The head restraint height was measured at the highest and lowest adjustment settings using the head room probe of the H-point machine, and was then positioned midway between those two points or the next lower lockable setting. The head restraint backset and head-to-head-restraint height were measured using the Head Restraint Measurement Device (HRMD) in combination with the SAE J826 manikin with a procedure adopted by IIHS (IIHS 2001). The H-point of the seat as positioned was then recorded and marked to be used later in positioning the dummy.

A $50^{th}$ percentile male Hybrid III dummy was used as the seat occupant for this study. The dummy was instrumented with triaxial accelerometers at the head CG and thorax CG, and a single accelerometer at T1. Angular rate sensors (IES 3100 series rate gyro) were mounted in the head and upper spine. The IES triaxial angular rate gyro was designed to meet the SAE J211/1 (rev. March 1995) CFC 600 frequency response requirement specified in FMVSS 202a and is capable of recording angular rates up to 4800 degree/second. The sensor weighs 22 grams and fits at the center of gravity of the Hybrid III dummy head on a custom mount. The Hybrid III head with the IES sensors was balanced so as to meet the mass specifications in Part 572. The upper neck and lower neck were instrumented with six-axis load cells, and the lumbar spine with a three-axis load cell.

The dummy was positioned in the test seat following the procedures outlined in S5.3.7 of FMVSS 202a (Figure 1) with the exception of the right foot and hands. The dummy was seated symmetric with respect to the seat centerline. Adjustments were made to align the hip joint with the seat H-point while keeping the head instrumentation platform level (± 0.5 degree). Both feet were positioned flat on the floor and the lower arms were positioned horizontally and parallel to each other with palms of the hands facing inward. The dummy was restrained using the OEM 3-point seatbelt harness for the corresponding seat during all tests. The position of the dummy head relative to the head restraint was measured in two ways: (1) the vertical distance from the top of the head to the top of the head restraint; and (2) the shortest horizontal distance between the head and the head restraint.

Video images were captured for these tests using two Phantom high-speed digital video cameras operating at 1000 frames per second. One camera was mounted on-board to provide a right lateral view of the dummy kinematics while the second camera was mounted overhead to provide a top view. Video collection was synchronized with the data acquisition system using a sled impact trigger with an optical flash that was visible within the field of view of both cameras to signal the time of initial sled impact.

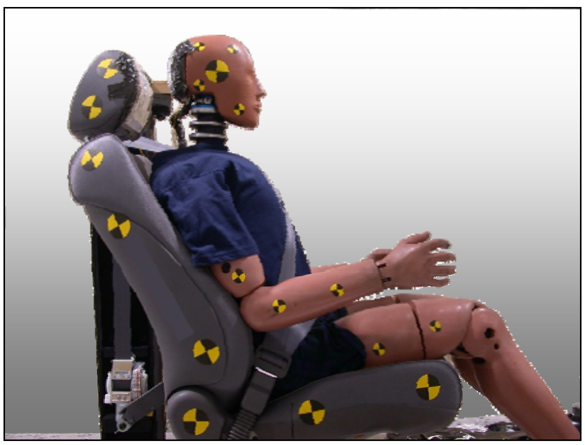

**Figure 1. Pre-impact setup of the dummy and seat for the FMVSS 202a rear impact sled tests.**

The sled was accelerated to an impact velocity of approximately 17.3 km/h. Upon impact, the sled experienced a deceleration-time curve that conformed to the corridor described in the FMVSS 202a standard when filtered to channel class 60, as specified in the SAE Recommended Practice J211/1 (rev. Mar 95) (Figure 2). Upon sled impact, the sensor and video data were collected synchronously, including a head-to-head restraint contact sensor and the sled linear accelerometer. All data were collected and processed in accordance with the procedures specified in SAE Recommended Practice J211/1 (rev. March 1995). Each seat was tested under FMVSS 202a dynamic conditions only once.

