COMPARISON OF HIC AND BrIC HEAD INJURY RISK IN IIHS FRONTAL CRASH TESTS TO REAL-WORLD HEAD INJURIES

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ABSTRACT

The Insurance Institute for Highway Safety (IIHS) has been measuring head injury criterion (HIC), a measure based on linear impact skull fracture data, to assess head injury risk in its front crash tests since 1995. In 2012, IIHS added instrumentation to measure brain injury criterion (BrIC), a rotationally based injury measure derived from animal data correlated to humans through computational modeling. BrIC is intended to complement HIC rather than replace it. Head injury risk associated with HIC and BrIC values measured with a Hybrid III dummy in 138 front crash tests was compared with real-world injury rates in similar frontal crash configurations calculated from the National Automotive Sampling System Crashworthiness Data System (NASS CDS) database.

NASS CDS identified 1.3-5 percent AIS3+ head injury rates in crashes similar to the test configurations. The mechanisms of injury represented by HIC and BrIC are a subset of all head injuries; therefore, the NASS-indicated head injury rates inherently may be an overprediction of injuries directly applicable to these formulas. In crash tests, HIC AIS3+ head injury risk ranged 0-22 percent and BrIC AIS3+ head injury risk ranged 3-85 percent. BrIC AIS3+ head injury risk greater than 50 percent was associated with a variety of head kinematic events including front airbag loading, head contact with instrument panel, and non-contact forward excursion.

The published injury risk curve for BrIC indicates that crash tests represent significantly higher serious head injury risk than observed in real-world crashes of similar configurations. Hybrid III may produce exaggerated measures of BrIC or, if accurate, the BrIC formula may need to be reexamined against the underlying animal test data to determine the limitations of BrIC, and the proposed injury risk curves need to be re-evaluated against real human injury risk. Despite its origins as an indicator of skull fracture risk, the range of HIC-based head injury risk observed in crash tests more closely reflects the real-world head injury rates than the range of BrIC-based head injury risk.

INTRODUCTION

According to the U.S. Centers for Disease Control and Prevention, 17 percent of all traumatic brain injury (TBI) is caused by traffic crashes, and these have the highest proportion leading to death of all causes of TBI (Faul et al., 2010). Not only are motor vehicle crashes a frequent source of TBI, but TBI is a frequent outcome of crashes and the number of fatalities attributable to these injuries is second behind injuries of the chest (Eigen and Martin, 2005). This is the case despite great progress at reducing the risk of head injuries in crashes. Front airbags have been associated with a 29 percent reduction in the risk of head injury in front crashes (Kahane, 2015). Side airbags with head protection reduce the odds of dying in side crashes by 37 percent (McCartt and Kyrychenko, 2007). Nevertheless, it has been suggested that head injury risk in crashes has been increasing during the past decade (Takhounts et al., 2013).

In modern passenger vehicles, airbags provide the principal means of protecting the head from impacts with the vehicle interior because such impacts are possible even when seat belts are used. Canadian Motor Vehicle Safety Standard No. 208 limits linear acceleration of the head in crash tests with belted dummies as a way of ensuring that passenger vehicles will be fit with airbags to protect a driver's head from impact against the steering wheel (Transport Canada, 2011). Similarly, linear accelerations of the head are limited in U.S. regulatory crash tests by requiring that the head injury criterion (HIC) remain below 1000 in unbelted front crash tests with both belted and unbelted dummies, in addition to side crashes against a rigid pole targeted at the dummy's head (Office of the Federal Register, 2011a, 2011b). HIC essentially is a measure of the linear impulse of the head's motion during a crash. It is largely based on the Wayne State Tolerance Curve (WSTC), which described a set of head impact experiments relating accelerations of cadaver skulls to the onset of skull fractures (Lissner et al., 1960, Society of Automotive Engineers, 1980). Skull fracture was used as an indicator of brain injury because a large proportion of people suffering fractures also are concussed (Melvin et al., 1993). Since its adoption as a regulatory limit in motor vehicle safety standards, HIC has been related to the risk of severe brains injuries — 4 and greater on the Abbreviated Injury Scale (AIS) — through the analyses of additional experiments with human surrogates (Mertz et al., 1996). Despite its widespread use for evaluating head injury risk in regulatory and consumer information crash tests, studies continue to reiterate that HIC was not developed as a comprehensive predictor of all head injuries, but rather an indication of translational-based skull fracture injuries involving impacts and not rotational-based injury mechanisms (Digges, 1998; Hess et al., 1980; Prasad and Mertz, 1985).

Head injuries remain a lingering concern to be addressed by further improvements in vehicle crashworthiness. Even among vehicle designs earning good ratings in the Insurance Institute for Highway Safety's (IIHS) moderate overlap front crash test, the head is the second most common seriously injured body region in front crashes (Brumbelow and Zuby, 2009). These head injuries often occurred in crashes with large deformations of the safety cage, but also were observed in crashes during which the safety cage remained largely intact, thereby suggesting a failure of the restraint system to protect the head from injury.

The IIHS small overlap front crash test illustrates one possible means by which occupants' heads are injured in front crashes of vehicles judged to provide good head protection. Especially in cases with large safety cage deformations, the dummy's head sometimes slides past the front airbag and impacts directly against the door, A-pillar, or instrument panel. This head injury mechanism also has been documented in real crashes (IIHS, 2012; Sherwood et al., 2009). HIC values in small overlap front crash tests with head impacts against the vehicle interior, however, indicate a relatively low risk of serious head injury, with values ranging from 82 to 651 and representing an AIS 3+ injury risk of essentially 0-14 percent. Observations like these raise the question about whether HIC is completely measuring TBI risk in crash tests.

Since the earliest studies of the biomechanics of brain injury, rotational motion of the head also has been hypothesized to create stresses and strains in the brain that manifest as the injuries observed in motor vehicle crashes (Melvin et al., 1993). Considerable effort has been expended on understanding the relationship between rotational movement of the head and TBI, but none have been widely employed in crash testing (Kimpara and Iwamoto, 2012; Kimpara et al., 2011, Newman et al., 2000). Recently, a measure of both linear and rotational accelerations has been developed for evaluating concussion risk in sports helmet testing (Rowson and Duma, 2012).

The National Highway Traffic Safety Administration (NHTSA) also has developed a brain injury criterion (BrIC) based on head rotational velocity that could be used in conjunction with HIC for a more complete evaluation of TBI risk in crash tests (Takhounts et al., 2011; Takhounts et al., 2013). The basis for BrIC is its correlation with measurements of strain in finite element (FE) brain models subjected to impacts. Specifically, maximum principal stress (MPS) and cumulative strain damage metric (CSDM) were highly correlated with BrIC when the measured head kinematics from head impact tests and crash tests were used as inputs to FE brain models. Both MPS and CSDM were related to AIS 4+ brain injury risk using data from animal experiments. The motions of the animals' head in these experiments were scaled to account for differences in size between the animal and human brains and then used as inputs to the FE brain models. Thus, the validity of BrIC as an indicator of human brain injury risk in crash tests depends on the validity of the scaling methods and the similarity of the head motions in the animal experiments to those experienced by occupants in motor vehicle crashes.

At least two studies have attempted to compare TBI risk predictions from crash tests with real-world injury experience. Prasad et al. (2014) found that BrIC values from NHTSA's oblique frontal crash tests estimate higher AIS 3+ brain injury risks compared with the actual rate of injury in similar real crashes. On average, BrIC values in NHTSA's crash tests suggest that the AIS 3+ injury risk was greater than 50 percent, compared with the real-world head injury rates in similar crashes of less than 2 percent. The Center for Applied Biomechanics at the University of Virginia has found that the correlations between BrIC and MPS and CSDM for various simulated tests are different from those reported by Takhounts et al. (2013) (Gabler et al., 2014). Of special concern is that these analyses show BrIC values from experimental pedestrian crashes indicate a 50 percent risk of AIS 2+ brain injury before the dummy's head impacts the vehicle, which seems an unrealistic assessment of pedestrian head injury risk.

OBJECTIVE

The objective of this study is to expand the comparison of head injury risk predicted by BrIC in crash tests with real-world injury rates in similar crash configurations. In particular, injury risk based on HIC and BrIC measured with a Hybrid III dummy in IIHS moderate and small overlap front crash tests are compared with real-world head injury rates in similar frontal crashes. In addition, several crash tests with indications of possible head injury risks are examined in detail to ascertain the extent to which BrIC augments the evaluation of these risks provided by HIC.

METHODS

Crash Test Data

IIHS has conducted standardized moderate overlap front crash tests since 1995 and standardized small overlap front crash tests since 2012 as part of its crashworthiness evaluation program. The moderate overlap test involves crashing a new vehicle into a deformable barrier at 64 km/h with 40 percent of the vehicle's width on the driver side aligned with the barrier. The small overlap test also is conducted at 64 km/h but involves aligning 25 percent of the vehicle's width with a rigid barrier. In both tests, a midsize male Hybrid III dummy is seated in the driver seat. Detailed test protocols are available from the IIHS website (iihs.org).

