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ABSTRACT

Active head restraints are being used to reduce the risk of whiplash in rear crashes. However, their evaluation in laboratory tests can vary depending on the injury criteria and test dummy. The objective of this study was to conduct barrier tests with BioRID and sled tests with Hybrid III to determine the most meaningful responses related to whiplash risks in real-world crashes. This study involved: (1) twenty-four rear barrier tests of the Saab 9000, 900, 9-3 and 9-5 with two fully instrumented BioRID dummies placed in the front or rear seats and exposed to 24 and 48.3 km/h barrier impacts, and (2) twenty rear sled tests at 5-38 km/h delta V in three series with conventional, modified and SAHR seats using the Hybrid III dummy. A new target superposition method was used to track head displacement and rotation with respect to T1. Insurance data on whiplash claims was compared to the dummy responses.

NIC is not a sufficient criterion to assess whiplash because it does not consistently correlate with seat performance in field crashes and its peak can occur at head restraint contact before the primary neck loads and displacements. Clear response differences were seen with head rotation and x-displacement with respect to T1 among the various seats and rear delta Vs. These responses describe neck kinematics in extension and flexion, and address many of the possible whiplash injury mechanisms. A Neck Displacement Criterion (NDC) is proposed to supplement other criteria until there is a clearer understanding of whiplash injury criteria. It is based on the displacement and rotation of OC-T1 and comparison to the natural range of motion. Responses are viewed in cross-plots of rotation vs x-displacement and z- vs x-displacement of OC with respect to T1.

INTRODUCTION

There is interest to develop a consumer test of the rear crash performance of seats and head restraints. RCAR (Research Council for Automotive Repair) has started testing with the BioRID dummy in various test conditions. Thatcham uses the dummy in its offset rear barrier tests evaluating damage repair. IIHS has already conducted rear barrier tests with BioRID (Zuby et al. 1999). GDV is conducting rear sled tests to evaluate seats with BioRID and the RID2 dummy, a rear impact dummy being developed by a European consortium. They are preparing a standard test procedure for EU with the University of Graz (Steiner et al. 1999). The primary criterion of whiplash performance for these evaluations has been the NIC criterion (Bostrom et al. 1996). While a range in NIC levels has been observed with different seats and head restraints showing correlation with laboratory tests (Bostrom et al. 2000), the sufficiency and validity of the criterion to real-world whiplash risks remains uncertain because of issues raised here and by Kim et al. (2001).

Over the years, there have been many studies addressing whiplash injury mechanisms. A widely considered mechanism involves injury of the facet joints in the posterior region of the cervical spine (Barnsley et al. 1995, Lord et al. 1996). Deformation of the facet joint is related to the combination of shear and extension of the vertebrae. There is an influence from compression of the vertebrae, which decreases shear stiffness of the neck and increases vulnerability to facet joint injury (Yang et al. 1997). Panjabi et al. (1999) recently proposed the IV-NIC (intervertebral neck injury criterion), which is based on the extension angle change of adjacent vertebrae in the cervical spine. The response is normalized by the physiologic range of motion of each vertebral unit and summed for the cervical spine. This has the effect of providing an overall measure of neck extension, and it also shows the risk of injury from local hyperextension or hyperflexion of each cervical vertebral unit.

Brault et al. (2000) proposed that neck extension can also result in contraction-induced injury of the sternocleidomastoid muscle; and, Nibu et al. (1997) proposed that upper cervical hyperextension could stretch the vertebral artery beyond its physiologic limit. Injury of the musculature and ligaments due to over stretch may result in headaches and muscle pain due to upper cervical spine hyperextension (Grauer et al. 1997, Panjabi et al. 1999, Walz, Muser 2000). These injury mechanisms focus on the hyperextension response of the cervical vertebrae, but do not address linear displacements associated with shear and compression forces acting between vertebrae or on the entire cervical spine. Kaneoka et al. (1999), Yoganandan et al. (1998) and Ono et al. (1997) found that T1 x- and z-acceleration may pinch the zygapophysial joint, but displacement is required for pinching.

Another possible mechanism involves pressure changes in the spinal CSF that may injure spinal ganglia (Svensson et al. 1993, 2000, Svensson 1993). The NIC formulation is based on this injury mechanism and derives risk from the x-acceleration and x-velocity of the head (OC) with respect to T1 during the S-shaped response, which occurs very early in the extension response (Bostrom et al. 1996). Interestingly, this response is solely derived from the x-displacement of the occipital condyles with respect to T1, and it neglects the potential influence of head extension angle and z-displacement changes of OC with respect to T1, which occur later.

These and various other injury criteria and mechanisms lack clinical validation largely because of the inability to clearly diagnose underlying injuries to neck muscles, nerves and soft tissues. The reliance on reported symptoms of neck pain, headaches, and tingling of the arm are vague and non-specific to pathology detectable by current means; and, the self-reporting of injury is fraught with uncertainty, not the least that financial gain may be received for an injury claim. However, even without clear diagnoses of whiplash disability, neck deformations seem to be a key factor in injury causation.

While the most widely considered criteria involve neck deformation, the most common measurements in sled and barrier tests are neck shear force, tension/compression force and bending moment. Moments and forces in the upper and lower neck are relatively easy to measure in a dummy, but they vary considerably during the dynamic interactions with the head restraint during head loading and rebound. Most information is available on the upper neck loadcell responses, although Prasad et al. (1997) has reported data from a lower neck loadcell and found the bending moment pertinent. Today, information is also being reported on vertebral accelerations that are measured to determine NIC. However, displacement (strain) most often has the strongest correlation with soft tissue injury (Viano et al. 1989).

The biofidelity of the Hybrid III dummy has been largely unknown for low-speed rear crashes until recently, except for its neck calibration performance to a moment-angle specification. It has been the most widely used in testing until the last few years, when studies have extended the understanding of biofidelity in neck responses for low-speed rear impacts (Foret-Bruno et al. 1991, Scott et al. 1993, Geigl 1995, Cappon et al. 2000). BioRID is increasingly being used and has better biofidelity than the Hybrid III when compared to volunteer and cadaver responses (Davidsson et al. 1998, 1999a,b, Linder et al. 2000). While the BioRID P3 has shown favorable comparisons to volunteer and cadaver responses in rear sled tests, there remain few dummies to evaluate crash performance, particularly in out-of-position conditions or crashes of higher severity. Furthermore, the dummy cannot be used in non-symmetric seating configurations or when there is an asymmetric deformation of the seat because of a high torsional stiffness of the spine. The RID2 dummy is also just emerging for testing.

While there remains a lack of consensus on the underlying injury mechanisms and dummies for whiplash risk assessment, there has been the development and implementation of whiplash prevention seats and active head restraints. The Saab Active Head Restraint (SAHR) system aimed to prevent the most serious, long-term disabilities that can occur after rear crashes with symptoms lasting more than 6 months. Although scant data are available, Krafft (1998) has shown that these injuries generally occur in high-speed rear crashes with substantial vehicle and seat deformation. The aim of SAHR was to reduce neck responses for the higher speed rear crashes and for out-of-position conditions where a low-speed crash can generate relatively high neck responses. Nonetheless, performance was also sought for low-speed tests. The principals of whiplash prevention with the SAHR system can be found in Viano, Olsen (2001) and will not be repeated here.

The RCAR consortium testing has mainly focused on in-position seating whereas numerous studies have offered the insight that an occupant is often leaning forward in the seat at a stop or during turning, or driving with a large recline angle of the seatback while sitting upright. These initial conditions increase the impact of the occupant into the seat and head restraint. In a recent field study of rear crashes, 80% occurred when the vehicle had just come to a stop at an intersection or to make a turn (Viano, Olsen 2001). This level is consistent with that observed by Warner et al. (1991), who found that vehicle braking causes the occupant to lean forward 70-100 mm at the most likely time of a rear impact.

Figure 1 shows the current research test matrix used to evaluate active head restraint systems (Viano 2002). Since a clear understanding of whiplash was not known, the tests included a series of in-position and out-of-position seating configurations with 350 mm and 550 mm gaps to reflect the potential range of real-world conditions resulting in whiplash. The matrix also included tests with the head restraint up and down, 50th% and 95th% male and 5th% female Hybrid III dummies and BioRID. The IIHS test condition (Zuby et al. 1999) was only one of nine impact conditions the dummies were exposed to for delta Vs of 10, 16, 20, 24 and 32 km/h. There were five additional tests to cover other real-world possibilities of occupant interaction with the seat and head restraint. For example, a test was run with an unbelted 5th% female Hybrid III in the rear seat in a 35 mph frontal NCAP condition with a belted 50th% male Hybrid III dummy in the driver seat.

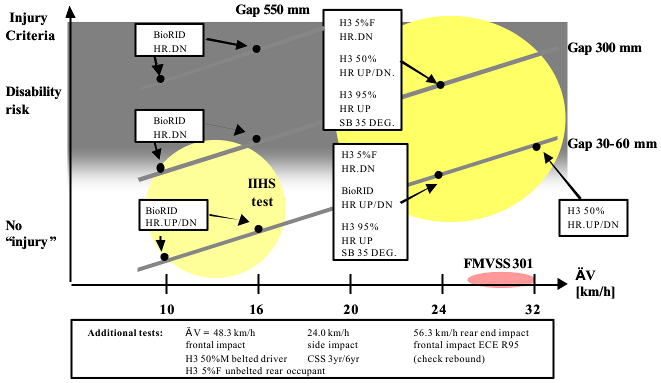

Figure 1: Test conditions to assess whiplash risks for in-position and out-of-position seating configurations with various test dummies, delta Vs and head restraint positions.

