OFFSET TEST PROCEDURE DEVELOPMENT AND COMPARISON

Carl L. Ragland
National Highway Traffic Safety Administration
United States
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ABSTRACT

Considerable worldwide attention has been directed to offset test development because past testing practices did not adequately address the structural integrity of passenger compartments for partial engagement car-to-car crashes or collisions into fixed narrow objects. National Highway Traffic Safety Administration (NHTSA) Research and Development has been conducting offset car-to-car and moving deformable barrier testing since the early 1980's in order to develop a offset test procedure that characterizes the crash environment in which serious injuries are projected to occur in an all airbag fleet. This paper will compare theoretical and actual results from car-to-car tests, the European test as used by the Insurance Institute for Highway Safety, and the NHTSA R&D test procedure using the moving deformable barrier.

INTRODUCTION

Various test procedures are being used to evaluate the protection of occupants provided by production vehicles in offset crashes. This paper will discuss the research program conducted by NHTSA to develop an offset test procedure. In addition, other test procedures being widely used will be briefly described and compared to the NHTSA research procedure.

European Test Procedure

The European Union has developed a test procedure (EU 96/79) for offset frontal crash testing [1] to address growing concerns that adequate protection is not provided by today's cars for most typical crashes involving some degree of offset and/or some degree of angle. This test was designed primarily to duplicate the crush patterns seen in real world crashes, thereby addressing intrusion induced injuries primarily to the lower leg region. This procedure designed by an international committee, has been widely accepted, and is used throughout Europe, Australia, and the U.S. This test consists of crashing the car into an energy absorbing aluminum honeycomb face which is mounted to a fixed barrier. Forty percent of the front vehicle width engages the honeycomb at a crash speed of 56 km/h.

Insurance Institute for Highway Safety (IIHS) Test Procedure

The IIHS has adopted the EU procedure except the crash speed was raised to 64 km/h to induce higher crush and evaluate the potential for more serious injuries. This higher severity crash test has also been adopted in Europe and Australia for comparing vehicle safety performance. The purpose of these tests are to provide information to consumers about the safety potential of the subject vehicle in offset crashes, particularly related to intrusion induced lower leg injuries. This paper will limit discussion to the IIHS procedure for which data are readily available for US vehicles.

National Highway Traffic Safety Administration (NHTSA) Research Test Procedure Development

NHTSA has conducted an extensive crash test program to develop an offset crash test procedure to meet the following goals: (1) has the potential to evaluate serious injuries and fatalities that may occur in a fleet equipped with airbags and manual restraints, (2) closely duplicates the crash response, crush and occupant kinematics seen in real world type crashes that cause these serious injuries, (3) provides supplemental crashworthiness information to the full barrier test which more effectively evaluates restraint effectiveness, (4) assures compatibility between different size vehicles, and (5) is repeatable and reproducible. With these goals in mind, tests were conducted using a wide variety of airbag equipped vehicles crashed in various car-to-car and car-to-barrier configurations. Other papers have presented some of the results of this testing and crash data analysis used to establish the crash condition [2,3]. This paper will present the theory behind development of the test procedure and some of the most relevant comparisons of crash test data.

NHTSA 30° research test with both vehicles moving.

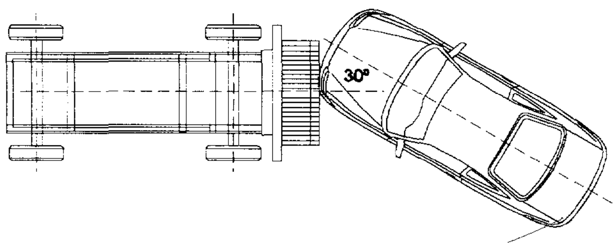

Figure 1. Configuration of moving deformable barrier test with both vehicles moving.

