Seat Design Characteristics Affecting Occupant Safety in Low- and High-Severity Rear-Impact Collisions

Marcy A. Edwards, Matthew L. Brumbelow, Rebecca E. Trempel, Timothy C. Gorjanc

Abstract Seat designs must have both the strength to retain an occupant in a high-severity rear impact and the energy-absorbing characteristics necessary to limit injuries in more frequent low-severity impacts. This study evaluated the relative performance of modern seats in high-severity rear impacts while also assessing if a necessary trade-off existed in occupant injury protection in low-severity rear impacts. Twenty-six high-severity simulated rear-impact tests were conducted on seats in the modern fleet. The results from these tests were analyzed for relationships with metrics from previously conducted low-severity simulated rear impacts and with insurance injury claim data. Additional analysis was done for low-severity test metrics and insurance injury claim data. The majority of seats tested had adequate occupant retention for a 78 kg occupant at the tested severity. Better occupant-retention metrics in the high-severity test were not linked with increases in low-severity injury test metrics or real-world injury claim rates, indicating that some seats in the modern fleet provide occupant retention at high severities and whiplash injury protection at low severities. Further, results showed that some metrics from the high-severity test had better correlations with insurance injury claim rates than any low-severity metrics and that a metric not currently used for whiplash evaluation, longitudinal pelvis displacement, showed enough potential for predicting injury claim rate that it warrants further research.

Keywords Rear impacts, High-severity rear impacts, Low-severity rear impacts, Seat design, Rear-impact occupant protection

I. INTRODUCTION

Vehicle seats provide the principal safety restraint for occupants in both low- and high-severity rear-end impacts. Like the three-point seatbelt, the vehicle seat must be designed to restrain the occupant's motion relative to the vehicle while limiting the forces imparted to the occupant. In 1968, the first U.S. regulations requiring safety performance for seating systems, Federal Motor Vehicle Safety Standard (FMVSS) 207, and head restraints, FMVSS 202, were issued. Together, these regulations required the presence of torso and head support and mandated the level of load that the supporting structure must withstand. While the head restraint regulation was updated in 2004, the seating system regulation has remained unchanged since 1968 and, as of 2003, had strength requirements two to three times lower than seats in the fleet [1]. In Europe, a similar regulation, Economic Commission for Europe (ECE) No. 17, has governed the safety performance of seating systems and head restraints since 1970.

Despite the lack of modifications to seating system regulation in the U.S., seat designs have seen significant improvements. The addition of dual recliners, where the seatback is controlled and strengthened on both sides of the seat, added significant strength to seatbacks, reducing seatback rotations and deformation asymmetry during rear impacts [2,3]. The introduction of IIHS (Insurance Institute for Highway Safety) head restraint geometry requirements and rear-impact sled tests, and the update of FMVSS 202 head restraint regulation in 2004, have increased the height and reduced the backset of head restraints, providing better support for the head, while also providing dynamic guidelines for reducing low-severity injuries. Several organizations in Europe, including the Swedish Road Administration, the International Insurance Whiplash Prevention Group (IIWPG) and the European New Car Assessment Programme (Euro NCAP), also introduced consumer information testing to influence better overall seat designs for low- to mid-severity rear impacts. Furthermore, many automakers, acting under due care, have implemented internal guidelines for occupant restraint in high-severity rear impacts [4].

M. A. Edwards (e-mail: medwards@iihs.org; tel: +1-434-985-4600) is a Research Engineer at the Insurance Institute for Highway Safety in Ruckersville, Virginia, USA. M.L. Brumbelow is a Senior Research Engineer at the Insurance Institute for Highway Safety in Ruckersville, Virginia, USA. R.E. Trempel is a Statistician at the Highway Loss Data Institute in Arlington, Virginia, USA. T.C. Gorjanc, Ph.D. is a Senior Research Scientist at XSENSOR Technology Corporation in Calgary, Alberta, Canada.

Additionally, a significant body of research has contributed to various vehicle seat design strategies for occupant protection in rear impacts. In 1968, Severy et al. conducted a series of rear-impact vehicle tests and concluded that the best way to protect an occupant in a rear impact was to provide a "rigid" seatback 700 mm in height and capable of resisting a torque of at least 1,808 Nm, but not greater than 3,728 Nm, without failure [5]. Saczaliski et al., in 1993, provided a case review of 46 real-world rear-impact crashes and found that many occupants were partially or totally ejected from their seat, though they were restrained by a seat belt, indicating that many seats were not strong enough to retain occupants [6]. Other researchers, such as Prasad et al., have cautioned that "yielding" seats actually provide better overall occupant protection in rear-impact crashes than stiffened seats [7]. The combined message of much of the published research on seat design is that "rigid" or "stiff" seats are necessary to prevent the loss of occupant retention and impact with vehicle interior components or other occupants in high-severity rear impacts, but "yielding" seats are necessary to limit injuries in more common, low-severity impacts.

Based on findings in the literature, more emphasis has been placed on achieving the benefits of both "rigid" and "yielding" seats in one design. Viano researched and developed a "High-Retention Seat" implemented by General Motors in 1997, with a high-strength seatback frame, but an energy-absorbing middle portion that allows the occupant to move into the seatback [4]. The Whiplash Protection System (WHIPS) generation 2 seat, designed by Volvo, also aims to provide robust rear-impact occupant protection using a strong seat with energy-absorbing cushioning and controlled deformation elements in the seat structure [8].

The U.S. National Highway Traffic Safety Administration (NHTSA) found that, in 2015, rear-impact crashes accounted for 27.1% of all passenger vehicle crashes and 26.3% of injuries, but only 7.4% of fatalities [9]. The majority (65%) of rear-impact crashes are low severity and have a change in velocity under 24 km/h [10]. Serious (MAIS 3+) injuries occur in only 9.8% of rear impacts and, of those, only about half reach the level of severe (MAIS 4+) injury [10]. While mild and moderate injuries dominate in rear-impact crashes, documented cases exist where front-seat occupants in a rear-impact crash move up the rotating seatback and over the head restraint to make contact with either a rear-seat occupant or rear-seat structure, resulting in serious injury [6,11,12]. Often, the role the seat plays in contributing to injury prevention in high-severity rear-impact crashes is hard to discern because of large intrusion into the rear-occupant compartment, but serious injury has been shown to occur without significant rear-occupant compartment intrusion [11,13].

Many regulatory and consumer information programs evaluate the dynamic performance of safety restraints in the frontal and side crash modes. Currently, though, there is no publicly available information on the dynamic performance of vehicle seats as safety restraints in high-severity rear impacts. NHTSA does conduct a high-severity rear impact fuel integrity test using a moving barrier, FMVSS 301R; however, though this test does include Hybrid III 50th male Anthropomorphic Test Devices (ATDs) as front-seat occupants, they are uninstrumented and there are no onboard video views. Further research is needed on the relative performance of modern seating systems in high-severity rear impacts and whether this performance is correlated to reduced protection in more common lower severity crashes. The current study evaluated seatback rotation and other occupant-retention characteristics in high-severity sled tests while using low-severity test results and insurance data to explore the possibility of a trade-off with low-severity crash protection.

II. METHODS

Twenty-six vehicle front seats were tested on an acceleration sled while oriented to simulate a rear-impact crash. The majority of seats tested were from vehicles in the midsize car class (Highway Loss Data Institute [HLDI] classification) in order to limit the confounding factors of vehicle weight and body style in the analysis of insurance data [14]. However, seats from a wide range of vehicle classes and makes were included in the test series to provide a more comprehensive assessment of high-severity seat performance in the fleet. A list of seats tested can be found in Table I.

