A STUDY OF BRAIN INJURY MECHANISMS IN VEHICLE CRASHES

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ABSTRACT

Brain injury has been researched since the 1940s and various methodologies have been discussed for evaluating brain injury risk in vehicle crash tests. In recent years, an angular velocity based brain injury criterion (BrIC) has been proposed by the National Highway Traffic Safety Administration (NHTSA) for use in regulatory or consumer vehicle safety assessment tests. One of the brain injury mechanisms can be explained by relative displacement between the brain and skull, resulting in brain deformation and strain. This paper states a hypothesis of this brain injury mechanism using a simple mass-spring-damper model. Then the hypothesis was verified by the Simulated Injury Monitor (SIMon) version 4.0, a finite element model of the human head developed by NHTSA, using a cumulative strain damage measure (CSDM) as the brain injury metric. In consequence, CSDM varies according to the input loadings, which have the same peak angular velocity but different levels of peak angular acceleration and loading durations. These results suggest that in order to evaluate brain injury risk accurately, an angular velocity based criterion may not always be sufficient and it may be necessary to consider the peak value of angular acceleration and the corresponding loading duration. This hypothesis was applied to NHSTA's research test data to prove its validity. It was found that brain injury risk predicted by CSDM can be comparatively lower than that predicted by BrIC and vice versa.

INTRODUCTION

Brain injury is caused by either a direct contact force to the head or inertial loading from an indirect impact. In either case, the head undergoes both translational and rotational motion. Rotational motion of the head is purported to be the major factor of causing strain-induced brain injury [1-4]. CSDM is widely employed in this field as an injury metric for strain-related brain injury which is calculated by the fraction volume of brain which exceeds a prescribed strain level threshold. The accumulated volume fraction of damaged brain are thought to be related to diffuse axonal injury [2-4].

SIMon was used to examine the effect of head rotational motion on CSDM using NHTSA's research test data. Three variations of input to the skull were parametrically used: (i) both translational and rotational acceleration, (ii) only translational acceleration and (iii) only rotational acceleration. In both frontal and side impact tests, case (iii) showed that CSDM was approximately at the same level as that seen for the combined acceleration loading in case (i). By contrast, CSDM was almost zero in case (ii). These results indicated that rotational motion of head was the major contributor to CSDM [5].

In recent years, BrIC has been proposed as a brain injury predictor by NHTSA. It is calculated with Eq. (1).

$$\mathbf{BrIC} = \sqrt{\left(\frac{\omega_x}{\omega_{xc}}\right)^2 + \left(\frac{\omega_y}{\omega_{yc}}\right)^2 + \left(\frac{\omega_z}{\omega_{zc}}\right)^2} \quad (1)$$

where ω_x, ω_y and ω_z are maximum angular velocities about the coronal, sagittal and transverse planes. ω_{xc}, ω_{yc} and ω_{zc} are the critical angular velocities around each axis based on CSDM shown in Table 1.

Table 1.
Critical angular velocity ω (rad/s) around each axis

ω_{xc}	66.20
ω_{yc}	59.10
ω_{zc}	44.25

The heads of anthropomorphic test devices (ATDs) were impacted using a pendulum with and without a pad, and the resultant translational and rotational accelerations were measured. SIMon was used with translational and rotational data measured with the sensors on ATDs' heads to calculate CSDM and the maximum principal strain (MPS) on the brain. Risk curves for diffuse axonal injury were proposed with regard to BrIC [6].

The purpose of this study was to examine the effect of the peak value and loading duration of the angular acceleration on CSDM. The present hypothesis of brain injury is that the brain displacement depends on the peak angular acceleration and the loading duration, resulting in brain strain as a consequence. Firstly, brain displacement is explained with a simple mass-spring-damper model (simple model) in which physical paramaters are roughly estimated in reference to cadaveric experiments [7]. Loading pulses to the skull were parametrically input as sinusoidal functions which cover more than 95% of the loadings in 74 NHTSA research tests (Tabel A1) used in the literature [8]. The results were validated with SIMon. Secondly, NHSTA's reserch test data are applied to SIMon to calculate CSDM. The angular velocity based predictor, BrIC, is examined as to whether it is a rational predictor of CSDM, one of the brain injury metrics. Close examination of the plots of CSDM vs. BrIC can show that brain injury risk predicted by CSDM can be comparatively lower than that calculated by BrIC and vice versa. The reasons for this inversion are examined in terms of the peak and the duration of the resultant angular acceleration.