Angular displacements of the dummy head and torso were calculated through numerical integration of the angular velocity data obtained from the rate gyro sensors in the head and upper spine. The relative head-torso relative angular displacement values were calculated at each time step by subtracting the torso angular displacement value from the corresponding head angular displacement value. The maximum head-torso relative rotation value in the posterior direction was used to evaluate the relative whiplash injury risk associated with the different seats tested according to the FMVSS 202a dynamic option. Data from the load cells in the upper and lower neck were used to calculate the Nkm index (Schmitt, 2001). The positive shear (head moves posterior relative to the neck) was used in calculating Nkm and in comparing the upper neck and lower neck shear forces between tests. The moment measured at the lower neck load cell was corrected to represent the lower neck moment.

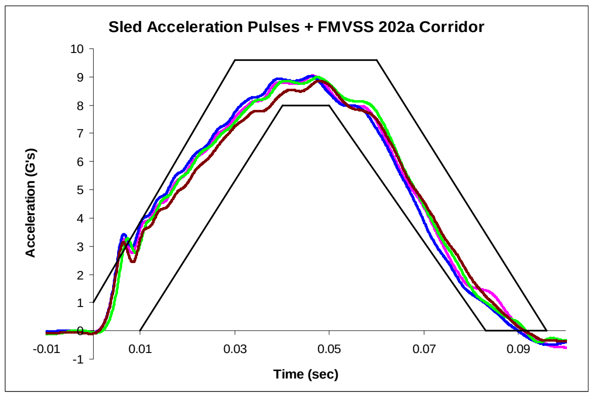


**Figure 2. Sled impact deceleration pulses of rear impact testing of the four seats along with the FMVSS 202a corridor.**

## RESULTS

The head restraint height (vertical distance from the top of the head to the top of the head restraint) and backset (horizontal distance from the head restraint to the back of the head), as measured using the HRMD, ranged 15-45 mm and 25-70 mm respectively, as the OEM head restraint was in its mid-position (Table 1). The similar measurements representing the horizontal and vertical position of the head restraint relative to the Hybrid III dummy head are also presented in

Table 1 for comparison. In general, the head of the seated dummy was lower, but further away from the head restraint than the HRMD (Table 1). Note that among the four seats tested only the Nissan Altima had an independent seat height adjustment where the seat was set at the lowest position while the front edge of the seat pan was at the lowest position relative to its rear edge. For the other seats, the requirement of having the seat pan front edge to be at the lowest position relative to its rear edge forced the overall seat to be at the highest position.

**Table 1: Head Restraint Geometric Measurements (Mid-Height Position)**

| | 2006 OEM Seat | Honda | Nissan | Saab | Subaru |
|---|---|---|---|---|---|
| HRMD | Backset (mm)* | 40 | 25 | 70 | 48 |
| HRMD | Head to HR Height (mm)* | 45 | 39 | 29 | 15 |
| Dummy | Horizontal Head to HR Distance(mm) | 59 | 48 | 78 | 76 |
| Dummy | Vertical Head to HR Distance(mm) | 45 | 32 | 19 | 12 |

* IIHS procedure (IIHS 2001) was used to set up the SAE J826 manikin and the seat back position

Table 2 presents the results of the dummy responses in the FMVSSS 202a optional dynamic test environment. The time that the dummy head made initial contact with the head restraint ranged from 56 to 74 milliseconds between the four seat tests, somewhat consistent with the horizontal head-to-head restraint distance values of the four seats (Table 1). The maximum posterior head-torso relative rotation of the Hybrid III dummy was less than 8 degrees for the Saab 9-3, Honda Civic, and the Subaru Outback, but exceeded the 12 degrees specified limit in FMVSS No. 202a for the Nissan Altima.

