KINEMATICALLY BASED WHIPLASH INJURY CRITERION

Shashi Kuppa, James Saunders, Jason Stammen
National Highway Traffic Safety Administration
Ann Mallory
Transportation Research Center Inc.
U.S.A
05-0211

ABSTRACT

NHTSA recently published the final rule that upgrades the FMVSS No. 202 head restraint standard (69 FR 74848). The rule provides requirements that would make head restraints higher and closer to the head so as to engage the head early in the event of a rear impact. The rule also has provisions for a rear impact sled test option with a Hybrid III dummy that is intended in particular for active head restraints that do not meet the head restraint position requirements.

This paper presents a whiplash injury criterion for use with the Hybrid III dummy in rear impacts and its application in rear impact tests. The injury risk curve, based on the head-to-torso rotation of the Hybrid III dummy, was developed using insurance claims data, and rear impact sled tests with the Hybrid III dummy. The feasibility of the application of this injury criterion in rear impact vehicle crash tests and sled tests has also been presented. The sled test data indicates that the developed whiplash injury criterion correctly predicts improved performance of head restraint and seat systems in the field.

INTRODUCTION

NHTSA estimates that between 1988 and 1996, there were annually, 805,851 occupants in outboard seating positions of passenger cars, light trucks and vans who sustained whiplash injuries. The annual cost of these whiplash injuries was approximately $8.0 billion (Final Regulatory Impact Analysis for FMVSS No. 202 Head Restraints, NHTSA-2004 19807, No. 1 at http://dms.dot.gov). When insurance claims are considered, whiplash injuries account for 70 percent of all bodily injury claims, 43 percent of medical costs, and overall cost approaching 9 billion dollars (Viano, 2003).

NHTSA recently published the final rule that upgrades the FMVSS No. 202 head restraint standard (69 FR 74848). The rule provides requirements that would make head restraints higher and closer to the head so as to engage the head early in the event of a rear impact. The rule also has provisions for a rear impact sled test option with a Hybrid III dummy that is intended in particular for active head restraints that do not meet the static head restraint position requirements such as head restraint height and backset.

Though some studies suggest that the BioRID II and RID 2 are more biofidelic than the Hybrid III dummy in low speed rear crashes, they are still undergoing change and have not attained universal acceptance in the biomechanical community (Prasad, et al., 1997, Kim, et al., 2001, 2003). The Hybrid III dummy was found to successfully rank OEM seats according to their associated frequency of whiplash injury claims (Heitplatz et al., 2003). It was also found to be a good tool for the design of effective head restraints (Viano, 2001, 2003). Therefore, NHTSA decided on the use of the Hybrid III dummy for whiplash injury assessment in the optional dynamic sled test of the FMVSS No. 202 upgrade.

INJURY CRITERION TO ASSESS WHIPLASH INJURY IN FMVSS NO. 202 DYNAMIC TEST OPTION

The symptoms associated with whiplash injury include pain in the neck, shoulders, or upper back, vision disorder, dizziness, headaches, unconsciousness, and neurological symptoms in the upper extremities. These symptoms may be short term or long term. The term “whiplash” to describe these injuries is derived from the neck kinematics during a rear impact. Initially, the unsupported head lags behind the torso due to inertia (retraction) and then rotates backward, forcing the neck into extension.

Yang et al. (1996) hypothesized that the relative motion of the head with respect to the torso results in shearing action causing relative motion between adjacent vertebrae that may be pronounced in the lower cervical vertebrae where the facet angle is less steep. This may cause stretching of lower cervical vertebrae facet capsules beyond the normal physiological range, resulting in injury and pain. Lee et al. (2004) demonstrated a relationship between facet joint distraction and capsular ligament strain resulting from whiplash kinematics, and pain using an in vivo animal model.

The various symptoms resulting from whiplash injury lead to various hypotheses of the mechanisms of injury and as a consequence different injury criteria. A description of the various proposed whiplash injury mechanisms and criteria has been presented in a technical report (Kuppa, 2004) in support of the FMVSS No. 202 Final Rule.

Some studies have demonstrated that the neck forces and moments along with head and T1 accelerations of the Hybrid III dummy in low speed rear impacts may not exhibit very good biofidelity. Therefore, whiplash injury assessment using NIC (Bostrom et al., 1996, Svensson et al., 2000), Nij (FMVSS No. 208, 2000), or Nkm (Muser et al., 2000, Schmitt et al., 2001) with the Hybrid III dummy responses may not be adequate.

