BRIC AND FIELD BRAIN INJURY RISK

Erik G. Takhounts
National Highway Traffic Safety Administration
USA

Vikas Hasija,
Bowhead (Systems & Technology Group)
USA

Matthew J. Craig
National Highway Traffic Safety Administration
USA

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ABSTRACT

This study investigates the adequacy of comparing the risk of brain injuries based on the available National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) field data to the risk predicted by Brain Injury Criterion (BrIC) measured from an Anthropomorphic Test Device (ATD) in NHTSA's Research Moving Deformable Barrier (RMDB) oblique tests (fleet). Finite Element (FE) analysis was utilized to simulate crashes with a given range of Principal Direction of Force (PDOF) and change in velocity (Delta-V) to illustrate their effect on the field vs. fleet risk comparison. The simulation based results indicate that BrIC is highly dependent on PDOF and Delta-V. The methods applied for estimating brain injury risk from the simulation results demonstrate the importance of accounting for the distributions of both PDOF and Delta-V when comparing brain injury risk estimates from the field data versus those calculated from fleet testing.

KEYWORDS: BrIC, field data analysis, fleet data analysis, head/brain injury

INTRODUCTION

In this study, we computed the risk of brain injuries based on the available NASS/CDS field data and compared it to the risk predicted by BrIC in FE simulations of various PDOF and Delta-Vs representing a range of frontal crash conditions. Previous analyses of the field data (for example, Laituiri et at., 2016; Prasad et al., 2014) included crashes at PDOFs 11, 12, and 1 o'clock (that is spanning from -40^0 [near side oblique] to $+40^0$ [far side oblique] for the drivers) and the damage extent 3-6 (Delta-V ranging from under 25 mph [approximately 66% of the cases with the 3-6 damage extent] to around 35 mph). The fleet data (NHTSA's RMDB oblique tests) have the PDOF range between $20\text{-}30^0$ for both near and far sides, and the Delta-V span of 31-37 mph.

The purpose of this study is to investigate the adequacy of such comparisons between field and fleet risks when neither PDOF nor Delta-V ranges are comparable between the two datasets. Because of such incompatibility of the Delta-V and PDOF ranges between the two datasets, FE analysis of various frontal crash Delta-V and PDOF was utilized together with PDOF and Delta-V ranges/distributions from fleet and field data to derive adjusted simulation based estimates of brain injury risk.

METHODS

The efforts of this study can be separated into three distinct phases: (1) estimation of brain injury risk from field data; (2) application of a vehicle model and simulation to measure BrIC over a wide range of frontal crash Delta Vs and PDOF values; and (3) application of different filtering/calculation techniques to estimate brain injury risk from simulation data from (2) while considering the range of Delta V observed in fleet testing and the distribution of PDOF in frontal crashes from field data. The third step was done specifically for the purpose of demonstrating limitations that can be present when comparing field and fleet data while not considering the associated ranges and distributions of Delta-V and PDOF in the two data sets.

Field Data Analysis: The inclusion criteria for the ranges of PDOF and Delta-V in the field data analyses in previous studies were rather wide due to a small sample size for the specific PDOF and Delta-V. For the current study, the "field" data is referred to as all NASS/CDS passenger car, light truck and van frontal crash cases with a PDOF of -40^0 to $+40^0$ and Delta-V range between 31 and 37 mph. The brain injury field risk of AIS 2+, 3+, and 4+ (AIS – abbreviated injury scale) was calculated from weighted 2000-2015 NASS/CDS age 15+ belted drivers involved in frontal crashes with a Delta-V range of 31-37 mph and deployed frontal airbags. The case vehicles were restricted to passenger cars, light trucks and vans. Cases with rollovers were excluded. The risk at each AIS level was calculated as the ratio or percent of injury cases to the total weighted case count for the target population described above.

