Whiplash Evaluation Procedure for Predicting Rear-Impact Occupant Protection in Modern Vehicle Seats

Marcy A. Edwards, Haden S. Bragg, Matthew L. Brumbelow

Abstract Though rear-impact neck-injury claim rates have decreased over the last 20 years, modern vehicles still show a range of occupant protection performance for vehicles rated Good in the IIHS vehicle seat/head restraint evaluation programme introduced in 2004. To encourage seat designs that further reduce injuries in rear-impact crashes, this study expanded on previous research to identify a combination of tests and metrics that relate to real-world injury, providing consumers with the means to differentiate levels of rear-impact protection between seats. Nineteen new seat designs were evaluated, using a BioRID dummy in both 16 km/h and 24 km/h rear-impact sled tests, and then combined with data from previously published tests to compose a dataset of 40 seat designs from three vehicle classes. Head contact time (HCT), head-to-pelvis relative velocity, pelvis displacement, Nkm, T1 X-acceleration and upper neck tension were used to develop a combined score for use in an overall evaluation, based on three design principles: head and spine support, stability of the head-to-head restraint interaction, and the rate energy is transferred to the occupant. A single score combining these six metrics from both test pulses was found to be a significant predictor of injury claim rate ($p < 0.05$).

Keywords Consumer ratings programmes, Rear-impact occupant protection, Rear impacts, Whiplash, Seat performance.

I. INTRODUCTION

In the USA, over 1.7 million rear-impact crashes are reported to police annually, accounting for 29% of all passenger vehicle crashes [1]. From insurer data (2005–2006), approximately 19% of exposed occupants suffer neck injuries in rear-impact crashes and about 1 in 4 of those suffer long-term injuries [2]. Given the number of people who experience injuries in rear-impact crashes, reducing whiplash-type injuries in these crashes has been a priority for consumer-information organisations for decades. In 1995, the Insurance Institute for Highway Safety (IIHS) began evaluating head restraints to ensure they could be adjusted high enough and close enough to support the head in a rear-impact crash [3]. In 2004, IIHS added a dynamic sled test to the assessment, using an impact pulse with a 16 km/h change in velocity and the rear-impact dummy BioRID to evaluate aspects of seat design not captured by geometry [4]. In 2009, the European New Car Assessment Programme (Euro NCAP) also added a dynamic rear-impact assessment, comprised of three impact severities, to its vehicle evaluations [5]. Assessments of the efficacy of IIHS's rear-impact evaluation have shown that Good-rated vehicle seats reduced injuries 11.2% relative to Poor-rated seats [6]. Research in 2015 on the efficacy of the Euro NCAP, Japan NCAP and IIHS rear-impact evaluation programs showed that ratings had significant correlations with risk for permanent medical impairment (PMI) [7]. IIHS observed a 39% decrease in rear-impact neck-injury claim rates between 1999 and 2008 [2]. Nevertheless, injury claim rates for modern vehicles still show a range of occupant protection performance for vehicles rated Good in the original IIHS dynamic test programme [8]. For this reason, IIHS has been researching ways to make meaningful updates to this programme that will encourage seat designs that further reduce injuries in rear-impact crashes.

Many factors affect injury outcomes for occupants in rear-impact crashes. Krafft *et al*. [9] studied injury outcomes related to crash severity measured with crash recorders and found that increasing change in velocity or mean acceleration increased severity and duration of injuries. Trempel *et al*. [6] and Kullgren & Krafft [10] studied the effect of sex on injury outcomes for rear impacts and found that, compared with males, females have a 29% higher risk of injury [6] and double the risk of symptoms lasting longer than one month and of injuries leading to PMI [10]. Jakobsson *et al*. [11] studied various occupant factors that affected injury risk in Volvo rear-end impacts from 1999

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to 2002 and found that increased stature, increased head-to-head restraint distance and the occupant's head being rotated at the time of the crash increased neck injury rates. Addressing some of this crash variability in consumer-information assessments can improve the robustness of safety solutions and reduce the likelihood of injury for a larger population.

Edwards & Brumbelow [8] explored the relationship between insurance injury claim rates and dummy output metrics from sled tests at three severities. Of the three crash pulses evaluated, the 24 km/h severity was the most meaningful for differentiating modern seat designs in a way that aligned with real-world injuries. In real-world rear-impact crashes with crash recorders, [9] found that rates for risk of whiplash symptoms lasting longer than one month increased steeply over 18 km/h, highlighting the importance of including higher severities in whiplash assessments. However, since different injury causation scenarios may exist for short- and long-term injuries, it is important to include multiple severities in assessments to avoid suboptimisation [9]. The 24 km/h pulse exercises the seat in ways that are meaningful for predicting real-world injuries for the newest designs but including the 16 km/h pulse ensures that safety strategies that improve performance at the higher speed do not worsen lower severity performance.

In [8], several metrics in the 24 km/h pulse were highlighted that predict real-world injury risk, including the time for the head to contact the head restraint (head contact time; HCT), maximum Nkm and peak T1 X-acceleration. The current study expanded the dataset from [8] for more robust statistical conclusions, including new metrics for head and spine support. The vehicles used to expand the dataset were chosen from the same vehicle class and represented a large range of automakers, which aided the development of a ratings programme that could differentiate seat performance in a way that aligns with injury claim rates.

II. METHODS

Nineteen new seat designs, representing 32 vehicle models, were evaluated using a BioRID dummy, which represents a 50th percentile male, in both 16 km/h and 24 km/h delta-V rear-impact sled tests. Seats were selected from current production vehicles in the IIHS small SUV vehicle class based on popularity and brand inclusion. Table I provides a list of all models tested. Crash pulses were chosen based on the findings of [8] that the 16 km/h and 24 km/h pulses (Appendix, Fig. A1) resulted in BioRID output metrics that had significant correlations with injury claim rates.

Dummy metrics were collected from BioRID in each of the rear-impact sled tests. Dummy sensors recorded upper neck sagittal shear force (Fx), tension force (Fz) and flexion/extension moment, head triaxial accelerations, T1 and L1 vertebrae vertical and longitudinal accelerations, and pelvis triaxial accelerations according to SAE J211 [12]. From these, additional whiplash injury metrics were calculated: Nkm (NEP, NFP, NEA, NFA), resultant relative velocities measured between BioRID spine segments and longitudinal pelvis displacement relative to the sled and seat according to equations shown in the Appendix, Table AI [13-15]. Resultant relative spine velocities were based on a proposal by [14] and were measured between the head and the T1 vertebra, L1 vertebra and pelvis; between the T1 vertebra and the L1 vertebra and pelvis; and between the L1 vertebra and pelvis. 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 HCT after the onset of the crash were recorded.