The focus of the tests reported in this paper is on in-position responses, because of the pending consumer test under development by the RCAR group. However, the potential importance of out-of-position conditions must be emphasized in an overall evaluation of occupant responses in low-speed rear crashes (Viano 2002, Strother et al. 1994). The results of many previous studies have shown that the severity of loading increases with gap behind the head, and low speed tests with a gap of 350 mm produce results more like an in-position test at considerably higher speed.

Field crash data are used to establish an inference between the laboratory tests and real-world crash injury. The Saab 9000 and 900 have a conventional head restraint, and the Saab 9-3 and 9-5 have the SAHR (Saab Active Head Restraint) system included in a modified seatback. The SAHR system has been in production since 1997. Folksam regularly evaluates whiplash claims for cars in Sweden by a method developed by Krafft (1998). Figure 2 shows the most recent data with the Saab 9000 and 900 in the "best performing" vehicle group with a low whiplash claims frequency. Folksam (2000) recognizes the Saab 900 as the best performing vehicle in rear crashes, so comparisons made to the performance of the Saab 9000 and 900 in this study are to vehicles with industry-leading performance in whiplash prevention.

Saab recently completed a field whiplash study in Sweden (Viano, Olsen 2001). All Saab vehicles are sold with a 3 year insurance policy from Dial Insurance AB, so a reasonably large database of crash information was available over an 18 month period. The incidence of whiplash claims was available for the Saab 9000, 900, 9-3 and 9-5, and this data could be compared to the laboratory test results to infer relationships between field performance and injury criteria and dummy responses.

Group 1 Best performing
Audi 100/A692-97
Opel Astra 92-97
Saab 900 94 -97
Volvo 850/S70/V70 92-98
Saab 9000 85-97

Group 2 (2.7 times increased disability risk than Group 1)
Ford Mondeo 93-
Mercedes 200/300 86-95
Nissan primera 91-96
Volvo 400 87-96
VW Golf/Vento 92-97
Volvo 700/900 82-98
VW Passat 89-96

Group 3 (4.8 times increased disability risk than Group 1)
Ford Escort 91-99
Mazda 323 90-95
Opel Vectra 89-95
Peugeot 405 88-97
Toyota Carina 88-92
Ford Fiesta 89-95

Figure 2: Three vehicle groups based on whiplash claims to Folksam insurance (2000).

The aims of this study were to: 1.) conduct a range of barrier and sled tests with the BioRID and Hybrid III dummy, 2.) measure neck displacement and rotation in terms of three time histories, OC rotation, x-displacement and z-displacement with respect to T1, which are viewed as cross-plots of head rotation versus x-displacement, and z- versus x-displacement, 3.) overlay the neck displacements on the natural range of motion, where responses from various crash severities and seating positions can be shown on the same graph, 4.) compare recently published whiplash injury claim data on Saab rear crashes with and without the SAHR active head restraint system to laboratory response data, and 5.) evaluate head and neck kinematic and biomechanical responses as an additional criteria to assess whiplash potential in real-world crashes of various seats and head restraint systems.

METHODS

Rear Barrier Crash Tests

Twenty-four rear barrier crash tests were conducted on the Saab 9000, 900, 9-3 and 9-5. The moving barrier tests were conducted at the Saab Crash Safety Center in Trollhattan, Sweden. The impact speed was 24 and 48.3 km/h and BioRID P2 dummies (an earlier but similar version as BioRID P3) were placed in the driver and front passenger seats, or the rear outboard and center seating positions. There were comparable tests with the front seat head restraint in the up and down position. Identical tests were also performed on manual and power seats.

The barrier crash test method was similar to FMVSS 301 with a rigid moving barrier of 1840 kg mass and the struck car standing still (Figure 3a). The vehicles represented an average specification with air conditioning, automatic transmission, 80 kg trunk load, 90% fuel and two occupants. In each test, two instrumented BioRID P2 dummies were placed in the front or rear seats. Figure 3b shows a schematic of the BioRID P2 dummy and instrumentation used.

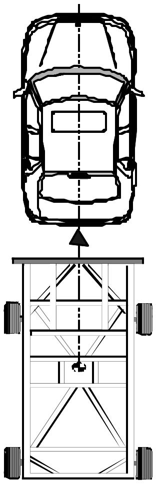

Figure 3a: FMVSS 301 barrier crash test configuration.

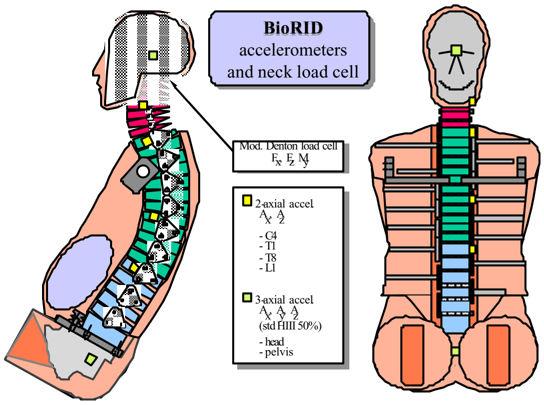

Figure 3b: BioRID dummy setup and instrumentation (Davidsson 2000).

The front seats were positioned in the down-most position and 25 mm forward of mid-position. The dummy was set to a 25° H-point/torsoline with a prescribed gap to the head restraint. Seatbelts were used and the belt pretensioner was active in the Saab 9-3/9-5. Manual and power adjusted seats were tested because they have different stiffness. All driver seats were adjusted with the head restraint in the upper most position and all passenger front seats had the head restraint in the down most position. Lumbar supports were in the non-activated position. In the rear seat, the BioRID P2 dummies were positioned in the left outer position and in the middle seating position with the head restraint in the upper most position if adjustable.

The BioRID P2 dummies were positioned in the front seat similar to the FMVSS 208 procedure for the Hybrid III dummy. With this procedure in Saab cars, the gap between head and head restraint in front seats was 58 mm. In rear seats, the gap varied from 76-140 mm depending on dummy position (left rear or middle rear) and the head restraint geometry. The cars were instrumented with two accelerometers, one on right rear sill and another on the left rear sill. Two onboard high-speed cameras with 1000 fps were mounted on the cars to study the dummy kinematics and seat performance. However, because of the oblique location of the cameras and movement of the dummy, detailed film analysis of the head and neck response was difficult, although kinematics were estimated. The films provide an overall perspective of the crash dynamics. The transducer data was filtered according to SAE recommended practices. The upper and lower neck x-accelerations were used to calculate NIC by the procedure in Bostrom et al. (1996) using SAE 180 filtering:

$$NIC = [0.2a_x + v_x^2]_{OC\text{-}T1} \qquad (1)$$

where a_x is the relative x-acceleration and v_x the relative x-velocity between the occipital condyles (or C1) and T1.

Rear Sled Tests

Twenty Hyge sled tests were conducted on seats with conventional, modified and active head restraints. The tests were conducted in three series at the Lear Seating Division, Southfield, Michigan. The first series involved rear sled tests at delta Vs from 5-38 km/h. The tests involved Saab 900 and 9-3 seats so a direct comparison could be made between a seat with and without the active head restraint. In a second series, identical tests were conducted at 18 km/h and 11 g pulse with a conventional luxury seat (baseline), the same seat with a modified head restraint that reduced the gap to the back of the head, the same seat fit with a Cervigard-shaped head restraint, and finally the seat fit with SAHR in a modified seatback according to the design principals described in Viano, Olsen (2001) and Viano (2002).

In the third series, the Saab SAHR and Volvo WHIPS seats were tested at 24 km/h and 13.3 g pulse to compare the performance at higher speed. For all the tests, the Hybrid III dummy was used. Instrumentation included the upper and lower neck loadcells, and the typical head, chest and pelvis triaxial accelerometers. Additional uniaxial accelerometers were mounted on the OC and T1 in the x-direction to calculate NIC. An open sled buck was used with a stanchion for the shoulder belt guide at the B-pillar. Kinematics from the inboard perspective was recorded on high-speed video.

Neck Displacement Response

A novel new approach was developed at Lear to visualize the head cg (and occipital condyle) translation and rotation with respect to T1. Figure 4 shows video images from two rear sled tests where the position of the head is shown with a projection of the initial head position using a moving reference frame fixed to the clavicle (T1). A photographic target was fixed to the clavicle of the dummy and included two adjacent circular targets. The spacing between them and the projection to a similar target at the head cg were used to superimpose a target on the clavicle for every fourth frame of the video. Since the superimposed target was fit to the two circles on the clavicle target, it showed the projection to the initial head position in a fixed reference frame attached to the clavicle or T1. Any x- or z-displacement and head rotation with respect to T1 can be easily seen in the video. This gives a clear indication of head and neck motion during the rear impact. However, conventional frame-by-frame video analysis was used to provide the displacement and rotation time-histories to ensure precision.

Figure 4: Kinematics of the Hybrid III dummy in rear sled tests with a superimposed reference target on the clavicle showing the initial head position in a moving reference frame fixed to T1. The peak head displacement and extension angle are shown with respect to T1. The left picture shows the peak head displacement for the baseline luxury seat and the right, the same seat with SAHR integrated into the seatback.

