NHTSA's Compatibility Research Program Update

Stephen Summers, Aloke Prasad, William T. Hollowell
National Highway Traffic Safety Administration

ABSTRACT

This paper provides an update of NHTSA's research activities in vehicle compatibility and aggressivity. This paper presents newly initiated efforts underway to develop test assessment methodologies intended to evaluate vehicle compatibility. The rigid barrier load cell data collected from 18 years of the agency's New Car Assessment Program testing are reviewed to evaluate potential test measures that may be used to evaluate a vehicle's compatibility in vehicle-to-vehicle crashes. These parameters are then evaluated using a series of vehicle-to-vehicle and moving deformable barrier (MDB)-to-vehicle tests. In these tests, the face of the MDB has been instrumented with an array of load cells to compute test measures. This study is part of NHTSA's ongoing compatibility research program and is being coordinated with the IHRA compatibility group.

INTRODUCTION

At the Fifteenth Enhanced Safety of Vehicles Conference held in Melbourne, Australia, during May 1996, a program of coordinated research was agreed upon that would be undertaken under the worldwide banner of International Harmonized Research Activities (IHRA). The research is comprised of six high priority areas in which nations would collaborate over a 5-year period. Among these is research in vehicle compatibility. The aim of the IHRA Vehicle Compatibility Working Group is to develop test procedure(s) designed to improve the compatibility of vehicle structures in front-to-front and front-to-side crashes, thus enhancing occupant protection in these crash modes. A secondary aim is to consider protection in vehicle impacts with pedestrians, heavy vehicles, and other obstacles

Despite the fundamental differences in the fleets found in the participating members' regions of the world, the IHRA Working Group remained focused on developing test procedures that could be used anywhere. While there were diverse views as to the types of tests that could be used, the members agreed to a work program that addresses the overall goals of the program. The program plan included efforts in using real world crash data to define the safety problem, using the findings from the review of crash data in combination with results obtained from crash testing and computer modeling to determine the key vehicle characteristics affecting vehicle compatibility, and the development of test protocols that evaluate the key characteristics which when used would ensure that vehicles become more compatible.

The Working Group members remained focused on developing test procedures that would be suitable anywhere (despite the identified differences in fleets among the participating regions). The consensus was that the test procedure(s) should include an evaluation of the force footprint imparted by a vehicle and, in parallel, evaluate the capability of the vehicle to sustain an overload condition on the occupant compartment. Recognizing that heavy and light vehicle collisions are inevitable, the overload condition is intended to establish performance levels for maintaining occupant compartment integrity. The particulars regarding these evaluations remain under further development and debate.

In the U.S. fleet, light trucks, vans, and sport utility vehicles (LTV's) currently account for over one third of light vehicles, but over half of all light vehicle-to-vehicle fatalities occur in collisions between cars and LTV's[1, 2]. Eighty one percent of these vehicle-to-vehicle fatalities occur to passenger car occupants. NHTSA's compatibility research program is investigating vehicle-to-vehicle compatibility issues and the implications of changing U.S. fleet composition upon fleetwide occupant safety. Previous studies undertaken in NHTSA have evaluated FARS and NASS GES data in terms of fatality ratios between striking and struck drivers to identify the safety problems related to the compatibility issues [1,2,3,4]. There have been numerous test programs conducted by NHTSA and others in an effort to identify vehicle characteristics that are associated with observed vehicle incompatibility in real world crashes. These studies have shown the relative significance of vehicles mass, stiffness and geometry in front-front and front-side crashes. This paper will focus on NHTSA's recent research efforts to develop test methods for evaluating vehicle compatibility.

EVALUATION OF NCAP LOADCELL DATA

Before any new testing was conducted, it was essential to review the existing test data to see if it can provide some insights toward vehicle-to-vehicle compatibility. A review of the existing NCAP load cell data was conducted to see if the distribution of forces across the fixed rigid barrier during an NCAP test can provide an estimate of vehicle compatibility. Out of the 684 frontal NCAP tests currently stored in NHTSA's crash test database, 478 tests had acceptable load cell data. These tests were performed from 1982 to present and were conducted at the six facilities listed in Table 1. The number of tests indicate only those tests that passed quality control.

Test Performer	Number of Tests
Veridian / Calspan	232
TRC	99
MGA	63
Mobility Systems	58
KARKO	19
Dynamic Sciences	7

Five of the six test facilities use similar load cell barriers, as shown in Figure 1 below. This barrier configuration measures a 4 by 9 grid of force data.