While there remains a lack of consensus on the underlying whiplash injury mechanism, many agree that limiting the relative head-to-torso motion may reduce the incidence of whiplash injuries (Viano, 2002, Yoganandan, 2000, Langweider, 2000). Sunderarajan et al. (2004) examined the effect of the head restraint position with respect to the head/neck on cervical facet stretch during low speed rear impacts with human post-mortem subjects. The study demonstrated that the maximum facet stretch was greater when the head-to-head restraint distance increased, suggesting an increase in whiplash injury potential.

Viano (2003a), using the Hybrid III dummy in rear impact sled tests, demonstrated that an increase in head-to-head restraint distance results in an increase in head-to-torso rotations of the Hybrid III dummy in rear impact sled tests. Therefore, head-to-torso rotation measurements on the Hybrid III dummy may be able to distinguish poor head restraint designs from the good designs. Tencer et al. (2003) found that a displacement based injury criterion was best suited to predict intervertebral displacements associated with whiplash injury. This further suggests that injury criteria based on relative head-to-torso motion of the Hybrid III dummy may be adequate in assessing whiplash injury risk.

Viano, et al. (2002) proposed the Neck Displacement Criteria (NDC) that rates seat and head restraint systems on the basis of the relative motion of the Hybrid III head with respect to its torso in rear impact tests. However, he did not associate the relative head motion with the risk of whiplash injury. One method of estimating whiplash injury risk as a function of Hybrid IIII dummy head/neck kinematics, is to relate whiplash injury risk for specific OEM seat systems in rear impact crashes in the field to Hybrid III neck kinematics in rear impact sled tests at different speeds with the same OEM seats.

Kuppa (2004) used whiplash injury claims data of the Saab 900 and Saab 9-3 along with corresponding rear impact sled tests with the Hybrid III dummy to develop a whiplash injury risk curve based on head-to-torso rotation of the Hybrid III dummy (Figure 1 and Equation 1). Though NDC developed by Viano (2002a) considers the head-to-torso rotation as well as the head-to-torso translation, Kuppa found the head-to-torso translation was highly correlated to the head-to-torso rotation (R^2=0.98) and so did not add any new information for evaluating whiplash potential of seat systems.

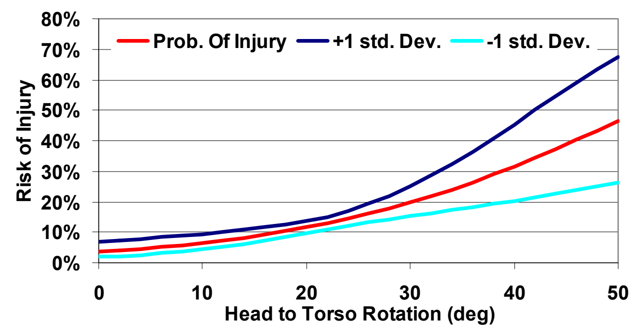

Figure 1. Risk of whiplash injury as a function of head-to-torso rotation of the 50th percentile adult male Hybrid III dummy in 16 km/h rear impact sled tests.

$$\textbf{prob. of whiplash injury} = \frac{1}{1 + e^{3.295 - 0.063\,\text{H/T rotation (deg)}}} \quad (1)$$

INSTRUMENTATION FOR MEASUREMENT OF HEAD-TO-TORSO ROTATION

The instrumentation used in rear impact tests to obtain head-to-torso rotation needs to be durable, allow unrestricted motion of the head and torso, and be lightweight and small so as not to change the dummy mass and inertial properties. NHTSA examined different instrumentation (accelerometers, electrogoniometers, gyro and magneto-hydrodynamic angular rate sensors) for obtaining head-to-torso rotations. In various research programs sponsored by NHTSA, magnetohydrodyanmic (MHD) angular rate sensors (ARS) were successfully employed for determining joint rotations. The MHD ARS are based on the principle that relative motion between a magnetic field and a conductive fluid produces an electropotential that is measured by the sensor (Laughlin, 1992).

MHD ARS were previously used to determine human foot position relative to the tibia during a plantar foot impact, position of the forearm relative to the upper arm during side air bag loading, and to determine neck extension angle during out-of-position airbag loading (Hall et al. 1997). The three dimensional position of a body segment with respect to another was determined by transforming the three-dimensional angular rates and linear accelerations into Eulerian space. The accuracy of the computed position and relative rotation was verified by demonstrating that the ARS results agreed to within 2 percent of ankle potentiometer data from an anthropomorphic crash test dummy (Hall et al., 1996). Tests on the spine and neck demonstrated that ARS was more accurate than photographic methods. Based on this prior experience for measuring joint motion, the dummy's head and torso was instrumented with Applied Technology Associates (ATA) magnetohydrodynamic (MHD) angular rate sensors (ARS).