The performance of the seats, as measured by the peak posterior head-torso relative rotation (Figure 3), did not correlate with the initial relative position between the dummy head and head restraint. The greatest rotation occurred in the seat having the smallest horizontal dummy head to head restraint distance as well as the smallest backset and one of the seats with the smallest head-torso relative rotations occurred in a seat having the largest of these static dimensions (Table 1 and Figure 3). The head restraint height did not appear to be a strong factor in seat performance as the head restraint at mid-position for all four seats were significantly higher than the head CG and were in the "Good" range for head restraint height as per the rating system by IIHS (IIHS 2001).

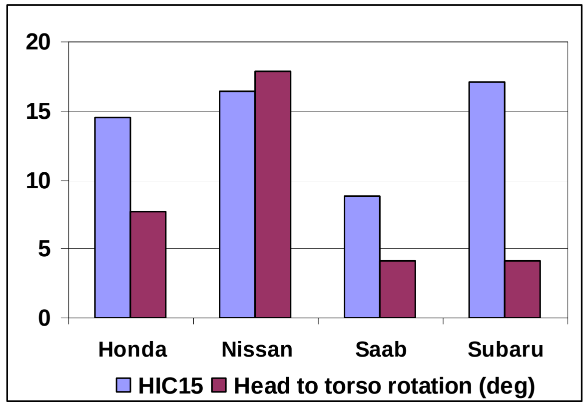


**Figure 3. FMVSS 202a injury measures (Head-torso relative rotation in degrees and HIC15) for the four OEM seats in rear impact tests.**

**Table 2: Dynamic Test Results**

| 2006 OEM Seat | Honda | Nissan | Saab | Subaru |
|---|---|---|---|---|
| Head Contact Time (ms) | 69 | 56 | 69 | 74 |
| Peak Head-Torso Rotation (deg) | 7.7 | 17.9 | 4.1 | 4.1 |
| Upper Neck Tension (N) | 81 | 97 | 101 | 36 |
| Upper Neck Shear (N) | 110 | 160 | 87 | 98 |
| Lower Neck Moment (Nm) | 9 | 26 | 2 | 10 |
| HIC 15msec | 14.5 | 16.4 | 8.8 | 17.1 |
| Nkm | 0.07 | 0.24 | 0.13 | 0.06 |
| Within FMVSS 202a Limits | Yes | No | Yes | Yes |

The HIC15 injury measure for all seats was less than 20 (Table 2, Figure 3), which is significantly lower than the specified limit of 500 in FMVSS No. 202a. The relative performance of the seats measured by the head-torso relative posterior rotation was consistent with several other biomechanical measures such as the upper neck shear force (Figure 4), lower neck extension moment (Figure 5), and upper neck

Nkm index (Figure 6). Those measures all showed that the Altima seat, which had the smallest horizontal dummy head-to-head restraint distance and backset at mid-height position, sustained the highest relative motion and neck loads. The Saab had the lowest relative motion and neck loads, except for Nkm, and had the largest horizontal dummy head-to-head restraint distance and backset.

