COMPARISON OF BIORID INJURY CRITERIA BETWEEN DYNAMIC SLED TESTS AND VEHICLE CRASH TESTS

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Paper No. 11-0235

ABSTRACT

The Insurance Institute for Highway Safety rates vehicle seat/head restraint designs as good, acceptable, marginal, or poor using a protocol by the Research Council for Automobile Repairs' International Insurance Whiplash Prevention Group (RCAR/ IIWPG). Studies of insurance neck injury claim rates for rear impact crashes show that vehicles with seats rated good have lower claim rates than vehicles with seats rated poor, but the relationship between acceptable/marginal ratings and claim rates is less clear.

To better understand the relationship between measured neck injury criteria and injury claim rates, a series of rear impact crash tests was conducted to determine the influence of crash pulse, as dictated by vehicle structure, on the performance of seat/head restraints. The role of head restraint adjustment also was examined by comparing BioRID responses in the driver position, with the restraint adjusted according to the RCAR/ IIWPG protocol, and in the front passenger position, with the restraint adjusted to its lowest position. In an attempt to match the severity of the RCAR/IIWPG crash pulse, vehicles were struck by a flat rigid barrier to create a velocity change of 16 km/h (10 mi/h).

Four small cars with rated seat/head restraints and varying real-world neck injury claim rates were selected. The 2006 Honda Civic and 2005 Chevrolet Cobalt both received good ratings in the RCAR/ IIWPG sled test, but the Civic had a relatively low neck injury claim rate compared with the Cobalt. The 2006 Saturn Ion and 2005 Ford Focus both received marginal ratings in the sled test, but the neck injury claim rate for the Ion was comparable with that for the good-rated Civic, and the Focus had the highest neck injury claim rate among the vehicles tested.

BioRID response ratings for the driver position matched the sled test ratings for the Cobalt and Focus but were one rating level lower for the Civic and Ion. BioRID response ratings for the passenger position were the same as those for the driver position for all vehicles except the Cobalt, which was one rating level lower. The findings suggest that changing the RCAR/ IIWPG protocol to include vehicle specific crash pulses and/or changing the restraint setup would not improve the relationship between seat/head restraint ratings and neck injury claim rates. Furthermore, examination of additional BioRID injury metrics not currently assessed under the protocol does not help explain real-world neck injury claim rates and does not support changing the current evaluation criteria. Additional research is needed to determine whether vehicle underride/override alters vehicle accelerations in a way that makes crash tests more predictive of neck injury claim risk in rear-end collisions.

INTRODUCTION

Whiplash describes a range of neck injuries related to the differential motion between a vehicle occupant's head and body. In 2007, an estimated 66 percent of all insurance claimants under bodily injury liability coverage and 57 percent under personal injury protection coverage reported minor neck injuries. For 43 and 34 percent of bodily injury liability and personal injury protection claims, respectively, neck sprains or strains were the most serious injuries reported. The cost of these claims is about $8.8 billion annually, which accounts for 25 percent of the total dollars paid for all crash injuries [1]. Whiplash injuries can occur in any crash but occur most often in rear-end collisions. There were more than 1.7 million police-reported rear-end collisions in the United States in 2009, and 26 percent of these resulted in injury [2]. Insurance claim data show that almost 20 percent of drivers in rear impact crashes claim to have neck injuries [3].

Since 2004, the Insurance Institute for Highway Safety (IIHS) has rated seats and head restraints based on a procedure developed by the Research Council for Automobile Repairs' International Insurance Whiplash Prevention Group (RCAR/IIPG) [4]. The two-stage procedure evaluates the ability of seats and head restraints to prevent neck injuries in rear impact crashes. First, head restraints must be located to support an occupant's head in a rear impact. Studies have shown that head restraints positioned close to an occupant's head and above the head's center of gravity can significantly reduce the risk of neck injury following a rear-end crash [5-7]. Seats/head restraints with good geometry then are subjected to a simulated

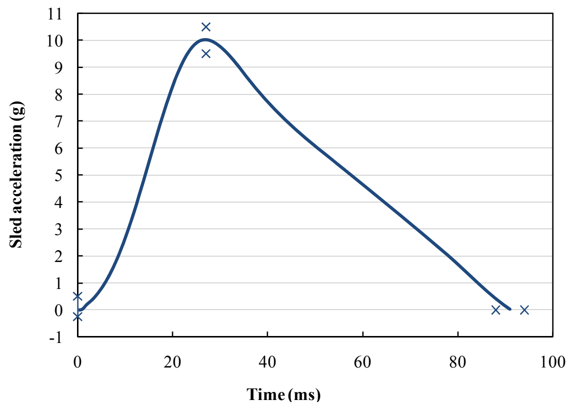

Figure 1. Target sled acceleration.