METHODS

To examine the relationship between the relative displacement of brain and the loading pulse, a hypothesis for the mechanism of brain displacement is explained using a simple model as shown in Fig.1. Direct contact to the head or indirect inertial loading induces skull rotation indicated by the blue arrow in the left diagram, while the brain has a tendency to keep its position with respect to the inertial frame at $t = t_0$. After some delay (Δt) following the impact, the brain then starts to rotate (indicated by the green arrow in the right diagram), consequently producing relative displacement between the brain and skull ($\Delta Y, \Delta Z$), which induces brain deformation and strain.

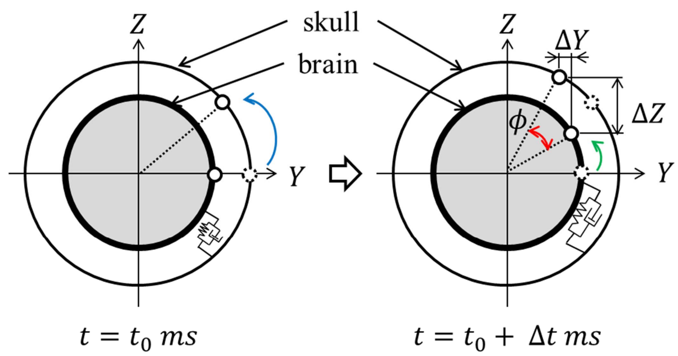


Figure 1. A Simple Brain Displacement Model

Assuming the input loading pulse to the head as a sinusoidal function [8-10], the equation of motion of the brain with respect to the skull, ϕ shown by red arrow in the right diagram, takes the form of Eq. (2).

$$I\ddot{\phi} + c\dot{\phi} + k\phi = A\Omega \sin \Omega t \tag{2}$$

The steady-state solution of Eq.(2) can be expressed by Eq. (3).

$$\boldsymbol{\phi} = \frac{\mathbf{A\Omega}}{\sqrt{(\Omega_0^2 - \Omega^2)^2 + 4\alpha^2\Omega}} \sin(\Omega t + \delta) \quad (3)$$

where, A: peak of the loading pulse, Ω: driving frequency, Ω_0: undamped angular frequency of the oscillator and δ : induced phase change. It is seen that the peak relative angle of the brain with respect to the skull is a function of the amplitude of the driving force A and the driving frequency Ω which is the inverse of loading pulse duration. Coefficients of damper, c, and spring, k, were roughly estimated from the results of a cadaver head impact test C386-T6 in the literature [7] in which one of the test was conducted in the coronal plane and the specimen was impacted in the left-side temporal region.

To determine the loading pulse to the simple model, the peak values of both angular velocity and angular acceleration were investigated using 80 NHTSA research tests (Tabel A1) used in the literature [8]. The test data were for frontal impacts, side impacts with a moving deformable barrier (MDB), side impacts to a rigid pole and vehicle-to-vehicle side impacts. The ATDs used were the Hybrid-III 50th Male and the ES-2. Six out of 80 tests were excluded because the peak angular acceleration or the peak angular velocity in these tests were more than three standard deviations away from the mean value of those 80 tests. Fig.2 shows the peak angular velocity vs. peak angular acceleration of the 74 tests (blue dots). The red dots mean loading pulses which cover more than 95% of the tests as shown by shaded area in red. These three input pulses shown with the red dots were applied as the sinusoidal functions shown in Fig.3. For validation of the brain displacement results calculated with the simple model, CSDM was calculated by the SIMon version 4.0, using a strain threshold of 0.25 [6]. The loading pulses were the same as the ones used with the simple model and were applied around the coronal axis.

