CORRELATING HUMAN AND FLEXIBLE DUMMY HEAD-NECK INJURY PERFORMANCE

Jacqueline G. Paver Ph.D.
Donald Friedman
Josh A. Jimenez
Center *for* Injury Research
United States

Paper Number 13-0282

ABSTRACT

The Center for Injury Research (C*f*IR) has developed methods to derive and correlate rollover dummy head-neck injury with NASS/CIREN data. In this paper, these methods are applied to other accident modes. Specifically, we investigated the application of the dummy rollover head-neck modifications, as well as structural injury risk, IARV, momentum exchange injury measures and criteria to frontal, offset and small overlap frontal and side impact testing.

Recently, NHTSA has implemented a comprehensive series of component regulations (FMVSS 126, FMVSS 216, FMVSS 226) [1-3] which, in combination, are intended to drastically reduce the number of crashes and occupant injury and fatalities in rollovers and other modes. However, the stiffness of the dummy neck and the disparity between IARV and momentum exchange injury measures were not addressed. We opine that injury and fatality rates are high because of poor dummy-to-human stiffness and substantially underestimated IARV injury criteria compared to consensus momentum exchange injury measures.

IIHS 40% offset and small overlap frontal and side impact tests were studied to observe the trajectory of the Hybrid III dummy head with production neck and evaluate injury measures. Then, the effect of substituting the production neck with the more flexible rollover neck was investigated. Estimates were made of the dummy head excursion, proximity of the head to vehicle structures at maximum excursion, the likelihood and severity of vehicle structure contact, and injury measures.
Results indicate that, while the flexible neck in a rollover increases head excursion by 3 inches when contacted at 7 mph, the frontal and side impact tests described here result in head contact with vehicle structures and exceed the rollover-developed AIS ≥3 momentum exchange injury criteria of the integrated bending moment (IBM) and single and double integration product of head resultant acceleration (HRA).

INTRODUCTION

This research has been addressing the rollover fatality problem for the last 12 years. The Department of Transportation (DOT) and the automobile industry have been addressing the total fatality problem since DOT's inception with the Traffic Safety Act of 1966. Some insight into the misrepresentations that delayed progress in reducing rollover fatalities and injuries has been documented. [4-13]. Although the size of the passenger vehicle fleet has increased substantially, the second author's research as a major contractor to the DOT from 1968 to 1985 had forecast much more substantial progress in reducing fatalities. One reason may be that the accident analysis of the NHTSA/Minicars Research Safety Vehicle (RSV) required passive protection airbag performance in a 30° angled impact mode. Many of today's supplemental restraint system airbags are too small to affect the trajectory or protect the head in such a test.

This introduction describes the highlights of the previously-reported [14] methodology used in addressing the rollover fatality and permanently-debilitating head-neck injury problem. The methodology section describes how the flexible rollover neck [15] research can be used to address the even larger problem of fatal and catastrophic head and neck injuries in frontal and side impacts.

Identifying the Problem

Figure 1 illustrates the magnitude of the U.S. rollover tragedy. From the inception of the Fatal Accident Reporting System (FARS) in 1978 until 2008 [16], more than 1,350,000 occupants were killed in all of the vehicle crash modes, of which almost 318,000 lives were lost in rollover crashes alone.

Accident Year	Rollover Fatalities	Total Fatalities	Accident Year	Rollover Fatalities	Total Fatalities
1978	10,340	50,331	1994	9,472	40,716
1979	10,674	51,093	1995	9,991	41,817
1980	11,137	51,091	1996	10,096	42,065
1981	10,663	49,301	1997	10,068	42,013
1982	9,038	43,945	1998	10,334	41,501
1983	8,959	42,589	1999	10,701	41,717
1984	9,294	44,257	2000	10,530	41,945
1985	9,028	43,825	2001	10,684	42,196
1986	10,181	46,087	2002	11,309	43,005
1987	10,452	46,390	2003	11,050	42,884
1988	10,772	47,087	2004	11,210	42,836
1989	10,263	45,582	2005	11,505	43,510
1990	10,163	44,599	2006	11,417	42,708
1991	9,797	41,508	2007	10,938	41,259
1992	9,097	39,250	2008	9,628	37,261
1993	9,026	40,150	Total	317,817	1,354,518

Figure 1. FARS fatalities from 1978 to 2008.