Typical ATA ARS have low cross axis and linear acceleration sensitivity and have a bandwidth in the range of 1 Hz to 1000 Hz. The extremely broad frequency bandwidth capability enables the MHD rate sensors to measure high frequency and transient angular motions reasonably well.

The low frequency of the MHD angular rate sensors can be extended well below 0.1 Hz by use of digital filtering of the post processing of the measurement data. The compensation filter (Laughlin, 1998) is supplied by ATA (ATA- Sensors) and is specific to the MHD ARS used. Voo et al. (2003) employed ATA MHD ARS in rear impact sled tests and demonstrated that the head rotation obtained from the uncompensated angular rate signal underestimated the extension neck rotation and overestimated the flexion rotation in rear impact tests while the compensated signal matched that from video analysis reasonably well.

Voo et al. (2003) evaluated three different measurement methods for angular rotation of a dummy head and torso in a rear impact crash environment and found the compensated signals from the ATA MHD angular rate sensors yielded rotation data closely matching the results from high-speed video images to within 3 degrees with a total displacement range up to 110 degrees. Linear acceleration data generally yielded less accurate angular displacement results.

APPLICATION OF ANGULAR RATE SENSORS IN REAR IMPACT TESTS

Voo et al. (2003, 2004) and Kleinberger et al. (2003) conducted rear impact sled tests with the 50th percentile Hybrid III dummy in seats with different head restraint heights and seatback strength. The dummy, positioned in a seat in accordance to FMVSS No. 202, was restrained with the available lap/shoulder belts. The seatback was inclined to 25^{o} from the vertical and the dummy was positioned so that its H-point was aligned with the H-point of the seat (Figure 2).

The dummy was instrumented with tri-axial angular rate sensors at the center of gravity (CG) of the head and the dummy thorax. The ARS mounting cube could accommodate the linear accelerometers at the CG and was about the same mass as the existing accelerometer cube in the Hybrid III head. There was negligible change of the head mass and the head moment of inertia by replacing the existing mounting cube with the ARS cube at the CG of the head. Another ARS cube was attached to the spine box such that it had no effect on the dummy interaction with the seat back.

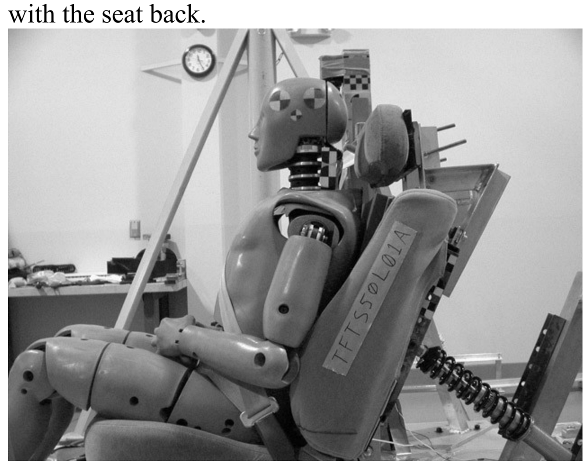

Figure 2. Instrumented Hybrid III dummy seated in a modified production seat.

Due to the symmetry of the dummy and the test condition, the head and torso rotated mainly in the sagittal plane. Therefore, rotational velocity data about the y-axis of the dummy provided reasonably good estimates of the rotation of the head and torso. The compensated angular rate signals along the y-axis at the head CG and the spine box were integrated (trapezoid integration) to obtain angular displacement of the head and the torso in degrees. The angular torso displacement was then subtracted from that of the head to obtain relative angular displacement (degrees) of the head with respect to the torso.

Sled tests were conducted using a sinusoidal sled pulse that fit within the FMVSS No. 202 dynamic test corridor with a nominal peak of 9 gs and duration of 90 milliseconds (Figure 3).

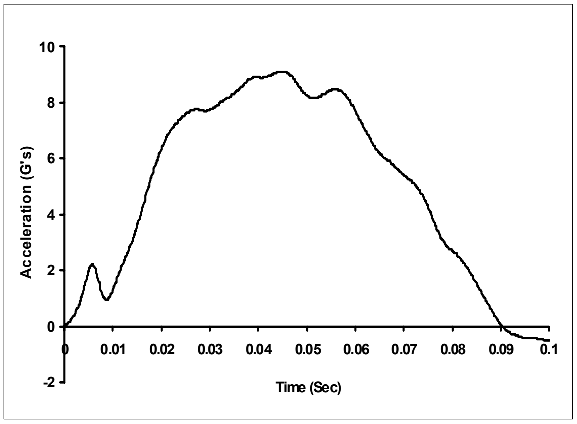

Figure 3. Sled pulse for rear impact tests complying with the FMVSS No. 202 specified sled pulse corridor.

