

VEHICLE COLLISION FORCE IN OFFSET BARRIER AND CAR TO CAR OFFSET TESTS

Hirotoishi Ishikawa⁽¹⁾, Kennerly H. Digges⁽²⁾, Jason B. Ennis⁽²⁾

(1) Japan Automobile Research Institute

(2) National Crash Analysis Center, the George Washington University

ABSTRACT

This paper examines the location, magnitude and direction of crash forces acting on vehicles during frontal offset crashes. Both car-to-car and car to deformable barrier are examined.

A frame by frame analysis of crash test films permits the principal crash force vector to be positioned relative to the vehicle's plane of deformation and center of gravity. Tests with left side overlaps conducted in North America are analyzed. The resulting analysis shows that the vehicle rotates first clockwise and then counterclockwise. The change in rotation is caused by a reversal in the direction of the lateral crash force. The analysis shows subtle differences in the transverse and rotational forces when comparing car-to-car and car to deformable barrier offset tests. These differences may influence the forces on the lower leg and the rebound kinematics of the occupant.

CRASH TESTING IN THE FRONTAL OFFSET MODE has become of increasing interest in recent years. Crash tests into an offset barrier with a deformable face have served as a basis for consumer information tests in Australia (Griffiths, 1994) and the United States (O'Neil, 1994). This form of testing is also being considered as a basis for a regulation in Europe and Australia (Lowne, 1994).

The offset deformable barrier (ODB) test is intended to simulate a car-to-car frontal crash, with the cars offset. Recently, the National Highway Traffic Safety Administration (NHTSA) in the United States conducted a series of car-to-car offset tests to examine the safety performances in this crash mode (Hollowell, 1994). Six of these tests involved midsize cars equipped with air bags which were crash tested using a 1991 Honda Accord as the crash partner. The tests were at 112 km/h (70 mph) closing speed and a vehicle overlap of 60 %.

The Insurance Institute for Highway Safety (IIHS) has tested fourteen 1995 model midsize cars into a deformable offset barrier and reported the results (IIHS Status Report, 1995). The crash speed was 64 km/h and the overlap was 40 %. IIHS has also tested models of the Oldsmobile Siera in a large variety of crash modes. These crash modes include offset car-to-car and car to offset deformable barrier.

In this study, the body of test data from IIHS and NHTSA has been analyzed in order to compare the forces imposed on vehicles during the various offset crash modes. Vehicle acceleration was determined from on board vehicle accelerometers when available. However, the instrumentation on the vehicles varies from test to test. In order to develop comparative vehicle acceleration data, film analyses of selected crash tests were conducted. The time history of the vehicle center-of-gravity position in the longitudinal and lateral direction was determined and the resulting acceleration calculated. The acceleration time histories for car-to-car and car-to-deformable barrier offset crashes are examined in the sections to follow.

CAR-TO-CAR CRASH TESTS

The NHTSA car-to-car offset crashes included six tests at 60 % left side overlap and 112 km/h closing velocity. The six cars tested were: The Isuzu Stylus, Chevrolet Corsica, Dodge Dynasty, Saab 9000, Volvo 740, and Accord Station Wagon. The crash partner for each of these vehicles was the Honda Accord Sedan. Table 1 shows the weights and speeds for each vehicle crash tested.

Film analysis of the motion of each vehicle was conducted, using about 5 ms time intervals. From the analysis, longitudinal and lateral accelerations were determined for the vehicle center of gravity. The longitudinal and lateral accelerations for the twelve vehicles in Table 1 are shown in Fig. 1.

The longitudinal (x-axis) acceleration trace has similar characteristics in all twelve cars. The peak acceleration ranges from 250 to 300 m/s² and it occurs at 0.05 to 0.07 sec. The pulse duration is about 0.15 sec. The peak lateral (y-axis) acceleration occurs at about the same time as the longitudinal acceleration, and ranges from 125 to 200 m/s². During this time period the acceleration produces a force to the right. The lateral acceleration reverses direction at around 0.075 sec, and produces a force to the left which peaks at around 0.08 to 0.12 sec. The peak force to the left (positive direction of y-axis) is about 50 % of the force to the right.

Table 1 - NHTSA car-to-car offset crashes

Test No.	Overlap (%)	Vehicle	Mass (kg)	Velocity m/s (km/h)
1544	60	Stylus	1207	16.2 (58.3)
		Accord	1365	16.2 (58.3)
1666	60	Corsica	1283	16.2 (58.3)
		Accord	1370	16.2 (58.3)
1678	60	Dynasty	1442	15.7 (56.5)
		Accord	1370	15.7 (56.5)
1704	60	Saab 9000	1456	16.1 (58.0)
		Accord	1370	16.1 (58.0)
1618	60	Volvo 740	1488	16.2 (58.3)
		Accord	1370	16.2 (58.3)
1676	60	Accord STW	1510	15.6 (56.2)
		Accord	1370	15.6 (56.2)