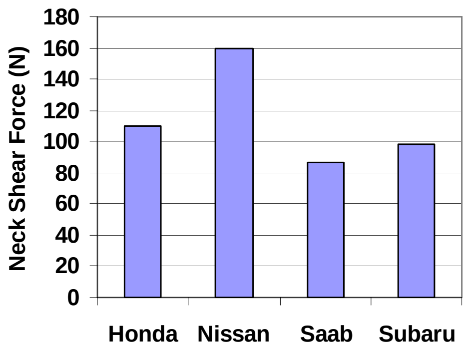


**Figure 4. Upper neck positive shear forces for the four OEM seats in the FMVSS 202a dynamic test.**

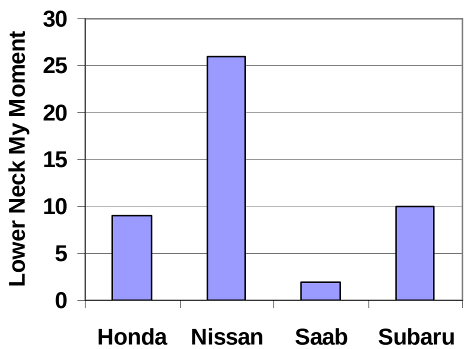


**Figure 5. Lower neck extension moments for the four OEM seats in FMVSS 202a dynamic test.**

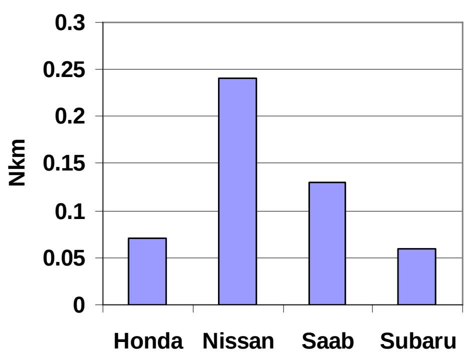


**Figure 6. Shear-bending load index (Nkm) for the four OEM seats in FMVSS 202a dynamic test.**

The time histories of the head, torso and head-torso relative rotation for the four OEM seats in the FMVSSS 202a dynamic tests are presented in Figures 7-10. The maximum posterior head-torso relative rotation occurred before the maximum head or torso rearward rotation in all the seats. The maximum lower neck extension moment occurred approximately at the time of maximum head-torso rotation in all the seats except for the Saab seat where it had occurred somewhat earlier (Figure 9). The maximum shear force occurred after the maximum lower neck extension moment with all the seats.

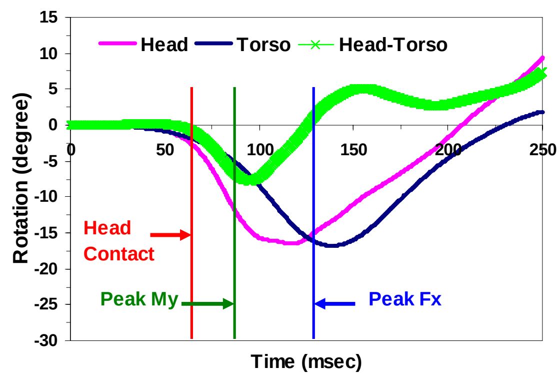


**Figure 7. Time histories of the head, torso, and head-torso relative rotation in the Honda Civic seat in FMVSS 202a dynamic test.**

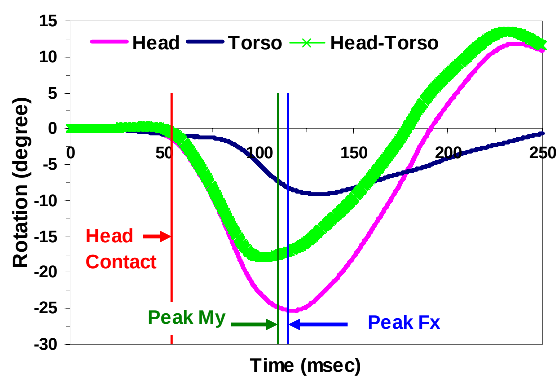


**Figure 8. Time histories of the head, torso, and head-torso relative rotation in the Nissan Altima seat in FMVSS 202a dynamic test.**

A detailed analysis of the dummy kinematics provided an understanding for the reasons why the Nissan Altima seat did not achieve the FMVSS 202a dynamic test requirements while the other three seats easily met the requirements. At the time of initial head contact with the head restraint, the head-torso rotation in the Altima seat was 0.9 degree (Figure 8) which was similar to that of the other three seats that ranged between 0.5 to 1.7 degrees (Figures 7, 9 and

10). However, after contact with the head restraint, the head continued to rotate up to a peak of 25 degrees in the Nissan Altima seat while the total torso rotation was only 9.1 degrees (Figure 8). The low torso rotation (lowest among all the seats tested) with respect to the head rotation (highest among all the four seats) resulted in high head-torso relative rotation with a peak of 17.9 degrees (Figure 8). On the other hand, the head restraints and the seat backs of the other three seats allowed the torso to undergo a similar total rotation as the head (Figures 7, 9, and 10). The seat-back stiffness, recliner stiffness, and the head restraint stiffness may have contributed to the different performances of the OEM seats.

