CONSIDERATION OF REPRESENTATIVENESS OF REAL-WORLD ACCIDENTS AND REPEATABILITY OF NEW NHTSA OBLIQUE OFFSET FRONTAL IMPACT TEST

Ryuuji Ootani
Taisuke Watanabe
Tomosaburo Okabe
Nissan Motor Co., Ltd.
Japan

Dix Jeff
Lam Joyce
Nissan Technical Center North America
USA

Muthanandam Muthukumar
Renault Nissan Technology and Business Center in India
India

Paper Number 15-0261

ABSTRACT

The National Highway Traffic Safety Administration has been considering introducing an oblique frontal offset impact test (oblique test) as a new crash test procedure. By means of accident data analysis, it was examined whether this oblique test can represent real-world accidents. Tests were also conducted using two identical vehicles to examine the repeatability of the oblique test. Representativeness of real-world accidents was examined by using the National Automotive Sampling System Crash Worthiness Data System (NASS-CDS) to investigate frontal impact accidents from 2004 to 2008. Repeatability of the oblique test was investigated by conducting the same crash test twice using a midsize sedan. In terms of percentage of the total number of real-world accidents, the most frequent accident modes observed were Full-engagement and Offset frontal impacts, accounting for about 30%. Accidents similar to the oblique test accounted for about 10%. In terms of representativeness of severe injuries, the percentage of brain rotational injuries and lower extremity injuries differed from real-world accident statistics. Brain rotational injuries were considerably different from real-world accidents. With regard to repeatability, vehicle deceleration (G) was almost the same. However, the degree of cabin deformation differed because of a difference in the buckling mode of the front longitudinal member. Another notable point in the oblique test is that, as the test vehicle weight increases, the Delta-V decreases. However, this tendency is not observed in real-world accidents. To ensure the validity and significance of introducing this test procedure, more test data are required along with continued evaluation and analysis of occupant protection performance based on actual test results.

INTRODUCTION

Occupant protection performance in frontal impacts is currently assessed in tests conducted under the New Car Assessment Program (NCAP) and by the Insurance Institute for Highway Safety (IIHS). The National Highway Traffic Safety Administration (NHTSA) has proposed introducing a frontal oblique offset impact test, which is different from the traditional test method. The NHTSA has been publishing results obtained from oblique tests and accident analysis. In 2011, Rudd et al. [1] conducted an analysis of small overlap and oblique accidents and also reported the factors causing injuries. In 2012, Saunders et al. [2] reported a small overlap and oblique test method and the results obtained for vehicle G and deformation. In 2013, Saunders and Parent [3] reported the results of additional oblique tests. Regarding the repeatability of the oblique test, the same authors [4] also published the results of a three-vehicle comparison using the same vehicle. For the THOR dummy, which is to be used in the oblique test, introduction of the Brain Injury Criteria (BrIC) is being considered. Saunders and Parent [5] discussed BrIC, and Dokko and Hasegawa [6] reported an evaluation of thoracic injuries using a human finite element model. Recent publications indicate that the studies related to the oblique test method and new THOR dummy have been increasing. In this study, attention was focused on analyzing the representativeness of real-world accidents and the repeatability of the oblique test.

REPRESENTATIVENESS OF REAL-WORLD ACCIDENTS

Method of accident analysis

The National Automotive Sampling System Crash Worthiness Data System (NASS-CDS) was used in this study to analyze injured occupants. Table 1 summarizes the extraction conditions of the accident analysis. The total number of MAIS3+ injured occupants was 3,214. The injured occupants were classified in nine types of crash configurations shown in Figure 1. In making this classification, "Small overlap" was classified based on the method proposed by the Medical College of Wisconsin [7]. "Offset", "Full-Engagement", "Narrow", "DYZ-NoRail", "Oblique", and "High/Low Vertical" were classified according to the taxonomy proposed by Sullivan et al. [8]. "Front-other" and "Side-other" were classified as other accident types.

Table 1.
Summary of NASS-CDS data extraction conditions

Data years	2004-2008
Vehicle model years	1959-2009
Deformation location	Front, Left & Right
PDOF (Principal Direction of Force) [degrees]	Left & Right: 0-40, 320-360
Rollover collisions	Not involved
MAIS	3+ injuries

Results of Accident Analysis

Figure 1 shows a breakdown of the accidents by crash configuration. The most frequent accident types are the Full-Engagement and Offset frontal impact, each of them accounts for 27% of the total. The second most frequent accident type is the Small overlap impact, which accounts for 13%. The next frequent accident types are the Narrow, DYZ-NoRail, Oblique, and High/Low Vertical in decreasing order. Other accidents (Front-other and Side-other) are 15%.

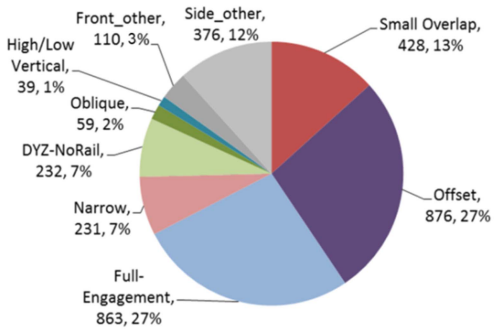

Figure 1. Accident breakdown by crash configuration

Among the results in Figure 1, Offset and Small overlap accidents were segmentalized in two directions: "Offset-Oblique" and "Offset-Colinear", "Small Overlap-Oblique" and "Small Overlap-Colinear". The results are shown in Figure 2. As a result of the segmentalization, the second most frequent accident type is "Offset-Oblique", which accounts for 15%. The next most frequent accident type is "Offset-Colinear", which accounts for 13%.

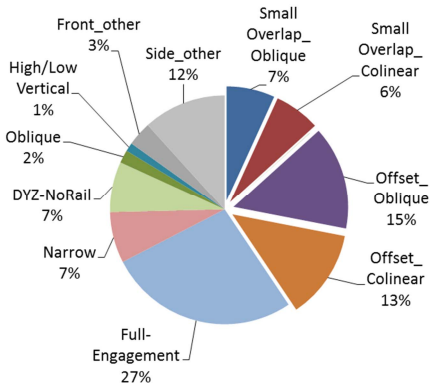

Figure 2. Accident breakdown by crash configuration segmentalized by direction

Among the results in Figure 2, Offset and Small overlap accidents were further segmentalized in terms of three types of collision partners: vehicle, pole and other object. The results are shown in Figure 3. As a result of the resegmentalization it is seen that the most frequent accident type is Full-Engagement, and the second most frequent type is "Offset-Oblique-Vehicle", which accounts for 12%. This "Offset-Oblique-Vehicle" is considered to be a crash configuration similar to the offset oblique impact test.