TABLE I
TEST MATRIX

Applicable Model Years	Make/Model	Vehicle Class	Applicable Model Years	Make/Model	Vehicle Class
2015-2019	Honda Fit	Mini car	2018-2019	Toyota Camry	Midsize car
2017-2019	Chevrolet Bolt	Small car	2012-2019	Volkswagen Passat	Midsize car
2017-2019	Mini Countryman	Small car	2017-2019	Kia Cadenza	Large car
2013-2015	Chevrolet Malibu	Midsize car	2017-2019	BMW 5 Series	Large luxury car
2013-2019	Ford Fusion	Midsize car	2017-2019	Mercedes E-class	Large luxury car
2013-2017	Honda Accord	Midsize car	2018-2019	Honda Odyssey	Minivan
2018-2019	Honda Accord	Midsize car	2018-2019	BMW X3	Small SUV
2015-2019	Hyundai Sonata	Midsize car	2017-2019	Jeep Compass	Small SUV
2012-2015	Kia Optima	Midsize car	2017-2019	Mazda CX-5	Small SUV
2014-2019	Mazda 6	Midsize car	2018-2019	Volkswagen Tiguan	Midsize SUV
2013-2018	Nissan Altima	Midsize car	2018-2019	Volvo XC60	Midsize luxury SUV
2015-2019	Subaru Legacy/Outback	Midsize car	2015-2019	Chevrolet Colorado	Small pickup
2012-2017	Toyota Camry	Midsize car	2016-2019	Toyota Tacoma	Small pickup

The same acceleration pulse was used for all tests and was derived from the FMVSS 301R barrier test. FMVSS 301R is a rear-impact fuel integrity test where 70% of the width of the vehicle on the fuel-filler side is impacted by a barrier travelling at 80 km/h. The FMVSS 301R test is widely used by the auto safety industry to represent high-severity rear-impact crashes. Research during the development of this test showed that it produces vehicle damage similar to survivable rear-impact crashes [15].

The pulse used in the current study was obtained by averaging the vehicle longitudinal accelerations collected from eight midsize cars in FMVSS 301R testing. Vehicle manufacturers were queried to voluntarily provide data for any current model midsize cars in their fleet; six manufacturers responded with data for eight vehicles. The resulting pulse had a 15 g peak acceleration and 36.5 km/h delta V (Fig. 1). While the individual vehicle accelerations provided by manufacturers of the included models are confidential, the standard deviation shown in Fig. 1 shows that all the midsize car accelerations had similar characteristics and are well represented by the averaged pulse. Further information on pulse average acceleration and delta V can be found in Appendix Table A-IV.

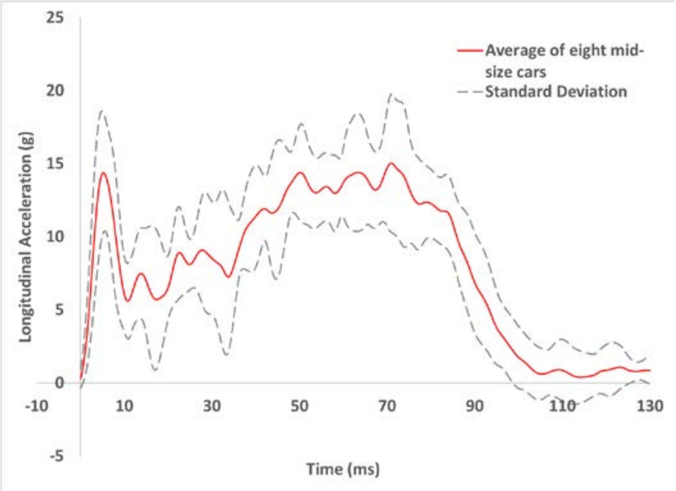


Fig. 1. Longitudinal acceleration averaged from eight midsize cars in the FMVSS 301R test used to obtain the sled pulse.

Tested seats were from the driver or right front-passenger location. Only unused production seats were included. Seat and belt anchorage locations were replicated from the production model vehicle, with the upper anchorage height positioned according to the manufacturer's recommendation. The seating adjustments were positioned to the mid-slide, full-down position with the seatback set according to the Society of Automotive Engineers (SAE) J826 procedure for a 25° H-point manikin (HPM) torso angle [16]. The full-down position was chosen to eliminate variability between seats with and without height adjustment. Production seat belts matching the vehicle model of the seat were used for each test. Vehicle manufacturers were queried for information on the deployment of pretensioners in rear-impact crashes for the vehicle model of the seat being tested and the deployment timing for the given pulse. Pretensioners were only activated if the manufacturer provided confirmation that the vehicle would deploy pretensioners in a rear-impact crash of the same severity. Vehicle manufacturers provided pretensioner information for 24 of the 26 seats tested, 11 of which had the belt pretensioner/pretensioners deployed during the test.

The Hybrid III 50th percentile male was used as the human surrogate for these tests. The only ATD designed for rear impacts, the BioRID II, was designed for use in impacts with a 24 km/h or lower delta V. Though it was primarily designed for frontal impacts, the Hybrid III is currently used for rear-impact dynamic evaluation in the FMVSS 202a head restraint regulation and the Global Trade Regulation (GTR) 7. The Hybrid III was positioned by matching the following targets: the H-point from the SAE J826 manikin, a pelvic angle of 22.5°, and a level head.

The dummy metrics measured included head triaxial accelerations; chest and pelvis longitudinal (x-axis) and vertical (z-axis) accelerations; head, chest and pelvis y-axis angular rates; upper neck, lower neck and lumbar spine x- and z-axis forces and y-axis moments; and chest deflections. Lap belt load was measured on the outboard side of the belt. Seatback triaxial acceleration and sled longitudinal acceleration were also collected. High-frequency noise propagated through the sled and into the dummy channels, forcing the use of lower frequency filters than those specified by SAE J211; channel filter classes for each sensor can be found in Appendix Table A-I [17].

The primary occupant-retention metrics were seatback rotation and pelvis displacement. Seatback rotation was measured for each seat by mounting angular rate sensors (ARS) to the left and right upper seatback frame, orientated about the y-axis. Angular rates were then integrated to provide rotation angle histories. This method of measurement was validated with film analysis using seatback targets. Vertical pelvis displacement was calculated by double integrating the vertical (z) pelvis acceleration relative to the sled with the sled coordinate system rotated to align with the pelvis, using the pelvis ARS. Longitudinal pelvis displacement was calculated by double integrating the longitudinal (x) pelvis acceleration relative to the sled with the pelvis coordinate system rotated to align with the sled, using the pelvis ARS. Longitudinal head displacement also was calculated by tracking the head center of gravity (CG) target with film analysis.

Very thin XSensor brand high-frequency, high-resolution pressure mats were placed between the dummy and seat to measure the load transferred to the occupant by the seat. One mat covered the seatback and another covered the head restraint. These pressure mats provided historical, two-dimensional mapping of the pressures between the seat and the occupant at a frequency of 2,475 Hz and 2,388 Hz, respectively, and at a resolution of 1.27 cm and 0.51 cm, respectively. Aggregating the pressures over the total area provided the measured load between the occupant and the seat. However, because of inaccuracies in calculating the loaded area and minimum pressure thresholds on the sensors, the load calculated is an estimation.

Pearson correlation coefficients were calculated to examine relationships between the metrics collected in these high-severity tests and those collected during previously conducted IIHS low-severity head restraint evaluation tests of the same seat designs. Metrics from IIHS low-severity tests included upper and lower neck forces and moments; T1 acceleration; neck injury criterion (NIC); head contact time (HCT); Nkm ; head rebound velocity, measured by integrating the head longitudinal acceleration relative to the sled; and pelvis longitudinal displacement, calculated by double integrating the longitudinal (x) pelvis acceleration relative to the sled [18,19]. The IIHS low-severity tests were conducted with the BioRID II according to the IIHS protocol, which has a pulse delta V of 16 km/h [20].

The insurance data analyzed in the current study were supplied to HLDI by U.S. automobile insurer sponsors of IIHS and HLDI. These companies account for more than 80% of privately insured passenger vehicles. Similar to police-reported crashes, the insurance data in aggregate are largely representative of low-severity crashes (Appendix Fig. A-1). Data from personal injury protection (PIP) and property damage liability (PDL) policies were used to calculate the rate of injury claims filed after rear-impact crashes. PIP covers medical payments for any injured occupant in the insured vehicle, without regard to fault. PDL covers physical damage to the not-at-fault (generally struck) vehicle in a multiple vehicle crash. To match the relevant crash mode of this study, only rear-impact PDL claims were used. The point-of-impact information was supplied by the damage-estimation services CCC Information Services Inc. and Mitchell International. These data were linked to HLDI data by Vehicle Identification Number (VIN) and crash date. Data from vehicle models with sled-tested seats and more than 1,000 rear-impact PDL claims with corresponding PIP coverage were used in the current study. All of these models were midsize cars (Table II). The injury claim rate for a given vehicle model was defined as the number of filed PIP claims divided by the number of filed PDL claims from policies with PIP coverage.