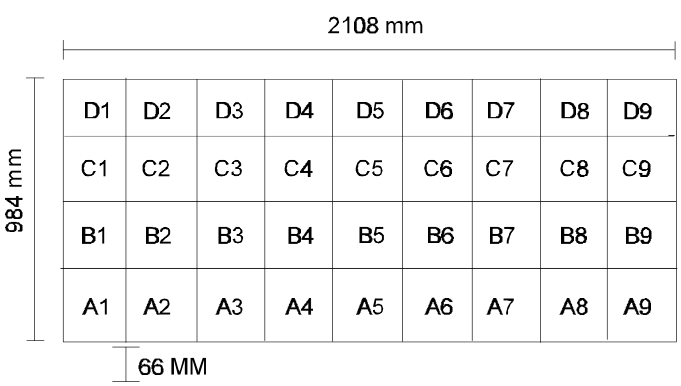

Figure 1: Loadcell barrier configuration

MGA Research, the sixth facility, uses a different load cell barrier that is longer and higher, but only measures a 2 by 3 array of force data. Each load cell "grid element" is measured using 5 load cells, but only the total force for each grid is reported. The geometry of the MGA barrier is shown in Figure 2. The loadcell data collected in MGA tests, although of reduced resolution, was otherwise acceptable and was used in this analysis.

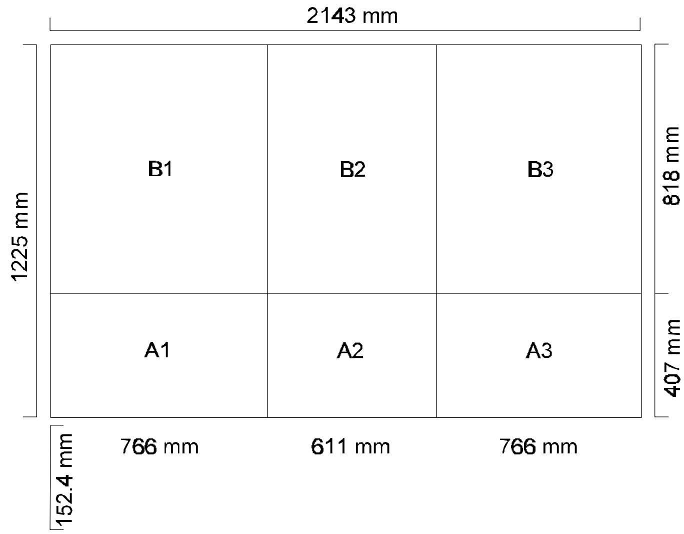

Figure 2: MGA Barrier configuration

The first step in evaluating the load cell measurements was to look at some measures of the vehicle stiffness. A reference accelerometer was identified for each test vehicle, where possible it was chosen near the drivers seating position. The load cell and accelerometer data were evaluated for consistency and combined to produce a force deflection signal. This signal was interpolated in 1 mm intervals from time zero to the first inflection point in the deflection. The force-deflection profiles were averaged by body style and weight categories as shown in Figure 3. The car test data were grouped based on test vehicle weight using the NCAP weight categories. The test weight averages 275 kg greater than the curb weight, but the weight difference varies considerably among vehicles. Also, the force deflection data were averaged at 1mm intervals. Since there is a significant difference in the crush distances, the number of tests averaged at each deflection interval is not the same. The number of tests averaged for each interval decreases as the deflection increases. Figures 4-10, show the average and standard deviations for each vehicle category. The number of tests averaged for each interval is shown in the top curve and relates to the axis along the right side. The area under the force-deflection signals is controlled by the mass of the vehicle and can be seen by comparing the profiles for the car groups.

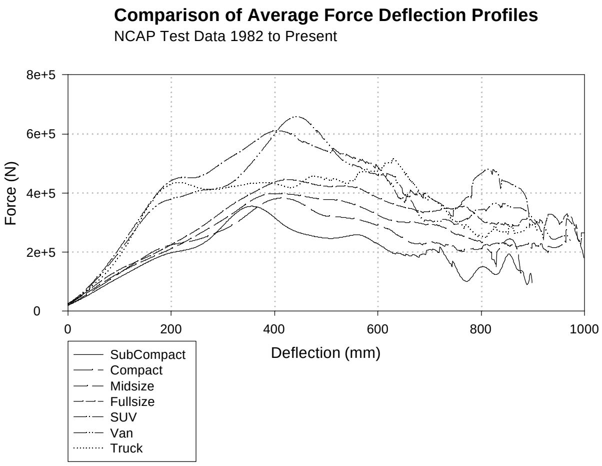

Figure 3: Average F-D profiles

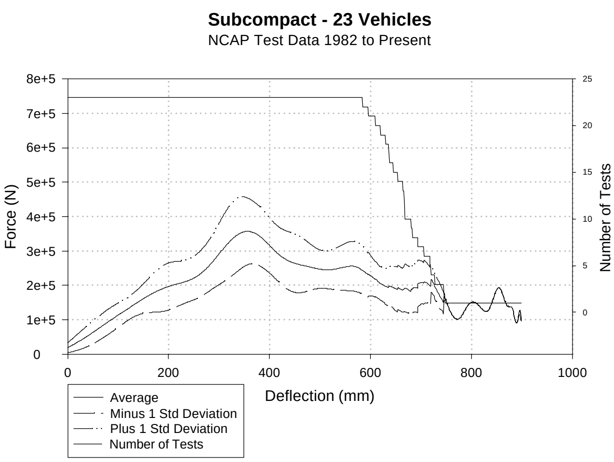

Figure 4: Test Weight < 1133.98 kg (2500 lbs)

