Relationship of Whiplash Injury Metrics and Crash Pulse Severity to Injury Claim Rates

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Abstract

While almost all modern seats receive good Insurance Institute for Highway Safety rear-impact ratings, they still are associated with a relatively large range of injury claim rates in insurance data. This study evaluated whether alternate rear-impact crash pulses and associated test metrics improve correlations with injury claim rates. A total of 50 rear impact sled tests were conducted using three different crash pulses: 16 km/h (Insurance Institute for Highway Safety, European New Car Assessment Programme (Euro NCAP)), 20 km/h (Japan NCAP) and 24 km/h (Euro NCAP). Poisson regression was used to study the effects of principal components and selected individual test metrics on the rate of rear-impact personal injury protection claims per property damage liability claim while controlling for vehicle class. After correlation analysis, six individual metrics were selected for modelling. Increasing values of three (all from the 24-km/h test) were estimated to increase the injury claim rate at $\alpha = 0.05$: T1 acceleration ($p = 0.01$), NKM ($p = 0.004$), and Head Contact Time (HCT) ($p = 0.04$). While many of the measures collected from the three different tests were correlated, results indicate the 24-km/h pulse is important for establishing meaningful differences between seat designs.

Keywords Consumer ratings programmes, rear-impact occupant protection, rear impacts, whiplash.

I. INTRODUCTION

In 2020, the U.S. National Highway Transportation Safety Administration (NHTSA) reported that rear-impact crashes accounted for 27.8% of all passenger vehicle crashes and 26.2% of injuries [1]. Insurers report that nearly two-thirds of insurance claims report neck injury as the most serious injury in a crash [2]. Though neck injuries in rear impacts are generally not life-threatening, the frequency of rear-impact crashes and related neck injuries makes addressing the societal cost of these injuries a priority. The Insurance Institute for Highway Safety (IIHS) and the Swedish Road Administration (SRA) in cooperation with Folksam Insurance both began publishing ratings in 2003 designed to encourage seat designs that reduce the risk of neck injury in rear-impact crashes. The SRA ratings evaluated seats based on three different pulses, while IIHS evaluations were based on a single pulse. In 2009, the European New Car Assessment Programme (Euro NCAP) also launched a rating programme to evaluate seats based on three different pulses. Today, NCAP programmes worldwide incorporate rear-impact whiplash assessments in their overall ratings using a variety of crash pulses and evaluation criteria.

The effectiveness of these programmes has been assessed several times since their inception. In 2008, [3] showed that the rate of neck injuries in IIHS good-rated seats was 15% lower than poor rated seats. In the same study, injury rates for treatment lasting more than 3 months were 35% lower for good- vs. poor-rated seats [3]. A study by [4] in 2015 looked at the relationship between test results for the Euro NCAP, IIHS and Japan NCAP (JNCAP) evaluation programmes and permanent medical impairment (PMI) rates from Folksam insurer data and found that all three ratings programmes aligned with rates of PMI. A more recent study by IIHS in 2016 showed that better rated seats (for all rating categories) in the IIHS evaluation had lower insurance injury claim rates [5]. Overall, IIHS observed a 39% decrease in neck injury claim rates between 1999 and 2008 [3]. The mechanisms for whiplash injury are still under investigation, and ratings organisations have long relied on dummy kinematics and principles of biomechanics to encourage seats that reduce loads and accelerations on occupants. Test metrics currently used in ratings programmes focus on reducing tension and shear forces and moments in the upper and lower neck, reducing accelerations and ensuring that the head and neck are supported early in the crash. Several researchers have studied proposed injury metrics and their relationships with insurer data. Reference [6] identified Neck Injury Criterion (NIC), NKM, upper neck loads and T1 X-acceleration as priority metrics for further analysis. A 2008 study by [3] found that alternate combinations of metrics did not improve on the correlations of the already established rating scheme using upper neck shear force and tension, T1 X-acceleration and time to head contacting the head restraint (HCT). Reference [4] in 2015 found that NIC from all three Euro NCAP pulses, upper neck tension in the high-severity pulse and rebound velocity in the low-severity pulse were the best predictors of permanent medical impairment.

From 2004–2022, IIHS used a 16-km/h delta V, 10 g peak acceleration pulse to evaluate seats with the BioRID dummy using upper neck shear force and tension, T1 X-acceleration and HCT. In 2006, shortly after IIHS began rating seats, only 16% of vehicles were rated good, but in 2022, 98% percent of vehicles were rated good with this method. While this has been associated with the overall improvements outlined above, insurer data for vehicles with good-rated seats still suggest a range of performance in real-world crashes. The rate of claims for injury coverage relative to those for property damage can range from 7% to 15% for modern vehicles. This translates into a large difference in the number of injuries given the high rates of rear-impact crashes. While IIHS ratings no longer differentiate between seats in ways that align with the range of injury claim rates, there are additional crash pulses and evaluation metrics that have not been used by IIHS. This study evaluated whether these alternate rear-impact crash pulses and associated test metrics improve correlations with injury claim rates for modern seats.

II. METHODS

A total of 50 sled tests were conducted on an acceleration sled oriented to simulate a rear-impact crash. Twenty-one unique seat designs were tested, representing 36 vehicle models. Eight seats from the midsize car class were tested with three different acceleration pulses (16 km/h, 20 km/h and 24 km/h) and 13 seats from the midsize SUV class were tested using only the 16-km/h and 24-km/h pulses. Table I provides a complete list of all seats tested. All seats received a good rating in the IIHS evaluation.

Crash pulses were chosen from current worldwide consumer-information programmes, including Euro NCAP, JNCAP and IIHS. Fig. 1 shows the Euro NCAP and IIHS 16-km/h pulse, the JNCAP 20-km/h and the Euro NCAP 24-km/h pulses used for testing. The highest delta V pulse has the lowest peak acceleration, but as the durations of all three pulses are similar, the mean accelerations align in severity with the delta V. The BioRID dummy was used as the human surrogate in these tests, and the seat and dummy were positioned according to the *IIHS Vehicle Seat/Head Restraint Evaluation Protocol, Dynamic Criteria*, regardless of which pulse was being tested [7].

