The potential use of DAMAGE, a rotation-based head injury criterion, in IIHS front and side -impact crash tests

Becky C. Mueller, Luke E. Riexinger, Raul A. Arbelaez

Abstract Insurance Institute for Highway Safety's (IIHS) front and side-impact crash tests currently evaluate dummy head protection based on metrics from linear accelerometers in the dummy's head and a dummy kinematics assessment through video evidence. This study investigated whether the rotation-based brain injury metric called diffuse axonal multi-axis general evaluation (DAMAGE) could identify poorly controlled head kinematics that current evaluation criteria do not capture. We calculated DAMAGE for 809 dummies in 636 IIHS front and side-impact crash tests from head angular rate sensors installed in a Hybrid III 50th percentile male dummy and a SID-IIs 5th percentile female dummy. Peak resultant acceleration, head injury criterion (HIC), DAMAGE, and assessments of the occupant restraint system and dummy kinematics were compared. Inclusion of the DAMAGE metric in crash test assessments increased the number of dummies where sensors identified uncontrolled head kinematics from 189 (23%) to 247 (31%). Potential countermeasures include airbags that minimise rotations in directions other than the primary impact. DAMAGE can supplement existing metrics to provide a broader assessment of head protection in crash tests. Some cases remain where neither linear nor rotation-based metrics identified kinematic deficiencies; therefore, restraints and kinematics assessments with video-based observations are still important for providing an overall head protection assessment.

Keywords brain injury, injury metrics, high-speed crash tests, rotational brain injury, airbags

I. INTRODUCTION

A Real-World Problem

According to the U.S. Centers for Disease Control and Prevention, approximately 70,000 people sustain fatal traumatic brain injuries (TBIs) annually [1]. TBIs, which have been called the "silent epidemic", are responsible for an additional 215,000 hospitalised people each year, often resulting in long-term cognitive or sensory deficiencies [2]. Traffic crashes are one of the most common sources of injury-induced TBIs, second to falls, accounting for 17% of all TBI-related fatalities, with the highest fatality rates among younger people aged 15 to 24 years old (4.7 per 100,000 people compared with 3.1 for all ages) [2].

The latest field data on roadway crashes indicate an opportunity to address occupant head injuries, specifically lower severity injuries such as Abbreviated Injury Scale (AIS) 2 injuries and concussions, which make up 60% of recorded head injuries [3]. At the AIS2+ level, head injuries were found in relatively similar frequency for frontal crashes (1.95%) and side crashes (2.12%), but significant differences were seen for different types of occupant [4]. Females were more vulnerable to head injuries, 1.5 times more likely to sustain AIS2+ injuries compared with males [4], although this difference disappears when controlling for vehicle type [5]. Through an analysis of crash investigations and hospital records, elderly people have been found to be more susceptible to brain bleeds [4][6]. Field data of crashes occurring at severities similar to Insurance Institute for Highway Safety (IIHS) frontal crash tests involved a 3% risk of skull fracture and a 7% risk of AIS4+ brain injury [7]. Specifically, examining real-world crashes with damage profiles matching IIHS small overlap and IIHS moderate overlap tests show a 1.3–5.0% risk of AIS3+ head injuries [8] and a 9.0–12.6% risk of AIS2+ head injuries [9].

Measuring Head Injuries in Crash Tests

In automotive crashes, head injuries are sustained from a range of mechanisms, requiring different sensors and associated metrics for a comprehensive evaluation of injury risk. The primary linear acceleration-based metric used in automotive safety is head injury criterion (HIC). The HIC, which measures the linear impulse of a head's motion during impact, is derived from the Wayne State Tolerance Curve and based on experiments relating accelerations of cadaver skulls to sustained skull fractures [10-11]. Since the 1990s, regulatory agencies and consumer safety information programmes in the USA and around the world have used HIC for evaluations of

B. Mueller (email: bmueller@iihs.org; tel: +1-434-985-4600) is a Senior Research Engineer, L. E. Riexinger is a Research Engineer, and R. A. Arbelaez is the Vice President of the Vehicle Research Center at the Insurance Institute for Highway Safety in Virginia, USA.

vehicle interiors and supplemental restraint systems in high-speed frontal and side crash tests with both belted and unbelted dummies [12-15]. Additionally, peak linear acceleration is used as an indicator of hard non-airbag contact with interior vehicle structures [15-17]. Experts have acknowledged that these linear acceleration-based metrics representing focal injuries such as skull fractures and hematomas from blunt impacts are unlikely to capture rotation-based head injury mechanisms of concussions and other diffuse brain injuries, which are also known to occur in automotive crashes [18-20].

In the 1990s, with the introduction of the IIHS moderate overlap crash test, IIHS overcame the known limitations of available injury metrics by introducing an assessment of the occupant restraint system and dummy kinematics (restraints and kinematics) in crash tests to capture observations of poorly controlled head kinematics through video evidence. The need for a supplemental assessment of head protection has been highlighted by tests where uncontrolled dummy kinematics (e.g. a head hitting an airbag, sliding off the airbag and then striking rigid interior surfaces) were accompanied by injury measures that indicated a low risk of injury. As new injury criteria, especially rotation-based ones, are developed, they can be added to IIHS assessments to provide more quantifiable biomechanics-based evidence for guiding vehicle restraint system designs.