16 km/h rear impact using BioRID IIg [8]. All seats are tested with the same crash pulse, which is a simplified approximation of crash pulses from modern vehicles (Figure 1). Thus, the evaluation does not include the influence of a vehicle's rear structure.

Performance criteria for the dynamic test are divided into two groups: two seat design parameters and two dummy response parameters. The first seat design parameter, time to head restraint contact, requires that the head restraint or seatback contact an occupant's head early in the crash. This is to reduce the time during a rear crash that the head is unsupported by the restraint. The second seat design parameter, forward acceleration of the occupant's torso (T1 X acceleration), measures the extent to which the seat absorbs crash energy so that an occupant experiences lower forward acceleration. Seats with features that reduce contact time or have effective energy-absorbing characteristics have been shown to reduce neck injury risk in rear crashes [5].

The two dummy response parameters, upper neck shear force and upper neck tension force, ensure that earlier head contact or lower torso acceleration actually results in less stress on the neck. Measured neck forces are classified low, moderate, or high (Figure 2). To receive a good dynamic rating, a head restraint must pass at least one of the seat design parameters and also produce low neck forces. Table 1 lists ratings for other possible combinations of these criteria.

Research involving US insurance claim data has shown that vehicles with seat/head restraint designs rated good in the RCAR/IIWPG test have lower rates of whiplash injury claims than vehicles with seats rated poor [3], after controlling for other factors that influence neck injury claim rates (i.e., insurance laws in effect where the crash occurred, gender of seat occupant, body type of struck vehicle, cost of damage,

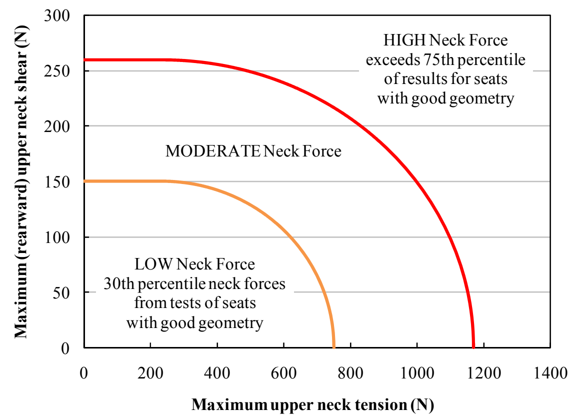

Figure 2. Neck force rating corridors.

Table 1
Dynamic rating requirements

Seat design criteria	Neck force classification	Dynamic rating
T1 X acceleration ≤9.5g OR Time to head restraint contact ≤70 ms	Low Moderate High	Good Acceptable Marginal
T1 X acceleration >9.5g AND Time to head restraint contact >70 ms	Low Moderate High	Acceptable Marginal Poor

and level of damage). Driver neck injury rates were 15 percent lower for vehicles with seats rated good than for vehicles with seats rated poor. Rates of driver neck injuries lasting 3 months or more were 35 percent lower for vehicles with seats rated good than for vehicles with seats rated poor. However, real-world neck injury rates associated with acceptable and marginal seats do not follow a linear trend as for rates associated with good and poor seats. Research involving Swedish insurance data has shown consistent findings [9]. One possible explanation for the lack of linearity is that vehicle characteristics not captured in the sled test are influencing real-world claim rates.

The objective of the current study was to determine whether vehicle-specific crash pulses could improve the relationship between seat ratings and real-world injury claim rates. A second objective was to investigate the effect of head restraint position on BioRID responses in full-vehicle rear impact tests. The RCAR/IIWPG protocol evaluates seats with their head restraints in the mid-height/mid-tilt position, but several studies have reported that adjustable head restraints often are left unadjusted [11-13]. Therefore, a comparison of injury measures between the RCAR/IIWPG head restraint position and the lowest restraint position may help explain the relationship between measured neck injury criteria and real-world injury claim rates.