In the previous study [8], a stepwise statistical method was used for parameter selection to help identify three output metrics as independent, significant predictors of injury claim rate for the 24 km/h pulse: HCT, maximum Nkm and T1 X-acceleration. These metrics represent three strategies for reducing the potential of occupant injury in rear-impact crashes: lower HCTs indicate better head and spine support, reducing maximum Nkm encourages stable interactions with the head restraint that reduces the loads and moments in the upper neck, and reducing T1 X-acceleration reflects reductions in the rate of energy transfer to the occupant during a crash. In this study, these metrics served as the foundation of IIHS's strategy to encourage improvements in seat designs. In addition to these, other metrics were selected for correlation analysis and modelling injury claim rate in this expanded dataset. Pelvis displacement was selected based on correlations with HCT and significant correlation with injury claim rates, whether measured in the 16 km/h or 24 km/h test [8]. Minimum pelvis displacement measures the maximum rearward pelvis motion with respect to the seat and sled. Upper neck shear force and extension/flexion moment were chosen based on their correlations with maximum Nkm. Upper neck tension was included because it reflects undesirable interactions observed in video between the dummy's head and head restraint. Relative spine velocities were included to explore metrics with a biomechanical foundation for encouraging spine support in rear impacts.

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. The insurance data in aggregate are largely representative of low-cost crashes (Appendix, Fig. A2), which likely also represent lower severity crashes. 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., Audatex 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 I provides PIP and PDL counts through June 2025 for each new make and model.

After combining the test results from the mid-size car and mid-size SUV vehicles published in [8] with the new test results from the small SUVs in this study, Poisson regression was used to evaluate the effects of the selected test metrics on the rate of rear-impact PIP claims per PDL claim while controlling for vehicle class. Trempel *et al*. [6] found that, though lighter vehicles typically have higher claim rates than heavier vehicles, the vehicle class variable mitigated the effect of curb weight in their regression model. Regression models were restricted to vehicles with at least 1,000 PDL claims. 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.

From this analysis, metrics of interest were further down-selected based on the significance of their correlation to injury claim rates or their relevance in achieving the three design strategies. Metrics of interest were also checked for negative correlations with each other, including across pulses. Negative correlations could indicate potential design trade-offs that limit improvements in overall test performance. After confirming that the selected combinations of metrics did not have negative correlations, a demerit system for these metrics, combining both the 16 km/h and 24 km/h tests, was defined that could serve as the basis of an evaluation programme for vehicle seat occupant protection in rear impacts. These demerits were translated into rating boundaries in line with the IIHS rating categories: Good, Acceptable, Marginal and Poor. The demerit totals and overall ratings were both evaluated using Poisson regression to verify their relevance to field crash outcomes while also controlling for vehicle class.

TABLE I

SMALL SUV REAR-IMPACT INSURANCE CLAIM DATA

Vehicle	Drive type	Model years	Personal injury protection (PIP) claims	Property damage liability (PDL) claims	Injury claim rate (PIP/PDL)
Audi Q3	4WD	2019–2024	211	2,358	8.9%
BMW X1	4WD	2023–2024	16	214	7.5%
Buick Encore GX	2WD	2024	9	121	7.4%
	4WD	2024	4	67	6.0%
Chevrolet Equinox	2WD	2024	43	340	12.6%
	4WD	2024	12	254	4.7%
Ford Bronco Sport	4WD	2021–2024	368	3,687	10.0%
Honda CR–V	2WD	2023–2024	61	492	12.4%
	4WD	2023–2024	170	1,540	11.0%
Hyundai IONIQ 5	2WD	2022–2024	16	191	8.4%
	4WD	2022–2024	37	487	7.6%
Hyundai Tucson	2WD	2024	42	340	12.4%
	4WD	2024	36	397	9.1%
Jeep Compass	2WD	2022	24	203	11.8%
	4WD	2022–2024	218	2,010	10.8%
Kia Sportage	2WD	2022–2024	273	1,847	14.8%
	4WD	2022–2024	277	2,440	11.4%
Mazda CX-50	4WD	2025	0	0	NA
Mercedes-Benz GLB	2WD	2020–2023	83	527	15.7%
	4WD	2020–2024	143	934	15.3%
Mitsubishi Outlander	2WD	2022–2024	169	997	17.0%
	4WD	2022–2024	192	1,589	12.1%
	4WD	2025	0	0	NA
Nissan Rogue	2WD	2021–2024	431	2,897	14.9%
	4WD	2021–2023	626	5,272	11.9%
Subaru Forester	4WD	2025	1	38	2.6%
Toyota RAV4	2WD	2019–2024	1,959	11,727	16.7%
	4WD	2019–2024	1,953	16,381	11.9%
Volkswagen Taos	2WD	2022–2024	119	958	12.4%
	4WD	2022–2024	79	766	10.3%
Volvo XC40	2WD	2019–2023	27	205	13.2%
	4WD	2019–2024	135	1,710	7.9%

III. RESULTS

Figure 1 shows a summary of the dummy output metrics from both the 16 km/h and 24 km/h pulses for the small SUVs. Values were only collected up to the time when the head left the head restraint on rebound. Upper Fx maximum and Nkm-NEA reported very small values for both pulses. HCT, Nkm-NFP, and head-to-T1 relative velocity (min. and max.) showed similar values across both pulses. Maximum Nkm, Nkm-NEP, upper neck Fx force minimum, T1 X-acceleration, upper neck extension moment, pelvis displacement and all the remaining relative spine velocities showed positive correlations with pulse severity. Upper Fz force, Nkm-NFA and upper flexion showed negative correlations with pulse severity.

