Seat Design Principles to Reduce Neck Injuries in Rear Impacts

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Objectives: In the 1990s, research was conducted at General Motors R&D Center on seat safety in rear impacts. It led to the development of high retention seats and an active head restraint to improve occupant safety. This article provides an overview of the design principles found from that research and focuses on seat characteristics that lower whiplash risks.

Methods: Sled and quasistatic seat testing showed how occupants interact with the seat in rear impacts and what seat characteristics improve occupant retention, energy management, and support of the head-neck, lowering injury risks. Neck displacements, moments, and forces were used to assess whiplash and more severe injury risks. A QST test was developed to quasi-statically push a dummy rearward into the seat to determine seat stiffness (k), frame strength (j), and peak bending moment (M_Hpt). These parameters were related to neck displacements associated with whiplash. Sled tests were run with in-position and out-of-position male and female Hybrid III dummies to assess performance. A high retention seat and active head restraint were developed and put into production in 1997.

Results: High retention seats have 2.3 times greater moment, develop 2.2 times greater load, but have the same stiffness as earlier yielding seats. Seat stiffness was found to be a principle characteristic related to neck displacements associated with whiplash. The combination of a stronger frame, yielding seatback, and high-forward head restraint in the high retention seat provides early head support and low neck displacements in rear impacts. Larger reductions in neck displacement were obtained by adding an active head restraint that moves the head restraint forward and upward by occupant penetration into the seatback. This substantially reduces head contact time, neck displacements, and loads.

Conclusions: Whiplash risks are related to seat stiffness, the position of the head restraint, and frame strength. Low seat stiffness allows the occupant to move into the seatback without high loads on the torso until the head-neck is supported by the head restraint. A strong seat frame reduces early seatback rotation that increases the gap to the head restraint and drops it in relation to the occupant’s head. A high and forward head restraint provides support of the head and neck. Large forces can be applied to the occupant once the head, neck, and torso are supported by the seat and head restraint without adverse loading of the spine. The addition of an active head restraint closes the gap behind the head before significant load develops on the neck. The movement provides a more upward trajectory of the head restraint. Low-speed rear crashes are not just a matter of whiplash; older occupants, some with cervical stenosis, are at risk for paralyzing spinal cord injury.

Keywords Whiplash; Seats; Head restraints; Spinal cord injury; Rear crashes; Injury biomechanics

SEAT STRENGTH AND HEAD RESTRAINTS

In the 1950s, front seats in automobiles were a bench design that accommodated occupants in one structure. The strength of the seat was 800 lbs with 400 lbs resistance at each side structure. Based on the available occupant loading data, a 16” moment arm was assumed for the rearward load by the occupants. This established a design target of 6,400 inlb per side structure. Anderson (1961), at General Motors Research Laboratories, undertook a comprehensive evaluation of seat performance in rear impacts with special attention to whiplash prevention. He studied stronger and weaker seats than in production and determined that the 6,400 inlb level provided the right balance between strength and neck loading. He studied neck extension and shear by crash testing and modeling. He also used anthropometry data to show that a 2.5”–3.0” increase in seatback height would provide head-neck support for a larger proportion of occupants. At that time, head restraints were not used and the seatback height was nominally 22”.

In the 1970s, bucket seats became more widely used for convenience in providing individual adjustment of the fore-aft position of the front seats. This also allowed the introduction of recliners that added adjustment of seatback angle. The recliner was a mechanism that had a release handle controlling a linkage or gear allowing adjustment of the rearward angle of the seatback with respect to the cushion. The 6,400 inlb strength
requirement carried over for bucket seats. They typically used one recliner on the outboard side of the seat frame. As time progressed, integrated or adjustable head restraints were added to the seatbacks.

NHTSA established minimum height requirements for head restraints in 1969 through FMVSS 202. Head restraints had to be 27.5" above the seating reference point (nominally the occupant’s H-point) in the fully extended position. NHTSA also established requirements for the rearward strength of front seats. The minimum moment strength was 3,300 inlb in FMVSS 207. This standard involves a test with a rearward point-load on the upper structural cross-member of the seatback. The moment is determined by the load supported on the seatback frame times the distance between the load and seating reference point. FMVSS 207 evaluates the seat frame without the suspension and trim covering.