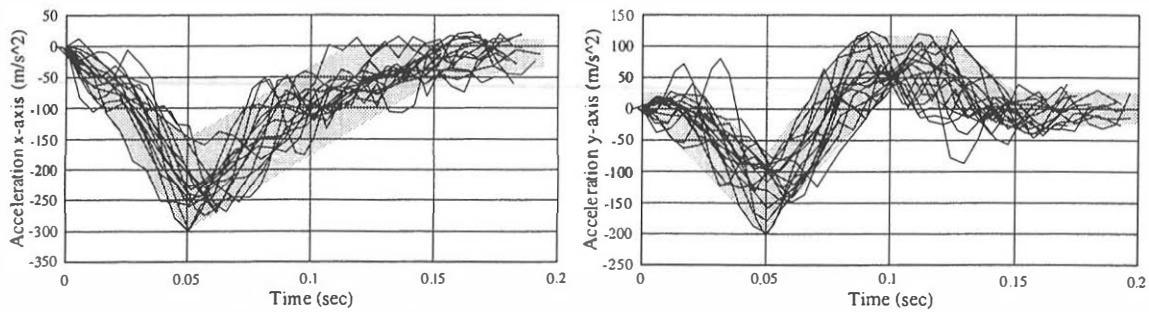


Fig. 1 - Longitudinal and lateral accelerations in NHTSA 60 % overlap car-to-car tests at 112 km/h closing speed (7 models, 12 cars)

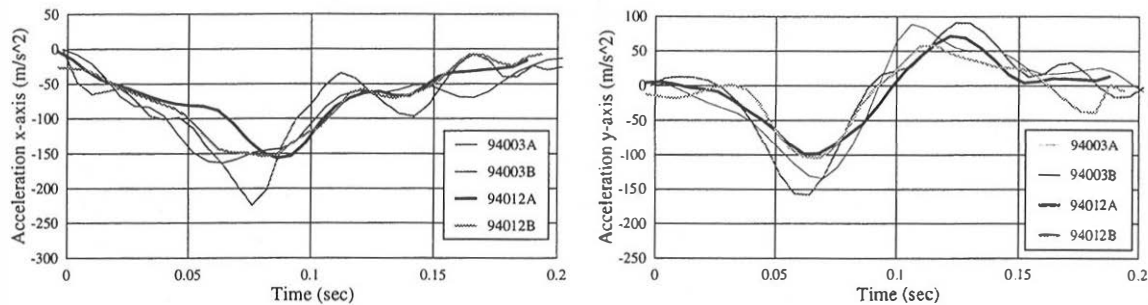


Fig. 2 - Longitudinal and lateral accelerations in IIHS 50 % overlap car-to-car tests at 112 km/h and 128 km/h closing speed (Oldsmobile Ciera , 4 cars)

The IIHS car-to-car offset crashes included two tests at 50 % left side overlap and 112 km/h and 128 km/h closing velocities. The two tests were both Oldsmobile Siera vs. Oldsmobile Siera. Table 2 shows the weights and speeds for each vehicle crash tested.

Longitudinal and lateral accelerations for the four vehicles in Table 2 are shown in Fig. 2. Vehicle accelerations from accelerometers were available in the IIHS data. However, some noise signals were found in the data, and so only the film data are used in Fig. 2.

The longitudinal (x-axis) and lateral (y-axis) accelerations of the IIHS data are similar to those of the NHTSA results. However, the peak accelerations tend to be smaller and occur later, compared to the NHTSA 60 % overlap crashes. The peak longitudinal acceleration ranges from 150 to 200 m/s² and occurs at 0.06 to 0.09 sec. The pulse duration is about 0.2 sec. The longitudinal peak acceleration is about 40 % lower and its time 0.02 sec later than in the NHTSA 60 % overlap car-to-car tests. The peak lateral acceleration occurs at around 0.07 sec. This is about the same time as the peak for the longitudinal acceleration. The lateral acceleration ranges from 100 to 150 m/s², about the same peak values as the NHTSA test data. The lateral acceleration reversal occurs at around 0.09 sec.

Table 2 - IIHS car-to-car offset crashes

Test No.	Overlap (%)	Vehicle	Mass (kg)	Velocity m/s (km/h)
94003	50	1988 Oldsmobile Ciera	1349	17.8 (64)
		1989 Oldsmobile Ciera	1350	17.8 (64)
94012	50	1986 Oldsmobile Ciera	1342	15.6 (56)
		1986 Oldsmobile Ciera	1395	15.6 (56)

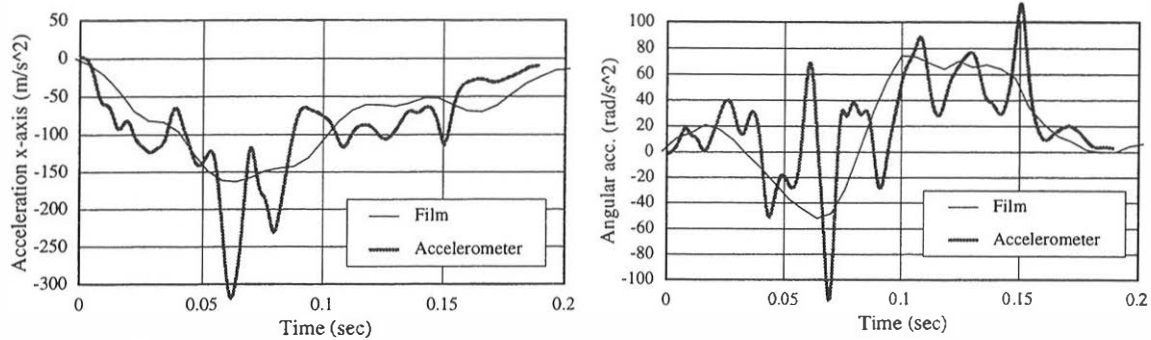


Fig. 3 - Longitudinal and angular accelerations calculated from film data and from accelerometers (94003A)

The peak lateral acceleration to the left is about half the magnitude of the acceleration to the right. The left acceleration peak occurs at around 0.12 sec.

