AN INVESTIGATION OF BRAIN INJURY RISK IN VEHICLE CRASHES (SECOND REPORT)

Takahiro, Kikuchi
Kaoru, Tatsu
Chinmoy, Pal
Shigeru, Hirayama
Nissan Motor Co., Ltd.
Japan

Paper Number 17-0002

ABSTRACT

In 2013, an angular velocity based brain injury criterion BrIC, has been proposed by the National Highway Traffic Safety Administration (NHTSA) for consumer vehicle safety assessment tests. In this study, the effect of duration of angular velocities on the predictor's precision was examined. The cumulative strain damage measure (CSDM) and the maximum principal strain were calculated with the data of 445 anthropomorphic test device (ATD) in various vehicle crash tests conducted by NHTSA and the Insurance Institute for Highway Safety (IIHS) using the Simulated Injury Monitor (SIMon ver. 4.0), a finite element model of human brain developed by NHTSA's research institute. The test dataset which composed of different risk levels of brain injury CSDM, MPS, BrIC and their corresponding angular velocities and durations were classified using Self-Organizing Maps (SOMs) combined with hierarchical clustering. The result showed that the differences of the probability of the risks between CSDM, MPS and the corresponding BrICs might be larger when the peak values of angular velocities were higher and the corresponding time durations were shorter.

INTRODUCTION

The level of head injury risk of occupants in vehicle crashes is usually evaluated with HIC which is calculated using three components of linear head acclerations of ATD. Therefore, it is not possible to predict the brain injury risk caused by head rotational motions by HIC.

Takhounts et al. proposed a kinematically based brain injury criterion, BrIC, to be used in regulatory or consumer safety vehicle safety assessment tests [1]. It is calculated with the peak values of angular velocities around three axis. If the time durations of critical angular velocities around three axis could be adujsted for loading signals to head, the coefficient of determination between CSDM and BrIC was not improved from the original formulation [2].

In our previous study, multi-variable regression analysis confirmed that, in addtion to the peak values of angular velocities, incorporating the peak values of angular acceleration around each axis would improve the accuracy of the predictor [3].

The purpose of this study was to examine the effect of head angular velocities around each axis and the corresponding time durations on the accuracy of BrIC. Data were obtained on 445 ATDs in vehicle crash tests conducted at NHTSA and IIHS. The probability of AIS 4+ brain injury risks based on CSDM, MPS, BrIC and their corresponding peak values of angular velocities and their time durations were classified and analyzed visually with SOMs, a kind of neural network algorithm, combined with hierarchical clustering alogorithm.

METHODS

Data set and variables

Frontal and lateral vehicle crash test data for 445 ATDs used in this study are shown in table 1.

Table 1.
Test conditions and number of ATD

Crash test condition		No. of ATDs
Frontal	Frontal RB	84
	Offset DB	20
	Small overlap RB	132
	Oblique offset MDB	57
Lateral	FMVSS 214 MDB	64
	IIHS MDB	46
	Pole	38
Vehicle to vehicle		4

RB : Rigid barrier, DB : Deformable barrier
MDB: Moving deformable barrier

These were obtained from NHTSA's [4] and IIHS's site [5].

The SIMon code developed by NHTSA was used to calculate CSDM and MPS with these test data. Strain threshold of 0.25 was used to calculate the CSDM for each test [1].

Probabilities of AIS 4+ brain injury risks were then calculated with these two metric and two probabilities of AIS 4+ brain injury were calculated by CSDM and MPS based BrIC with the formulation in the literature [1]. In addition, the peak values of angular velocities around three axis of dummy head and the corresponding time durations were calculated for each test to classify dummy data.

A time duration of angular velocity used in this study was defined as shown in figure 1 [2]. T_{left} and T_{right} shown in Figure 1 are the closest intersection of time axis to the maximum value of angular velocity. The time duration is $T_{right} - T_{left}$.

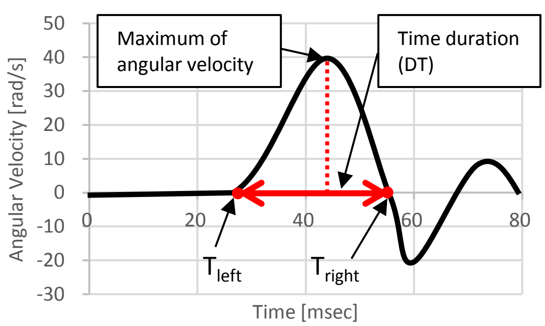


Figure 1. Duration of angular velocity

12 variables used for classification of dummy data are shown in table 2. These variables were non-dimensionalized by dividing them with the range from minimum to maximum after subtracting the minimum value for the corresponding variables when Euclidian distances as proximity of dummy data were calculated.