TABLE II

REAR-IMPACT INSURANCE CLAIM DATA

Vehicle Make/Model	Curb Weight (kg)	Number of Property Damage Liability Claims	Number of Personal Injury Protection Claims	Injury Claim Rate (PIP/PDL)
2015–2019 Subaru Outback	1,639	3,071	227	7.4%
2015–2019 Subaru Legacy	1,575	1,288	109	8.5%
2014–2019 Mazda 6	1,466	3,214	276	8.6%
2013–2017 Honda Accord	1,445	24,961	2,909	11.7%
2013–2019 Ford Fusion	1,564	8,802	1,075	12.2%
2012–2019 Volkswagen Passat	1,479	7,981	1,035	13.0%
2013–2015 Chevrolet Malibu	1,414	6,066	789	13.0%
2015–2019 Hyundai Sonata	1,484	5,555	790	14.2%
2012–2015 Kia Optima	1,465	9,129	1,307	14.3%
2012–2017 Toyota Camry	1,518	30,441	4,498	14.8%
2013–2018 Nissan Altima	1,446	19,351	2,979	15.4%

Linear regression was used to model the effects of different metrics recorded during the high- and low-severity sled tests on the injury claim rates. All regression models were weighted using the number of PDL claims for each vehicle. While the vehicle curb weight of these midsize cars was only a significant predictor of injury rate in some regression models, it was included in all the models based on its relationship to injury in larger datasets and to facilitate comparison of the regression output [21]. Separate regression models were fit for individual test metrics. When the effect of a given metric was statistically significant at the $p = 0.05$ level, that metric was used as a covariate in additional models to evaluate the effect of the remaining test metrics while controlling for the original variable. All models were calculated using the R programming language.

III. RESULTS

High-Severity Tests

The occupant-retention performance of seats in the high-severity test was quantified using maximum dynamic seatback rotation and vertical pelvis displacement. For the 26 seats tested, there was a range of performance according to these metrics, with maximum dynamic seatback rotation ranging from 15.4° to 47.2°, and vertical pelvis displacements up the seatback ranging from 41 to 144 mm. Maximum dynamic seatback rotation was measured on both the left and right, however, seating material interfered with the sensor and caused a loss of data on one side for some seats. All seats with data for only one side had left-to-right side relative plastic deformations of 1° or less. Maximum dynamic seatback rotations are shown in Fig. 2 and vertical pelvis displacements are shown plotted against seatback rotation in Fig. 3; pictures of each seat at the maximum dynamic seatback rotation angle are shown in Appendix Table A-II. While dynamic vertical pelvis displacements were relatively low, the seat with the greatest seatback rotation was unable to restrain the dummy during the rebound phase of the test, resulting in submarining under the lap belt. The manufacturer did not provide pretensioner information for this seat, so results could change with pretensioner deployment. The

11 tests in which the seat belt pretensioner was activated tended to have lower vertical pelvis displacement; only 2 seats without a pretensioner had excursion values under 67 mm, the maximum for seats with pretensioners. Pretensioner activation did not appear related to maximum dynamic seatback rotation; seats with activated pretensioners ranged in seatback rotation from 15.4° to 27°. Maximum dynamic seatback rotation was correlated with longitudinal head displacement (Fig. 4). Upper and lower neck loads and moments measured in the high-severity tests were all well below frontal and side impact injury assessment reference values (IARVs) for the Hybrid III 50th male published by Mertz, Irwin and Prasad in 2003 [22].

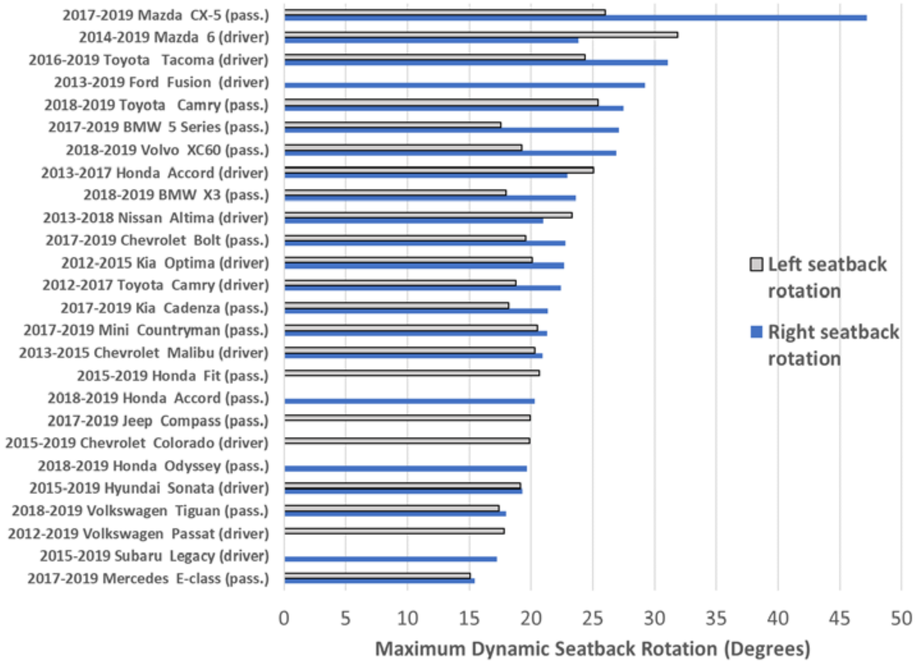


Fig. 2. Maximum dynamic seatback rotation.

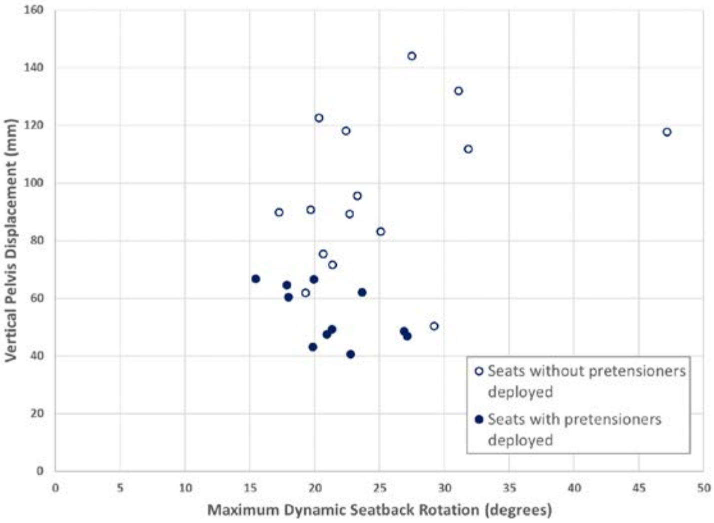


Fig. 3. Vertical pelvis displacement vs. seatback rotation.

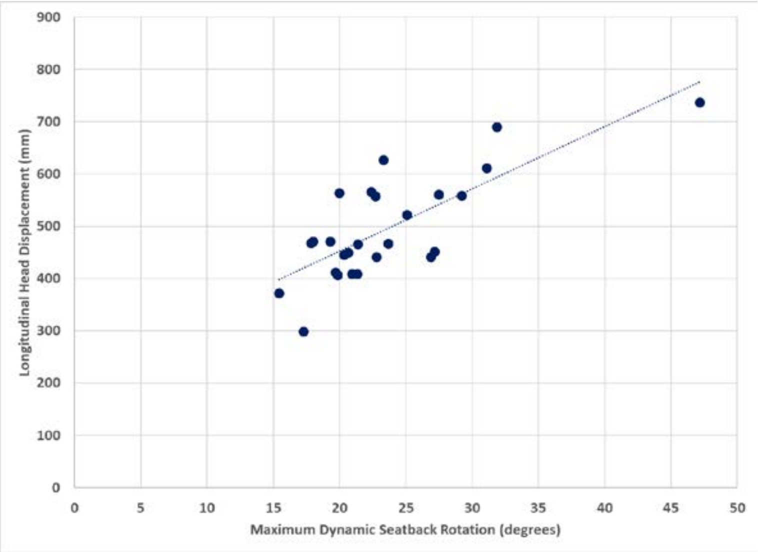


Fig. 4. Longitudinal head displacement vs. seatback rotation.