The basic test procedure chosen by NHTSA for development uses a MDB (moving deformable barrier), as described in FMVSS (Federal Motor Vehicle Safety Standard) 214, striking the front corner of the subject vehicle. This configuration was identified by crash data to represent crashes with a high risk of serious injury or fatality [2,3]. Figures 1 through 3 show the various crash configurations tested with the deformable barrier. To address the more severe crashes and the more serious injuries, a closing speed of 113 km/h (70 mph) was chosen for most testing. For medium weight vehicles this collision is similar in speed to the NCAP test at 35 mph, but since the crash is offset and oblique, the crush to the subject vehicle is much more extensive. Smaller vehicles experience higher velocity changes due to their lighter mass, whereas larger vehicles are subjected to lower velocity changes using this test procedure. Similar differences exist in real world crashes between light and heavy vehicles.

NHTSA 30° research test with MDB crabbed15° and vehicle stationary.

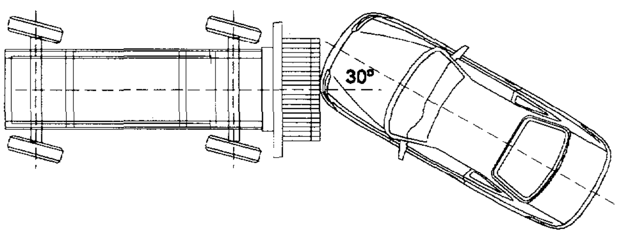

Figure 2. Configuration of moving deformable barrier test with struck vehicle stationary and barrier crabbed

NHTSA 25° research test with vehicle stationary.

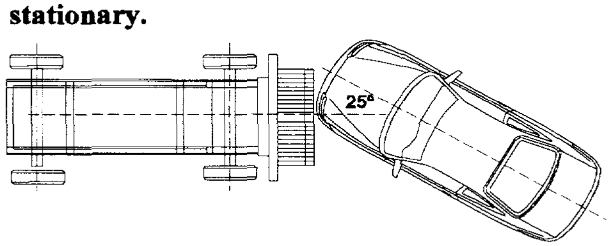

Figure 3. Configuration of MDB test with struck car stationary and barrier moving at oblique angle to centerline of car.

Various test procedures were examined and compared in terms of dummy response, vehicle response and crush. These procedures were then compared to various car-to-car staged collisions. The car-to-car staged collisions and MDB tests were conducted at various overlap amounts, speeds and angles. In developing this test procedure, variations of the EU directive were considered. Early in the development of the NHTSA procedure, plans were made to test a variety of vehicles using the proposed EU fixed barrier. However, after conducting one test with a medium sized car, NHTSA concluded that the procedure would not address serious and critical injuries. Since the main objective of this research test was to address serious injuries, the MDB test was chosen in favor of the EU barrier.

Another NHTSA program investigated offset test procedures for different objectives. In this program, Congress directed the agency to investigate an offset test procedure for harmonization with European standards [4]. The agency has conducted several crash tests at lower speeds than those investigated in this research. These tests utilized the EU barrier, but the objectives of the test series was quite different from the research presented in this paper. The low severity offset testing focused on evaluating the benefits of adopting the EU procedure by comparing responses for 5th and 50th percentile dummies [5].

THEORY

The following section will discuss the theoretical basis for development of the moving deformable barrier test. Energy absorbed by the subject car in the test procedure will be compared to theoretical energy absorbed in car-to-car crashes and full rigid barrier tests (as a baseline reference). Also the European test procedure will be compared in terms of energy absorbed by the subject car. The absorbed energy in the European and NHTSA tests will be discussed as it relates to its effect on compatibility for various size cars.

Energy Absorption

Energy comparisons are appropriate for examining offset test procedures, because in offset crashes, crush levels are much higher due to partial engagement of the structure. To compare energy consumed by vehicles from several weight classes, energy consumed per unit weight (N-m/kg) is used for normalizing these values independent of weight. This method allows comparison between weight classes and accounts for the fact that cars are capable of absorbing energy proportional to their size. From another perspective, all vehicles consume the same amount of unit energy when crashed into a rigid barrier at any given speed, if rebound energy is either assumed negligible or constant. That is, energy in a barrier crash is directly proportional to mass according to the well known formula:

$$KE = \frac{1}{2} m v^2$$

where;