As shown in Figs. 1 and 2, the longitudinal and lateral accelerations in the IIHS 50 % overlap car-to-car crashes are generally comparable to the NHTSA 60 % overlap crashes, although the test vehicle and overlap ratios were different.

Linear and angular accelerations, velocities and displacements calculated from film data and from accelerometers (filter class CFC 60 Hz) were compared to validate the film analysis. The accuracy of the film analysis in calculating linear and angular accelerations is considered to be acceptable, as shown in Fig. 3.

OFFSET DEFORMABLE BARRIER (ODB) TESTS

The IIHS has conducted an extensive series of ODB crashes in 40% left front overlap configuration. Table 3 lists fifteen different cars tested at 64 km/h and three similar cars tested at 60 km/h.

Figure 4-(1) shows the longitudinal and lateral accelerations for Oldsmobile Siera tested at 60 km/h and 64 km/h into a deformable offset barrier. The longitudinal acceleration trace, taken from film analysis, has similar characteristics for all four cars. The peak acceleration is about 200 m/s² and occurs at around 0.1 sec. The longitudinal peak acceleration is about the same in magnitude and about 0.05 sec later compared to the IIHS car-to-car tests shown in Fig. 2. The pulse duration is about 0.2 sec, similar to the car-to-car tests. The peak lateral acceleration occurs at 0.06 to 0.9 sec, about 0.01 to 0.04 sec earlier than the peak longitudinal acceleration. The ranges are from 50 to 100 m/s², about 50 % lower than the IIHS car-to-car tests. During this period the acceleration produces a force to the right. The lateral accelerations reverse direction at around 0.12 sec and produce a force to the left which peaks at around 0.15 sec. The peak force to the left (positive direction of y-axis) is about 30 to 50 % of the force to the right. The reversal of the lateral acceleration is moderate in the Oldsmobile Siera ODB crashes at 60 km/h and 64 km/h.

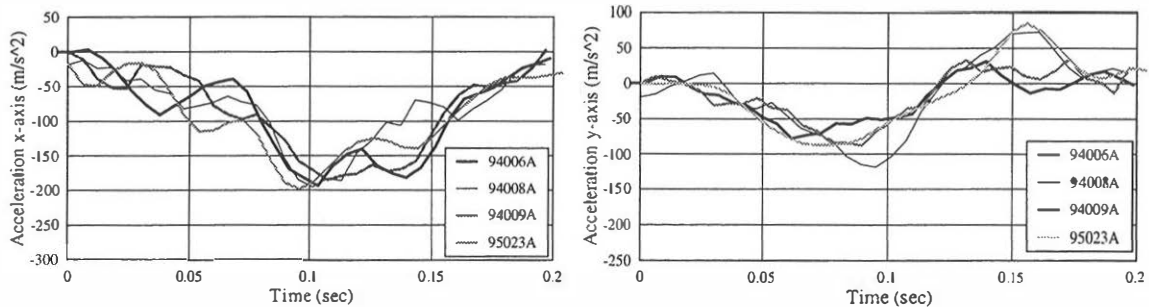
Figure 4-(2) shows the longitudinal and lateral accelerations for fourteen 1995 year models tested at 64 km/h into a deformable offset barrier. Their average longitudinal and lateral accelerations are also indicated. The accelerations of the

Table 3 - IIHS ODB (EEVC barrier) crashes

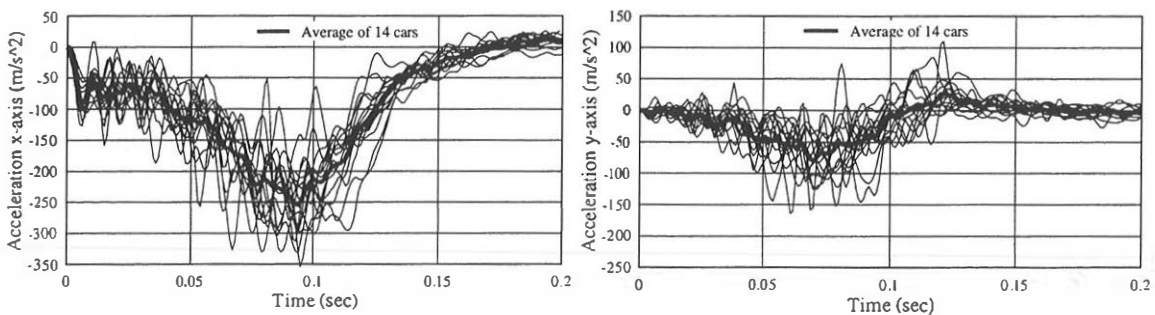
Test No.	Overlap (%)	Vehicle	Mass (kg)	Velocity m/s (km/h)
94006	40	1986 Oldsmobile Ciera	1386	16.7 (60)
94008 *1	40	1986 Oldsmobile Ciera	1409	16.7 (60)
94009 *2	40	1986 Oldsmobile Ciera	1387	16.7 (60)
95023	40	Oldsmobile Ciera	1428	17.9 (64)
95004	40	1995 Subaru Legacy	1380	17.9 (64)
95005	40	1995 Volvo 850	1565	17.9 (64)
95006	40	1995 Mazda Millenia	1593	17.9 (64)
95007	40	1995 Toyota Camry	1511	17.9 (64)
95008	40	1995 Mitsubishi Galant	1459	17.9 (64)
95009	40	1995 Honda Accord	1452	17.9 (64)
95010	40	1995 Ford Contour	1431	17.9 (64)
95011	40	1995 Chevrolet Lumina	1645	17.9 (64)
95012	40	1995 Nissan Maxima	1507	17.9 (64)
95013	40	1995 Ford Taurus	1565	17.9 (64)
95014	40	1995 Chevrolet Cavalier	1362	17.9 (64)
95015	40	1995 Chrysler Cirrus	1553	17.9 (64)
95016	40	1995 Volkswagen Passat	1557	17.9 (64)
95017	40	1995 Saab 900	1489	17.9 (64)