For the sled tests, head (OC) rotation and x- and z-displacement were determined with respect to T1. These responses are likely related to whiplash injury due to the cumulative effects of neck shear, tension and compression forces and bending moments that displace the head and neck with respect to T1. This approach extends the hypothesis of Panjabi et al. (1999), which is based on individual vertebral rotations summed over the whole cervical spine, and includes the considerations of Yang et al. (1997) involving neck compression and shear effects on facet loading. The combination of OC rotation and displacement with respect to T1 includes neck deformations at various levels of the cervical spine. These responses are important for an overall assessment of neck injury risks and are driven by T1 motion, which involves translation and rotation from seat and head restraint loading (Davidsson 2000).

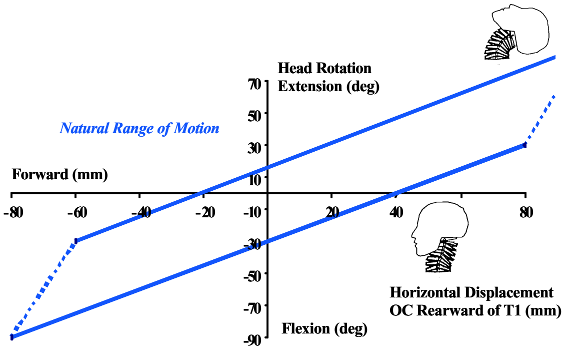

Figure 5a: Corridor for head (OC) rotation versus x-displacement of OC-T1 from volunteers in rear sled tests without head support. The corridor bounds the natural range of motion, including the S-shaped response and hyperextension (modified from Viano, Davidsson 2001).

Neck Displacement Criterion (NDC)

Figure 5a shows the corridor bounding the natural range of motion of OC rotation versus x-displacement with respect to T1. The corridor is based on 10 volunteers in rear sled tests in rigid and standard seats without head support (Viano, Davidsson 2001). It is a trapezoidal shape with a natural 40 mm rearward x-displacement with no head rotation. Rearward x-displacement without head rotation gives the S-shaped response. This occurs by shear force and extension moments on the lower neck that may cause facet joint loads on the lower cervical spine as the x-displacement increases. For facet joint loading, injury risk is directly proportional to the degree of head rearward displacement and head rotation, based on the vertebral rotation concept initially proposed by Panjabi et al. (1999).

As the head extension angle increases, the hyperextension response occurs at larger rearward x-displacement and head (OC) rotations of 60^0-80^0. In this case, the progression from the S-shaped response to hyperextension involves greater rotation of the upper cervical vertebrae with potential injury of all facet joints in the neck. The dotted line indicates that the maximum voluntary displacement has not been determined at the threshold of injury; and, the flexion corridor is shown only to visualize the complete curve. It needs to be determined from separate volunteer tests and analysis. For any motion sequence, neck injury risks increase as the combined response is close to the corridor and falls outside the natural range of motion. Given a sled or barrier test, time-history responses are cross-plotted and superimposed on the graph. Head contact with the head restraint and interactions can be clearly seen in the responses leading to rebound where the flexion response is assessed.

The vertical displacement of the head (OC) with respect to T1 is another factor in neck injury. Yang et al. (1997) have shown that with compression of the neck, the muscles and ligaments relax lowering the shear stiffness of the vertebral response. This increases vertebral displacement and load on the facets. Figure 5b cross-plots the z- and x-displacement of the OC with respect to T1 and shows the corridor for the natural range of motion. Again, the S-shaped response and hyperextension responses fall into extremes of the natural range of motion. The head rotation angle and z- and x-displacement of OC with respect to T1 show the response of the neck that may be linked to various mechanisms of whiplash injury from vertebral rotation, shear and compression.

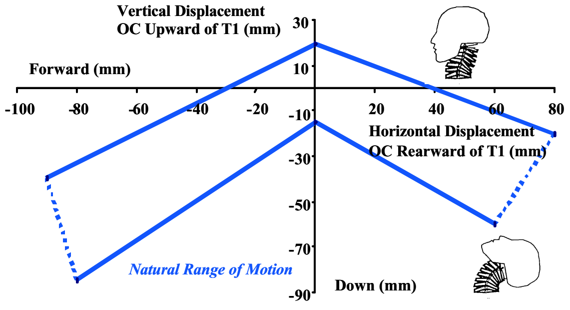

Figure 5b: Corridor for neck z- and x-displacement between OC-T1 from volunteers in rear sled tests without head support. The corridor bounds the natural range of motion, including the S-shaped response and hyperextension (modified from Viano, Davidsson 2001).

The neck displacement responses reflect the sum of effects of neck moments and forces that vary through a rear crash and may be used to visualize various injury mechanisms. Figures 5a and 5b include a visualization of the natural range of motion for flexion and similarly may provide a means of assessing injury risks during rebound from a rear crash, so the full assessment of risks by various mechanisms and throughout the crash is considered because of a lack of fundamental understanding of injury mechanisms and the timing of injuries.

The x-displacement time history of the OC motion with respect to T1 can also be used to calculate NIC. This can be done by differentiation of the x-displacement to get the x-velocity and differentiation again to determine the relative x-acceleration between the two points. Calculating NIC from differentiation of the x-displacement response avoids many of the filtering issues that have arisen from analysis of OC and T1 BioRID x-acceleration responses; and, it avoids the potential misalignment of the sensitive axes of the OC and T1 accelerometers when head rotation occurs; but, differentiation has its own numerical issues and the accuracy needs to be verified.

RESULTS

Rear Barrier Crash Tests

Table 1 shows the average and standard deviation in delta V for the two barrier test speeds. The average delta V ranged from 15.7-16.3 km/h for the 24 km/h rear barrier impacts, and 26.7-27.4 km/h for the 48.3 km/h barrier tests. Figure 6 shows the rear impact damage in the 24 km/h crash tests for the four Saab models. The damage is limited to the bumper and exterior sheet metal with essentially no frame damage. Figure 7 shows the damage for the 48.3 km/h crash tests. In this case, there is more extensive damage of the body frame with crush up to the rear wheels.

Table 1: Vehicle Delta Vs in Rear Barrier Crashes
(Average ± standard deviation)

Car Model	Vehicle Test Weight kg	Test speed 24 km/h km/h	Test speed 48.3 km/h km/h
Saab 9-5	1835 ± 10	15.9 ± 0.5	27.0 ± 0.0
Saab 9-3	1635 ± 10	16.2 ± 0.4	27.4 ± 0.5
Saab 900	1620 ± 10	16.3 ± 0.3	26.7 ± 0.5
Saab 9000	1760 ± 10	15.7 ± 0.1	27.0 ± 1.0

Figure 8 gives the NIC results for the front seating positions for the 24 km/h and 48.3 km/h tests, and the full results can be found in the Appendix. For these tests, NIC is determined from the x-accelerations of the head and T1 using Eq. 1. For the 9-5 and 9-3, NIC was 36% and 44% lower with the head restraint in the up compared to the down position. The opposite trend was seen in the 9000 for the 48.3 km/h tests, where NIC was 37% higher in the up head restraint position. Figure 9 gives the NIC results for the rear seating positions for the 24 km/h and 48.3 km/h tests, and the peak responses can be found in the Appendix. The rear seating positions often had higher NICs than the front seats.

Figure 6: Vehicle static crush with 24.0 km/h barrier speed. The top left is the Saab 9000, top right Saab 900, bottom left the Saab 9-5 and bottom right the Saab 9-3.

Figure 7: Vehicle static crush with 48.3 km/h barrier speed. The top left is the Saab 9000, top right Saab 900, bottom left the Saab 9-5 and bottom right the Saab 9-3.

Figure 10 plots the peak NICs for the two barrier impact speeds, seating positions and head restraint placements for the front seat tests. In 6 out of 14 possible comparisons, NIC was lower in the 48.3 than 24 km/h tests. Response variations within a vehicle type with different seat and head restraint positions were as great as between vehicles. NIC was primarily determined by the relative x-acceleration between the head and T1; the relative velocity was not an important factor. The NIC range of 12-45 represents peak relative accelerations of 6-22 g.

Saab 9-5

Barrier speed	Manual seat		Power seat		Mean values
[km/h]	HR up	HR down	HR up	HR down	
24	18	25	17	28	22.0
48	18	33	22	37	25.8
				Car model average	24.9

Saab 9-3

Barrier speed	Manual seat		Power seat		Mean values
[km/h]	HR up	HR down	HR up	HR down	
24	15	22	18	-	18.2
48	14	24	12	29	19.8
				Car model average	19.0

Saab 900

Barrier speed	Manual seat		Power seat		Mean values
[km/h]	HR up	HR down	HR up	HR down	
24	19	20	23	24	21.4
48	14	23	38	38	28.4
				Car model average	24.9

Saab 9000

Barrier speed	Manual seat		Power seat		Mean values
[km/h]	HR up	HR down	HR up	HR down	
24	45	-	27	33	34.9
48	22	18	38	25	25.6
				Car model average	30.3

Figure 8: Summary NIC results for the front seat in the Saab rear barrier crash tests.