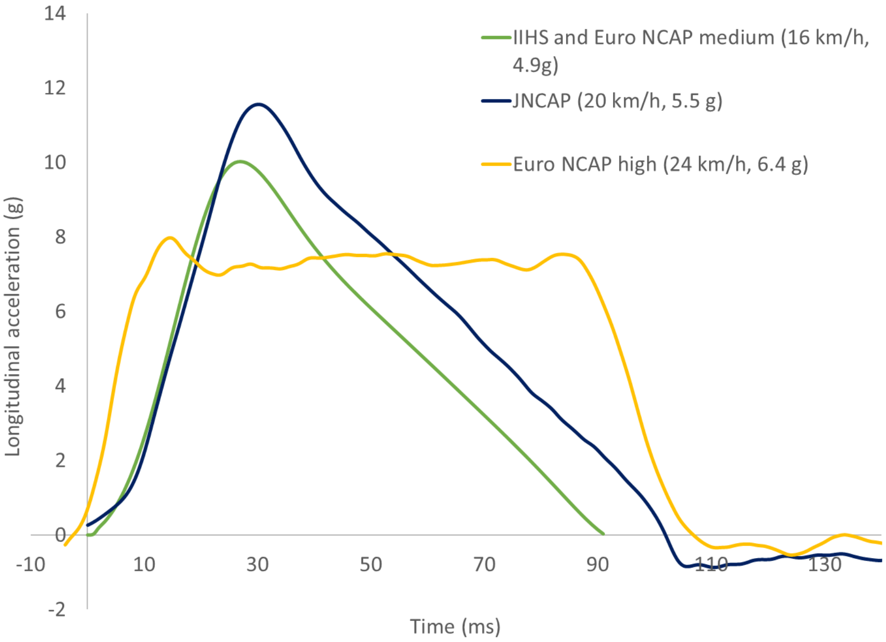

Fig. 1. Longitudinal acceleration pulses used in sled testing from IIHS, Euro NCAP and JNCAP.

Twenty dummy metrics (Fig. 2) were collected from BioRID in the rear-impact sled tests using the three different acceleration pulses. Dummy sensors recorded upper and lower neck sagittal shear force (Fx), tension force (Fz) and flexion/extension moment, head triaxial accelerations, T1, L4 and L1 vertebrae longitudinal accelerations, and pelvis vertical and longitudinal accelerations. From these, additional whiplash injury metrics were calculated: NIC, NKM (NEP, NFP, NEA, NFA), rebound velocity and longitudinal pelvis displacement relative to the sled and seat [8] [9]. Upper neck extension/flexion moments reported in this paper have been corrected to reflect the moments at the Occipital Condyle/C1 vertebrae junction rather than at the location of the upper neck load cell. Externally, sled accelerations and the time for the head to contact the head restraint (HCT) after the onset of the crash were recorded.

Fitting 40 separate models to the injury claim rate data would increase the possibility of a Type I error, in which metrics correlated with injury outcome by chance are assumed to be risk factors. Principal component analysis (PCA) was used for dimensionality reduction and to identify the test pulses and test metrics contributing to the most variation among the tested seat designs. PCA is a technique that creates new variables (*principal components* or PCs) from linear combinations of the existing variables, resulting in a lower dimension approximation of the full dataset. The PCA was based on all seats tested at the 16- and 24-km/h severities. Each PC represents the unique linear combination of all metrics that maximises the variance across the tested seats after controlling for any higher order PCs. For example, the first principal component (PC1) captures the largest amount of variation among seats, while PC2 captures the most variation remaining after controlling for PC1. Due to a sensor failure, one seat was missing lower neck shear in the 16-km/h test; for the PCA, the mean value for the other seats was applied.

The insurance data analysed in the current study were supplied to the Highway Loss Data Institute (HLDI) by U.S. automobile insurer sponsors of IIHS and HLDI. These companies account for more than 85% 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 (San Diego, USA). These data were linked to HLDI data by Vehicle Identification Number (VIN) and crash date. 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 1 provides PIP and PDL counts through February 2020 for each make and model. While insurance data do not allow a specific evaluation of whiplash-related injuries, [2] found that 59% and 54% of PIP claimants report neck sprain or strain and back sprain or strain injuries, respectively, for all crash types. This indicates that reducing neck and back injuries should be the focus of seat evaluations in rear impacts, where these may be the only injury reported.

Poisson regression was used to study the effects of the principal components (PCs) and selected individual test metrics on injury claim rates. The Poisson distribution describes the probability of observing a certain discrete number of independent events. Each regression model estimated the number of PIP claims based on vehicle class and one test metric, with the log of the number of PDL claims included as an offset term. Scale parameters were estimated within the Poisson models to control for overdispersion.

TABLE I

REAR-IMPACT INSURANCE CLAIM DATA

Vehicle applicable model years/make/model	Vehicle class	Number of property damage liability claims	Number of personal injury protection claims	Injury claim rate (PIP/PDL)	Tested speeds		
					16 km/h	20 km/h	24 km/h
2015–2019 Subaru Outback	Car	3,071	227	7.4%	X	X	X
2015–2019 Subaru Legacy	Car	1,288	109	8.5%	X	X	X
2014–2021 Mazda 6	Car	3,214	276	8.6%	X	X	X
2013–2017 Honda Accord	Car	24,961	2,909	11.7%	X	X	X
2013–2019 Ford Fusion	Car	8,802	1,075	12.2%	X	X	X
2012–2022 Volkswagen Passat	Car	7,981	1,035	13.0%	X	X	X
2015–2019 Hyundai Sonata	Car	5,555	790	14.2%	X	X	X
2012–2017 Toyota Camry	Car	30,441	4,498	14.8%	X	X	X
2013–2018 Nissan Altima	Car	19,351	2,979	15.4%	X	X	X
2013–2018 Hyundai Santa Fe	2WD SUV	1,332	189	14.2%	X		X
2018–2021 Volkswagen Tiguan	2WD SUV	890	115	12.9%	X		X
2018–2020 Kia Sorento	2WD SUV	991	152	15.3%	X		X
2016–2021 Mazda CX-9	2WD SUV	440	43	9.8%	X		X
2014–2021 Jeep Cherokee	2WD SUV	3,450	498	14.4%	X		X
2018–2021 Volkswagen Atlas	2WD SUV	467	59	12.6%	X		X
2015–2021 Nissan Murano	2WD SUV	1,531	198	12.9%	X		X
2014–2019 Toyota Highlander	2WD SUV	4,272	542	12.7%	X		X
2016–2021 Honda Pilot	2WD SUV	1,942	197	10.1%	X		X
2013–2021 Chevrolet Traverse	2WD SUV	4,769	591	12.4%	X		X
2018–2019 Ford Explorer	2WD SUV	676	61	9.0%	X		X
2011–2021 Jeep Grand Cherokee	2WD SUV	5,307	451	8.5%	X		X
2011–2021 Dodge Durango	2WD SUV	3,317	415	12.5%	X		X
2019–2021 Subaru Ascent	4WD SUV	572	60	10.5%	X		X
2013–2018 Hyundai Santa Fe	4WD SUV	1,191	131	11.0%	X		X
2018–2021 Volkswagen Tiguan	4WD SUV	1,149	101	8.8%	X		X
2018–2020 Kia Sorento	4WD SUV	723	84	11.6%	X		X
2016–2021 Mazda CX-9	4WD SUV	843	61	7.2%	X		X
2014–2021 Jeep Cherokee	4WD SUV	7,657	893	11.7%	X		X
2018–2021 Volkswagen Atlas	4WD SUV	788	72	9.1%	X		X
2015–2021 Nissan Murano	4WD SUV	1,929	239	12.4%	X		X
2014–2019 Toyota Highlander	4WD SUV	7,819	877	11.2%	X		X
2016–2021 Honda Pilot	4WD SUV	5,012	478	9.5%	X		X
2013–2021 Chevrolet Traverse	4WD SUV	3,500	369	10.5%	X		X
2018–2019 Ford Explorer	4WD SUV	1,095	107	9.8%	X		X
2011–2021 Jeep Grand Cherokee	4WD SUV	19,387	1,904	9.8%	X		X
2011–2021 Dodge Durango	4WD SUV	5,322	596	11.2%	X		X