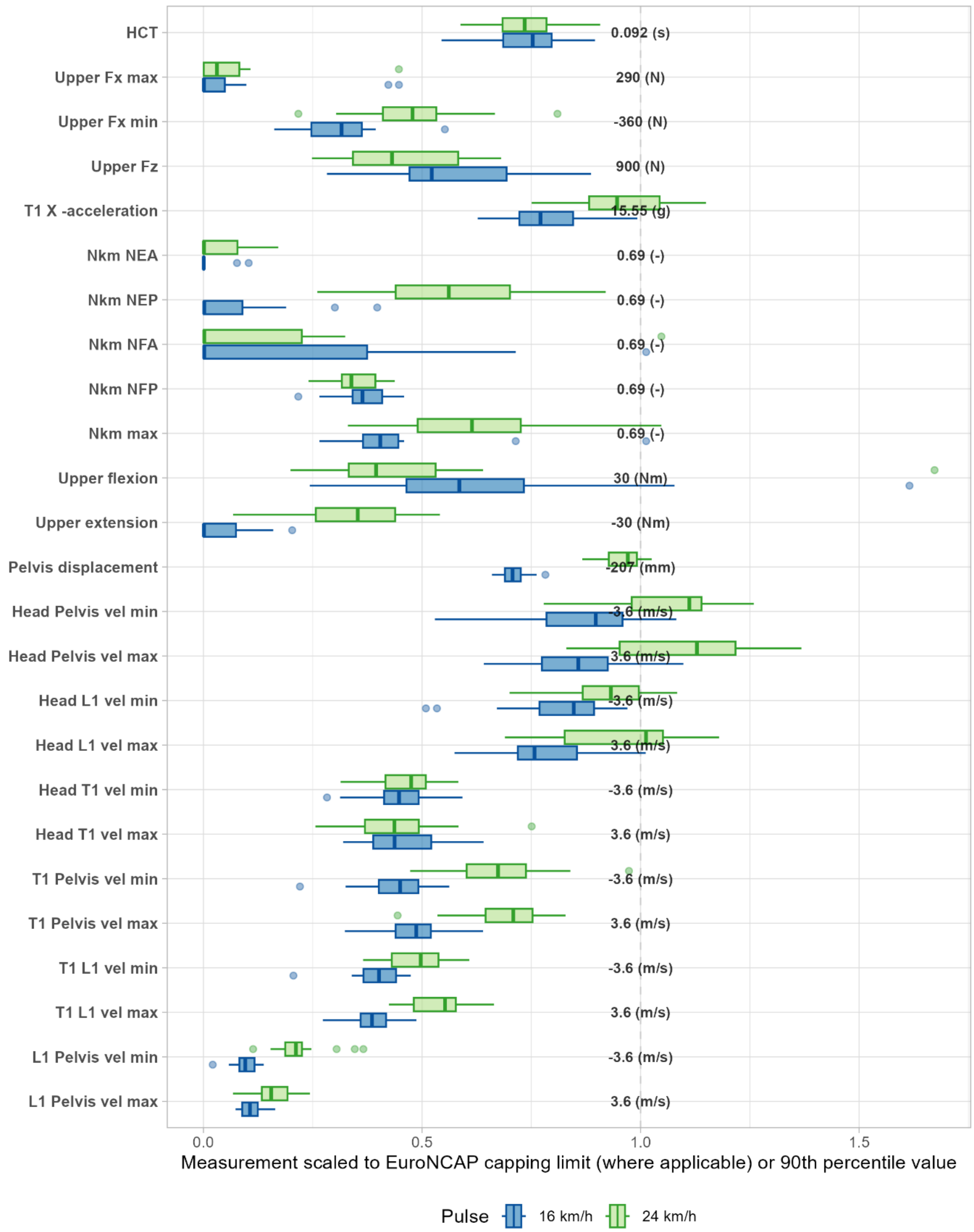

Fig. 1. Range of test results normalised by the Euro NCAP mid-pulse capping limit, except for pelvis displacement and all relative spine velocities which were normalised by the 90th percentile value. The median, quartiles, whiskers and outliers are provided for each metric by pulse [16].

Individual Metric Poisson Regression Analysis (Mid-size Cars, Mid-size SUVs and Small SUVs)

Poisson regression models of injury claim rate using individual metrics while controlling for vehicle class showed nine of the metrics were significant predictors at the $\alpha = .05$ level. These included the metrics previously identified as significant in [8]: T1 X-acceleration and maximum Nkm in the 24 km/h pulse, but not HCT (Table II). Several of the newly added relative spine velocity metrics were also significant at the $\alpha = .05$ level, including the relative velocity between the head and pelvis for the 24 km/h pulse. Relative velocity between the head and pelvis in the 16 km/h was near significant ($p = .06$). All metrics analysed with a p value less than .1 were included in Table II. The injury rate ratios in Table II provide the estimated change in injury claim rates for a change of 1 standard deviation in the metric. For example, a 1.9 g increase in T1 X-acceleration in the 24 km/h pulse is estimated to increase injury claim rate by 7.3%. The inverse relationship between pelvis displacement and injury claim rate is expected; increases in the magnitude of pelvis displacement result in decreases in injury claim rates. All of the models showed differences in estimated PIP/PDL rates by vehicle class, many of which were statistically significant. For example, the model that included pelvis displacement in the 16 km/h pulse showed that, relative to cars, 2WD mid-size SUVs had a rate ratio of 0.90 ($p = 0.17$), 4WD mid-size SUVs had a rate ratio of 0.82 ($p = 0.001$), 2WD small SUVs had a rate ratio of 1.19 ($p = 0.028$) and 4WD small SUVs had a rate ratio of 0.83 ($p = 0.004$).

TABLE II

POISSON REGRESSION RESULTS FOR INDIVIDUAL METRICS

Metric	1 SD	Injury rate ratio	95% CI	*p* value
Pelvis displacement (16 km/h)	10 mm	0.947	(0.91, 0.97)	0.002
Pelvis displacement (24 km/h)	17 mm	0.939	(0.9, 0.97)	0.004
Head-to-pelvis relative velocity minimum (24 km/h)	0.7 m/s	1.076	(1.01, 1.14)	0.02
T1 X-acceleration (24 km/h)	1.9 g	1.073	(1.01, 1.13)	0.021
T1-to-pelvis relative velocity minimum (16 km/h)	0.4 m/s	1.062	(1.01, 1.11)	0.022
Maximum Nkm (24 km/h)	0.12 ()	1.055	(1, 1.1)	0.037
Head-to-L1 relative velocity minimum (24 km/h)	0.6 m/s	1.055	(1, 1.1)	0.045
Nkm-NFA (24 km/h)	0.14 ()	1.079	(1, 1.16)	0.050
T1-to-L1 relative velocity maximum (24 km/h)	0.3 m/s	1.065	(1, 1.13)	0.050
Rebound velocity (16 km/h)	0.4 m/s	1.060	(1, 1.12)	0.053
Head-to-pelvis relative velocity minimum (16 km/h)	0.8 m/s	1.054	(0.99, 1.11)	0.060
Nkm-NFP (16 km/h)	0.04 ()	1.049	(0.99, 1.1)	0.084
Head contact time (HCT) (24 km/h)	10 ms	1.050	(0.99, 1.1)	0.092

Metric Selection and Grouping

The three independently predictive groups of metrics from [8] provided a foundation for designing an assessment programme to encourage robust safe seat designs based on three design principles: head and spine support, stable interaction between the head and head restraint, and management of the rate of energy transfer to the occupant. Since more metrics from the 24 km/h pulse in [8] were significant in predicting claim rates, this pulse was prioritized in metric selection. Improved head and spine support is the first principle and was represented by HCTs in the earlier study. Since the relative velocity between the head and pelvis in the 24 km/h pulse was a significant predictor of injury in this study and has a biomechanical foundation for head and spine support, it was chosen as the primary metric for differentiating head and spine support in seats. Though HCT in the 24 km/h pulse was no longer significant (Table II) in this expanded dataset, it was included in the head and spine support design principle to prevent very late support from the head restraint. Reduced Nkm represents the second design principle, which is improved interaction between the head and head restraint to reduce the loads and moments in the upper neck. A rating category comprised of Nkm and upper neck axial tension was created to assess this aspect of seat design. While tension was not a significant predictor of injury rate, it was included to provide a more comprehensive analysis of the ways that a head restraint can interact with the head and neck to increase neck forces and moments. The third design principle is represented by T1 X-acceleration and pelvis displacement, using the metrics to evaluate the seat's ability to reduce the rate that crash energy is transferred to the occupant. Much like force-limiting in a seat belt, controlled deformation of the seat-back interior elements absorbs crash energy early in the crash while allowing more occupant displacement relative to the vehicle, reducing force and acceleration.

A correlation analysis was conducted to evaluate whether there may be inherent conflicts or trade-offs between the three design principles outlined above. Negative correlations between variables either within one pulse or across both pulses could indicate potential design conflicts. Correlations between HCT, head-to-pelvis relative velocity, maximum Nkm, upper neck tension force, T1 X-acceleration and pelvis displacement from both pulses are shown in Fig. 2. Since it is a negative-value metric, head-to-pelvis relative velocity was inverted so that a positive correlation between HCT and head-to-pelvis relative velocity indicates that higher values of HCT correlate with larger negative values of head-to-pelvis relative velocity. Since larger negative values of pelvis displacement are advantageous, this metric was not converted. Smaller negative values of pelvis displacement have a positive correlation with higher values of HCT. Most metrics showed either positive correlations or little to no correlations both within the same pulse and across pulses. The largest negative correlations were between T1 X-acceleration in the 16 km/h pulse and head-to-pelvis relative velocity in the 16 km/h and 24 km/h pulses (r = −0.24 and r = −0.30, respectively).