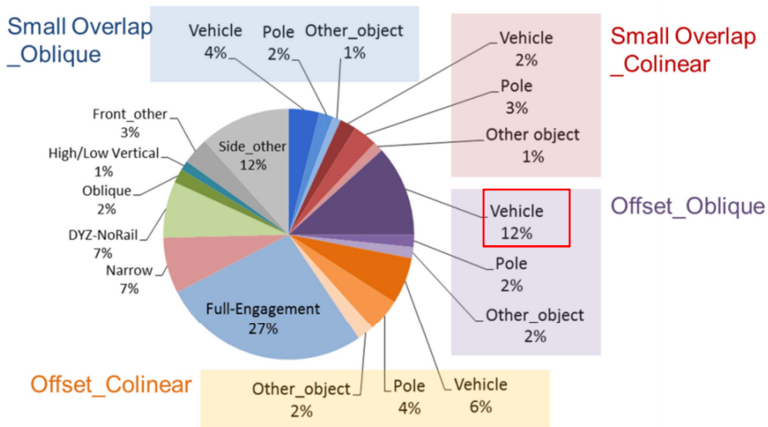

Figure 3. Accident breakdown by crash configuration segmentalized by direction and collision partner

Figure 4 shows the cumulative distribution of Delta-V of the "Offset-Oblique-Vehicle" type, and Figure 5 shows the frequency distribution. These data exclude unkown Delta-Vs. The number of seriously injured occupants (MAIS3+) was 256. The results indicate that Delta-V of 56 km/h covers 90% of the cases and the cumulative percentage of Delta-V less than 45 km/h was 75%.

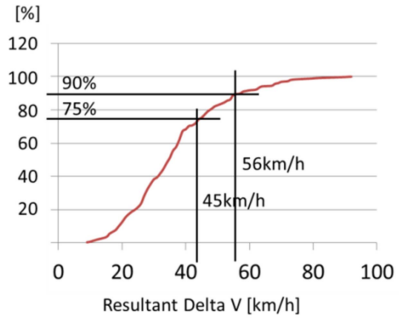

Figure 4. Cumulative distribution of Delta-V

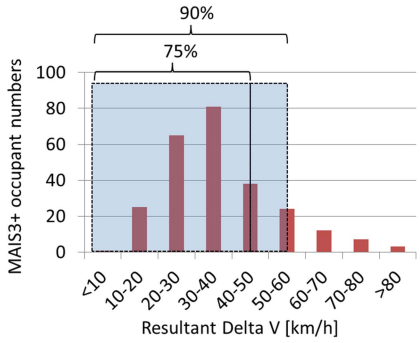

Figure 5. Frequency distribution of Delta-V

Method of Detailed Accident Analysis

A more detailed accident analysis was then conducted using NASS-CDS data. The data sets were the same as those used in [1]. Table 2 shows the extraction conditions of this accident analysis. These conditions were applicable to 19 out of 117 number of total occupants used in [1]. The accidents involving these 19 occupants were analyzed.

Table 2.
Summary of NASS-CDS data extraction conditions for detailed analysis

Data years	1998-2009
Vehicle model years	1998-2005
Deformation location	Left offset only
PDOF (Principal Direction of Force) [degrees]	320-350
Collision partner	Vehicle only
Rollover collisions and multiple crashes	Not involved
Occupants	Driver only
	Belted
	Not ejected
AIS	3+ injuries

Comparison between NHTSA test results and detailed accident analysis results

The results of the accident analysis were compared with the results obtained for 16 vehicles in oblique frontal impact tests (Table 3) in a study conducted by NHTSA. Figure 6 shows the configuration of the oblique frontal impact test, and Table 3 is the list of vehicles used. In this oblique frontal impact test, the dolly with barrier impacts the target vehicle at 56mph (90 km/h) and the angle of the stationary vehicle is 15 degrees and the overlap is 35 percent on the driver side of the vehicle. In this paper, an oblique offset impact in real-world accidents is referred to as an Accident Oblique Offset Impact (AOOI) and an oblique offset imapct in the NHTSA research test is referred to as an Oblique Offset Impact (OOI).

Table 3.
List of vehicles used in oblique frontal impact test conducted by NHTSA

Report No.	Name	Model Year	Test vehicle weight [kg]
7458	Smart For two	2011	1034
7441	Toyota Yaris	2011	1331
8086	Nissan Versa R	2013	1438
8084	Nissan Versa	2013	1451
8089	Hyundai Elantra	2013	1590
7431	Chevrolet Cruze	2011	1662
7428	Ford Fiesta	2011	1671
8085	Toyota Camry R	2012	1752
8096	Honda CRV	2012	1757
8088	Toyota Camry	2012	1759
7467	Buick Lacrosse	2011	1944
8087	Ford Taurus	2013	2123
8097	Honda Odyssey	2012	2210
7476	Ford Explorer	2011	2363
7457	Dodge Ram 1500	2011	2611
8099	Chevrolet Silverado	2012	2624

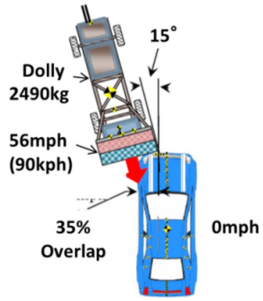

Figure 6. NHTSA offset oblique impact test

Delta-V Direction Figure 7 compares the results for the Delta-V direction, which is calculated with Eq. (I). Most of the Delta V-direction is within 10-20 degrees, and the average Delta-V direction of AOOI and OOI is almost the same.