*1: Single-stage barrier

*2: Two-stage barrier



(1) Oldsmobile Ciera (3 cars at 60 km/h, 1 car at 64 km/h)



(2) 1995 year models (14 cars at 64 km/h)

Fig. 4 - Longitudinal (x) and lateral (y) accelerations in IIHS ODB tests

IIHS ODB crashes at 64 km/h are similar to those at 60 km/h. The peak longitudinal acceleration ranges from 200 to 350 m/s² and occurs at around 0.1 sec. The peak longitudinal acceleration is similar and 0.05 sec later than in the NHTSA car-to-car tests. The pulse duration is about 0.18 sec, 0.03 sec longer than in the NHTSA car-to-car tests. The peak lateral acceleration occurs at around 0.07 sec, about 0.03 sec earlier than the peak longitudinal acceleration, and ranges from 50 to 150 m/s², about 50 % lower than the in NHTSA car-to-car tests.

FORCE ANALYSIS OF CAR-TO-CAR TESTS

Detailed force analyses have been conducted for specific car-to-car tests. The tests selected are the Oldsmobile Ciera to Oldsmobile Ciera offset crashes conducted by the IIHS. The closing speeds are 112 km/h and 128 km/h, and the overlap is 50 %.

Figure 5 shows the time history of the normal and tangential impact forces at the contact surface. Impact forces were calculated by multiplying the C.G. acceleration by the vehicle mass. From the film analysis, contact surfaces were determined and calculated to be inclined 40 degrees relative to the vehicle front end during the collision. Tire forces were assumed to be negligible during the collision. The crash pulse in the normal direction peaks at around 0.07 sec with a value of 200 to 300 kN, and the duration is around 0.12 sec. The tangential crash pulse keeps lower than about 50 kN for the first 0.07 sec and then maximizes at around 0.1 to 0.13 sec with a value of about 150 kN. The tangential crash pulse duration is around 0.2 sec.

As shown in Fig. 2, the longitudinal and lateral accelerations both peak at around 0.07 sec and the peak lateral acceleration to the right is close in magnitude and time phase to the peak longitudinal acceleration. These phenomena can be explained by considering the time histories of the normal and tangential impact forces at the contact surface. That is, the peak values of the longitudinal and lateral accelerations at around 0.07 sec are caused mainly by the normal interaction force at the contact surface. The lateral acceleration reversal and the second peak at around 0.12 sec are due to the tangential interaction force.

Figure 6 shows the angular acceleration and displacement in the 50 % overlap Oldsmobile Ciera to Oldsmobile Ciera offset crashes. The first peak of the angular acceleration is about - 50 rad/s² (clockwise) occurring at around 0.06 sec, approximately when the normal impact force maximizes. The second peak of the angular acceleration is about 80 rad/s² (counterclockwise) at around 0.12 sec, comparable to when the tangential impact force maximizes. As a result, the vehicle rotates first clockwise and then counterclockwise.

In order to gain insight into the crash forces on vehicles during offset tests, a force vector analysis was conducted from the film analysis. A typical result is shown in Figs. 7 and 8. Figure 7 shows the vehicle contact at 0.05 sec. The resultant crash force vector acts at the center of the segment of damage. Both vehicles are in contact along the segment of damage. At this time instant, the lateral force acts to the right and the resultant force vector produces a clockwise

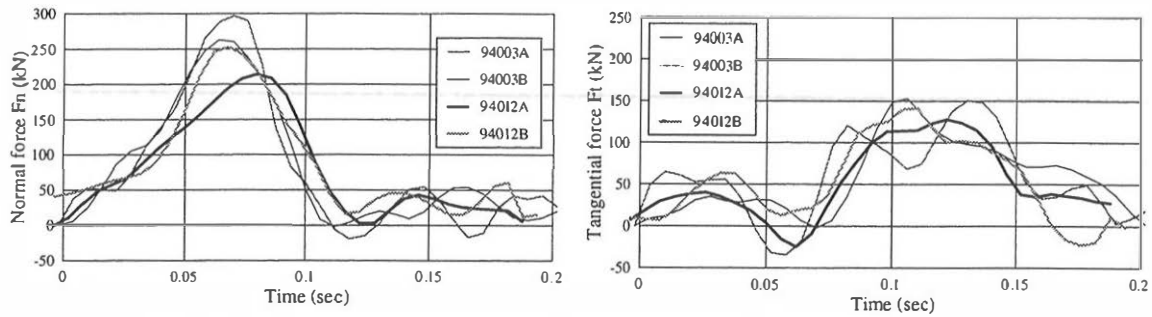


Fig.5 - Normal and tangential forces at the contact surface in 50 % overlap car-to-car test