High-Severity Occupant Retention and Low-Severity Test Metrics

Pearson correlation coefficients were calculated to assess potential trade-offs between high- and low-severity test performance (Table III). Whiplash injury metrics analyzed included upper and lower neck forces and moments, T1 acceleration, NIC, HCT and Nkm. Nkm was analyzed for all modes of upper neck shear force and lateral-axis moment: NEA (extension-anterior), NEP (extension-posterior), NFA (flexion-anterior), and NFP (flexion-posterior), where anterior indicates head rearward movement relative to the chest [19]. Between the two high-severity occupant-retention metrics, correlations to whiplash injury metrics were stronger for vertical pelvis displacement than for seatback rotation. The strongest negative correlations were between vertical pelvis displacement and upper neck tension, upper and lower neck shear, upper neck flexion moment and lower neck extension moment, NIC and Nkm-NFA ($-0.46 < r < -0.31$) (Table III). Similarly strong positive correlations existed between vertical pelvis displacement and Nkm-NEP and upper neck extension.

TABLE III

PEARSON CORRELATION COEFFICIENTS FOR HIGH-SEVERITY VS. LOW-SEVERITY METRICS

	High-Severity Metric	
IIHS Metric	Seatback Rotation	Vertical Pelvis Displacement
Upper neck tension	+0.09	−0.37
Upper neck shear	−0.06	−0.32
Upper neck flexion	−0.05	−0.31
Upper neck extension	+0.06	+0.38
Lower neck tension	+0.15	−0.09
Lower neck shear	0.00	−0.46
Lower neck flexion	−0.14	+0.24
Lower neck extension	−0.09	−0.44
T1 acceleration	−0.06	−0.16
NIC	−0.11	−0.34
Head contact time	−0.18	−0.27
Nkm (NEA, NEP, NFA, NFP)	+0.18, +0.05, −0.09, −0.07	−0.20, +0.49, −0.36, 0.00

High-Severity Occupant Retention and Insurance Injury Data

Weighted linear regression models were used to assess potential trade-offs between high-severity occupant retention and real-world injury claim rates in rear impacts. Claim rates from insurance data are shown in Table II. The models did not indicate statistically significant relationships between lower maximum dynamic seatback rotation or vertical pelvis displacement and insurance injury claims. While controlling for vehicle curb weight, a 10° increase in seatback rotation was associated with an injury claim rate reduction of 1.5% (R^2_{adj}=-0.13, p=0.5), and a 50 mm increase in pelvis z displacement was associated with an injury claim rate increase of 1.7% (R^2_{adj}=-0.01, p=0.25). A model controlling for both metrics produced estimates of similar magnitudes and did not provide a better fit to the data (R^2_{adj}=-0.04).

Additional regression analysis was conducted to identify if any other high-severity test metrics were related to real-world injury claim rates. A separate weighted linear regression model was fit for each of the test metrics that were collected in all 11 midsize car tests while controlling for vehicle curb weight. Nkm-NEA was the only metric that had a statistically significant effect on injury claim rate at the p = 0.05 level. A 0.1 unit increase in Nkm-NEA was estimated to increase the injury claim rate by 1.8% (R^2_{adj}=0.67, p=0.002). Upper neck rearward shear was the only metric with an estimated negative effect on injury claim rate, indicating that a 100 N increase in shear was associated with a 5.1% reduction in injury claim rate. However, this result was not statistically significant (R^2_{adj}=0.12, p=0.13) and the measured shear values were largely under 100 N, which is 3% of the IARV.

Additional models controlling for Nkm-NEA indicated that dynamic seatback rotation and vertical pelvis displacement still did not have significant effects on injury claim rates (p=0.35 and p=0.22, respectively). A model including Nkm-NEA and longitudinal pelvis displacement was the only one with statistically significant effects for two test metrics and provided the best fit to the real-world insurance injury claim rates (R^2_{adj}=0.87) (Fig. 5). Detailed results for selected regression models are shown in Table IV, and test results for Nkm-NEA and longitudinal pelvis displacement are shown in Appendix Table A-III.

TABLE IV
REGRESSION MODEL RESULTS

Model	Term	Estimate	p-value	R^2_{adj}
1	Intercept	0.301	0.19	−0.13
	Curb weight (100 kg)	−0.009	0.53	
	Rotation (10°)	−0.015	0.51	
2	Intercept	0.267	0.20	−0.01
	Curb weight (100 kg)	−0.011	0.42	
	Pelvis z displacement (50 mm)	0.017	0.25	
3	Intercept	0.310	0.18	−0.08
	Curb weight (100 kg)	−0.012	0.42	
	Rotation (10°)	−0.014	0.51	
	Pelvis z displacement (50 mm)	0.017	0.28	
4	Intercept	0.381	0.01	0.67
	Curb weight (100 kg)	−0.019	0.04	
	Nkm-NEA (0.1 unit)	0.018	0.002	
5	Intercept	0.483	<0.001	0.87
	Curb weight (100 kg)	-0.020	0.004	
	Nkm-NEA (0.1 unit)	0.019	<0.001	
	Pelvis x displacement (50 mm)	-0.023	0.01	

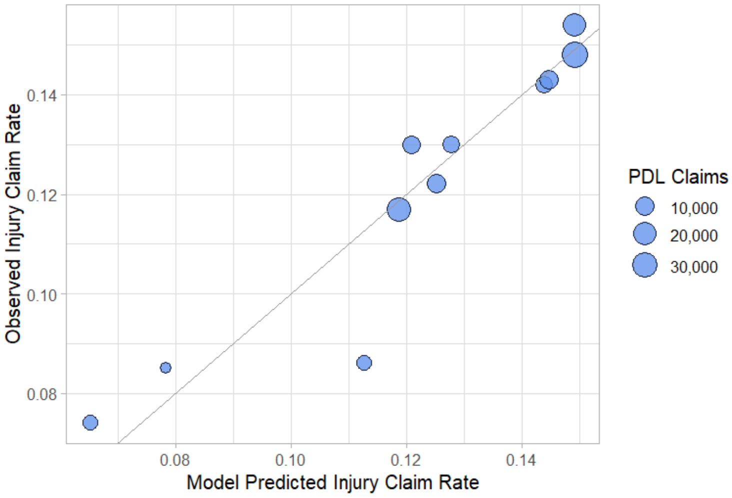


Fig. 5. Predicted vs. observed claim rate for midsize cars. Regression model included vehicle curb weight, Nkm-NEA and longitudinal pelvis displacement.

Low-Severity Test Metrics and Insurance Injury Data

To provide a comparison with the high-severity test results, a similar regression analysis was conducted using whiplash metrics measured for the same seats during low-severity (IIHS) tests. Individual models including each of the test metrics indicated that none of them had a statistically significant effect on injury claim rate at the $p = 0.05$ level. Upper and lower neck shear forces and moments, NIC, HCT and T1 acceleration had the weakest effects ($R^2_{adj} \leq -0.09$, $p \geq 0.4$). Head rebound velocity and longitudinal pelvis displacement, a metric not typically used in whiplash evaluations, had stronger effects ($R^2_{adj} = 0.15$ and 0.24, $p = 0.11$ and 0.06, respectively). Test results for longitudinal pelvis displacement are shown in Appendix Table A-III.

Pressure Sensor Data

The relationships between the maximum load measured by the XSensor pressure sensor in the high-severity tests and the maximum dynamic seatback rotation, vertical pelvis displacement and longitudinal pelvis displacement were evaluated. Pearson correlation coefficients between each of these three metrics and estimated maximum load all were negative, indicating that lower values of each metric tended to produce higher loads between the seat and the occupant, but the relationships were weak ($-0.39 < r < -0.14$). Fig. 6 shows the estimated load plotted against the seatback rotation for the two seats with the lowest injury claim rates in the insurance data. The Mazda 6 had higher seatback rotations and lower loads between the occupant and seat. The Subaru Legacy/Outback had lower seatback rotations, higher estimated loads and lower injury claim rates than the Mazda 6.