KE = kinetic energy
m = mass of the vehicle
v = velocity

To calculate energy absorbed by each car in car-to-car oblique collisions, the proportion of energy is empirically derived from an oblique crash test with two Tauruses. The proportion of energy is based on the post-test crush of each car according to the the following formulas:

$$E_1 = F\,d_1$$
$$E_2 = F\,d_2$$

where;

E_1 = The energy absorbed by vehicle 1
E_2 = The energy absorbed by vehicle 2
F = average force exerted on the vehicles during crash (equal and opposite)
d_1 = the maximum crush distance for vehicle 1
d_2 = The maximum crush distance for vehicle 2

also: $E_1 / E_2 = d_1 / d_2$ (energy ratio)

This ratio was calculated from film analysis motion of the CG's as 1.27, where vehicle 1 was the struck Taurus. That is the struck Taurus crushed 27% more than the striking Taurus. Expressed a different way, 56% of the total energy (1.27/2.27) was absorbed by the struck Taurus and 44% (1/2.27) by the striking Taurus. The striking car in an oblique crash absorbs less energy and is thus more aggressive to the struck car because the stiffer center of the striking car engages the softer corner of the opposing vehicle. This 56% to 44% proportion of total energy is assumed for other vehicles, regardless of the vehicle size, due to lack of additional data.

Compatibility

In this analysis, compatibility is assumed to be related only to energy sharing between vehicles in a multi-vehicle crash, although other factors such as geometry may influence compatibility. This and other factors are not considered in this analysis because compatibility differences of cars subjected to these offset test procedures is mostly a factor of crush energy. While it is recognized there are many other factors affecting compatibility such as geometry and crash mode (front-to-side and front-to-rear impacts for instance), this paper will focus only on front-to-front structural and mass compatibility. This approach for selection of a frontal test procedure is supported by crash data analysis, since most fatal and serious injury frontal crashes occur in front-to-front vehicle collisions. Therefore this paper will focus on theoretical crush energy consumed by the subject cars in various test procedures and car-to-car frontal collisions. Theoretical changes in velocity for these cars are also compared along with their crash deceleration environments (crash pulses). The results will help to understand the effects on future vehicle designs in response to the requirements (voluntary or regulatory) of various crash test procedures.

TEST PROCEDURE

Energy Comparison

Energy comparisons are made for the IIHS test procedure, the NCAP test procedure, and the NHTSA research test procedure. The EU and IIHS test procedure are identical except the IIHS procedure is closer to the speed of severe and injury causing crashes in the U.S. fleet. Conclusions made in this analysis for the IIHS test procedure apply equally to the EU test procedure and visa versa.

The NHTSA test procedure configuration shown in figures 2 and 3 is used to compute the energy dissipated by the honeycomb barrier face with the barrier moving at 113 km/h. To make the calculations, assumptions have to be made about the vehicle stiffness and thus the extent of honeycomb crush. For these assumptions two scenarios are used. One assumption is that honeycomb energy is absorbed proportional to the total energy in the crash, with the heaviest car fully crushing the honeycomb. Another scenario assumes the smaller cars are stiffer, thereby crushing the full depth of honeycomb similar to a heavier car. Therefore, in the second scenario, energy absorbed by the barrier is constant across the full range of vehicles. A third scenario may be envisioned where the large car is too soft to crush the full extent of the honeycomb. Since this third scenario is unlikely, only the first two scenarios will be considered. The honeycomb force-crush properties are known from development work for the FMVSS 214 barrier [6].

The energy absorbed by the FMVSS 214 face on the moving deformable barrier is estimated to be 155 kN-m, when fully crushed in the second scenario. The fixed deformable barrier used in the IIHS or EU 96/79 procedure is estimated to absorb only 65 kN-m based on its width and design [1]. Since the fixed deformable barrier face is capable of absorbing a much smaller quantity of energy than the moving deformable barrier face and the maximum force to crush the honeycomb is less than the maximum force exerted by car frontal structures, it seems reasonable to assume in the EU type test that all available honeycomb energy was absorbed for all size vehicles. Note this assumption may not be valid for lower speed crashes, particularly involving smaller vehicles.