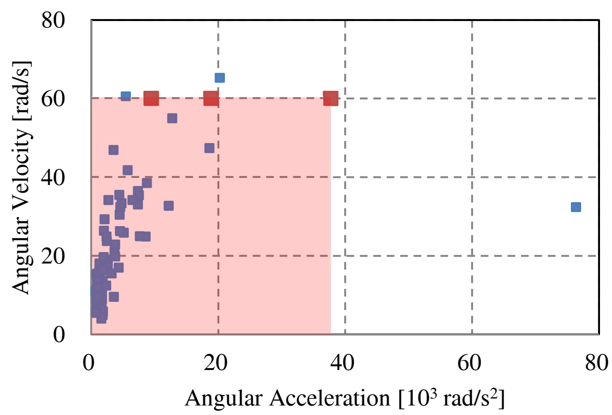


Figure 2. Peak Angular Velocities and Angular Accelerations from 74 NHTSA Tests and Loading Pulses

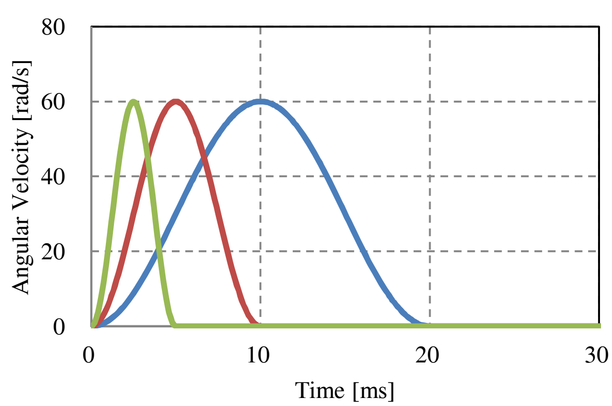


Figure 3. Angular Velocities as Input Pulses

In addition to the calculation above, the nine accelerometer data measured on ATDs' heads in 74 NHTSA research tests were applied to SIMon to calculate CSDM values under the loadings in vehicle crashes. BrIC was also calculated to examine whether it is a rational brain injury metric for predicting CSDM. In addition, the correlation between the angular acceleration and the gradient of CSDM, which is calculated from the difference of CSDM at time t and t+Δt (Δt=1ms), was examined by plotting their distributions with respect to time in order to estimate when and how much volume fraction of the brain exceeds the threshold strain level of 0.25.

RESULTS

The relative displacements between the brain and skull calculated with the simple model are shown in Fig.4. The colors of curves correspond to the ones of the input loadings shown in Fig.3. The graph legend means the peak values of the angular acceleration of the input loading pulses. The results show that the relative displacements varied even though the peak angular velocities did not change as shown in Fig.3. The loading pulse having the longest loading duration due to the lowest peak acceleration shown with blue curve produces the largest relative displacement of the brain. This suggests that the longer is the loading duration due to the lower peak acceleration, the larger is displacement.

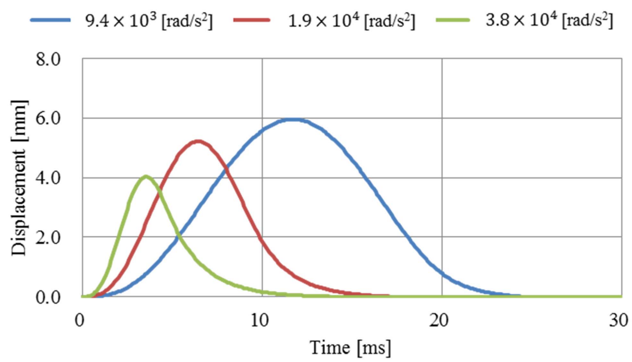


Figure 4. Relative Displacement between the Brain and Skull calculated by Simple Model

Fig.5 shows the time histories of CSDM calculated by SIMon using the same input pulses of the simple model shown in Fig.3. The legends of the graph correspond to the peak values of the angular acceleration of the input loading pulse. Referring to the blue curve, the CSDM value for the loading pulse having the longest loading duration and the lowest peak angular acceleration, reaches a level of 50% at around 25 ms. On the other hand, referring to the green curve, the CSDM value for the input loading having the shortest loading duration and the highest peak angular acceleration, reaches a level of 22% at around 10 ms.