Severy et al. (1968) conducted rear crash tests with seats of varying strength. Their work was a factor in establishing the head restraint standards. They also studied seat strength. Figure 1 shows a sequence from test X-104, which was a 55 mph car-to-car crash. The 50% male driver was in a 33,000 inlb bucket seat with seatback height of 28" and the 95% male, right-front passenger was in a similar seat with a 3" offset of the head to the seatback. Severy et al. (1968) observed that the rigid driver’s seat reclined to 41 degrees in the crash and that the head center of gravity (cg) moved rearward over the top of the seatback. The driver’s neck extension was 79 degrees and the whiplash motion progressed until the driver’s eyes were pointing rearward at a time when the head acceleration was 42 g.

Figure 2 summarizes the situation found by Severy et al. (1976) with rigid seats when the head was not fully supported through the crash and hyperextended over the seatback. Yielding seats were found to better maintain neck alignment as the occupant was accelerated forward (Blaisdell et al., 1993; Prasad et al., 1997; Viano et al., 2007, 2008).

During the 1970s to 1980s, the strength of seats gradually increased. Within General Motors, the requirements for 6,400 inlb strength were tightened by adding goals for a maximum 10 degree change in recline angle at the target load and that the seatback frame should return to within 5 degrees of its initial position on unloading. By the late 1980s, the ultimate load supported by seats was well above the minimum requirement of FMVSS 207 and the design target of 6,400 inlb. However, the head restraint requirement in FMVSS 202 for height was not changed and there was no specification on gap as seats became stronger. In addition, the vast majority of occupants failed to raise adjustable head restraints high enough to reduce whiplash. This fact was first reported by O’Neill et al. (1972) and remained essentially the same 20 years later (Viano and Gargan, 1996). Even head restraints adjusted to the highest position allowed neck extension.

In the early 1990s, General Motors R&D Center undertook an in-depth study of seat characteristics to improve occupant safety.
in rear impacts (Viano, 2002, 2003a–i). This led to establishing a minimum seatback strength of 1,700 Nm (15,000 inlb) in 1995 using a quasistatic seat test (QST). The QST involved a 50% male dummy on the seat that was loaded rearward into the seatback through the lumbar joint. The test included the dummy’s weight on the seat cushion to load the seatback in a manner similar to sled and vehicle testing. The dummy was free to move up-down and sideways during rear loading. The test used a fully trimmed seat, so the occupant loaded the seatback through the seat trim and suspension. The test used the contour of the back of the dummy’s pelvis and torso to load the seatback and allowed the seatback to rotate rearward and twist in a manner similar to what was observed in sled testing. The effective moment arm for the occupant load was 22 cm (8.7’’). This meant that occupant loads on the seat were substantially higher than loads associated with a similar moment in FMVSS 207 tests, because the moment arm in FMVSS 207 tests was typically 12–14”.

The QST provided data on seat stiffness (k), frame strength (j), ultimate load (F), bending moment (Mthp), and energy transfer (E). It is a destructive test that determines seat deformations that occur over a range of rear crashes. QST data showed that as seats increased in strength, they also increased in stiffness. The increase in seat stiffness was found to cause higher loads on the occupant’s torso and greater neck displacements before head restraint contact (Viano, 2003h). This may be one reason for the increase in whiplash during the 1970s to 1990s.

**SEAT STIFFNESS**

Since the 1950s, there has been an understanding that vehicle interior components need to yield under occupant load to reduce injury risks. Yielding lengthens the load duration and lowers forces. It was also known that energy needed to be absorbed to reduce occupant rebound. In the 1960s, automotive interior components were designed for occupant protection by yielding on impact. Yielding is defined as the load developed by deformation; it is stiffness (k), where the load is divided by the deformation distance in units of kN/m (lb/in). By reducing stiffness, yielding displacements increased, accelerations lowered, and injury risks were reduced. Interior components, such as the energy-absorbing steering column, high-penetration-resistant windshield, padded interior, and seatbacks were designed to yield.

Anderson (1961) GM Research study confirmed yielding seatback structures of 6,400 inlb strength reduced neck extension and shear in rear impacts. The yield load was below the level causing high neck loads. The yielding seatback also reduced occupant rebound. Rebound was considered important because early field accident data showed that contact with front interior components was responsible for much of the injury in rear impacts (Schwimmer and Wolf, 1962). That finding was also made by NHTSA three decades later (Partyka, 1992).