Since 2012, driver dummies in IIHS moderate and small overlap tests have been equipped with sensors to measure the rotational movement of the head. Specifically, an orthogonal array of three angular rate sensors measures the rotational velocity about the head's center of gravity. The resulting dataset includes 17 moderate overlap and 121 small overlap crash tests of 2012-15 model year vehicles from which both HIC and BrIC can be calculated.

HIC is calculated according to Equation 1, where a(t) is the vector resultant linear acceleration at time t and $t_2 - t_1$ is the time interval during the crash that is no longer than 15 ms in duration and that maximizes the expression in brackets. HIC is related to the risk of AIS 4+ injury according to Equation 2 (Mertz et al., 1996) and to the risk of AIS 3+ injury according to Equation 3 (NHTSA, 1995).

(Equation 1): $$HIC_{15} = \left\{\left(\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2.5}(t_2-t_1)\right\}_{max}$$

(Equation 2): $$PR_{AIS4+} = Normal\left(\frac{HIC-1434}{430}\right)$$

(Equation 3): $$PR_{AIS3+} = \frac{1}{1+e^{\left(3.39+\frac{200}{HIC}\right)-0.00372*HIC}}$$

Angular velocity measurements are filtered to channel frequency class 60 according to Society of Automotive Engineers recommended practice J211 before calculating BrIC according to Equation 4, where ω_i is the single absolute value of the maximum magnitude velocity measurement about the i^{th} axis (x, y, z corresponding to posterior-anterior, laterally to the right, superior-inferior directions) during the test. BrIC is related to the risk of brain injury according to Equations 4 and 5 (Takhounts et al., 2013).

(Equation 3): $BRIC = \sqrt{\left(\frac{\omega_x}{66.25_{rad}}\right)^2 + \left(\frac{\omega_y}{56.45_{rad}}\right)^2 + \left(\frac{\omega_z}{42.87_{rad}}\right)^2}$

(Equation 4): $PR_{AIS3+} = 1 - e^{-\left(\frac{BRIC}{0.987}\right)^{2.94}}$

(Equation 5): $PR_{AIS4+} = 1 - e^{-\left(\frac{BRIC}{1.204}\right)^{2.94}}$

Real-World Head Injuries

Cases of real-world front crashes were obtained from the National Automotive Sampling System Crashworthiness Data System (NASS CDS) crash data collection program conducted and maintained by NHTSA. The NASS CDS sample contains more detail than is available from police crash reports because investigators visit the crash site, examine the vehicles involved, and collect injury data from hospital or coroner reports. The sample is intended to be representative of all tow-away crashes occurring in the United States. The total number of crashes investigated ranged from 4,000 to 5,600 during 2004-12, the years used in the study. Each case is assigned a sample weight, based on its likelihood of being investigated, that scale the individual crash observations to nationwide estimates.

The sample of NASS CDS crashes used in this study were intended to include damage and occupant patterns similar to IIHS small and moderate overlap test configurations. Consequently, only passenger vehicles (body type = 1-49) from model years 2000 and later that received a good rating in the IIHS moderate overlap test were included. Further restricting the case model year range to correspond exactly with the crash test model years (2012-15) likely would have yielded too few crashes for analysis. A broader group of front-damaged vehicles were chosen based on NASS classifications, and damage photographs were used to further categorize which cases reflect patterns similar to crash tests. Front crashes were identified as having damage to the frontal plane in the principal impact according to the crash deformation classification (CDC) as well as a principal direction of force (PDOF) between 30 degrees left of center and 30 degrees right of center. To further ensure the sample consisted of vehicles with damage similar to the crash tests, only vehicles with a vertical distribution of damage extending from the bumper to level of the hood were included. Thus, vehicles that underrode their crash partner or had significant damage to the undercarriage were excluded. Additionally, only vehicles with extent-of-damage classification of 3 or greater were included, as this is typical of the damage observed in the comparison crash tests. Vehicles involved in a rollover or fire were excluded because of the difficulty in identifying injury mechanisms. Finally, only drivers who were using lap/shoulder belts and not ejected from the vehicle were examined.

After obtaining the 880 cases meeting the NASS coding criteria, all remaining assessments of crash configurations and severity were based on photographs of vehicle damage. Vehicles with damage originating from the right side of the vehicle (right offset), both frame rails significantly engaged (full overlap), or narrow center damage were excluded because of their dissimilarity to comparison crash tests. Small or moderate overlap configurations were defined based on the extent to which the left longitudinal frame rail was engaged in the crash. If the left frame rail was not engaged or only minimally so, the subject vehicle was classified as having small overlap damage; if only the left frame rail was significantly damaged, then the vehicle was classified as having moderate overlap damage. Severity, classified as less than, equal to, or greater than crash tests, was determined by comparing case photographs of exterior damage extent to example crash test photos of damage representing similar vehicles.

Crashes meeting the criteria for small and moderate overlap configurations, including an AIS 3+ head injured driver, were examined in detail to collect specific information about the injuries including their possible causation. Photographic evidence, medical records, and investigator notes were used to determine evidence of head contact with interior components.

RESULTS

Real-World Crashes

There were 880 frontal crashes involving good-rated passenger vehicles from model years 2000 and later. Of these, 343 cases (86,389 weighted) were determined to be small or moderate overlap configurations with damage offset to the driver side. There were no drivers with AIS 3+ head injuries in moderate and small overlap front crashes that were less severe than the IIHS tests in this sample; therefore, lower severity crashes were excluded from in-depth analysis. The final sample included 168 cases (17,276 weighted) of small or moderate overlap configurations with damage offset to the driver side at equal or greater severities. Most of the cases were of similar severity to the corresponding IIHS crash test, as the distribution of cases by severity and damage shows (Figure 1). Of these 168 cases, 51 drivers had a head injury of any severity. The distribution by AIS severity level of the most severe head injuries for these 51 drivers is shown in Figure 2. Among the crashes with driver head injuries at the AIS 3+ level, most were more severe than their corresponding IIHS crash test (Figure 3). Appendix A contains details about the head injuries for each of the 17 drivers injured at the AIS 3+ level.

Table 1 shows head injury rates (weighted data) for drivers exposed to front left offset crashes that were at least as severe as IIHS tests. The risk of sustaining a serious head injury is greater in front crashes with small overlap damage than those with moderate overlap damage. The AIS 4+ risk is lower than the AIS 3+ injury risk, but the difference is proportionally smaller among small overlap crashes. There were five drivers with skull fractures resulting in fracture rates (weighted data) of 0.2 and 0.9 percent for moderate and small overlap crashes, respectively. Two other drivers, both in moderate overlap crashes, had fractures limited to the facial bones.

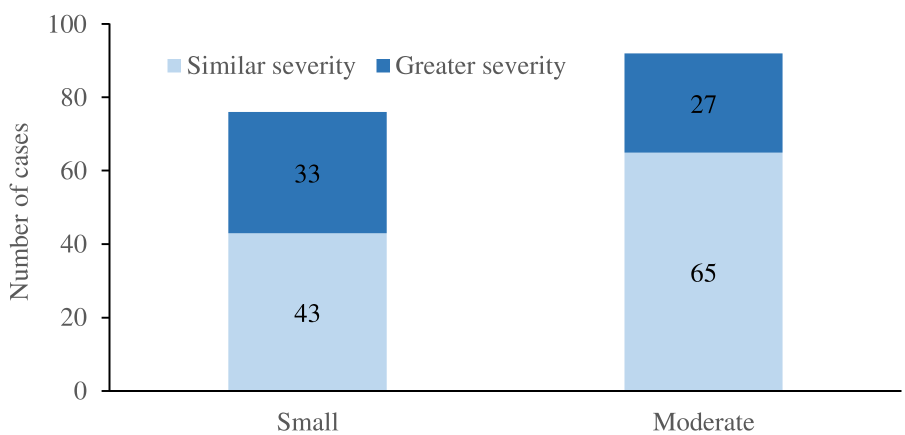

Figure 1. Case distribution.