	HCT 16K	Head Pelvis vel min 16K	Max NKM 16K	Upper Fz 16K	T1 X Acc 16K	Pelvis displacement 16K	HCT 24K	Head Pelvis vel min 24K	Max NKM 24K	Upper Fz 24K	T1 X Acc 24K	Pelvis displacement 24K
HCT 16K	1.00	0.81	0.46	0.65	-0.08	0.08	0.87	0.71	0.15	0.43	-0.09	0.37
Head Pelvis vel min 16K	0.81	1.00	0.33	0.66	-0.24	0.46	0.78	0.83	0.04	0.39	-0.06	0.57
Max NKM 16K	0.46	0.33	1.00	0.34	0.11	0.03	0.30	0.23	0.31	0.35	-0.16	-0.03
Upper Fz 16K	0.65	0.66	0.34	1.00	0.16	0.18	0.56	0.58	-0.14	0.70	-0.19	0.35
T1 X Acc 16K	-0.08	-0.24	0.11	0.16	1.00	-0.08	-0.12	-0.30	-0.16	0.17	0.12	-0.04
Pelvis displacement 16K	0.08	0.46	0.03	0.18	-0.08	1.00	0.25	0.37	-0.11	0.19	0.18	0.73
HCT 24K	0.87	0.78	0.30	0.56	-0.12	0.25	1.00	0.74	0.14	0.33	[illegible]	0.48
Head Pelvis vel min 24K	0.71	0.83	0.23	0.58	-0.30	0.37	0.74	1.00	0.09	0.48	-0.17	0.55
Max NKM 24K	0.15	0.04	0.31	-0.14	-0.16	-0.11	0.14	0.09	1.00	-0.05	0.09	-0.19
Upper Fz 24K	0.43	0.39	0.35	0.70	0.17	0.19	0.33	0.48	-0.05	1.00	-0.16	0.30
T1 X Acc 24K	-0.09	-0.06	-0.16	-0.19	0.12	0.18	[illegible]	-0.17	0.09	-0.16	1.00	0.20
Pelvis displacement 24K	0.37	0.57	-0.03	0.35	-0.04	0.73	0.48	0.55	-0.19	0.30	0.20	1.00

Fig. 2. Correlation table showing Pearson correlation coefficients for selected metrics in both the 16 km/h and 24 km/h pulses.

Rating Boundaries and Demerit System

After confirming that the metrics selected for the rating programme were not likely to create design conflicts, the measurements from the mid-size car, mid-size SUV and small SUV tests at both pulses were combined to evaluate the existing range of performance among tested vehicles and to establish rating boundaries. Results from each of the three rating categories are presented below. Rating boundaries and demerit values are also shown in Table AII.

Head and spine support

Head and spine support is represented by HCT and the relative velocity between the head and pelvis. Figure 3 shows measured values for all tested seats at both severities. As shown in Fig. 2 and Fig. 3, these two metrics are strongly correlated in both tests. Because relative velocity was a predictor of injury claim rates (Table II) and may better represent the biomechanical principle of relative motion as a whiplash injury causation scenario, it was prioritised over HCT in this rating category. Demerit boundaries for head-to-pelvis relative velocity were selected at 3.0 m/s and 4.0 m/s for the 16 km/h pulse, and at 3.5 m/s and 4.5 m/s for the 24 km/h pulse (Fig. 3). HCT was retained to encourage early head support as a design strategy, but a single downgrade threshold at a higher percentile of the observed test values was selected (0.08 s; Fig. 3). Since HCT shows little variation between pulse severities (Fig. 1), the same boundary is used for both the 16 km/h and 24 km/h tests.

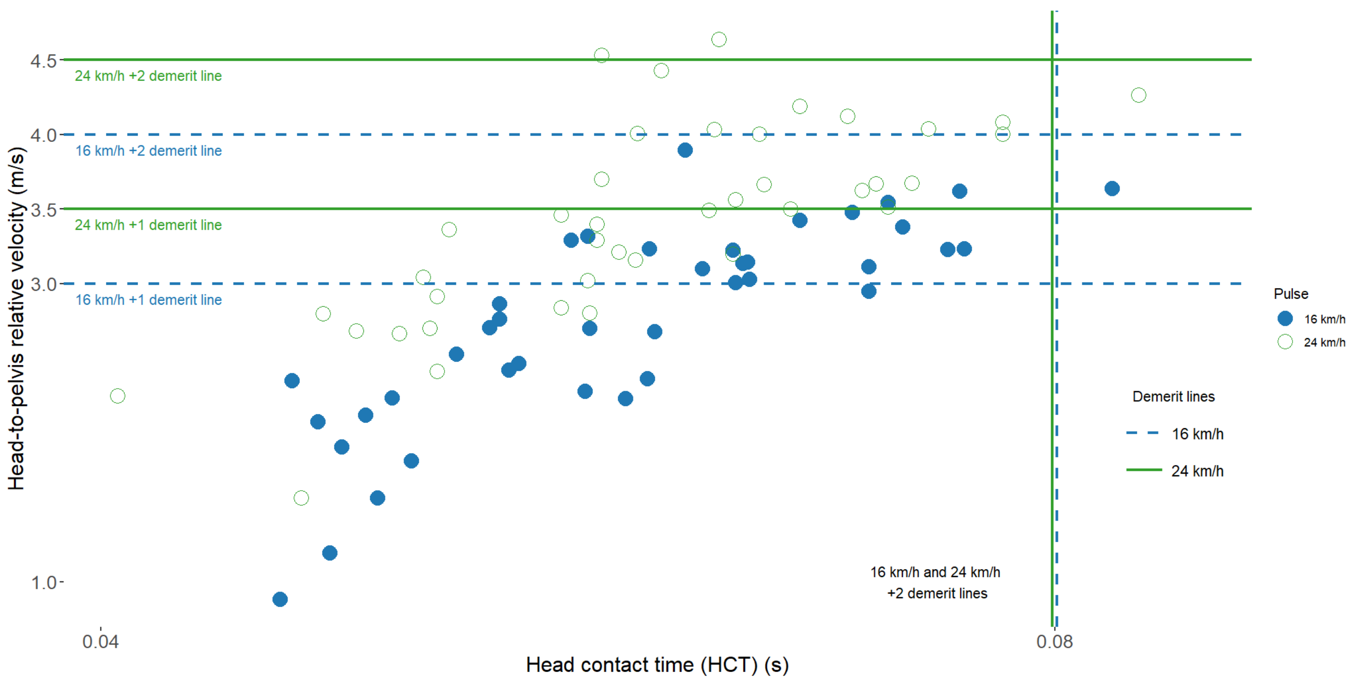

Fig. 3. Head and spine support: test results for head-to-pelvis relative velocity cross-plotted with head contact time with demerit thresholds for each test severity. See Appendix Table AII for more details on calculation of demerits.

