Role of the Seat in Rear Crash Safety
Other SAE titles of interest:

Vehicle Crash Mechanics
by Matthew Huang
(Order No. R-284)

Occupant Protection and Crashworthiness
Technology Collection on CD-ROM
(updated annually)

To obtain more information or to order this book, contact SAE at 400 Commonwealth Drive, Warrendale, PA 15096-0001; (724) 776-4970; fax (724) 776-0790; e-mail: publications@sae.org; website: www.sae.org/BOOKSTORE.
Role of the Seat in Rear Crash Safety

David C. Viano
All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

For permission and licensing requests, contact:

SAE Permissions
400 Commonwealth Drive
Warrendale, PA 15096-0001 USA
E-mail: permissions@sae.org
Fax: 724-772-4028
Tel: 724-772-4891

Library of Congress Cataloging-in-Publication Data

Viano, David C.
Role of the seat in rear crash safety / David C. Viano.
p. cm.
Includes bibliographical references and index.
ISBN 0-7680-0847-6

TL242.V5 2002
629.2'31--dc21
2002066955
CIP

Copyright 2002 Society of Automotive Engineers, Inc.

ISBN 0-7680-0847-6

SAE Order No. R-317

Printed in the United States of America.
Contents

Table of Contents ................................................................. v
Abbreviations and Acronyms .................................................... vii
Preface ................................................................ xi

Chapter 1  Significance of Rear Crash Injuries .......................... 1
Chapter 2  Head Restraint Position during Normal Driving: Implications to Neck Injury Risks in Rear Crashes ............... 21
Chapter 3  A New Procedure to Evaluate Occupant Interactions with the Seat in Rear Crashes: A Quasistatic Seat Test (QST) .... 35
Chapter 4  GMSEAT: A Computer Program to Evaluate Quasistatic Seat Tests (QST) .................................................. 89
Chapter 5  Role of the Seat in Rear Crash Safety ...................... 115
Chapter 6  Performance Criteria for Quasistatic Seat Tests (QST) and Head Restraint Placement ........................................... 199
Chapter 7  Performance Criteria for Free-Standing Rear Seats .... 219
Chapter 8  Ultra-High Retention Seat ...................................... 227
Chapter 9  Human Head, Neck, and Torso Responses to Pendulum Impacts on the Back ......................................................... 259
Chapter 10 Biofidelity of Rear Impact Dummies for Pendulum Impacts to the Back .............................................................. 285
Role of the Seat in Rear Crash Safety

Chapter 11  Self-Aligning Head Restraint (SAHR) System for Whiplash Prevention .............................................. 299

Chapter 12  The Effectiveness of SAHR Active Head Restraint in Preventing Whiplash ........................................... 347

Chapter 13  Energy Absorption Properties of Head Restraints ................................................................. 371

Chapter 14  Neck Biomechanical Responses with Active Head Restraint Systems: Rear Barrier Tests with BioRID and Sled Tests with Hybrid III ................................................................. 393

Chapter 15  Neck Displacements of Volunteers, BioRID P3, and Hybrid III in Rear Impacts: Implications to Whiplash Assessment by a Neck Displacement Criterion (NDC) .................................................. 427

Chapter 16  High Retention Seat Performance in Quasistatic Seat Tests ......................................................... 447

Index .................................................................................................................................................. 465

About the Author ............................................................................................................................. 491
ABBREVIATIONS AND ACRONYMS

AAAM Association for the Advancement of Automotive Medicine
ABTS All Belts to Seat, Integrated Lap-Shoulder Belt System in Seat
ATD Anthropomorphic Test Device, Dummy

B-plane Horizontal Plane through the Head cg of the 95% Seated Driver
BZ-plane Same as B-plane
BX-plane Vertical Plane 20 mm behind the Back of Head Ellipse of the 95% Seated Driver
BioRID Biofidelic Rear Impact Dummy Developed by a Swedish Consortium
BioRID P3 Latest Design of the BioRID Dummy
BioSID Biofidelic Side Impact Dummy

C3, C7 Third and Seventh Cervical Vertebrae in the Neck
cg Center of Gravity
CSF Cerebral Spinal Fluid

D QST Group of Domestic Production Seats
DOT U.S. Department of Transportation

EA Energy Absorption
ECE Economic Commission for Europe
EuroNCAP European New Car Assessment Program of Vehicle Crash Testing
EuroSID European Side Impact Dummy
Eyellipse Cluster of Eye Positions for Seated Drivers