Table 2.
Variables for classification of ATD data

No	**Variable Name**	**Description**
1	CSDM	Cumulative strain damage measure
2	MPS	Maximum principal strain
3	BrIC	Brain rotational injury criteria
4	DTx	Duration of angular velocity around fore-aft axis
5	DTy	Duration of angular velocity around horizontal axis
6	DTz	Duration of angular velocity around vertical axis
7	P_{CSDM}	The probability of AIS 4+ brain injury based on CSDM
8	P_{MPS}	The probability of AIS 4+ brain injury based on MPS
9	P_{BrIC_CSDM}	The probability of AIS 4+ brain injury predicted by CSDM based BrIC
10	P_{BrIC_MPS}	The probability of AIS 4+ brain injury predicted by MPS based BrIC
11	DIFF_CSDM	Difference between P_{CSDM} and P_{BrIC_CSDM}
12	DIFF_MPS	Difference between P_{MPS} and P_{BrIC_MPS}

Visualizing test data with SOMs [6]

A schematic diagram of SOM is shown in Figure 2. SOMs were used to visualize in which tests probabilities of AIS 4+ brain injury based on CSDM and MPS were well-predicted by BrIC and also identified the tests where they were not well-predicted. The ATDs' data were non-linearly mapped on a two-dimensional layer where the locations of the input data were determined based on the weighted Euclidian distances. The weighted values of variables from #7 to #12 in table 2 were set to zero to prevent highly correlated variables from affecting the SOM results.

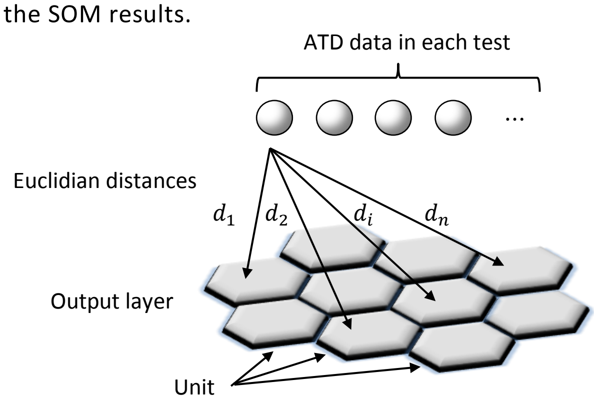


Figure 2. Self-Organizing Maps

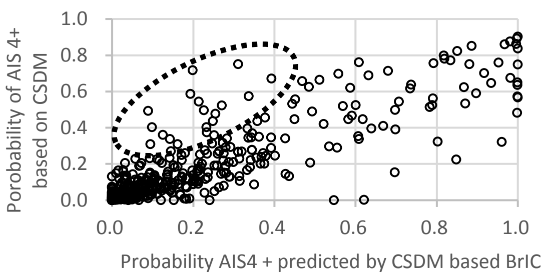
RESULTS

Comparison of level of brain injury risk

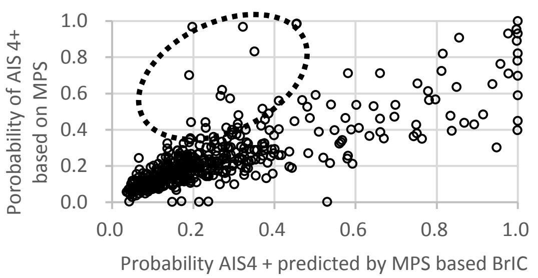
Figure 3(a) shows the comparison of brain injury risk predicted by CSDM (vertical axis) and that of BrIC (horizontal axis), while Figure 3(b) shows the comparison of brain injury risk predicted by MPS (vertical axis) and that of BrIC (horizontal axis).

The results inside the dotted ellipse indicates that P_{CSDM} and P_{MPS} values were higher than those of P_{BrIC}. Therefore, BrIC underestimated the levels of brain injury risks compared with CSDM and MPS in these tests.

The accuracy of the prediction in such severe loadings will be important when there is a possibility of high brain injury risk in a vehicle safety performance test. Therefore, the effect of the peak level of head angular velocities around each axis and their corresponding time durations on the accuracy of BrIC were thoroughly examined.