Voo et al. (2003, 2004) and Kleinberger et al. (2003) found that the peak head-to-torso rotation of the dummy not only depended on the head restraint position (height and backset) but also on the rigidity of the head restraint, recliner stiffness and seat cushion stiffness. Seats with low recliner stiffness resulted in greater seat back rotation, later contact time of the head with the head restraint, and greater head and torso rotation. Sled tests with different types of head restraints suggested that a more rigid head restraint might have a protective advantage over a more flexible one in rear impacts. Kleinberger et al. (2003) also reported repeatable head and torso rotation values obtained from the ATA MHD angular rate signals.

NHTSA conducted 3 repeat FMVSS No. 301 type rear impact crash tests of a 2004 Jeep Liberty. The crash involved a flat barrier impacting a stationary vehicle in the rear at 30 mph. The average change in velocity of the Jeep Liberty was 26.4 km/h. The head restraint height from the H-point along the torso line was 836 mm and the backset was 85 mm (according to the measurement procedure in FMVSS No. 202 upgrade). While the head restraint height met the head restraint height requirement specified, it did not meet the backset requirement of 55 mm as per FMVSS No. 202 final rule.

The seat back was inclined to 25 degrees from vertical and along with the standard instrumentation on the Hybrid III 50th percentile male dummy, it was also instrumented with ATA MHD ARS-06 angular rate sensors at the CG of the dummy head and at the spine to obtain head-to-torso rotation.

The HIC15 values of the driver and passenger in the three tests were less than 100 and the coefficient of variance was 1.3 percent (Figure 4). The mean head-to-torso rotation in the three tests for the driver was 45 degrees while that for the rear passenger was 30 degrees. The coefficient of variation of head-to-torso rotation for the driver and rear passenger was less than 10 percent (Figure 4).

The sled test data from Kleinberger et al. (2003) and the vehicle crash tests suggest that the head-to-torso rotation obtained from MHD ARS are repeatable in sled and vehicle crash test environment.

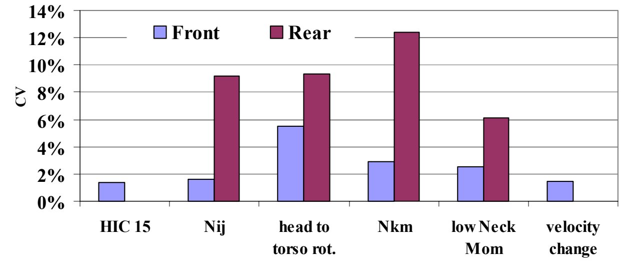

Figure 4. Coefficient of variation of injury measures from three repeat FMVSS 301 type rear impact tests with the Jeep Liberty.

VALIDATION OF HEAD-TO-TORSO ROTATION MEASUREMENT FOR WHIPLASH INJURY ASSESSMENT

Farmer et al. (2002) examined the effects of head restraint and seat redesign on neck injury risk in rear end crashes by examining automobile insurance claims. The results indicated that the improved geometric fit of head restraints observed in many newer vehicle models reduced the risk of whiplash injury. In particular, Farmer examined the improved geometry of the 2000-2001 Ford Taurus head restraints over that of the 1999 Ford Taurus. The 1999 Ford Taurus head restraint received a "poor" rating based on the IIHS evaluation procedure (IIHS, 2004) while the 2001 Ford Taurus received an "acceptable" rating. After controlling for the effect of crash severity, Farmer estimated an 18 percent effectiveness of the 2000-2001 Ford Taurus over that of the 1999 Ford Taurus in mitigating whiplash injuries.

Mallory and Stammen (2005) conducted low speed rear impact tests with the 50th percentile male Hybrid III dummy in 1999 and 2001 Ford Taurus seats. The objective of these tests was to investigate the ability of head-to-torso rotation and other whiplash injury criteria to distinguish the performance of the 1999 and 2001 Model year Ford Taurus in rear impacts in comparison to the relative effectiveness reported by Farmer et al. (2002).

Rear impact sled tests using sled pulses that were within the FMVSS 202 specified corridor were conducted with 1999 and 2001 Ford Taurus seats. The Hybrid III dummy was instrumented to measure head and T1 accelerations, as well as upper and lower neck loads. In addition, ATA MHD ARS-06 angular rate sensors were attached at the head CG and the dummy spine to measure head and torso angular rates. Head-to-head restraint contact time was determined using a contact switch on the head restraint and confirmed using high-speed video.