Rotational Brain Injury Criteria

Criteria to measure rotation-induced brain injuries such as concussions and diffuse axonal injury have been discussed since the early days of brain injury biomechanics [21-22], but the success of HIC in reducing head injuries overshadowed past efforts to further their development. Studies of airbag effectiveness showed 29% and 37% reductions in fatal head injuries for front and side crashes, respectively, indicating that HIC's use in crash testing has been an effective tool for reducing injury [23-24]. However, there also is evidence of HIC's shortcomings. Brain injury risk in tow-away crashes with belted occupants doubled during the 2000s from 0.17% to 0.35% [25], and observations from laboratory tests showed dummies striking the vehicle interior were measuring low HIC values and peak accelerations [8]. These brain injuries, including concussions and diffuse axonal injury, are caused by rotational mechanisms that are unlikely to be detected by HIC, which is designed to capture skull fractures and hematomas from hard impacts. This suggests that linear accelerations were likely not responsible for the increase in field injuries, and a separate criterion specifically designed to identify rotational injury mechanisms may be required to capture these additional injuries. Researchers identified a high correlation between peak angular velocity and strain values from a finite element (FE) head model for pure rotational impacts [26] and that angular velocity was a stronger predictor of mild TBI than acceleration [27].

In the 2010s, sports injury researchers focusing on head impacts, concussions and helmet design developed many injury criteria with rotational or both rotational and linear characteristics [28-29]. The National Football League rates helmets using a criterion called the head acceleration response metric (HARM), which is based on both linear and rotational metrics [30].

Since 2000, more than a dozen rotational brain injury criteria have been proposed to evaluate head injury risk in automotive crashes [31-35]. The basis for many of these criteria are either purely kinematic measurements [35-36] or kinematic measurements tuned to strains from FE models of the brain, specifically: the maximum principal strain (MPS); the cumulative strain damage measure (CSDM), a cumulative volume fraction that exceeds a given threshold of MPS; and the maximum von Mises stress criterion [37]. A variety of FE head models are used in the automotive safety field. These include the simulated injury monitor (SIMon) [38], KTH Royal Institute of Technology model [39], global human body modeling consortium (GHBMC) model [35], total human model for safety (THUMS) [31], and Strasbourg University FE head model (SUFEHM) [40]. Most of these were developed and validated with the same human and animal datasets, though researchers have found differences in biofidelity of different models when compared to post mortem human subject tests in terms of brain motion, pressure and strain [41].

FE head model-based metrics are better suited for the impact duration and complexity of head motion experienced by dummies in high-speed car crash tests. Interactions between the dummy's head and airbag often result in combinations of translational and rotational motion occurring in multiple directions, where FE model-based metrics can account for the anisotropic nature of brain. Formulas that can account for the timing of rotational velocities and accelerations in different directions provide additional insight into the complex head motion. In contrast, purely kinematic metrics such as resultant angular acceleration or change in angular velocity are most relevant to pure rotational events [26] and associated thresholds were often derived from scenarios such as a head strike with the ground from sports that involve simpler head motions and shorter durations. Comparisons of various purely kinematic and FE head model-based metrics in crash test conditions confirm that FE-model based metrics consistently have higher correlations (R^2) to FE head models [36][42]. Additionally, many FE-model based metrics have injury risk functions to assess injury at levels up to AIS 4+ [43-44] and some metrics, UBrIC and DAMAGE, have small female specific critical values [45], while for purely kinematic based metrics, thresholds are typically at AIS1 or AIS 2 levels [35][46], directionally specific, and currently no female-specific thresholds exist. In 2013, NHTSA introduced the brain injury criterion (BrIC), an FE head model kinematics-based metric based on the SIMon FE model with an associated injury risk function applicable to all crash test dummies [25]. NHTSA intended to introduce BrIC along with the THOR dummy in future U.S. NCAP crash test evaluations [47]. Early critiques of BrIC identified flaws with the formula and an overprediction of injury from the risk curve, which posed a challenge for industry-wide acceptance [8][48-52]. In 2015, Euro NCAP considered adopting BrIC to fulfil its goal of adding a rotation-based brain injury metric to crash test evaluations [53], but ultimately decided to pursue other metrics due to industry's opposition [54].

As a reaction to BrIC's limitations, researchers have proposed alternative formulas and revisited injury data for improved risk functions. Researchers at the University of Virginia developed the universal brain injury criteria (UBrIC), a kinematics-based metric [42], and the diffuse axonal multi-axis general evaluation (DAMAGE), a multi-body system model of brain strain [55]. Both criteria originally were tuned to 50th percentile male head injuries and later updated with 5th percentile female-specific versions using the GHBMC FE model [45]. Honda also developed a second-order system model based on the GHBMC FE model called convolution of impulse response for brain injury criteria (CIBIC) for the 50th percentile male [56] and later introduced an updated version called eCIBIC based on MPS-99 [57]. Comparisons of how closely various rotational brain injury criteria can replicate FE model brain strain in a variety of automotive crash scenarios indicate DAMAGE as the frontrunner of available finite element brain model based rotational injury metrics for use in automotive crash testing, though UBrIC and CIBIC are often close behind [31][58-59]. This is not surprising, as many of these rotational criteria are derived from the same FE models. A comparison to the KTH FE model in frontal impacts found DAMAGE to have the best goodness of fit (0.84), followed by CIBIC (0.74) and UBrIC (0.68) [39]. A R^2 comparison of metrics to MPS95 in the GHBMC FE model across front and side crash, sled test and sport data indicated DAMAGE was the highest (0.91), followed by CIBIC (0.88), BRIC (0.75) and change in angular velocity the lowest (0.68) [42]. New risk curves have been developed for all potential criteria [43], but concerns about these curves overpredicting risk remain, especially for lower severity level injuries [60]. Euro NCAP adopted DAMAGE for frontal crash test evaluations but introduced it prior to the release of the new injury risk functions; therefore, performance boundaries were set based on current fleet performance rather than an injury risk function [61]. Recent comparisons of DAMAGE from frontal crash tests and real-world brain injury rates indicate THOR largely overpredicts real-world injury occurrence while Hybrid III dummies are consistent with real-world rates [44].