Saab 9-5 Sedan

Barrier speed	Left	Middle	Mean values
[km/h]	HR up	HR up	
24	26	19	22.3
48	29	38	33.3
		Car model average	27.8

Saab 9-5 HB

Barrier speed	Left	Middle	Mean values
[km/h]	HR up	HR up	
24	31	38	34.4
48	53	69	61.0
		Car model average	47.7

Saab 900/9-3

Barrier speed	Left	Middle	Mean values
[km/h]	HR up	HR up	
24	20	30	25.0
48	13	32	22.5
		Car model average	23.8

Saab 9000 CS

Barrier speed	Left	Middle	Mean values
[km/h]	HR up	HR up	
24	15	26	20.5
48	34	33	33.5
		Car model average	27.0

Figure 9: Summary NIC results for the rear seat in the Saab rear barrier crash tests.

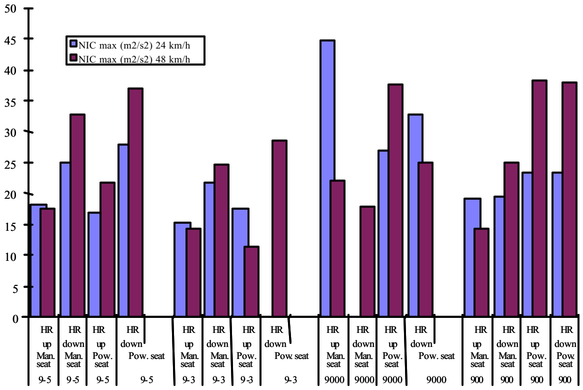

Figure 10: NIC results for the rear barrier crash tests of the Saab 9000, 900, 9-3 and 9-5.

Rear Sled Tests

Figure 11 shows the NIC, x-displacement and head rotation for the 16 km/h delta V tests of the Saab 9-3 with SAHR active head restraint system and the Saab 900 with standard head restraint. The Hybrid III responses with the Saab 900 and head restraint in the down position were the highest in this comparison at 16 km/h rear delta V. Higher responses are also seen in the peak upper neck shear force, tension and bending moment (Figure 12).

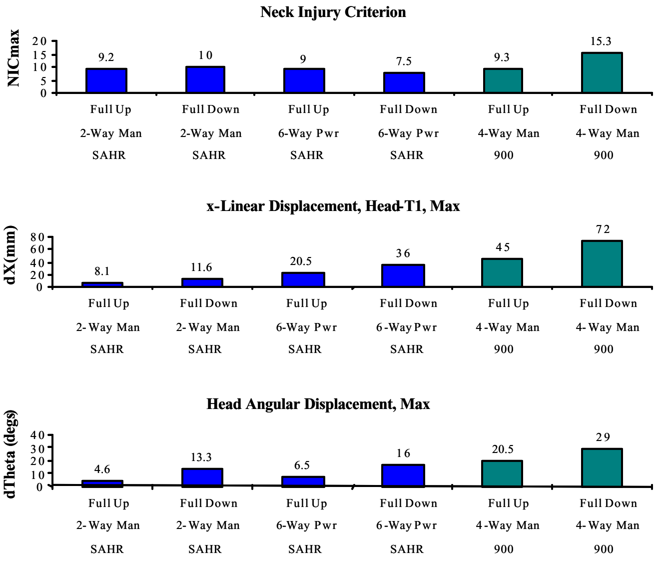

Figure 11: NIC and neck displacement responses in rear sled tests at 16 km/h with the Hybrid III dummy in the Saab 9-3 and Saab 900.

Table 2 gives the dummy responses from the Saab 9-3 and 900 sled tests. In the lowest speed tests, NIC was lower for the Saab 900 than the Saab 9-3 even though the impact speed was higher. However, head rotation and x-displacement were more than double in the Saab 900 than with SAHR in the 9-3.

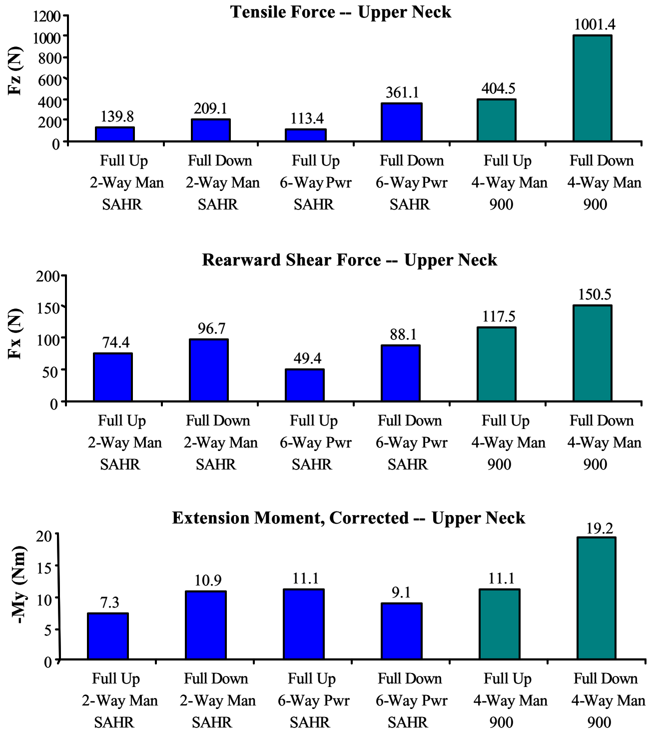

Figure 12: Upper neck loads in the rear sled tests at 16 km/h with the Hybrid III the Saab 9-3 and Saab 900.

Table 2: Rear Sled Tests of the Saab 900 and Saab 9-3 with

Test	ÄV	Amax	H3	H/R & Position	Head Gap	Head-Chest Kinematics			Upper Neck Loads			
	km/h(mph)	(g)			(mm)	NIC (m2/s2)	Äè (deg.)	dX, mm NICmax/ dXmax	My, Corr. (Nm) (-)My	(+)My	Fx (N)	Fz (N)
9-3 2-way man	7.6 (4.7)	8.7	50%	Up - IP	45	7.9	6.0	5/11.1	-3.8	10.7	56	114
900 4-way man	10.5(6.5)	9.6	50%	Up - IP	49	6.7	15.5	0/32.5	-4.5	12.5	121	321
9-3 2-way man	16 (9.9)	11.9	50%	Up - IP	43	9.2	4.6	2 / 8.1	-7.3	13.0	74	140
9-3 2-way man	16 (9.9)	11.9	50%	Down-IP	44**	10	13.3	3 / 11.6	-10.9	15.0	97	209
9-3 6-way pwr	16.4(10.2)	13.4	50%	Up - IP	41	9	6.5	14/20.5	-11.1	15.5	49	113
9-3 6-way pwr	16(9.9)	13.2	50%	Down-P	65**	7.5	16.0	36/36	-9.1	18.1	88	361
900 4-way man	16(10.2)	11.7	50%	Up - IP	50	9.3	20.5	0/45	-11.1	16.6	118	405
900 4-way man	17(10.5)	12	50%	Down-IP	80**	15.3	29.0	35.5/72	-19.2	18.5	151	1001
9-3 6-way pwr	23.5(14.6)	13.3	50%	Mid - IP	46	7.5	10.0	17.5/36.5	-15.3	19.2	63	166
900 4-way man	26(16.2)	13	50%	Up - IP	50	10.8	22.5	36/57.5	-12.6	18.4	117	435
9-3 2-way man	38 (23.6)	14.8	50%	Up - IP	44	9.1	11.4	0.5 / 6.3	-30.4	12.8	71	114
9-3 2-way man	38.2(23.7)	14.6	50%	Up - OOP	354	71*	35.4	21.5 / 30	-45.9	34.0	211	1631
9-3 2-way man	25.7 (16)	12.4	5%	Down-IP	54	12.1	1.3	0/0	-3.9	7.2	45	82
9-3 2-way man	25.4(15.7)	12.4	5%	Down-OOP	213	32*	6.0	NA / 26.9	-17.8	19.2	58	273

NOTES:
IP -- In Position OOP -- Out Of Position
Lap & shoulder belts used for all tests, except 6-way power
If applicable, D-ring adjusted to full up for 50%, (2) notches from full up for 5%
H3 neck used for all tests

Max loads include rebound -- if applicable
* Questionable NIC due to out-of-position
** H/R adjusted to position at full up, then lowered to full down
Man. 2-way full down is higher than pow. 6-way full down

An additional video analysis was made to determine the OC-T1 displacements for several of the 16 km/h sled tests. Table 3 compares the Saab 9-3 and 900 results with the head restraint in the up and down position. With SAHR in the down position, there are 34% lower neck displacements on average than the Saab 900 standard head restraint in up position. This performance was a principal design goal of the active head restraint system and provides greater protection with the SAHR head restraint down than a standard head restraint in the up position. When the seats are compared with the head restraints in the up or down position, there was a 72% and 61% reduction with SAHR, respectively.