Frontal Crash FE Simulation: An FE model of a mid-size sedan was created and the GHBMC-OS (Global Human Body Modeling Consortium Simplified 50^{th} Percentile Male, v1.8) FE model was utilized to simulate crashes at various PDOFs and Delta-Vs (Figure 1).

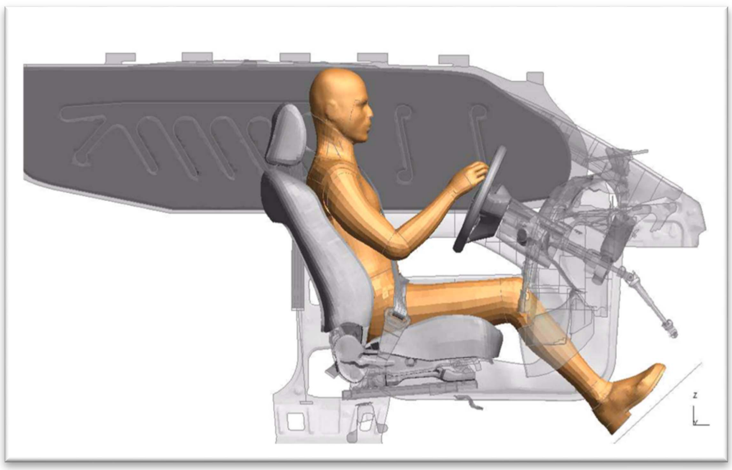

Figure 1: GHBMC-OS 50^{th} % male FE model in a mid-sized sedan.

BrIC values were calculated for each combination of the investigated parameters (Table 1). The simulations were done without any structural deformation of the vehicle model (i.e. were run similar to a model of a sled test). No attempts were made to recreate/reconstruct actual field cases nor replicate the results of a specific crash test. Instead, the model was developed to represent an average passenger car. The range of Delta-V and PDOF values that were simulated overlap what was observed in NHTSA's RMDB oblique fleet testing, where PDOF ranges from 20^0 to 30^0 for both near and far sides, and the Delta-V spans from 31 mph to 37 mph. The simulated PDOF range covers what would normally be defined as a frontal crash in NASS-CDS when considering 11 o'clock to 1 o'clock frontal crashes.

Table 1. Investigated parameters in FE simulation of frontal crashes (MFR is Mass Flow Rate).

Parameters	Baseline value	Range
Delta-V	35 mph	25 mph - 47 mph
PDOF (degrees)	0	-40 (320) to +40
Frontal airbag friction	0.5	N/A
Frontal airbag MFR (scaling factor)	1	N/A
Frontal airbag firing time (ms)	18	N/A
Load limiter (N)	3000	N/A
Side airbag friction	0.5	N/A
Side airbag MFR (scaling factor)	1	N/A
Side airbag firing time (ms)	18	N/A

Estimation of Brain Injury Risk: Using a single set of FE simulation results over a range of applicable frontal crash Delta-V and PDOF (per Table 1), simulation based brain injury risks were calculated while considering the PDOF and Delta-V ranges associated with the respective field and fleet data. Brain injury risk was calculated from the simulated BrIC values using the CSDM based risk functions described in Takhounts et al. (2013).

Three simulation based estimates of brain injury risk were calculated. The first was based on a simple average of BrIC for all simulations from 31 to 37 mph. The second version limited the average risk calculation to the PDOFs observed in NHTSA's RMDB oblique fleet testing (20-30^0). The final method used to estimate risk using the simulated BrIC data considered all simulation data over Delta-Vs of 31-37 mph (same as the first version), but with weighting applied based on the distribution of PDOFs obtained from the NASS/CDS field data for the Delta-V range of 31-37 mph.

RESULTS

Field Data Analysis: The distribution of PDOFs obtained from the NASS/CDS field data was very close to normal with the maximum at 0^0 (full-frontal crashes) representing approximately half of all the crashes (Figure 2). The NASS/CDS filter used to produce Figure 2 was the same as described above for the calculation of brain injury field risk.