FARS Fatal Accident Reporting System, U.S. Crash Fatality Database
F1, F2 Production Foreign Seats Grouped by Peak QST H-point Moment
Fx, Fz Neck Shear and Tension Forces, and Horizontal and Vertical Ram Load in QST
Flex Width Seat Design Incorporating a Perimeter Frame and Pelvic Catcher System
FMVSS U.S. Federal Motor Vehicle Safety Standard

G1, G2 Production GM Seats Grouped by Seat Type
GES General Estimates of U.S. Car Crashes and Injuries
GM General Motors Corporation
GMSEAT Software Program to Analyze QST Data

Harm Societal Cost of Injury Equal to the Product of Injury Severity and Cost/Severity
H-point Center of the Greater Trochanter, Center of the Pelvis
HEADREST Software Program to Analyze MTS Data on Head Restraint EA Properties
HR High Retention Seats That Meet QST Requirements
## Role of the Seat in Rear Crash Safety

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid III</td>
<td>Frontal Crash Test Dummy Defined in FMVSS 208 and EuroNCAP Testing</td>
</tr>
<tr>
<td>Hyge</td>
<td>Commercial Hydraulic Sled System Simulating High Acceleration Crashes</td>
</tr>
<tr>
<td>ICBC</td>
<td>Insurance Corporation of British Columbia, Canada (<a href="http://www.icbc.com">www.icbc.com</a>)</td>
</tr>
<tr>
<td>IIHS</td>
<td>Insurance Institute for Highway Safety (<a href="http://www.IIHS.org">www.IIHS.org</a>)</td>
</tr>
<tr>
<td>IRCOBI</td>
<td>International Research Council on the Biomechanics of Impact</td>
</tr>
<tr>
<td>ISC</td>
<td>Annual Automotive Safety and Crash Biomechanics Conference in Europe</td>
</tr>
<tr>
<td>L-Zone</td>
<td>Horizontal Lumbar Zone between the Top of the Pelvis and the Bottom of the Ischium</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low Density Polystyrene</td>
</tr>
<tr>
<td>LT</td>
<td>Long-Term Whiplash Injury Lasting &gt;10 Weeks</td>
</tr>
<tr>
<td>LTV</td>
<td>Light Trucks, Multi-purpose Passenger Vehicles, and Vans</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Variable Displacement Transducer</td>
</tr>
<tr>
<td>MTS</td>
<td>Hydraulic Material Testing Machine</td>
</tr>
<tr>
<td>My</td>
<td>Neck Extension Moment</td>
</tr>
<tr>
<td>MT</td>
<td>Medium-Term Whiplash Injury Lasting 1–10 Weeks</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NASS</td>
<td>U.S. National Accident Sampling System</td>
</tr>
<tr>
<td>NCAP</td>
<td>New Car Assessment Program Crash Test at 35 mph</td>
</tr>
<tr>
<td>NDC</td>
<td>Neck Displacement Criterion</td>
</tr>
<tr>
<td>NHTSA</td>
<td>U.S. National Highway Traffic Safety Administration</td>
</tr>
<tr>
<td>NIC</td>
<td>Neck Injury Criterion for Whiplash Assessment</td>
</tr>
<tr>
<td>OC</td>
<td>Occipital Condyles</td>
</tr>
<tr>
<td>OOP</td>
<td>Out-of-Position, Occupants Leaning Forward in the Seat</td>
</tr>
<tr>
<td>PS</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>QST</td>
<td>Quasistatic Seat Test, Subsystem Test of Dummy Loading a Seatback</td>
</tr>
<tr>
<td>RCAR</td>
<td>Research Council for Automotive Repair (<a href="http://www.RCAR.org">www.RCAR.org</a>)</td>
</tr>
<tr>
<td>RID</td>
<td>Rear Impact Dummy Neck</td>
</tr>
<tr>
<td>RID2</td>
<td>Rear Impact Dummy Under Development by a European Consortium</td>
</tr>
<tr>
<td>S-plane</td>
<td>Horizontal Plane at the Top of the Shoulder of the 95% Seated Driver</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SAHR</td>
<td>Self-Aligning Head Restraint or Saab Active Head Restraint</td>
</tr>
<tr>
<td>SgRP</td>
<td>Seating Reference Point</td>
</tr>
<tr>
<td>ST</td>
<td>Short-Term Whiplash Injury Lasting &lt;1 Week</td>
</tr>
<tr>
<td>v8</td>
<td></td>
</tr>
</tbody>
</table>
### Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stapp</td>
<td>U.S. Colonel John Paul Stapp Responsible for Human Tolerance Data, Annual Car Crash Conference in the U.S.</td>
</tr>
<tr>
<td>THOR</td>
<td>Advanced Frontal Impact Dummy</td>
</tr>
<tr>
<td>T1, T9</td>
<td>First and Ninth Thoracic Vertebrae</td>
</tr>
<tr>
<td>TrackEye</td>
<td>Computer Software to Automatically Track Points in High-Speed Video</td>
</tr>
<tr>
<td>TSL</td>
<td>Total Seat Lift</td>
</tr>
<tr>
<td>UHR</td>
<td>Ultra-High Retention Seat</td>
</tr>
<tr>
<td>UMTRI</td>
<td>University of Michigan Transportation Research Institute</td>
</tr>
<tr>
<td>USPTO</td>
<td>U.S. Patent and Trademark Office</td>
</tr>
<tr>
<td>VTS</td>
<td>Vehicle Technical Specification</td>
</tr>
<tr>
<td>WSU</td>
<td>Wayne State University, Detroit, MI</td>
</tr>
<tr>
<td>WSU 3-2-2-2</td>
<td>Nine Accelerometer Array to Measure Rotational Acceleration</td>
</tr>
<tr>
<td>2D, 3D</td>
<td>Two and Three Dimensions</td>
</tr>
</tbody>
</table>