The 1990s GM research looked for ways to maintain a low stiffness (yielding) seat as the strength of the frame was increased. The concept of a perimeter seat frame was tested over a range of rear crash severities. It improved occupant retention and energy transfer while lowering neck responses. It was called a high retention seat; its design enabled the introduction of a “new generation” of yielding seats. The high retention seat was introduced in 1997. It had a strength >1,700 Nm (15,000 inlb) and stiffness of 25 kN/m (140 lb/in). The stiffness was comparable to that of yielding seats of the 1970s and 1980s.

During the development of the high retention seat, benchmark QST testing was conducted on seats from around the world. This work showed that the stronger seat frames were also stiffer. Figure 3 shows the trend in seat stiffness (k) and frame strength (j) from the older seat designs of the 1960s to 1980s to the strongest seats in production in the early 1990s. Frame strength (j) is defined as the change in seatback angle with occupant load. As the strength of the seat increases, j decreases. The seats were also stiff, with k about 34 kN/m (195 lb/in) or more. Seat stiffness is important for the following reason. In a crash, deformation of rear vehicle structures develops force, accelerating the vehicle forward. Vehicle displacement is the double integral of the acceleration in the crash. There is a time delay in the seat displacement and occupant loading.

An occupant is loaded by the forward displacement of the seat. The force (F) on the occupant’s torso is determined by the relative displacement (x) between the torso and vehicle, and the stiffness (k) of the seat: F = kx. When the occupant’s torso is forced forward, it also pushes rearward on the seatback. Force on the seatback causes rearward rotation (θ) of the seat frame. The change in seatback angle is determined by the force and frame strength (j): θ = jF. Combining the two relationships shows that the change in seatback angle is related to the jk product: θ = jkF in a given crash. The j and k properties of seats were determined in QST testing. These two seat properties relate to occupant acceleration and neck loading in rear crashes. They relate to whiplash risks.

Figure 4 shows the effect of a stiff, strong seat with conventional head restraint (left images). Occupant responses are shown in four images from the crash sequence in a low-speed (18 km/h or 11 mph) rear sled test. A cycle of loading occurs in the test. Early as the seat is displaced to the right, the torso is
Kinematics with a strong, stiff seat and conventional head restraint (left) and the same seat modified using an active head restraint (right) in 16 km/h (10 mph) sled tests conducted at Lear Corp.

loaded. The load increases quickly because of the high stiffness of the seat. The early loading causes the occupant to push back on the seat and rotate the seatback frame rearward, pulling the head restraint away from the occupant before it supports the head. In the second image, the head is slightly rearward of its initial position at the start of the test (first image). The initial position of the head cg is shown by the superimposed white target on the high-speed video.

The third image in the left sequence shows the head just about to contact the head restraint. The seatback has rotated rearward and the head has velocity toward the head restraint. This increases the kinetic energy of the head and results in considerable deformation into the head restraint. The end result in the fourth image is significant rearward displacement of the head cg from its initial position in a low-speed impact. The x displacement of the head cg is 68 mm rearward, z displacement is 17 mm downward, and head rotation is 32 degrees rearward, causing neck extension. The stiff, strong seat sets up a cycle of loading that involves the seat pushing on the occupant, building up load; the occupant pushes back, rotating the frame rearward; the occupant moves further rearward to contact the head restraint and the buildup in head kinetic energy deforms the head restraint and increases neck responses.

Figure 5 shows that seatback rotation moves the head restraint rearward and down, increasing the gap behind the head and lowering it compared to the head cg. The occupant’s head had to move significantly rearward to contact the head restraint because early loads on the seatback rotated it rearward away from the head. At contact, the head restraint has dropped to a less favorable position to limit neck displacement.

The seat used in Figure 4 was one of the strongest on the market in the early 1990s. However, the simultaneous increase in seat stiffness (increase in k) negated the benefit in reducing seatback rotation early in a rear crash with a strong seat frame (a decrease in j). This can be seen by the relationship for change in seatback angle: \( \theta = jk \).

Table I summarizes the typical characteristics of seats to rearward occupant loading. These are nominal values representative of the many seats tested in the early 1990s. What is interesting is the \( jk \) product. The product is \( jk = 68 \) degrees/m for yielding seats of the 1960 to 1990s, even as the maximum H-point moment gradually increased over three decades. The foreign benchmark of the strongest seats available in the early 1990s was also stiffer, such that \( jk = 72 \) degrees/m, a value larger than for older yielding seats. This provides an explanation for the performance seen in the low-speed test shown in Figure 4. It was surprising to see the amount of seatback rotation occurring with a strong seat in a low-speed test. The high \( jk \) product explains why there was so much seatback rotation early in the test. The level of rotation was similar to what was observed with older yielding seats that have a similar \( jk = 68 \) degrees/m.