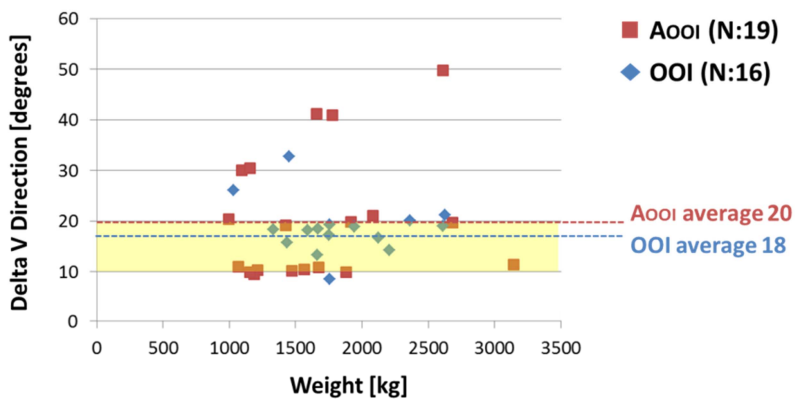

Figure 7. Relationship between Delta-V direction and vehicle weight

Delta-V Direction = Tangent (longitudinal Delta-V / Lateral Delta-V) *(I)*

Relationship between Delta-V and Vehicle Weight Figure 8 shows the relationship between the resultant Delta-V (longitudinal and lateral) and vehicle weight. In OOI, a strong correlation exists between the two. Delta-V of 41 km/h for the heaviest vehicle is the minimum velocity of all the Delta-V values; Delta-V of 67 km/h for the lightest vehicle is the maximum velocity and is approximately 1.6 times higher than that of the heaviest vehicle. On the other hand, weak correlation is observed between Delta-V and vehicle weight in AOOI. Delta-V in OOI is almost at the upper limit of Delta-V in AOOI.

Figure 9 shows the relationship between the resultant Delta-V and vehicle weight ratio. The vehicle weight ratio used in this study is explained here. The vehicle weight ratio in AOOI is found by dividing the weight of the impacted vehicle by the weight of the collision partner because the crash configuration is a car-to-car collision. In contrast, OOI is a research moving deformable barrier (RMDB)-into-stationary vehicle impact test. For this reason, the vehicle weight ratio cannot be calculated in the same way. For a better comparison between AOOI and OOI, as shown in Figure 10, the OOI test condition was translated into a car-to-car test at an initial velocity of 64 km/h and a vehicle weight of 1750 kg. The initial velocity and vehicle weight were derived using the law of conservation of momentum. The initial velocity was the same as in the offset deformable barrier (ODB) imapct test conducted by IIHS and EuroNCAP, and the vehicle weight was calculated with Eq. (II). For reference, the resultant Delta-V of the Toyota Camry R (1752 kg) and the Honda CRV (1757 kg), both of which weigh close to 1750 kg, was 52 km/h and 54 km/h, respectively. These values are similar to Delta-V of 56 km/h, having a cumulative composition ratio of

90% in Figure 4. The weight of the collision partner was 1750 kg, and the vehicle weight ratio was calculated by dividing the impacted vehicle weight by 1750 kg.

The results plotted in Figure 9 are almost the same as those in Figure 8. It is seen that the resultant Delta-V and vehicle weight ratio have a strong correlation in OOI but little correlation in AOOI.

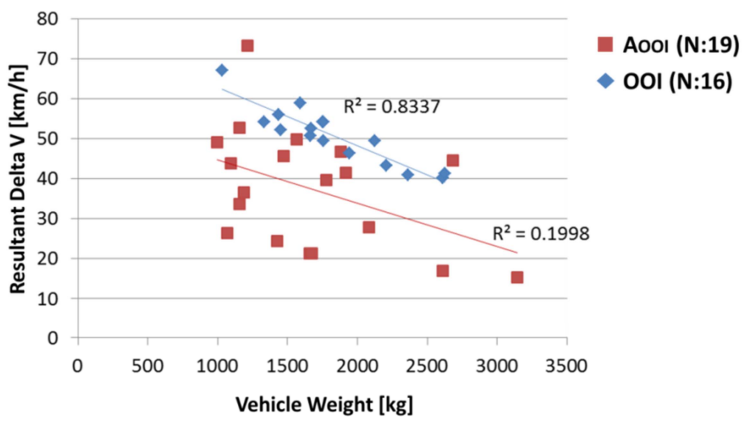

Figure 8. Relationship between resultant Delta-V and vehicle weight

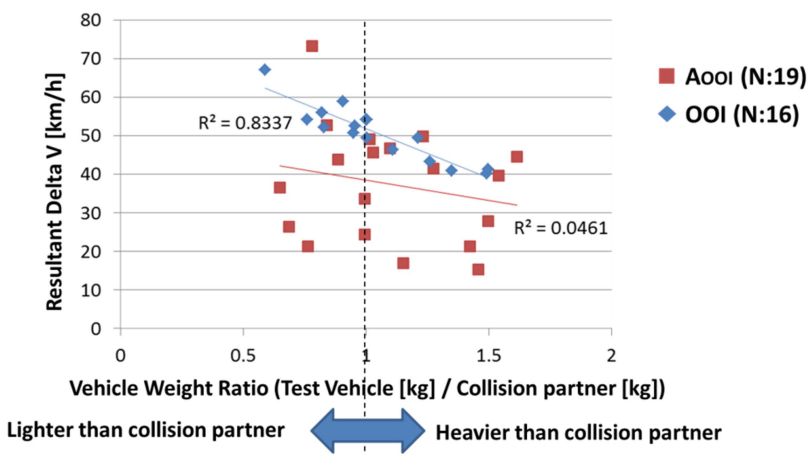

Figure 9. Relationship between resultant Delta-V and vehicle weight ratio

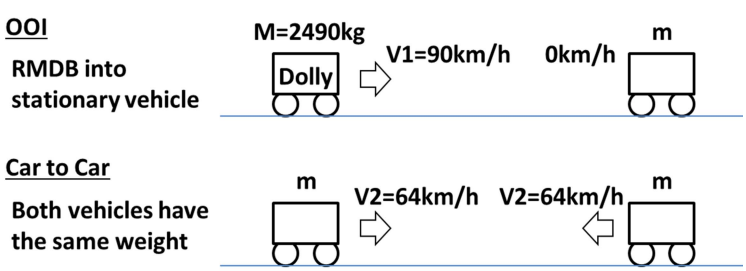

Figure 10. Translation method to equivalent car-to-car impact

$$2*m*V2 = M*V1 \qquad m=1750\ kg \qquad (II)$$

Injuries in AOOI Figure 11 shows the percentages of AIS3+ injuries by body region in AOOI. The most frequent type is knee, thigh, and hip (KTH) & lower leg (40%) injuries, followed by upper extremity (28%) and thorax (20%) injuries. Small percentages of injuries are seen for head (8%) and abdomen (2%).