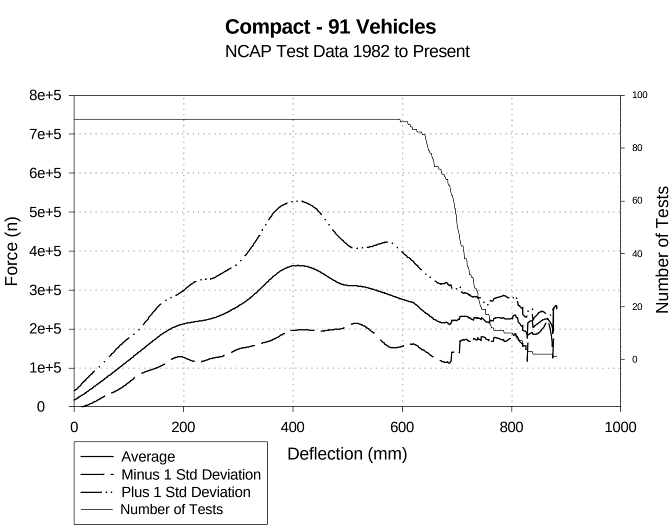

Figure 5: Test Weight < 1360.7 kg (3000 lbs)

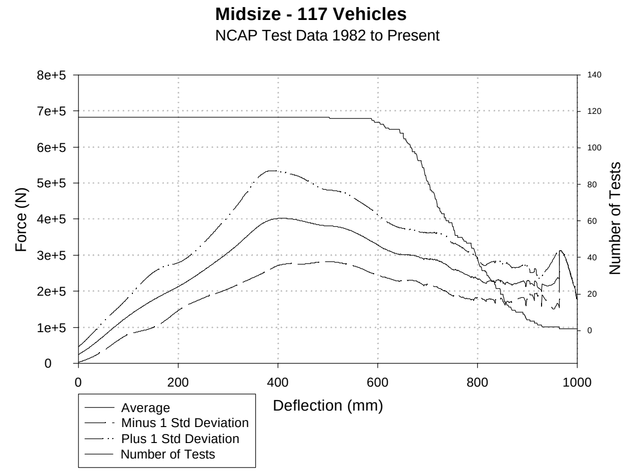

Figure 6: Test Weight < 1587.6 kg (3500 lbs)

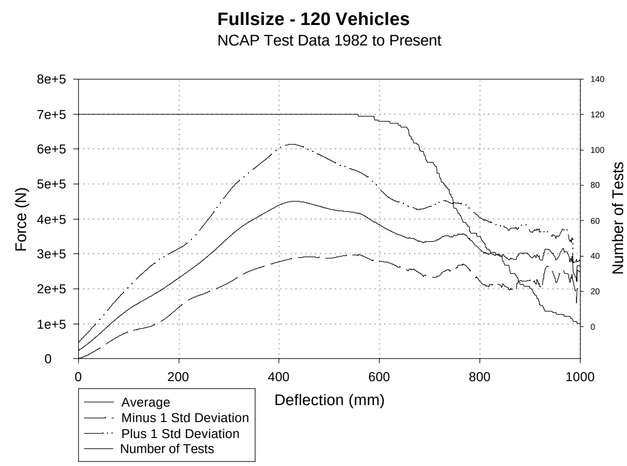

Figure 7: Test Weight > 1587.6 kg (3500 lbs)