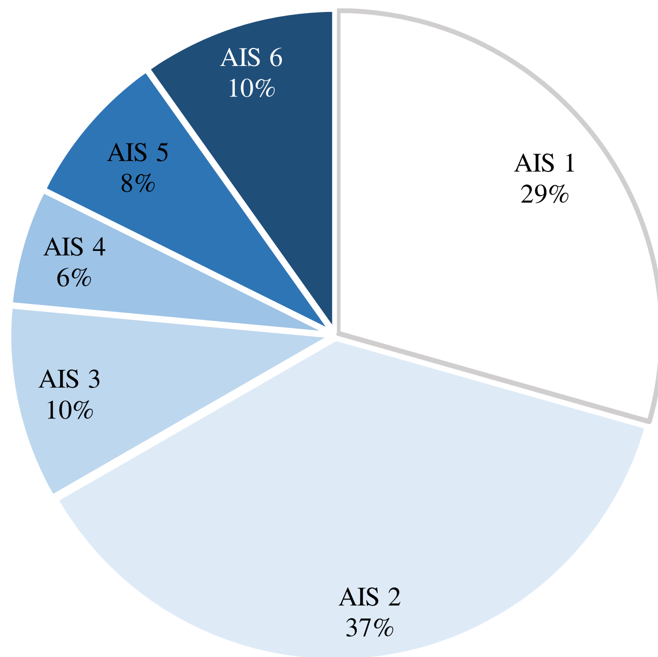

Figure 2. Distribution of head injury severity for 51 head-injured drivers.

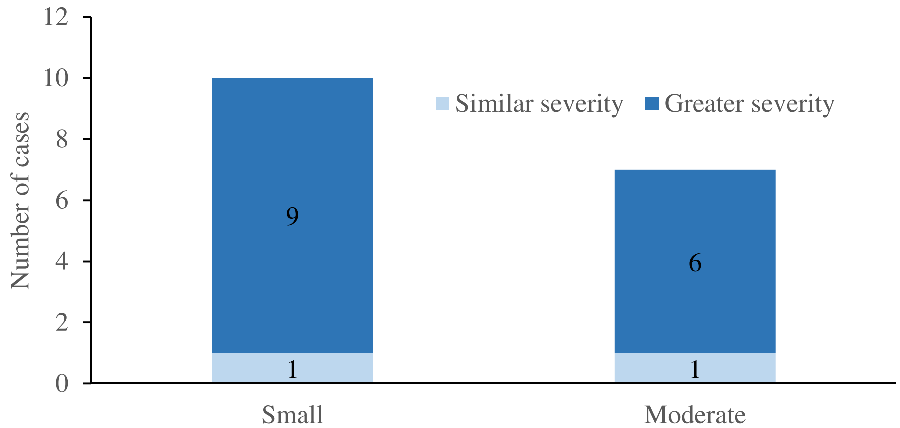

Figure 3. Head injured cases.

Table 1.
Head injury rates for real-world crashes of equal or greater severity as IIHS tests.

	Moderate overlap (10,027)	Small overlap (7,249)
Skull fracture		
Cases (weight)	2 (21.84)	3 (67.29)
Rate	0.2%	0.9%
AIS 3+		
Cases (weight)	7 (117.21)	10 (330.8)
Rate	1.2%	4.6%
AIS 4+		
Cases (weight)	5 (67.11)	7 (247)
Rate	0.7%	3.4%

It is likely that the heads of all of the drivers injured at the AIS 3+ level made at least minimal contact with the driver airbag. Examination of the vehicle photographs, consideration of documented external injuries to the face and head, along with investigator-coded contact sources suggested that 10 of these drivers' heads also likely contacted some part of the vehicle interior other than the airbag — four in moderate overlap crashes and six in small overlap crashes. The other seven drivers' heads also may have contacted something besides the airbag, as the lack of contact evidence does not preclude its possibility.

Crash Tests

Table 3 shows the range and the average of HIC and BrIC values for each sample of crash tests. Appendix B contains details about the HIC and BrIC values calculated for each of the 128 crash tests. On average, HIC values were greater in moderate overlap crashes, but the highest HIC values were measured in small overlap tests. The average BrIC values were similar from the two different crash tests and, again, the highest measures were recorded in small overlap tests. Table 4 shows the average estimated injury risks associated with these measures. For both injury severity levels and both crash types, BrIC indicates a much higher risk of brain injury than HIC. BrIC suggests that the AIS 3+ injury risk is 6.5-13 times greater than predicted by HIC, and the AIS 4+ injury risk is 40-67 times greater than indicated by HIC. BrIC suggests that serious brain injury risks are greater in small overlap than moderate overlap crashes, while HIC suggests the opposite. Not surprisingly, HIC and BrIC are not highly correlated, as shown in Figure 4, although they are more so in small overlap than moderate overlap crash tests.

Table 3.
HIC and BrIC: Moderate (n=17) and small overlap (n=121) front crash tests at 64 km/h.

	HIC		BrIC	
	Moderate	Small	Moderate	Small
Minimum	116	39	0.43	0.3
Average	259	173	0.64	0.69
Maximum	459	651	0.88	1.24

Table 4.
Average brain injury risk based on HIC and BrIC measured in crash tests at 64 km/h.

	Skull/facial fracture risk	AIS 3+ risk		AIS 4+ risk	
	HIC	HIC	BrIC	HIC	BrIC
Moderate overlap crash test (n=17)	0.6%	4.1%	27%	0.4%	16%
Small overlap crash test (n=121)	0.1%	2.5%	32%	0.3%	20%

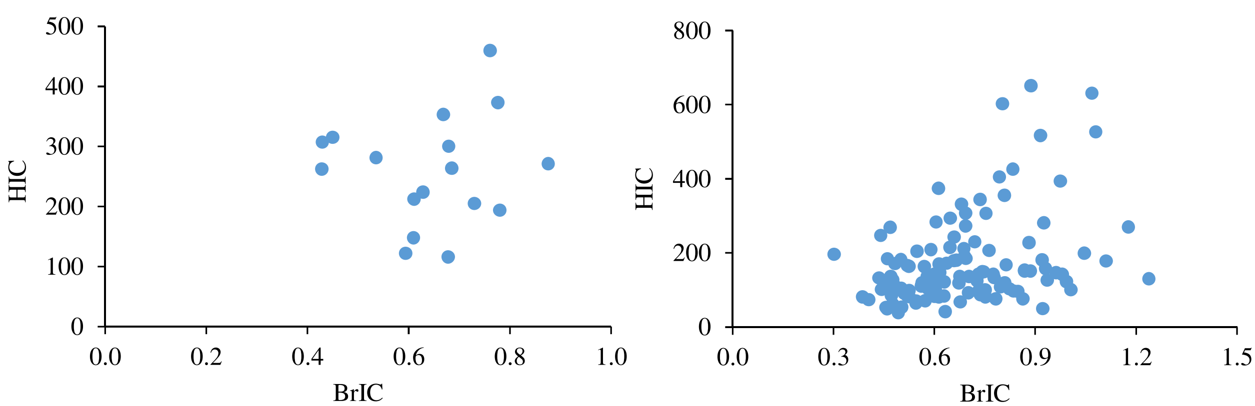

Figure 4. HIC and BrIC values for moderate (left) and small overlap (right) crash tests.

Associating HIC and BrIC with kinematic events provides some insight into the specific brain injury risks highlighted by each measure. Small overlap crash tests were used for this analysis because the moderate overlap tests lack the camera coverage necessary to identify kinematic events of the head. Three classes of events were defined for this analysis: airbag contact, hard contact, and unrestrained head motion. The HIC timeframe always encompassed the main contributing event, but choosing a contributing event for BrIC was not always straightforward, as each of the three peak rotational velocities may occur at different times during the crash. An approximate way of identifying the kinematic event most responsible for a particular BrIC value consists of using the event associated with the greatest peak. Ninety percent of tests had at least two components of BrIC occurring during the same event. Table 5 shows the HIC and BrIC values associated with three classes of kinematic events. The lowest values for HIC and BrIC were measured while the head was in contact with the airbag. The highest values for BrIC also occurred as a result of airbag contact, while the highest values for HIC occurred when the head impacted some interior surface other than the airbag. On average, HIC also was higher from hard contacts than the other classes of head motion. Free forward motion of the head after it slid off the airbag, on average, was associated with higher BrIC values than either contact with the airbag or hard interior surfaces.

Table 5.
HIC and BrIC values for different kinematic events in 64km/h small overlap front crash tests.

	HIC			BrIC		
	Airbag	Unrestrained motion	Hard contact	Airbag	Unrestrained motion	Hard contact
Minimum	39	54	42	0.3	0.53	0.47
Average	163	172	205	0.66	0.77	0.72
Maximum	527	426	651	1.24	1.07	0.89

A close examination of 10 crash tests where the HIC timeframe included significant head impacts other than with the inflated airbag offers further insight into the ability of BrIC to augment the assessment of head injury risk based on crash tests. Table 6 shows the HIC and BrIC values, times associated with the three BrIC components, and non-airbag impacts between the dummy's head and vehicle interior. In all cases, the HIC time interval (not shown) includes the interior impact of interest. As before, HIC and BrIC are not highly correlated (0.24) (Figure 5) and, in every case, BrIC indicates a higher risk of AIS 3+ injury than HIC, with BrIC risk assessment ranging 2.4-58 times higher than HIC. In five tests, the greatest contributor (largest component peak) to BrIC occurs at a time greater than 4 ms from the impact highlighted within the HIC timeframe; therefore, BrIC cannot be associated with that impact. The correlation between HIC and BrIC among the remaining five tests is 0.60 (Figure 5), with BrIC indicating a risk ranging 2.2-23 times higher than HIC.