III. RESULTS

Fig. 2 shows a summary of the dummy metrics from all pulses. With the exception of rebound velocity, values were only collected up to the time when the head left the head restraint on rebound. Upper neck maximum shear force, NKM-NEA, lower neck minimum shear force, flexion and extension reported very small values across all pulses. Other metrics like NKM max, NKM-NEP, pelvis displacement, rebound velocity, T1 X-acceleration, upper neck extension moment and shear force minimum showed positive correlation with pulse severity. NIC and HCT both showed similar ranges of values across all three pulse severities.

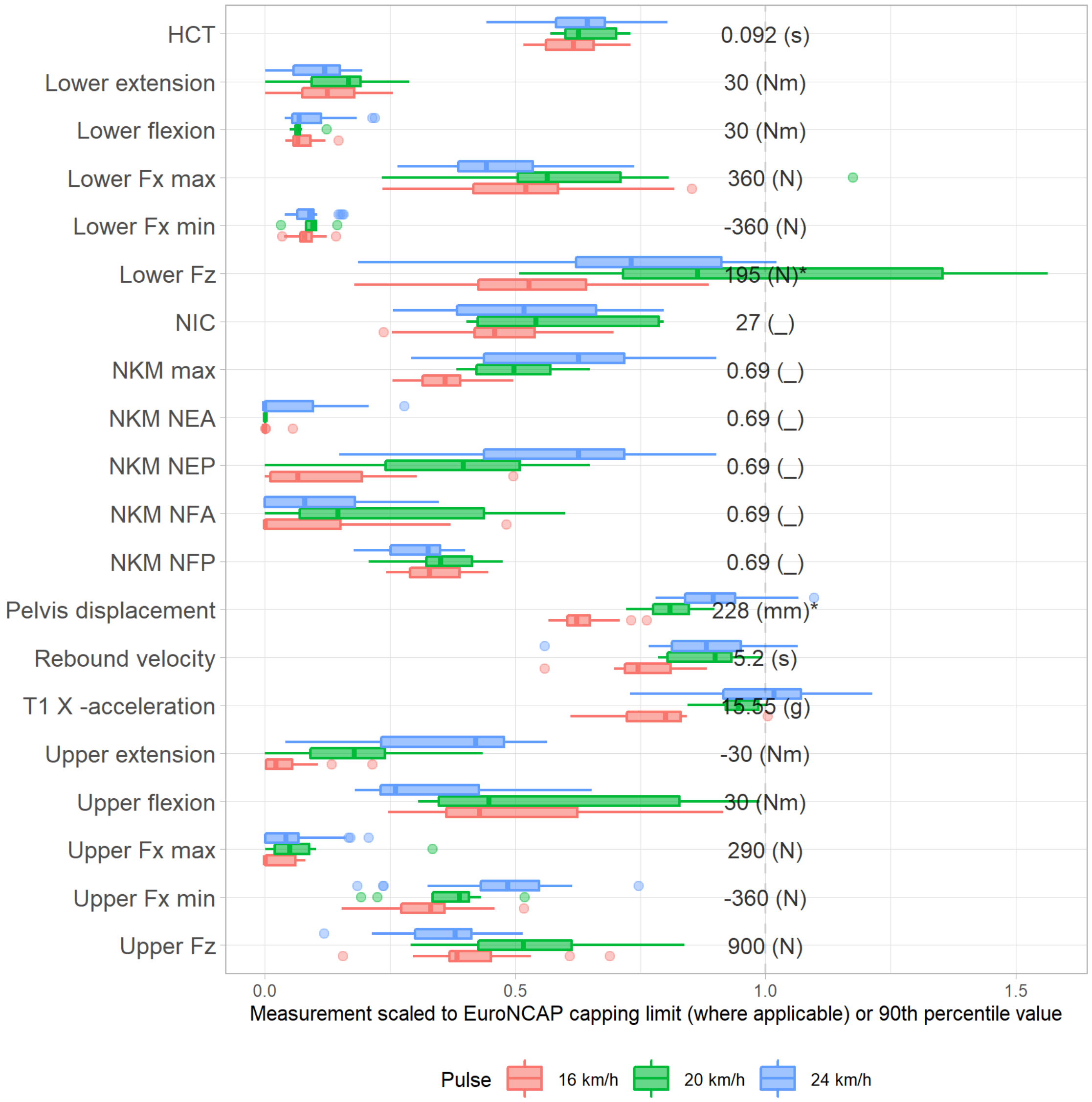

Fig. 2. Range of test results normalised by the Euro NCAP mid-pulse capping limit where applicable, or by the 90th percentile value with quartiles, whiskers and outliers for each metric by pulse [10].

20-km/h (JNCAP) Results

Eight seat designs from the midsize car class were evaluated at all three pulse severities. To determine whether the full number of tests was needed with additional seat models, the results for the middle-severity pulse (20 km/h) were analysed for their relationship with injury claim rates. Poisson regression models of injury claim rates (Table A-II) showed that none of these metrics were significant at the α = 0.05 level, so further testing of additional seat designs focused only on the 16-km/h and 24-km/h pulses.

Principal Component Analysis

PCA (Fig. 3) showed that the first five PCs accounted for 70% of the variance among the 21 tested seat designs. PCs are ordered by their contribution to the variance in the dataset, so the highest order PC (PC1) captures the largest contribution to the dataset variance. All 40 metrics contributed to each PC, but the degree to which they contribute differs. Table A-I shows the loadings for each of the first five PCs. The loadings are the values multiplied by each test metric (scaled to the number of standard deviations from the mean) during the linear combination that forms each PC. Metrics with high-loading magnitudes contributed more to a PC than those with low magnitudes, while the sign of the loading indicates whether higher or lower values of each metric increase the PC score. Table III lists the metrics with the highest loading magnitude for each PC, and Table II provides the calculated PC scores for PCs 1–5 for each vehicle.