METHODS

Driver neck injury rates were obtained from rear impact claims supplied by two automobile insurers. These claims, which were the same as those used to establish the relationship between injury ratings and real-world neck injury claim rates, were based on 2005-06 model year vehicles involved in rear impact crashes between January 1, 2005 and September 30, 2006 [3]. A total of 2,857 claims, when weighted by their sampling probabilities, were treated as being representative of 10,183 claims. Table 2 lists the injury rates by rating category with 95 percent confidence intervals and the range of estimates for the individual vehicle models in each group. The main finding was apparent that injury rates were lower, on average, for vehicles with seats rated good than for vehicles with seats rated poor, but it also was clear that injury rates for individual models in each rating group varied considerably. Some of this variation was due to the influence of variables that ultimately were controlled for in regression analyses reported in Farmer et al. [3]. The premise of the current study was to ascertain whether two vehicle models with the same rating but different injury rates would be rated differently after taking vehicle-specific crash pulse or alternate head restraint positioning into account.

Four small cars with rated seat/head restraints and varying neck injury claims rates were selected for full-vehicle crash tests. The 2006 Honda Civic and 2005 Chevrolet Cobalt both received good ratings in the RCAR/IIWPG sled test, but the Civic had a low neck injury claim rate compared with the Cobalt. The 2006 Saturn Ion and 2005 Ford Focus both received marginal ratings in the sled test, but the Ion had a neck injury claim rate comparable with that for the good-rated Civic, whereas the Focus had the highest neck injury claim rate among the four vehicles. Table 3 lists injury rates, number of weighted claims, and IIHS dynamic ratings for the vehicles tested. Although the differences in injury rates were not statistically significant, it was expected the differences more likely were due to variations in vehicle crash pulse rather than variations associated with body type, size/weight, or market class, as these characteristics were similar among all four models chosen.

The four vehicles identified in the claims study were subjected to rear impact crash tests. BioRID IIg dummies were positioned in the driver and front passenger seats of each vehicle. The driver dummy was positioned based on the RCAR/IIWPG dynamic protocol with the head restraint in the test position [4]. The passenger dummy also was seated based on the RCAR protocol with the exception that the head restraint was adjusted to its lowest position. All BioRID setup measurements were similar between the sled tests and full-vehicle crash tests except for head restraint height (Appendix A). Because the vehicles had been driven for 4-5 years prior to testing, the heights of the head restraints were significantly taller relative to the dummy's head than the new seats tested on the sled, likely due to compression of the seat foam associated with use.

Table 2
Driver neck injury rates by IIHS rating

Rating	Injury rate	95% confidence interval	Range
Good	16.15	13.50, 18.81	3.9-70.5
Acceptable	21.11	17.71, 24.52	0-33.3
Marginal	17.73	14.66, 20.80	0-100
Poor	19.16	16.04, 22.28	0-38.0

Table 3.
Injury claim rates and IIHS dynamic ratings

Vehicle	Claims (weighted)	Injury rate	95% confidence interval	IIHS rating
Civic	179	14.59	7.82, 21.35	Good
Ion	139	16.92	16.40, 33.52	Marginal
Cobalt	163	24.96	2.52, 31.32	Good
Focus	160	26.58	9.16, 44.00	Marginal

Table 4.
Mass of striking and struck vehicles

Vehicle	Mass (kg)
IIHS crash cart	1,479
2005 Ford Focus	1,462
2006 Honda Civic	1,451
2005 Saturn Ion	1,496
2005 Chevrolet Cobalt	1,498

After dummy positioning, each vehicle was struck in the rear by the IIHS side impact crash cart [14]. To eliminate any influence of underride/override, the deformable aluminum element was not attached to the barrier, resulting in a flat rigid impactor surface. In an attempt to match the severity of the RCAR/IIWPG crash pulse, vehicles were impacted to create a change in velocity (delta V) of 16 km/h (10 mi/h). Because the mass of the IIHS crash cart and test vehicles were very similar (Table 4), an impact speed of 32 km/h was chosen. The brakes on the struck vehicles were applied to simulate a stopped vehicle. BioRID injury criteria for the driver and passenger positions were evaluated to determine the RCAR/IIWPG rating.

The EuroNCAP whiplash assessment is based on results from three tests with different sled accelerations, one of which is the same as the RCAR/IIWPG crash pulse. The assessment includes three criteria — neck injury criterion (NIC), Nkm, and head rebound velocity — in addition to criteria used by RCAR/IIWPG. The relationship between these criteria and real-world injury claim rates also was examined [15].