Development of Rollover Injury Risk Based on Vehicle Structural Performance

In 2008, the IIHS published data on 22,000 SUV's involved in rollover crashes with incapacitating injuries [17]. Results indicated that the injury rate was reduced by 25% for each increment of vehicle strength-to-weight ratio (SWR) from SWR 2 to 3. The IIHS also derived a relationship between window breakage in rollovers, described in terms of ejection rate, and SWR. The IIHS reported that ejection rate decreased with increasing vehicle SWR .

At approximately the same time, a compilation of JRS and other rollover tests confirmed their results. C*f*IR defined the following momentum exchange dummy measures:

- a momentum exchange function, called the Integrated Bending Moment (IBM), and
- single and double integration product of head resultant acceleration (HRA).

Figure 2 is a composite plot of structural injury risk and momentum exchange injury measures showing rate reduction with increasing SWR. Results show that these parameters correlated with residual crush at an IBM value of 13.5 and a HRA exceeding a criteria of 48.

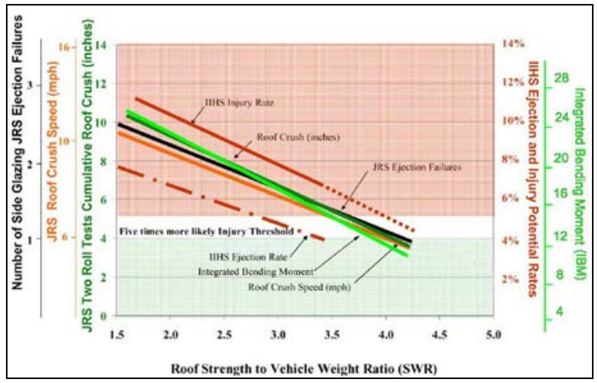

Figure 2. Composite plot of injury measures showing rate reduction with increasing vehicle SWR.

In 2008, NHTSA confirmed a NASS statistical analysis indicating that, in rollover crashes, vehicles with post-crash negative headroom (more roof crush than original headroom) were 5 times more likely to be injurious (at any level of injury) than vehicles with post-crash positive headroom **[**18]. Figure 3 is a plot of positive and negative post-crash headroom as a function of vehicle SWR in JRS rollover tests.

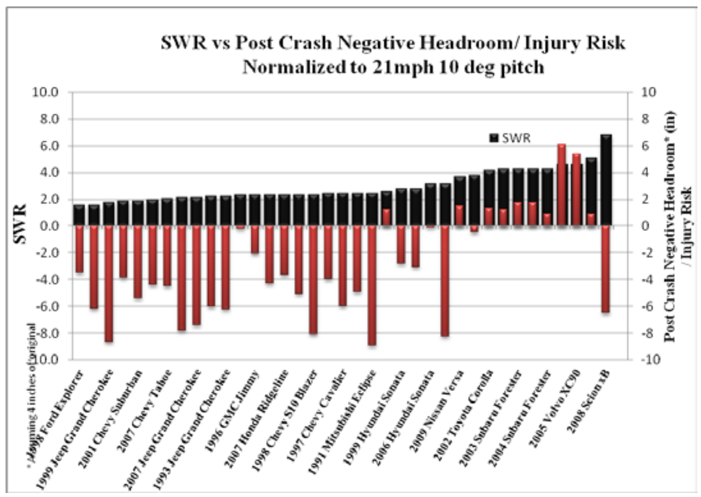

Figure 3. Post-crash positive and negative headroom in order of ascending vehicle SWR.

In 2009, a statistical analysis of NASS and CIREN files [19] evaluated the probability and odds ratio of rollover fatalities and head, spine and spinal cord injury as a function of vehicle residual crush. For residual crush in bands of 0 to 3½, 3½ to 6, 6 to 12 and 12 inches and above, the corresponding ratings in order are "good," "acceptable" and "poor." The "acceptable" probability is roughly 30% greater than "good" and the probability of "poor" is 2.5 times greater than "acceptable."

Figure 4, the fatality probability chart, shows increasing probability of fatality with increasing vehicle residual crush.

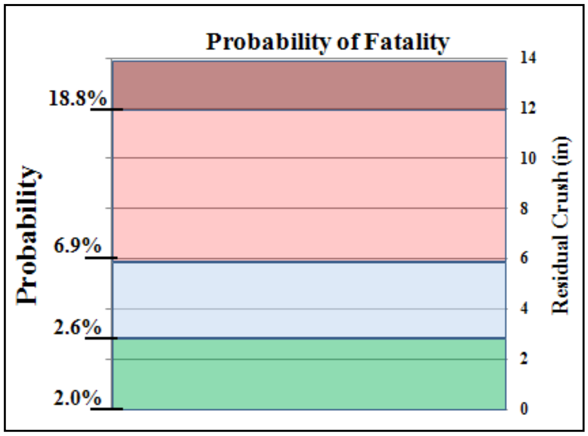

Figure 4. A fatal probability function vs. residual crush.