\[
d\theta = \theta_0 + d\theta, \text{ or Neck Extension Angle Change Between the Occipital Condyles and T1.}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d\theta)</td>
<td>Seatback Angle Change from the Initial Recline Position</td>
</tr>
<tr>
<td>(\theta_0)</td>
<td>Initial Seatback Recline Angle from Vertical</td>
</tr>
<tr>
<td>(\theta)</td>
<td>(\theta = \theta_0 + d\theta), or Neck Extension Angle Change Between the Occipital Condyles and T1.</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>Ratio of the Specific Heat of Gas</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>Stress in kPa</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>Strain</td>
</tr>
<tr>
<td>(\dot{\varepsilon})</td>
<td>Strain Rate in 1/s</td>
</tr>
</tbody>
</table>
Early Seat Testing in Rear Impacts

My first involvement with seat testing was in 1980 when occupant kinematics were investigated in rear sled tests. The initial angle of the seatback was varied from $20^\circ$–$35^\circ$ to assess the potential influence of recline angle on occupant interactions with the seat for increasing speeds of rear crash. The tests demonstrated that the occupant was retained on the seat when the seatback angle was less than $60^\circ$ from vertical. When the angle rotated to more than $60^\circ$ in the test, the occupant ramped up and off the seat. At the time, I recall noting that the seats performed well, and energy was absorbed by progressive deformation of the recliner mechanism. These test results were published more than a decade later (Viano 1992a), as a basis for seat safety research in the 1990s.

A second series of the tests was conducted in 1980 with a lap-shoulder belted occupant in pure rear and oblique rear impacts. The belts improved occupant retention. Again, controlled deformation in the recliner absorbed energy and the yielding of the seatback provided force to gradually accelerate the occupant (Viano 1992b). The tests did not show a further need for investigation of seat performance at the time, and I went on to pursue other safety research in 1981.

Field Study of Belted Occupant Fatalities

In the mid-1980s, a field study of fatal crashes was conducted with belt-restrained, front seat occupants. The cases were made available by Motors Insurance Corporation, which gave a $10,000 insurance policy payout on the death of any passenger belted in a fatal crash. One aspect of the policy was that the cases would be made available for research on the cause and prevention of crash injuries. Each crash was thoroughly investigated, and there was a wealth of information on the pre-crash vehicle maneuvers and the crash circumstances (Viano, Ridella 1996a, 1996b, Ridella, Viano 1996).

Data from 144 fatalities in 123 crashes were available for the study of potential changes to improve the safety of belted occupants. Front airbags were judged to be the most important additional safety feature (Viano 1992c). However, there were a few cases of 4–6 o’clock impacts by heavy trucks where there was evidence of seatback twist and excursion of the driver toward the point of impact. Subsequent head impact with intruding surfaces was the
cause of death. These cases exposed one mode of injury by seatback twist and suggested a potential area for safety improvement.