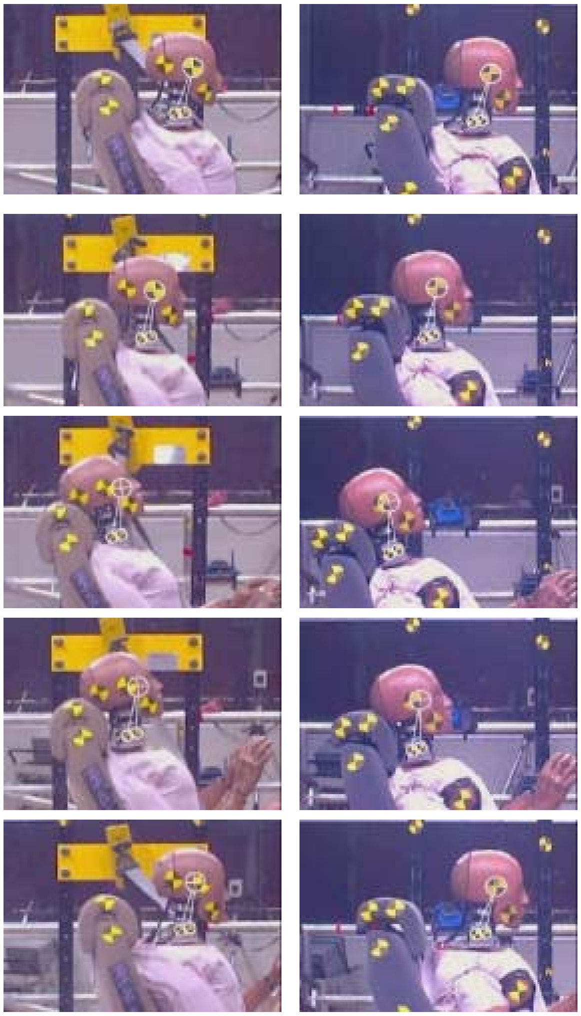

Figure 13: Dummy kinematics with the target superposition method showing head rotation and displacement in 16 km/h rear sled tests. The left column shows the Saab 900 and the right, the Saab 9-3 with SAHR active head restraint system. The tests were with the head restraint in the down position, showing the greater control of head-neck kinematics with the SAHR system.

Figure 13 shows the target superposition for two comparable sled tests at 16 km/h. The Saab 900 seat is fit with a standard head restraint (left column) and the Saab 9-3 has the SAHR active head restraint system (right column). Both tests involved a low head restraint position. The head is seen to displace and rotate more in the Saab 900 test. The increased compliance of the Saab 9-3 upper seatback reduces neck displacements early in the loading and the forward and upward motion of the SAHR system supports the head as it deforms the foam in the head restraint. This action holds the head more forward reducing its rotation and rearward displacement.

Table 3: OC-T1 Rotation and Displacement in 16 km/h Sled Tests of the Saab 9-3 and 900

	è (deg)	x (mm)	z (mm)
SAHR 9-3			
Up	6.5	4.9	-2.1
Down	16.0	18.4	-3.6
Std 900			
Up	20.5	31.9	-5.8
Down	29.0	40.4	-22.5

Figure 14: Dummy kinematics with the target superposition method showing head rotation and displacement in the 18 km/h rear sled tests. The left column shows a baseline seat and the right, the same seat with the SAHR system included.

Figure 14 shows another example of the target superposition technique for two comparable sled tests in the second series with the head restraint up. The same seat is shown with a standard head restraint (left column) and SAHR active head restraint system (right column). The head displaces and rotates more with the standard head restraint, especially later in the crash sequence as the head deforms the head restraint. The neck displacements are much greater in the baseline test, even with the head restraint in the up-most position. The forward and upward motion of the active head restraint again helps support the head as it deforms the foam in the head restraint lowering neck displacements.

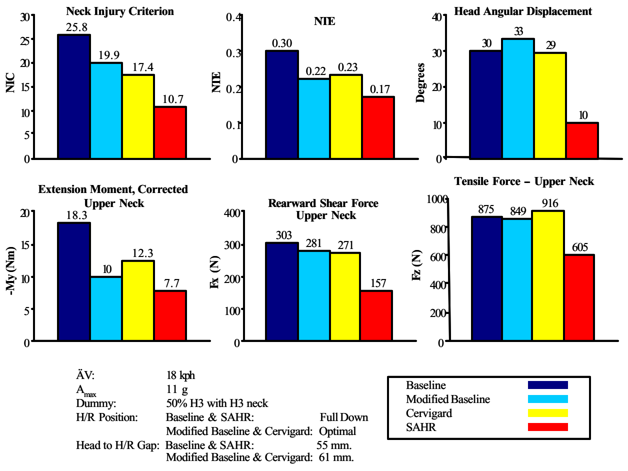

Figure 15: Peak head and neck responses in 18 km/h rear sled tests with a baseline luxury seat, and the same seat fit with a thicker head restraint, the Cervigard-shaped head restraint and with SAHR implemented in the seatback.

Figure 15 summarizes the key responses from the four tests conducted in the second sled series. The baseline seat has the highest neck and head responses and the SAHR system gives the lowest. When the head restraint is made thicker, reducing the initial gap behind the head, or when the Cervigard-shaped head restraint is used (also with a smaller initial gap), an intermediate level of response is produced. These data show that SAHR implemented in a seat can reduce neck biomechanical responses in a rear crash.

In the third series, the Saab SAHR and Volvo WHIPS seats were evaluated in comparable 24 km/h rear sled tests. Figure 16 summarizes the key responses, and shows lower peak neck biomechanical responses with the SAHR system. These responses allow comparisons when field data on WHIP become available.

Figure 17 cross-plots NIC versus x-displacement rearward for three sled tests at 16 km/h from the first series. NIC_{max} usually occurs at head restraint contact, before maximum neck displacements. In the sled test with the Saab 900 and head restraint up, NIC_{max} occurs at about 2 mm of x-displacement rearward. This is a situation where the maximum x-displacement of the head cg occurs much later and reaches about 45 mm. The other two responses give a direct comparison of the Saab 900 and Saab 9-3 SAHR with the head restraint in the down position. In these tests, the NIC_{max} occurs at about half of the maximum head displacement. Since NIC_{max} often occurs before the primary head restraint interactions, the criterion does not differentiate head restraint designs or injuries occurring at that time.

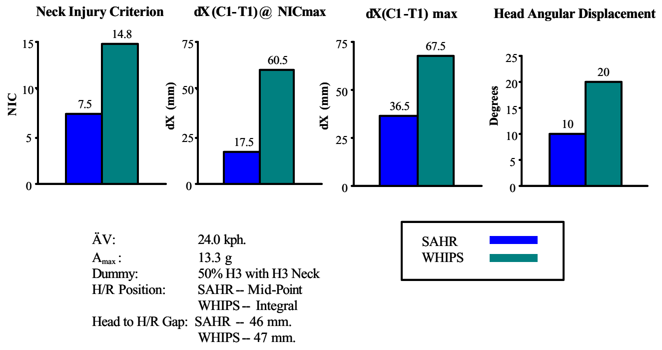

Figure 16: Comparison of SAHR and WHIPS with the head restraint in the mid-position and a 24 km/h and 13.3 g sled pulse.

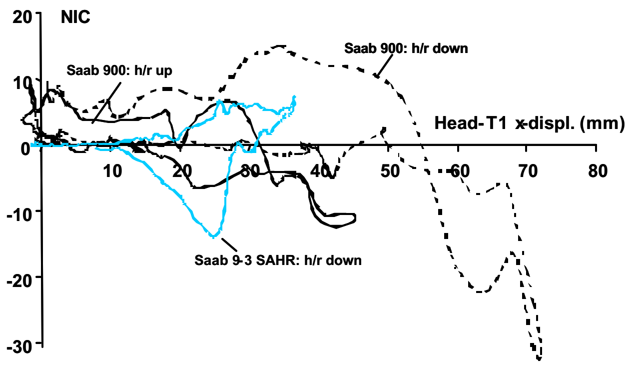

Figure 17: Cross-plot of NIC vs the rearward x-displacement of the head cg for three 16 km/h sled tests.

DISCUSSION

Neck Responses Related to Whiplash

After the testing and review of the literature on underlying neck injury mechanisms, neck displacement responses seem to be meaningful in assessing whiplash risks in low-speed rear crashes. Humans have a natural range of motion for head rotation, and horizontal and vertical displacement. When the biomechanical response approaches and exceeds that range, the risks of injury increase by any one of several mechanisms. The Neck Displacement Criterion (NDC) assesses the overall neck response from the occipital condyles to T1 that is contributed to by each vertebral element. For extension, horizontal displacement without head rotation simulates the S-shaped response that may occur early in a crash and involves extension of the lower cervical vertebrae. As head extension increases, the combined response reflects the risk of hyperextension (see Figure 5a) where the upper and lower vertebrae are in hyperextension.

To our knowledge, a neck displacement response and NDC have not been previously proposed in this format. Their use has been found to be a robust approach when various seats and head restraint concepts have been evaluated; and, it lends itself to easy, direct measurement in sled or barrier tests. The neck displacement responses include three time histories: OC (head) rotation, x- and z-displacement of OC-T1; and, they are presented as two cross-plots of OC (head) rotation versus x-displacement and the z- versus x-displacement of OC with respect to T1.

The IV-NIC criterion proposed by Panjabi et al. (1999) addresses vertebral rotations that may load the facet joints. This is an important factor. When the individual responses are summed for the cervical spine, the full rotation can be compared to the natural range of motion. The individual responses address the potential for a hyperextension (or hyperflexion) injury at each adjacent vertebrae. This helps locate the cervical level at greatest risk of injury. However, the IV-NIC does not include neck x- and z-displacements as part of the criterion. Shear and compression forces are a factor in neck injury at the facet joints. Yang et al. (1997) and Deng et al. (2000) have shown that compression of the cervical spine relaxes the ligaments and muscles lowering the shear stiffness of the vertebrae; and the research of Siegmund et al. (1997, 2000), Winkelstein et al. 1999, Yoganandan et al. (2000), McConnell et al. (1995), Matsushita et al. (1994) and van den Kroonenberg et al. (1998) also shows that vertebral displacement is important. These studies demonstrate that the assessment of whiplash risks may need to include the x- and z-displacement of the head OC with respect to T1 along with OC rotation to fully evaluate injury risks at the facet joint and other regions of the neck. The speed of neck deformation may be an additional factor that can be addressed by differentiation of the OC-T1 rotations and displacements, but more analysis is needed to consider this effect.