Objective

This study investigated the potential for a rotation-based brain injury metric called DAMAGE to identify uncontrolled dummy head kinematics not captured by current evaluation criteria.

II. METHODS

IIHS Crash Test Dataset

IIHS began installing triaxial angular rate sensor (ARS) arrays in dummy heads in 2012. Analysis in this study included IIHS high-speed front and side crash tests where head ARS data were collected. In 64-km/h frontal crashes (moderate and small overlap), injury metrics for the driver and right front-passenger seating positions were evaluated using Hybrid III 50th percentile male dummies. Since 2022, the IIHS front moderate overlap test has included a Hybrid III 5th percentile female dummy in the rear-outboard seating position, but was not included in this study. Linear and rotational head injury metrics evaluated in this study were based on the head impacting an external source, but none of the rear-seated dummy heads contacted objects during the crashes, therefore the metrics would not apply. For additional information, see the Appendix. For IIHS side crashes conducted at 50 km/h (original IIHS evaluation) and 60 km/h (updated evaluation), SID-IIs 5th percentile female dummies in the driver and rear-outboard seating positions were used for the head injury analysis.

All tests were conducted in accordance with the IIHS front and side-impact crash test protocols [62-66]. Tests where at least one angular rate sensor malfunctioned were excluded from the analysis. To allow the focus of this study to be on primary head loading and head contacts, data analysis was limited to the first 100 ms for side crashes and the first 200 ms for frontal crashes, which excluded kinematics and hard contacts that occurred during rebound. The degree to which rebound kinematics of crash test dummies represent human response is unknown, and for some crash configurations, the head restraints are removed to accommodate photography, which may result in interactions with the vehicle interior that are not representative of occupants in real-world crashes.

Current IIHS Head Injury Metrics

Head injury criterion (HIC) is an acceleration-based metric that measures the linear impulse of a head's motion during impact (Eq. 1) and can be scaled for use with dummies of different sizes [67]. IIHS's crashworthiness evaluation protocols (a) limit the calculation of HIC to a maximum time window ($t_2 - t_1$) of 15 ms (HIC_{15}) and (b) limit HIC_{15} thresholds to 700 and 779 for the 50th percentile male and 5th percentile female dummies, respectively, which are associated with a 5% risk of severe injury [68].

$$HIC_{15} = max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1) \qquad (Eq. 1)$$

Where *a(t)* = resultant head acceleration at time t and t_1 and t_2 represent times within the impact event. The maximum time window is 15 ms.

Maximum linear acceleration is measured from the peak value of the resultant head acceleration. In IIHS testing, a peak resultant head acceleration greater than 70 g that results from a contact between the head and a hard surface of the vehicle interior results in a downgrade of the overall head injury rating.

Restraints and kinematics: Because injury metrics alone do not always provide a full assessment of potential risks in a crash, observations of the restraint system and dummy kinematics are considered and may potentially downgrade a vehicle's overall rating. Video and data are reviewed to assess potentially injurious scenarios such as unstable head-to-airbag interactions like the head slipping off the frontal or side airbag, the head bouncing between the frontal and side airbags, and mistimed airbag deployments. A complete list of restraints and kinematics evaluations can be found in the IIHS front and side-impact rating guidelines [16][69-71].

Rotational Brain Injury Metric for Consideration

DAMAGE is a second-order system constructed using a physical mass-spring-damper analogue to represent the maximum brain strain due to rotational motion around each axis of the head [42]. A matrix form of the second-order system is shown in Eq. 2. There are critical values, $c_{xx}, c_{xy,}c_{xz}$, specifically for the 50th percentile male based on MPS-95 from the GHBMC 50th percentile male (v4.3) FE model [42] and 5th percentile female brain based on MPS-95 from the GHBMC 5th percentile female (v5.1) FE model [45]. DAMAGE threshold was based on AIS4+ injury level for a more direct comparison to the HIC threshold and preferable because studies indicated that at the lower injury severity level, the associated risk curve is overpredictive [55]. A DAMAGE value of 0.4 was chosen as a threshold for this analysis as it is both similar to the Euro NCAP's lower limit and is associated with approximately a 5% risk of AIS4+ brain injury, similar to the head injury rate for the HIC threshold [44].