**Seat Safety Research**

In late 1989, I returned to seat performance in rear crashes. I had been thinking about the rotation of the seatback as the occupant is accelerated forward in a crash. It was clear that the more severe the crash, the greater the acceleration of the occupant, and the greater the seatback deflection. This effect meant that the rotation of the seatback would increase with crash severity until the seatback angle exceeded 60° with a subsequent loss of occupant retention. In this case, even belted occupants can ramp up the seatback and slide out of the lap belt. This situation is related to the narrowing of the body from the pelvis to the knees and the initial slackening of the lap belt as the pelvis moves rearward in the crash.

I thought of ways to stabilize the seatback rotation in a rear crash and came up with an idea in 1990. The approach involved a normally slack cable that could be tightened by displacement of the seat pivot rearward and by rotation of the seatback in a severe rear crash (USPTO 1994). The cable provides load to resist seatback rotation. When the cable is connected to the seatback above the center of pressure of the occupant loading, there is a triangulation of loads, and the system is self-limiting. The greater the load by the occupant, the greater was the tension in the cables, and the greater the resistance to seatback rotation.

The Ultra-High Retention seat concept was pursued with the development of prototype hardware and testing in severe rear impacts. This work is described in Chapter 8. It showed that a cable can limit seatback rotation, but the approach required a complicated pivot mechanism and resulted in much higher internal loads on the seat frame.

A number of important observations were made about seat frame designs and occupant interactions. The first was the benefit in allowing a horizontal or dropping trajectory of the pelvis into the seatback. Another was the benefit of pocketing the pelvis in a compliant seatback design since this increased occupant retention. The research on this seat concept led to interactions with the seat business unit of General Motors, the Inland-Fisher-Guide Division (IFG).

**Collaboration with Inland-Fisher-Guide/Delphi Seating**

In late 1990, I changed focus to the study of conventional seats and formed a partnership with Mr. Richard (Dick) Neely at IFG to conduct research on the rear crash performance of front bucket seats. Our ambition was to develop a next generation of lightweight and low cost seats in what was termed a component-set strategy. This meant that one seat would provide the needs of a range of vehicles. Their approach was a Flex Width seat, which could have different widths to fit various vehicle installations, but otherwise common components.

Dick was the manager of advanced seats, and our interest coincided in benchmarking seat performance in rear crashes. I agreed to help them develop a next generation seat with
improved occupant retention in severe rear crashes and lower whiplash risks in low-speed impacts. I was well aware that rear crashes posed a low risk of fatal injury, but was motivated by the opportunity and challenge of the historic controversy on seat design principles for safety in rear crashes. This was the often-quoted conflict between “rigidized” and “yielding” seats in providing overall occupant protection in low- to high-speed rear crashes.

Our first work was to conduct a series of benchmark tests on production seats from various manufacturers. A 19.3 mph (31.1 km/h) rear crash sled severity was selected, and the dummy was unbelted in the tests. These tests demonstrated the ability of several top-end seats to retain an unbelted occupant on the seat in a severe rear crash. Similar tests on domestic seats showed that seatback rotation was typically greater than 60° and the occupant ramped up the seat.

Quasistatic Seat Testing (QST)

As new seat concepts were being considered, I started an effort at the General Motors (GM) Research and Development (R&D) Center to develop a subsystem test to evaluate occupant interactions with the seat in a rear crash. After considering the FMVSS 207 procedure with a point loading on the seat frame only, I felt that occupant loading was needed to reflect the real-world interactions that might occur, including seatback rotation and twist, occupant ramping and lateral displacement, and seat frame, trim, and suspension deformation.

The concept of a Quasistatic Seat Test (QST) was pursued late in 1991 through 1992. Various methods were considered to push the dummy into the seatback. Eventually, a contoured aluminum cylinder was pressed against the lumbar joint of the dummy and held in place by a stirrup bolted to the metal pelvic block. This approach allowed the upper body to rotate rearward when loaded into the seatback and the approach mimicked occupant kinematics observed in rear sled tests. This work is described in Chapter 3 and included a dummy loading into the seatback of a fully trimmed seat (USPTO 1995a). It is a destructive test, so all deformation modes of the seat are observed.