Neck forces and moments

Maximum Nkm and upper neck tension are used to evaluate neck forces and moments. Nkm is a normalised metric combining upper neck shear force and moment with values ranging from 0 to 1. In the 24 km/h pulse, maximum Nkm is primarily a combination of extension moment and posterior shear force. In contrast, maximum Nkm in the 16 km/h pulse is primarily a combination of flexion moment and posterior shear force. Figure 4 shows the results from the 16 km/h and 24 km/h tests for seats from the mid-size car, mid-size SUV and small SUV vehicle classes and the established demerit lines. Rating thresholds for Nkm in the 24 km/h test represent lower percentiles of the observed test data, reflecting the fact that this measurement was identified as a significant predictor of injury in both the original [8] and in this expanded study. Demerit boundaries for maximum Nkm were set to 0.3 and 0.5 for the 16 km/h pulse and to 0.35 and 0.55 for the 24 km/h pulse. Upper neck tension was not a significant predictor of injury claim rate in either the original study or this expanded study. However, it does indicate undesirable interactions where the head and neck are pulled in tension by the head restraint. For this reason, it was included as an evaluation metric with the goal of preventing excessive neck tension as seat designs evolve. Demerit thresholds were set to

500 N and 700 N for both pulses because higher neck tensions were actually observed in the lower severity pulse (Fig. 1).

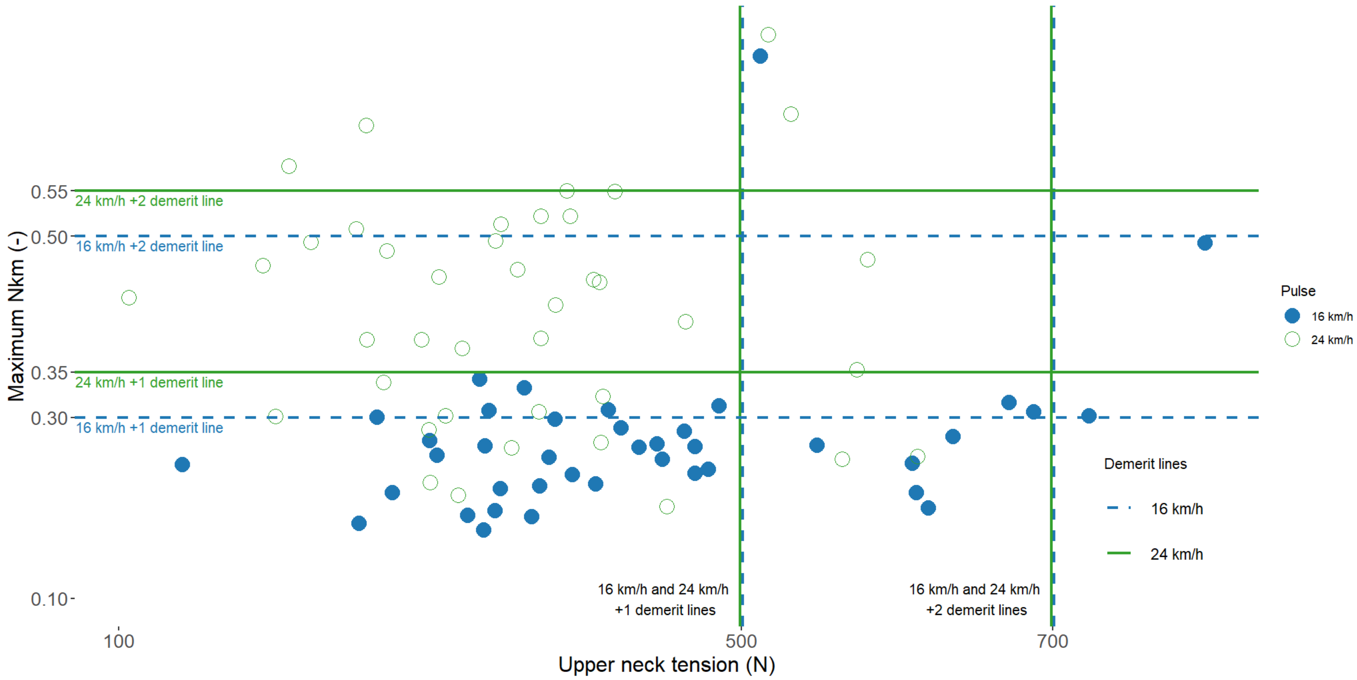

Fig. 4. Neck forces and moments: test results for maximum Nkm cross-plotted with upper neck tension with demerit thresholds for each test severity. See Appendix Table AII for more details on calculation of demerits.

Management of rate of crash energy transfer

Maximum X-acceleration of the T1 vertebra and maximum pelvis displacement relative to the sled are used to evaluate a seat design's management of the rate that crash energy is transferred to the occupant. When measured in the 24 km/h test, both these metrics were significant predictors of injury claim rate, as was pelvis displacement in the 16 km/h test (Table II). Figure 5 shows the results from the 16 km/h and 24 km/h tests for seats from the mid-size car, mid-size SUV and small SUV vehicle classes and the established demerit lines. Demerit thresholds for T1 X-acceleration were set at 12.0 g and 15.0 g for the 16 km/h pulse, and at 14.0 g and 17.0 g for the 24 km/h pulse. Demerit thresholds for pelvis displacement were set to −150 mm and −130 mm for the 16 km/h pulse, to reflect its importance in predicting injury claim rates for that severity. Demerit thresholds for the 24 km/h pulse were set to −190 mm and −170 mm.