RESULTS

In all four crash tests, peak vehicle accelerations were higher than the RCAR/IIWPG crash pulse (Figure 3). Vehicle accelerations also ramped up more quickly and delta Vs were higher than the RCAR/IIWPG target pulse. The RCAR/IIWPG protocol specifies a delta V between 14.8 and 16.2 km/h, whereas the crash tests produced delta Vs ranging from 18 to 19 km/h (Figure 4). Vehicle acceleration for the Saturn Ion was significantly different from those for the other vehicles. The Ion's peak acceleration was lower and occurred much later than those for the other vehicles, and was even later than the RCAR target pulse. Despite its lower and later peak acceleration, the Ion had the highest average acceleration between impact and 91 ms and the largest delta V (Table 5).

Based on RCAR/IIWPG seat and injury measures, the driver dummy in one of the four vehicles was rated good. The driver dummy in the Chevrolet Cobalt had low neck forces (Figure 5) and passed the seat design criteria with an early head contact time (Figure 6). The driver dummy in the Honda Civic also had an early head contact time but, with moderate neck forces, would have been rated acceptable. The driver dummies in Ford Focus and Saturn Ion both failed the seat design criteria and had moderate and high neck force ratings, respectively, resulting in a marginal rating for the Focus and poor rating for the Ion. For all four vehicles, upper neck shear force increased in the full-vehicle crash test compared with the sled test. Upper neck tension decreased for all vehicles except the Ion. The T1 longitudinal (X) acceleration increased for three of the vehicles, which was expected based on increases in vehicle accelerations. The decrease in T1 X acceleration for the Focus may have resulted from greater seat back rotation. Following the test, the seat back had rotated 12 degrees rearward, which was 4 degrees farther rearward than the seat in the sled test. Head contact time for each of the vehicles occurred earlier in the full-vehicle crash test compared with the sled test, also as a result of increased delta V.

With head restraints in the lowest position, none of the passenger dummies would have received a good rating (Figures 7 and 8). Passenger dummies in the Cobalt

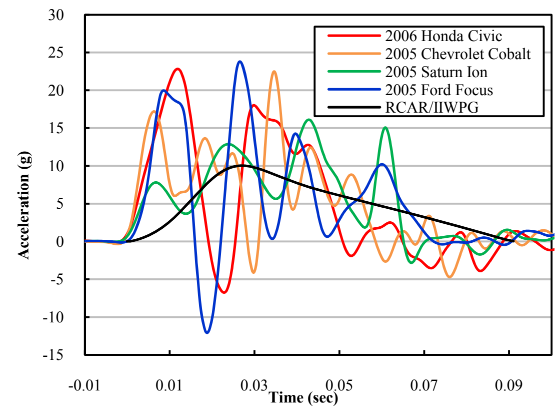

Figure 3. Longitudinal acceleration for vehicle crash tests.

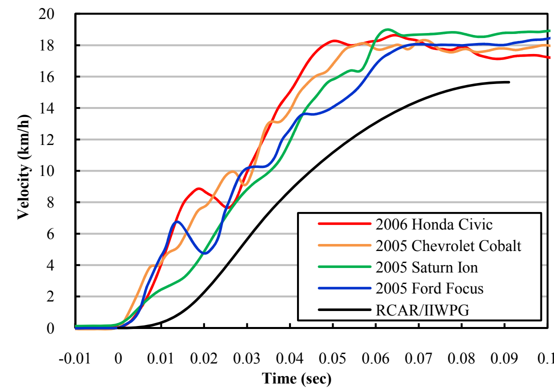

Figure 4. Change in velocity for vehicle crash tests.

Table 5.
Vehicle acceleration characteristics

Vehicle	Peak accel. (g)	Delta V (km/h)	Average accel. (g)
2006 Honda Civic	22.8	18.6	5.34
2005 Chevrolet Cobalt	22.5	18.3	5.56
2005 Saturn Ion	16.1	19.0	5.78
2005 Ford Focus	23.8	18.1	5.61
IIWPG crash pulse	10.0	15.6	4.82

and Civic both were rated acceptable with early head contact times and moderate neck forces. The passenger dummy in the Focus would have been rated marginal by failing the seat design criteria and having moderate neck forces. The passenger dummy in the Ion would have received a poor rating by failing the seat design criteria and having high neck forces. For all passenger dummies, upper neck shear force decreased and upper neck tension increased compared with the driver dummies. T1 X acceleration and head contact time were similar between driver and passenger dummies. These results were consistent with differences between driver and passenger BioRID

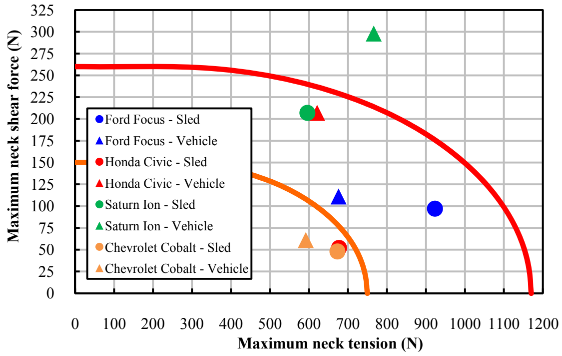

Figure 5. Neck force classification: sled vs. vehicle driver.