The same seats that were tested on the sled at high severity were evaluated in the QST procedure. The deformation modes of the seat frame and occupant interactions were compared. They showed remarkable similarity to that observed in the rear sled tests. The results were encouraging, that a new subsystem test could be used in the development of future seat hardware. The QST became the basis for refining the Flex Width seat, which was IFG’s main effort on a component-set seat frame. This seat was targeted for introduction in the 1997 Grand Prix. The QST determined the energy transfer capability of the seat and its weakest modes of deformation under occupant loading in high severity crashes.

Various transducers were used in the QST to evaluate seatback rotation and twist, occupant ramping and lateral displacement, loads at the seat base and applied by the occupant, and energy transfer capability. This information was put in a standard report. Several hundred QSTs were conducted and provided information on the performance of a wide range of seat types. As the test became a standard procedure to evaluate seats, a computer program was
developed to evaluate the transducer responses and provide a routine test report with all pertinent results. The program is called GMSEAT, and it is described in Chapter 4.

**Initial Whiplash Studies**

During this time, Dr. Martin Gargan joined the group as a surgical research fellow from the Royal College of Surgeons in the United Kingdom. His interest was whiplash, and we embarked on a field evaluation of head restraint placement during normal driving and sled testing to simulate the field conditions. A video was made available from the Insurance Institute for Highway Safety (IIHS) that was originally used to determine seatbelt wearing rates during normal driving. The video gave a clear vantage of the seating position and head restraint placement.

The video showed that a majority of drivers had not raised the adjustable head restraint to the most favorable height to prevent whiplash. It also showed a range of gaps behind the head. Eight categories of head restraint heights and gaps were used to sort the nearly 2000 cases. Sled tests were then conducted at 8, 12, and 16 mph (12.9, 19.3, and 25.8 km/h) to simulate the human response for the heights and gaps observed in the field study. The sled tests showed a threefold increase in neck extension as the head restraint height varied from high (above the ear) to low (below the chin), and a twofold increase in neck extension as the gap increased from small (<4") to large (>12"). This work is described in Chapter 2 and was published in *Accident Analysis and Prevention* (Viano, Gargan 1996).

**Perimeter Frame Seat**

The work with the Flex Width seat continued in two areas. One was the refinement of performance in severe rear crashes, and the other, the needs for head restraint placement for whiplash prevention in low-speed impacts. For the high severity crashes, several modifications were made in the typical seat frame designs of the late 1980s and early 1990s. These approaches were first used in the Ultra-High Retention seat concept and included a perimeter seat frame, open and compliant seatback suspension, low profile rear seat cushion frame, and a deformable, pelvic catcher strap. These approaches to seatback design allowed the occupant to displace between the side frames of the seatback by deformation of the seat suspension. This approach allowed a very strong seat frame to minimize seatback rotation and a yielding deformation of the suspension to gradually accelerate the occupant forward in a severe rear crash. It also enhanced retention by pocketing the pelvis and lower back and allowed the use of a strong seat frame with a yielding performance. These features are included in a U.S. patent granted on the perimeter frame seat design (USPTO 1996).

The perimeter frame and pelvic catcher approach proved to be one way to address the historic concerns for a rigidized seat. These included the potential for higher injury risks with a very strong seatback by rebound, out-of-position loading and neck extension causing whiplash. Sled tests were conducted from low to high severity rear delta V and with normal and out-of-position male and female Hybrid III dummies. This work is described in Chapter 5 and showed that a strong seatback could be developed with good performance in
all conditions. The seat exceeded the benchmark performance in reducing ramping and lowering whiplash responses, and was practical in mass and cost for volume production use.

The cooperation with IFG seating proved to be a unique and rewarding experience. With their emphasis on developing new seat systems and my ongoing research focus on occupant protection, there was genuine collaboration, resulting in innovative new concepts and solutions to the long-standing issues of seat design. For example, the Flex Width seat included many design features new to the industry, and the introduction of the 1997 Grand Prix saw a seat that was nearly three times stronger than its predecessor for occupant retention in rear crashes up to 22 mph (35.4 km/h) delta V, and it included a head restraint that was 3” higher and 2.5” more forward to reduce whiplash risks in low- to high-speed crashes. What was additionally remarkable was that the seat weighed less and cost less than the 1996 Grand Prix seat with comparable features. Much of this refinement was due to the QST test. The perimeter frame design introduced a high volume seat with improved rear crash safety. The seat exceeded the benchmark of the top-end group that was much more costly and heavier in achieving similar performance.