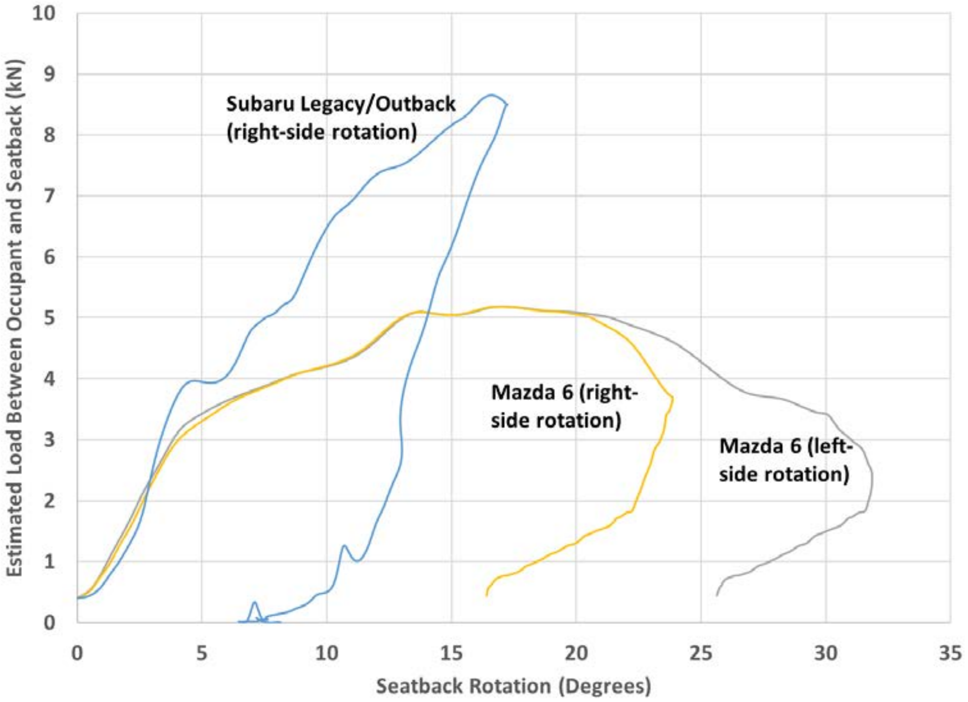


Fig. 6. Calculated load between occupant and seatback vs. seatback rotation for seats with low-injury claim rates in insurance data.

IV. DISCUSSION

In rear-impact crashes, the seat provides the primary occupant restraint for preventing hard impact with the vehicle interior or other occupants. This series of tests was conducted to provide information on the relative performance of modern seats as occupant restraints in high-severity rear-impact crashes, while also assessing if trade-offs exist in occupant injury protection performance for low-severity rear-impact crashes.

Viano simulated high-severity rear impacts and reported that when seatbacks rotate rearward beyond 60° from vertical, restraint is diminished, allowing the occupant to move up and off the seatback [4]. This injury causation scenario was observed in NASS-CDS crash case #2011-049-57A reported by Viano and Parenteau, where the seatback rotated rearward significantly, and the occupant moved up the seatback beyond the head restraint and impacted the rear seatback, resulting in brain and cervical spine injury [11]. The seats in the current study had dynamic rotation angles from 15.4° to 47.2°; when accounting for the initial angle, this results in a range of 36.5° to 70.5° from vertical. Of the 26 seats tested in the current study, only one exceeded the 60° threshold observed by Viano. None of the belted occupants in these tests were ejected from the seat during initial loading; however, the one seat with the highest seatback rotation allowed the occupant to submarine under the lap belt during rebound and sled braking, which could be relevant in real-world crashes with subsequent impacts. Based on the seatback rotations and observed occupant retention, the majority of seats in modern vehicles likely provide adequate occupant restraint for belted occupants at this crash severity. However, seat restraint performance is significantly affected by occupant mass. In the NASS-CDS case cited previously, the 141 kg driver suffered fatal injuries while the 68 kg right front passenger had no documented injuries. The seatback rotations measured in the current test with a 78 kg ATD would increase with occupant mass or crash severity, but the relative performance of the seats likely would remain similar. As expected, longitudinal head displacement was correlated to seatback rotation, indicating that higher seatback rotations could increase the risk of head impacts with interior components or other occupants.

One effect of significant vertical movement of the occupant up the seatback is the increased risk of head injury to occupants in both rows as the head restraint is bypassed. Saczalski et al. studied injury to rear-seated children in rear-impact crashes and found that head-to-head contact was one source of serious head injury [12]. In the current study, vertical pelvis displacement ranged from 41 to 144 mm. Belt pretensioner deployment appeared to reduce vertical pelvis displacement in this test series. While paired tests of the same seat with and without pretensioner deployment were not conducted, the maximum displacement for the 11 of the seats with deployed pretensioners was 67 mm, while only 2 of the 15 seats without pretensioner deployment had displacements below this value. This trend contrasts with the findings of Viano et al. on the influence of lap belt pretensioning systems, though the majority of belt pretensioning systems deployed in the current test series activated in both the lap belt and retractor [23].

Early research on seat design indicated the possibility of a design conflict between rear-impact occupant injury protection in high- and low-severity crashes. Much research supported "stiff" or "rigid" seatbacks for high-severity occupant retention or "yielding" seatbacks to limit occupant loads in more frequent, lower severity crashes. However, research later shifted to developing designs that could meet the restraint demands for a range of crash severities. The results of the current study suggest that modern seat designs are capable of maintaining a level of high-severity crash protection, as measured by seatback rotation and vertical pelvis displacement, without a necessary reduction in low-severity crash protection. There were no strong negative correlations between high- and low-severity test metrics for the 26 tested seats. Of the metrics with some negative correlation with high-severity vertical pelvis displacement, most of these seats had very low values of upper neck shear and Nkm-NFA in the low-severity whiplash tests (median values of 0.1 N and 0.00, respectively). As indicated by the magnitude of the correlation coefficients, the remaining metrics with a negative relationship to vertical pelvis displacement, upper neck tension, lower neck shear, upper neck flexion moment, lower neck extension moment and NIC showed a wide range of vertical pelvis displacements over a small range of low-severity test results. This demonstrates that greater vertical pelvis displacement in the high-severity test is not required to achieve better results in the low-severity test. For the 11 seats from midsize cars with insurance claim data, ATD retention in the high-severity tests did not have a significant effect on injury claim rates.

While results of the current study suggest that a protection trade-off is not necessary, they do not imply that all seat designs avoid such a trade-off. For example, the seat with the highest dynamic rotation (31.9°) of all the midsize cars had one of the lowest injury claim rates. It is possible that this design achieves a relatively low-injury risk in low-severity crashes at the expense of retention at higher severities. However, comparing the one design with an even lower injury claim rate (Fig. 6) demonstrates that lower overall seat strength is not a requirement for better real-world results. Other research has described in more detail how trade-offs may be avoided. Viano described the "High-Retention Seat," which reduced seatback rotations with a strong frame while limiting the energy transfer to the occupant with a compliant seatback inside the frame [24]. The introduction of the original Volvo WHIPS energy-absorbing seat was associated with significantly reduced neck injury claims in rear-impact crashes [25]. The manufacturer claims the WHIPS generation 2 represents further progress toward optimization with a “robust design, even support and energy absorption in different crash severities [8].”

In addition to analyzing whether modern seats provide protection in both low- and high-severity rear impacts, the current study allowed a comparison of the relationship between test metrics collected at both severities and the injury claim rates for 11 midsize cars. The only metric with a statistically significant effect on injury claim rate while controlling for vehicle curb weight was Nkm-NEA in the high-severity test. Given that this metric was measured on an ATD not designed for rear-impact testing and in a test significantly more severe than the one used to assess common whiplash injuries, this finding requires further research. An additional regression model including high-severity Nkm-NEA and longitudinal pelvis displacement while controlling for vehicle curb weight provided an even better fit to the insurance injury claim rates. This model indicated that, after controlling for the beneficial effects of higher vehicle curb weight, seats that limited Nkm-NEA while allowing more longitudinal pelvis displacement into the seat produced lower injury claim rates.

While the association between high-severity test metrics and injury claim rates was unexpected, the effects of each of the variables in this regression model are supported by previous findings. Vehicle weight is a known factor in risk of injury in rear-impact crashes [21]. Nkm combines upper neck longitudinal shear force with upper neck extension and flexion moment [19]. The particular mode that was maximized in the high-severity test series, NEA, combines head rearward shear force and extension moment, a combination that can be observed when the head is not well supported. Longitudinal pelvis displacement may quantify the energy-absorbing characteristics of a seat. Greater pelvis displacement into the seatback implies that more crash energy was used in the deformation process and less was transferred to the occupant. Viano described the energy management capabilities of seats in terms of their ability to maintain a similar recline angle using a strong perimeter frame while allowing pelvis and torso displacement into the seatback, and, when combined with good head restraint support, demonstrated that these characteristics help control neck loads and extension [4]. These design principles align with the results of the current study. Combining these seat design principles with good overall occupant-retention performance in high-severity tests could provide seat designs optimized for occupant protection over a wide range of severities.