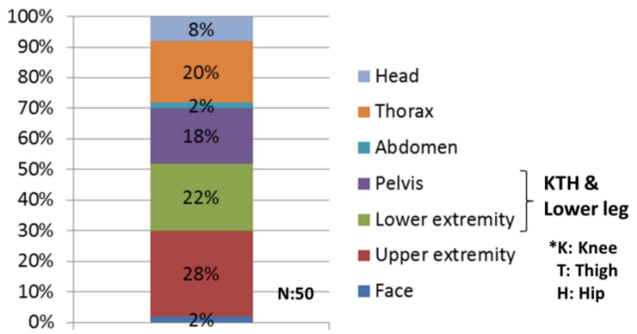

Figure 11. AIS3+ injury percentages by body region

Figures 12 and 13 show the details of AIS3+ head injuries and injury sources in AOOI. Number of injuries N:4 in Figure 12 is small and all of them involve brain damage. Injury sources are safety belt and left B-pillar.

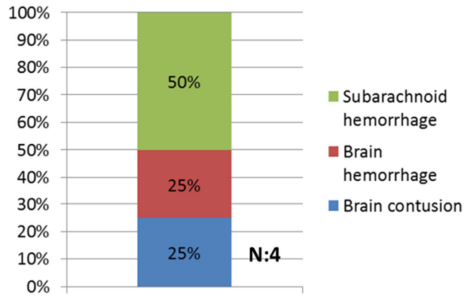

Figure 12. Details of AIS3+ head injuries

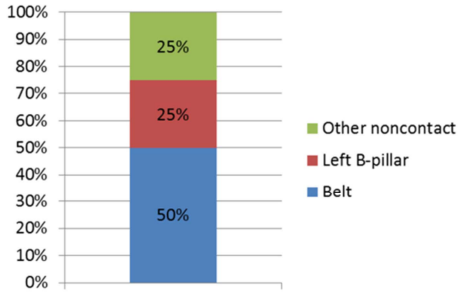

Figure 13. Sources of head injuries

Figures 14 and 15 show the details of AIS3+ thorax injuries and injury sources in AOOI. Thorax injuries comprise rib fracture, lung contusion, and thorax cavity damage. The main injury sources are left-side object and steering wheel.

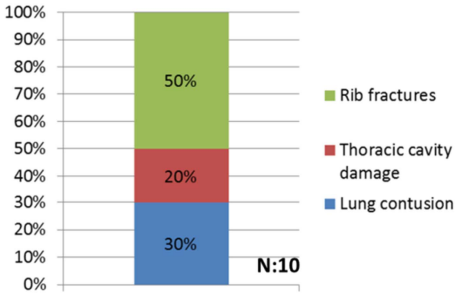

Figure 14. Details of AIS3+ thorax injuries

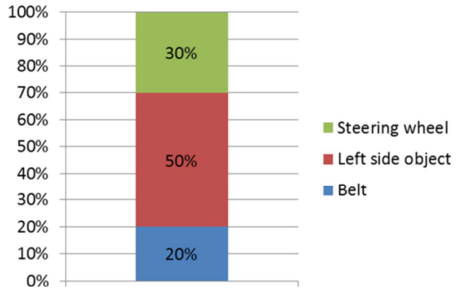

Figure 15. Sources of thorax injuries

Figures 16 and 17 show the details of AIS3+ KTH & lower leg injuries and injury sources in AOOI. All injuries are fractures, the most frequent of which are femur fractures, followed by acetabulum and tibia fractures. The main injury sources are the kneee bolster, the left-side object and the floor panel.

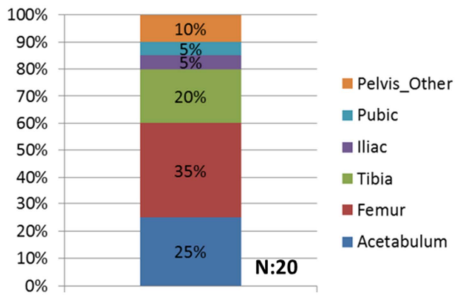

Figure 16. Details of AIS3+ KTH & lower leg injuries

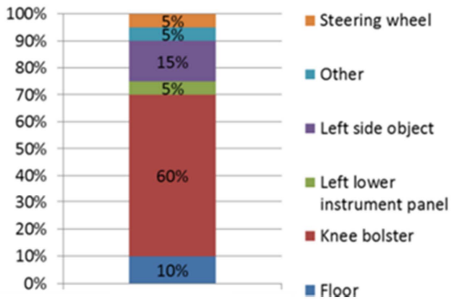

Figure 17. Sources of KTH & lower leg injuries

Figures 18 and 19 show the fracture points of AIS3+ KTH & lower leg injuries and injury sources for the femur, acetabulum and tibia in AOOI. Fracture occurs equally in both the right and left legs. Pelvis and upper leg fractures in particular occur frequently. Tibia fracture occurs in only the right leg. The injury sources for the acetabulum are the knee bolster, left lower instrument panel, and the steering wheel. The injury sources for the femur are the knee bolster and the left-side object, and for the tibia the knee bolster and the floor panel.