A new measurement method is being developed to directly give the displacement data usually determined from film analysis and by using the target superposition method. The approach involves the use of a goniometer made up of potentiometers fixed to the occipital condyles and T1, and an LVDT measuring the change in distance between the rotational potentiometers during a test. In a test, the potentiometer on the head gives rotation about the occipital condyles and the rotation of the pot attached to T1 and the distance change gives the horizontal and vertical displacement of the occipital condyles with respect to T1. This measurement method is most useful in rear barrier tests where a clear lateral view of the head-neck response is not always possible because of interferences from vehicle pillars and body structures, rotation of the seatback and dummy kinematics. The measurement technique offers an approach to directly determine NDC in extension and flexion during dummy tests.

For historic reasons, the neck moment and force responses at the occipital condyles and base of the neck (T1-C6 junction) have been measured in rear crashes. Head rotation and moment are used to calibrate the neck of the Hybrid III dummy, but similar performance criteria have not been established for horizontal and vertical displacement, even as the natural range of motion shown in Figure 5 is a logical approach. In recent low-speed rear crash testing, limits on peak neck shear and bending have been proposed (Steiner et al. 1999), but the neck dynamics are quite varied during the various phases leading up to head contact, head restraint loading and rebound, and the responses are even more complicated in out-of-position tests. An advantage of using neck displacement is that it gives the cumulative effect of all dynamic loads between the OC and T1 over the full crash duration and shows head interactions with the head restraint causing neck deformation. One option, however, may be to assess the force and moments as a function of neck displacement. In this way, a large force or moment when the neck is at the extreme of the natural range of motion may be more injurious than high loads with small neck displacements. The advantage of this approach needs to be considered further.

The proposal to measure neck displacements in rear sled and barrier tests is based on physical principals of displacement-related injuries of the neck. While the responses to be determined are known, it is too early to define tolerance levels. This work will require analysis of human volunteer responses, such as those from Ono et al. (1999), Davidsson et al. (1999b) and Davidsson (2000). Also, the determination of the dummy biofidelity with regard to OC-T1 rotation and displacement is needed to adjust tolerances from the human to the test device. In the interim, adequate film coverage and instrumentation should be used in rear sled and barrier tests, so that displacement data can be obtained in laboratory tests. This will allow a careful evaluation of head interactions with the head restraint and determination if any rate effects may need to be considered in a final proposal for injury tolerances. Also, a well defined T1 kinematic (rotation and translation in a fixed inertial reference) is needed for the determination of biofidelity and injury assessment.

Neck injury criteria that are based on acceleration of the vertebrae are a problematic approach to assessing whiplash and should be avoided. The NIC criterion uses the x-acceleration and integrated velocity difference between the occipital condyles and T1 to assess whiplash risks. More recently, Jakobsson (2000) suggested using the relative velocity difference for each adjacent vertebrae as a measure of risk. These approaches are fraught with technical problems of drift, stability and filtering of the signals, instability of integration, and increasing inaccuracies with whole body rotations that change the orientation of the accelerometer's active axis with respect to the inertial reference frame. As more biomechanical information is determined on human responses, deformation of the body has been found to be a meaningful approach to assessing injury. Acceleration of a point or difference between points has been generally found to be an unreliable approach. This was the case in the rear barrier and sled tests with BioRID and Hybrid III.

seats. More troubling is that in a number of other tests, the peak NIC occurs with inappreciable x-displacement of the neck. It is unlikely that injury can occur to any soft tissues of the neck without displacement. Even the hydraulic injury mechanism proposed by Aldman (Svensson et al. 1993) requires a volume change of the cervical CSF space to create a pressure pulse. The Saab 900 head restraint up test shown in Figure 17 is a good example of peak NIC occurring with only 2 mm of x-displacement.

Table 4: Field Crash Statistics from Single-Event Rear Crashes of Saabs in Sweden (results in parentheses exclude pre-existing cases of whiplash) and Rear Barrier Test Results with BioRID and Sled Test Results with Hybrid III

	# Cases	**First Evaluation**			**Final Evaluation**			**BioRID NIC**			**Hybrid III**		
Saab		**MT**	**LT**	**Rate**	**MT**	**LT**	**Rate**	**24dn**	**24**	**All**	**NIC**	**Ang.**	**x-Disp.**
9000	37(37)	5	3	8.1%	3(3)	4(4)	10.8%(10.8%)	33	35	30			
900	48(45)	1	6	12.5%	2(1)	3(1)	6.3%(2.2%)	22	21	25	12	25	59
9-3	38(37)	1	1	2.6%	1	1(0)	2.6%(0%)	22	18	19	9	10	19
9-5	54(52)	0	2	3.7%	0	2(0)	3.7%(0%)	27	19	25			

Further Evaluation of IIHS Rear Crash Tests

Figure 18 shows the NIC results from rear crash tests of the Saab 9-3 SAHR, Volvo WHIPS and GM Grand Prix conducted by IIHS (1999). The original paper by Zuby et al. (1999) did not include neck displacements, which were determined in this study. The SAHR and WHIPS show similar NIC responses and the Grand Prix is rather close. This is interesting because the initial design head gap in the Grand Prix was 81 mm compared to around 45 mm in the tests with the WHIPS seat and SAHR active head restraint system.

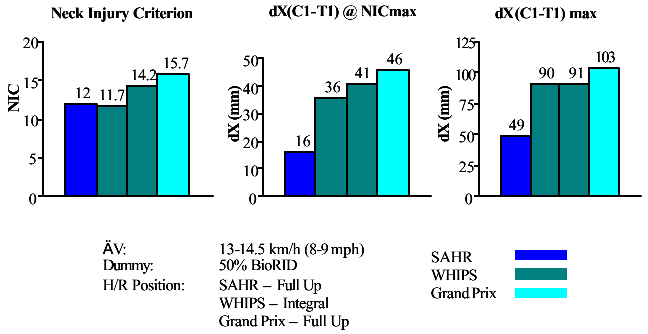

Figure 18: Additional analysis of IIHS rear barrier tests to explore the head x-displacement with respect to T1 for the SAHR, WHIPS (2 tests) and Grand Prix seats.

More interesting is the maximum head x-displacement with respect to T1. This shows a much lower response with the SAHR system than either WHIPS or the Grand Prix. This displacement reflects a lower shear load on the neck. When the x-displacement is compared at the time of maximum NIC, there is also a lower response with the SAHR indicating an earlier difference. However, NIC peaks very early in the x-displacement response for some

Saab Field Crash Data and Interpretation of Laboratory Tests

A study was recently completed on Saab vehicles in real-world rear crashes (Viano, Olsen 2001). A short summary is given here as background for the inference to laboratory tests. Rear crashes were investigated in Sweden from September 1998 through April 2000, and insurance records were evaluated for whiplash. The vehicles included the Saab 900 and 9000 that were equipped a conventional head restraint and the Saab 9-3 and 9-5, which included the SAHR active head restraint as standard equipment in the front seats.

Dial Insurance AB provided an accident report and a photograph of the damaged vehicle, and a special questionnaire was mailed to the occupants involved in the rear crashes. The outcome was recorded as no injury (NI), short-tem pain lasting <1 week (ST), medium term whiplash injury lasting <10 weeks (MT), and long-term whiplash extending >10 weeks (LT). Demographic information was also obtained.

177 front-seat occupants were in the crashes. Table 4 summarizes the main results. There were 85 cases in cars without an active head restraint, and 92 cases in cars with the SAHR system. In the first evaluation, SAHR reduced the risk of MT-LT whiplash injury by (75 ± 11)% from an incidence of (18 ± 5)% in vehicles with standard head restraints to (4 ± 3)% with SAHR in rear crashes. If only LT cases are considered, the reduction was 69% from 11% in the Saab 900/9000 to 3% in the Saab 9-3/9-5. Occupant demographics were statistically similar in age, weight and height.

In a follow-up phone interview in February 2001, the rate of long-term whiplash disability was 6.1% in the Saab

900/9000. This involved some reclassification of injuries and the removal of a few individuals with pre-existing whiplash injury from the sample. On this basis, there were no cases (0%) of long-term disability with SAHR in Saab 9-3/9-5 rear crashes, since the three individuals with LT claims had pre-existing neck injuries from earlier rear crashes. None of these individuals felt that the current accident aggravated their existing medical disability.