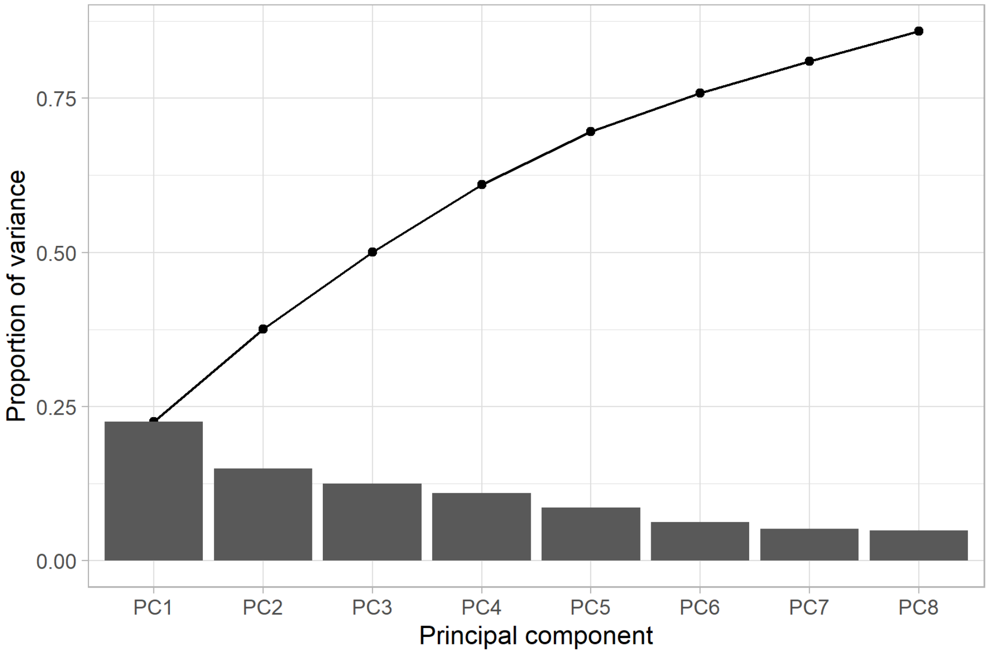

Fig. 3. Contribution of each principal component (PC) to variance in the dataset.

High values of PC1 described seats with high values of lower neck extension, shear force (maximum Fx, or head rearward) and tension, and upper neck tension from the 16-km/h pulse in combination with low values of upper neck shear force (minimum Fx, or head forward) from both pulses. Seats with high values of PC2 were those with high NKM-NEP from the 16-km/h pulse and upper neck extension from both pulses. PC3 described seats with high values of HCT, maximum NKM, NKM-NEP and upper neck extension from the 24-km/h pulse. Seats with high values of PC4 had high upper neck flexion and maximum NKM from the 16-km/h pulse and high NKM-NFP from both pulses. PC5 described seats with high values of upper neck extension and upper neck shear force (minimum Fx, or head forward) from the 16-km/h pulse and upper and lower neck tension and lower neck shear force (maximum Fx, or head rearward) from the 24-km/h pulse.

TABLE II

PRINCIPAL COMPONENT VALUES FOR EACH MAKE (PC1–PC5)

Make	Model	Vehicle class	PC1	PC2	PC3	PC4	PC5
Subaru	*Legacy*	Car	−5.94	−0.35	−3.65	−2.28	−1.81
Subaru	*Outback*	Car	−5.94	−0.35	−3.65	−2.28	−1.81
Volkswagen	*Passat*	Car	4.73	−2.43	−0.99	1.01	−0.94
Hyundai	*Sonata*	Car	1.14	−0.48	2.13	1.38	1.18
Toyota	*Camry*	Car	0.20	−1.91	0.52	−0.22	−0.13
Nissan	*Altima*	Car	−3.86	3.27	0.86	2.72	−0.43
Honda	*Accord*	Car	−3.61	1.50	−0.99	−0.78	−1.23
Ford	*Fusion*	Car	5.38	0.25	−3.52	−2.10	2.11
Mazda	*6*	Car	−0.05	0.60	−0.54	1.40	0.11
Subaru	*Ascent*	SUV	−1.16	−4.62	−0.29	−1.82	2.49
Hyundai	*Santa Fe*	SUV	−0.51	−0.78	1.56	−1.70	−0.15
Volkswagen	*Tiguan*	SUV	0.97	−0.23	3.44	−3.48	−2.53
Kia	*Sorento*	SUV	−1.01	5.88	1.97	−1.26	5.16
Mazda	*CX-9*	SUV	−2.12	−1.35	−1.19	−0.93	1.02
Jeep	*Cherokee*	SUV	1.67	−1.14	1.80	3.42	−1.26
Volkswagen	*Atlas*	SUV	1.45	0.86	2.85	−3.97	−1.98
Nissan	*Murano*	SUV	−4.89	−0.87	0.93	2.09	−0.93
Toyota	*Highlander*	SUV	−1.24	−2.83	−0.92	1.12	2.02
Honda	*Pilot*	SUV	1.11	−2.88	1.32	2.02	1.10
Chevrolet	*Traverse*	SUV	2.05	2.29	1.18	2.43	−1.05
Ford	*Explorer*	SUV	4.38	2.98	−1.07	−0.15	−1.63
Jeep	*Grand Cherokee*	SUV	1.33	2.24	−5.42	1.08	−1.11
Dodge	*Durango*	SUV	1.33	2.24	−5.42	1.08	−1.11

TABLE III

TOP FIVE CONTRIBUTORS TO EACH PRINCIPAL COMPONENT (PC)

PC1	PC2	PC3	PC4	PC5
Lower neck extension (16 km/h)	NKM-NEP (16 km/h)	HCT (24 km/h)	Upper neck flexion (16 km/h)	Upper neck Fz (24 km/h)
Lower neck Fx max (16 km/h)	Upper neck extension (16 km/h)	Max NKM (24 km/h)	NKM-NFP (16 km/h)	Upper neck extension (16 km/h)
Upper neck Fz (16 km/h)	HCT* (16 km/h)	NKM-NEP (24 km/h)	Max NKM (16 km/h)	Lower neck Fz (24 km/h)
Lower neck Fz (16 km/h)	Lower neck Fx min* (24 km/h)	Lower neck flexion* (16 km/h)	NKM-NFP (24 km/h)	Lower neck Fx Max (24 km/h)
Upper neck Fx min* (24 km/h)	Upper neck extension (24 km/h)	Upper neck extension (24 km/h)	Lower neck Fx min* (16 km/h)	Upper neck Fx Min (16 km/h)

*Metrics have negative loading (all others are positive).