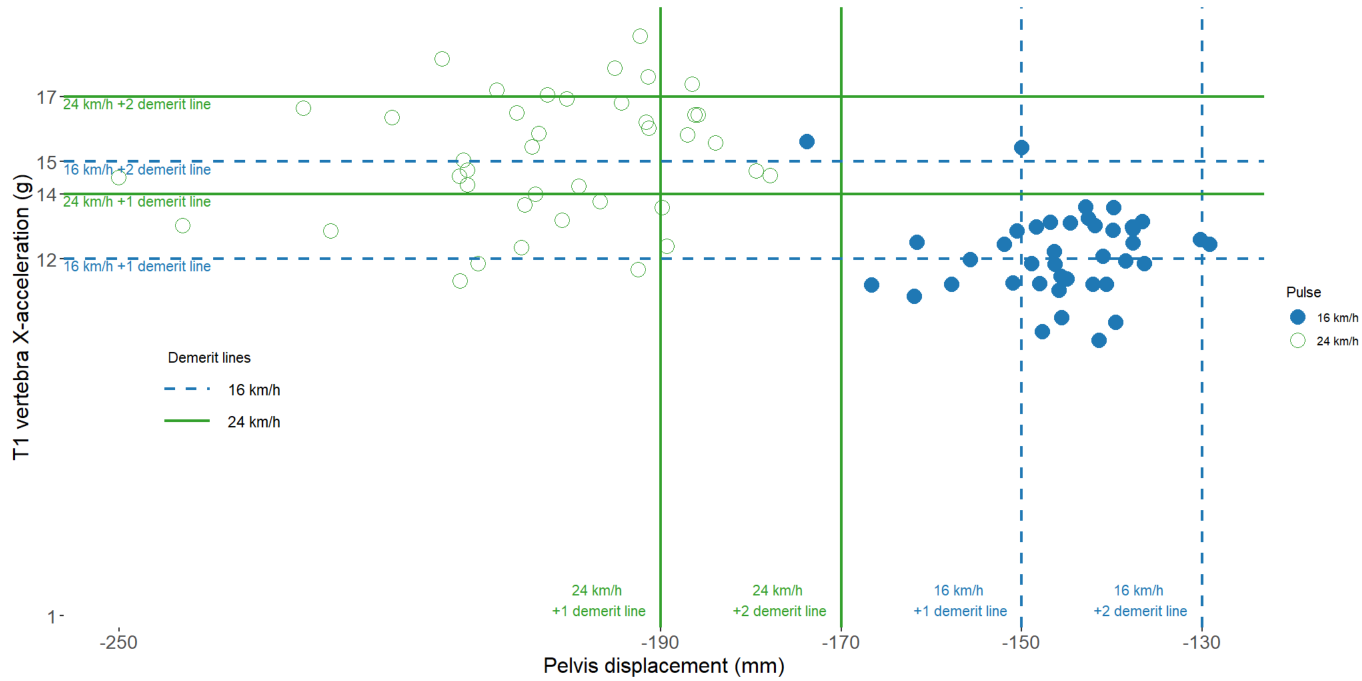

Fig. 5. Management of the rate of energy transfer to the occupant: test results for T1 X-acceleration cross-plotted with pelvis displacement with demerit thresholds for each test severity. See Appendix Table AII for more details on calculation of demerits.

Poisson Regression of Demerit Totals and Overall Ratings

Demerits for each rating group were assigned according to Table AII and summed across both pulses [17]. Demerits totals ranged from 1 to 12 for the 40 seats tested. Of the 40 seat designs analysed, 12 accumulated the most demerits in the 16 km/h tests, 18 accumulated the most demerits in the 24 km/h pulse and 10 had equal demerits in both pulses. Table III shows the distribution of the categories with the highest demerit value for each pulse. The rate of energy transfer category accumulated the most demerits of the three categories at both severities. For the 24 km/h pulse, it was followed by the neck forces and moments category and then the head and spine support category. For the 16 km/h pulse, the second highest category was the head and spine support followed by the neck forces and moments category. Demerit totals were then divided into an overall rating of Good, Acceptable, Marginal or Poor according to Table AIII [17]. Of the 40 seats, 11 received a Good rating, 20 an Acceptable rating, 6 a Marginal rating, and 3 a Poor rating. The sum of the demerits and the overall ratings were evaluated in separate Poisson regression models to verify their relevance to field injury claim rates. Results are shown in Table IV. Each additional demerit was associated with a 2.2% increase in injury claim rate ($p = 0.047$), while each step down in the overall rating (e.g. Good to Acceptable) was associated with a 8.0% increase in injury claim rate ($p = 0.021$). Both regression models estimated similar vehicle type effects as the models based on individual test metrics, with PIP/PDL rate ratios for the different SUV classes ranging from 0.80 – 1.23 relative to cars.

TABLE III

POISSON REGRESSION RESULTS FOR DEMERIT TOTALS AND OVERALL RATINGS

	Number of seat designs where listed category had the most demerits [a]		
Test severity	Head and spine support	Neck forces and moments	Rate of energy transfer
16 km/h	14	13	35
24 km/h	13	23	28

[a] Totals equal more than 40 when the highest value occurs in multiple categories.

TABLE IV
POISSON REGRESSION RESULTS FOR DEMERIT TOTALS AND OVERALL RATINGS

Metric	Unit change	Injury rate ratio	95% CI	*p* value
Sum of demerits (16 km/h + 24 km/h)	1 demerit	1.022	(1.00, 1.04)	0.047
Rating group (Good, Acceptable, Marginal, Poor)	1 rating group	1.080	(1.02, 1.15)	0.021

IV. DISCUSSION

This study expanded the test and field crash datasets from [8] to support a new ratings system that can provide consumers with information on the relative ability of modern seats to provide occupant protection in rear impacts. The analysis included results from both 16 km/h and 24 km/h delta-V sled tests for 40 seats and associated injury claim rates for each vehicle. The three metrics highlighted in [8], T1 X-acceleration and maximum Nkm from the 24 km/h test, continued to be significant predictors of injury claim rate in this expanded dataset. Increases of 1 standard deviation of these metrics resulted in a predicted 5.5–7.3% increase in injury claim rates. While HCT from the 24 km/h pulse was no longer a significant predictor of injury in this expanded study, another metric, head-to-pelvis relative velocity, which has more biomechanical foundation for encouraging spinal alignment, was a significant predictor; increasing this metric by 1 standard deviation in the 24 km/h pulse resulted in a predicted 7.6% increase in injury claim rates. While some of these metrics have been included in IIHS and other NCAP whiplash assessment programmes and have historically shown relevance in predicting injuries [2,6,7], they were no longer correlated with claim rate differences between modern seats when measured in the 16 km/h test [8]. The finding that they can still predict injury rates when measured in the higher severity 24 km/h delta-V pulse indicates that these three metrics provide the foundation for a three-part whiplash-prevention strategy: head and spine support; stable head-to-head restraint interactions; and crash energy transfer rate management.

Supporting the head and spine during a rear impact is an important strategy for reducing the relative motions between head and spine segments that can lead to injury. Though the pain associated with whiplash injury may result from different injury mechanisms [18], limiting these relative motions is a universal strategy for preventing injury. This study identified that the peak relative velocity between the head and pelvis in both the 16 km/h and 24 km/h delta-V tests can be used to identify seats with lower injury claim rates and better occupant protection. A 1 m/s change (the difference between 0 and 2 demerits) in head-to-pelvis relative velocity in 24 km/h tests was associated with predicted injury claim rate increase of 10.8%. The time between the beginning of the crash and when the head restraint first makes contact with the head to provide support (HCT) in the 24 km/h test was no longer a significant predictor ($\alpha = .05$) of injury claim rates. Therefore, HCT was chosen as a secondary metric in the head and spine support rating category as one strategy for reducing relative motion. Though head-to-pelvis relative velocity and HCT are correlated, a single boundary for HCT was included in the head and spine support design category based on a desire to prevent very high head contact times and on its performance in the regression analysis ($p < .1$). One threshold was defined for both pulses to discourage designs that only provide very late head support.

The head restraint and seat should also provide stable support for the head and spine to reduce the loads and moments experienced in the upper neck. Head restraint shape, position, construction and connection to the seat can all affect the forces experienced by an occupant. Nkm was originally proposed by [13] to capture the combined effect of sagittal shear force and anterior-posterior moment on occupant injury. In the current study, this metric in the 24 km/h pulse was a significant predictor of injury claim rate. An Nkm increase of 0.2 (the difference between 0 and 2 demerits) was associated with a 9.2% increase in predicted injury claim rate. Nkm was included in Euro NCAP's whiplash assessment using a sliding scale until 2018, when the assessment was changed to evaluate Nkm with a single capping limit [16,19]. A prior study [7] found that overall Euro NCAP assessment was predictive of PMI, but that maximum Nkm alone was not. In the current study, injury was defined as a PIP claim filed for vehicles with a rear-impact damage claim (PDL). PIP claims are comprised of any type of injury, but [20] reports that neck sprain or strain and back sprain or strain are the most commonly reported injuries. The Folksam insurance data used in [7] define injury as a PMI diagnosis given that a rear-impact injury claim was filed. It is possible that the IIHS and Folksam data represent different types of whiplash injury and are associated with different dummy metrics. The head interacts with the head restraint differently at different impact speeds. In the 24 km/h pulse, maximum Nkm is primarily a combination of extension moment and posterior shear force. In contrast, maximum Nkm in the 16 km/h pulse is primarily a combination of flexion moment and posterior shear force. Furthermore, the upper neck axial tension tended to be greater in the 16 km/h tests than in the 24 km/h tests (Fig. 1). Though it was not a significant predictor of injury claim rate, upper neck axial tension was included in the rating criteria for stable head restraint support to more fully represent the ways that a head restraint can increase forces in the neck. The differences in occupant–seat interaction in the two tests highlight the need to include evaluations at multiple severities to robustly assess seat performance.