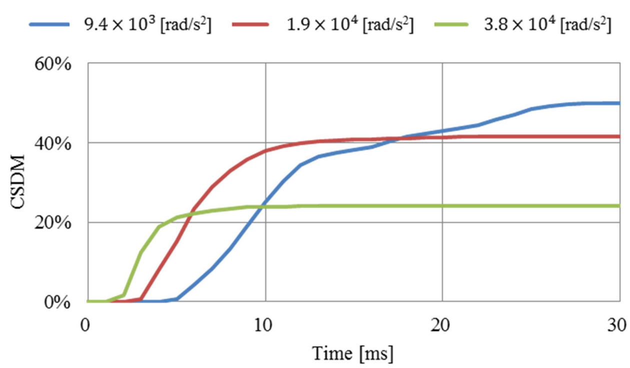
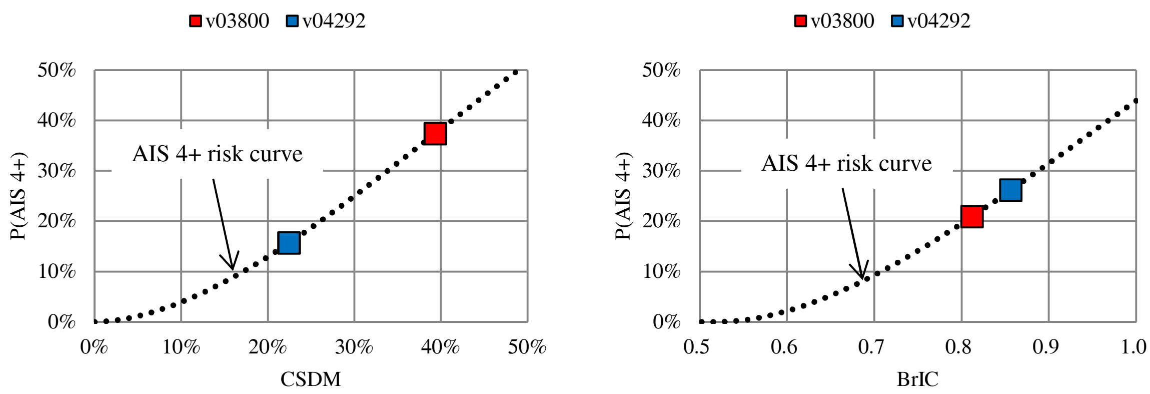


Figure 5. CSDM Data calculated with SIMon

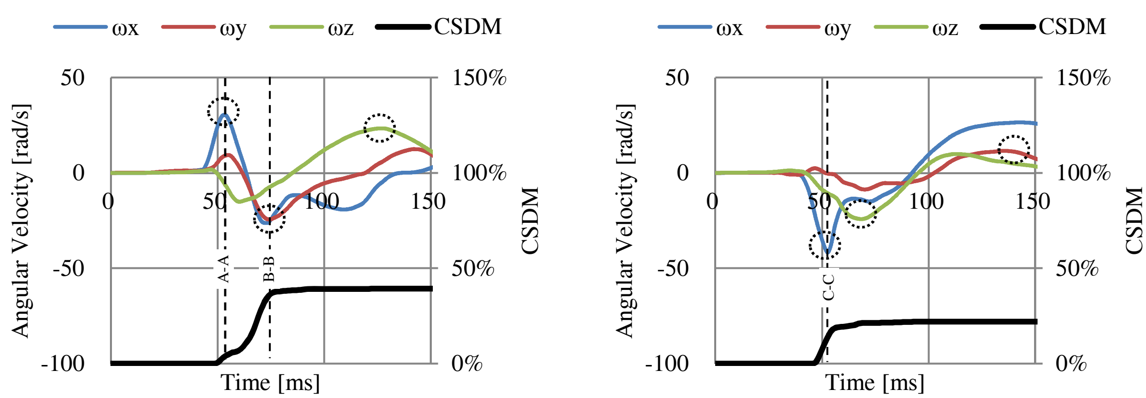
Next, the above hypothesis obtained from the calculation by the simple model and SIMon was applied to NHSTA's research test data to prove its validity. In consequence, comparison of a pair of research tests (v03800 and v04292) shows that the brain injury risk predicted by CSDM can be comparatively lower than that calculated by BrIC and vice versa as shown Fig.6. The CSDM (Fig. 6a) and BrIC (Fig. 6b) values of these two tests, corresponding to their individual AIS 4+ brain injury risk curves, are plotted in blue and red squares on the dotted curves [6]. The CSDM value in the v03800 test is about two times higher than that of the v04292 test; while the BrIC value in v03800 is 0.05 lower than that in v04292.