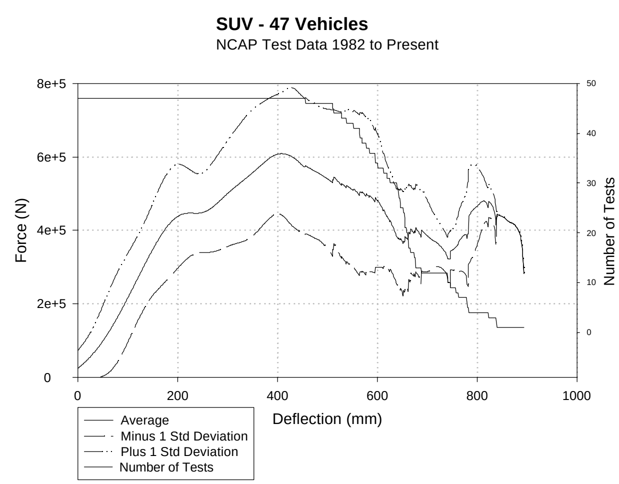

Figure 8: SUV

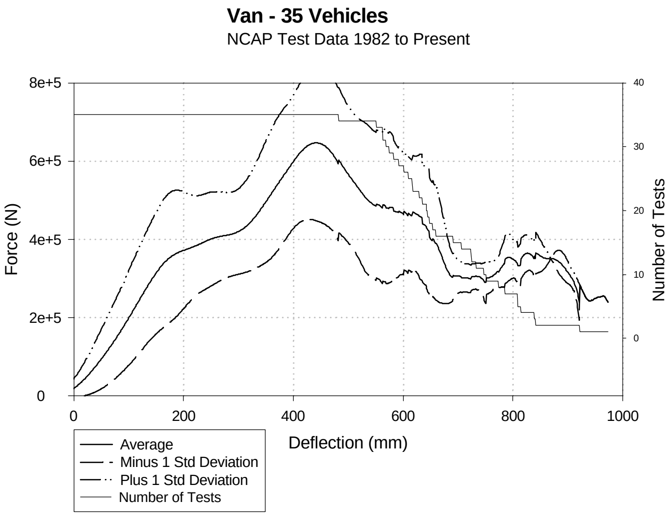

Figure 9: Van

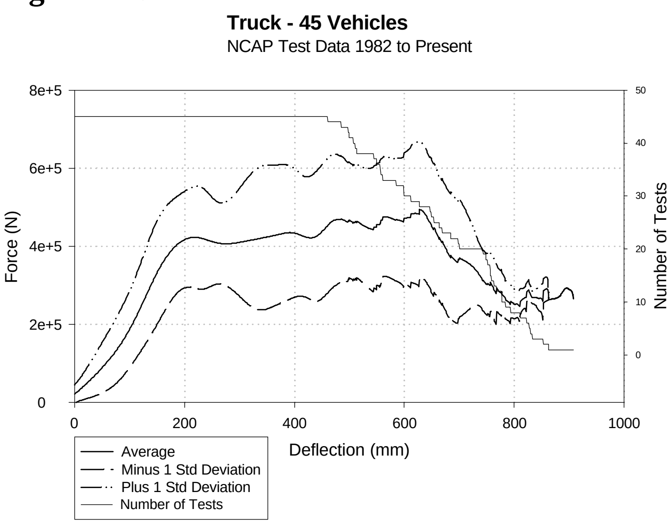

Figure 10: Trucks

Many of the NCAP tests measured significant forces prior to the indicated time zero causing the deviations in force levels at time zero as shown in Figures 4-10. However the data submitted by the test labs were not modified to correct these deviations. Examining the Force deflection profiles shows a striking consistency of the initial stiffness or slope of the force deflection curve among the car groups and within the SUV, truck, and van body styles. This dichotomy in initial stiffness may have some implications for compatibility in side impact collisions. The area under the force deflection signal is a function of the weight of the test vehicle, therefore it is not surprising to observe the increase in force between weight categories and the wide variability among the LTV categories, which cover a large range in weight.

Several methods were examined to try and characterize the initial stiffness for each test vehicle. These all involved using linear regression of the force deflection data over variable length deflections. After reviewing several alternatives, the initial stiffness for each test was determined by computing a linear fit over the longest crush distance with an $R^2 > 0.95$. The region of the fit was constrained to, start within the first 200 mm of deflection to reflect the initial stiffness of the vehicle. Only 9 tests out of 478 did not display linear behavior within the first 200 mm. The initial stiffness measurements for the remaining 469 vehicles will be evaluated against field crash data and presented in a future report.

Having established the trends in vehicle stiffness, it was desired to evaluate the load distribution across the barrier faces. The NCAP test data were analyzed to determine the average height at which the vehicles transferred force to the rigid barrier, as described in Reference 6. At any instant in time, the average height of force is computed as follows.

$$\frac{\sum_{1}^{N} FiHi}{\sum_{1}^{N} Fi}$$

Where F_i are the individual force measurements and H_i is the height of the load cell. This average height of force is computed for each time step and an overall average is computed using the force-time signal as a weighting function. This methods weights the average height of force to height at which the higher loads were transferred. The average height of force is shown in Figure 11 for the seven vehicle groups This figure shows the average height increases with car weight and a higher average height for the SUV and truck categories.

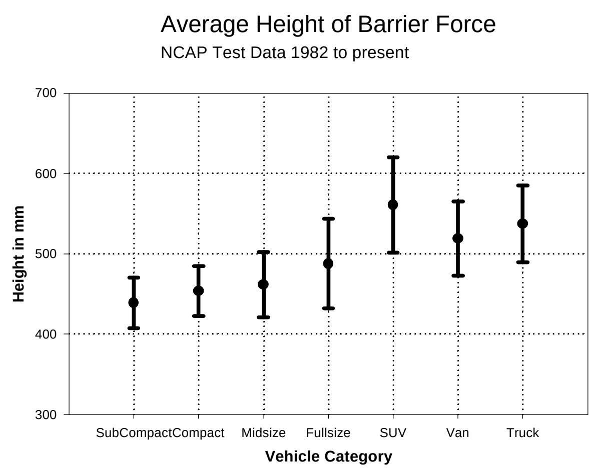

Figure 11: Average Height of Force

The power for the crash is computed by multiplying the force by the instantaneous velocity of the vehicle's center of gravity. The peak power was also computed for each of the NCAP tests. Figure 12 shows the average peak power for each of the vehicle categories.