The neck injury measures Nij, Nkm, and NIC were computed as reported by Kleinberger et al. (2003). Nij, head-to-torso rotation, and corrected lower neck moments (moment at the base of the neck as per Prasad (1997)) were lower in the 2001 Taurus than the 1999 Taurus suggesting that all three injury measures correctly predict the improved effectiveness of the 2001 Taurus head restraint over that of the 1999 Taurus (Table 1). However, NIC and Nkm were higher for the 2001 Taurus than the 1999 Taurus suggesting a reverse trend from field observations.

Since the head-to-torso rotation injury measure has an associated whiplash injury risk curve, the relative effectiveness of the 2001 Taurus over the 1999 Taurus model can be developed using head-to-torso rotations obtained in tests with these two seats.

Table 1. Injury measures of the Hybrid III dummy in 1999 and 2001 Ford Taurus in FMVSS No. 202 type rear impact sled tests.

Injury Measure	1999 Taurus	2001 Taurus
HIC15	30.7	28.5
NIC (m^2/s^2)	19.5	23.9
Nij	0.21	0.08
Nkm	0.35	0.36
Head-to-torso rotation (deg)	38.1	29.5
Corr. Lower neck moment (Nm)	69.3	54.6
T1 accel. (gs)	10.8	12.1
Head to head rest. contact time (ms)	120.5	111.7
Upper neck shear force Fx (N)	302.2	264.7
Upper neck tension force Fz (N)	1038	489

The risk of whiplash injury estimated by head-to-torso rotation for the 1999 Taurus is 29 percent while that for the 2001 Taurus is 19.5 percent (obtained using Equation 1). The whiplash injury risk is 9.5 percent lower in the 2001 Taurus resulting in 33 percent improved effectiveness over the 1999 Taurus. The improved effectiveness of the 2001 Taurus seat over that of the 1999 Taurus seat estimated from the sled test data (Table 1) is higher than the 18 percent reported by Farmer (2004). This higher effectiveness in the sled tests may be related to the fact that the sled tests were conducted with the head restraints in the highest position while in the real world, adjustable head restrained are not always optimally positioned and many times left unadjusted in their lowest position (Lubin and Sehmer (1993)).

Figures 5 and 6 present the timing of the peaks of various measures along the head-to-torso rotation time-history. Peak chest acceleration and NIC occur early in the impact event, about the time of head-to-head restraint contact, while the peaks of Nij, upper and lower neck extension moment, Nkm occur closer to the time of peak head-to-torso rotation. Kuppa (2004) found that peak corrected lower neck extension moment of the Hybrid III dummy was correlated (R^2=0.96) to its head-to-torso rotation in rear impact sled tests. Figures 5 and 6 indicate that lower neck moment peaks a little earlier than peak head-to-torso rotation.

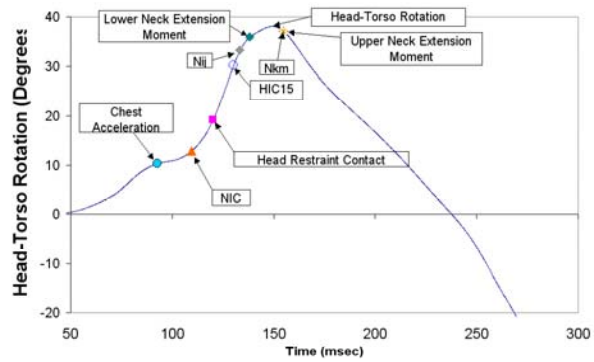

Figure 5. Relative timing of injury measures overlaid on the head-to-torso rotation time history curve in the rear impact test with the 1999 Ford Taurus

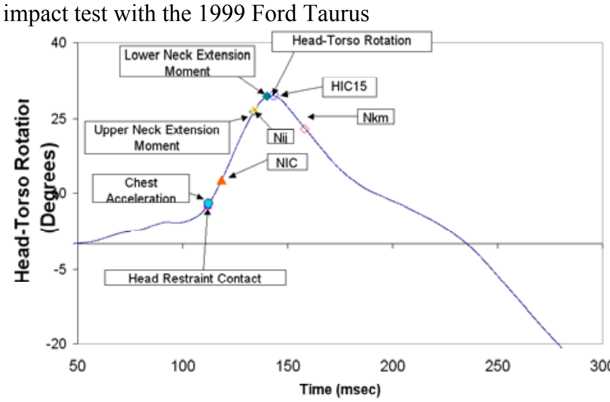

Figure 6. Relative timing of injury measures overlaid on the head-to-torso rotation time history curve in the rear impact test with the 2001 Ford Taurus

DISCUSSION

The head-to-torso rotation of the Hybrid III dummy, obtained from ATA MHD angular rate sensors, in rear impact sled tests and vehicle crash tests was found to be reasonably accurate and repeatable. This demonstrates the feasibility of head-to-torso rotation as a whiplash injury measure to evaluate head restraint/seat systems in the FMVSS No. 202 optional dynamic test.