None of the typical metrics for whiplash injury assessment collected in the low-severity tests had significant effects on injury claim rate. In fact, the longitudinal pelvis displacement of BioRID into the seat, a metric not currently used in assessing whiplash performance, was the best predictor of injury claim rate. In combination with the significant effect of Hybrid III longitudinal pelvis displacement in the high-severity tests after controlling for Nkm-NEA, this suggests that longitudinal pelvis displacement should be further evaluated for its ability to predict relative risk of real-world injury. Taken together, the results from both test severities indicate the possibility that the current IIHS test severity may not be the most relevant for assessing real-world injury risk in modern seats. All of the seat designs included in the current study achieved good ratings in the IIHS whiplash evaluation and 98% of current model year vehicles have a good IIHS whiplash rating. The lack of significant relationships between injury metrics and outcomes for the good-rated seats in this study does not imply that the whiplash evaluation is irrelevant to real-world injury outcomes. In fact, Farmer et al. found a lower risk of neck injury was associated with good whiplash ratings and Trempel et al. found a strong correlation between better IIHS whiplash ratings and lower injury claim rates [21,25]. The results do imply, however, that a higher severity test may better discern the differences between seats already highly rated by IIHS. An analysis of injury symptom duration related to crash recorder-based crash severity by Krafft et al. found that 7 of the 15 occupants with symptoms lasting one month or longer experienced a crash delta V greater than the IIHS pulse (16 km/h) [26]. Additional research should address the possibility that higher severities may be more relevant than the current IIHS severity for assessing real-world injury risk in modern seats.

The results of this study are limited in several ways. First, the Hybrid III dummy and related IARVs were designed for frontal impacts, though the dummy currently is used in U.S. and global rear-impact regulation protocols. Additionally, the critical values used in calculating the injury criteria Nkm were based on research conducted with the BioRID II dummy and with the Hybrid III dummy equipped with the RID neck, while the current study used the standard Hybrid III neck.

There are further limitations associated with the correlation of test metrics with real-world insurance data. Injury claim rate analyses were based on a sample of 11 midsize cars; especially for assessing validity of the Nkm and longitudinal pelvis displacement result, more data are needed. Additionally, analyses were performed using raw insurance claim rates and did not control for factors such as age and gender of the rated driver. Analyses controlling for vehicle and rated driver factors will be performed in future research. Furthermore, factors such as crash severity and structural alignment between vehicles also could influence the real-world injury claim rates. However, the large number of claims used per vehicle in this study largely mitigates the influence of these variables on the injury claim rate.

V. CONCLUSION

The majority of seats in this test series provided adequate occupant retention for a 78 kg ATD in this 36 km/h delta V simulated rear impact. However, there was a range of performance as measured by seatback rotation and vertical pelvis displacement, and this could be relevant to the protection offered to occupants of greater mass or in higher severity crashes. Lower values of seatback rotation or vertical pelvis displacement in the high-severity test were not strongly linked with increases in low-severity injury test metrics or real-world injury claim rates, indicating that some seats in the modern fleet provide occupant retention at high severities and whiplash injury protection at low severities. High-severity test metrics had a greater effect on the midsize car rear-impact injury claim rates than low-severity test metrics. After controlling for curb weight, seats which limited high-severity test Nkm-NEA while allowing greater longitudinal pelvis displacement were associated with lower real-world injury claim rates. The longitudinal pelvis displacement in low-severity tests was a better predictor of injury claim rates than commonly used whiplash injury test metrics.

VI. ACKNOWLEDGEMENTS

The authors greatly appreciate the generous support of several automakers for this test series and would like to thank Ford Motor Company, Honda R&D Americas, Inc.; Hyundai America Technical Center, Inc.; Nissan North America, Inc.; Toyota Motor North America R&D and Volkswagen Group of America, Inc. for donating vehicle seats and/or facilitating the purchase and assembly of seats.

VII. REFERENCES

[1] Saunders, J., Molino, L.N., Kuppa, S., and McKoy, F.L. Performance of seating systems in a FMVSS No. 301 rear impact crash test. *Proceedings of 18th International Technical Conference on the Enhanced Safety of Vehicles*, 2003. Nagoya, Japan.

[2] Herbst, B.R., Meyer, S.E., Oliver, A.A., and Forrest, S.M. Rear impact test methodologies: quasistatic and dynamic. *Proceedings of 21st International Technical Conference on the Enhanced Safety of Vehicles*, 2009. Stuttgart, Germany.

[3] Molino, L.N. Determination of moment-deflection characteristics of automobile seatbacks, in *NHTSA Technical Report 4064*. 1998, National Highway Traffic Safety Administration, DOT Docket Management System: Washington, DC, USA.

[4] Viano, D.C., "Role of the Seat in Rear Crash Safety". 2002, Warrendale, PA, USA: SAE International.

[5] Severy, D.M., Brink, H.M., and Baird, J.D. Vehicle design for passenger protection from high-speed rear-end collisions, in *SAE Technical Paper 680774*. 1968, SAE International: Warrendale, PA, USA.

[6] Saczalski, K.J., Syson, S.R., Hille, R.A., and Pozzi, M.C. Field accident evaluations and experimental study of seat back performance relative to rear-impact occupant protection, in *SAE Technical Paper 930346*. 1993, SAE International: Warrendale, PA, USA.

[7] Prasad, P., Kim, A., Weerappuli, D.P.V., Roberts, V., and Schneider, D. Relationship between passenger car seat back strength and occupant injury severity in rear end collisions: Field and laboratory studies, in *SAE Technical Paper 973343*. 1997, SAE International: Warrendale, PA, USA.

[8] Jakobsson, L., Lindman, M., Björklund, M., and Victor, T. Rear-end impact – crash prevention and occupant protection. *Proceedings of IRCOBI Conference*, 2015. Lyon, France.

[9] National Highway Traffic Safety Administration. Traffic Safety Facts 2016, in *Report DOT HS 812 554*. May 2018, National Center for Statistics and Analysis, U.S. Department of Transportation: Washington, DC, USA.

[10] Viano, D.C. and Parenteau, C.S. Serious injury in very-low and very-high speed rear impacts. *Proceedings of SAE World Congress*, 2008. Detroit, MI, USA.

[11] Viano, D.C. and Parenteau, C.S. Effectiveness of the revision to FMVSS 301: FARS and NASS-CDS analysis of fatalities and severe injuries in rear impacts. *Accid Anal Prev*, 2016. 89: p. 1–8.

[12] Saczalski, K.J., Burton, J.L., Lewis, P.R., Friedman, K., and Saczalski, T.K. Study of seat system performance related to injury of rear seated children & infants in rear impacts. *Proceedings of ASME 2002 International Mechanical Engineering Congress & Exposition (IMECE)*, 2002. New Orleans, LA, USA.

[13] Tatem, W.M. and Gabler, H.C. Preliminary analysis of serious-to-fatal injury in rear impact crashes in the United States. *Proceedings of IRCOBI Conference*, 2017. Brussels, Belgium.

[14] Highway Loss Data Institute. Technical Appendix. May 2010: Arlington, VA, USA.

[15] Ragland, C.L. Research tests to develop improved FMVSS 301 rear impact test procedure. *Proceedings of 16th International Technical Conference on the Enhanced Safety of Vehicles*, 1998. Windsor, Ontario, Canada.

[16] Society of Automotive Engineers. Devices for use in defining and measuring vehicle seating accommodation, in *Surface Vehicle Standard (J826)*. 2015, SAE International: Warrenton, PA, USA.

[17] Society of Automotive Engineers. Instrumentation for impact test – Part 1 – Electronic instrumentation, in *Surface Vehicle Recommended Practice (J211)*. 1995, SAE International: Warenton, PA, USA.

[18] Boström, O., Svensson, M.Y., et al. A new neck injury criterion candidate-based on injury findings in the cervical spinal ganglia after neck extension trauma. *Proceedings of IRCOBI Conference*, 1996. Dublin, Ireland.