The following structural injury risk measures were identified in previously-published analyses of more than 50 JRS dynamic rollover tests: SWR, major radius (MR) at the A-pillar, structural roof elasticity, impact angle, pitch and/or yaw [20]. These dynamic tests also identified vehicles with grossly underestimated injury potential based on static roof strength tests alone. Figure 5 shows residual crush, normalized to a single test protocol, plotted on the fatality risk chart to 12 inches of residual crush of Figure 4.

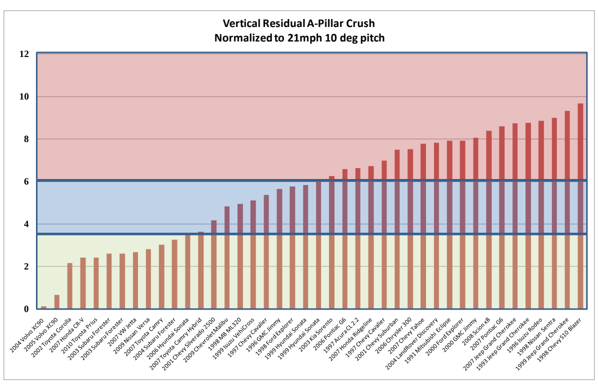

Figure 5. Residual crush normalized to 21 mph and 270° roll rate.

Development of a Prototype Flexible Rollover Dummy Neck, Measures and Criteria

An investigation of the stiffness and orientation of the production Hybrid III neck revealed that it was not representative of the current population of vehicle occupants. [21] The dummy neck stiffness and orientation were modeled from volunteer tests of young military personnel in the early 1960's. In these tests, volunteers were instructed to resist rotation of the head during substantial inertial forward acceleration.

We determined that the dummy neck in a rollover test should be more flexible (i.e., the stiffness of the production Hybrid III dummy neck is 10 times the normal untensed neck) and should be inclined 30° in flexion to compensate for its lack of lordosis (i.e., the production Hybrid III dummy neck is axially-aligned).

A matched-pair of 1998 Ford Explorer tests were performed. In one of the tests, the production Hybrid III dummy neck was preflexed 30° forward. Results demonstrated reductions in dummy injury measures with the preflexed neck.

Humanetics ATD fabricated a prototype "flexible" rollover neck. Its stiffness was equal to about 30% of the production neck. The lower neck mounting brackets flexed the neck 30° forward.

C*f*IR conducted experiments comparing the head excursion of the production and prototype flexible rollover neck under identical test conditions. The results at 10 and 15 mph, shown in Figure 6, demonstrate increased head excursion with increasing impact speed. At 15 mph, the flexible neck moved forward about 4 inches farther than the production neck.

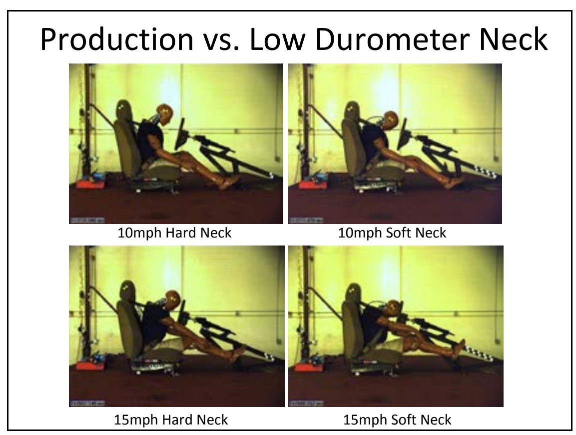

Figure 6. Comparison of the production and prototype flexible rollover neck at maximum head excursion.

The IARV injury criteria were recalibrated relative to the production neck. In tests with either neck, there was no correlation between injury risk, described by residual crush, and injury measures, described by IARV. The only consensus injury measures were roof crush and roof crush speed based on criteria developed by McElhaney [22]. Figure 7 is a map of those injury measures.