PCA Poisson Regression Analysis

Though PC1 describes features that have the greatest variance in the test dataset, this is not necessarily the best combination of predictors of injury claim rates. Poisson regression was conducted to study the effect of the first five PCs on claim rate while controlling for vehicle class. Table IV shows model results. Overall, compared to cars, two-wheel-drive (2WD) SUVs and four-wheel-drive (4WD) SUVs were estimated to have 13% and 21% lower injury claims rates, respectively. PC1, PC2 and PC5 did not show statistically significant relationships with injury claim rate (p = .48, p = .70 and p = .24, respectively), and model results for PC4 showed a borderline significant relationship with injury claim rate (p = .053). Model results for PC3 showed that high values of this PC were associated with increased injury claim rate (p = 0.02).

TABLE IV

POISSON REGRESSION PCA MODEL RESULTS

Term	Estimate	*p* value
Intercept	−2.007	-
PC1	**0.006**	**0.479**
PC2	**0.005**	**0.697**
PC3	**0.027**	**0.020**
PC4	**0.031**	**0.053**
PC5	**0.022**	**0.238**
Vehicle class (2WD SUV vs. cars)	−0.135	0.048
Vehicle class (4WD SUV vs. cars)	−0.240	0.000

Individual Metric Poisson Regression Analysis

Some individual test metrics were selected for inclusion in regression models. A two-stage selection process was used. First, metrics were grouped based on their correlation to each other, with a Pearson correlation coefficient of 0.7 used as a threshold. Second, within each group of correlated metrics, the single metric with the highest magnitude loading from PC3 was selected as the representative metric. PC3 was the highest order PC that had a statistically significant relationship with injury rate (Table IV). This reduction method resulted in seven groups (Table V), comprising 23 of the 40 metrics collected from both pulses. One group contained HCT and pelvis displacement from both pulses and the remaining groups all contained metrics associated with the upper and lower neck load cells from both pulses.

TABLE V

INDIVIDUAL METRICS GROUPED BY CORRELATION

Group: Representative metric	Correlated metrics
1: HCT (24 km/h)	HCT (16 km/h) Pelvis displacement (24 km/h) Pelvis displacement (16 km/h)
2: Max NKM (24 km/h)	NKM NEP (24 km/h) Upper neck extension (24 km/h)
3: Upper neck Fx Max (24 km/h)	NKM-NEA (24 km/h)
4: Lower neck Fx Max (24 km/h)	Upper neck Fz (24 km/h) Lower neck Fz (24 km/h)
5: NKM-NFP (24 km/h)	NKM-NFP (16 km/h) Max NKM (16 km/h)
6: Upper neck extension (16 km/h)	NKM-NEP (16 km/h)
7: Lower neck Fz (16 km/h)	Upper neck Fz (16 km/h) Lower neck Fx Max (16 km/h) Lower neck extension (16 km/h) Upper neck Fx Max (16 km/h) NKM-NFA (16 km/h)

After grouping correlated metrics, 17 metrics remained that were not strongly correlated with any other metric. The representative metric from each of the groups (Table V) and all of the non-correlated metrics were sorted according to their relative contribution to PC3 (Fig. 4). A threshold loading value of 0.2 was used to select metrics for inclusion in individual Poisson models of injury claim rate. These criteria resulted in six metrics being chosen for modelling: HCT, Max NKM, T1 acceleration and upper neck maximum Fx from the 24-km/h pulse, and lower neck flexion and T1 acceleration from the 16-km/h pulse. As shown in Fig. 4, the metrics from the higher severity test made positive contributions to PC3, while those from the lower severity test made negative contributions.