$$DAMAGE = \beta max_t\{|\vec{\delta}(t)|\}$$

$$\vec{\delta} = [\delta_x(t)\delta_y(t)\delta_z(t)]^T$$

$$\begin{bmatrix} m_x & 0 & 0 \\ 0 & m_y & 0 \\ 0 & 0 & m_z \end{bmatrix}\begin{Bmatrix} \ddot{\delta}_x \\ \ddot{\delta}_y \\ \ddot{\delta}_z \end{Bmatrix} + \begin{bmatrix} c_{xx}+c_{xy}+c_{xz} & -c_{xy} & -c_{xz} \\ -c_{xy} & c_{xy}+c_{yy}+c_{yz} & -c_{yz} \\ -c_{xz} & -c_{yz} & c_{xz}+c_{yz}+c_{zz} \end{bmatrix}\begin{Bmatrix} \dot{\delta}_x \\ \dot{\delta}_y \\ \dot{\delta}_z \end{Bmatrix} +$$

$$\begin{bmatrix} k_{xx}+k_{xy}+k_{xz} & -k_{xy} & -k_{xz} \\ -k_{xy} & k_{xy}+k_{yy}+k_{yz} & -k_{yz} \\ -k_{xz} & -k_{yz} & k_{xz}+k_{yz}+k_{zz} \end{bmatrix}\begin{Bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{Bmatrix} = \begin{bmatrix} m_x & 0 & 0 \\ 0 & m_y & 0 \\ 0 & 0 & m_z \end{bmatrix}\begin{Bmatrix} \ddot{u}_x \\ \ddot{u}_y \\ \ddot{u}_z \end{Bmatrix} \qquad (Eq.2)$$

Where β is a scale factor that relates maximum resultant displacement of the system to the MPS95 value from the GHBMC FE brain model, *m* is a diagonal matrix of system masses, *c* and *k* are symmetric matrices that contain the damping and stiffness parameters and $\ddot{\delta}, \dot{\delta}, \delta, \ddot{u}$ are time history vectors of accelerations, velocities, displacements, and applied acceleration time histories, respectively.

There are a number of other rotational brain injury metrics that have been proposed over the years including BrIC, GAMBIT, CIBIC, E-CIBIC, and UBRIC [25][31][35][42]. All rotational brain injury metrics utilise some combination of the angular acceleration and angular velocity signals. For sake of comparison, the peak resultant angular acceleration and the peak angular velocity were computed and summarised. Individual comparison metrics were not computed in this analysis because of limitations of the metric. Among the head loading observed, many involved complex rotations in multiple axes at differing points in time. Out of all potential metrics, DAMAGE is the only one where the formula accounts for the simultaneous contribution of both rotational velocity and rotational acceleration in all three directions to head injury and has critical values specific to the 50th percentile male and 5th percentile female sizes. A recent study indicated that between the Hybrid III and THOR dummies, DAMAGE values from Hybrid III more closely predict real-world traumatic brain injury rates [44].

Metric Comparisons

The current and proposed metrics for evaluating uncontrolled head kinematics in IIHS crash tests were compared to identify scenarios where the various linear, rotational, and video-based metrics provide the same or different assessments. This will help identify where DAMAGE has the greatest potential to supplement existing criteria for identifying possible vehicle improvements. For each metric, a threshold value was assigned where values above the threshold would be considered an indicator of uncontrolled head kinematics. For metrics currently used in IIHS testing, thresholds were based on previously established ratings downgrade values (Table I).For DAMAGE, a threshold value of 0.4 [44] was chosen to best match the injury level, AIS4+, and risk percentage, 5%, associated with the HIC threshold. For some aspects of the analysis, peak linear acceleration and HIC were combined into a “linear acceleration metrics” category to compare against the rotational metric of DAMAGE.

TABLE I

SUMMARY OF HEAD INJURY METRICS DOWNGRADES

Metric	Downgrade threshold
Head injury criterion (HIC)	Hybrid III 50th percentile male dummy: >700 SID-IIs 5th percentile dummy: >779
Peak resultant linear acceleration	>70 g
Restraints and kinematics	Acceptable, marginal or poor, based on demerits for head protection (as described in IIHS’s rating guidelines)
DAMAGE	>0.4

III. RESULTS

Data from 809 dummies in 636 crash tests were included in the study. A summary of the ranges of head injury metrics and averages by IIHS crash test mode and seat position are shown in Table II. Across all crash tests, HIC values ranged from 10 to 1,178, and DAMAGE values ranged from 0.04 to 0.69, and peak linear accelerations ranged from 14g to 142 g. The average DAMAGE value was highest for moderate overlap drivers, while the average HIC and average peak accelerations were highest for side-impact rear passengers. The HIC threshold was only exceeded in the side crash for two of the drivers. Peak accelerations above 70 G were observed in all crash modes and seat positions except the driver in the passenger small overlap test and DAMAGE values above threshold levels were observed in all crash modes and seat positions.