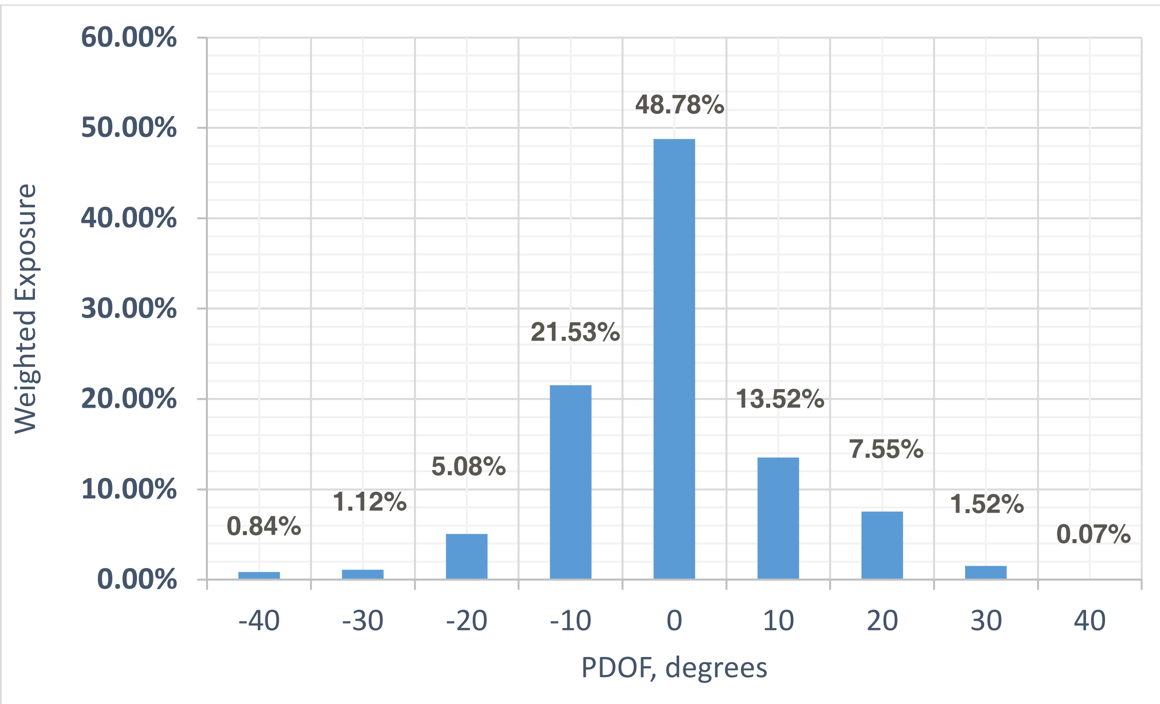

Figure 2: Weighted distribution of PDOF at Delta-V range 31-37 mph from the NASS/CDS field data.

The brain injury field risk from NASS/CDS of AIS2+, 3+, and 4+ for the Delta-V range of 31-37 mph (and PDOF of -40^0 to +40^0) was 7.59%, 3.34%, and 2.40% respectively. All brain injury cases at the three AIS levels were included in the respective risk calculations regardless of whether there was an accompanying skull and/or facial fracture.

Frontal Crash FE Simulation: Table 2 lists the values of BrIC from the simulation results for the parameters and ranges described in Table 1.

Table 2. Values of BrIC computed from the simulations for various Delta-V and PDOF.