<table>
<thead>
<tr>
<th>Seat Type</th>
<th>k (kN/m)</th>
<th>j (deg/kN)</th>
<th>jk (deg/m)</th>
<th>Force Limit (kN)</th>
<th>H-pt Moment (Nm)</th>
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<tbody>
<tr>
<td>1960-70s Yielding</td>
<td>20</td>
<td>3.4</td>
<td>68</td>
<td>3.0</td>
<td>660</td>
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<tr>
<td>Seat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980-90s Yielding</td>
<td>20</td>
<td>3.4</td>
<td>68</td>
<td>5.0</td>
<td>1100</td>
</tr>
<tr>
<td>Seat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foreign Benchmark</td>
<td>40</td>
<td>1.8</td>
<td>72</td>
<td>7.7</td>
<td>1700</td>
</tr>
<tr>
<td>High Retention Seat</td>
<td>20</td>
<td>1.4</td>
<td>28</td>
<td>10.0</td>
<td>2200</td>
</tr>
<tr>
<td>ABTS</td>
<td>40</td>
<td>1.0</td>
<td>40</td>
<td>20.0</td>
<td>4400</td>
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</table>
WHIPLASH IN LOW-SPEED REAR CRASHES

Seat stiffness and frame strength are important characteristics controlling neck displacements and whiplash risks in low-speed rear crashes. Figure 6 shows neck displacement and the time of head contact with the head restraint for three different seat types. The time of head contact is inversely related to the severity of crash for tests above 10 km/h (6 mph) and is longest for the strong, stiff seat. This is consistent with what was observed in Figure 4. The lowest head contact times occurred with the high retention seat, which is a strong, yielding seat. The early contact time is related to low forces on the torso as the body penetrates between the side members of the seatback frame. There is also a small change in seatback angle early in the crash because \( jk = 28 \) degrees/m.

In contrast, the strong, stiff seat has \( jk = 72 \) degrees/m, nearly three times that of the high retention seat. Neck displacements at head restraint contact are significantly higher with the strong, stiff seat than the early yielding seats or the high retention seat. The data in Figure 6 are consistent with the IIHS goal for <70 ms contact with the head restraint (RCAR-IIWPG, 2007). With the high retention seat, the head contact time was 72 ms in a 16 km/h (10 mph) rear sled delta V. The need for a low stiffness is also consistent with the IIHS goal of T1 acceleration <9.5 g. Low seat stiffness gradually accelerates the torso, limiting T1 acceleration.

Table II shows seat characteristics for 27 different high retention seat designs from the major seat suppliers for General Motors. All of the suppliers provide seats to other domestic and foreign automotive manufacturers. The average QST data for high retention seats is compared to that from 29 earlier yielding seat designs that did not meet the high retention requirements. The average H-point moment for high retention seats is 2,537 ± 703 Nm (22,440 ± 6,220 inlb). This is 2.3 times greater than the early seats. The peak force of the high retention seats is 14.4 ± 3.7 kN (3,240 ± 830 lbs); this is 2.2 times that of the earlier designs.

**Table II** Comparison of high retention seats and earlier designs, including strength, energy transfer and stiffness (modified from Viano, 2003d)

<table>
<thead>
<tr>
<th></th>
<th>GM High Retention</th>
<th>GM Pre-HR</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td># Tests</td>
<td>27</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>H-point Moment (Nm)</td>
<td>2537 ± 703</td>
<td>1092 ± 189</td>
<td>132%</td>
</tr>
<tr>
<td>Angle @ 1700Nm(deg)</td>
<td>36 ± 13</td>
<td>56 ± 12</td>
<td>−35%</td>
</tr>
<tr>
<td>Energy @ 60 deg (J)</td>
<td>3659 ± 1140</td>
<td>1274 ± 390</td>
<td>187%</td>
</tr>
<tr>
<td>Peak Force (kN)</td>
<td>14.4 ± 3.7</td>
<td>6.6 ± 1.3</td>
<td>118%</td>
</tr>
<tr>
<td>Stiffness (N/mm)</td>
<td>25.3 ± 4.9</td>
<td>24.7 ± 4.9</td>
<td>2%</td>
</tr>
</tbody>
</table>
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