(a)



(b)

Figure 3. Comparison results of brain injury risk predicted by (a) CSDM and BrIC; (b) MPS and BrIC

Cluster analysis of dummy data

The name and cluster locations are shown in Fig. 4.

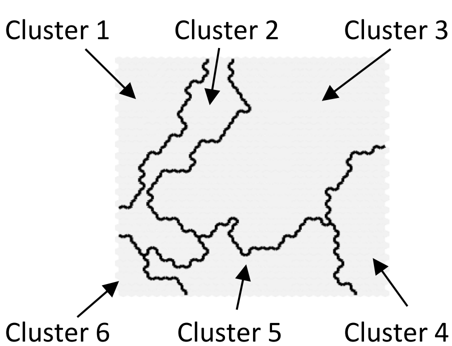


Figure 4. Self-Organizing Maps and cluster names

6 clusters were found to be appropriate to analyze the effect of variables on the precision of BrIC. Table 3 shows the number of dummy in each cluster.

Table 3.
Number of ATD in each cluster

No. of Cluster	No. of dummy data
1	26
2	40
3	286
4	50
5	38
6	5

Figure 5 shows the output layers for each variable such as P_{CSDM}, P_{MPS}, etc. Black dots in each map represent ATDs' data in all tests and are located in the same positions in all maps. The values of the variables in each region increase as the color of the regions becomes warmer.

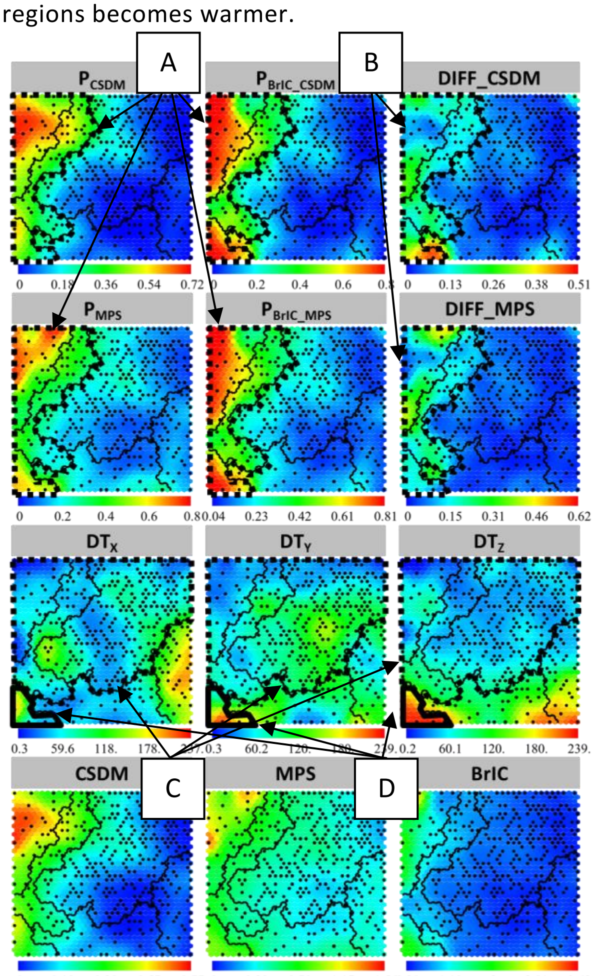


Figure 5. Self-Organizing Maps

Relatively higher levels of brain injury risk of the ATDs' data based on CSDM, MPS and their corresponding BrICs gathered on the left side of these maps and classified into cluster 1, 2 and 6 (marked as A). The output layers of the variable "DIFF_CSDM" and "DIFF_MPS" showed that clusters 1, 2 and 6 had relatively higher values of this variable than the other clusters (marked as B).

The output layers of the variable "DT_X", "DT_Y", "DT_Z" showed that clusters 1, 2 and 3 had data which had relatively shorter time duration of angular velocities than the other clusters (marked as C), while tests which had relatively longer time durations of angular velocities were classified into cluster 6 (marked as D).

Here comparing data from cluster 1, 2, 3 would be helpful to clarify the mechanisms why the probability of AIS 4+ based on CSDM and MPS were not predicted well by corresponding BrIC values in some tests like as shown by dotted ellipse in Figure 1, compared to those well-predicted in other tests like cluster 3. In addition, the number of test data that belonged to those clusters were comparatively large except cluster 6 which contained only five test data.