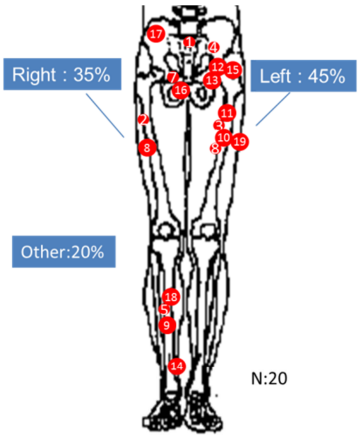

Figure 18. Fracture points of KTH & lower leg

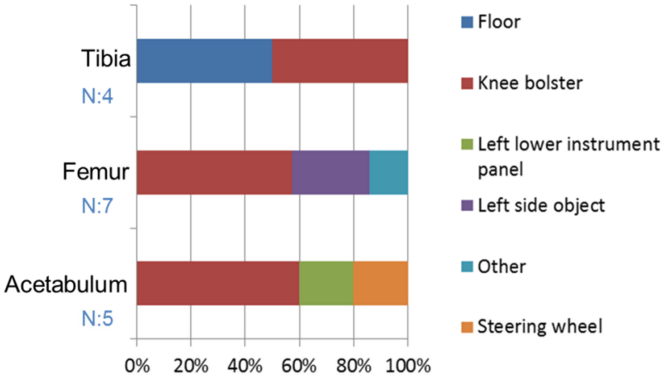

Figure 19. Sources of acetabulum, femur, and tibia injuries

<u>Comparison of injuries between AOOI and OOI</u> Figure 20 compares the percentages of serious injuries occurring in AOOI and OOI. In AOOI, AIS3+ injuries were treated as serious injuries, and the percentage of serious injuries was calculated in the following way: (a) at first, AIS3+ injury numbers of the driverside occupant were counted and (b) then it is diveded by the total number of injuries of the body region. For example, regarding the percentage of head serious injury, the percentage of serious injuries is 16% (3/19), where 3 was AIS 3+ and total numbers of injuries was 19. In OOI, the percentage of serious injuries was calculated in the following way: (a) at first, the injury numbers of the driverside dummy which exceeded the reference Injury Assessment Reference Value (IARV) were counted and (b) then it is diveded by the total number of injuries of the body region. For example, regarding the percentage of head serious injury, the percentage of serious injuries is 25% (4/16), where 4 exceeded IARV and total numbers of injuries was 16. It will be noted that the IARV of thorax injuries was not determined, so the upper deflection (53 mm) and lower deflection (46 mm) [2] were used as provisional values. The Brain Rotational Injury Criterion (BRIC) was also used as head injury value. As a result, the percentage of BRIC head injuries in OOI differed greatly from the percentage of AIS3+ head injuries in AOOI. As for KTH & lower leg injuries, the percentage of acetabulum and femur serious injuries differed between AOOI and OOI.

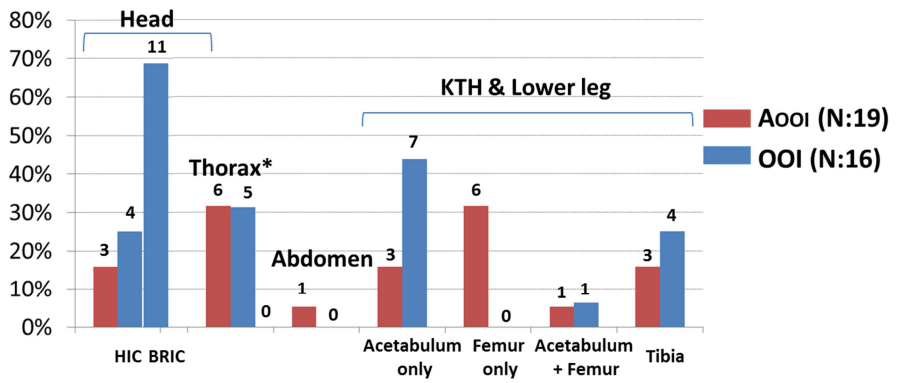

Figure 20. Comparison of serious injury percentages between AOOI and OOI

REPEATABILITY OF OBLIQUE TEST

Test Conditions

To examine the repeatability of the oblique offset impact test (OOI), a comparison was made for the vehicle deformation and G level in two tests conducted with the same vehicle. Table 4 shows the test conditons and vehicle specification for OOI. The vehicle used was a midsize sedan. The initial velocity and the test vehicle weight were almost the same in OOI#1 and OOI#2 tests. A 50th percentile male THOR-NT frontal impact test dummy was seated in the driver's seat. A Hybrid-III dummy was seated in the front passenger's seat. The THOR-NT dummy was a tentative version manufactured by GESAC and was different from the THOR dummies used in NHTSA's OOI research tests.

Table 4.
Test conditions and vehicle specification of OOI test

No.	Vehicle	Weight [kg]	Velocity [km/h]
OOI #1	V6 3.5L 2WD	1868	90.1
OOI #2		1870	90.4

Dummy	
Driver (Left)	THOR-NT (GESAC)
Passenger (Right)	Hybrid-III

Comparison results

Summary Figure 21 shows photographs of the post-test vehicles and barriers. The comparison did not show any significant difference for the vehicle and the barrier deformations between OOI#1 and OOI#2.

Figure 21. Photographs of the post-test vehicles and barriers

Difference in Vehicle Deformation Figures 22 and 23 compare the cabin deformation and floor deformation of the post-test vehicles, respectively. The cabin deformation around the front door opening was almost the same in OOI#1 and OOI#2; the maximum deformation point was the part of the door front near the lower A-Pillar, and the amount of deformation was 44 mm. On the other hand, floor deformation differed in the longitudinal and vertical directions. In the longitudinal direction, C2 and D2 showed large differences, with the maximum difference being 36 mm. In the vertical direction, B2, C2 and D2 showed large differences, with the maximum difference being 58 mm. Generally the vehicle deformation is greater in OOI#2 than in OOI#1.