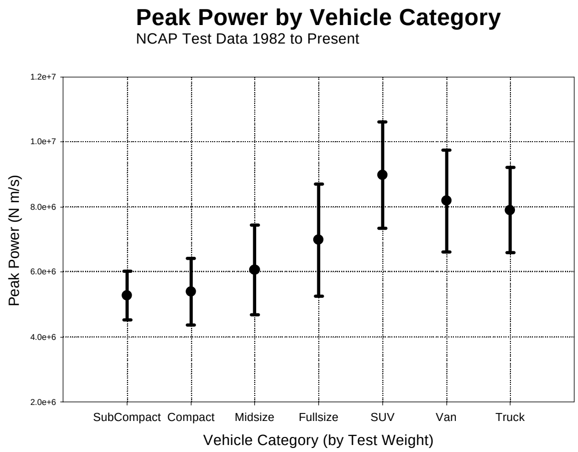

Figure 12: Peak Power

The peak power shows a general increase with car weight and the SUV, truck, and van categories are significantly above the passenger car categories.

CORRELATION OF TEST METRICS TO CRASH DATA

The significance of the test derived metrics can only be established by comparison to the field crash data. A recent study by UMTRI, see Reference 7, compared preliminary vehicle metrics derived from NCAP test data to real world crash performance as measured in FARS and NASS GES. In this study, it was necessary to decode the VIN data in order to map the field crash data to the corresponding NCAP test results. Not all NASS regions provide VIN information, so considerable effort was necessary to develop national estimates. Not surprisingly, there was a strong correlation between vehicle weight and aggressivity measures based on struck driver fatalities rates. An equivalent stiffness was used, based on post test deformation (X) , where stiffness (k) was defined as shown below. (m= mass, v = velocity)

$$k = \frac{(mv^2)}{X^2}$$

These stiffness values were not found to have any significant correlation to the vehicle's aggressivity, even when the data were corrected for the dominant effect of the weight ratio of the vehicles. The study also evaluated unweighted averages for the height of force. The average height of force was shown to have a mild correlation with aggressivity, but only after correcting for the weight ratio of the vehicles involved in the crash. This study is currently being updated to include the vehicle metrics previously discussed, initial stiffness, weighted average height of force, and peak power. Additionally, the study is being augmented with an additional two years of FARS and NASS GES data and will try to separate aggressivity data for frontal and side impact collisions. The updated study is expected to be released towards the end of 2001.

EVALUATION OF COMPATIBILITY TEST PROCEDURES

The NCAP test derived metrics may have some potential for estimating a vehicle's compatibility. However, the NCAP test procedure does not account for the weight ratio of the vehicles involved in a vehicle to vehicle test. An NCAP test simulates a vehicle running into itself at 56 kmph. This is useful for measuring a vehicle's load distribution, but it does not fully evaluate occupant protection in real world vehicle-to-vehicle crashes where the change in velocity is a function of the weight of the collision partner. It is desirable to investigate test methods that can account for the weight ratio between the test vehicle and an average or expected collision partner. A second concern with rigid barrier testing is that the rigid wall will fully engage all of the structure of the test vehicle and does not allow for any override or underride that may occur in a real world crash.

NHTSA is investigating the use of a moving deformable barrier, MDB, with load cell instrumentation behind the honeycomb face. The goal would be to design an MDB that represents an average vehicle and to require occupant survivability in the struck vehicle, or self-protection. The test procedure must also place limits on the amplitude and distribution of the forces measured on the face of the MDB, or partner-protection. As a preliminary test of this concept, a test program was devised using a load cell moving deformable barrier, LCMDB, developed for side impact testing[8]. A preliminary test series was conducted to see if the load cell instrumentation can provide sufficient data to distinguish between aggressive and non aggressive vehicles. A full frontal test was used to provide the maximum coverage of the load cells and to provide for some limited correlation with NCAP test data. Using a fixed mass for the LCMDB, the vehicle weight ratio and the resulting change in velocity for the struck vehicle is controlled by weight of the subject vehicle. Thus, the severity of the crash will depend upon the mass of the test vehicle.

This preliminary test series was also conducted to evaluate the load distribution in LCMDB-to-vehicle crashes and to compare damage and injury measurements in an equivalent vehicle-to-vehicle crash. Three tests were conducted and are shown in Table 2 below.