TABLE II

RANGE OF HEAD INJURY METRICS CALCULATED FOR IIHS FRONT AND SIDE CRASH TEST DUMMIES

		Driver small overlap	Moderate overlap	Passenger small overlap		Side impact	
		Driver	Driver	Driver	Right front passenger	Driver	Rear passenger
DAMAGE	*N*	283	157	59	61	125	124
	Minimum	0.11	0.10	0.08	0.09	0.09	0.04
	Maximum	0.69	0.62	0.51	0.66	0.57	0.62
	Average	0.30	0.31	0.20	0.26	0.24	0.21
HIC	Minimum	22	57	13	33	10	24
	Maximum	651	459	239	478	1178	733
	Average	160	204	79	174	184	205
Peak acceleration	Minimum	24	28	16	23	14	24
	Maximum	139	93	55	103	142	104
	Average	45	49	31	46	48	52
Rotational acceleration	Minimum	828	816	658	700	1342	973
	Maximum	7025	5019	2890	6936	10043	6798
	Average	2293	2173	1405	2072	3199	2926
Rotational velocity	Minimum	11.6	13.8	13.5	14	11.8	8.6
	Maximum	57.8	47.7	55.2	50.5	61.2	67.4
	Average	29.4	27.7	23.6	28.1	34.5	29.3

The number of dummies for which a metric exceeded the threshold value by crash type and dummy position is summarised in Table III. The most common metric exceeding threshold values varied by crash type: restraints and kinematics for small overlap and side impact tests and DAMAGE for moderate overlap tests. Across all crash types, HIC was the least common metric to exceed its threshold value.

It was common for more than one metric to exceed threshold values, and the combinations of metrics indicating downgrades by crash type and dummy position are shown in Table IV. For moderate overlap crashes, DAMAGE values alone identified 75% of the defined downgrades. For small overlap crashes, restraints and kinematics alone identified 55% of downgrades, but DAMAGE identified another 18%. Head downgrades in side impacts were more common from a combination of linear and restraints and kinematics metrics, and the addition of DAMAGE was the least impactful, only 8%.

TABLE III
NUMBER OF DUMMIES OBSERVED WITH DOWNGRADED METRICS BY CRASH TYPE AND DUMMY SEAT POSITION

	Driver small overlap	Moderate overlap	Passenger small overlap		Side impact		All
	Driver	Driver	Driver	Right front passenger	Driver	Rear passenger	
Total dummies downgraded (N)	137	33	2	26	22	27	247
Total dummies downgraded (%)	48%	21%	3%	43%	18%	22%	31%
HIC	0%	0%	0%	0%	2%	0%	0%
Peak acceleration	6%	5%	0%	13%	9%	12%	7%
DAMAGE	20%	19%	2%	13%	6%	4%	20%
R & K*	38%	0%	2%	33%	14%	15%	20%

*R & K = restraints and kinematics.

TABLE IV
COMBINATIONS OF DOWNGRADED METRICS

	Driver small overlap	Moderate overlap	Passenger small overlap		Side impact		All
	Driver	Driver	Driver	Right front passenger	Driver	Rear passenger	
DAMAGE only	9%	16%	2%	5%	2%	2%	7%
Linear metrics only	1%	3%	0%	2%	1%	5%	2%
R&K *only	27%	0%	2%	23%	7%	7%	13%
DAMAGE+linear metrics	0%	3%	0%	3%	1%	0%	1%
DAMAGE+linear metrics+R&K	1%	0%	0%	2%	2%	1%	1%
Linear metrics+R&K	3%	0%	0%	7%	5%	6%	3%
DAMAGE+R&K	7%	0%	0%	2%	0%	1%	3%
Total	48%	21%	3%	43%	18%	22%	31%
No Downgrades	52%	79%	97%	57%	82%	78%	69%

[a] Linear metrics = HIC or peak acceleration.

*R & K = restraints and kinematics.

The various combinations of metrics exceeding threshold values (HIC, peak acceleration and DAMAGE) observed in these crash tests were associated with different patterns of head motion. Most dummies demonstrated well-controlled head motion and stable interaction with the airbags, with all HIC, peak acceleration and DAMAGE values below thresholds (n = 562). Dummies for which only the DAMAGE metric was above the threshold (n = 79) typically had heads that remained engaged with the airbag but exhibited large rotations about at least one axis not associated with the primary impact, as shown in Fig. 1. Dummies with linear sensors exceeding the threshold (with or without restraints and kinematics downgrades) and with DAMAGE values below the threshold (n = 43) had trajectories that were straight into the airbag with enough force to bottom out the cushion and strike vehicle interior structures or the steering wheel rim below, as shown in Fig. 2. Dummies where linear and DAMAGE metrics were above the threshold were the least frequent (n = 17) but had the most complex kinematics; for example, the head engaged with the airbag but a lack of coverage or sufficient air cushion resulted in a hard contact, which initiated head rotations in directions other than the primary impact, as shown in Fig. 3.

In these cases, the high rotation often occurred during the same event as the hard contact or immediately following the hard contact.