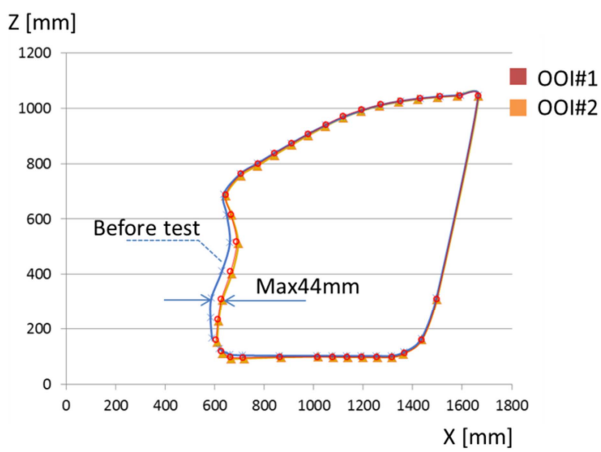

Figure 22. Comparison of cabin deformation

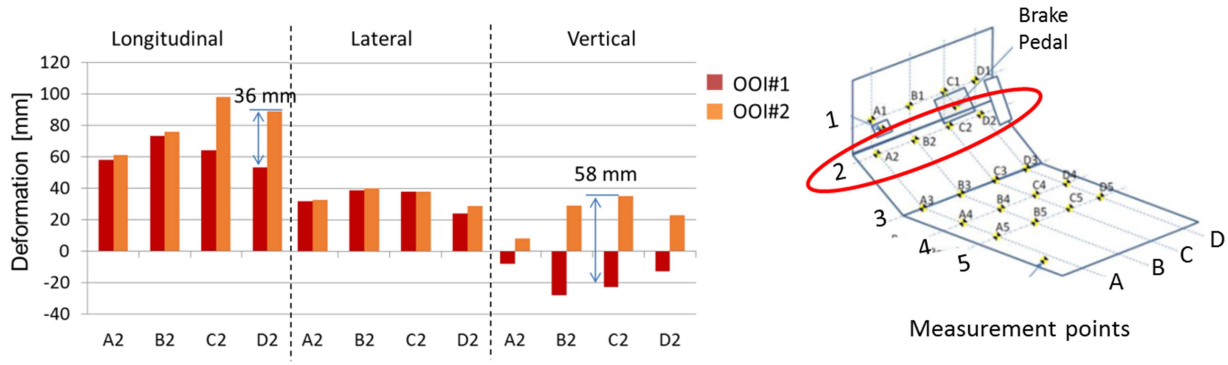

Figure 23. Comparison of floor deformation

The factors causing the difference in the floor deformation seen in Figure 23 were then examined. Figure 24 shows the deformation of Row 1 on the dash panel and mearument points 6, 7, 8 on the dash lower cross member. Figure 25 presents photographs of the post-test dash panels. The difference (52 mm) in the deformation at location 8 was especially large. In addition, as seen in Figure 25, the deformation mode of the dash panel near the dash lower cross member differed. In order to investigate the reason of these differences, the deformation of the front longitudinal member which is connected to the dash lower cross member in the engine compartment was then examined.

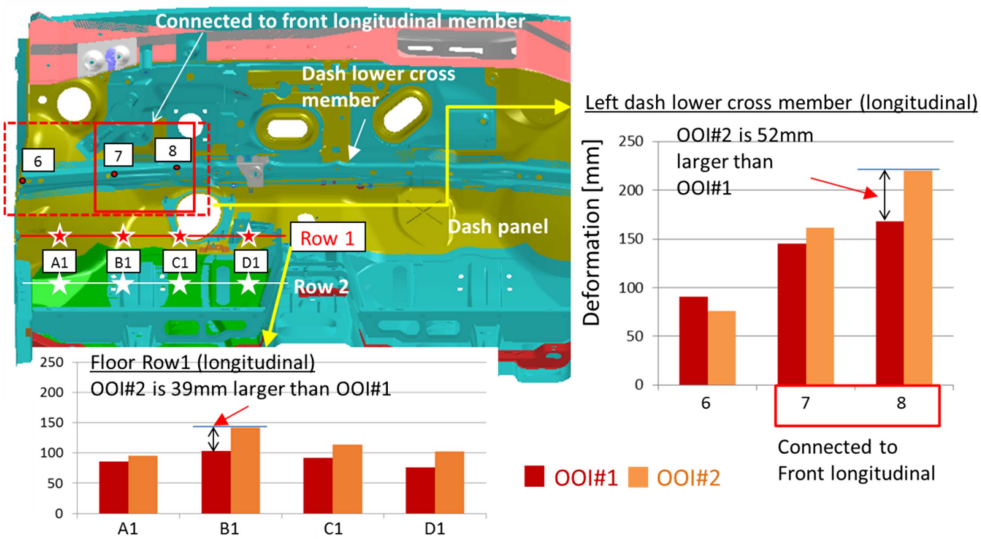

Figure 24. Comparison of dash panel and dash lower cross member deformation

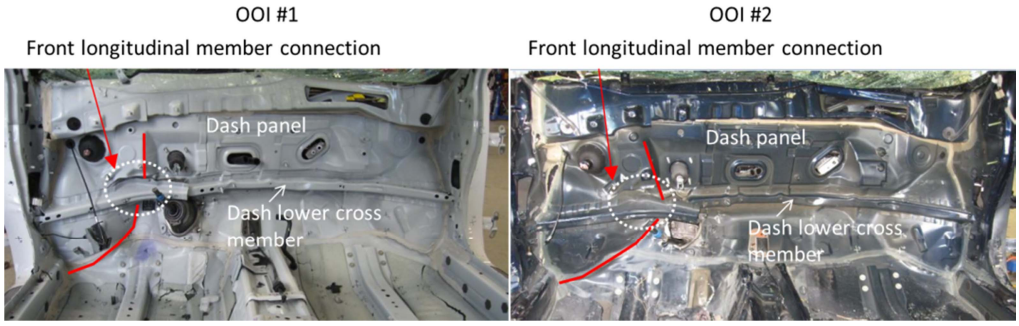

Figure 25. Photographs of dash panel deformation

Figures 26 and 27 show the measured deformation modes of the front longitudinal member. These results indicate that the deformation mode in OOI#1 differed from that in OOI#2 and that rearward displacement in OOI#2 was

larger than that in OOI#1. Two bending points occurred in the front longitudinal member and bumper reinforcement beam in OOI#1 and OOI#2, but the bending locations were different. The bending points in OOI#1 occurred only in the front longitudinal member, whereas in OOI#2, there were one bending point each on the front longitudinal member and the bumper reinforcement beam. Figures 28 and 29 show photographs of the post-test front longitudinal member and bumper reinforcement beam, respectively. It is seen in these photographs that the deformation mode and bending locations of the front longitudinal member and bumper reinforcement beam differed between the two tests.

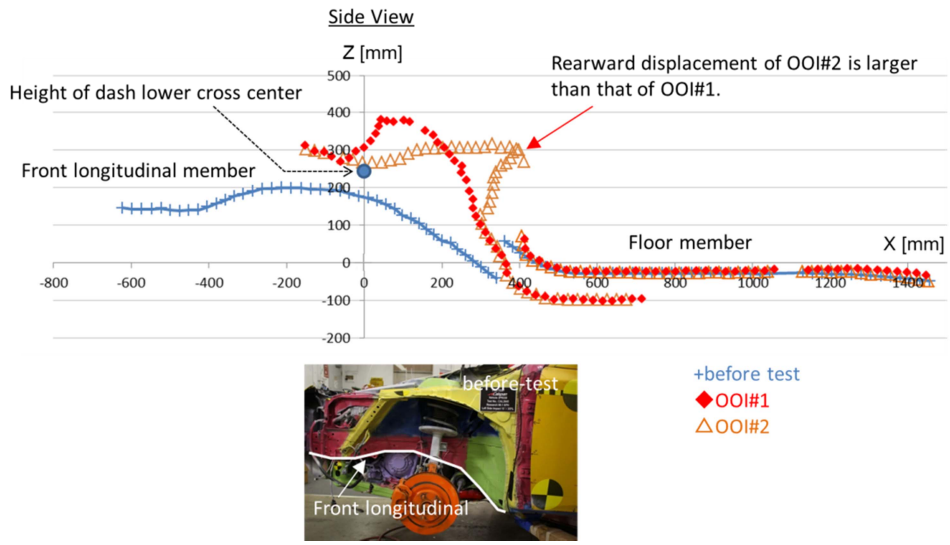

Figure 26. Comparison of front longitudinal member deformation (side view)