Test	Vehicle 1	Vehicle 2
3362	LCMDB, 56.2 kmph, 2051 kg	1996 Plymouth Neon, 55.9 kmph, 1382 kg
3413	LCMDB, 56.2 kmph, 1377 kg	1997 Dodge Caravan, 56.8 kmph, 2138 kg
3414	1997 Dodge Caravan, 56.5 kmph, 2060 kg	1996 Plymouth Neon, 55.9 kmph, 1378 kg

The baseline test was a full frontal collinear crash involving a 1996 Plymouth Neon and a 1997 Dodge Caravan, each moving 56 kmph. In the second test, the weight of the LCMDB was adjusted to match the Dodge Caravan, and the LCMDB was fitted with an FMVSS No. 214 barrier face. This LCMDB was impacted into the Plymouth Neon. In the third test, the LCMDB weight was adjusted to match the Plymouth Neon and the Dodge Caravan was impacted. This test series was intended to see if an MDB impact could produce vehicle acceleration, crush, and occupant responses similar to that in vehicle-to-vehicle tests.

INJURY CRITERIA

All vehicles had a belted 50^{th} percentile male dummy in the drivers seat and a belted 5^{th} percentile female in the passenger seat. The computed injury criteria for the dummies are shown in Tables 3 and 4 below. The injury criteria for the Neon driver struck by the LCMDB are generally severe, and considerably higher than measured for the baseline driver. The Neon passenger injury measures are significantly less severe and are generally consistent between the baseline and LCMDB tests. For all passengers, except the baseline Neon, the head data had numerous significant spikes that prevented computing HIC values. The Caravan passenger, when struck by the LCMDB, had an exceptionally high neck extension which led to the high maximum Nij value. Additionally, the chest injuries were higher for both the driver and passenger struck by the LCMDB. The HIC and right femur injury criteria for both the Caravan driver and the passenger were generally consistent between the baseline and the LCMDB test.

Driver 50^{th} male	Baseline Caravan	LCMDB Caravan	Baseline Neon	LCMDB Neon
15 ms Hic	638	621	521	1414
Max Nij	0.58	0.47	0.54	0.86
Chest G's	44.6	51.3	69.0	100.4
Chest Disp.	29	45	40	39
L Femur	2839	5545	5299	9113
R Femur	5596	6384	6717	12053

Passenger 5^{th} female	Baseline Caravan	LCMDB Caravan	Baseline Neon	LCMDB Neon
15 ms Hic			411	
Max Nij	0.70	3.34	0.89	0.90
Chest G's	34.9	48.3	55.8	55.3
Chest Disp.	29	33	35	34
L Femur	4770	5937	4862	6304
R Femur	3242	3533	3262	3589

INTRUSION

The collisions with the LCMDB produced significantly more deformation and intrusion in the Neon than the baseline test. The Caravan had slightly higher intrusion in the baseline test than in the LCMDB test, but the change was small compared to the Neon tests. The maximum exterior crush was unchanged for the Caravan tests.

Max in mm	Baseline Caravan	LCMDB Caravan	Baseline Neon	LCMDB Neon
Toepan Intrusion	274	212	189	521
Exterior Crush	588	586	528	606

CRASH PULSE

One of the goals for this test series was to evaluate the potential for using an MDB to approximate a vehicle-to-vehicle crash environment. The acceleration of the Neon center of gravity is plotted in Figure 13 for the Neon-Caravan and the Neon-MDB tests. The acceleration profiles are generally close in shape and timing. The peak acceleration when struck by the MDB is slightly higher. The corresponding acceleration plots for the Caravan-Neon and Caravan-MDB tests are shown in Figure 14. Here there is a significant difference in pulse duration, an odd drop in acceleration around 40 ms, and a higher peak acceleration for the Caravan-MDB test. The overall crash pulse shape and timing are generally similar.