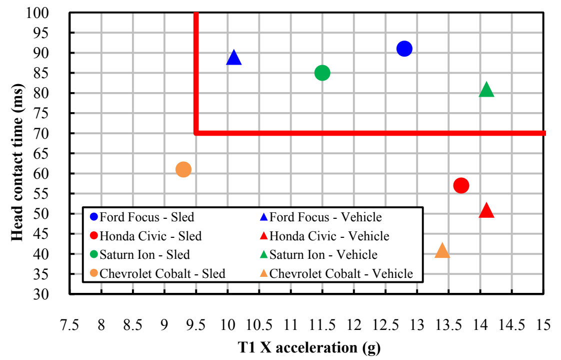

Figure 6. Seat design criteria: sled vs. vehicle driver.

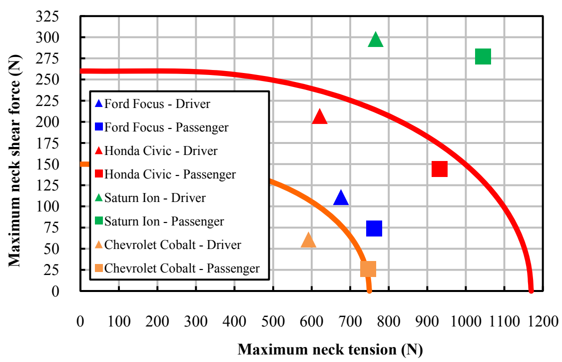

Figure 7. Neck force classification: driver vs. passenger.

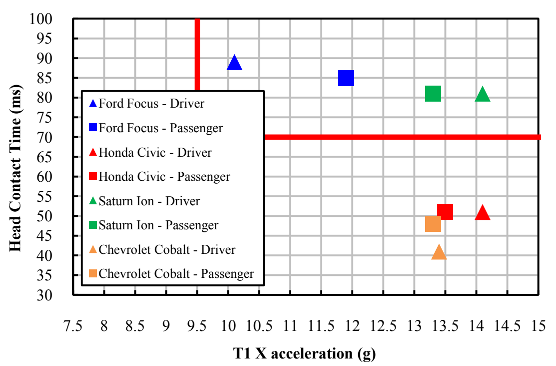

Figure 8. Seat design criteria: driver vs. passenger.

Table 6.
EuroNCAP criterion

Criterion	Performance Higher	Performance Lower	Capping limit
Neck injury criterion (NIC)	11.00	24.00	27.00
Maximum Nkm	0.15	0.55	0.69
Head rebound velocity (m/s)	3.2	4.8	5.2
Neck shear Fx (N)	30	190	290
Neck tension Fz (N)	360	750	900
T1 X acceleration (g)	9.30	13.10	15.55
Restraint contact time (ms)	57	82	92

setup measurements. In every case, BioRID backset was smaller for the passenger dummy compared with the driver dummy, whereas the height between the head and head restraint was significantly greater for the passenger dummy with the head restraint in the full-down position.

BioRID responses also were compared with neck injury metrics used in the EuroNCAP whiplash seat assessment (Table 6). Only the Ion had NIC values above the lower performance limit for EuroNCAP rating, with values for the driver and passenger dummies above the capping limit. The driver and passenger dummies in the Civic and passenger dummy in the Cobalt had maximum Nkm values above the capping limit. The driver and passenger dummies in the Ion and driver dummy in the Cobalt had maximum Nkm values above the lower performance limit. The driver and passenger dummies in the Focus had maximum NKm values between the lower and higher performance limits. The driver and passenger dummies in the Civic had head rebound velocities above the EuroNCAP capping limit, and the passenger dummy in the Ion had a head rebound velocity above the lower performance limit. Head rebound velocities for all other dummies were between the lower and higher performance limits. EuroNCAP results are contrary to real-world claim rates. The Civic and Ion had the lowest real-world claim rates but the highest dummy injury measures. The Cobalt and Focus had the lowest dummy injury measures but the highest real-world claim rates. Summaries of EuroNCAP injury metrics, NIC, maximum Nkm, and head rebound velocity, are shown in Figures 9-11.