The sensitivity of HIC and BrIC to vehicle design changes was examined from comparison tests of three models that were redesigned or modified to improve small overlap front crashworthiness. The Mazda 6 was first evaluated for small overlap crashworthiness in model year 2012, and the full-model redesign was evaluated in model year 2014. In both tests, the Mazda 6 overall rating was acceptable. However, the earlier model received a restraints and kinematics score of marginal because the dummy's head slid off the driver airbag and impacted the door sill. The HIC in this test was 148, low enough that head protection was rated good. The full-model redesign in 2014 also received an acceptable overall rating even though the dummy's head remained in contact with the airbag during its forward excursion. Unfortunately, the head struck the steering wheel through the airbag, resulting in a HIC of 331, which was

Table 6.
HIC and BrIC timing related to hard contacts.

Vehicle	Test ID	Hard contact source	Hard contact time	HIC	AIS 3+	BrIC	AIS 3+	BrIC peak component times x	y	z
2012 Mazda 6	CEN1220	Door sill	124	148	1%	0.62	23%	174	**120***	135
2014 Mazda 6	CEN1305	Steering wheel through airbag	122	331	6%	0.68	29%	139	**124***	131
2014 Kia Forte	CEN1318	Instrument panel	122	355	7%	0.81	43%	176	**110***	77
2013 Toyota RAV4	CEN1319	Instrument panel	120	283	5%	0.60	22%	125	**129***	132
2013 Toyota Prius C	CEN1328	Instrument panel	119	426	9%	0.83	46%	82	**119***	84
2013 Toyota Yaris	CEN1331	Instrument panel	137	127	1%	0.94	58%	146	**139***	122
2014 Ford Fiesta	CEN1343	Instrument panel	108	509	13%	0.80	43%	123	**111***	87
2014 Fiat 500L	CEN1414	A-pillar	101	228	3%	0.88	52%	108	108	**105***
2015 Hyundai Sonata	CEN1427	Steering wheel through airbag	105	405	8%	0.79	42%	123	109	**115***
2015 Honda Fit	CEN1430	Steering wheel through airbag	87	651	22%	0.89	52%	102	**92***	88

*Maximum individual component

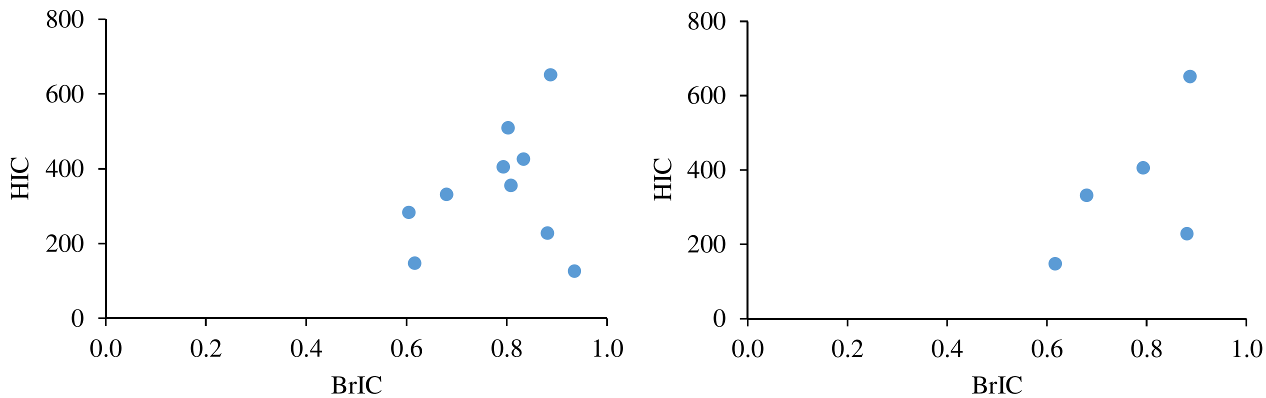

Figure 5. Correlation of HIC and BrIC in all tests with head contacts (left) and tests where HID and BrIC both associated with hard contact (right).

higher than in the test of the earlier design, and head protection was downgraded to acceptable because of a peak acceleration of 108 g despite the improved restraints and kinematics rating. The BrIC values for the two tests were similar, 0.62 and 0.68, despite differences in the head motions between tests.

The 2013 Honda Fit was rated poor overall because its safety cage collapsed in the small overlap test and the dummy's head struck the instrument panel after sliding off the airbag. This impact was associated with a HIC of 517, but the BrIC (0.92) recorded in this test was due to head motion occurring beforehand. The 2015 model was rated acceptable in the small overlap test, largely due to a greatly improved safety cage. However, the dummy's head struck the steering wheel through the airbag, resulting in a HIC of 651 and a BrIC of 0.89.

The Toyota RAV4 was first tested in model year 2013, receiving a poor overall rating, and then tested again in model year 2015 after it had been modified for better small overlap crashworthiness. In the test of the 2013 model, the dummy's head slid off the airbag and impacted against the instrument panel, producing a HIC of 283 and a BrIC of 0.60. The modified design earned a good overall rating due largely to a stronger safety cage. In addition, the head impact against the instrument panel was eliminated, resulting in a lower HIC of 163 associated with the head's interaction with the airbag and a BrIC of 0.57.

Head impacts with the steering wheel through the airbag in tests of the 2015 Honda Fit and 2014 Mazda 6 were identified by HIC as more risky than impacts against the instrument panel and doorsill in the earlier models of each; however, the assessment of risk by BrIC was only slightly different between the newer and older designs. Similarly, HIC values suggest brain injury risk was halved with the modifications implemented in the 2015 RAV4 compared with the 2013 model, but the BrIC risk assessment was similar between the two designs.

DISCUSSION

BrIC values measured in IIHS frontal offset crash tests estimated a much larger risk of brain injury than observed in real crashes with similar offset crash damage and at least the same damage extent. This overestimation is larger for moderate overlap front crashes (18 times) than small overlap ones (6 times), and about the same for both AIS 3+ and AIS 4+ injury levels. Only 16 of these 139 tests resulted in the dummy's head impacting a hard surface inside the vehicle, indicating that BrIC predicts high levels of serious and severe brain injury risk as a result of contacting only the airbag. This is contrary to the NASS CDS cases examined in this study in which at least 70 percent of those drivers with AIS 3+ brain injuries apparently impacted a hard surface in the vehicle.

HIC values measured in IIHS frontal offset crash tests indicated a much lower risk of serious and severe brain injuries than BrIC (Table 4). With the exception of AIS 3+ injury risk in moderate overlap crashes, these measures suggest a lower risk of brain injury than observed in the NASS CDS crashes with frontal offset crash damage. The estimated AIS 4+ injury risk in small overlap crash tests is less than one-tenth of that observed in real crashes with this damage pattern and at least the same damage extent. Skull fracture risk based on HIC (Mertz et al., 1996) overestimates injury risk in moderate overlap crash tests (0.6 percent) compared with what was observed in the real crash sample (0.2 percent), but the risk in small overlap crash tests (0.4 percent) is lower than that seen in real crashes (0.9 percent), though neither deviates significantly. The underestimation of skull fracture and brain injury risks in these crash tests is understandable given that nearly all of the NASS CDS sample have more damage than the test vehicles. The source of overestimation by BrIC is unknown.

While both BrIC and HIC estimate quite different head injury risks in frontal offset crash tests than observed in similar real crashes, the estimates from HIC are closer to the real injury rates. However, HIC indicates moderate overlap crashes present a higher head injury risk than small overlap crashes, while real crash data indicated higher injury rates in small overlap crashes. The relative risks estimated by HIC may better align with a larger sample of real crashes more comparable with the crash tests; however, it seems unlikely that they would yield brain injury rates as high as the BrIC estimates, as this crash sample included generally more severe impacts than the crash tests.

Even though BrIC appears to correctly assess the relative brain injury risk between these two crash types, it is unknown whether BrIC correctly identifies why small overlap crashes are more injurious. Table 5 shows that the majority of BrIC values were associated with the head's contact with the inflated airbag and free motion of the head following airbag contact. In contrast, the average and highest values of HIC in these tests were associated with head impacts against hard surfaces in the vehicle interior, which is more consistent with real crash observations. Eight of the 17 NASS CDS cases had drivers with face or skull injuries not likely caused by contacting the inflated airbag or as a result of post-airbag forward motion alone. An additional two drivers were injured in ways that suggest their head's contacted something other than the airbag. The remaining drivers also may have impacted against something hard despite the lack of evidence recorded in the investigation file. It is unclear why BrIC brain injury risk estimates would be higher for seemingly more benign events than the head impacts that produced strong linear accelerations.