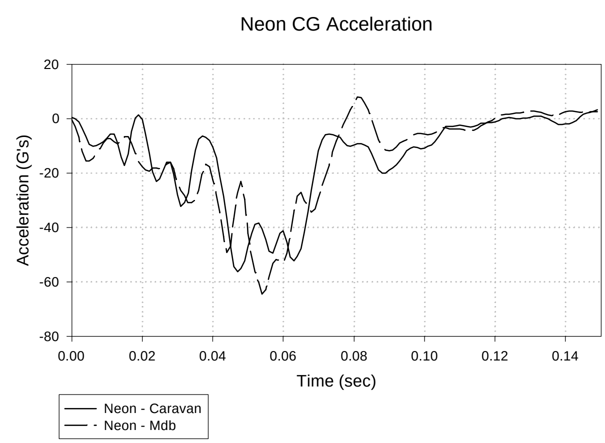

Figure 13: Comparison of Neon Acceleration

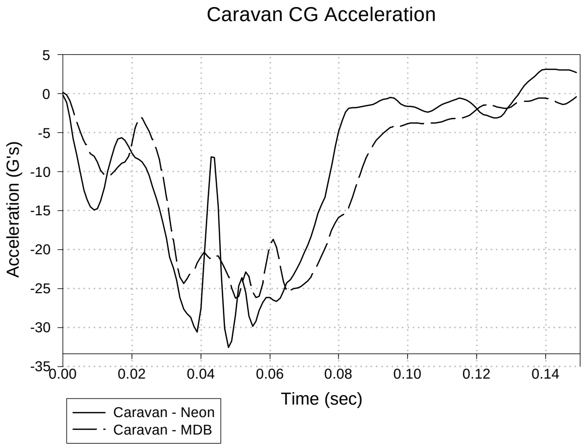

Figure 14: Comparison of Caravan Acceleration

FORCE DISTRIBUTION

Another goal for this test series was to see if the LCMDB can distinguish, based on load cell measurements, between striking the Neon and the Caravan. Before comparing force data, it is important to evaluate the accuracy of the force measurements. Assuming a constant mass for the LCMDB, the total measured force, divided by the mass should approximate the acceleration-time history of the LCMDB. Figures 15 and 16 compare the predicted and measured velocity profiles for the Neon-LCMDB and Caravan-LCMDB tests respectively. The two curves starting at 56 kmph and slowing down represent the measured and loadcell estimated velocity profile for the LCMDB, Approximately 40 percent of the change in velocity is not accounted for in the Neon-LCMDB test. The Caravan LCMDB test is better; however, still 15 percent of the change in velocity is not accounted for. This type of discrepancy is not generally observed in the NCAP test data and this simple impulse / velocity check was one of the primary factors used for quality control in reviewing the NCAP data.

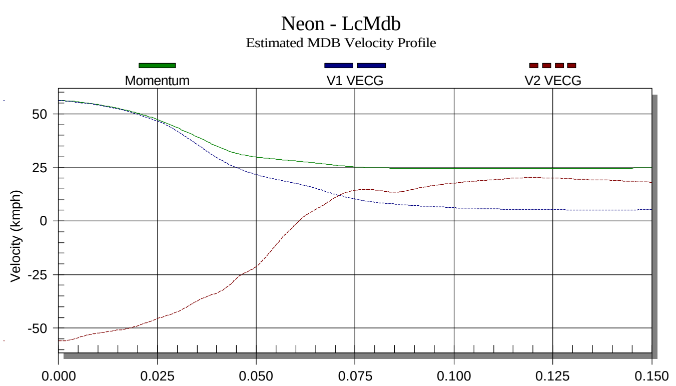

Figure 15: Evaluation of Force Data, Neon Test

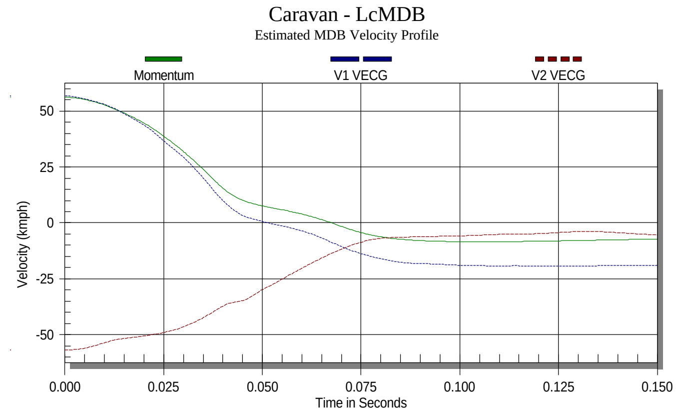

Figure 16: Evaluation of Force Data, Caravan Test

The missing force data may be understood by examining the crush patterns of the MDB face from the Neon test, shown in Figures 17 and 18. Figure 17 shows a two inch mounting surface below the bottom edge of the honeycomb face. Corresponding to this bottom edge in Figure 18, there is a noticeable crease in the deformed honeycomb. While 40 percent is a lot of force to be transferred through this small surface, this is clearly a design issue that should be addressed if an LCMDB is to be used for compatibility testing. A similar, but less severe folding pattern was also observed in the Caravan-LCMDB test.

Figure 17: Crushed MDB Face, Neon Test

Figure 18: Crushed MDB Face, Neon Test

The evaluation of the NCAP test data focused on the distribution of the force data across the surface of the load cell matrix. Figures 19 and 20 compare the impulse or time integral of the force data as measured in the NCAP and LCMDB tests respectively. These two plots cannot be directly compared because of the different geometry of the load cells. Figure 21 shows a comparison of the load cell layouts. The LCMDB effectively measures the locations corresponding to the middle two rows of the rigid barrier wall. Over this region, the LCMDB measurements are more widely distributed than for the rigid barrier. This distribution of force may be attributed to bumper element on the MDB face which was designed to spread out the load across the side of the vehicle. The bumper element is working against the goal of estimating the compatibility of the striking vehicle from the distribution of force on the load cell face. Because a significant percentage of the force was not measured in the Neon test, no strong conclusions can be reached about the distribution of force measurements from this test series.