Figure 4 shows the results of the unit energy calculations for the IIHS test procedure at 64 km/h, the NCAP test at 56.5 km/h (for reference), and the moving deformable barrier at 113 km/h, resulting in a 56.5 km/h delta v for equal weight cars. The unit energy absorbed by cars tested with the moving deformable barrier using the two previously stated assumptions about extent of energy absorption is shown on figure 4 as MDB1 and MDB2. MDB1 denotes the case where the honeycomb absorbs energy in proportion to the total energy of the crash 124 kN-m, 141 kN-m, and 155 kN-m for the light medium and heavy cars, respectively. The bars labeled MDB2, refer to the case where energy absorbed by the honeycomb is constant at 155 kN-m. Looking at the bar chart for MDB1 and MDB2 shows that MDB1 tests require less energy absorption for cars as weight increases, whereas MDB2 tests require similar energy absorption by weight of car. To explain the MDB1 case in physical terms, it is typical for larger cars to crush less, while small cars crush more in car-to-car crashes due to stiffness differences. The same phenomena may occur in the MDB testing with the honeycomb absorbing more energy when struck by the large car (i.e. less energy absorbed by large car) and less energy when struck by the smaller car. This situation is far less than ideal for the small car, because intrusions would be disproportionately large for the small car. A more ideal situation for compatibility is one in which control of intrusion is balanced against a stiffer structure. The result would be as seen in figure 4 as MDB2, in which the smaller car is actually stiffer than the larger car.

As shown in figure 4, crash testing with the EU barrier requires less unit energy to be absorbed by *smaller* vehicles than by larger vehicles. NCAP testing, which represents hitting a fixed object or equal weight car, shows a constant unit energy requirement for all size cars. In car-to-median weight car testing more unit energy is typically absorbed by small cars than large cars.

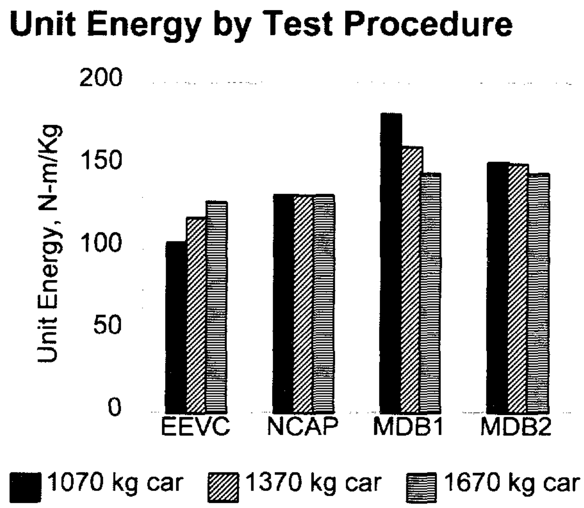

Figure 4. Unit energy absorbed by subject vehicles subjected to various test procedures.

Figure 5 shows the comparison of energy absorbed by the subject car in both collinear and oblique offset tests. Notice that the energy requirements imposed by the IIHS test is opposite in the trend by car size to that required by car to car or deformable barrier testing. Since energy absorbed is proportional to the amount of crush, small cars tested with the EU barrier may crush less than in most

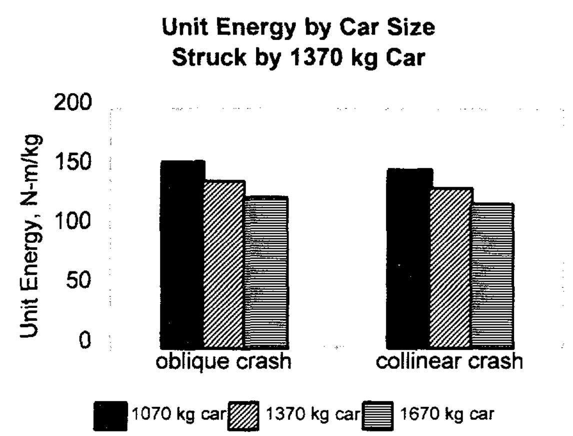

Figure 5. Comparison of unit energy absorbed by cars when struck by a medium size (1370 kg) car.