The lack of correlation between HIC and BrIC in the full crash test dataset suggests BrIC may be providing different indications of brain injury risk than HIC alone. However, the observations of the kinematic events associated with BrIC raise questions about whether BrIC is accurately identifying injurious events in a given crash test. For the five tests in which both HIC and BrIC could be associated with the same head impacts against the vehicle interior, HIC estimated an AIS 3+ injury risk of 2-20 percent and BrIC estimated a risk of 23-53 percent. While the BrIC estimates of brain injury risk were high relative to real crash injury rates, they may correctly indicate that the head impacts observed in these tests posed a greater brain injury risk than indicated by HIC.

BrIC seems insensitive to changes in vehicle design, while HIC makes distinctions. This is problematic for the process of developing countermeasures that can reduce BrIC in frontal crashes. Some of this insensitivity stems from the possibility that BrIC may be based on measurements from different times and events during the test. Takhounts et al. (2013) state that a time-based calculation of vector resultant rotation velocity did not yield a better correlation with measures of strain in the FE brain models than the formulation used here. As long as the time-based calculation still exhibits a reasonably strong correlation, its use may prove to be a better tool for evaluating head injury risks in crash tests than the version currently considered by NHTSA.

CONCLUSIONS

Serious and severe brain injury risk estimates from offset crash tests based on BrIC are much higher than injury rates observed in a sample of crashes with similar damage type but greater severity. HIC appropriately estimates lower brain injury risk in tests less severe than real crashes with similar offset damage patterns. When both HIC and BrIC can be associated with the same head impact, the higher risk estimate from BrIC may be an indication that a brain injury risk exists that is not identified by HIC. It is not clear why BrIC predicts such high brain injury risks with contact between the head and airbag or free motion of the head afterward. If accurate, the injuries indicated by BrIC may be difficult to prevent except by reducing crash severity through the application of crash avoidance technologies.

REFERENCES

Brumbelow ML, Zuby DS. 2009. Impact and injury patterns in frontal crashes of vehicles with good ratings for frontal crash protection. *Proceedings of the 21st International ESV Technical Conference* (CD-ROM) Washington, DC: National Highway Traffic Safety Administration.

Digges KH. 1999. Injury measurements and criteria. Keynote address at the Specialists' Meeting of the RTO Human Factors and Medicine Panel. *RTO Meeting Proceedings 20: Models for Aircrew Safety Assessment: Uses, Limitations, and Requirements*, pp. K2-1-5. Report no. RTO-MP-20. Quebec, Canada: Canada Communications Group Inc.

Eigen AM, Martin PG. 2005. Identification of real world injury patterns in aid of dummy development. Paper no. 05-0219. *Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles*. Washington, DC: National Highway Traffic Safety Administration.

Faul M, Xu L, Wald MM, Coronado VG. 2010. Traumatic brain injury in the United States; Emergency department visits, hospitalizations, and deaths, 2002-2006. Atlanta, GA: Centers for Disease Control and Prevention.

Gabler LF, Panzer MB, Crandall JR. 2014. On the application of BrIC to the biomechanics of various automotive impact scenarios. Presented at the 42nd International Workshop on Human Subjects for Biomechanical Research. San Diego, California.

Hess RL, Weber K, Melvin JW. 1980. Review of literature and regulation relating to head impact tolerance and injury criteria. Report no. UM-HSRI-80-52-l. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Hodgson V, Thomas L. 1972. Effect of long-duration impact on head. SAE Technical Paper 720956. Warrendale, PA: Society of Automotive Engineers.

Insurance Institute for Highway Safety. 2012. Small overlap crashes: New consumer-test program aims for even safer vehicles. *Status Report* 47(6). Arlington, VA.

Kahane CJ. 2015. Lives saved by vehicle safety technologies and associated Federal Motor Vehicle Safety Standards, 1960 to 2012, Passenger cars and LTVs, with reviews of 26 FMVSS and the effectiveness of their associated safety technologies in reducing fatalities, injuries, and crashes. Report no. DOT HS 812 069. Washington, DC: National Highway Traffic Safety Administration.

Kimpara H, Iwamoto M. 2012. Mild traumatic brain injury predictors based on angular accelerations during impacts. Ann Biomed Eng. 40(1):114-26.

Kimpara H, Nakahira Y, Iwamoto M, Rowson S, Duma S. 2011. Head injury prediction methods based on 6 degree of freedom head acceleration measurements during impact. Int J Automot Eng 2:13-19.

Lissner HR, Lebow M, Evans FG. 1960. Experimental studies on the relation between acceleration and intracranial pressure changes in man. Surg Gynecol Obstet. 111:329-38.

McCartt AT, Kyrychenko SY. 2007. Efficacy of side airbags in reducing driver deaths in driver-side car and SUV collisions. Traffic Injury Prevention 8(2):162-170.

Melvin JW, Lighthall JW, Ueno K. 1993. Ch 12. Brain injury biomechanics. *Accidental Injury: Biomechanics and Prevention* (eds Nahum AM, Melvin JW), pp 268-291. New York: Springer-Verlag.

Mertz H, Irwin A. 1994. Brain injury risk assessment of frontal crash test results. SAE Technical Paper 941056. Warrendale, PA: Society of Automotive Engineers.

Mertz H, Prasad P, Nusholtz G. 1996. Head injury risk assessment for forehead impacts. SAE Technical Paper 960099. Warrendale, PA: Society of Automotive Engineers.

National Highway Traffic Safety Administration. 1995. Final economic assessment; FMVSS No. 201 Upper interior head protection. Washington, DC: U.S. Department of Transportation.

National Highway Traffic Safety Administration. 2008. Consumer information; New Car Assessment Program. Docket no. NHTSA-2006-26555. Federal Register 73(134): 40016-40050. Washington, DC: National Archives and Records Administration.

Newman JA, Shewchenko N, Welbourne E. 2000. A proposed new biomechanical head injury assessment function - the maximum power index. Stapp Car Crash J. 44:215-47.

Office of the Federal Register. 2011a. *Code of Federal Regulations*; Title 49 Transportation, Part 571 Federal Motor Vehicle Safety Standards, Standard No. 208 Occupant Crash Protection. Washington, DC: National Archives and Records Administration.

Office of the Federal Register. 2011b. *Code of Federal Regulations*; Title 49 Transportation, Part 571 Federal Motor Vehicle Safety Standards, Standard No. 214 Side Impact Protection. Washington, DC: National Archives and Records Administration.

Prasad P, Dalmotas D, German A. The field relevance of NHTSA's oblique research moving deformable barrier tests. *Stapp Car Crash J*. 58:175-196. Ann Arbor, MI: The Stapp Association.

Prasad P, Mertz HJ. 1985. The position of the United States delegation to the ISO Working Group 6 on the use of HIC in the automotive environment. SAE Technical Paper 851246. Warrendale, PA: Society of Automotive Engineers.

Research and Technology Organization, North Atlantic Treaty Organization. 1999. *RTO Meeting Proceedings 20: Models for Aircrew Safety Assessment: Uses, Limitations, and Requirements*. Report no. RTO-MP-20. Quebec, Canada: Canada Communications Group Inc.

Rowson S, Duma SM. 2013. Brain injury prediction: assessing the combined probability of concussion using linear and rotational head acceleration. Ann Biomed Eng. 41(5):873-82.

Sherwood CP, Nolan JM, Zuby DS. 2009. Characteristics of small overlap crashes. Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles (CD-ROM). Washington, DC: National Highway Traffic Safety Administration.

Society of Automotive Engineers. 1980. Human Biomechanics and Simulations Standards Committee, Standard J885B 198004. Warrendale, PA.

Takhounts EG, Craig MJ, Moorhouse K, McFadden J, Hasija V. 2013. Development of brain injury criteria (BrIC). Stapp Car Crash J. 57:243-66.

Takhounts EG, Hasija V, Ridella SA, Rowson S, Duma SM. 2011. Kinematic rotational brain injury criterion (BrIC). Proceedings of the 22nd International Technical Conference on the Enhanced Safety of Vehicles. Paper No. 11-0263. Washington, DC: National Highway Traffic Safety Administration.

Transport Canada. 2014. Motor Vehicle Safety Regulations; Schedule III: Canada Motor Vehicle Safety Standard No. 208 Occupant Protection in Frontal Impacts. Ottawa, Ontario.

Versace J. 1971. A review of the severity index. SAE Technical Paper 710881. Warrendale, PA: Society of Automotive Engineers.

Appendix A. Head Injuries

Table A-1. Real-world head injuries.