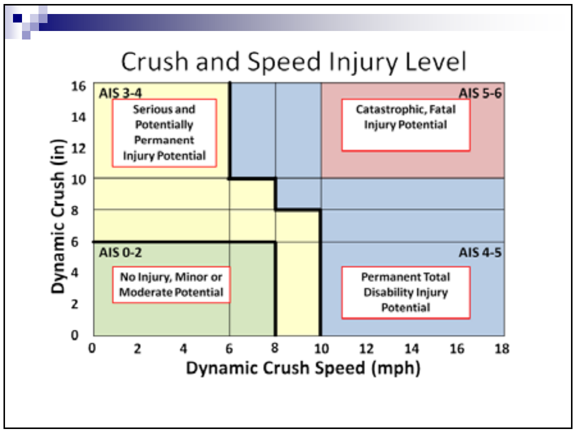

Figure 7. Consensus injury criteria map of dynamic crush injury risk criteria.

The following structural injury risk and dummy injury measure criteria were evaluated:

- the structural injury risk performance measures of the elastically-corrected residual crush and the product of roof crush and crush speed,
- the adjusted IARV lower neck Fz and My, and
- the dummy momentum exchange injury measures of dummy IBM and HRA.

Each was normalized to its AIS ≥ 3 reference value. For each JRS rollover test, the percentage of structural injury risk and dummy measure criteria were determined and compared. Results for the 2009 Ford F-150 are illustrated in Figure 8.

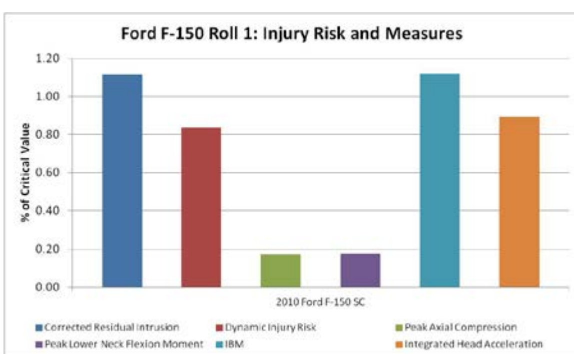

Figure 8. Injury risk, IARV and momentum exchange test results of the 2009 Ford F-150.

METHODS

In 2000, regulatory frontal occupant crash protection testing was modified for vehicles equipped with advanced airbags. In 2010, IIHS compared the performance of vehicles equipped with advanced airbags to vehicles with 1st-generation airbags. Surprisingly, IIHS found a 15% increase in fatalities with advanced airbags [23].

The accident analysis of the NHTSA/Minicars RSV required passive protection airbag performance in a 30° angled impact mode [24]. This requirement was based on the yearly societal costs of injuries and fatalities as a function of vehicle damage areas and deltaV from the MDAI and ACIR files shown in Figure 9.

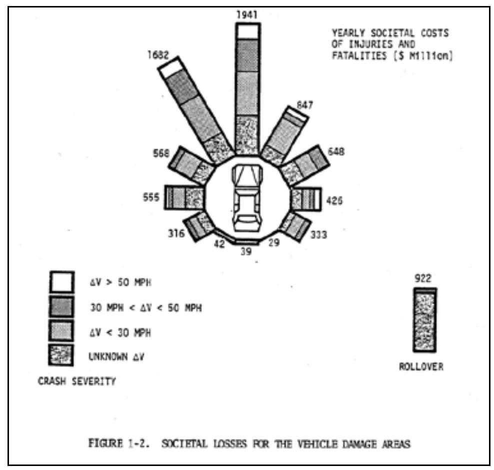

Figure 9. Societal losses as a function of deltaV and vehicle damage areas.

In motor vehicle crashes, the Principal Direction of Force (PDOF) dictates an occupant's kinematic trajectory. Supplemental restraint system airbags are not designed to cushion the head at PDOF angles greater than 9°. Most of today's supplemental restraint system airbags are too small to affect the trajectory or protect the head in such a test. Rather, the head is deflected laterally by the deploying airbag.

In this paper, the following test modes were studied.

- Frontal 30° angled barrier test PDOF~9° [25],
- IIHS 40 mph 40% offset deformable barrier test PDOF~15°,
- IIHS 40 mph 25% small overlap deformable barrier test PDOF~20°,
- Angled impact test (of Figure 7) PDOF~30° [26].