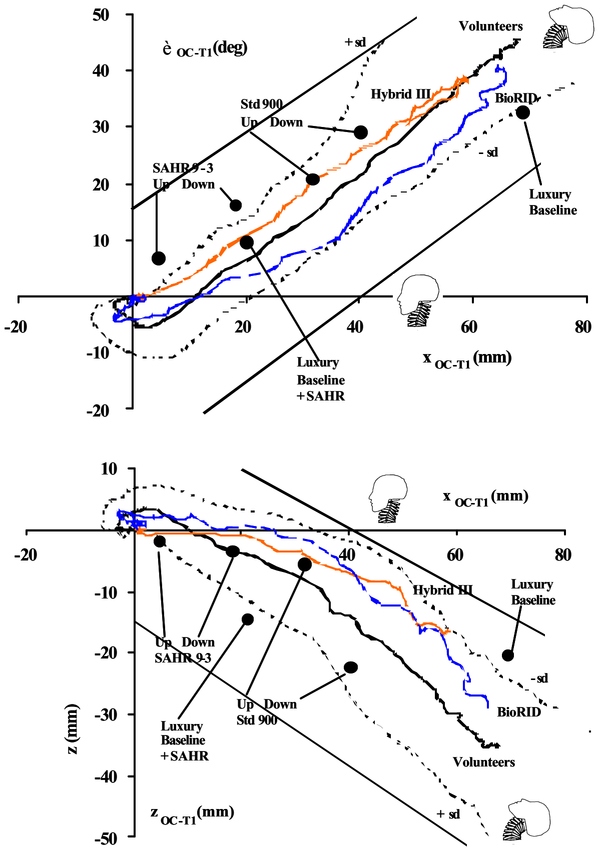

Figure 19: Peak NDC in Hybrid III for the Saab 9-3 SAHR and 900 with the head restraint in the up or down position at 16 km/h, and a luxury seat with and without SAHR in 18 km/h rear sled tests. Also shown are the average and ±1sd response and corridor for volunteers, and Hybrid III and BioRID responses in a 9.3 km/h sled tests with rigid seat without head support (modified from Viano, Davidsson 2001).

Included in Table 4 are summary results from the BioRID and Hybrid III tests. Based on the field results from the Saab 9-3 and 9-5 crashes, NIC values up to 27 are unlikely to represent response levels that are consistent with a risk of disabling whiplash injury. One might conclude that NICs in the range of 30-35 are consistent with an 11% chance of whiplash, as found in the Saab 9000 cases; however, this does not determine a correlation with injury or provide support for use of the criterion. While the NIC from Hybrid III seems to show a correct trend, the full data from testing does not support its use in evaluating whiplash. Neck displacements show a more consistent relationship to the field injury results.

Figure 19 plots the peak OC-T1 neck displacements from four 16 km/h tests with the Saab 9-3 and 900. There are lower values with the 9-3 SAHR, irrespective of head restraint position. Also shown are the 18 km/h results from the baseline luxury seat and when SAHR was implemented in it, both with an up head restraint position. The results are well within the corridors for the natural range of voluntary motion and are consistent with the free-head motion of the Hybrid III in a 9.3 km/h sled tests, which is also shown. The various data are superimposed to show how this type of cross-plot allows the merging of results for comparison. Obviously, additional data and analysis are needed with a wider range of seats and test conditions before performance goals can be established for Hybrid III and BioRID. However, the use of NDC seems to be a worthy additional approach for whiplash assessment.

The rear seating position with BioRID often had higher NICs than the front seats. This is an opposite trend from what has been seen in field crashes (Lovsund et al. 1988). The low incidence of whiplash in the rear seating positions may be related to the horizontal trajectory of the head restraint as the seatback is integral to the car structure and does not rotate rearward under occupant load. This may be one factor in the safety performance among demographic considerations, even though the gap was somewhat higher than that of the front seats in the barrier tests.

Problems with BioRID and Hybrid III Dummies

A number of issues were found with the BioRID and Hybrid III dummies used in the rear barrier and sled tests. The BioRID dummy has a high torsional, shear and extension/compression compliance of the spine. This is due to the pinned connection of the vertebral elements and the cable tensioning system of the spine. The dummy needs spinal compliances that at least mimic that of the Hybrid III dummy and eventually more humanlike responses.

Torsional compliance is needed in situations where the seatback rotation is not symmetric and one side twists rearward more than the other. This situation is accentuated with lateral positioning of the dummy in the seat. Many important injury criteria are based on the premise that neck compression and shear contribute to whiplash injury. While the dummy matches biomechanical corridors for volunteer and cadaver responses for free head motion (Davidsson et al. 1999b), proper force-deflection compliance of the neck is needed with head restraint interactions. Other modes of neck deformation also need to be simulated (Ono et al. 1998, 1999). In addition, some increased rebound was seen with the BioRID, and there were difficulties in handling the dummy and placing it in the design seating position.

For the Hybrid III dummy, the rigid thoracic spine causes earlier seat loading particularly when there is a structural cross-member in the upper back region. This causes earlier responses than the human. Also, the rearward protrusion with the lower neck loadcell made it impractical for use in some test conditions. Both these situations prevent the Hybrid III dummy from simulating the displacement and rotation of T1 that would occur in volunteers and BioRID during rear sled tests (Davidsson 2000). Realistic T1 kinematics, including translation and rotation, are needed to drive the base of the neck and initiate the biomechanical responses associated with whiplash.

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Table A1: Front Seat BioRID Responses in 24 km/h Rear Moving Barrier Tests
(HR up/dn – head restraint in the up or down position)

	SAAB 9-5				SAAB 9-3				SAAB 9000 CS				SAAB 900 M94			
	Man.seat		Pow.seat		Man.seat		Pow.seat		Man.seat		Pow.seat		Man.seat		Pow.seat	
	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn
Crash number	K2262		K2313		K2314		K2263		K2264		K2316		K2265		K2315	
Vehicle weight (kg)	1835		1835		1635		1635		1760		1760		1620		1628	
Max acc. (g)	9.6		9.1		9.9		9.5		12.9		8.9		10.4		9.9	
Mean acc. (g)	4.0		3.8		4.7		4.6		4.7		4.3		4.8		5.0	
Delta v (km/h)	16.3		15.4		16.2		15.8		15.6		15.6		16.0		16.4	
Belt pret.	No	No	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No
Gap Head to HR (mm)	58	58	58	58	58	58	58	58	58	58	58	58	58	58	58	58
Head x-acc. (g)	23	29	21	29	23	29	24	30	33	37	26	31	29	51	29	47
Head z-acc (g)	7	12	7	13	7	12	6	15	16	13	13	11	10	19	12	18
C4 x-acc. (g)	20	18	15	18	19	18	19	18	17	24	15	19	22	24	22	22
C4 z-acc. (g)	5	14	5	14	7	10	4	15	16	15	14		14	12	13	15
T1 x-acc. (g)	12	17	11	16	14	15	13		22		14	18	18	20	19	19
T1 z-acc. (g)	5	8	4	6	7	7	6	13	7	9	6	6	7	12	7	12
T8 x-acc. (g)	10	13	10	11	13	12	11	14	10	13	11	11	11	9	11	11
T8 z-acc. (g)	3	6	4	4	4	6	3	6	4	5	4	4	4	7	5	7
L1 x-acc. (g)	8	9	8	9	10	12	10	11	10	10	8	11	11	9	10	10
L1 z-acc. (g)	8	6	6	7	7	6	5	6	7	6	4	7	6	5	5	5
Pelvis x-acc (g)	10	12	11	13	13	12	11	11	10	10	10	9	12	10	11	11
Pelvis z-acc (g)	3	4	4	4	5	5	4	4	4	4	4	5	4	3	4	4
Head contact start (ms)	80	105	85	106	65	89	71	102	96	98	94	102	77	108	84	101
Head contact end (ms)	160	168	162	164	152	152	155	166	161	163	167	168	140	173	149	167
Vel. at head contact (m/s)	4.5	4.8	4.4	4.4	4.3	4.4	4.4	4.2	4.5	3.9	4.3	4.1	4.2	3.7	4.5	4.2
HIC 36	59	79	53	84	58	87	59	88	70	68	62	66	71	83	85	84
Head angle diff	24	40	22	41	18	33	24	43	46	40	35	44	25	47	25	36
Max. head angle at time	120	138	114	123	106	117	115	127	134	118	127	122	111	122	109	124
NIC max (m^2/s^2)	18.3	24.9	17.0	28.0	15.2	21.8	17.6		44.7		27.1	32.8	19.1	19.5	23.4	23.5
Time NIC max (ms)	82	96	75	93	71	78	72		87		93	86	77	91	92	90
T1 angle diff.	26	35	23	33	25	32	23	38	25	26	26	29	20	31	26	31
T1 angle max at Time(ms)	113	137	115	123	112	120	118	132	124	118	127	128	106	127	110	125
Rebound head vel rel. car (m/s)	3.7	4.0	3.5	3.8	4.4	4.2	3.9	4.2	3.2	3.4	4.1	4.3	3.2	4.1	3.7	3.8
Rebound T1 vel. rel. car (m/s)	2.7	2.5	2.9	2.8	3.0	2.8	3.1		4.7		2.8	3.1	2.2	2.5	2.8	2.5
Rebound T8 vel. rel. car (m/s)	2.3	2.0	2.2	1.8	2.8	2.1	2.6	1.7	1.7	2.2	2.6	2.3	2.2	1.0	2.5	2.3
Neck Fx (head rw) (N)	10	289	1	487	0	296	1	411	204	276	107	346	54	551	12	608
Neck Fx (head frw) (N)	304	127	144	294	133	266	231	163	131	106	129	180	144	126	141	176
Neck Fz Tension (N)	298	1810	661	1068	506	968	354	2028	791	1736	1075	1041	545	1904	920	1060
Neck Fz Comp. (N)	17	97	31	41	0	66	38	25	41	26	4	34	142	38	22	25
Neck My Ext. (Nm)	15	4	6	24	5	24	12	6	37	3	5	27	18	5	5	28
Neck My Flexion (Nm)	8	11	2	12	1	10	8	15	6	11	5	6	12	22	4	6