NASS-CDS case ID	Occupant ID	NASS case weight	Type of overlap	Impact side	Impact severity	Head MAIS	Evidence of head impact: External injuries	Evidence of head impact: Facial/Skull fractures	Evidence of head impact: Vehicle evidence	Number of AIS 3+ head injuries	List of AIS 3+ head injuries (AIS)
200549156	58681	8.113	Moderate	Near	Greater	4	—	—	Makeup on frontal airbag	2	R cerebrum hematoma (4), R cerebrum subarachnoid hemorrhage (3)
200849138	90861	9.584	Moderate	Near	Greater	6	Facial abrasions and contusions	Basilar skull, maxilla, mandible, nasal fractures	Steering wheel bent	2	Brain stem laceration (6), basilar skull fracture (4)
200973074	102687	38.929	Moderate	Near	Greater	3	Scalp and chin contusions	—	Bent steering wheel	1	Cerebrum brain swelling/edema (3)
200981154	105483	27.983	Moderate	Near	Greater	4	Chin laceration	Mandible fracture	Hair evidence on A-pillar	2	L cerebrum small hematoma (4), cerebrum brain swelling/edema (3)
201149139		12.26	Moderate	Near	Greater	6	Forehead abrasions	Basilar skull, maxilla, mandible, zygoma fractures	—	2	Brain stem laceration (6), basilar fracture (3)
201179125		8.206	Moderate	Near	Greater	3	—	Orbit, nasal fracture	—	2	L cerebrum hematoma (3), R cerebrum hematoma (3)
201249063		12.21	Moderate	Near	Similar	5	Scalp contusions	—	—	3	Brain stem hemorrhage (5), cerebrum bilateral subdural small hematoma (4), R cerebrum contusion (3)
200473241	49180	14.998	Small	Near	Greater	5	Whole scalp contusions	Basilar and vault skull, maxilla, nasal, orbit fracture	Blood evidence on steering wheel and airbag	12	Multiple vault fractures (3), basilar skull fracture (4), multiple cerebrum hematoma (5,5,5), brain stem (5), cerebrum brain swelling/edema (5), cerebrum laceration (4), cerebrum contusion (3)
200649023	68818	10.286	Small	Near	Greater	6	Forehead, nose cheek abrasions	Basilar and vault skull	—	3	Brain stem laceration (6), basilar fracture (4), vault fracture (2)
200705021	74218	118.769	Small	Near	Greater	6	Whole face abrasions	Teeth fracture	—	4	L cerebrum subarachnoid hemorrhage (3), R cerebrum subdural hemorrhage (4), brain stem transection (6), cerebrum swelling (3)
200943250	100508	42.007	Small	Near	Greater	4	—	Basilar and vault skull, orbit and nasal fracture	Blood/bio evidence on frontal airbag	13	Multiple vault fractures (4), basilar fracture (4), multiple cerebrum subarachnoid hemorrhage (3), hematoma (4,5), contusion (3), brain swelling (5), R-L infarctions (3), brain stem laceration (5)
200949089	101901	12.488	Small	Near	Greater	5	—	—	Hair evidence on roof rail	4	Cerebrum hematoma (5), cerebrum brain swelling/edema (3), cerebrum contusion (3), L cerebrum subarachnoid hemorrhage (3)
200975216	103812	29.106	Small	Near	Greater	3	—	—	Bent steering wheel rim	1	Multiple L cerebrum contusion (3)
200981007	105183	19.941	Small	Near	Greater	6	—	—	—	1	Brain stem laceration associated with spinal cord laceration (6)
200982010	105510	7.029	Small	Near	Greater	3	—	—	Skin transfer evidence on frontal airbag	2	R cerebrum subarachnoid hemorrhage (3), L cerebrum subarachnoid hemorrhage (3)
201206073		28.992	Small	Near	Greater	4	—	—	Bent steering wheel	4	R cerebrum subarachnoid hemorrhage (3), L cerebrum subarachnoid hemorrhage (3), cerebrum edema and compression (4), R cerebrum hematoma (3)
200675096	71165	47.826	Small	Near	Similar	3	Deep scalp laceration	—	Hair and blood evidence on A-pillar	2	L cerebrum contusion (3), R cerebrum subarachnoid hemorrhage (3)

Appendix B. Crash Test Data

Table B-1. Moderate overlap tests.

Vehicle model	Test ID	Class	BrIC	AIS 3 BrIC	AIS 4 BrIC	HIC	AIS 3 HIC	AIS 4 HIC	HIC contact source
2013 Ford Escape	CEF1206	Small SUV	0.61	23%	14%	212	3%	0.2%	Airbag
2013 Dodge Dart	CEF1207	Small car	0.63	24%	15%	224	3%	0.2%	Airbag
2013 Nissan Altima	CEF1208	Midsize car	0.61	22%	13%	148	1%	0.1%	Airbag
2014 Mazda 6	CEF1301	Midsize car	0.68	29%	18%	116	1%	0.1%	Airbag
2013 BMW X1	CEF1302	Small SUV	0.88	51%	33%	271	4%	0.3%	Airbag
2013 Buick Encore	CEF1303	Small SUV	0.78	40%	25%	194	2%	0.2%	Airbag
2014 Fiat 500 L	CEF1304	Small car	0.68	29%	18%	300	5%	0.4%	Airbag
2014 Jeep Cherokee	CEF1305	Midsize SUV	0.73	35%	21%	205	3%	0.2%	Airbag
2013 Chevrolet Spark	CEF1306	Minicar	0.76	38%	24%	459	11%	1.2%	Airbag
2014 Maserati Ghibli	CEF1307	Large car	0.45	10%	6%	315	5%	0.5%	Airbag
2014 Mitsubishi Mirage	CEF1308	Minicar	0.69	30%	18%	264	4%	0.3%	Airbag
2014 BMW 2 Series	CEF1401	Midsize car	0.59	21%	13%	122	1%	0.1%	Airbag
2014 Nissan Rogue	CEF1402	Small SUV	0.67	28%	17%	353	7%	0.6%	Airbag
2015 Subaru WRX	CEF1403	Small car	0.78	40%	25%	373	7%	0.7%	Airbag
2014 Ford C-Max	CEF1404	Small car	0.43	9%	5%	307	5%	0.4%	Airbag
2014 Mazda 5	CEF1405	Small car	0.43	9%	5%	262	4%	0.3%	Airbag
2014 Hyundai Veloster	CEF1406	Small car	0.54	16%	10%	281	4%	0.4%	Airbag

Table B-2. Small overlap tests.