As safety restraints, vehicle seats are an important tool for reducing the rate of energy transferred to the occupant in a rear-impact crash. One measure of the rate of transferred energy early in the crash event is the acceleration in the torso at the T1 vertebra. In the current study, T1 X-acceleration was a significant predictor of injury claim rates. A 3.0 g increase (the difference between 0 and 2 demerits) in T1 X-acceleration in the 24 km/h pulse was associated with a predicted injury claim rate increase of 11.9%. T1 acceleration was included in the IIHS vehicle seat/head restraint evaluation (introduced in 2004) using a pass/fail threshold of 9.0 g in combination with a HCT threshold of 70 ms. In combination with low neck forces, a seat was only required to pass either threshold to achieve a Good rating. Almost all tested seats passed the HCT requirement, but not the T1 X-acceleration requirement. Like maximum Nkm, T1 X-acceleration was not identified as a significant predictor of PMI by [7]. Based on the findings of the current study, however, maximum T1 X-acceleration was chosen as one of two metrics for distinguishing the ability of the seat to manage the rate of energy transfer. Pelvis displacement is the second metric in this rating category, because one strategy for reducing the rate of transfer of crash energy is allowing the pelvis to sink into the seat back. This can be done by deforming the interior elements of the seat back or allowing controlled deformation and translation of the seat back relative to the seat pan [21]. To measure this, [15] used the displacement measured from double integration of the pelvis accelerometers. Due to the high severities tested in that study, angular rate sensors and initial positions were used to correct the reference frame so that the pelvis and sled X-accelerations aligned. Subsequent analysis found that, due to the controlled nature of the pelvis, this was not necessary for lower severity impacts. Therefore, in the current study, pelvis displacement is simply a double integration of the pelvis X-accelerometer relative to the sled X-accelerometer. Pelvis displacement in both the 16 km/h and 24 km/h pulses was a significant predictor of injury claim rate in this study. Increasing the amount of pelvis displacement by 20 mm (the difference between 0 and 2 demerits) for the 16 km/h and 24 km/h pulses was associated with decreases in the predicted injury claim rate of 10.0% and 7.1%, respectively.

Demerit counts for each of the three parts of the whiplash-prevention strategy showed that performance of the seat designs varied across rating categories and, for some seats, across pulses. A Poisson regression model using the total demerits for all three categories and both pulses showed that each additional demerit was associated with a 2.2% increase in injury claim rate, a result that was strongly significant. This underscores the importance of including all three design principles and both pulses in the overall assessment. Poisson regression also confirmed that the ratings programme remained predictive of real-world injuries even after condensing 18 possible demerits into four categories (Good, Acceptable, Marginal, Poor). A change in rating from Poor to Good would be associated with a 21% decrease in injury claim rate. The average claim rate for all vehicles included in this study was 11.1%. With a conservative estimate of 1.7 million rear-impact crashes per year [1], a 21% decrease in injury claim rate could improve injury outcomes for as many as 40,000 exposed occupants.

Adding an additional impact severity to IIHS's whiplash-prevention assessment is a first step in incorporating more of the crash variability seen in real-world crashes. This analysis identified relevant metrics and an overall evaluation to improve the correlation between whiplash ratings and real-world injury. However, some limitations exist. Analyses were performed using raw insurance claim rates and did not control for factors such as age and sex of the rated driver. Likewise, other than sled test measurements and vehicle class, there were no explicit controls for vehicle differences that could affect injury, such as curb weight or interactions between vehicle types. 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. PIP claims also do not provide information on occupant position relative to the head restraint, so the relationship of any individual injury claim to the IIHS occupant test position is unknown. To mitigate the influence of these variables, a minimum PDL claim threshold of 1,000 per vehicle was used for inclusion in the injury claim analyses in this study. Additionally, a separate study conducted to address these limitations found the total demerit score was a significant predictor of police-reported injury rates for drivers in rear impacts, even while controlling for sex, age, and differences between the striking and struck vehicle [22]. Further, the three foundational design principles for seat design were the results of a step-wise statistical approach to parameter selection in [8], however, the final metric selection in this study was more subjective to address potential test outcomes that currently don’t exist in the dataset.

V. CONCLUSIONS

This research demonstrates that results from 16 km/h and 24 km/h tests can be combined into a whiplash-prevention evaluation that distinguishes between modern seats in a way that corresponds to real-world injury rate differences. Six dummy metrics are used to encourage a three-part whiplash-prevention strategy: head and spine support; stable head-to-head restraint interactions to reduce neck loads and moments; and management of the rate of transfer of crash energy to the occupant. Head and spine support is assessed using head-to-pelvis relative velocity and head contact time. Stable head-to-head restraint interactions are assessed with maximum Nkm and upper neck axial tension. Rate of transfer of crash energy is measured with T1 X-acceleration and pelvis displacement. While many of these metrics were significant predictors of injury claim rate on their own, combining the results from these three groups and two severities produces a total demerit score and overall rating that are strong predictors of injury while providing an assessment that covers a wider range of the variation in real-world crash conditions and potential injury mechanisms. The updated assessment will encourage seat and head restraint designs that provide increased protection against whiplash injuries.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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VIII. APPENDIX

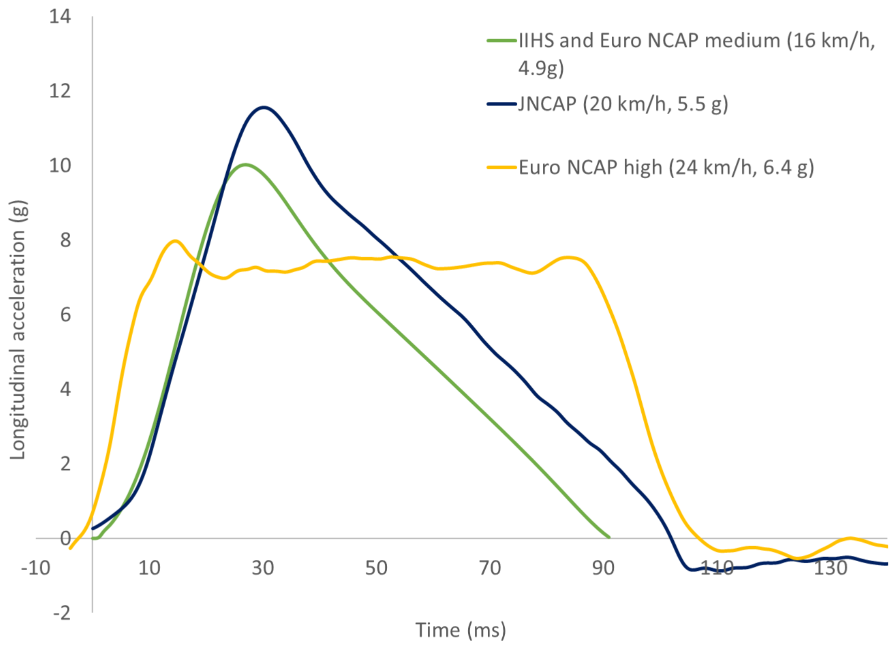

Fig. A1. Longitudinal acceleration pulses from IIHS, Euro NCAP and JNCAP used in sled testing in [8]. Only the 16 km/h and 24 km/h of these were used in the current study.