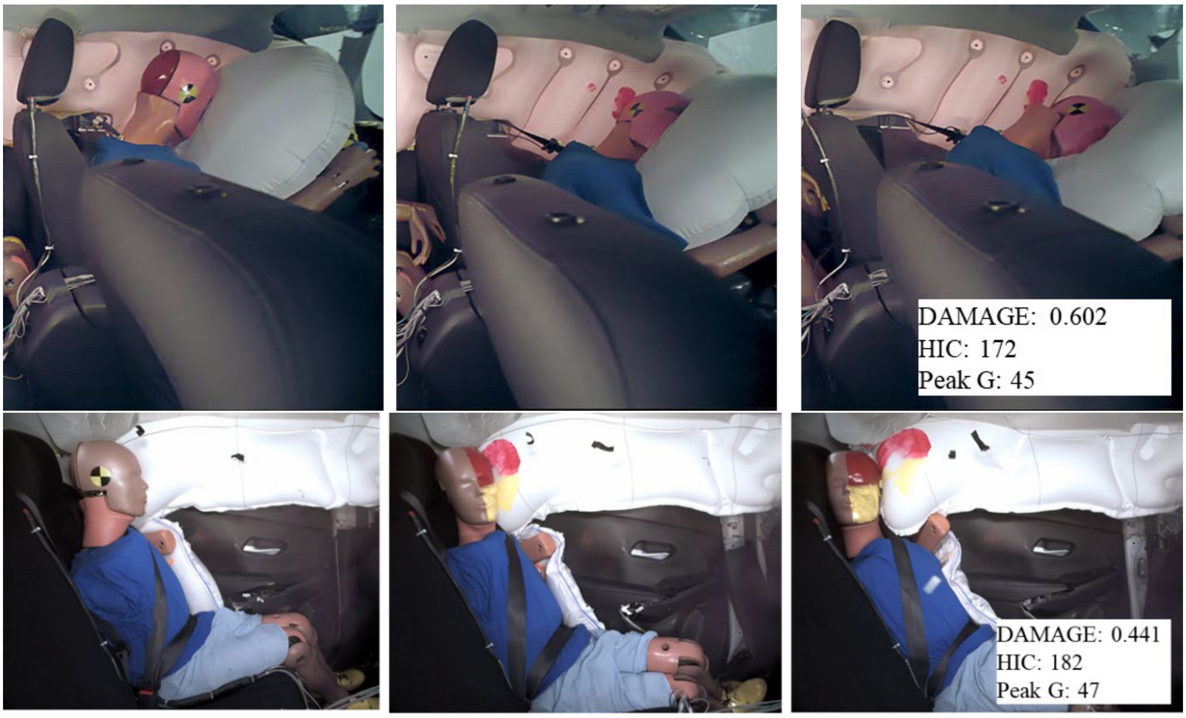

Fig. 1. Examples of DAMAGE downgrades but no linear acceleration downgrades for the 2021 Chevrolet Equinox moderate overlap driver *(top)* and 2022 Nissan Sentra side impact rear passenger *(bottom)*.

Fig. 2 Examples of peak acceleration downgrades but no DAMAGE downgrades for the 2018 Tesla Model S driver-side small overlap driver (*top)* and 2022 Ford Ranger side impact rear passenger (*bottom)*.

Fig. 3. Examples of DAMAGE and peak acceleration downgrades for the 2017 BMW 330i driver-side small overlap driver (top) and 2022 Chevrolet Malibu side impact rear passenger (bottom).

Restraints and kinematics downgrades were applied to 165 dummies. For 27 (16%) of these dummies, the linear acceleration metrics were also above threshold values. DAMAGE was above its threshold for 21 (13%) of the dummies with restraints and kinematics downgrades. For nine dummies, both linear acceleration metrics and DAMAGE were above threshold values. For the remaining 108 (65%) dummies with restraints and kinematics downgrades, no dummy sensors exceeded the threshold. These were typically cases where the head had minimal engagement with the airbag but did not contact any other structures or exhibit significant rotation, as shown in Fig. 4.

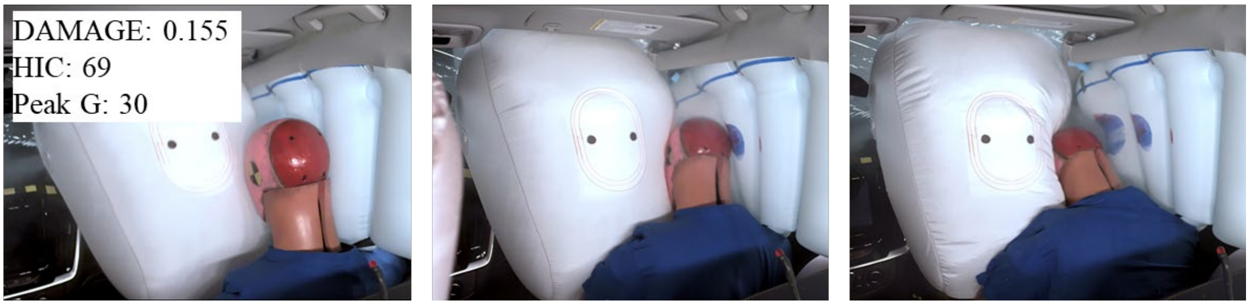

Fig. 4. Passenger-side small overlap right front-passenger head slides off the airbag without linear acceleration or DAMAGE downgrades for the 2021 Chevrolet Traverse.

For 58 dummies, DAMAGE was the only metric that identified uncontrolled head kinematics. These dummies were mostly moderate overlap drivers (n = 25) and small overlap drivers and right-front passengers (n = 29). There were not restraints and kinematics downgrades in these cases (Fig. 1), as this criterion was designed to identify whether the dummy's head remains fully engaged with the head-protecting airbag but does not currently judge velocity or the amount of head rotation during airbag engagement.