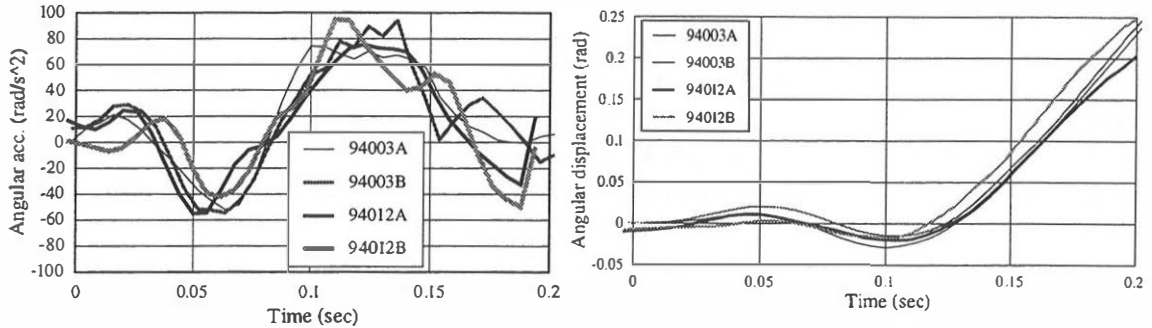


Fig. 6 - Angular acceleration and displacement in 50 % overlap car-to-car test

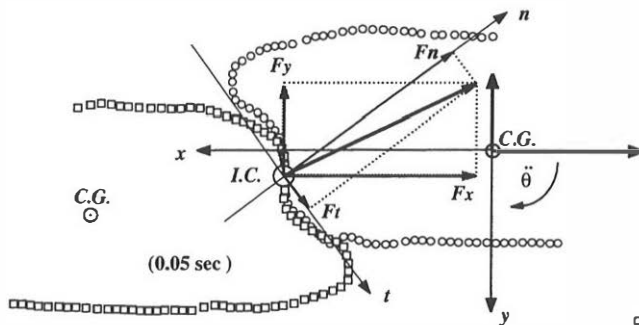


Fig.7 - Force vector at 0.05 seconds

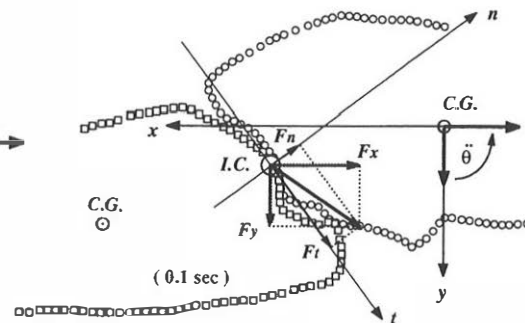


Fig.8 - Force vector at 0.1 seconds

rotation of the vehicle. Figure 8 shows the vehicle contact at 0.1 sec. At this time instant, the longitudinal force is less than half its peak value and the lateral force has reversed direction. The resultant force vector acts to rotate the vehicle counterclockwise. The change in rotation is caused by a reversal in the direction of the lateral crash force.

The vehicle rotation in the NHTSA 60 % car-to-car crashes was similar to the IIHS 50 % car-to-car crashes. However, the clockwise rotation in the NHTSA data was significant when compared to the IIHS 50 % car-to-car crashes.

FORCE ANALYSIS OF ODB TESTS

Crash tests of the Oldsmobile Ciera into a deformable barrier were selected for detailed force analysis. The tests, conducted by IIHS, were at 40 % overlap

into a deformable barrier at 60 km/h and 64 km/h.

Figure 9 shows the time histories of the normal and tangential impact forces at the contact surface. Calculations on impact force and contact surface were done using the film analysis as previously described. The crash pulse in the normal direction peaks at around 0.1 sec, with a value of 200 to 300 kN, and the duration is around 0.2 sec. Comparing this result with the car-to-car tests indicates that the peak normal force is similar and occurs much later (0.1 sec vs 0.06 sec). The tangential crash pulse keeps lower than 50 kN for the first 0.08 sec and maximizes at around 0.14 sec with a value of about 200 kN, which is almost comparable to the car-to-car result.

Figure 10 shows the angular acceleration and displacement in the 40 % ODB test. The first peak of the angular acceleration is about -30 rad/s² (clockwise) occurring at around 0.07 sec, about 0.03 sec earlier than the peak time of the normal impact force. The second peak of the angular acceleration is about 60 to 80 rad/s² (counterclockwise) at around 0.13 to 0.15 sec, about the same time as the tangential impact force maximizes. The clockwise angular acceleration develops from 0.05 sec and continues for about 0.03 to 0.05 sec, with a peak value of about 30 rad/s², which about 50 % of the peak in the car-to-car crashes shown in Fig. 6. The vehicle clockwise rotation in the ODB tests is less than in the car-to-car tests.

COMPARISON OF CAR-TO-CAR AND ODB CRASHES

Figure 11 shows force vectors in car-to-car and ODB tests from 0 to 0.2 sec,

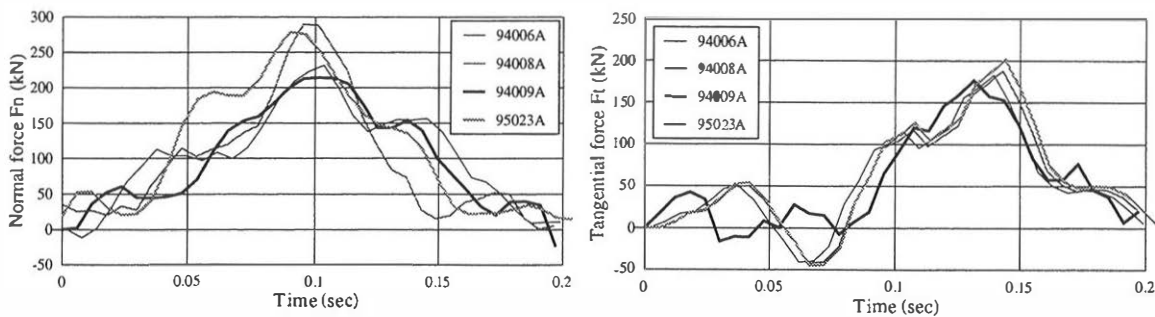


Fig. 9 - Normal and tangential forces at the contact surface in 40 % overlap ODB test