**Seat Performance Specifications**

As the seat development work led to a world-class product in terms of crash performance, weight, and cost, General Motors formed a task force to develop new seat specifications for all of its front seats. The QST became the central subsystem test to evaluate seat performance in rear crashes. The rationale for new seat specifications is described in Chapters 5 and 6. The specifications were approved in February 1995 and applied to all new seats introduced after 1997. Additional work was undertaken to expand the requirements for freestanding rear seats. This work is described in Chapter 7.

**Active Head Restraint**

The concept for an active head restraint was first considered in 1992 when thinking of countermeasures for the field situation that few drivers properly adjust their head restraints in normal driving. The Self-Aligning Head Restraint (SAHR) concept was a natural extension of the perimeter seat frame design and emphasis on using a compliant seatback that allowed occupant penetration between the side frames of the seatback. The concept for raising and moving the head restraint forward in a rear crash is covered in a U.S. patent (USPTO 1995b). The first prototype testing was undertaken in 1993.

The aim of the SAHR system was to provide better low-speed performance with the active head restraint in the down position than a standard head restraint in the high position above the head center of gravity (cg). The aim was to address the 90% of drivers who do not place the head restraint in the most favorable position to prevent whiplash. By increasing seatback compliance and raising and moving the head restraint forward early in a crash, the occupant’s neck gets earlier support, and the head develops a lower impact velocity with the head restraint. Also, the trajectory of the head restraint during loading is a critical factor in its performance. The intention of SAHR is to use the upward motion of the head restraint to
compensate for the normal downward trajectory due to rotation of the seatback in a rear crash. The design principles and development work on the SAHR active head restraint are described in Chapter 11.

The initial development work on the SAHR system aimed for implementation in the Flex Width seat, and Mladen Humer and Dick Neely from IFG provided the engineering development. The initial design used the upper cross-member of the seat frame as a fulcrum to slide and pivot the head restraint. The lower end of the head restraint posts was attached to a platen behind the occupant's upper back. A linkage and spring held the platen in place and guided the upper and forward movement of the head restraint when activated by occupant loading in a rear crash.

As the development testing showed favorable reductions in head extension and neck responses, Saab, a subsidiary of General Motors, became aware of the technology and showed interest in using it in its new seat planned for the Saab 9-5 in 1997. Delphi Interior (a renaming of the IFG Seat Division) developed a team to meet the program needs of the Saab platform, and development work was started on the Saab 9-5 prototype seatback. As the SAHR mechanism was integrated into the seat frame, there was considerable re-engineering of the seatback to allow occupant penetration and activation of the platen that rotates the head restraint upward and forward. The work was accomplished, and further development of the SAHR mechanism was pursued.

Initially, the SAHR work was conducted in the U.S., but as production intent hardware was being finalized, a Delphi team in Wuppertal, Germany, under the leadership of Jack Pikaart and Gerard Roose started to take over the final engineering and manufacturing work. Delphi eventually worked with Lear seating in Sweden for the final seat assembly of the SAHR seat. The system debuted in 1997, and it took on the name Saab Active Head Restraint (SAHR), keeping the original acronym. It was the first active head restraint system used in a production vehicle. Since then, other companies in the GM Group and other manufacturers have introduced the SAHR system.

While working on the SAHR introduction, a series of questions arose about the energy absorbing properties of the head restraint as part of the SAHR system performance. A subsystem test program was developed to benchmark the Energy Absorption (EA) properties of head restraints in use. This work led to design objectives for energy absorption by the foam and metal structures in the head restraint and its stiffness, which control head loading and rebound. This work is discussed in Chapter 13.

Rear Impact Biomechanics

During 1993, biomechanical work was undertaken with Wayne State University (WSU) to learn more about the human response to loading on the upper back. The whiplash testing showed that upper back and shoulder loading was the initiating factor for motion of the upper thoracic spine, particularly T1, and neck extension, loads and moments. The research on
human responses is described in Chapter 9 and was published in the journal, *Crash Prevention and Injury Control* (Viano, Hardy, King 2001).