IV. Discussion

Traumatic brain injuries remain a prevalent injury sustained in real-world automotive crashes despite advances in vehicle crashworthiness and the availability of head-protecting airbags [1], and field data analysis indicates that the majority of remaining head injuries may be rotation-based concussion-like injuries [3]. Currently, IIHS crash tests evaluate head protection based on linear acceleration-based crash test metrics such as HIC and peak resultant acceleration that were not designed to identify rotation-based injury mechanisms and, therefore, are unlikely to drive vehicle design changes that would mitigate these kinds of injuries. IIHS vehicle ratings also use a video based kinematics assessment of uncontrolled head motion to capture additional mechanisms of head injury, but it is not comprehensive. The addition of a rotational metric to identify cases of uncontrolled head kinematics due to high rotations that were not captured by current test's linear-acceleration and video-based metrics could differentiate vehicle performance. Of the available purely kinematic based metrics or FE head model-based metrics, we chose DAMAGE because the formula can capture the complexities of multi-axis head rotation experienced in car crashes, is highly correlated to FE brain models [36][42], has critical values for representing the 50th percentile male [42] and 5th percentile female [45] and AIS4+ injury predictions from frontal crashes with the Hybrid III dummies are shown to correlate well with real-world injury rates [44]. DAMAGE corroborates some instances of poorly controlled head kinematics based on video evidence and identifies opportunities for airbag design improvements in ways that are feasible for automakers. Additionally, previous research boosts our confidence that the DAMAGE formula, though simpler than a full FE brain model, captures the same conditions contributing to brain strain across a variety of impact conditions [31][39][58-59].

However, a few remaining research questions must be answered before DAMAGE can be part of a crashworthiness ratings programme. Additional research is needed to gain a better understanding of dummy neck biofidelity. Many of the Hybrid III dummies with DAMAGE > 0.4 exhibited large axial rotations of the neck, a twisting of the neck that is not part of standard dummy calibration procedures. Few studies have compared dummy and human neck responses in this axial direction. One potential outcome would be the addition of new dummy-neck-calibration test conditions to ensure dummy neck performance is consistent and produces repeatable rotations. Additionally, the necks of SID-IIs 5$^{\mathbf{th}}$ percentile female and Hybrid III 50$^{\mathbf{th}}$ percentile male dummies must be assessed to determine if correction factors specific to dummy type or dummy size are needed to account for the different stiffness properties of various dummies.

Additional research into injury risk functions is required before potential rating boundaries can be set for DAMAGE. Despite the prevalence of mild TBI from field data analysis, DAMAGE was examined at the AIS4+ level due to overprediction of injury risk curves at the lower AIS2+ level identified by other researchers [72]. These kind of overpredictions are common for brain injury risk curves and are a consequence of the limited experimental data available for developing these risk functions, including constrained impact conditions and large assumptions related to scaling animal data . Euro NCAP has circumvented the use of an injury risk function for setting its DAMAGE performance limits, by applying a threshold just above the worst performer for a set of recently tested vehicles, 0.42, and a second upper boundary at a proportion higher, 0.47. IIHS plans to analyse the crash test data and, examine sensor data and video evidence to inform decisions on a value of DAMAGE that best differentiates controlled and uncontrolled head kinematics in crash tests independent of the established injury risk curves.

Brain injury is inherently difficult to study and assess because of the complexity of the brain injury response and limited experimental data to generate more accurate risk functions across a wider range of conditions. Calculating tissue-level head injury metrics through an FE model is optimal as the most comprehensive method to assess the complexity of brain injury response in crash tests, capable of capturing localised strains that produce contusions, subdural hematomas or micro bleeding that leads to diffuse axonal injury [27] but may not be ideal for consumer evaluation testing due to simulation run times and model accessibility [55]. Mathematical formulas derived from FE models can serve a suitable compromise with less computational time and greater accessibility compared with FE brain models, but provide similar comparative evaluations of brain strain [31][58-59]. Each FE model-based criterion has different limitations directly related to the shortcomings of the FE model from which it was approximated.

Out of the many available FE head model based rotational injury criteria, DAMAGE is the most promising to be a future crash test ratings metric because it is finalised, has consistently shown high correlation to brain FE models when exercised in a variety of automotive crash configurations [31][39][58-59], and can be used across IIHS's dummy fleet because it has critical values specific to 5th percentile females and 50th percentile males [45]. Initially, both UBrIC and DAMAGE were considered for this analysis, but the time-independent nature of UBrIC was less suitable for the complex or multiple impact scenarios that often occur in IIHS crash tests compared with the time-dependent nature of DAMAGE. With Euro NCAP implementing DAMAGE into its frontal test with a mobile progressive deformable barrier, this may provide an opportunity to harmonise criteria and move toward the automotive safety community converging on DAMAGE as a more widely used tool for assessing rotational brain injury. Furthermore, many other criteria were not considered because they are in various stages of completeness; have not been widely vetted against injury datasets; or in the case of BRIC, still have not been modified to address previously identified shortcomings [8].

Overall, DAMAGE presents IIHS with an opportunity to address a new mechanism for measuring rotation-based head injury that previous linear acceleration based and video-evidence metrics in our crash tests have not covered. The addition of DAMAGE as a biomechanics-based mathematical formula for vehicle performance rather than qualitative interpretations of complex kinematics from video footage will provide clear design targets for crashworthiness evaluation programmes. Vehicle manufacturers will then be able to use these targets to improve restraint designs. Vehicle designers have already identified countermeasures that can be introduced to reduce the high-speed rotations captured by DAMAGE. These could include frontal airbags with low-tension centres to capture the head rather than redirect it, and longer side-curtain airbags that prevent the occupant's head in side crashes from approaching or contacting the door-sill and have chambers that evenly load the side of the head. Additionally, inflatable seat belts may serve as supplemental stabilisers for the occupant's head.