typical real world crashes of comparable speed. Since the objective of the IIHS test is to compare test vehicles under extensive crush conditions simulating offset collinear collisions, the results may be misleading in favor of the smaller cars. To compensate for this discrepancy, test velocity may be adjusted inversely proportional to weight. Alternatively, the test severity may be reduced and the honeycomb stiffened to increase the proportion of energy absorbed by the barrier when struck by larger cars, and to decrease the proportion of energy absorbed by the barrier when struck by small cars.

Delta V Comparison

The difference in delta V levels can be seen in figure 6. Delta v's are compared for the various test procedures and car-to-car crashes. The delta v's shown as VTV-1 represents the subject vehicle struck by a medium weight car in a collinear crash with each vehicle moving at 56.5 km/h or the MDB moving at 113 km/h striking the stationary vehicle. The delta v's shown as VTV-2 represent the subject car moving at 56.5 km/h struck by a medium weight (1370 kg) car or a moving barrier at 56.5 km/h in an oblique configuration as shown in figure 1. Figure 6 shows that the IIHS test procedure produces a delta v for all size vehicles slightly higher than the small car delta v when struck by the moving barrier or medium weight car. This higher delta v is necessary to compensate

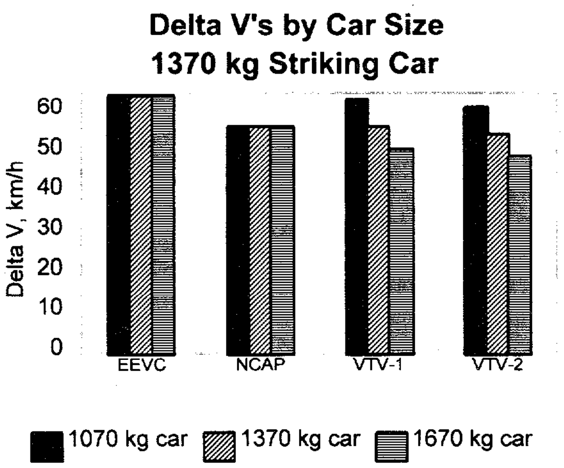

Figure 6. Delta V's by crash mode for various test configurations.

for the energy absorbed by the barrier. The MDB test procedure produces delta v's identical to the car-to-car crashes.

Compatibility Comparison

In the IIHS test procedure as previously discussed, the unit energy absorption required for a small car is much less than for a large car. Since this trend is opposite to car-to-car crashes, the results of meeting such a test requirement may be counter productive. It may be possible to design the structure of a small car to crush more and still perform well in this test relative to a large car in the test. Since the deformable fixed barrier test imposes higher unit energy requirements on the large cars, it is also possible for the larger cars to become stiffer to meet acceptable voluntary or regulatory performance requirements. In contrast, fixed rigid barrier testing requires that the unit energy remain constant across the range of vehicle sizes. Therefore, we would expect neither an improvement nor a decrease in vehicle compatibility from fixed barrier testing.