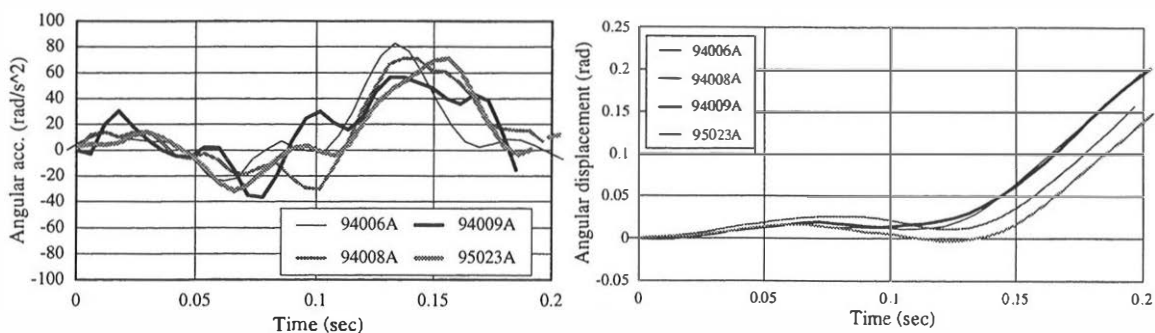


Fig. 10 - Angular acceleration and displacement in 40 % overlap ODB test

in which longitudinal and lateral forces are plotted sequentially at about 5 ms time intervals.

The force vector of the car-to-car test initially acts to propel the vehicle 30 to 40 degrees to the right and rearward relative to the vehicle center line. The force maximum is at 0.064 sec. At this time, the lateral crash force reverses its direction and the longitudinal crash force decreases, causing the force vector to sweep to the left. During this period of 0.064 to 0.106 sec, the magnitude of the crash force vector retains more than 50 % of its peak value. After 0.106 sec the vector is inclined at approximately 45 degrees to the left rearward.

The force vector of the ODB test initially acts to the right and rearward relative to the vehicle center line. It maximizes at 0.104 sec. The peak force vector, with a similar magnitude, occurs much later (0.104 sec vs. 0.064 sec) and inclines with a much smaller angle (13 degrees vs. 40 degrees) relative to the vehicle center line compared to the car-to-car test. After contributing to a peak force vector at 0.104 sec, the lateral crash force reverses its direction for a short time.

The force vectors obtained from the car-to-car and ODB tests show subtle differences in their direction and time phase.

Figure 12 shows the lower tibia peak axial force and its time in the NHTSA 60 % overlap car-to-car and IIHS 1995 40 % overlap ODB tests. The peak axial force of the lower tibia tends to be higher in the right leg than in the left leg, especially in the car-to-car crashes. Additionally, the peak axial force of the right lower tibia is higher in the NHTSA car-to-car tests than in the IIHS ODB tests. The time of the peak axial force both in the right and left lower tibias is around 0.05 sec in the NHTSA car-to-car tests, whereas in the IIHS ODB tests it is around 0.08 sec in many cases. It should be noted that, in case of the NHTSA car-to-car tests, the peak time of the axial force almost coincides with the peak time of the vehicle longitudinal and lateral accelerations. However, in the ODB tests the lower tibia