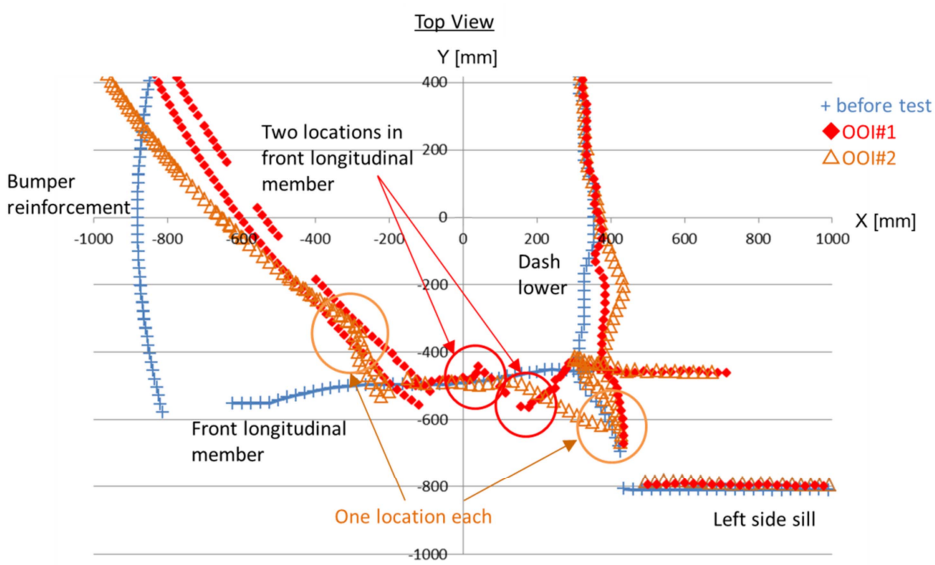

Figure 27. Comparison of front longitudinal member deformation (top view)

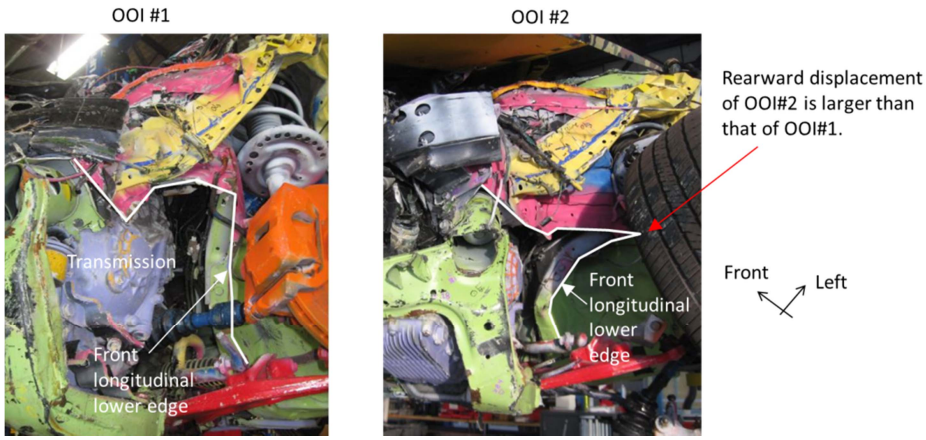

Figure 28. Photographs of front longitudinal member deformation

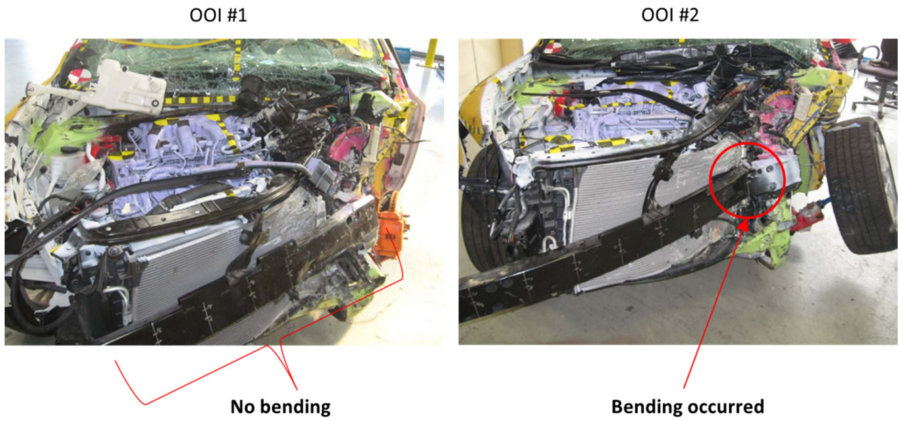

Figure 29. Photographs of bumper reinforcement beam deformation

The difference in floor deformation between OOI#1 and OOI#2 is presumed to be due to the following sequences. Initially, the deformation mode of the front longitudinal member differs, and larger rearward displacement occurs in OOI#2 than in OOI#1; then the dash lower cross member connected to the front longitudinal member undergoes large deformation toward the cabin side, this results in larger floor deformation in OOI#2 than in OOI#1. In a series of OOI research tests, NHTSA has conducted the repeatability evalluation using three same vehicles [4] (Figure 30). The variation of floor Row 1 deformation were at a similar level to the test results in this study as shown in Figure 24.