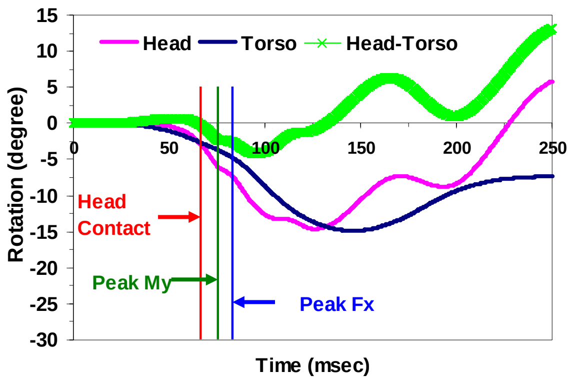


**Figure 9. Time histories of the head, torso, and head-torso relative rotation in the Saab 9-3 seat in FMVSS 202a dynamic test.**

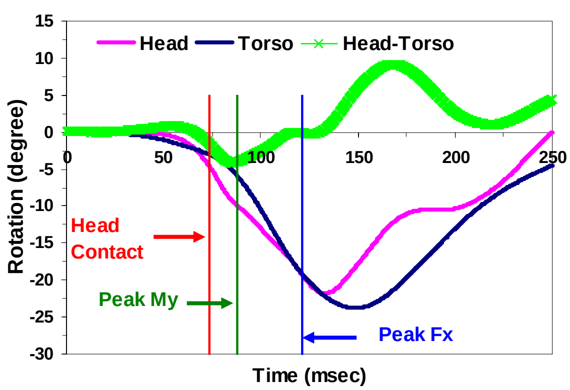


**Figure 10. Time histories of the head, torso, and head-torso relative rotation in the Subaru Outback seat in FMVSS 202a dynamic test.**

## DISCUSSION

IIHS evaluated the 2006 Honda Civic, Nissan Altima, Saab 9-3, and the Subaru Outback using both their head restraint static measurement procedure as well as their dynamic test procedure (Table 3). The Honda Civic, Saab 9-3 and the Subaru Outback received "good" geometric and dynamic ratings, resulting in an overall "good" rating. The Nissan Altima received an "acceptable" geometric and dynamic rating, resulting in an overall "acceptable" rating. Note that the head restraint geometric rating by IIHS is based on height and backset measured in the lowest position or in the most favorably adjusted and locked position of the head restraint. The final static geometric rating is the better of the two, except that if the rating at an adjusted position is used, it is downgraded one category. The head restraint geometric measurements in this study were obtained with the head restraint at a locked position which is approximately mid-point of the highest and lowest position, since that is the position of the head restraint for the dynamic test.

**Table 3: IIHS Seat Ratings and Dynamic Test Data using the BioRID Dummy**

| 2006 OEM Seat | Honda | Nissan | Saab | Subaru |
|---|---|---|---|---|
| Geometric Rating | G | A | G | G |
| Peak T1 Accel. | 13.7 | 9.7 | 16.2 | 11.2 |
| Head Contact Time (ms) | 62 | 64 | 64 | 67 |
| Peak Neck Shear (N) | 52 | 221 | 11 | 37 |
| Peak Neck Tension (N) | 677 | 660 | 287 | 308 |
| Dynamic Rating | G | A | G | G |
| Overall Rating | G | A | G | G |

The FMVSS 202a requirement of the 55 mm limit on the head restraint backset is more stringent than the IIHS backset limit of 75 mm for a "good" rating. This suggests that the seats that meet the FMVSS 202a static measurement requirement would likely receive a "good" geometric rating from IIHS unless the height dimension was insufficient. Comparison of the performance of the four OEM seats tested in the FMVSS 202a optional dynamic test procedure and the IIHS dynamic test procedure suggests that seats with active head restraints that are within the FMVSS No. 202a dynamic test limits are likely to obtain a "good" dynamic rating by IIHS. However, according to the IIHS procedure, if the seats with active head restraints do not obtain a "good" or "acceptable" geometric rating, they are not tested dynamically.