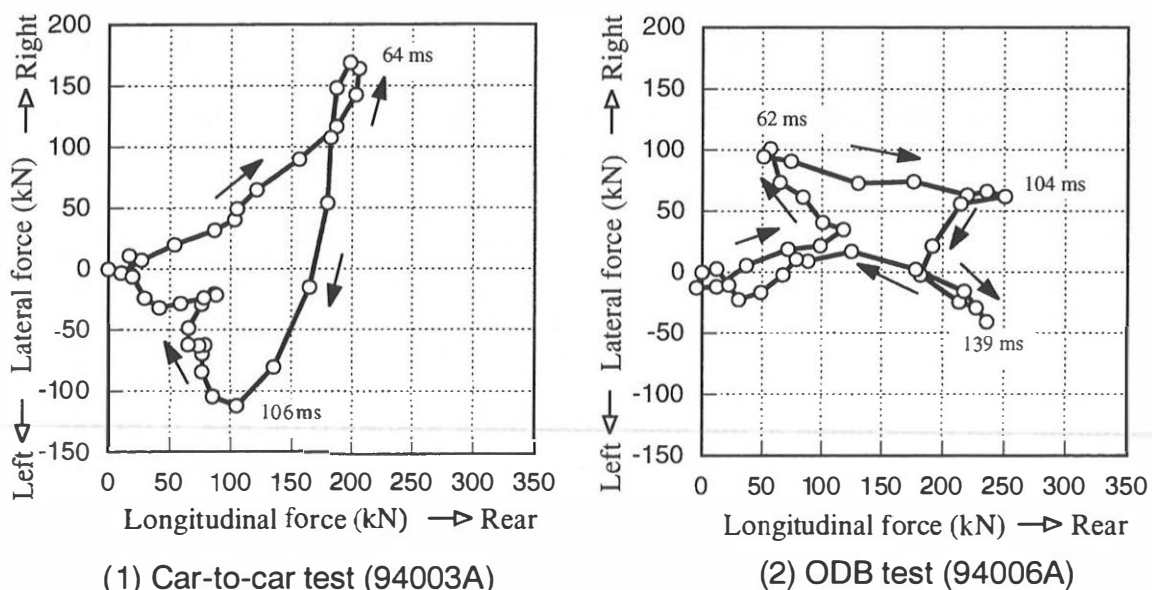


Fig. 11 - Comparison of force vectors between car-to-car and ODB tests

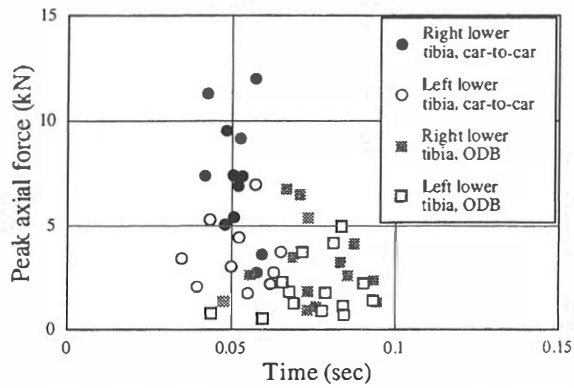


Fig. 12 - Peak axial force and its time of lower tibia in the NHTSA 60 % overlap car-to-car and IIHS 40 % overlap ODB tests.

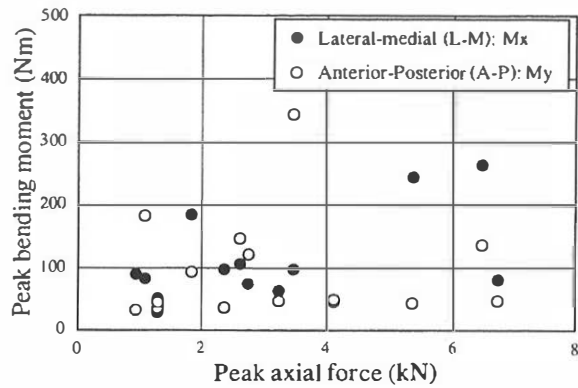


Fig. 13 - Relationship between peak axial force and L-M and A-P bending moments of right lower tibia in 40 % overlap ODB tests.

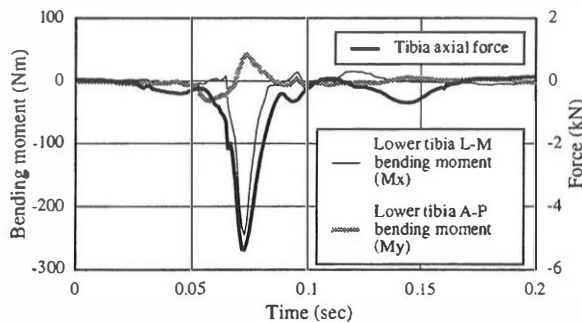


Fig. 14 - Axial force and L-M and A-P bending moments of right lower tibia in 40 % overlap ODB test.

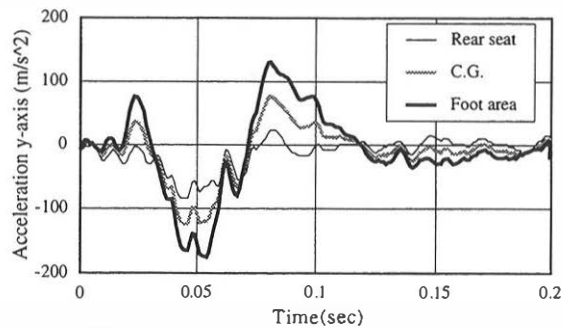


Fig. 15 - Typical lateral accelerations in rear seat, C.G. and foot area in 60 % overlap car-to-car test.

axial force maximizes at around 0.08 sec, near the peak time of the vehicle lateral acceleration, and 0.02 sec earlier than the peak time of the vehicle longitudinal acceleration.

Figure 13 shows the relationship between the peak axial force and peak lateral-medial (L-M) and anterior-posterior (A-P) bending moments of the right lower tibia in the IIHS 1995 40 % overlap ODB tests. There seems to be no correlation between the peak axial force and the peak L-M and A-P bending moments at the right lower tibia.

Figure 14 shows the time histories of the axial force and lateral-medial (L-M) and anterior-posterior (A-P) bending moments of the right lower tibia in a IIHS 1995 ODB test. In almost all cases, the lower tibia axial force and L-M and A-P bending moments maximized simultaneously. The only exceptions in the 14 tests were 2 cases with the right leg and 5 cases with the left leg. In 5 cases of the 7 exceptions, the peak times of the axial force were around 0.05 sec, 0.03 sec earlier compared to the typical cases. It should be noted that these peak times tend to coincide with the peak time of the vehicle lateral acceleration, rather than the peak time of the longitudinal acceleration.