Since the moving deformable barrier test imposes a harsher crash environment on the smaller vehicles due to higher energy absorption and higher delta v (representative of the overall crash environment), the natural tendency to meet the test requirements will be to increase the stiffness of the smaller cars (as well as improving restraints) to compensate for the increased crush. The unit energy requirements for large cars also remain high compared to fixed barrier testing, even though the change in velocity is lower. Additionally the energy requirement for a large car is independent of its structural stiffness as seen by the energy comparison of figure 4 for large cars tested with the MDB. However, a large stiff car would see a harsher crash environment in terms of crash pulse in this procedure. Therefore in meeting the requirements of this procedure large car stiffness would likely be reduced or maintained at a minimum level that would still mitigate the compartment intrusion. Therefore fleet compatibility would tend to improve in response to the moving deformable barrier test procedure in order to optimize the vehicle structure to provide an acceptable or high level of occupant protection. Physically, small cars would be required to reduce compartment intrusion through improved structural stiffness while imposing more crush (energy absorption) on the moving deformable barrier while heavier cars would maintain the same or perhaps softer structures in order to balance compartment integrity with crash pulse severity. In the MDB test the smaller vehicle is exposed to higher velocity change due to mass. This phenomenon which is not controllable by improved design, combined with a poor structure would allow for excessive crush resulting in an extremely harsh crash environment in terms of survivability. The only available countermeasure for a light vehicle would be to increase structural stiffness (and improve restraints) such that the honeycomb is fully crushed (to the maximum extent) without excessive stiffness which would cause even higher occupant loading due to increased acceleration of the compartment. The larger vehicle on the other hand experiences a different crash environment. The higher mass which reduces velocity change also requires higher energy absorption. Therefore the near total crush of the honeycomb is very easy to achieve, but excessive crush and bottoming of the honeycomb structure will result in very high compartment deceleration. To improve occupant protection, softening the structure and/or improving restraints may be necessary.

CRASH TESTING

Energy Comparison

The calculated unit energy consumed by Ford Taurus vehicles in actual crash tests is shown in Table 1. Table 1 also summarizes the test configurations and data for these crash tests. The proportion of energy absorbed by each Taurus in a single car-to-car crash test was determined by the ratio of post-test crush measurements as previously discussed, and is shown in table 1. The unit energy level of 164 kN-m/kg for the oblique car-to-car Taurus test is significantly higher than the 155 kN-m/kg for the large car in the MDB1 test shown in figure 4. This difference is due to a higher speed and a heavier bullet vehicle in the Taurus tests. The Taurus test weight was approximately 1570 kg and the moving deformable barrier weighs 1595 kg to approximately match the Taurus weight.In this crash test, the honeycomb absorbed energy was assumed to be at the maximum of 155 kN-m as previously described for MDB1. The unit energy absorbed by the Taurus in the MDB test was calculated as 164 kN-m/kg, slightly higher than in the car-to-car test. In contrast, the calculated unit energy absorbed by the Taurus was 125 kN-m/kg in the EU test and 132 kN-m/kg in the NCAP test. While these energies are similar to each other they are significantly lower than the car-to-car oblique test and the MDB test, but are comparable to the car-to-car collinear test at 132 kN-m/kg. This difference is explained by the different crushing of two cars in an oblique and offset crash where one vehicle is striking the relatively soft corner of the opposing vehicle (subject vehicle in this study) with its stiffer mid front section.

Crash Pulse Comparison

The following will compare structural and dummy response for the 1992-1995 Ford Taurus (identical model years) models which were crash tested in five crash configurations. The crash conditions were: (1) car-to-car collinear offset at 50% overlap and 35 mph (abbreviated VTV-1); (2) a rigid barrier NCAP test at 35 mph and full engagement (abbreviated NCAP); (3) a 40 mph and 40% overlap into a deformable fixed barrier (conducted by Insurance Institute for Highway Safety abbreviated IIHS); (4) a car-to-car 30 degree oblique offset at 59% overlap and each vehicle moving at 38 mph (abbreviated VTV-2); (5) and a moving deformable barrier to car 30 degree oblique offset at 53% overlap and each vehicle moving at 36 mph (abbreviated MDB).

Table 1. 1992-1995 Ford Taurus Test Conditions and Results

	Test Conditions				Driver ATD Response			
	Unit Energy, N-m/kg	Test Configuration	Closing Speed, km/h	Overlap, %	HIC	Chest 3 ms Clip	Max Femur, Newtons	Max Tibia Index
Car-to-car, collinear	132	collinear	113	50%	530	45.4	5654	1.0
Car-to-car, oblique	164	see figure 1	119	59%	411	51.0	5824	1.7
MDB-to-car	170	see figure 1	113	53%	461	54.8	6708	2.4
MDB-to-stationary car	161	see figure 2	111	47%	497	62.5	7532	2.3
MDB-to-stationary car	168	see figure 2	113	68%	620	61.8	15620	1.4
MDB-to-stationary car	130	see figure 2, except @ 45°	109	65%	363	44.9	7223	1.6