During the mid-1990s, a consortium of Saab, Autoliv, Volvo, and Chalmers University in Sweden developed the BioRID dummy to evaluate occupant responses in low-speed rear crashes. A project was started to compare the BioRID P3 and Hybrid III dummies to the human response data collected at WSU. The biofidelity evaluations are described in Chapter 10, were presented in the AAAM conference (Linder et al. 2000), and will be published in the journal, *Traffic Injury Prevention* (Linder et al. 2002).

**Lightweight ABTS Seat and Lear's Purchase of Delphi Seating**

In 1994, attention shifted to All Belts to Seat (ABTS) designs, and a project was started with Delphi Interior to develop a lightweight ABTS seat. Various concepts were considered to integrate the belts into the seat and reach a lightweight frame. Since load limiting of the shoulder belt was being used to balance the restraint loads from the seatbelt and airbag in frontal crashes, approaches were considered that allowed a standard retractor to be installed in the seatback and the introduction of a load-limiting element outside of the belt retractor. A flexible tower was considered for the shoulder belt EA guide that allowed load limiting only in frontal and far-side oblique frontal crashes for the driver, and otherwise provided a fixed shoulder belt for near-side oblique frontal, rear, and rollover crashes. The concept received a U.S. patent (USPTO 1998).

Development tests were pursued and simulation work showed promise for the concept. This work was stopped in 1996, when GM sold the seat business unit of Delphi Interior to Lear Corporation. The sale involved all of the intellectual property on seating, including the SAHR active head restraint, Flex Width perimeter seat frame and pelvic catcher, QST procedure, Ultra-High Retention seat, and Ultra-Light ABTS seat patents. This also coincided with the closing of seat safety research between the GM R&D Center and Delphi Interior. Since then, cooperation has developed with Gerry Locke and Mladen Humer at Lear Seating in Southfield, Michigan.

**SAHR Field Effectiveness**

By the end of 2000, there was enough field crash data with the Saab 9-5 and 9-3 in Sweden to study the effectiveness of the SAHR active head restraint in rear crashes. The results are most favorable and are described in Chapter 12 (Viano, Olsen 2001 and Viano 2001). They give a warm feeling to everyone involved in the development of the first active head restraint system, and they prove the seat design concepts of a perimeter frame, seatback compliance with a stiff frame, and activation of the head restraint by occupant loading. These approaches reduce whiplash without compromising occupant retention in a severe rear crash.

Also in 2000, a rear-moving barrier study was conducted at Saab to evaluate vehicles with and without the SAHR active head restraint system. The tests involved the BioRID dummy and emphasized the Neck Injury Criterion (NIC) for whiplash assessment, which are being
considered by an international consortium of insurance companies (RCAR) for a consumer safety test and evaluation of vehicles. These tests demonstrated an inconsistency between the field performance statistics and NIC responses in the BioRID dummy.

A more in-depth evaluation of the results and complementary testing at Lear Corporation USA showed that head rotation and horizontal translation between the occipital condyles (OC) and T1 are meaningful responses related to whiplash performance. The NIC criterion was found to be an insufficient performance criterion because NIC is essentially determined prior to or just at head restraint contact, and it is not influenced by subsequent head restraint interactions. The tests also demonstrated deficiencies in both the Hybrid III and BioRID dummies in reflecting the essential biomechanical responses of the human in a low-speed rear crash. This work is described in Chapter 14 and may help lead RCAR and other consumer testing organizations to a meaningful, real-world, relevant assessment procedure for whiplash prevention in rear crashes. This was presented at the 2002 SAE Congress (Viano, Olsen, Locke, Humer 2002).

Human Volunteer Responses

An important need for consumer testing of whiplash is a meaningful injury criterion, test dummy, and assessment procedure. In Chapter 14, a Neck Displacement Criterion (NDC) is proposed based on dummy testing of various seats and head restraint systems in low-speed rear impacts. In Chapter 15, the voluntary range of neck motion was determined for 9.3 km/h rear sled tests of ten volunteers without head support. Data on the OC-T1 neck rotation and displacement were used to define the average and standard deviation in response and establish a corridor bounding the volunteer responses. The Hybrid III and BioRID dummies were compared to the average volunteer response, and initial performance targets are proposed using the corridors for the natural range of motion and inferences from Saab seat testing and field performance. That study was presented at a special Whiplash Workshop on October 9, 2001, as part of the IRCOBI Conference on the Isle of Man, and it will be published in the journal, *Traffic Injury Prevention* (Viano, Davidsson 2002).