[19] Schmitt, K.U., Muser, M.H., and Niederer, P. A new neck injury criterion candidate for rear-end collisions taking into account shear forces and bending moments. *Proceedings of 17th International Conference on the Enhanced Safety of Vehicles*, 2001. Amsterdam, The Netherlands.

[20] Insurance Institute for Highway Safety. "Vehicle seat/head restraint evaluation protocol, dynamic criteria" Internet https://www.iihs.org/ratings/about-our-tests/test-protocols-and-technical-information. [cited 2019 May 16th].

[21] Trempel, R.E., Zuby, D.S., and Edwards, M.A. IIHS head restraint ratings and insurance injury claim rates. *Traffic Inj Prev*, 2016. 17(6): p. 590-596.

[22] Mertz, H.J., Irwin, A., and Prasad, P. Biomechanical and scaling bases for frontal and side impact injury assessment reference values. *Stapp Car Crash J*, 2003. 47: p. 155-188

[23] Viano, D.C., Parenteau, C.S., and Burnett, R. Influence of belt pretensioning on dummy responses in 40 km/h rear-impact sled tests. *Traffic Inj Prev*, 2012. 13(1): p. 65-71.

[24] Viano, D.C. Seat properties affecting neck responses in rear crashes: A reason why whiplash has increased. *Traffic Inj Prev*, 2003. 4(3): p. 214-227.

[25] Farmer, C.M., Wells, J.K., and Lund, A.K. Effects of head restraint and seat redesign on neck injury risk in rear-end crashes. *Traffic Inj Prev*, 2003. 4(2): p. 83-90.

[26] Krafft, M., Kullgren, A., Ydenius, A., and Tingvall, C. Influence of crash pulse characteristics on whiplash associated disorders in rear impacts – Crash recording in real life crashes. *Traffic Inj Prev*, 2002. 3(2): p. 141-149

[27] Highway Loss Data Institute. Distribution of PDL claims by claims by claim size, 2017 calendar year. *Loss Bulletin*, 2018. 35(18): p. 1-6.

VIII. APPENDIX

TABLE A-I

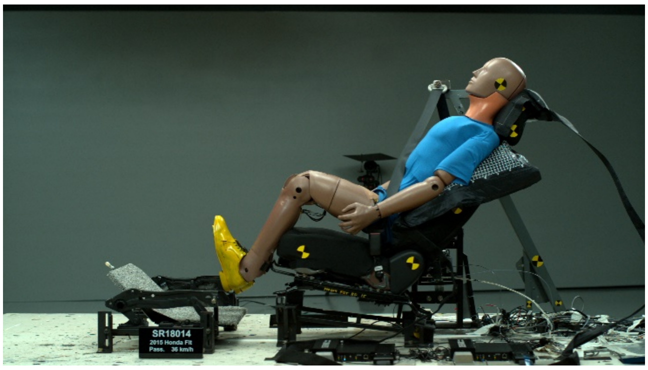
CHANNEL FILTER CLASSES FOR EACH DUMMY SENSOR

Sensor	Filter
Head accelerations	CFC 1000
Chest accelerations	CFC 180
Pelvis accelerations	CFC 1000
Head, chest, pelvis angular rate	CFC 180
Upper and lower neck forces and moments	CFC 60
Lumbar forces and moments	CFC 600
Chest deflections	CFC 600
Lap belt load	CFC 60
Sled acceleration	CFC 60

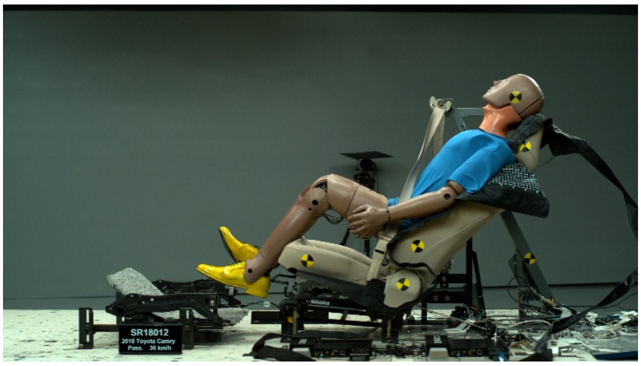
[17]

TABLE A-II

VIDEO FRAME OF EACH TESTED SEAT TAKEN AT THE MAXIMUM DYNAMIC SEATBACK ROTATION ANGLE



2019—2019 Honda Fit (110 ms)



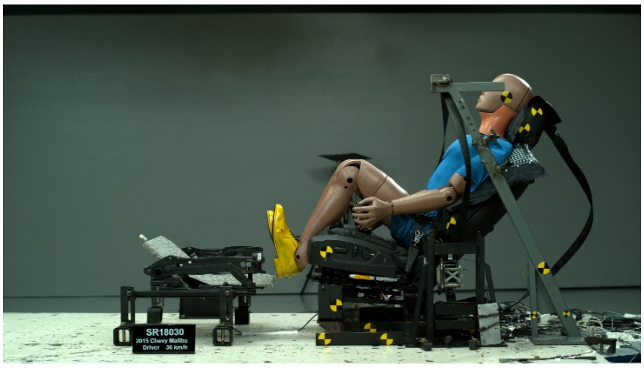
2018-–2019 Toyota Camry (118 ms)

2017-–2019 Chevrolet Bolt (111 ms)

2012-–2019 Volkswagen Passat (108 ms)

2017-–2019 Mini Countryman (110 ms)

2017-–2019 Kia Cadenza (111 ms)



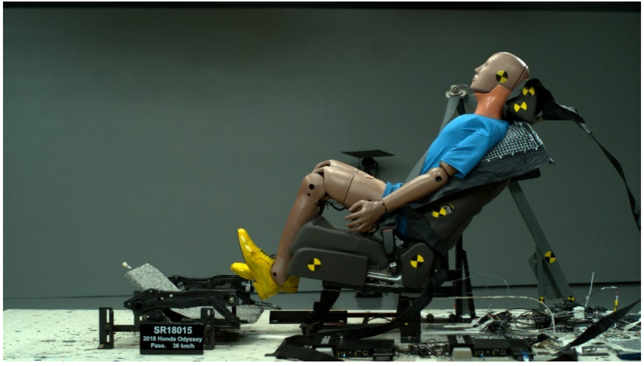
2013-–2015 Chevrolet Malibu (106 ms)

2017-–2019 BMW 5 Series (123 ms)

2013-–2019 Ford Fusion (133 ms)

2017-–2019 Mercedes E-class (101 ms)

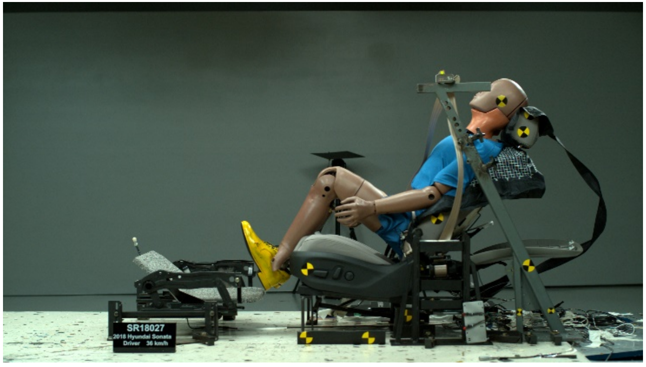
2013-–2017 Honda Accord (117 ms)



2018-–2019 Honda Odyssey (110 ms)

2018-–2019 Honda Accord (109 ms)

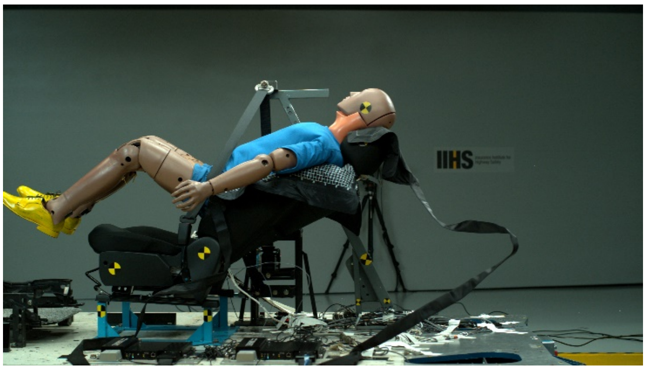
2018-–2019 BMW X3 (117 ms)