Figure 15 shows the time histories of the lateral accelerations in the rear seat, C.G. and foot area in a NHTSA 60 % overlap car-to-car test. Vehicle accelerations in different locations are calculated by compensating the angular

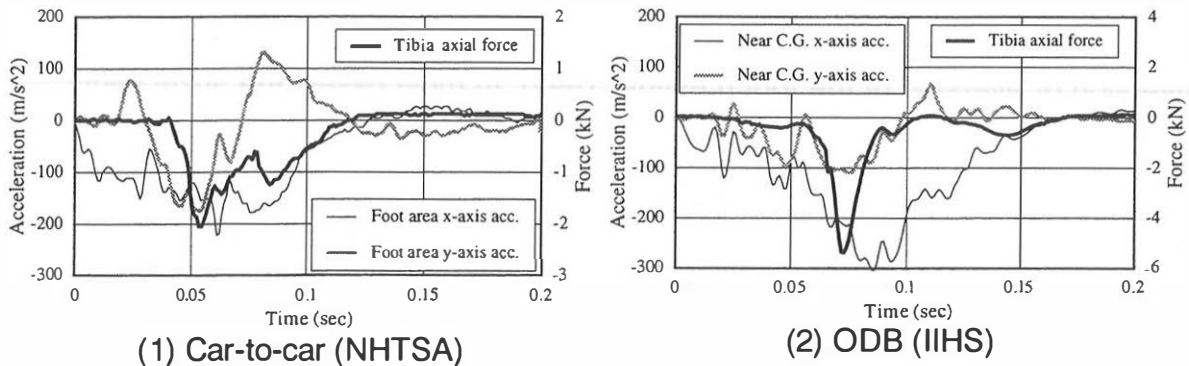


Fig. 16 - Vehicle longitudinal and lateral accelerations and tibia axial force in NHTSA 60 % overlap car-to-car and IIHS 40 % overlap ODB tests

acceleration and the positions. The lateral whiplash accelerations are observed both in car-to-car and ODB tests, but are less significant in the ODB tests. Note that the lateral whiplash acceleration is more significant in front seat foot area than in rear seat area where the vehicle crash test accelerometers are located.

Figure 16 shows the typical time histories of the vehicle longitudinal and lateral accelerations and the right lower tibia axial force in the NHTSA car-to-car and IIHS ODB tests.

In the NHTSA 60 % overlap car-to-car crash, the lower tibia axial force maximizes at around 0.05 sec and then retains 50 % of its peak value for about 0.03 sec. The longitudinal and lateral accelerations in the foot area also maximize at around 0.05 sec. During the period of 0.05 to 0.08 sec, the foot area longitudinal acceleration remains at a high level and the foot area lateral acceleration develops two peaks in opposite directions.

In the IIHS 1995 40 % overlap ODB tests, the lower tibia axial force and the vehicle lateral acceleration maximize at around 0.07 sec simultaneously, then the vehicle near C.G. longitudinal acceleration peaks at around 0.09 sec. Comparing this result to the car-to-car crash indicates that the lateral inertia force activated at the foot-ankle region is less significant in the ODB tests compared to the car-to-car crashes.

DISCUSSION

Examination of the lower tibia axial force data from the car-to-car tests indicates that the peak force coincides in time with the peak lateral and longitudinal vehicle accelerations. During the 0.03 sec period of high axial tibia loading, the lateral acceleration reverses direction, causing whiplash like forces. The ODB test data indicates that the timing of the tibia loading period is different from the car-to-car tests. The opportunity for ankle whiplash loading may be reduced by the shorter loading period, the later onset of loading, and the reduced lateral acceleration exhibited in the ODB tests.

A recent report on lower limb injuries in frontal collision indicates that 30 % of the injuries occurred in the absence of intrusion (Thomas, 1995). Earlier research

in the United States found that a high fraction of ankle injuries were induced by inversion or eversion of the foot (Lestina, 1992). In most cases, the ankle bents laterally rather than in the direction expected under pure longitudinal loading through the brake pedal or toe pan. These results suggest that multidirectional inertia forces, including the lateral whiplash acceleration observed in car-to-car offset crashes, may influence the mechanism of lower limb injuries. The lateral acceleration in car-to-car offset crashes is significant and reverses the direction in short time. However, this phenomenon is less pronounced in ODB tests. An examination of dummy kinematics during the initial 0.15 sec of the crash suggests that lateral acceleration has little influence on the observed dummy motion. However, it is possible that it could influence the foot-ankle region which is in direct contact with the decelerating structure. In addition, the occupant rebound kinematics could be influenced. Further examination of this phenomenon by finite element modeling is now underway.

ACKNOWLEDGMENTS

The authors would like to thank the Insurance Institute for Highway Safety (IIHS) for giving us the opportunity to use the test data from car-to-car crashes and car to deformable barrier tests conducted by the IIHS.

REFERENCES

- Griffiths M., et al., Australia's New Car Assessment Program, Paper No. 94-S8-O-14, 14th ESV Conference, Munich, Germany, 1994.
- Hollowell W. T., Hitchcock R. J., Improved Frontal Impact Crash Test Data, Paper No. 94-S8-O-09, 14th ESV Conference, Munich, Germany, 1994.
- Lestina D. C., Kuhlmann T., Keats T., and Alley R., Mechanisms of Fracture in Ankle and Foot Injuries to Drivers in Motor Vehicle Crashes, 36th Stapp Car Crash Conference, SAE paper 922521, 1992.
- Lowne R. W., EEEVC Working Group 11, Report on the Development of a Front Impact Test Procedure, Paper No. 94-S8-O-05, 14th ESV Conference, Munich, Germany, 1994.
- O'Neill B., Lund A. K., Zuby D. S., Preuss C. A., Offset Frontal Impacts - A Comparison of Real-World Crashes with Laboratory Tests, Paper No. 94-S4-O-19, 14th ESV Conference, Munich, Germany, 1994.
- Status Report of Insurance Institute for Highway Safety - Crash Worthiness Evaluations, Insurance Institute for Highway Safety, 1995.
- Thomas P., Charles J., Fay P., Lower Limb Injuries - The Effect of Intrusion, Crash Severity and the Pedals on Injury Risk and Injury Type in Frontal Collisions, 39th Stapp Car Crash Conference, SAE paper 952728, 1995.