EuroNCAP injury metrics were compared between sled tests and full-vehicle crash tests. Results indicated NIC values were higher for the Cobalt and Ion and lower for the Civic and Focus in full-vehicle tests. For all vehicles except the Focus, maximum Nkm values for driver dummies were higher in full-vehicle tests than in sled tests. For all vehicles, head rebound velocities for driver dummies were higher in full-vehicle tests than in sled tests.

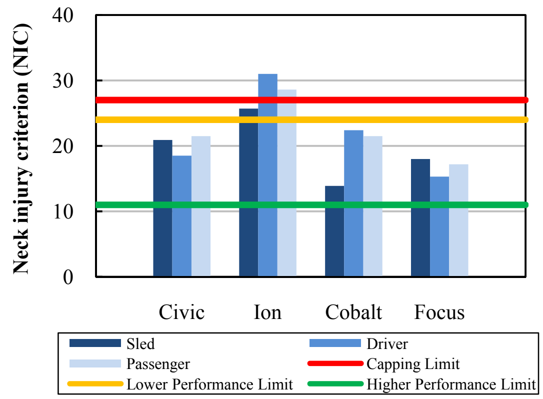

Figure 9. EuroNCAP results: neck injury criterion (NIC).

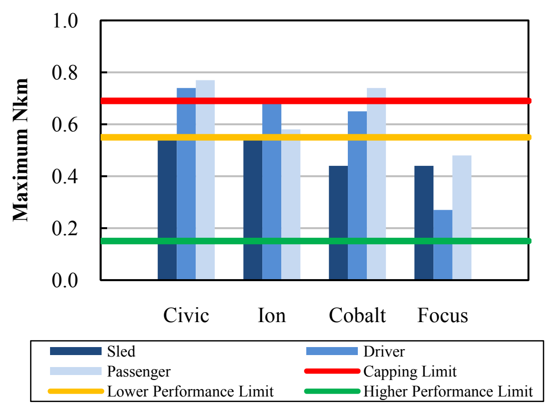

Figure 10. EuroNCAP results: maximum Nkm.

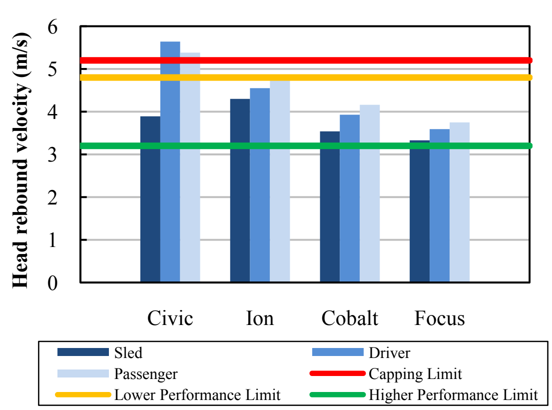

Figure 11. EuroNCAP results: head rebound velocity.

EuroNCAP injury measures were compared between the driver and passenger dummies. NIC values were higher for the passenger dummies in the Civic and Focus but lower for passenger dummies in the Cobalt and Ion. Maximum Nkm values also were higher for the passenger dummies in every vehicle except the Ion. For all vehicles except the Civic, head rebound velocities were higher for passenger dummies than for driver dummies.

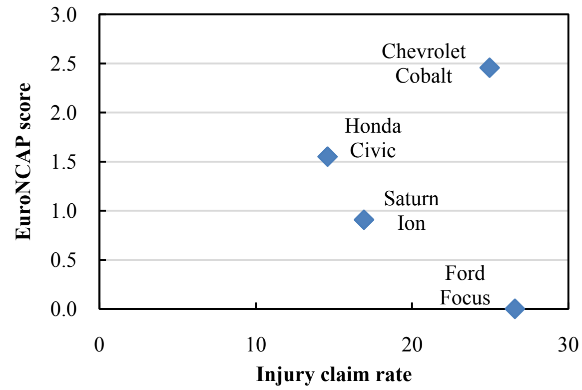

Figure 12. EuroNCAP scores for sled tests vs. injury claim rates.