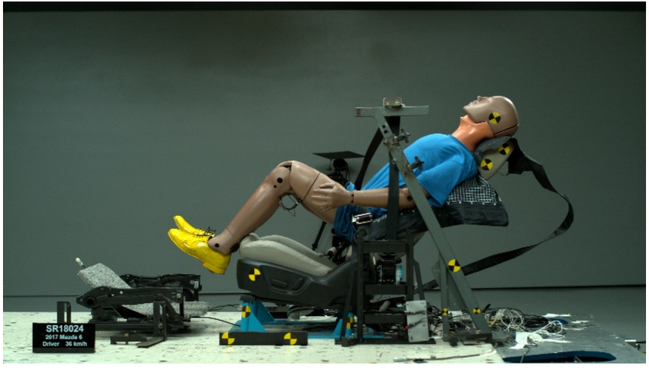
2015–2019 Hyundai Sonata (110 ms)

2017–2019 Jeep Compass (109)

2012–2015 Kia Optima (115 ms)



2017–2019 Mazda CX-5 (200 ms)



2014–2019 Mazda 6 (143 ms)

2018–2019 Volkswagen Tiguan (102 ms)

2013–2018 Nissan Altima (133 ms)

2018–2019 Volvo XC60 (111)

2015–2019 Subaru Legacy/Outback (107 ms)

2015–2019 Chevrolet Colorado (111 ms)

2012–2017 Toyota Camry (115 ms)

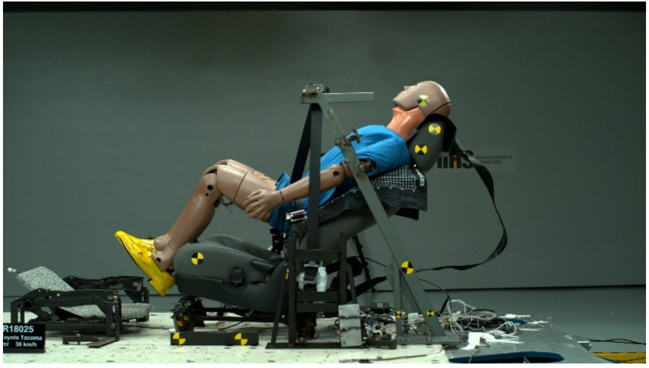

2016–2019 Toyota Tacoma (162 ms)

TABLE A-III
TEST RESULTS FOR NKM-NEA AND LONGITUDINAL PELVIS DISPLACEMENT

	High-Severity Longitudinal Pelvis Displacement (mm)	High-Severity Nkm-NEA	Low-Severity Longitudinal Pelvis Displacement (mm)
2017–2019 Mercedes E-class	121	0.02	118
2015–2019 Subaru Legacy	235	0.12	162
2012–2019 Volkswagen Passat	186	0.13	130
2018–2019 Volkswagen Tiguan	148	0.15	142
2015–2019 Hyundai Sonata	158	0.18	138
2018–2019 Honda Odyssey	153	0.00	128
2015–2019 Chevrolet Colorado	176	0.09	141
2017–2019 Jeep Compass	193	0.08	153
2018–2019 Honda Accord	183	0.42	148
2015–2019 Honda Fit	156	0.00	157
2013–2015 Chevrolet Malibu	165	0.04	139
2017–2019 Mini Countryman	150	0.19	143
2017–2019 Kia Cadenza	173	0.18	134
2012–2017 Toyota Camry	181	0.31	141
2012–2015 Kia Optima	217	0.32	157
2017–2019 Chevrolet Bolt	147	0.07	126
2013–2018 Nissan Altima	195	0.27	145
2018–2019 BMW X3	175	0.00	138
2018–2019 VolvoXC60	176	0.18	125
2013–2017 Honda Accord	190	0.09	167
2018–2019 Volvo XC60	178	0.20	125
2017–2019 BMW 5 Series	136	0.00	112
2018–2019 Toyota Camry	209	0.31	136
2013–2019 Ford Fusion	162	0.18	142
2016–2019 Toyota Tacoma	203	0.00	121
2014–2019 Mazda 6 4dr	219	0.15	148
2017–2019 Mazda CX-5	212	0.15	154

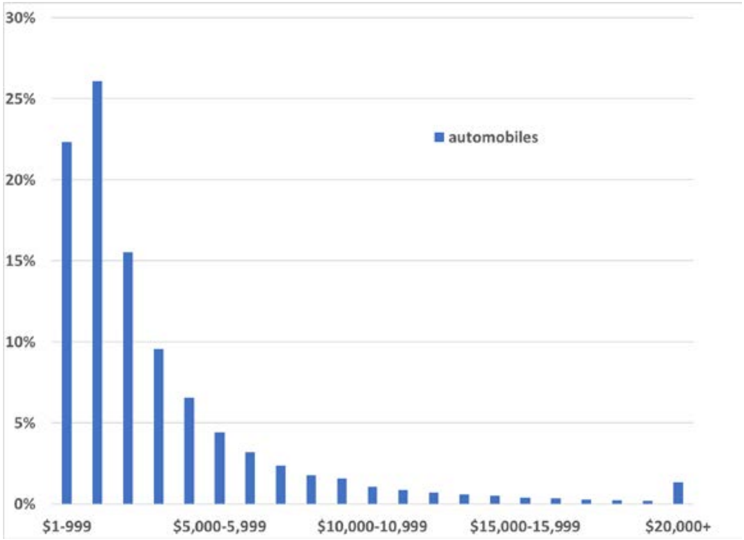


Fig. A-1. Distribution of PDL claims by claim size, 1981–2018 model years, calendar year 2017 [27].

TABLE A-IV

VEHICLE AND AVERAGE PULSE CHARACTERISTICS

	Average	Midsize car A	Midsize car B	Midsize car C	Midsize car D	Midsize car E	Midsize car F	Midsize car G	Midsize car H	Standard Deviation
Mean Acceleration (g)	6.8	7.0	6.8	7.3	6.4	6.4	7.2	7.2	6.5	0.4
Delta V (km/h)	36.5	37.7	36.3	38.5	35.5	33.7	38.4	38.8	34.8	1.8

Erratum

Seat Design Characteristics Affecting Occupant Safety in Low- and High-Severity Rear-Impact Collisions

Marcy A. Edwards, Matthew L. Brumbelow, Rebecca E. Trempel, Timothy C. Gorjanc

Further examination of the video footage of the Mazda CX-5 seat test in this study suggests the possibility that one of the dummy instrumentation cables may have activated the seat back recline lever during the test, resulting in increased seatback rotation; though post-test investigation of the seat could not conclusively confirm this. As such, the dynamic recline angle presented in the paper should not be interpreted as definitive evidence of what might occur when other Mazda CX-5 seats of similar construction are subjected to the same dynamic loads.

With the exception of the descriptions of the range of seat performance, the observations and conclusions presented in the paper are not affected by excluding the result of the Mazda CX-5. The following table revises Table III from the paper with Pearson coefficients recomputed without the Mazda CX-5 dynamic recline angle result.

Pearson Correlation Coefficients for High-severity vs. Low-severity Metrics

IIHS Metric	**High-Severity Metric**			
	Seatback Rotation		Vertical Pelvis Displacement	
	With CX-5	Without CX-5	With CX-5	Without CX-5
Upper neck tension	+0.09	+0.24	−0.37	−0.36
Upper neck shear	−0.06	−0.02	−0.34	−0.34
Upper neck flexion	−0.05	+0.14	−0.31	−0.28
Upper neck extension	+0.06	+0.23	+0.38	+0.43
Lower neck tension	+0.15	+0.14	−0.09	−0.11
Lower neck shear	0.00	+0.18	−0.46	−0.44
Lower neck flexion	−0.14	−0.18	+0.24	+0.26
Lower neck extension	−0.09	+0.17	−0.44	−0.40
T1 acceleration	−0.06	+0.16	−0.16	−0.11
NIC	−0.11	+0.05	−0.34	−0.31
Head contact time	−0.18	−0.16	−0.27	−0.25
Nkm (NEA, NEP, NFA, NFP)	+0.18, +0.05, −0.09, −0.07	+0.32, +0.22, −0.07, +0.05	−0.20, +0.49, −0.36, 0.00	−0.20, +0.54, −0.36, +0.04