The crash pulse for the car-to-car collinear, NCAP, and EU tests are shown in figure 7. Note that the car-to-car 50% test and the NCAP test are somewhat

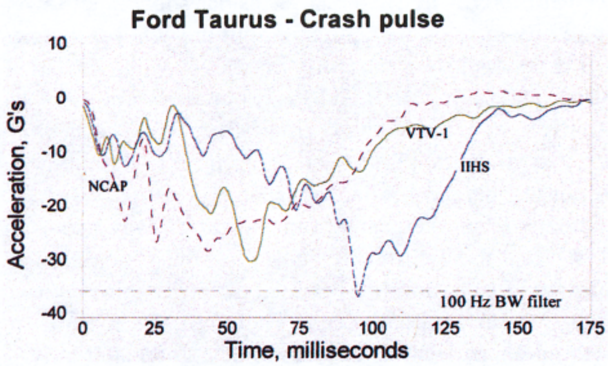

Figure 7. Comparison of Taurus Crash Pulse for car-to-car collinear offset, NCAP, and IIHS crash tests.

similar in peak amplitude, but the peak occurs approximately 14 milliseconds later in the car-to-car collinear test. The crash pulse resulting from the IIHS test does not appear similar to either the NCAP or the car-to-car crash pulse. In the IIHS test the dissipation of energy occurs much more slowly and the peak acceleration is higher and much later.

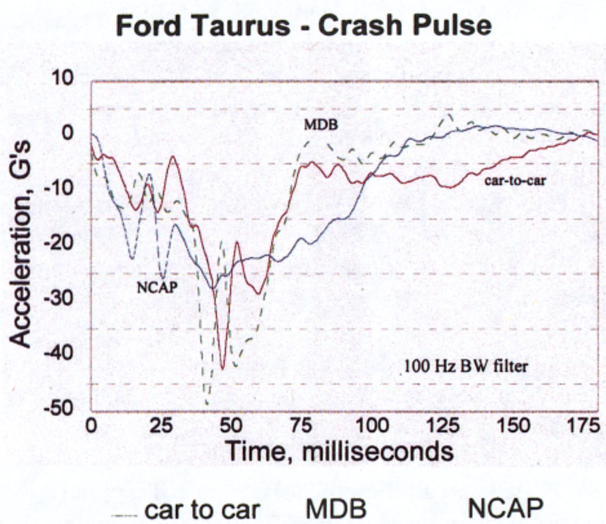

Figure 8. Comparison of Taurus crash pulse for car-to-car oblique, NCAP, and moving deformable barrier crash tests.

Figure 8 compares the crash pulse for the car-to-car oblique test with the moving deformable barrier and NCAP tests. This figure shows that the moving deformable barrier test matched the car-to-car oblique (VTV-2) response very well. The peak accelerations occur at nearly the same time and are similar in amplitude. In contrast, the difference in peak acceleration between the NCAP and either of the two other Taurus tests became quite apparent. However, the overall response from the Taurus NCAP agreed fairly well with the car-to-car and MDB tests.

Dummy Response and Kinematics

Figure 9 shows the comparison of dummy responses for the five crash test conditions for the Taurus. Values are expressed in percentages of "injury assessment reference values" or IARVs. These reference values are defined in FMVSS 208 except for the "tibia index"which uses a reference value of 1.3, as defined by the EU 96/79 standard. The tibia index is computed by the formula:

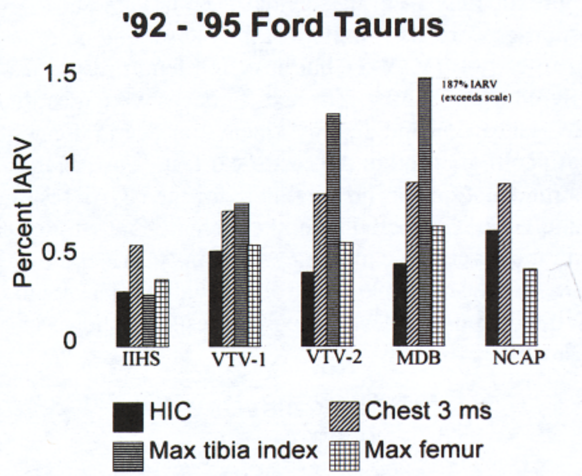

Figure 9. Percent IARV for Taurus in various crash configurations.