Linder et al. (2004) conducted sled test reconstructions of real world rear impacts and correlated whiplash injury risk observed in the field to dummy measurements and various injury criteria. From the test data of 25 real world reconstructions using the BioRID II dummy, the researchers found NIC, Nkm, T1 acceleration, upper neck shear force (Fx) and axial force (Fz), and head-to-head restraint contact time to correlate well with whiplash injury risk. Linder proposed injury threshold levels for NIC of 16.7, Nkm of 0.37, T1 acceleration of 9.6 gs upper neck shear force (Fx) of 178 N and upper neck axial force (Fz) of 659 N that correspond to less than 10 percent of whiplash injury persisting for more than one month.

The Insurance Institute for Highway Safety (IIHS, 2004) recently released the International Insurance Whiplash Prevention Group (IIWPG) procedure for rating of seats and head restraints for neck injury prevention that is somewhat based on the Linder (2004) study. Seat systems that obtain a "good" or "acceptable" rating according to the IIHS geometric evaluation of their head restraints, are put through a dynamic rear impact sled test with the BioRID II dummy simulating a rear crash with a velocity change of 16 km/h. The evaluation is based on seat design parameters and test dummy response parameters. The seat design parameters are time to head restraint contact and maximum forward T1 acceleration that are classified into "pass" and "fail" categories. The test dummy response parameter is based on a vector sum of maximum upper neck tension and upper neck rearward shear force and is classified into "low", "moderate", and "high" neck force categories. The vector sum of neck tension and shear has no biomechanical interpretation but is merely a statistical interpretation of data obtained from dynamic sled tests of 102 seats with good static geometric ratings. The seat design and neck force classifications are combined, resulting in a dynamic rating of the seat ranging from "good" to "poor".

The sled pulse corridor specified in FMVSS No. 202 is similar to the IIWPG 16 km/h sled pulse. While FMVSS No. 202 employs head-to-torso rotation of the Hybrid III dummy to assess whiplash injury potential, the IIWPG uses head-to-head restraint contact time, maximum T1 acceleration, and a vector sum of upper neck tension and shear forces of the BioRID II to evaluate head restraint/seat systems.

The 2001 and the 1999 Taurus seats used in the Mallory et al. study (2005) did not meet the head restraint position requirements (at least 800 mm head restraint height along torso line above H-point and a backset no greater than 55 mm) of the FMVSS No. 202 Final Rule in 69 FR 74848 (Table 2). IIHS geometric head restraint rating for the 1999 and 2001 Taurus models was "poor" and "acceptable", respectively.

Table 2. Head restraint geometric position measurement according to that specified in FMVSS No. 202.

Vehicle	Horizontal (mm)		Vertical (mm)	
HR position	Down	Up	Down	Up
1999 Taurus	125	85	695	714
2001 Taurus	65	70	747	794

In the tests with the 1999 and 2001 model Ford Taurus, the head-to-torso rotations of 38.1 and 29.5 degrees (Table 1), respectively, were higher than the 12 degree limit specified in FMVSS No. 202.

The head-to-head restraint contact time of the 1999 and 2001 Taurus were greater than 70 msec and the peak T1 accelerations exceeded 9.5 gs (Table 1) resulting in the two Taurus models receiving a "fail" rating of the seat design criteria proposed by IIWPG. The maximum upper neck tensile force of 1038N and 489 N and the upper neck shear of 302 N and 265 N for the 1999 Taurus and the 2001 Taurus, respectively, give the two Taurus models a IIWPG neck force classification of "high". Though the IIWPG ratings are based on the BioRID II dummy measurements, the Hybrid III measurements applied to the IIWPG rating would give the 1999 and 2001 Ford Taurus an overall "poor" rating.

Mallory and Stammen (2005) also conduced low speed rear impact sled tests using the BioRID II dummy in 1999 and 2001 model year Ford Taurus seats. The sled pulses were identical to those used in the tests with the Hybrid III dummy in the Ford Taurus seats presented earlier in this paper. The injury measures in the tests with the BioRID II are presented in Table 3. In both the tests with the Ford Taurus seats, the T1 accelerations of the BioRID II exceeded 9.5 gs and the time to head restraint contact exceeded 70 ms. The measured upper neck shear and tensile force of the BioRID II are in the high force range of the IIWPG neck force classification. This results in an IIWPG rating of the 1999 and 2001 Ford Taurus of "poor".

The IIWPG procedure for rating seats and head restraints rated the 1999 and the 2001 Ford Taurus seats as "poor" when applied to the rear impact sled test data with the BioRID II as well as with the Hybrid III dummy.