DeltaV	PDOF=-40	PDOF=-30	PDOF=-20	PDOF=-10	PDOF=0	PDOF=10	PDOF=20	PDOF=30	PDOF=40
DV 25	0.553	0.688	0.534	0.524	0.462	0.482	0.625	0.699	0.707
DV 27	0.635	0.664	0.506	0.502	0.448	0.485	0.661	0.756	0.747
DV 29	0.713	0.683	0.498	0.481	0.469	0.497	0.661	0.821	0.824
DV 31	0.814	0.784	0.561	0.498	0.505	0.508	0.627	0.896	0.899
DV 33	0.855	0.784	0.619	0.536	0.527	0.519	0.71	1.066	0.9597
DV 35	0.959	0.759	0.593	0.615	0.555	0.548	0.986	1.268	1.008
DV 37	1.07	0.769	0.617	0.796	0.609	0.563	1.29	1.334	1.05
DV 39	1.196	1.05	0.738	0.883	0.62	0.571	1.465	1.3	1.13
DV 41	1.53	1.31	0.872	1.06	0.657	0.609	1.53	1.256	1.3
DV 43	1.693	1.098	0.989	1.23	0.697	0.607	1.61	1.39	1.765
DV 45	1.668	0.948	1.175	1.379	0.698	0.621	1.71	1.768	2.698
DV 47	1.824	1.074	1.31	1.147	0.654	0.651	1.81	2.26	3.95

Estimation of Brain Injury Risk: As previously noted, estimation of brain injury risk given the simulation results presented in Table 1 was done in three different ways.

The first version simply takes the average BrIC from the simulation results (Table 2) across all PDOFs for the Delta-V range of 31-37 mph (as was done by other researchers such as Prasad et al., 2014; Laituiri et at., 2016). The resulting average BrIC of 0.78 corresponds to 48.00%, 24.00%, and 17.00% risk of AIS2+, 3+, and 4+ brain injury (CSDM based injury risk from Takhounts et al. 2013).

The second version considers the same Delta-V range as above but limited to PDOFs of -30 to -20 and 20 to 30 degrees. As previously noted, this represents the range of PDOF observed in NHTSA RMDB oblique crash testing. The resulting average BrIC of 0.854 corresponds to 64.60%, 34.70%, and 25.80% for AIS 2+, 3+ and 4+, respectively, which is approximately an order of magnitude higher than that calculated from the NASS/CDS field data and in the same range obtained directly from the ATDs in NHTSA's RMDB oblique tests. This calculation was made by taking a simple average of BrIC values (from Table 2) for the Delta-V and PDOF ranges noted above (see bold rectangles in Table 2).

The prior two simulation based risk estimates did not consider the frequency or exposure of the respective PDOF/Delta V combinations in the field. Discrepancies in prediction among various studies can occur when the distribution of PDOF in the field is not considered in the calculation of averages. The formula for the average BrIC that includes the distribution of PDOF in the field is:

$$BrIC_{Ave} = \sum_{-\theta}^{+\theta}(\alpha_i BrIC_i), \quad (1)$$

where θ is the PDOF angle ranging from -40 to +40 degrees, α_i is the field exposure for each PDOF given in Figure 2, $BrIC_i$ is the average BrIC for 31-37 mph for each PDOF given in Table 2. For example, for a full-frontal case at 0 degree PDOF, the α_0 = 48.78% = 0.4878, and $BrIC_0$ = (0.505 + 0.527 + 0.555 + 0.609)/4 = 0.549. Average BrIC values for each PDOF at 31-37 mph are given in Table 3.

Table 3. Average values of BrIC (in bold) for the 31-37 mph Delta-V range.

	PDOF (degrees)								
	-40	-30	-20	-10	0	10	20	30	40
Delta-V = 31-37	**0.925**	**0.774**	**0.598**	**0.611**	**0.549**	**0.535**	**0.903**	**1.141**	**0.979**

Taking PDOF exposure from Figure 2 and corresponding values of BrIC from Table 3, the average BrIC calculated from equation 1 is:

$BrIC_{Ave} = \sum_{-\theta}^{+\theta}(\alpha_i BrIC_i)$ = 0.925*0.0084 + 0.774* 0.0112 + 0.598*0.0508 + 0.611*0.2153 + 0.549*0.4878 + 0.535*0.1352 + 0.903*0.0755 + 1.141*0.0152 + 0.979*0.0007 = 0.605.