(a) *(b)*

Figure 6. AIS 4+ Risk Curves for (a) CSDM and (b) BrIC based on CSDM of Brain Injuries

Fig.7 shows time histories of the angular velocities and CSDM in (a) v03800 and (b) v04292. In both tests, the maximum angular velocities in the three axes are marked by dotted ellipses, which are used to calculate BrIC. Thorough observation of Fig.7 (a) shows the results for the v03800 test in which an increase of CSDM is seen after 50 ms. At nearly the same time, the angular velocity around the x-axis and y-axis changes from positive (A-A) to negative peak (B-B). Hence, the change in angular velocity, i.e. the angular acceleration in this period seems to cause the increase in CSDM from 0 to 39%. On the other hand, Fig. 7(b) shows the results for the v04292 test in which an increase of CSDM is seen around 50 ms (C-C). In this test, the value of the change in angular velocity may be about one half of that for v03800. The CSDM value is also about one half of that for v03800. These results suggest that the magnitude of the change in angular velocity seems to be related to the value of the CSDM.



(a) *(b)*

Figure 7. Angular Velocities and CSDM in (a) v03800 and (b) v04292

Fig.8 shows CSDM versus BrIC plot of 74 tests. Among the tests results as marked in dotted ellipse as shown in Fig.8, the pair of tests, such as shown above in Fig.6 and Fig.7, can be seen frequently. For example, within one dotted ellipse, the lower right plots have relatively higher BrIC values than the upper left plots, while CSDM values of the lower right plots are lower than the ones of the upper left plots. The pair of tests shown above in Fig.6 and Fig.7 are marked in black.

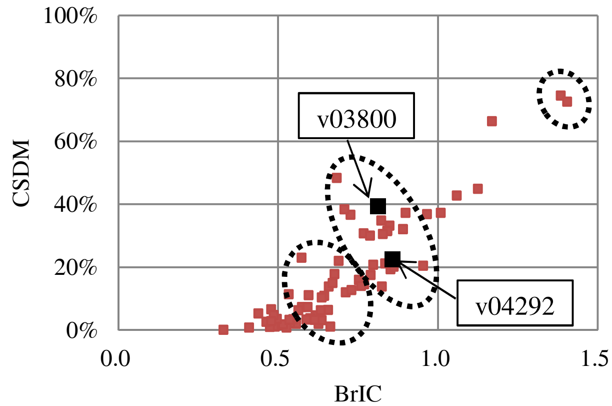
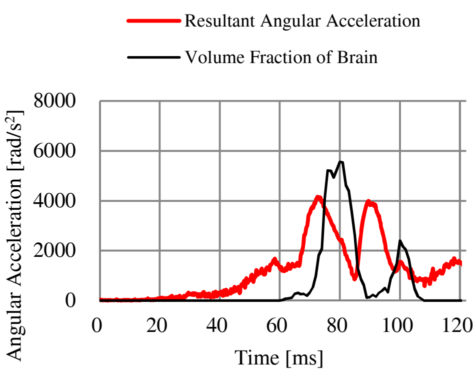
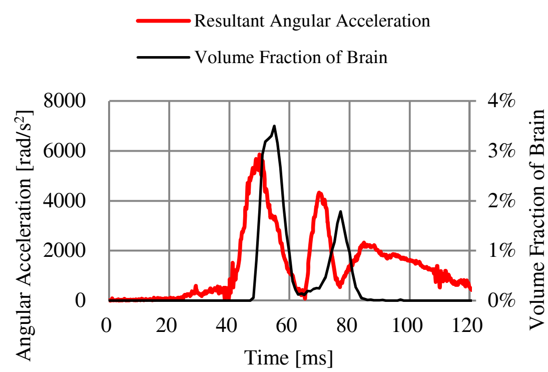