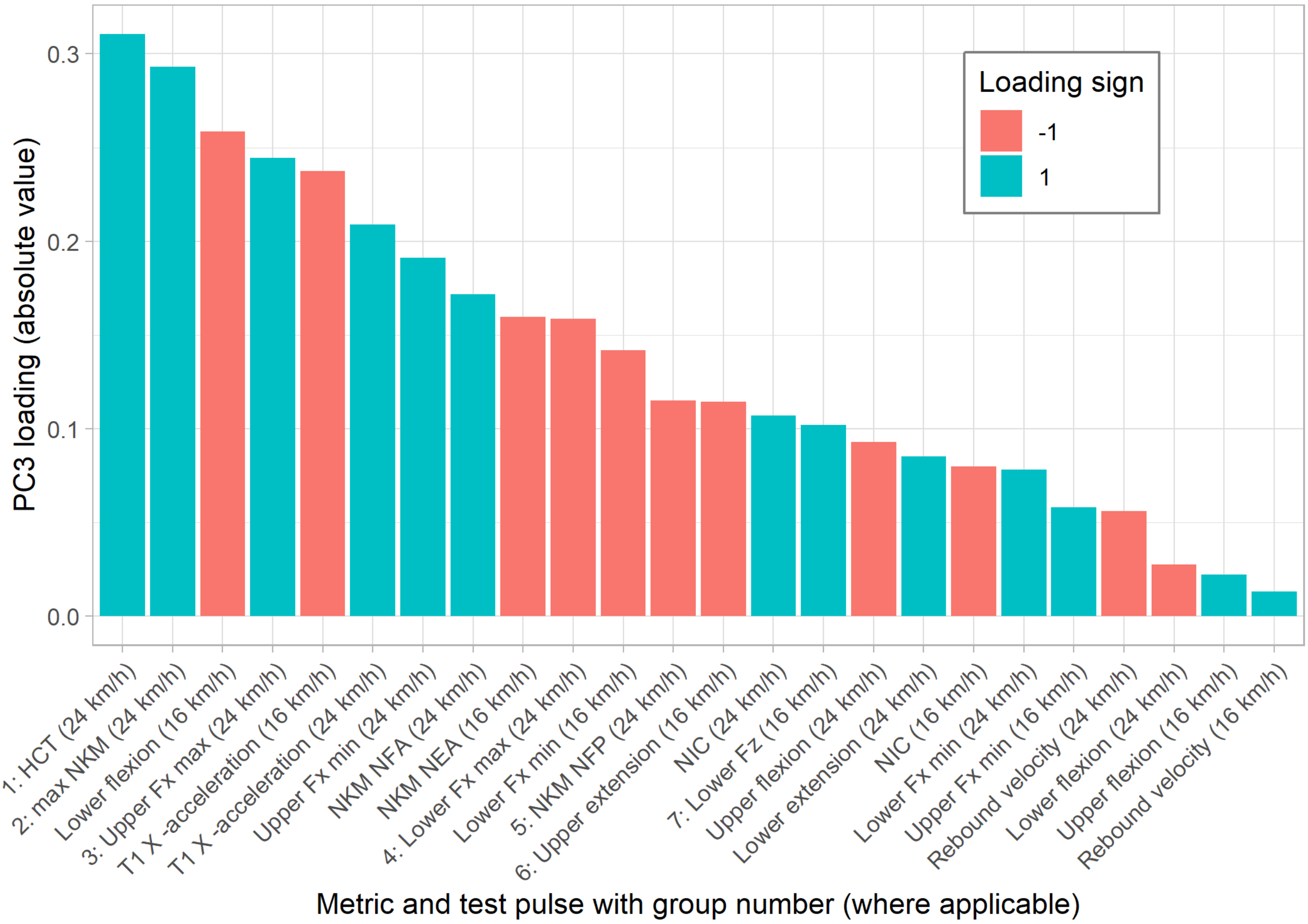

Fig. 4. PC 3 loading values for each metric.

Results for each of the Poisson models using a single test metric are shown in Table VI. Increases in three of the metrics were associated with increases in injury claim rates that were significant at α = 0.05: T1 acceleration (*p* = 0.01), maximum NKM (*p* = 0.004), and HCT (*p* = 0.04), all from the 24-km/h test. In the 24-km/h pulse, a 10-ms increase in HCT was associated with a 7% increase in injury claim rate, a 0.1 increase in maximum NKM was associated with a 6% increase in injury claim rate and a 5-g increase in T1 acceleration was associated with a 26% increase in injury claim rate.

TABLE VI

POISSON REGRESSION INDIVIDUAL METRICS MODEL RESULTS

Model	Term	Rate ratio	p-value
1	**HCT (24 km/h) (+10 ms)**	**1.065**	**0.04**
	Vehicle class (2WD SUV vs. cars)	0.903	0.15
	Vehicle class (4WD SUV vs. cars)	0.802	<0.001
2	**Max NKM (24 km/h) (+0.1)**	**1.064**	**0.004**
	Vehicle class (2WD SUV vs. cars)	0.917	0.19
	Vehicle class (4WD SUV vs. cars)	0.821	0.001
3	**Upper neck Fx max (24 km/h) (+100 N)**	**1.122**	**0.57**
	Vehicle class (2WD SUV vs. cars)	0.9	0.16
	Vehicle class (4WD SUV vs. cars)	0.793	<0.001
4	**T1 X-acceleration (16 km/h) (+5 g)**	**0.942**	**0.59**
	Vehicle class (2WD SUV vs. cars)	0.911	0.24
	Vehicle class (4WD SUV vs. cars)	0.804	0.003
5	**Lower neck flexion (24 km/h) (+5 Nm)**	**0.815**	**0.24**
	Vehicle class (2WD SUV vs. cars)	0.897	0.15
	Vehicle class (4WD SUV vs. cars)	0.796	<0.001
6	**T1 X acceleration (24 km/h) (+5 g)**	**1.257**	**0.01**
	Vehicle class (2WD SUV vs. cars)	0.972	0.69
	Vehicle class (4WD SUV vs. cars)	0.856	0.01

IV. DISCUSSION

Results of the regression analysis showed 2WD SUV and 4WD SUVs have 13% and 21% lower injury claim rates than cars, respectively, which aligns with previous studies showing that increasing struck-vehicle mass is beneficial in reducing injuries in rear-impact crashes [5]. However, the wide range of injury claim rates in each of the three vehicle classes (Table I), as well as considerable overlap in rates between classes, highlights the potential for a well-designed evaluation program to reduce injury rates across the fleet.

Much of the variance among the seat designs tested for this study did not correlate with real-world injury claim rates. Seats had the greatest variation when assessed by a combination of upper and lower neck shear and tension forces along with lower neck extension moments, primarily as measured in the 16-km/h test. But this first principal component was not a significant predictor of injury rate. Neither was PC2, which described the degree to which seat designs had high upper neck extension in combination with low HCT. This suggests that many of the largest differences in modern seat designs that can be measured in a sled test environment do not correspond to differences in rear-impact injury outcomes in the field. This may be a function of the improvement in sled test ratings over the past 20 years and the associated injury rate reductions [5]. Though some of the metrics with the greatest loading in PC1 and PC2 align with strategies for reducing whiplash injury (e.g., reducing neck forces), the mechanisms for whiplash injury are still unknown. Seats are designed with many purposes, including occupant protection in other crash modes, and the metrics with the most loading in PC1 and PC2 may be capturing another aspect of seat design not related to occupant injury in rear impact crashes. The correspondence between individual metrics and outcomes in the field should be taken into consideration when selecting metrics for evaluation. Prioritizing metrics in evaluations with no relationship to injury outcomes could encourage seat designs with no benefit or even a disbenefit for occupants.

Despite the lack of correlation with real world injury for PC1 and PC2, this study indicates there are remaining differences between designs that are relevant to field outcomes that can be assessed with a refocused sled test programme. The third principal component, which mainly described the seat’s ability to maintain low HCT and upper neck extension in the 24-km/h test, was a statistically significant predictor of injury claim rate. While many of the individual test metrics were strongly correlated with each other, preventing conclusive statements about which are the best predictors of injury, three factors appear especially important. Seat designs with the lowest injury claim rates were those with low HCT in both tests, and low NKM (specifically NEP) and T1 X-acceleration in the higher severity test.

HCT from the 24-km/h pulse was chosen as the representative metric for Group 1 (Table V) and regression indicated it is a significant predictor of injury claim rate (Table VI). HCTs from both the 24-km/h and 16-km/h pulses were correlated with each other and with pelvis displacement from both pulses, which indicates that strategies for increasing pelvis displacement and decreasing HCT in either pulse confer benefits at other severities. Allowing the occupant to sink into the seatback reduces the energy transferred to the occupant while also allowing the seat to support the neck and head earlier in the crash.