Note that the sum of α_i in the formula above equals to 1 indicating that all possible PDOF exposures in Figure 2 are accounted for.

The risks of AIS 2+, 3+, and 4+ brain injury for BrIC = 0.605 are 8.08%, 3.40%, and 2.39% respectively. All the presented above values of BrIC (based on CSDM per Takhounts et al. 2013) are tabulated below in Table 4.

Table 4. Risks of AIS2+, 3+, and 4+ brain injury based on the field data and various BrIC values.

	AIS 2+	AIS 3+	AIS 4+
Average Field Weighted Risk for Delta-V 31-37 mph – NASS/CDS	7.59%	3.34%	2.40%
BrIC = 0.78 - simulation based average BrIC for Delta-V 31-37 mph and all PDOF	48.00%	24.00%	17.00%
BrIC = 0.854 - simulation based average BrIC for Delta-V 31-37 mph and PDOFs -30^0 to -20^0 and +20^0 to +30^0	64.60%	34.70%	25.80%
BrIC = 0.605 - simulation based average BrIC at Delta-V 31-37 mph weighted by the probability of occurrence of crash at each PDOF from -40^0 to +40^0	8.08%	3.40%	2.39%

When the average BrIC is calculated per equation 1, i.e., considering the actual PDOF exposure in the field given in Figure 2, as given in the last row in Table 4, the simulation based brain injury risks at various severities are comparable to those taken directly from the field (first row in Table 4).

Other formulas calculate such risks by simply lumping together all the risks at various PDOFs into one simple average without considering the PDOF exposure. Such calculations implicitly assume that the field PDOF exposure is uniform, i.e., a rectangular rather than normal distribution of PDOF given in Figure 2, with equal exposure coefficients in equation 1. However, when PDOF exposure is considered, the risks of brain injury calculated by BrIC are comparable to those obtained directly from the NASS/CDS field data.

Similar considerations are applicable when the range of Delta-V becomes wider (as in Prasad et al., 2014). In this case the Delta-V distribution in the field must be accounted for and equation (1) for calculating average BrIC should be modified (equation 2) to include an additional coefficient representing the Delta-V exposure in the field:

$$BrIC_{Ave} = \sum_{-\theta}^{+\theta}\sum_{dv1}^{dv2}(\alpha_i \beta_j BrIC_{ij}), \qquad (2)$$

where βj is the Delta-V exposure at each PDOF, dv_1 and dv_2 are the lowest and highest Delta-Vs under consideration (for example, if all the values of BrIC were used from Table 2, then dv_1 = 25 mph and dv_2 = 47 mph), and $BrIC_{ij}$ is the value of BrIC at a given PDOF and Delta-V. Similarly, for the analysis of the field (and/or fleet) data based brain injury risk, the risks at each PDOF and Delta-V should be weighted according to equation (2). In the case when such field data resolution is not available (due to small sample size), some averaging may be assumed as was demonstrated above using equation (1). However, when 66% of the cases are under Delta-V of 25 mph (such as the case when considering the damage extent range of 3 to 6 used in Prasad et al., 2014), which corresponds to much lower values of BrIC compared to those at 35 mph (see Table 2), then lumping all the data together and taking a simple average will predictably lead to incorrect assessment of the brain injury risk.

If a brain injury risks comparison between field and fleet data is to be made, then both PDOF and Delta-V ranges in the field and fleet datasets should be the same and the distributions of PDOF and Delta-V that occur in the field must be accounted for in the fleet data.

CONCLUSIONS

Simulation based results indicate:

1. BrIC is highly dependent on Delta-V and PDOF (Table 2).
2. When overall field risk of brain injury is compared to that calculated by BrIC from the fleet data, both Delta-V and PDOF ranges should be comparable between the two datasets and the distributions of PDOF and Delta-V that occur in the field data must be accounted for in the fleet data.
3. When conclusion 2 is satisfied, the brain injury risks for field and fleet are comparable (Table 4).

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