Vehicle model	Test ID	Class	Delta V	Peak Accel	Vehicle motion	BrIC	AIS 3 BrIC	AIS 4 BrIC	HIC	AIS 3 HIC	AIS 4 HIC	HIC contact source	BrIC contact source
2012 Hyundai Sonata	CEN1219	Midsize car	47	-34	Translate	0.99	64%	44%	123	1%	0.1%	Airbag	Airbag
2012 Mazda 6	CEN1220	Midsize car	41	-38	Translate	0.62	23%	14%	148	1%	0.1%	IP	IP
2012 Suzuki Kazashi	CEN1221	Midsize car	43	-23	Translate	0.58	20%	12%	104	1%	0.1%	Forward excursion	Forward excursion
2013 Ford Escape	CEN1222	Small SUV	48	-21	Translate	0.62	23%	14%	122	1%	0.1%	Forward excursion	Forward excursion
2012 Honda CR-V	CEN1223	Small SUV	44	-26	Translate	0.73	35%	22%	102	1%	0.1%	Forward excursion	Forward excursion
2012 Nissan Rogue	CEN1224	Small SUV	50	-27	Translate	0.39	7%	4%	82	0%	0.1%	Airbag	Airbag
2012 Kia Optima	CEN1225	Midsize car	44	-32	Translate	0.46	11%	6%	53	0%	0.1%	Airbag	Airbag
2012 Jeep Patriot	CEN1226	Small SUV	48	-24	Translate	0.75	37%	23%	81	0%	0.1%	Forward excursion	Forward excursion
2012 Mitsubishi Outlander Sport	CEN1227	Small SUV	48	-34	Translate	0.52	15%	9%	84	0%	0.1%	Airbag	Airbag
2013 Subaru Legacy	CEN1228	Midsize car	56	-28	Rotate	0.56	18%	11%	110	1%	0.1%	Airbag	Airbag
2012 Honda Accord	CEN1229	Midsize car	56	-33	Rotate	1.11	75%	55%	178	2%	0.2%	Airbag	Airbag
2012 Nissan Maxima	CEN1230	Midsize car	61	-23	Translate	0.54	17%	10%	65	0%	0.1%	Airbag	Airbag
2013 Nissan Altima	CEN1231	Midsize car	52	-42	Translate	0.78	40%	25%	143	1%	0.1%	Airbag	Airbag
2012 Volkswagen Passat	CEN1232	Midsize car	56	-37	Rotate	0.69	31%	19%	307	5%	0.4%	Forward excursion	Forward excursion
2012 Volkswagen Jetta	CEN1233	Midsize car	55	-29	Rotate	0.69	30%	19%	191	2%	0.2%	Forward excursion	Forward excursion
2013 Honda Accord coupe	CEN1234	Midsize car	57	-35	Rotate	0.98	62%	43%	142	1%	0.1%	Airbag	Airbag
2013 Jeep Wrangler	CEN1235	Small SUV	44	-27	Translate	0.96	61%	41%	147	1%	0.1%	Airbag	Airbag
2013 Ford Fusion	CEN1236	Midsize car	—	—	Translate	0.50	14%	8%	54	0%	0.1%	Forward excursion	Forward excursion
2013 Hyundai Tucson	CEN1237	Small SUV	55	-36	Rotate	0.93	57%	38%	158	2%	0.2%	Forward excursion	Forward excursion
2013 Honda Civic (coupe)	CEN1301	Small car	60	-35	Rotate	0.76	38%	24%	207	3%	0.2%	Airbag	Airbag
2013 Honda Civic (sedan)	CEN1302	Small car	62	-34	Rotate	0.97	62%	42%	394	8%	0.8%	Airbag	Airbag
2013 Subaru Forester	CEN1303	Small SUV	56	-33	Rotate	0.48	12%	7%	127	1%	0.1%	Airbag	Airbag
2013 Volvo XC60	CEN1304	Midsize SUV	43	-21	Translate	0.51	14%	8%	91	1%	0.1%	Airbag	Airbag
2014 Mazda 6	CEN1305	Midsize car	57	-40	Rotate	0.68	29%	18%	331	6%	0.5%	Airbag	SW through airbag
2013 Mazda CX-5	CEN1306	Small SUV	52	-29	Rotate	0.73	35%	21%	95	1%	0.1%	Airbag	Airbag
2013 BMW X1	CEN1307	Small SUV	51	-26	Rotate	0.30	3%	2%	196	2%	0.2%	Airbag	Airbag
2013 Buick Encore	CEN1308	Small SUV	50	-26	Translate	0.86	49%	32%	76	0%	0.1%	Forward excursion	—
2013 Volkswagen Tiguan	CEN1309	Small SUV	54	-27	Rotate	0.74	35%	22%	87	0%	0.1%	Forward excursion	Forward excursion
2013 Hyundai Elantra	CEN1310	Small car	56	-27	Rotate	0.65	26%	16%	215	3%	0.2%	Airbag	Airbag
2013 Buick Encore	CEN1311	Small SUV	53	-31	Rotate	1.01	65%	45%	101	1%	0.1%	Forward excursion	Forward excursion
2013 Chevrolet Cruze	CEN1312	Small car	45	-26	Translate	0.55	17%	10%	70	0%	0.1%	Forward excursion	Forward excursion
2013 Chevrolet Sonic	CEN1313	Small car	51	-36	Translate	1.05	69%	49%	199	3%	0.2%	Forward excursion	Forward excursion
2013 Ford Focus	CEN1314	Small car	48	-32	Rotate	0.78	40%	25%	133	1%	0.1%	Airbag	Airbag
2013 Nissan Sentra	CEN1315	Small car	47	-28	Rotate	0.74	35%	22%	344	6%	0.6%	Forward excursion	Forward excursion
2013 Volkswagen Beetle	CEN1316	Small car	48	-27	Rotate	0.65	26%	16%	294	5%	0.4%	Forward excursion	Forward excursion
2013 Kia Soul	CEN1317	Small car	40	-25	Translate	0.60	22%	13%	83	0%	0.1%	Forward excursion	Forward excursion
2014 Kia Forte	CEN1318	Small car	47	-27	Rotate	0.81	43%	28%	355	7%	0.6%	IP	IP
2013 Toyota RAV4	CEN1319	Small SUV	45	-24	Translate	0.60	22%	13%	283	5%	0.4%	IP	IP
2014 Scion tC	CEN1320	Small car	40	-30	Translate	0.58	20%	12%	127	1%	0.1%	Forward excursion	Forward excursion
2013 Dodge Dart	CEN1321	Small car	36	-33	Translate	0.63	24%	15%	84	0%	0.1%	Airbag	—
2013 Dodge Dart	CEN1322	Small car	42	-43	Translate	0.46	11%	6%	184	2%	0.2%	Airbag	Airbag
2014 Mitsubishi Outlander	CEN1323	Midsize SUV	45	-28	Translate	0.61	23%	14%	81	0%	0.1%	Airbag	Airbag
2013 Mazda 2	CEN1324	Minicar	42	-34	Translate	0.92	56%	38%	281	4%	0.4%	Forward excursion	Forward excursion

Vehicle model	Test ID	Class	Delta V	Peak Accel	Vehicle motion	BrIC	AIS 3 BrIC	AIS 4 BrIC	HIC	AIS 3 HIC	AIS 4 HIC	HIC contact source	BrIC contact source
2013 Fiat 500	CEN1325	Minicar	46	-29	Rotate	0.89	52%	34%	151	2%	0.1%	IP	IP
2014 Honda Odyssey	CEN1326	Minivan	54	-31	Rotate	1.24	85%	66%	130	1%	0.1%	Airbag	Airbag
2013 Mercedes-Benz C class	CEN1327	Midsize car	51	-28	Rotate	0.44	10%	6%	248	4%	0.3%	Airbag	Airbag
2013 Toyota Prius C	CEN1328	Minicar	50	-31	Rotate	0.83	46%	30%	426	9%	1.0%	IP	IP
2013 Hyundai Accent	CEN1329	Minicar	44	-24	Translate	0.80	42%	27%	108	1%	0.1%	IP	IP
2013 Kia Rio	CEN1330	Minicar	48	-32	Translate	0.67	28%	17%	180	2%	0.2%	Forward excursion	Forward excursion
2013 Toyota Yaris	CEN1331	Minicar	54	-27	Rotate	0.94	58%	39%	127	1%	0.1%	IP	IP
2014 Toyota Corolla	CEN1332	Small car	56	-32	Translate	0.87	50%	33%	154	2%	0.1%	Airbag	Airbag
2014 Mercedes-Benz M class	CEN1333	Midsize SUV	55	-27	Rotate	0.50	14%	8%	182	2%	0.2%	Airbag	Airbag
2014 Nissan Versa	CEN1334	Minicar	43	-26	Translate	0.78	40%	25%	77	0%	0.1%	Forward excursion	Forward excursion
2013 Chevrolet Spark	CEN1335	Minicar	40	-23	Translate	0.84	46%	30%	97	1%	0.1%	Airbag	Airbag
2014 Volvo XC90	CEN1336	Midsize SUV	44	-33	Translate	0.48	12%	7%	62	0%	0.1%	Airbag	Airbag
2014 Subaru Impreza	CEN1337	Small car	58	-40	Rotate	0.44	9%	5%	133	1%	0.1%	Airbag	Airbag
2014 Infiniti Q50	CEN1338	Midsize car	52	-23	Rotate	0.55	17%	10%	204	3%	0.2%	Airbag	Airbag
2014 Acura MDX	CEN1339	Midsize SUV	60	-28	Rotate	0.48	12%	7%	171	2%	0.2%	Airbag	Airbag
2013 Honda Fit	CEN1340	Minicar	53	-26	Rotate	0.92	55%	37%	517	14%	1.6%	IP	IP
2014 Acura RLX	CEN1341	Large car	55	-36	Rotate	0.87	50%	33%	151	2%	0.1%	Airbag	Airbag
2014 Mitsubishi Mirage	CEN1342	Minicar	43	-31	Rotate	0.92	56%	37%	50	0%	0.1%	Forward excursion	Forward excursion
2014 Ford Fiesta	CEN1343	Minicar	48	-31	Rotate	0.80	43%	27%	509	13%	1.6%	IP	IP
2014 Volvo S80	CEN1344	Large car	43	-20	Translate	0.44	10%	6%	102	1%	0.1%	Airbag	Airbag
2014 Mazda CX-5	CEN1345	Small SUV	58	-38	Rotate	0.92	56%	37%	181	2%	0.2%	Airbag	Airbag
2014 Mazda 3	CEN1346	Small car	54	-38	Rotate	0.59	21%	12%	209	3%	0.2%	Airbag	Airbag
2014 Toyota Prius	CEN1347	Small car	47	-26	Translate	0.61	23%	14%	170	2%	0.2%	Forward excursion	Forward excursion
2014 Toyota Highlander	CEN1348	Midsize SUV	52	-23	Translate	0.52	15%	9%	99	1%	0.1%	Forward excursion	Forward excursion
2014 Toyota Camry	CEN1349	Midsize car	46	-28	Translate	0.73	34%	21%	125	1%	0.1%	Airbag	Airbag
2014 Chevrolet Equinox	CEN1401	Midsize SUV	33	-19	Translate	0.46	11%	6%	49	0%	0.1%	Airbag	Airbag
2014 Ford Explorer	CEN1402	Midsize SUV	42	-28	Translate	0.70	31%	19%	93	1%	0.1%	Forward excursion	Forward excursion
2014 Toyota 4 Runner	CEN1403	Midsize SUV	39	-17	Translate	0.73	35%	22%	142	1%	0.1%	Airbag	Airbag
2014 Jeep Grand Cherokee	CEN1404	Midsize SUV	53	-27	Rotate	0.64	25%	15%	172	2%	0.2%	Airbag	Airbag
2014 Honda Pilot	CEN1405	Midsize SUV	47	-17	Translate	0.63	25%	15%	42	0%	0.1%	Forward excursion	Forward excursion
2014 Kia Sorento	CEN1406	Midsize SUV	43	-23	Translate	0.66	27%	16%	179	2%	0.2%	Forward excursion	Forward excursion
2014 Nissan Rogue	CEN1407	Small SUV	46	-24	Translate	0.69	31%	19%	185	2%	0.2%	Airbag	Airbag
2014 Mazda CX-9	CEN1408	Midsize SUV	38	-29	Translate	0.47	11%	7%	137	1%	0.1%	Door sill	Doorsill
2014 BMW 2 Series	CEN1409	Midsize SUV	51	-23	Translate	0.47	11%	7%	269	4%	0.3%	Airbag	Airbag
2014 Mini Countryman	CEN1410	Small car	41	-27	Translate	0.68	29%	18%	68	0%	0.1%	Airbag	Airbag
2014 Mitsubishi Lancer	CEN1411	Small car	48	-34	Rotate	0.81	44%	28%	168	2%	0.2%	Forward excursion	Forward excursion
2014 Chevrolet Malibu	CEN1412	Midsize car	48	-27	Translate	0.56	18%	11%	112	1%	0.1%	Airbag	Airbag
2015 Audi A3	CEN1413	Midsize car	51	-39	Rotate	0.82	45%	29%	103	1%	0.1%	Airbag	Airbag
2014 Fiat 500L	CEN1414	Small car	46	-22	Rotate	0.88	52%	34%	228	3%	0.3%	A-pillar	A-pillar
2014 Hyundai Veloster	CEN1415	Small car	51	-26	Rotate	0.75	37%	23%	100	1%	0.1%	Forward excursion	Forward excursion
2014 Nissan Juke	CEN1416	Small car	40	-25	Translate	0.40	8%	4%	74	0%	0.1%	Forward excursion	Forward excursion
2015 Honda Fit	CEN1417	Minicar	51	-36	Rotate	1.07	71%	51%	631	20%	3.1%	Forward excursion	Forward excursion
2015 Subaru WRX	CEN1418	Small car	52	-27	Rotate	0.46	11%	6%	116	1%	0.1%	Airbag	Airbag
2015 Hyundai Genesis	CEN1419	Large car	61	-32	Rotate	0.45	10%	6%	106	1%	0.1%	Airbag	Airbag