High Retention Seat Performance in QST

The performance of seats was evaluated after 5 years of testing to the QST specifications for high retention (HR). This study is described in Chapter 16 and occurred in late 2001. Twenty different seat types were evaluated from the four primary seat suppliers. The results showed that seats have substantially increased in capability to retain an occupant in rear crashes. On average, there has been a 2.3-times increase in H-point moment and 2.9-times increase in energy transfer capability for the seats tested from 1998-2000 as compared to pre-HR designs of the late 1980s and early 1990s. This gives a calculated delta V performance to 42.5 km/h with seatback rotations below 60° using the 50th percentile Hybrid III male dummy, a 69% increase from the pre-HR performance. Importantly, the “yielding” behavior of the high retention seats is equivalent to the pre-HR designs, because the new generation of seats uses a perimeter frame seatback and low rear profile design that provides compliance to pocket the lower torso.
### Aim of the Book

A goal of the research in this book was to address the historic debate over seatback stiffness, energy absorbing yielding, occupant retention and whiplash prevention, and to provide a scientific foundation for the direction GM pursued in the development and validation of future seat designs. Those requirements and the development of seat innovations were the basis for a comprehensive study of the role of the seat in rear crash safety from 1990–1995 and follow-on studies through 2001 with Saab, Lear, and other research groups.

This book describes the multi-year research study into the role of the seat in rear crash safety. The first effort was to address the needs for occupant retention in the more severe rear crashes by energy management of the seat and uniform acceleration of the occupant forward. Then the needs for an adequately positioned head restraint and changes in the compliance of the seatback were addressed to lower the risks of the whiplash in low-speed crashes.

Over the years of the investigation into occupant protection by seat design, several new concepts were developed. For severe rear crashes, a perimeter seat frame concept was developed to improve occupant retention and energy transfer in volume produced seats (USPTO 1996). This concept was introduced on the market in the 1997 GM W-car and many subsequent models to improve retention of belted and unbelted occupants in severe rear crashes. This was a high retention seat that also included a much higher and more forward head restraint to support the head and neck. The perimeter seat frame and pelvic catcher seat in the 1997 Grand Prix received the following award:

**Perimeter Frame Seat Award**
1996 “Boss” Kettering Innovation award from General Motors, United States

For low-speed crashes, the active head restraint system, called SAHR (USPTO 1995b), was designed to prevent whiplash, irrespective of the initial position of the head restraint at the time of the crash. It was introduced as an industry first in the 1997 Saab 9-5, and then the Saab 9-3. The SAHR active head restraint system has received numerous international awards, including the following:

**SAHR Awards**
1996 Danish Association of Polio, Traffic and Accident Victims Special Prize
1997 Prince Michael Road Safety Award, Great Britain
1997 Windscreens O’Brien Safety Award, Australia’s Most Prestigious Safety Award
1998 “Boss” Kettering Innovation award from General Motors, United States
1999 Prince Bertil Traffic Safety Award, Sweden
2000 Whiplash Associate Disorder Insurance Award, British Columbia, Canada
2001 World Traffic Safety Achievement Award

Since the initial patent was granted for the SAHR active head restraint system in 1995, there have been more than 21 U.S. patents granted to 14 different companies on active head restraints for vehicles that build upon the basic principles in the SAHR patent. This demonstrates innovation and leadership in changing the technology available to improve the qual-
ity of life for the motoring public and reduce the risks for whiplash. The SAHR system has spawned many new safety approaches to seat design.

The 1999 GM LeSabre was the first introduction of the combination of a high retention seat and SAHR active head restraint. This package was called the "Catchers Mitt™" seat, and it has received the following awards:

SAHR and Perimeter Frame Seat (Catcher's Mitt™ Seat) Awards
1996 Body Innovation Award from the International Body Engineering Organization
1997 Design and Technology Award from Automotive and Transportation Interiors

Other innovative concepts were developed, but not introduced on the market, including an Ultra-High Retention seat (USPTO 1994) and Ultra-Light ABTS (USPTO 1998).

Each of the sixteen chapters included in the book was written as a stand-alone paper, so there is some redundancy in introductory materials, methodology, results, and discussion. It was felt that the original paper format should be preserved in the compilation of the research.

REFERENCES