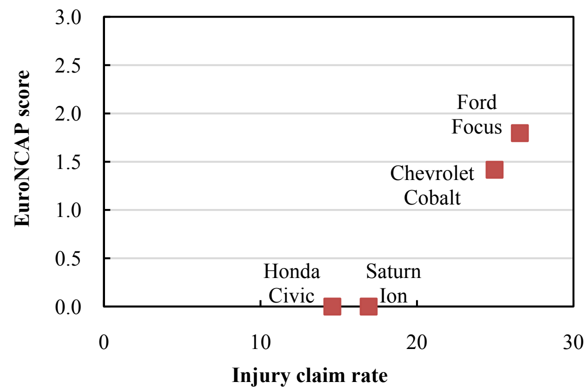

Figure 13. EuroNCAP score for driver dummies vs. injury claim rates.

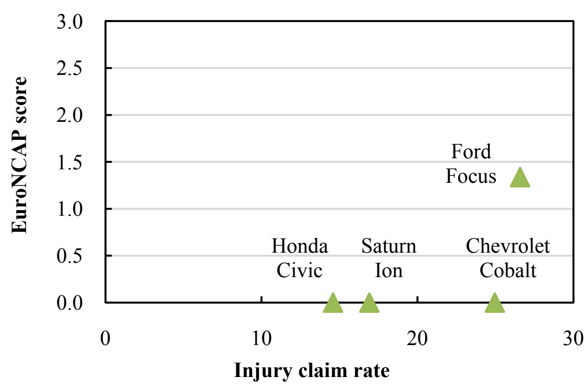

Figure 14. EuroNCAP score for passenger dummies vs. injury claim rates.

The EuroNCAP injury metrics failed to correlate with real-world injury claim rates for any of the three test conditions. In fact, dummy injury measures were lower for vehicles with higher real-world injury claim rates and higher for vehicles with lower real-world injury claims. Calculations of the EuroNCAP whiplash score (0-3) also showed no correlation to real-world injury claim rates for sled test results as well as results for driver and passenger dummies in full-vehicle tests (Figures 12-14).

DISCUSSION

The higher BioRID injury measures for the driver dummy in full-vehicle crash tests were consistent with higher vehicle accelerations compared with the RCAR/IIWPG crash pulse. This resulted in two seats being rated lower than in the sled test and two being rated the same. However, the vehicle-specific accelerations did not reorder the seat ratings based on these results in a way that was more consistent with real-world injury claim rates (Table 7).

Table 7
RCAR/IIWPG Ratings

Vehicle	Claim rate	Sled rating	Driver rating	Passenger rating
Civic	14.59	Good	Acceptable	Acceptable
Ion	16.92	Marginal	Poor	Poor
Cobalt	24.96	Good	Good	Acceptable
Focus	26.58	Marginal	Marginal	Marginal

Differences in injury measures observed between driver and passenger dummies in full-vehicle tests also were expected based on differences in BioRID setup measurements. The fact that upper neck shear force decreased and upper neck tension increased can be explained by the lower head restraint locations for passenger dummies. As with results for driver dummies, injury measures for passenger dummies in full-vehicle tests would yield lower ratings for the seats than ratings based on sled tests. However, these lower ratings were no better correlated with real-world injury claim rates than the sled test ratings. Furthermore, there is no combination of driver and passenger results that better correlates with real injury rates.

The vehicle-specific accelerations observed in this test series also do not explain the injury risk, but vehicle accelerations from flat barrier tests may not be representative of real-world rear impact accelerations. IIHS research has shown that some cars have a tendency to be underriden or overridden by striking vehicles [16]. Research by Thatcham shows that vehicle accelerations are significantly different depending on whether or not a vehicle's rear bumper system engages the striking vehicle's front bumper [17]. Vehicles with a tendency to be overridden or underriden tended to have lower vehicle accelerations. If the four vehicles in this test series had different override/underride tendencies, then it is possible that taking these tendencies into account would yield results different from those observed here.

CONCLUSIONS

Changing the RCAR/IIWPG protocol to include vehicle-specific crash pulses and/or changing restraint setup would not improve the relationship between seat/head restraint ratings and neck injury claim rates. Examination of additional BioRID injury metrics not currently assessed under the protocol does not help explain real-world neck injury claim rates and does not support changing the current evaluation criteria. Additional research is needed to determine whether vehicle underride/override alters vehicle accelerations in a way that makes crash tests more predictive of neck injury claim risk in rear-end collisions.

ACKNOWLEDGMENT

This work was supported by the Insurance Institute for Highway Safety.