Figure 6 shows the average values of twelve variables for cluster 1, 2 and 3. The values of DIFF_CSDM for cluster 1 and 2 were the almost same. They were approximately three times as that of cluster 3. The value of DIFF_MPS of cluster 1, on the other hand, was larger than that of cluster 2 and three times larger than that of cluster 3 (marked as E).

The average values of time duration of angular velocities around x and y axes in cluster 1 and 2 were shorter than those of cluster 3 in this manner while that of angular velocity around z were close to each other (marked as F).

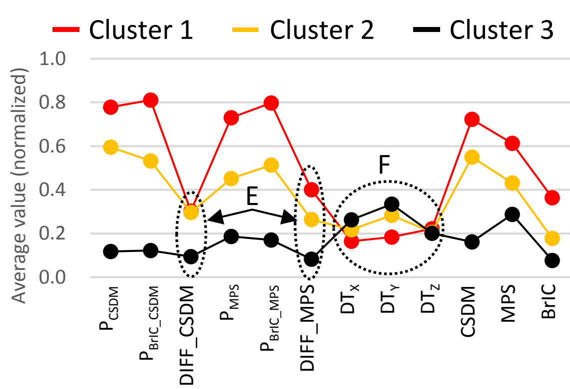


Figure 6. Average values of each cluster

Figure 7 shows the distributions of time duration of angular velocities around three axis for cluster 1, 2 and 3. There were some tests in which the time durations of angular velocities around three axis were extremely short (marked as dotted ellipse).

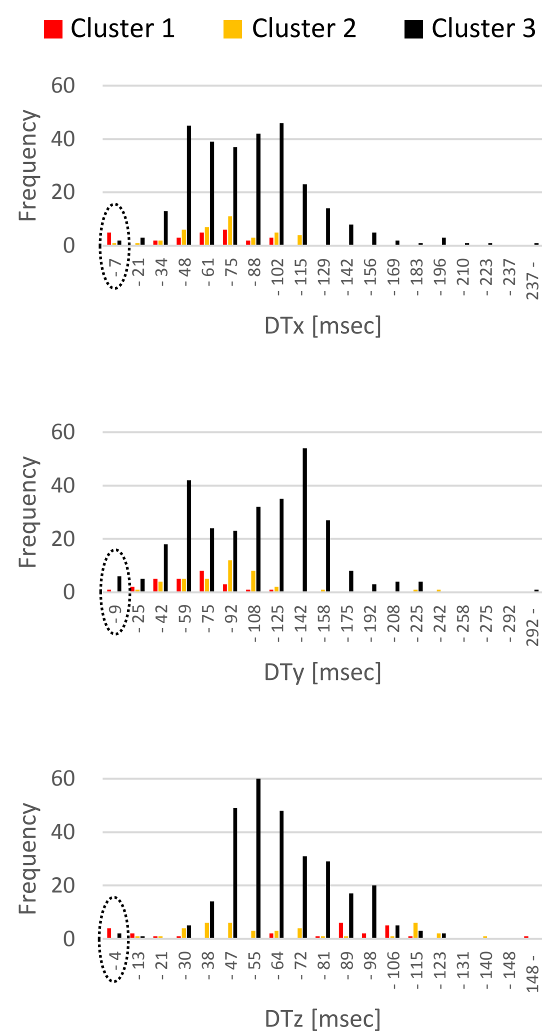


Figure 7. Distribution of duration of angular velocities around each axis

DISCUSSION

Effect of time duration of angular velocities on the precision of BrIC

Figure 5 shows test data which had relatively higher probability of AIS 4+ brain injury based on CSDM, MPS and BrIC were classified to cluster 1 and 2. The number of data in cluster 1 and 2 were 26 and 40 respectively and not so few. Moreover, those clusters had the tests which had relatively higher

"DIFF_CSDM" and "DIFF_MPS" values, indicating that BrIC was less accurate in predicting the brain injury risk based on CSDM and MPS in these clusters (marked as B). In Figure 6, a comparison of the average values of cluster 1, 2 and 3 indicated that the precision of BrIC of cluster 1 and 2 which had higher probability of AIS 4+ brain injury and shorter time duration of angular velocities were worse than that of cluster 3. Based on these findings, the differences of the probability of risks among CSDM, MPS and the corresponding BrICs might be larger when the data have higher peak values of angular velocities and shorter time durations. Such typical examples were compared and shown in Figure 8(a), 8(b), in which the upper graph corresponds to the result of shorter time duration and the lower graph is related to the result of relatively longer time duration. They had close values of probability of AIS 4+ brain injury predicted by CSDM and MPS based BrIC (marked as dotted ellipse in Figure 8(a), 8(b)).