Of the six individual test metrics included in regression models, maximum NKM from the 24-km/h test had the strongest relationship with injury claim rate (Table IV). The NKM metric is aimed at capturing the risk of injury from combined upper neck sagittal moment and shear force. The metric is calculated for each of the four combinations of extension-flexion moment and anterior-posterior shear force using critical values published by [9]. Max NKM is the maximum value of these four modes and, for the 24-km/h pulse, usually represented NKM-NEP, the combination of extension moment and the head moving forward relative to the cervical spine [9]. This is motion that might occur when the head restraint loads the head primarily below the head centre of gravity (CG). The dominant factor in the Max NKM metric for the 24-km/h pulse was the upper neck extension moment. In the 16-km/h pulse, however, NKM-NFP usually produced the maximum value, indicating the extension moments measured in the 24-km/h pulse, which were associated with injury rate, did not occur in the 16-km/h pulse.

T1 X-acceleration is a measure of the acceleration of the T1 vertebra. Reducing accelerations in the thoracic spine reduces the loads in the cervical spine necessary to accelerate the head along with the torso, which is an indication of the seat's effectiveness in absorbing the energy of the crash. T1 X-acceleration from both pulses were primary contributors to the variation in PC3, but only T1 X-acceleration from the 24-km/h pulse was a significant predictor of injury claim rate. Fig. 1 shows that many of the test metrics are sensitive to test severity, including HCT, NKM and T1 X-acceleration, and that at higher severities these metrics have a larger range of results. Fig. 1 shows that not only do T1 X-acceleration values have a larger range at the higher severity, but the magnitudes also increase with severity. From Folksam insurer data analysed by [11], delta V and mean acceleration are both significant predictors of duration of whiplash symptoms. Metrics with a strong relationship with test severity that also have a large range for seats tested at a single severity may be valuable in differentiating how energy is translated to the occupant through the seat.

Of the metrics modelled individually, the best predictors of injury claim rate came from the 24-km/h pulse. In addition, the first PC, which consisted of loading magnitudes that were greatest for the 16-km/h pulse, was not associated with statistically significant differences in injury claim rate. The fourth principal component also consisted of loading magnitudes that were greatest for the 16-km/h pulse and had a borderline significant relationship with injury claim rate. These findings suggest that, while the 16-km/h pulse does produce dummy measures that allow differentiation between modern seat designs, and while some of these measures are correlated to injury rates, the 24-km/h pulse has greater value in quantifying performance in ways that align with real-world outcomes. Reference [11], reported that the average delta V for occupants with whiplash symptoms lasting longer than one month was 20 km/h, which is between the 16 km/h and 24 km/h pulses, while those with symptoms lasting under one month was 10.3 km/h. In 2004, IIHS began using a combination of HCT, T1 X-acceleration and upper neck shear force and tension with the 16-km/h pulse to rate seats. In 2008, [3] conducted an analysis of the relationship between individual test metrics from this pulse and neck injury claim rates using model year 2005–2006 vehicles. They found none of the individual test metrics (which were similar to those included in this study) were highly correlated with neck injury rates. Combinations of metrics were also studied but did not provide a meaningful improvement over the previously established combination of HCT, T1 X-acceleration and upper neck shear force and tension. However, seat designs have changed over time, as demonstrated by changes in IIHS ratings. In 2006, only 16% of vehicles were rated good by IIHS, but in 2022, 98% percent of vehicles were rated good. Significant changes have occurred in the fleet in seat design over the last 14 years and, for these modern seats, a higher test severity and additional metrics may be most relevant for predicting injury claims. Additionally, seat designs in the fleet have converged over the last 20 years to all perform similarly according to specified rating metrics using BioRID in a 16 km/h pulse. Though there is a range of performance in field data, BioRID may not be a sensitive enough tool to distinguish meaningful differences in modern seat design at a 16 km/h test severity and a higher severity test may be necessary for BioRID to measure these differences.

In 2013, [12] studied BioRID results with the 16-km/h pulse and found that lower values of NIC, rearward X-displacement of the Occipital Condyle and maximum L1 X-acceleration reduced the risk of permanent medical impairment (PMI). More recently, in 2015, [4] also looked at relationships between test metrics for the IIHS, Euro NCAP and JNCAP evaluations and risk of PMI for whiplash-associated disorder (WAD) claims between 1998 and 2013 from the Folksam insurer database. The study concluded that the overall rating from each of the three rating schemes was correlated with risk of PMI. In contrast with the current study, however, [4] found that HCT, T1 X-accceleration and NKM were less correlated with PMI than other metrics and that NIC in all three pulses and upper neck Fz in the 24-km/h pulse were the best predictors of PMI. Though the model years of the vehicles observed in [4] were not reported, since the claims studied spanned 1998–2013, these vehicles represent an older generation of designs where the relevant metrics for predicting injury claim rates may differ from modern seats.

Additionally, one notable difference between the IIHS/HLDI and the Folksam datasets is the definition of injury. The 2008 IIHS study defined injury as a neck injury claim filed for vehicles with a rear-impact damage claim (PDL) [3]. In the current study, injury was defined as a personal injury protection (PIP) claim filed for vehicles with a rear-impact damage claim (PDL). Personal injury protection claims are comprised of any type of injury, but are dominated by neck injuries for rear impacts. The Folksam data defines injury as a PMI diagnosis given that a rear-impact injury claim was filed. Given the different definitions, it is possible that the IIHS and Folksam data represent different types of whiplash injury and are associated with different dummy metrics, and it is worth considering the results of both studies when designing a seat evaluation program.

This study has several limitations. Analyses were performed using raw insurance claim rates and did not control for factors such as age and gender of the rated driver. Likewise, other than sled test measurements, there were no explicit controls for vehicle differences that could affect injury, such as curb weight. While all regression models included a covariate for vehicle class, it is possible that there are demographic or vehicle differences within classes that are collinear with test performance. Additionally, PIP claims do not provide information on the seating position of the claimant, so it was assumed that the claimant was a front-seat driver or passenger based on the substantially higher occupancy rate for those seating positions relative to rear-seating positions. Our findings assume the large number of claims used per vehicle in this study largely mitigates the influence of these variables on the injury claim rate. Analyses were based on a sample of eight midsize cars and 13 midsize SUVs. More observations are needed to assess the relative value of individual metrics in predicting claim rates. Additional vehicle models will be included in future research.

V. CONCLUSION

After data reduction using PCA and correlation analysis, the best predictors of injury claim rate were HCT, Max NKM and T1 X-acceleration from the 24-km/h pulse. Of these, HCT also had correlations with HCT in the 16-km/h pulse and with pelvis displacement in both pulses. Max NKM had correlations with NKM-NEP and upper extension moment for the 24-km/h pulse. T1 X-acceleration had no strong correlations with other metrics. While many of the measures collected from the three different tests were correlated, results indicate the 24-km/h pulse may be best suited for establishing meaningful differences between seat designs. At this severity, T1 acceleration, NKM and HCT were selected as representative measures that were associated with injury rates, but other metrics correlated with these also may be important considerations for improved seat designs. Significant changes have occurred in the fleet in seat design over the last 20 years. For modern seats, a higher test severity and additional metrics may improve the ability of test outcomes to predict injury claims.