Table A2: Front Seat BioRID Responses in 48.3 km/h Rear Moving Barrier Tests
(HR up/dn – head restraint in the up or down position)

	SAAB 9-5				SAAB 9-3				SAAB 9000 CS				SAAB 900 M94			
	Man.seat		Pow.seat		Man.seat		Pow.seat		Man.seat		Pow.seat		Man.seat		Pow.seat	
	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn	HR up	HR dn
Crash number	K2340		K2339		K2338		K2337		K2334		K2333		K2335		K2336	
Vehicle weight (kg)	1835		1835		1635		1635		1760		1760		1620		1620	
Max acc. (g)	18.3		19.1		17.6		18.3		15		16.3		17.6		18.1	
Mean acc. (g)	6.4		6.5		6.5		6.5		8.5		7.2		6.1		6.5	
Delta v (km/h)	27		27		27		28		26		28		26		27	
Belt pret.																
Gap Head to HR (mm)	58		58		58		58		58		58		58		58	
Head x-acc. (g)	27	33	25	31	22	31	17		62	38	17	25	27	34	29	27
Head z-acc (g)	15	25	13	23	14	21	7		26	46	17	15	10	8	11	17
C4 x-acc. (g)	25	40	21	33	20	30	14	26	30	18	18	18	24	35	31	18
C4 z-acc. (g)	5	21	6	16	5	15	5	14	26	15	16	16	12	18	13	14
T1 x-acc. (g)	17	26	18	21	15	20	16	23	45	8	16	16	18	26	23	18
T1 z-acc. (g)	7	13	6	8	8	9	5	7	18	10	6	11	80	12	13	8
T8 x-acc. (g)	14	20	16	17	15	17	12	15	29	16	13	11	14	14	16	14
T8 z-acc. (g)	5	10	6	7	5	6	4	5	15	33	6	6	47	8	6	8
L1 x-acc. (g)	13	18	13	13	13	16	12	13	12	12	13	12	15	14	14	16
L1 z-acc. (g)	7	8	9	10	7	7	7	12	9	7	8	8	6	7	6	9
Pelvis x-acc (g)	17	18	18	19	15	17	19	19	22	21	24	20	15	19	16	18
Pelvis z-acc (g)	6	7	5	7	5	6	4	5	7	6	7	7	4	6	5	6
Head contact start (ms)	74	101	81	97	59	91	45	81			111	118	73	97	77	94
Head contact end (ms)	200	195	200	183	202	165	103				156	157	186	194	245	235
Vel. at head contact (m/s)	6.0	6.9	6.6	7.1	4.8	6.0	3.4	5.7			7.5	7.1	5.0	5.6	5.9	6.0
HIC 36	96	133	95	166	78	175	32		282	23	38	47	61	111	61	40
Head angle diff	44	72	43	73	42	67	35	78			30	71	37	22	32	70
Max head angle at time	125	133	126	137	124	122	131	141			96	161	110	90	122	133
NIC max (m^2/s^2)	17.7	32.8	21.9	36.8	14.4	24.5	11.6	28.6	22.0	18.0	37.6	24.9	14.3	22.9	38.2	38.0
Time NIC max (ms)	63	93	89	95	64	92	63	95	78	56	96	137	80	74	83	105
T1 angle diff.	40	49	38	50	38	40	27	48			28	60	31	23	28	38
T1 angle max at time	123	130	128	133	130	124	137	139			96	161	110	90	127	136
Seat stat. deflection	16	12	16	12	15	8	15	12					24	21	26	27
Rebound head vel rel. car (m/s)	2.5	2.2	3.0	3.1	3.3	3.4	4.1	3.1	2.3	3.2	2.3	1.8	4.0	3.5	1.3	1.4
Rebound T1 vel. rel. car (m/s)	2.7	2.5	3.7	3.2	3.6	3.3	3.7	3.3	4.9	4.7	3.4	3.7	2.8	3.1	2.2	2.6
Rebound T8 vel. rel. car (m/s)	1.9	1.2	2.0	1.4	2.8	2.0	2.3	2.0	2.5	2.3	2.0	2.2	3.1	2.6	1.5	1.2
Neck Fx (head rw) (N)	39	533	93	474	35	682	56	362	619	452	168	64	50	196	41	120
Neck Fx (head frw) (N)	305	232	222	220	310	416	180	110	111	120	34	374	150	246	146	120
Neck Fz Tension (N)	1127	1294	1280	1560	1173	18	630	1217	1001	943	1660	9	873	1235	2300	1109
Neck Fz Comp. (N)	80	123	142	86	101	1	65	87	441	77	4	1	10	44	18	131
Neck My Ext. (Nm)	16	41	13	46	16	32	7	37	3	16	1	23	5	41	7	35
Neck My Flexion (Nm)	5	24	5	22	5	18	2	11	34	7	11	9	2	10	4	9

Table A3: Rear Seat BioRID Responses in 24 km/h (left group) and 48.3 (right group)
Rear Moving Barrier Tests (HR up – head restraint in the up)

	9-5 NB		**9-5 HB**		**9000 CS**		**9-3, 900**		**9-5 NB**		**9-5 HB**		**9000 CS**		**9-3, 900**	
	left	middle	left	middle	left	middle	left	middle	left	middle	left	middle	left	middle	left	middle
	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up	HR up
Crash number	K2347		K2345		K2341		K2343		K2348		K2346		K2342		K2344	
Vehicle weight (kg)	1835		1835		1760		1620		1835		1835		1760		1620	
Max acc. (g)	9.5		8.6		10.5		9.7		18.1		16.3		13.3		18.2	
Mean acc. (g)	3.8		3.9		4.2		4.2		6.4		6.6		7.4		6.5	
Delta v (km/h)	16		16.4		15.8		16.6		27		28		27.1		27.2	
Belt pret.	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Gap Head to HR (mm)	125	140	85	125	80	120	76	106	125	140	125	140	100	120	76	106
Head x-acc. (g)	29	31	27	25	51	38	26	41	45	40	42	42	33	28	39	58
Head z-acc (g)	13	21	15	13	40	28	17	13	20	19	9	13	28	11	17	21
C4 x-acc. (g)	21	31	25	20	48	48	29	42	42	29	38	56	32	40	53	58
C4 z-acc. (g)	14	17	14	13	34	23	12	20	24	20	17	28	28	12	12	21
T1 x-acc. (g)	15	25	21	17	43	32	17	20	27	24	34	34	24	42	30	51
T1 z-acc. (g)	8	14	8	8	19	17	7	6	17	28	14	32	10	19	11	27
T8 x-acc. (g)	12	11	16	15	15	13	13	11	22	48	30	38	27	29	20	27
T8 z-acc. (g)	4	9	6	7	13	16	5	6	15	9	13	14	60	8	5	16
L1 x-acc. (g)	9	10	16	14	10	11	11	10	22	37	26	27	26	28	18	21
L1 z-acc. (g)	6	9	8	10	8	10	7	9	12	11	15	27	16	11	7	10
Pelvis x-acc (g)	9	11	16	15	12	11	13	14	22	22	23	25	32	19	19	18
Pelvis z-acc (g)	4	6	4	5	7	12	4	6	10	7	12	13	6	6	6	9
Head contact start (ms)	27	90	55	77	71	86	58	82	57	64	35	52	51	59	46	59
Head contact end (ms)	146	115	106	135	122	95	149	190	105	136	96	97	210	203	100	94
Vel. at head contact (m/s)	1.6		3.7	4.4	3.9	1.5	3.7	4.4	3.9	4.2	3.0	5.0	4.0	0.7	3.2	4.0
Head imact roof	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes
HIC 36	59	60	62	53	114	105	57	102	129	121	123	232	117	67	154	265
Head angle diff.	XX	30	23	48	13	34	33	43	32	53	11	79	37	62	22	45
Max head angle at time	97	98	83	100	82	78	93	106	80	90	67	42	96	101	65	88
NIC max (m^2/s^2)	25.8	18.7	30.8	37.9	14.9	26.3	19.6	30.3	29.0	37.5	52.9	69.1	33.8	33.1	13.4	31.6
Time NIC max (ms)	73	82	58	59	67	70	67	76	54	55	45	52	55	43	55	57
T1 angle diff.	45	40	24	52	22	30	31		30	60	17		94		70	
T1 angle max at time	95	97	74	95	100	88	87		83	79						
Neck Fx (head rw) (N)	76	68	6	85	30	40	27	1050	210	496	38	331	104	64	33	1248
Neck Fx (head frw) (N)	130	129	142	141	282	223	136	87	67	54	249	213	118	206	118	100
Neck Fz Tension (N)	1354	99	1217	740	528	255	1105	175	1863	1330	2086	1378	1370	822	2565	1875
Neck Fz Comp. (N)	100	756	102	206	878	1077	80	572	829	1311	375	531	186	322	192	276
Neck My Ext. (Nm)	1	11	2	16	3	11	4	7	2	21	6	25	2	11	3	31
Neck My Flexion (Nm)	8	41	8	13	15	42	6	40	20	33	15	53	13	12	7	38