This study demonstrated that initial head restraint position relative to the head may not be a reliable indicator for the dynamic performance of seats with active head restraints. Real-world data and experimental studies have shown that a head restraint positioned closer to the head would provide more effective whiplash mitigation. Though the head restraints of all four OEM seats moved forward and closer to the head in a similar manner during the rear impact tests, their performance after the initial head contact differed (Figures 7-10). The Nissan Altima seat did not meet the optional dynamic test requirement of 12 degrees head-torso rotation, as a result of the large differential between the head and torso rotation after the initial head contact. This is evidenced in Figure 8, where the torso rotation is significantly smaller than that of the head.

Kinematic evaluation of the video data indicated that the seat back of the Altima was too stiff to allow sufficient torso movement into the seat back such that the torso and the head move together to minimize their relative motion. In contrast, the seat back stiffness, recliner stiffness, and the head restraint stiffness of the Honda Civic, Saab 9-3, and the Subaru Outback seats appeared to be optimized so that the head and torso rotated together and thereby minimized the relative rotation between the head and the torso at this test speed (Figures 7, 9, and 10). In addition, the head restraint of the Altima seat appeared to be too compliant, thus allowing too much posterior head rotation after the head made the initial contact with the head restraint. Previous research has found that a less rigid head restraint can increase the neck injury risk in rear impact (Voo 2004).

There are some seat positioning differences between the FMVSS 202a procedure and that of IIHS (NHTSA 2004, IIHS 2001):

- The FMVSS 202a seat positioning procedure, which this study attempted to follow, resulted in the seats of the Honda Civic, Saab 9-3 and Subaru Outback being at their highest position in order to obtain as shallow angle for the seat pan, which results in the highest H-point position relative to the seat back. The IIHS procedure would place those same seats at their lowest position regardless of the resulting seat pan angle (as per section 5.1.5 and 5.1.7 of IIHS 2001). This resulted in those same seat pans being adjusted to the most rearward tilted position (as per section 5.1.5 and 5.1.7 of IIHS 2001). On the other hand, both procedures would set the Nissan Altima seat at its lowest position. The IIHS procedure would then place the seat pan at the mid-range of inclination.
- All the seats in this study were set at the mid-point between the most forward and most rearward positions of the seat track. The IIHS procedure would have set them at the most rearward position (as per section 5.1.6 of IIHS 2001).

Those seat positioning differences might have resulted in differences in head-restraint position measurement and/or dummy position relative to the head restraint. However, we do not believe that those differences have significantly altered the relative dynamic performance of the seats tested in this study and the similar ones by IIHS, even though different dummies (Hybrid III and BioRID) were used.

This study has demonstrated the complexity of designing a seat to mitigate whiplash injuries during a rear impact collision. Seats with active head restraints that have superior static (undeployed) geometry may not necessarily perform relatively well under dynamic conditions, whereas seats that do not have superior static (undeployed) geometry may still perform relatively well dynamically. The Saab 9-3 seat, for example, had an initial backset measurement of 70 mm (using the HRMD) but was still able to limit the head-torso relative rotation to approximately four degrees.

Results from this study demonstrated the importance of considering both the seat back and head restraint designs as a complete seating system to provide optimal protection to the occupants. Head restraint designs that are too compliant or seat-back designs that are too stiff may both result in excessive motion of the head relative to the torso.


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