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APPENDIX A

Table A-1.
2006 Honda Civic BioRID setup measurements

Measurement	Sled	Driver	Passenger
Seatback angle (°)	13.9	14.2	14.3
Pelvic angle (°)	27.5	24.7	28.0
Backset, down (mm)	41.8	40.4	44.8
Height, down (mm)	100.6	86.7	81.4
Backset, up (mm)	56.7	55.4	60.1
Height, up (mm)	31.1	17.4	14.2
Backset, RCAR (mm)	51.6	50.9	55.6
Height, RCAR (mm)	57.5	44.6	39.0

Table A-2.
2005 Chevrolet Cobalt BioRID setup measurements

Measurement	Sled	Driver	Passenger
Seatback angle (°)	2.3	2.0	1.6
Pelvic angle (°)	27.2	24.7	25.7
Backset, down (mm)	36.1	42.5	43.9
Height, down (mm)	109.0	84.4	72.0
Backset, up (mm)	38.5	44.7	44.9
Height, up (mm)	51.6	24.2	13.0
Backset, RCAR (mm)	37.6	44.2	44.0
Height, RCAR (mm)	67.3	39.3	28.0

Table A-3.
2006 Saturn Ion BioRID setup measurements

Measurement	Sled	Driver	Passenger
Seatback angle (°)	10.7	8.6	9
Pelvic angle (°)	27.2	24.4	26.1
Backset, down (mm)	77.2	77.8	75.7
Height, down (mm)	118.5	96.7	105.1
Backset, up (mm)	89.6	87.7	87.6
Height, up (mm)	53.0	28.1	35.2
Backset, RCAR (mm)	84.9	84.2	82.6
Height, RCAR (mm)	78.5	51.7	61.8

Table A-4.
2005 Ford Focus BioRID setup measurements

Measurement	Sled	Driver	Passenger
Seatback angle (°)	14.8	14.5	14.2
Pelvic angle (°)	27.7	26.2	26.1
Backset, down (mm)	51.7	51.8	49.4
Height, down (mm)	104.6	81.7	78.7
Backset, up (mm)	68.9	68.8	68.1
Height, up (mm)	39.5	14.6	11.6
Backset, RCAR (mm)	58.7	58.9	57.4
Height, RCAR (mm)	78.2	54.6	50.9

APPENDIX B

Table B-1.
2005 Chevrolet Cobalt test results

Criteria	Sled	Driver	Passenger
Neck shear force (N)	48	61	26
Neck tension (N)	673	592	746
T1 X acceleration (g)	9.3	13.4	13.3
Head contact time (ms)	61	41	48
IIHS rating*	G	G	A
Neck injury criterion (NIC)	13.9	22.4	21.5
Head rebound velocity	3.54	3.93	4.16
Maximum Nkm	0.44	0.65	0.74

*G = good, A = acceptable, M = marginal, P = poor

Table B-2.
2006 Honda Civic test results

Criteria	Sled	Driver	Passenger
Neck shear force (N)	52	207	144
Neck tension (N)	677	621	932
T1 X acceleration (g)	13.7	14.1	13.5
Head contact time (ms)	57	51	51
IIHS rating*	G	A	A
Neck injury criterion (NIC)	20.9	18.5	20.5
Head rebound velocity	3.89	5.64	5.38
Maximum Nkm	0.55	0.74	0.77

*G = good, A = acceptable, M = marginal, P = poor

Table B-3.
2006 Saturn Ion test results

Criteria	Sled	Driver	Passenger
Neck shear force (N)	207	298	277
Neck tension (N)	596	766	1045
T1 X acceleration (g)	11.5	14.1	13.3
Head contact time (ms)	85	81	81
IIHS rating*	M	P	P
Neck injury criterion (NIC)	25.7	31.0	28.6
Head rebound velocity	4.3	4.55	4.85
Maximum Nkm	0.55	0.68	0.58

*G = good, A = acceptable, M = marginal, P = poor

Table B-4.
2005 Ford Focus test results

Criteria	Sled	Driver	Passenger
Neck shear force (N)	97	111	74
Neck tension (N)	923	676	762
T1 X acceleration (g)	12.8	10.1	11.9
Head contact time (ms)	91	89	85
IIHS rating*	M	M	M
Neck injury criterion (NIC)	18.0	15.3	17.2
Head rebound velocity	3.33	3.59	3.75
Maximum Nkm	0.44	0.27	0.48

*G = good, A = acceptable, M = marginal, P = poor