Figure 8. CSDM versus BrIC of 74 tests calculated by SIMon

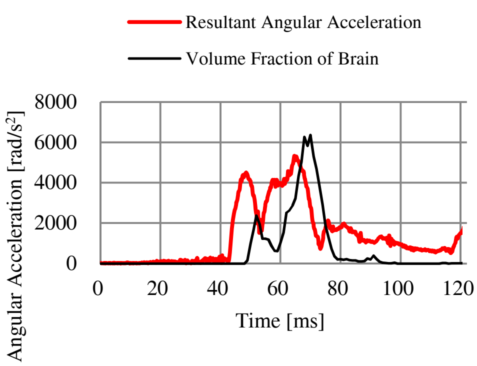
Fig.9 shows time histories of the resultant angular acceleration and the volume fraction of the brain in 4 tests. The test numbers are shown below the corresponding graphs. These graphs show that the volume fraction of the brain that exceeds the strain level of 0.25 increases just after the resultant angular acceleration increases. These results suggest that the rate of change in CSDM might be influenced by the resultant angular acceleration.



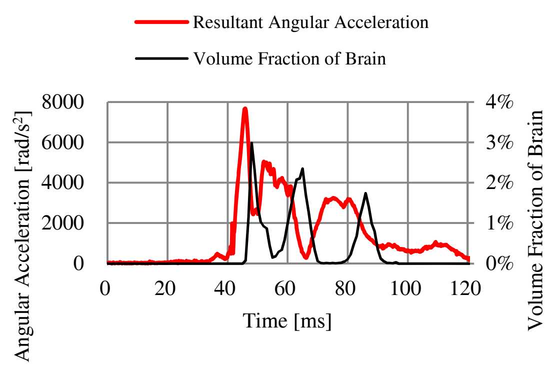
(a) v03952



(b) v04547



(c) v03800



(d) v04380

Figure 9. Resultant Angular Acceleration and Volume Fraction of Bran in 4 tests

DISCUSSION

An injury criterion based only on angular velocity might not be an accurate brain injury metric for predicting CSDM values. The peak values of relative displacement between brain and skull calculated by simple model varied under the different loading pulses with the same peak angular velocity. The results of simple model were verified by FEM

based SIMon model. The CSDM values calculated by SIMon showed the same tendency as that of the simple model. In the vehicle crash test, BrIC, one of the angular velocity based injury criterion, not always accord with the predicted result based on CSDM value calculated by SIMon as shown in Fig.6 and Fig.7. The CSDM value in the v03800 test is approximately twice as large as the value in the v04292 test. However, the BrIC value in the former test hovers at a level of just 0.05 lower than that in the latter test. Such pairs of tests are found frequently as shown in Fig.8. Within one dashed ellipse in Fig.8, the lower right plots have relatively higher BrIC values than the upper left plots, but CSDM values of the lower right plots are lower than the upper left ones. This inversion of the relationship between CSDM and BrIC might lead to mislead consumers about the crash safety performance of vehicles, if the present BrIC estimation is used in regulatory or consumer vehicle safety assessment tests.
Presumably, one of the reasons why BrIC does not necessarily predict CSDM value is that BrIC considers only the absoulte peak angular velocity and does not take into account the peak value of angular acceleration and corresponding loading duration. The peak value and loading duration of angular acceleration might affect the relative displacement of the brain as shown Eq.(3) and Fig.4. This hypothesis was verified by SIMon as shown in Fig.5. The loading pulse having the longest loading duration due to the lowest peak acceleration produces the largest relative displacement of the brain and CSDM value. The gradient of CSDM with respect to time showed when and how much volume fraction of the damaged brain swelled. Fig.9 indicated that the volume fraction of the damaged brain increased with increasing resultant angular acceleration with some delay. These results suggest that the rate of change in CSDM might be influenced by the resultant angular acceleration.