Vehicle model	Test ID	Class	Delta V	Peak Accel	Vehicle motion	BrIC	AIS 3 BrIC	AIS 4 BrIC	HIC	AIS 3 HIC	AIS 4 HIC	HIC contact source	BrIC contact source
2014 Ford C-Max	CEN1420	Small car	49	-23	Rotate	0.69	30%	18%	212	3%	0.2%	Forward excursion	Forward excursion
2014 Mercedes-Benz E Class	CEN1421	Large car	60	-38	Rotate	0.52	15%	9%	164	2%	0.2%	A-pillar	A-pillar
2015 Volkswagen GTI	CEN1422	Small car	55	-27	Rotate	0.66	27%	17%	243	4%	0.3%	Airbag	Airbag
2014 Scion FR-S	CEN1423	Small car	50	-32	Translate	0.57	19%	11%	71	0%	0.1%	Airbag	Airbag
2014 Mazda 5	CEN1424	Small car	54	-23	Rotate	0.63	24%	15%	122	1%	0.1%	Forward excursion	Forward excursion
2014 Chevrolet Volt	CEN1425	Small car	51	-32	Translate	0.60	22%	13%	101	1%	0.1%	Airbag	Airbag
2014 Nissan Leaf	CEN1426	Small car	51	-29	Rotate	0.85	48%	31%	96	1%	0.1%	Forward excursion	Forward excursion
2015 Hyundai Sonata	CEN1427	Midsize car	58	-34	Rotate	0.79	42%	26%	405	8%	0.8%	Airbag	SW through airbag
2014 Scion xB	CEN1428	Small car	47	-26	Translate	0.69	31%	19%	273	4%	0.3%	Airbag	Airbag
2014 BMW 5 Series	CEN1429	Large car	58	-33	Rotate	0.47	12%	7%	86	0%	0.1%	Airbag	Airbag
2015 Honda Fit	CEN1430	Minicar	59	-43	Rotate	0.89	52%	34%	651	22%	3.4%	Airbag	SW through airbag
2014 Infiniti Q70	CEN1431	Large car	53	-25	Translate	0.48	12%	7%	109	1%	0.1%	Airbag	Airbag
2015 Chrysler 200	CEN1432	Midsize car	57	-43	Rotate	0.67	29%	17%	119	1%	0.1%	Airbag	Airbag
2015 Subaru Legacy	CEN1433	Midsize car	58	-31	Rotate	0.56	18%	11%	120	1%	0.1%	Airbag	Airbag
2015 Kia Soul	CEN1434	Small car	54	-28	Rotate	0.61	23%	14%	374	7%	0.7%	Airbag	Airbag
2014 Lincoln MKS	CEN1435	Large car	44	-26	Translate	0.53	15%	9%	82	0%	0.1%	IP	IP
2015 Kia Forte	CEN1436	Small car	56	-44	Rotate	0.75	36%	23%	149	2%	0.1%	IP	IP
2015 Volkswagen Jetta	CEN1437	Midsize car	55	-27	Translate	0.75	37%	23%	306	5%	0.4%	Forward excursion	Forward excursion
2014 Chrysler Town & Country	CEN1438	Minivan	48	-23	Translate	0.72	34%	21%	230	3%	0.3%	IP	IP
2015 Toyota Sienna LE 4-door	CEN1439	Minivan	57	-28	Rotate	0.57	19%	11%	118	1%	0.1%	Forward excursion	Forward excursion
2014 Mini Cooper	CEN1440	Minicar	43	-33	Translate	0.52	15%	9%	166	2%	0.2%	Airbag	Airbag
2015 Kia Sedona	CEN1441	Minivan	59	-26	Rotate	0.81	43%	28%	120	1%	0.1%	Airbag	Airbag
2015 Acura TLX	CEN1442	Midsize car	52	-47	Rotate	0.70	32%	19%	136	1%	0.1%	Airbag	Airbag
2015 Honda Accord 2- door	CEN1443	Midsize car	55	-23	Rotate	1.18	81%	61%	270	4%	0.3%	Airbag	Airbag
2015 Honda CR-V	CEN1444	Small SUV	49	-25	Translate	0.68	29%	18%	137	1%	0.1%	Airbag	Airbag
2014 Nissan Quest	CEN1445	Minivan	53	-17	Rotate	1.08	73%	52%	527	14%	1.7%	Airbag	Airbag
2015 Toyota Avalon	CEN1446	Large car	50	-49	Translate	0.58	20%	12%	137	1%	0.1%	Airbag	Airbag
2015 Nissan Pathfinder	CEN1447	Midsize SUV	41	-18	Translate	0.49	13%	8%	39	0%	0.1%	Airbag	Airbag
2015 Lexus RC	CEN1448	Midsize car	57	-24	Rotate	0.50	14%	8%	105	1%	0.1%	Airbag	Airbag
2015 Lexus NX	CEN1449	Small SUV	48	-25	Translate	0.74	36%	22%	150	2%	0.1%	Airbag	Airbag
2015 Lexus CT	CEN1450	Small car	45	-30	Translate	0.60	22%	13%	142	1%	0.1%	Airbag	Airbag
2015 Toyota RAV4	CEN1451	Small SUV	54	-32	Rotate	0.57	19%	11%	163	2%	0.2%	Airbag	Airbag
2015 Toyota Prius V	CEN1452	Midsize car	58	-41	Translate	0.62	23%	14%	193	2%	0.2%	Airbag	Airbag
2015 Kia Sedona	CEN1453	Minivan	61	-25	Rotate	0.68	29%	18%	102	1%	0.1%	Airbag	Airbag