DAMAGE has the potential to provide IIHS with a more complete assessment of occupant head protection. In this study, DAMAGE uniquely identified a subset of dummies (7%) with high-speed rotations contributing to uncontrolled head kinematics. But for another 13% of front and side crash test dummies in this study, all sensor-based metrics fell below the threshold for downgrades and only video evidence revealed uncontrolled head kinematics. This suggests that even with the inclusion of DAMAGE as a rotational brain injury criterion, a restraints and kinematics assessment remains necessary to capture the entire range of potential head injury mechanisms in automotive crashes.

V. Conclusion

For 809 crash test dummies in IIHS front and side crash tests, DAMAGE, a rotational brain injury metric, was calculated and compared with existing IIHS head injury assessments of HIC, peak linear acceleration and restraints and kinematics. Inclusion of the DAMAGE metric in crash test assessments increased the number of dummies where sensors identified uncontrolled head kinematics from 189 (23%) to 247 (31%). Airbags designed to reduce DAMAGE values would evenly load the head and limit head rotation in directions other than the primary impact. There remain some cases in which neither linear nor rotational sensor metrics identify uncontrolled head motion that is visible through video analysis. This means that restraints and kinematics video-based observations remain important for providing a comprehensive head protection assessment.

IIHS will continue to monitor DAMAGE for all crash test dummies in front and side crash tests, while progress is made to answer outstanding research questions.

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VIII. APPENDIX: REAR-OCCUPANT DUMMIES IN THE FRONTAL MODERATE-OVERLAP TEST

Rear-occupant dummies used in IIHS's frontal moderate-overlap crash test, specifically Hybrid III 5th percentile female dummies, were part of this study's initial scope for identifying whether a rotational brain injury criterion could supplement existing metrics for poorly controlled head kinematics. None of the dummy heads contacted vehicle structures during forward motion; therefore, acceleration-based criteria were not applicable and DAMAGE values excluding timeframes associated with dummy-chin-to-chest contact were all below 0.3, a level considered non-injurious, suggesting that other assessment tools are necessary to identify head injury risks in these crashes.

Analysis of 112 dummies revealed that none of the dummy heads contacted any vehicle structures during the primary crash event. The only recorded contacts were the dummy's chin contacting its chest during forward excursion. From a review of dummy design, there is low confidence that this is a biofidelic response of a human in the same scenario; therefore, linear-acceleration and rotational velocity data were clipped to before chin-to-chest contacts for our evaluation. For rating vehicles, linear accelerations and calculated HIC values are from a time frame excluding the chin-to-chest impact.

Additionally, dummy heads that do not contact the vehicle structure are not evaluated for HIC, as it is a metric fundamentally based on head impacts. DAMAGE values ranged from 0.1 to 0.65, with 82 dummies having DAMAGE values below 0.4 (73%). For all dummies with DAMAGE greater than 0.4, the peak DAMAGE occurred during the chin-to-chest contact event; see Fig. A1 for an example. When that time frame was excluded from evaluation, all peak DAMAGE values associated with forward excursion dropped below 0.3 (0.12–0.3; Fig. A2), the level at which brain injury is no longer expected [72]. Observations from the 112 rear-occupant dummies with no external head contacts indicate that for modern vehicles in moderate overlap tests, crash forces alone absent contact are unlikely to generate the 30 rad/s or greater head rotations that are associated with severe head injuries [22].

Fig. A1. Example of peak DAMAGE occurring for a moderate overlap rear-occupant dummy during chin-to-chest contact for the 2021 Hyundai Tucson.

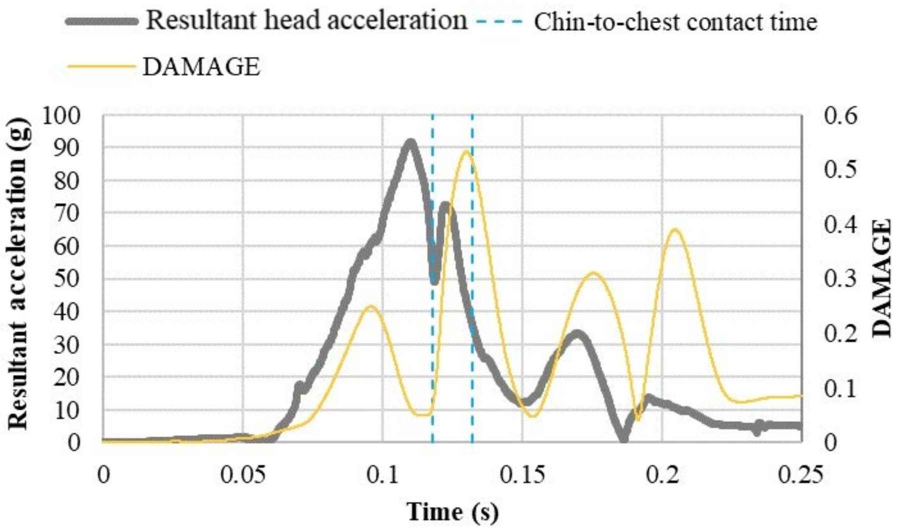

Fig. A2. Comparison of resultant linear acceleration and DAMAGE times relative to chin-to-chest contact time for the 2021 Hyundai Tucson. Peak reported DAMAGE was from the timeframe prior to chin-to-chest contact.