CONCLUSIONS

This study highlighted the importance of considering the peak value of angular acceleration and the corresponding loading duration when evaluating brain injury risk based on CSDM. In addition, an injury criterion based only on an angular velocity might cause misunderstanding of consumers about the crash safety of vehicles with respect to brain injury risk. More research is needed before adopting such criteria for evaluating brain injury risk in regulatory or consumer vehicle safety tests.

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Appendix

Table A1. NHTSA's research tests data.

Frontal impact tests			Side impact tests		
Test Number	**Occupant**	**Test Condition**	**Test Number**	**Occupant**	**Test Condition**
v04303	Driver	Vehicle into barrier	v03800	Driver	MDB into vehicle
v04242	Driver	Vehicle into barrier	v04551	Driver	MDB into vehicle
v04205	Passenger	Vehicle into barrier	v03875	Driver	MDB into vehicle
v04273	Driver	Vehicle into barrier	v03899	Driver	MDB into vehicle
v04198	Driver	Vehicle into barrier	v03818	Driver	Vehicle into pole
v03897	Driver	Vehicle into barrier	v04547	Driver	MDB into vehicle
v04266	Passenger	Vehicle into barrier	v04380	Driver	MDB into vehicle
v04247	Driver	Vehicle into barrier	v03845	Driver	Vehicle into pole
v03916	Driver	Vehicle into barrier	v04497	Driver	Vehicle into pole
v04081	Passenger	Vehicle into barrier	v04547	Passenger	MDB into vehicle
v04264	Passenger	Vehicle into barrier	v03898	Driver	Vehicle into pole
v03901	Passenger	Vehicle into barrier	v04551	Passenger	MDB into vehicle
v04250	Driver	Vehicle into barrier	v03799	Passenger	MDB into vehicle
v04251	Driver	Vehicle into barrier	v04380	Passenger	Vehicle into pole
v04215	Passenger	Vehicle into barrier	v03820	Driver	Vehicle into pole
v04237	Passenger	Vehicle into barrier	v04456	Passenger	MDB into vehicle
v04080	Driver	Vehicle into barrier	v03819	Passenger	MDB into vehicle
v04205	Driver	Vehicle into barrier	v04378	Driver	Vehicle into pole
v04090	Driver	Vehicle into barrier	v04292	Driver	Vehicle into vehicle
v04264	Driver	Vehicle into barrier	v04498	Driver	Vehicle into pole
v04090	Passenger	Vehicle into barrier	v03803	Passenger	MDB into vehicle
v04223	Passenger	Vehicle into barrier	v03802	Driver	Vehicle into pole
v04267	Passenger	Vehicle into barrier	v04292	Passenger	Vehicle into vehicle
v04215	Driver	Vehicle into barrier	v03803	Driver	MDB into vehicle
v04242	Passenger	Vehicle into barrier	v04482	Driver	Vehicle into vehicle
v04259	Driver	Vehicle into barrier	v03800	Passenger	MDB into vehicle
v03987	Driver	Vehicle into barrier	v04471	Driver	Vehicle into pole
v03915	Driver	Vehicle into barrier	v04313	Driver	Vehicle into pole
v04255	Passenger	Vehicle into barrier	v03819	Driver	MDB into vehicle
v04235	Driver	Vehicle into barrier	v04086	Driver	MDB into vehicle
v04235	Passenger	Vehicle into barrier	v04284	Driver	Vehicle into pole
v04265	Passenger	Vehicle into barrier			
v04292	Passenger	Vehicle into barrier			
v04240	Driver	Vehicle into barrier			
v04237	Driver	Vehicle into barrier			
v04259	Passenger	Vehicle into barrier			
v04198	Passenger	Vehicle into barrier			
v03915	Passenger	Vehicle into barrier			
v03952	Driver	Vehicle into barrier			
v03901	Driver	Vehicle into barrier			
v04241	Driver	Vehicle into barrier			
v04252	Driver	Vehicle into barrier			
v03952	Passenger	Vehicle into barrier			

GLOSSARY

ATD: anthropomorphic test device
BrIC: brain injury criteria
CSDM: cumulative strain damage measure
MPS: maximum principal strain
NHTSA: National Highway Traffic Safety Administration
SIMon: Simulated Injury Monitor