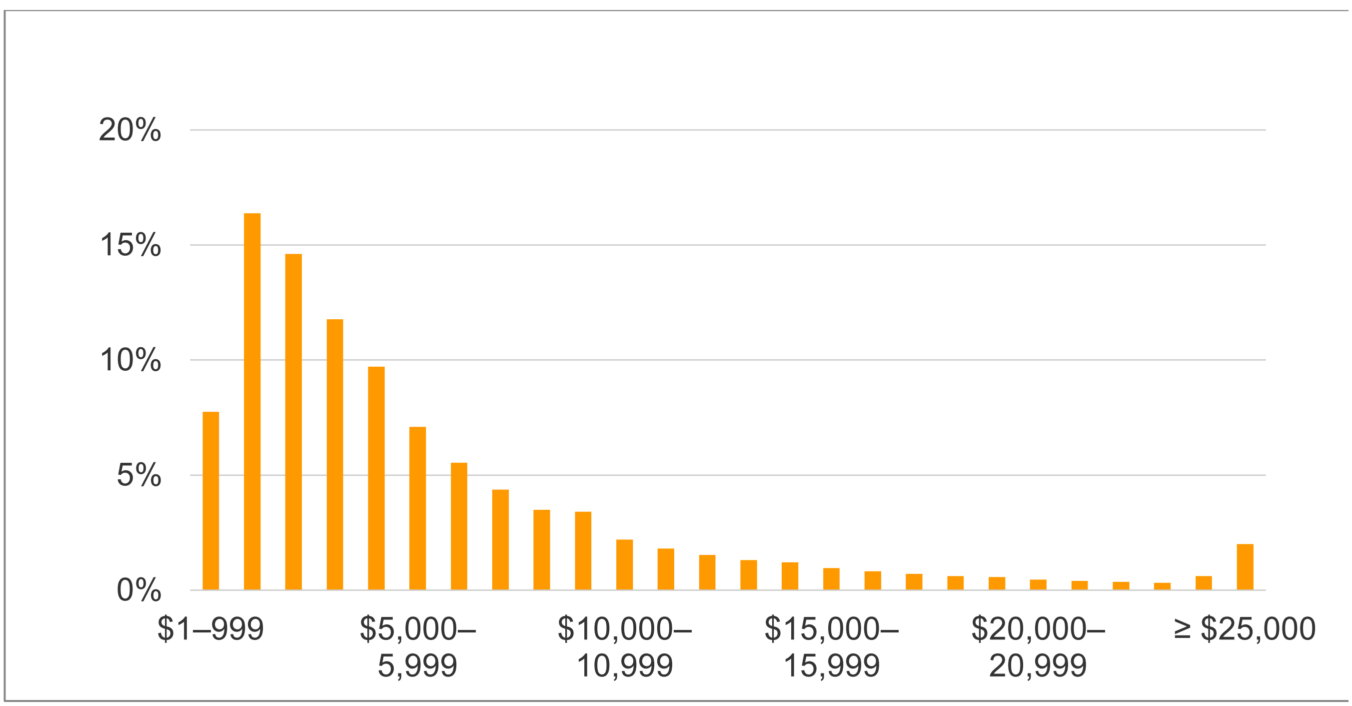

Fig. A2. Distribution of PDL claims by claim size, model year 2019–2025 vehicles, calendar year 2024 [23].

TABLE AI

TABLE OF EQUATIONS FOR CALCULATED METRICS

Calculation	Equation number
Pelvis displacement $= \min\left(\iint a_{pelvis_x} dtdt - \iint a_{sled_x} dtdt\right)$	(Equation 1)
$v_{region_x} = \int a_{region_x} dt$	(Equation 2)
$v_{region_z} = \int a_{region_z} dt$	(Equation 3)
$v_{region} = \sqrt{{v_{region_x}}^2 + {v_{region_z}}^2}$	(Equation 4)
Head-to-pelvis relative velocity $= \min(v_{head} - v_{pelvis})$	(Equation 5)
$Mocy = Upper\ y\ moment - Upper\ x\ force\ *\ .01778$	(Equation 6)
$NKM = \frac{Fx(t)}{Fint} + \frac{Mocy(t)}{Mint}$	(Equation 7)
$T1_{x_{acceleration}} = \max\left(avg(T1_{x_{acc(left)}}, T1_{x_{acc(right)}})\right)$	(Equation 8)

TABLE AII

DEMERITS FOR 16 KM/H AND 24 KM/H PULSES

16 km/h		**+1 demerit line [a]**	**+2 demerit line [a]**	**Group total demerits [b]**
Head and spine support	Head-to-pelvis relative velocity (minimum) (abs_val) (m/s)	3.0 m/s	4.0 m/s	0–3
	Head contact time (ms)	n/a	80 ms	
Stable head-to-head-restraint interaction	Maximum Nkm	0.30	0.50	**0–3**
	Upper neck tension maximum (N)	500 N	700 N	
Management of energy transferred to the occupant	T1 X-maximum acceleration (g)	12.0 g	15.0 g	**0–3**
	Pelvis displacement (minimum) (mm)	−150 mm	−130 mm	
24 km/h		**+1 demerit line [a]**	**+2 demerit line [a]**	**Group total demerits [b]**
Head and spine support	Head-to-pelvis relative velocity (minimum) (abs_val) (m/s)	3.5 m/s	4.5 m/s	**0–3**
	Head contact time (ms)	n/a	80 ms	
Stable head-to-head restraint interaction	Maximum Nkm	0.35	0.55	**0–3**
	Upper neck tension maximum (N)	500 N	700 N	
Management of energy transferred to the occupant	T1 X-maximum acceleration (g)	14.0 g	17.0 g	**0–3**
	Pelvis displacement (minimum) (mm)	−190 mm	−170 mm	
			Total	0–18

Note: n/a = not applicable (because there is one threshold for the head contact time metric).

[a] Values greater than the listed demerit threshold in Table AII will receive the listed demerit. For example, for the 16 km/h pulse, a maximum Nkm value of 0.30 receives 0 demerits and 0.31 receives 1 demerit. All values are rounded to the decimal places shown in Table AII before demerits are applied.

[b] Total demerits in each group are capped at 3.

TABLE AIII

RATING CATEGORIES BASED ON THE SUM OF DEMERITS FROM 16 KM/H AND 24 KM/H PULSES

	Good	**Acceptable**	**Marginal**	**Poor**
Total demerits (sum from Table AII)	0–3	4–6	7–9	10–18