Table 3. Injury measures of the BioRID II dummy in 1999 and 2001 Ford Taurus in FMVSS No. 202 type rear impact sled tests.

Injury Measure	1999 Taurus	2001 Taurus
HIC15	35.1	47.9
NIC (m^2/s^2)	36.9	40.1
Nij	0.39	0.13
Nkm	0.93	0.72
Head-to-torso rotation (deg)	18.4	2.6
Lower neck moment (Nm)	17.1	41.5
T1 accel. (gs)	12.3	14.4
Head to head rest. contact time (ms)	155.2	104
Upper neck shear force Fx (N)	609.8	364.8
Upper neck tension (N)	1090	716.7

This poor rating, along with the failure of both Taurus seats to meet the updated FMVSS No. 202 requirements suggest that though the 2001 Taurus demonstrated improved performance over the 1999 Taurus in mitigating whiplash injury, substantial improvements are still needed. IIHS also suggested the need for further improvement by giving the 2004-05 Ford Taurus head restraint and seat a "marginal" rating according to the IIWPG evaluation procedure.

CONCLUSIONS

This paper presents a kinematically based injury measure (head-to-torso rotation) to evaluate whiplash injury potential in rear impact tests using the Hybrid III 50th percentile male dummy. Head-to-torso rotation obtained from magnetohydrodynamic angular rate sensors in rear impact tests were found to be reasonably accurate and repeatable. Peak head-to-torso rotation of the HIII dummy in FMVSS No. 202 dynamic option sled tests was able to correctly rank the effectiveness of head restraint/seat systems according to their observed field effectiveness.

REFERENCES

ATA Sensors, "Extending the Frequency Response of the MHD Angular Rate Sensors," Application Note AN-01 Rev A, http://www.atasensors.com/Sensors2/application_note_an01_rev_a.htm.

Bostrom, O., et al., "A New Neck Injury Criterion Candidate Based on Injury Findings in the Cervical Spinal Ganglia After Experimental Neck Extension Trauma," Proceedings of the IRCOBI Conference, 1996.

Farmer, C., Wells, J., Lund, A., "Effects of Head Restraint and Seat Redesign on Neck Injury Risk in Rear-End Crashes," Report of Insurance Institute for Highway Safety, October, 2002.

Hall, G., Crandall, J., Klopp, G., Pilkey, W., "Angular Rate Sensor Joint Kinematics," Shock and Vibration, Vol. 4, pp. 223-229, 1997.

Hall, G., Crandall, J., Klisch, S., Klopp, G., Pilkey, W., "Measurement of Joint Motion Using Magnetohydrodynamic Angular Rate Sensors," Technical Note, Shock and Vibration Digest, 28(5), 1996.

Heitplatz, F., Sferco, R., Fay, P., Reim, J., Kim, A., Prasad, P., "An evaluation of Existing and Proposed Injury Criteria with Various Dummies to Determine their Ability to Predict the Levels of Soft Tissue Neck Injury Seen in Real World Accidents," 18th International Technical Conference on the Enhanced Safety of Vehicles, 2003.

Insurance Institute for Highway Safety (IIHS), "Procedure for Rating Seats/Head Restraints," http://www.hwysafety.org/vehicle%5Fratings/head%5Frestraints/head.htm, 2004.

Insurance Institute for Highway Safety (IIHS), "Rationale for IIWPG Ratings of Seats and Head Restraints for Neck Injury Prevention – International Insurance Whiplash Prevention Group," http://www.iihs.org/vehicle_ratings/iiwpg_rationale.pdf, December, 2004.

Kim, A., et al., "A Comparison of the Hybrid III and BioRID II Dummies in Low Severity, Rear Impact Sled Tests," Proceedings of the Forty-Fifth Stapp Car Crash Conference, Paper No. 01S-22, 2001.

Kim, A., Anderson, K., Berliner, J., Hassan, J., Jensen , J., Mertz, H., Pietsch, H., Rao, A., Scherer, R., Sutterfield, A. "Comparison Tests of BioRID II and RID 2 with Regard to Repeatability, Reproducibility and Sensitivity for Assessment of Car Seat Protection Potential in Rear-End Impacts, Stapp Car Crash Journal, Vol. 47, October, 2003.

Kleinberger, M., et al., "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems, NHTSA Docket 98-4405-9, U.S. DOT, Washington, D.C.

Kleinberger, M., Voo, L., Merkle, A., Bevan, M., Chang, S., "The Role of Seatback and head Restraint Design Parameters on Rear Impact Occupant Dynamics," 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan, 2003.