The trajectory of the Hybrid III dummy head with production neck was observed and injury measures were evaluated. Then, the effect of substituting the production neck with the more flexible rollover neck was investigated. Estimates were made of the dummy head excursion, proximity of the head to vehicle structures at maximum excursion, the likelihood and severity of vehicle structure contact, and injury measures.

RESULTS

Figures 10 and 11 shows the dummy head near the A-pillar in the IIHS small (25%) overlap frontal tests at 40 mph.

Figure 10. IIHS 2012 Kia Soul small (25%) overlap test at 40 mph at maximum head excursion.

Figure 11. IIHS 2012 Acura TSX small (25%) overlap test at 40 mph at maximum head excursion.

Figures 12 and 13 shows videotape frames from IIHS 40% offset frontal tests of a 1996 (top) and 1999 (bottom) Hyundai Sonata into a deformable barrier at 40 mph.

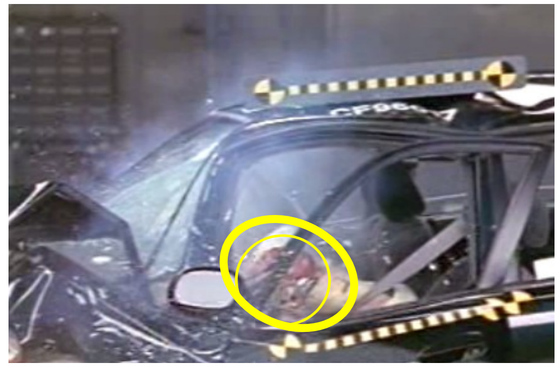

Figure 12. IIHS 1996 Hyundai Sonata (40%) offset frontal test at 40 mph at maximum head excursion.

Figure 13. IIHS 1999 Hyundai Sonata (40%) offset frontal test at 40 mph at maximum head excursion.

The frames in Figures 13 and 14 show that the head was deflected by the airbag. The proximity of the head at maximum excursion was about 4 inches and 1 inch from internal 1996 and 1999 vehicle component structures, respectively.

In the IIHS small (25%) overlap tests at 40 mph, the dummy head is not as close to the A-pillar as in the frontal offset tests despite the PDOF and the deflection off the airbag because of the substantially-reduced deltaV. If a test had been run with the 30° angled impact requirement of the RSV, the head would have contacted the A-pillar because the airbag effects are less.

Figure 14 is a frame from an IIHS side impact of a 2006 Crown Victoria without airbags at 30 mph.

Figure 14. IIHS 2006 Crown Victoria side impact test (no airbags) at maximum head excursion.

Results indicate that, while the flexible neck in a rollover increases head excursion by 3 inches when contacted at 7 mph, the frontal and side impact tests described here result in head contact with vehicle structures and exceed the rollover-developed AIS ≥3 momentum exchange injury criteria of the IBM and HRA.

DISCUSSION

Frontal airbags were mandated and implemented in passenger cars in 1995. However, NHTSA estimates less than a 20% savings of lives by airbags in frontal impacts compared to the number of lives lost. With required supplemental restraint systems and a greater than 80% belt usage, we expect a greater reduction than 20%. The fact that vehicle safety design is based on testing with the production Hybrid III neck (and its limitations) and IARV injury criteria that underestimate human injury by a factor of two explain, in part, this disparity. The next step in this research is to conduct sled tests at various PDOF angles with both the Hybrid III production and the prototype flexible rollover neck to measure and validate our estimates of head excursion, IARV, structural injury risk, and momentum exchange injury measures.

LIMITATIONS

These studies are based on estimates of head excursion from videotapes recorded by the IIHS. The estimates of head excursion with the substitution of the prototype flexible rollover neck are judgments indicative of the authors' broad experience with frontal and side impact research and regulatory test performance. The difference in IARV and momentum exchange injury measures were experimentally-validated and published previously.

CONCLUSIONS

- The Hybrid III dummy production neck is not representative of the injury population.
- IARV does not represent human injury potential and underestimates it by 50% or more.
- Head-neck inclination and neck stiffness has a significant effect on injury and fatality potential in all accident modes.
- Vehicle occupant protection systems designed and rated using the production Hybrid III dummy may be the principal cause of high death and injury rates.

ACKNOWLEDGEMENTS

The IIHS has graciously provided access to their testing results and videos and given permission to publish the video frames contained in this paper.