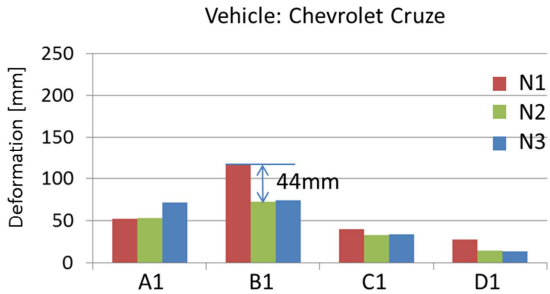

Figure 30. Result of floor deformation in NHTSA research test

<u>Difference in vehicle G and velocity</u> Figure 31 compares the vehicle deceleration (G) and Figure 32 compares the vehicle velocity. Deceleration was measured at the vehicle's center of gravity, and velocity was calculated by

integrating G. It is seen that the peak G values differed by a factor of 7G between the longitudinal direction and by a factor of 12G between the lateral direction. However the overall wave shapes and timing of the peaks were similar in both the longitudinal and lateral directions between OOI#1 and OOI#2. Longitudinal velocity differed by 2km/h, but lateral velocity was almost the same.

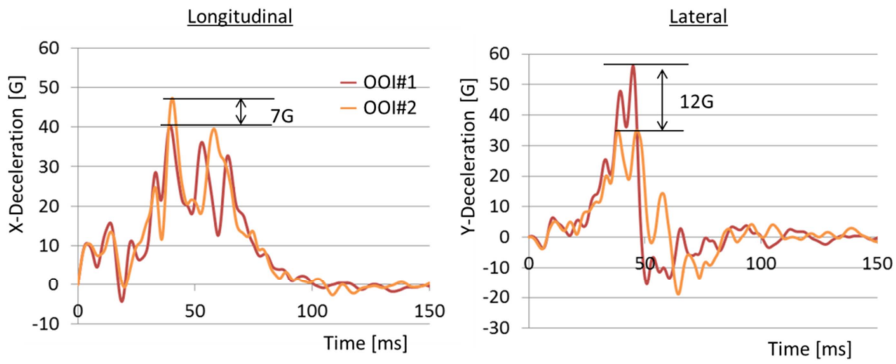

Figure 31. Comparison of vehicle deceleration

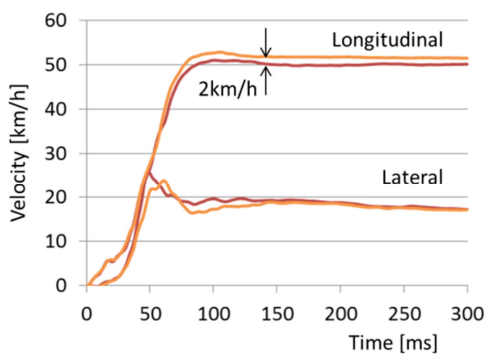

Figure 32. Comparison of vehicle velocity

DISCUSSION AND CONCLUSION

Real-world frontal impact accidents were classified into 9 crash configurations based on the method in the literature [7], [8]. The most frequent accident types are Full-engagement and Offset, followed by Small overlap accidents in that order. Small overlap and Offset accidents were then reclassified in terms of two directions: Offset-Oblique, Offset-Colinear and Small Overlap-Oblique, Small Overlap-Colinear and three collision partners: vehicle, pole, and other object. It was found that an Offset-Oblique-Vehicle accident similar to the offset oblique impact (OOI) test was the second most frequent crash configuration next to Full-engagement. However, this Offset-Oblique-Vehicle accident accounts for only approximately 10% of all frontal impact accidents. Regarding crash severity, in the AOOI, the resultant Delta-V of approximately 56 km/h covers a cumulative accident coverage of 90%. In the OOI tests, a strong correlation was seen between the resultant Delta-V and vehicle weight and the resultant Delta-V of lighter vehicles tended to be higher than 56 km/h. The lightest vehicle is higher than 64km/h in the offset deformable barrier (ODB) imapct test. Therefore it is thought that additional vehicle structural countermeasure for lighter vehicles to address the current OOI test procedure may produce stiffer vehicles and shorter crash pulses and in consequence negatively affect the safety of vulnerable elderly drivers. As for the representativeness of the percentages of serious injuries, a large difference was seen between the accident data and the test results, especially for head injuries (BRIC). Differences between the accident data and the test results were also seen for lower extremity injuries, especially accetabulum and femur injuries.

Regarding repeatability of the OOI test, vehicle deformation, G values, and velocity were compared by conducting two tests using the same midsize sedan. The results showed that G values and velocity did not show any notable difference. However, floor deformation differed due to a difference in the deformation mode of the front

longitudinal member, which was caused by a difference in the bending location of the member and the bumper reinforcement beam. This difference in floor deformation was similar to the difference reported in a couple of OOI reserach tests previously carried out by NHTSA. The amount of this difference in floor deformation may affect the details and dimensions of countermeasures. These results suggest that further studies are required to validate the introduction of the OOI as a new crash test procedure in regulatory testing or NCAP.

REFERENCES

[1] Rodney W. Rudd, Mark Scarboro, James Saunders, "Injury Analysis of Real-World Small Overlap and Oblique Frontal Crashes", 2011 ESV, Paper Number 11-0384.

[2] James Saunders, Matthew Craig and Daniel Parent, "Moving Deformable Barrier Test Procedure for Evaluating Small Overlap/Oblique Crashes", 2012 SAE, No 2012-01-0577.

[3] James Saunders and Dan Parent, "Assessment of an Oblique Moving Deformable Barrier Test Procedure", 2013 ESV, Paper Number 13-0402.

[4] James Saunders and Daniel Parent, "Repeatability of a Small Overlap and an Oblique Moving Deformable Barrier Test Procedure", 2013 SAE, No 2013-01-0762.

[5] James Saunders and Daniel Parent, "Repeatability of a Small Overlap and an Oblique Moving Deformable Barrier Test Procedure", 2013 SAE, No 2013-01-0762.

[6] Yasuhiro Dokko and Takahashi Hasegawa, "Evaluation of Thoracic Injury of the Occupants in Small Overlap/oblique Impact Using a Human FE Model", 2013 JSAE, No152-20135332.

[7] Erik G. Takhounts and Vikas Hasija, "An Operational Definition of Small Overlap Impact for Published NASS Data", 2013 STAPP, No 243-266.

[8] Kaye Sullivan, Scott Henry and Tony R. Laituri, "A Frontal Impact Taxonomy for USA Field Data", 2008 SAE, No 2008-01-0526.

[9] NHTSA, "NASS Analysis in Support of NHTSA's Frontal Small Overlap Program", 2011.

GLOSSARY

AOOI: Accident Oblique Offset Impact

OOI: Oblique Offset Impact

PDOF: Principal Direction of Force

IARV: Injury Assessment Reference Value

KTH: Knee Thigh Hip

BRIC: Brain Rotational Injury Criterion