Kuppa, S., "Injury Criteria and Anthropomorphic Test Devices for Whiplash Injury Assessment," NHTSA Docket No. 19807, http://dmses.dot.gov/docimages/p80/313219.pdf.

Langweider, K., Hell, W., Schick, S., "Evolution of a Dynamic Seat Test Standard Proposal for a Better Protection After Rear End Impact," Proceedings of the International Conference on the Biomechanics of Impact, 2000.

Laughlin D., "A magnetohydrodynamic angular motion sensor for anthropomorphic test device instrumentation," Proceedings of the 33rd Stapp Car Crash Conference, Society of Automotive Engineers, Inc., Warrendale, PA, 1989.

Laughlin DA, "Digital Filtering for Improved Automotive Vehicle and Crash Testing with MHD Angular Sensors," Applied Technology Associates, 1998.

Lee, K., Davis, M., Mejilla, R., Winkelstein, B., "In Vivo Cervical Facet Capsule Distraction: Mechanical Implications for Whiplash and Neck Pain," Stapp Car Crash Journal, Vol. 48, pp. 373-396, November, 2004.

Linder, A., Avery, M., Kullgren, A., Krafft, M., "Real-World Rear Impacts Reconstructed in Sled Tests," Proceedings of the International Conference on the Biomechanics of Impact (IRCOBI), Graz, Austria, September 2004.

Lubin, S., and Sehmer, J., "Are Automobile Head Restraints Used Effectively?" Canadian Family Physician 39:1584-1588, 1993.

Mallory, A., Stammen, J., "Comparative Evaluation of Rear Impact Dummies – Static Seat Interaction and Dynamic Testing," NHTSA Docket No. 19807, 2005

Muser, M., Walz, F., Zellmer, H., "Biomechanical Significance of the Rebound Phase in Low Speed Rear End Impacts," Proceedings of IRCOBI Conference, 2000.

Prasad, P., Kim, A., Weerappuli, D., "Biofidelity of Anthropomorphic Test Devices for Rear Impact," Proceedings of the Forty-First Stapp Car Crash Conference, pp. 387-415, SAE Paper No. 973342, 1997.

Schmitt, K., Muser, M., Niederer, P., "A New Neck Injury Criterion Candidate for Rear-End Collisions Taking into Account Shear Forces and Bending Moments," 17th ESV Conference, Paper No. 124, 2001.

Sundararajan, S., Prasad, P., Demetropoulos, C., Tashman, S., Begeman, P., Yang, K., King, A., "Effect of Head-Neck Position on Cervical Facet Stretch of Post Mortem Human Subjects During Low Speed Rear-End Impacts," Stapp Car Crash Journal, Vol. 48, pp. 331-372, November, 2004.

Svensson, M., Bostrom, O., Davidsson, J., Hansson, H., et al., "Neck Injuries in Car Collisions – A Review Covering a Possible Injury Mechanism and the Development of a New Rear Impact Dummy," Accident Analysis and Prevention, 32: 167-175, 2000.

Tencer, A., Mirza, S., Huber, P., "A Comparison of Injury Criteria used in Evaluating Seats for Whiplash Protection," Traffic Injury Prevention,5:56-66, 2004.

Viano, D., Olsen, S., "The Effectiveness of Active Head Restraint in Preventing Whiplash," Journal of Trauma, 51: 959-969, 2001.

Viano, D., Davidsson, J., "Neck Displacements of Volunteers, BioRID P3 and Hybrid III in Rear Impacts: Implications to Whiplash Assessment by a Neck Displacement Criterion (NDC)," Traffic Injury Prevention, 3: 105-116, 2002.

Viano, D. C., "Role of the Seat in Rear Crash Safety," Society of Automotive Engineers, Inc., Warrendale, PA, 2003.

Voo, L., Merkle, A., Shin Sung, C., Kleinberger, M., "Comparison of Three Rotation Measurement Techniques in Rear Impact Application," Society of Automotive Engineer, Inc., Warrendale, PA, 2003.

Voo, L., Merkle, A., Wright, J., Kleinberger, M., "Effect of Head Restraint Rigidity on Whiplash Injury Risk," Society of Automotive Engineers Congress, 2004.

Yang, K. H., Begeman, P., Muser, M., Niederer, P., Walz, F., "On the Role of Cervical Facet Joints in Rear End Impact Neck Injury Mechanisms," SAE 970497, in Motor Vehicle Safety Design Innovations, 1997.

Yoganandan, N., Pintar, F., "Mechanics of Head Ache and Neck Pain in Whiplash, In: Eds. Yoganandan, N; Pintar, F.,: Frontiers in Whiplash Trauma, IOS Press, The Netherlands, ISBN 1 58603 012 4, pp. 173-185.