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VIII. APPENDIX

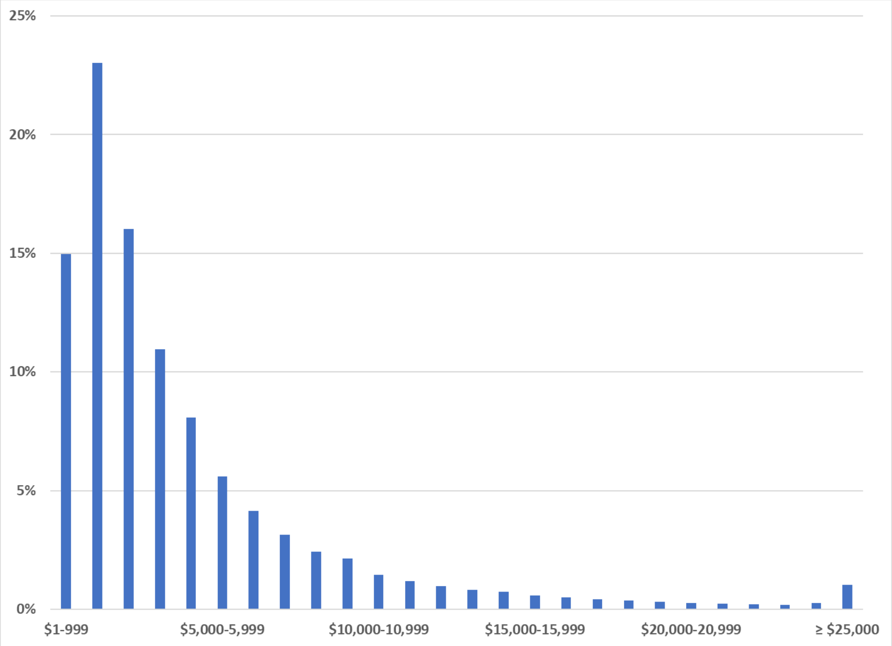

Fig. A-1. Distribution of PDL claims by claim size, 1981–2022 model years, calendar year 2021 [13].

TABLE A-I
INDIVIDUAL METRIC CONTRIBUTION TO EACH PRINCIPAL COMPONENT (PC)

	PC1		PC2		PC3		PC4		PC5	
	16 km/h	24 km/h	16 km/h	24 km/h	16 km/h	24 km/h	16 km/h	24 km/h	16 km/h	24 km/h
HCT	0.000	0.082	-0.258	-0.216	0.250	0.311	-0.115	-0.085	0.011	0.014
Upper neck Fx max	0.240	0.100	0.084	0.167	-0.054	0.244	-0.004	-0.146	-0.234	0.100
Upper neck Fx min	-0.219	-0.244	0.085	-0.085	0.058	0.191	0.020	0.145	0.257	0.040
Upper neck Fz	0.285	0.136	-0.058	-0.103	-0.024	-0.090	0.051	0.177	0.091	0.312
T1 X-acceleration	0.033	-0.035	0.064	-0.156	-0.237	0.209	0.249	0.081	-0.079	-0.214
NKM NEA	0.139	0.032	0.005	0.216	-0.160	0.203	-0.112	-0.260	0.143	0.103
NKM NEP	-0.088	-0.120	0.311	0.177	0.011	0.272	-0.005	0.102	0.176	-0.103
NKM NFA	0.157	0.040	0.153	0.200	0.047	0.172	0.124	0.152	-0.162	0.078
NKM NFP	-0.149	-0.170	-0.098	-0.168	0.008	-0.115	0.322	0.291	0.062	0.049
Max NKM	-0.085	-0.117	0.074	0.165	0.071	0.293	0.305	0.135	0.173	-0.109
Rebound velocity	0.157	-0.048	0.121	-0.112	0.013	-0.056	0.167	0.157	-0.169	-0.231
NIC	0.192	0.209	-0.193	-0.166	-0.080	0.107	0.053	-0.016	-0.127	0.099
Upper neck flexion	0.062	0.039	0.069	0.179	0.022	-0.093	0.346	0.239	-0.125	0.092
Upper neck extension	0.058	-0.029	0.298	0.223	-0.115	0.251	-0.073	0.055	0.275	-0.134
Lower neck Fx max	0.286	0.219	-0.045	0.091	-0.064	-0.159	0.112	0.057	-0.059	0.260
Lower neck Fx min	-0.094	-0.028	-0.023	-0.234	-0.142	0.078	-0.278	0.039	0.028	0.238
Lower neck Fz	0.249	0.074	-0.109	0.003	0.102	0.024	0.032	0.189	0.119	0.261
Lower neck flexion	-0.188	-0.196	-0.078	-0.160	-0.258	-0.028	-0.034	0.121	0.002	0.117
Lower neck extension	0.298	0.235	-0.059	0.199	0.000	0.085	0.028	0.091	-0.186	0.062
Pelvis displacement	0.134	0.124	-0.141	-0.216	0.246	0.212	0.093	0.005	0.169	0.198

TABLE A-II

POISSON REGRESSION RESULTS FOR INDIVIDUAL METRICS FROM THE JNCAP (20 KM/H) PULSE

Model	Estimate	SE	t value	p value
Max NKM	−1.24	0.65	−1.92	0.10
Rebound velocity	0.26	0.14	1.91	0.10
Pelvis displacement	0.01	0.00	1.75	0.12
Lower neck extension	0.04	0.03	1.47	0.19
Upper neck Fz	0.00	0.00	1.32	0.23
Lower neck Fx max	0.00	0.00	1.11	0.31
NKM-NEA	279.62	255.72	1.09	0.31
NIC	0.01	0.01	1.09	0.31
Lower neck Fz	0.00	0.00	1.05	0.33
HCT	10.69	11.16	0.96	0.37
Upper neck extension	−0.01	0.01	−0.95	0.37
Lower neck Fx min	0.00	0.01	0.73	0.49
NKM-NEP	−0.26	0.39	−0.66	0.53
NKM-NFP	0.81	1.26	0.65	0.54
Upper neck Fx min	0.00	0.00	−0.55	0.60
NKM-NFA	0.20	0.41	0.49	0.64
T1 X-acceleration	0.04	0.09	0.43	0.68
Lower neck flexion	−0.04	0.13	−0.32	0.76
Upper neck flexion	0.00	0.01	0.27	0.79
Upper neck Fx max	0.00	0.00	−0.16	0.88