$$M_r/225 + F_z/35{,}900$$

where,

M_r = resultant upper or lower tibia moment in Newton-meters

F_z = upper or lower tibia compressive force in Newtons.

A very good match is noted between the oblique car-to-car (VTV-2) dummy responses and the MDB test. This is especially true for the head, chest and femur comparisons, but the tibia response was 43% higher in the MDB test. This match is expected since the MDB test was designed to duplicate this car-to-car test mode. As previously noted, the crash pulses of these two tests also matched well. Is does become apparent that due to the limited crush of the MDB honeycomb, the MDB test is slightly more aggressive, resulting in slightly higher vehicle response and higher dummy femur response. The IIHS test responses is compared to the offset collinear (VTV-1) response for which it was designed to replicate. Referring to figure 7 shows very little similarity between the crash pulses from these two tests. Comparing dummy responses from figure 9 shows much lower dummy responses for all major injury indicators, including the leg values, even though the IIHS crash is at a significantly higher speed.

Comparing the NCAP test to the other test configurations shows the NCAP pulse more closely resembling the oblique car-to-car (VTV-2) pulse than any of the others. The peak acceleration for the car-to-car collinear (VTV-1) pulse and NCAP pulse are similar in amplitude, but significantly shifted in time (approximately 14 milliseconds). Dummy chest responses were also similar for the NCAP and oblique car-to-car test (VTV-2), but head and femur responses differed significantly. These differences were most likely due to intrusion and dummy kinematics due to the angled crash configuration in the car-to-car test. Lower leg instrumentation was not available for the NCAP test and could not be compared. Another vehicle that was tested with the deformable moving barrier in NCAP and by IIHS was the '95 - '96 Chevrolet Cavalier. The results for the dummy in these three crash tests are shown in figure 10.

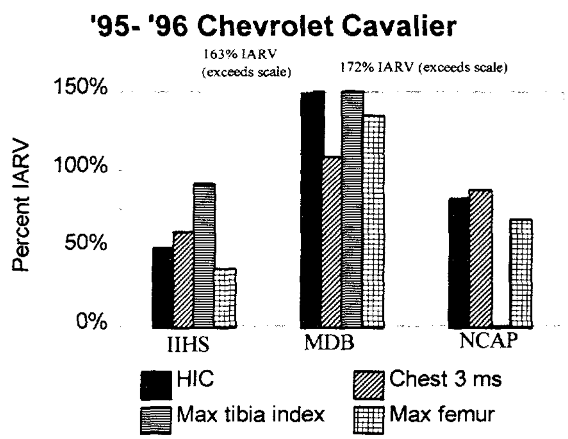

Figure 10. Percent IARV for '95 -'96 Chevrolet Cavaliers subjected to three crash tests.

CONCLUSIONS AND RESULTS

The IIHS test procedure was compared to the NHTSA MDB test procedure in terms of energy absorption, dummy response, and vehicle compartment accelerations. The IIHS test series has shown that lower extremity injuries are addressed, but the MDB test series addresses the lower extremity injuries as well. Additionally, the MDB addresses the serious injuries that are likely to occur in an all airbag fleet. It was shown that the MDB test produces compartment and dummy responses that are similar to responses seen in comparable severity car-to-car crashes. It was also shown that the deformable barrier has the potential for improving compatibility between different vehicles in high-speed frontal collisions. Therefore, the moving deformable barrier test appears to be a good alternative test method to assure better front-to-front compatibility. This test method also provides good correlation with real world crashes, evaluates the potential for serious injuries and fatalities, and complements the full barrier test.

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