REFERENCES

[1] U.S. Department of Transportation, Final Rule FMVSS 126, 4-6-2007.
[2] U.S. Department of Transportation, Federal Register Final Rule FMVSS 216, Vol. 74, No. 90, 5-12-2009.
[3] U.S. Department of Transportation, Federal Register Final Rule FMVSS 226, Vol. 76, No. 12, 1-19-2011.
[4] Federal Register, "Roof Intrusion Protection for Passenger Cars - Proposed Motor Vehicle Safety Standard 216." Docket #2-6; Notice 4, 1-6-1971
[5] "Fisher Body Test Report, Body-Static Roof Intrusion Tests - 1970 and 1971 F, H, A, X, and B Styles." March 1971.
[6] "The National Archives – Conversation Among President Nixon, Lide Anthony Iacocca, Henry Ford II, and John D. Ehrlichman." April 1971.
[7] Orlowski, K.F, R T Bundorf, E A Moffatt, "Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics," Society of Automotive Engineers, Paper No. 851734, 1985.
[8] Bahling, G.S. , R.T. Bundorf, G.S. Kaspzyk, E.A. Moffatt, K. F. Orlowski and J.E. Stocke, "Rollover and Drop Tests – The Influence of Roof Strength on Injury Mechanics Using Belted Dummies," Society of Automotive Engineers, Paper No. 902314, 1990.
[9] Moffat, E.A., J. Padmanaban, "The Relationship Between Roof Strength and Occupant Injury in Rollover Accident Data," Report No. FaAA-SF-R-95-05-37, May 1995.
[10] Moffat, E.A., et al., "Matched-Pair Rollover Impacts of Rollcaged and Production Roof Cars

Using the Controlled Rollover Impact System (CRIS)," SAE, 2003.
[11] R.W. Nightingale, J.H. McElhaney, D.L. Camacho, M Kleinberger, B.A. Winkelstein, B.S. Myers, “The Dynamic Responses of the Cervical Spine: Buckling, End Conditions, and Tolerance in Compressive Impacts,” Society of Automotive Engineers, Paper No. 973344, 1997.
[12] J.G. Paver and D Friedman, “Is BFD a Hyperflexion Injury or Compression with Localized Bending Injury or Both?” International Crashworthiness Conference 2012, Milano, Italy. 2012. Paper No. 2012-111.
[13] B.L. Allen, et al., "A Mechanistic Classification of Closed, Indirect Fractures, and Dislocations of the Lower Cervical Spine," Philadelphia, PA, 1982.
[14] Friedman, D., Rico, D., Mattos,G.,Paver, J. PhD., “Predicting and Verifying Dynamic Occupant Protection”, ESV Conference, Paper 11-0090, June 2011, Washington DC
[15] Ibid.
[16] Fatality Analysis Reporting System Database www-fars.nhtsa.dot.gov
[17] Brumbelow, M., E.R. Teoh, D.S. Zuby and A.T. McCart, “Roof Strength and Injury Risk in Rollover Crashes,” Insurance Institute for Highway Safety, March 2008.
[18] Strashny, A., ‘The Role of Vertical Roof Intrusion and Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face during FMVSS No. 216 Rollovers: An Updated Analysis”, DOT HS 810 847 4, October 2007.
[19] Mandell, S., R. Kaufman, C.D. Mack and E.M. Bulger. 2010. "Mortality and Injury Patterns Associated with Roof Crush in Rollover Crashes." Accident Analysis and Prevention, 2010, 10.1016/j.aap.2010.02.013.
[20] Friedman, D., J. Paver and R. McGuan, “Design, Development and Validation of Rollover Dummy Injury Measures,” International Crashworthiness Conference, Milano, Italy 2012.
[21]Paver, J., D Friedman, J Caplinger, “Rollover Crash Neck Replication and Injury Potential Assessment”, International IRCOBI Conference on the Biomechanics of Injury, Bern, Switzerland: 2008.
[22] McElhaney, J., R. Snyder, J. States, M.A. Gabrielsen, “Biomechanical Analysis of Swimming Pool Neck Injuries,” Society of Automotive Engineers, Inc., 1979.
[23] IIHS Status Report, “Airbags Have Evolved”, Vol. 45. No. 1, Feb 6, 2010
[24] Ausherman, V.K, Khadilkar, A.V, Syson, S.R., Strother, C.E., Struble, D.E., ”Technical Final Report, The Minicars Research Safety Vehicle Program”, September 1981 RSV Paper.
[25] Friedman, D., “Subcompact Car Crashworthiness,” Transportation Research Board, January, 1975.
[26] Insurance Institute for Highway Safety: www.iihs.