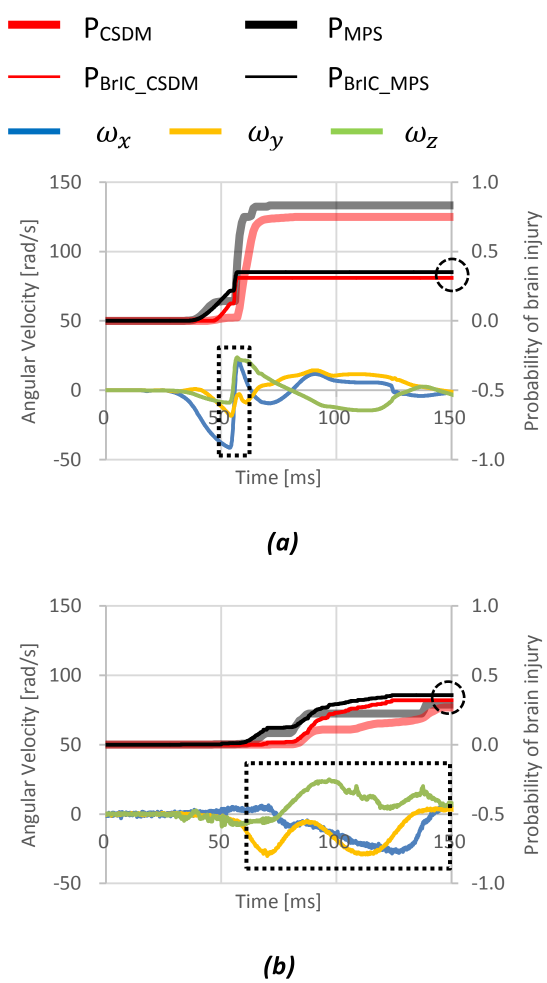


Figure 8. Typical cases with (a) shorter (b) longer time duration of angular velocities

Figure 8(a) shows the probabilities of AIS 4+ brain injury based on CSDM and MPS that increased up to about 80% after 50 msec. But the probabilities of AIS 4+ brain injury predicted by CSDM and MPS based BrIC were approximately one half of that for CSDM and MPS. During that period, the values of angular velocity around x and z axis switched from negative peak to positive peak (marked as dotted square). This result suggested that considering the values from negative (positive) peak to positive (negative) peak might contribute to improve the precision of the predictor based on CSDM and MPS. In contrast, Figure 8 (b) shows the probabilities of AIS 4+ brain injury based on CSDM, MPS and BrIC that gradually increased in accordance with the increase of angular velocities. The probabilities of AIS 4+ brain injury based on CSDM, MPS and the corresponding BrIC reached close values at 150 msec.

CONCLUSIONS

Vehicle crash test data for 445 ATDs obtained from NHTSA and IIHS were analyzed using SOMs and hierarchical cluster analysis to investigate the effect of time duration of angular velocities around three axes on the level of precision of BrIC. Findings are summarized below.

1. The differences of the probability of the risks between CSDM, MPS and the corresponding BrICs might be larger when the peak values of angular velocities were higher and the correspondig time durations were shorter.
2. In addition to time durations of angular velocities, incorporating the values of peak-to-peak of angular velocity around each axis into the predictor's formulation might improve its level of precision.

REFERENCES

[1] Takhounts, E.G. et al. 2013. "Development of Brain Injury Criterion (BrIC)", Stapp Car Crash Journal Vol. 57, pp. 243 – 266

[2] Takhounts, E.G. 2015. "BrIC Update: Does BrIC Depend on the Signal Time Duration?" IRCOBI- NOCSAE-Snell-PDB TBI Workshop

[3] Kikuchi, T. 2016. "Investigation of Brain Injury Mechanisms in Vehicle Crashes", In Proceedings of the JSAE Annual Congress

[4] http://www.nhtsa.gov/

[5] https://techdata.iihs.org/login.aspx

[6] Kohonen, T. 2001. "Self-Organizing Maps" Springer-Verlag