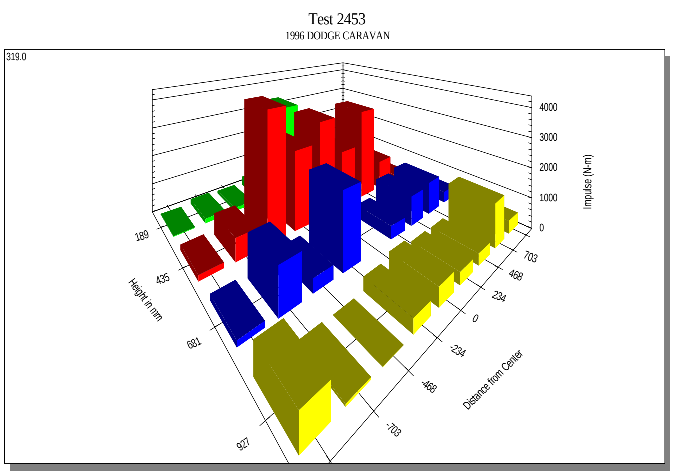

Figure 19: Distribution of Force - NCAP test

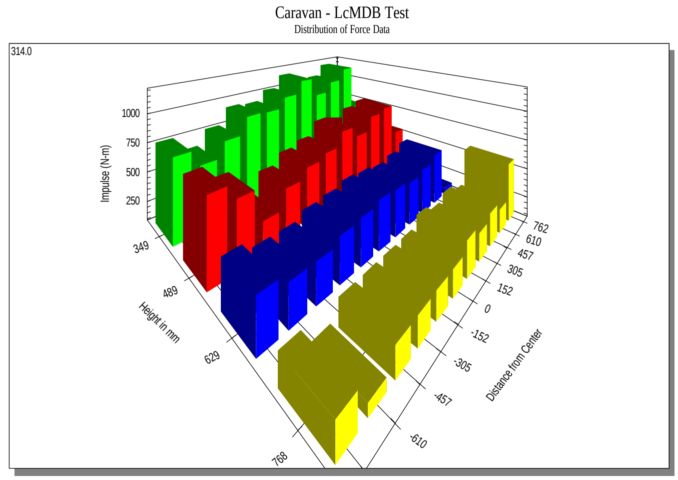

Figure 20: Distribution of Force - LcMDB

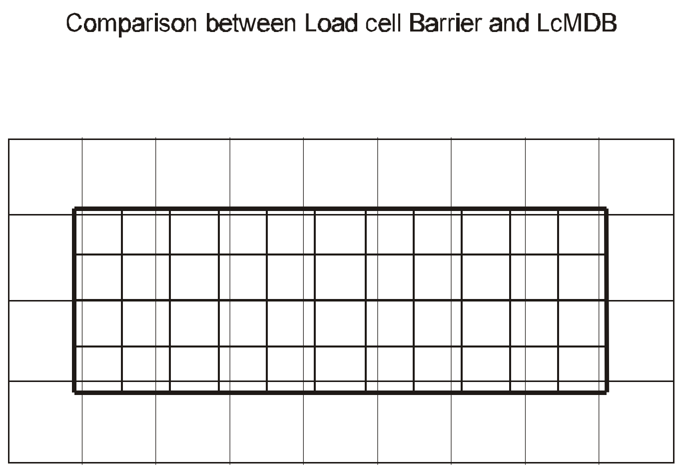

Figure 21: Overlay of NCAP and LcMDB measurements

CONCLUSION

NHTSA's compatibility research program is attempting to develop and evaluate compatibility test measures from new and existing test data. These measures should show some correlation to real world crash data and should consider both the self and partner protection aspects of vehicle compatibility. Initial testing using an existing load cell MDB produced a crash environment that reasonably replicated a vehicle to vehicle crash, but the load cell data did not produce a satisfactory measure of the striking vehicles compatibility. Additional research will be necessary to see if an MDB face can be designed that will meet the goals or approximating the crash performance of an average vehicle and providing an estimate of the compatibility of the striking vehicle.

ACKNOWLEDGMENTS

The authors would like to acknowledge to contributions of the IHRA Compatibility research group for their advice and feedback on this research program.

REFERENCES

1. H. Gabler, W.T. Hollowell, "The Aggressivity of Light Trucks and Vand in Traffic Crashes", SAE Paper 980908, March 1998

2. H. Gabler, W.T. Hollowell, "The Crash Compatibility of Cars and Light Trucks", Journal of Crash Prevention and Injury Control

3. H. Joksch, "Vehicle Aggressivity: Fleet Characterization Using Traffic Collision Data"",DOT HS 808 679, February 1998

4. H. Joksch, ""Fatality Risks in Collisions between Cars and Light Truck",DOT HS 808 802, October 1998

5. S. Summers, A. Prasad, W.T. Hollowell, "NHTSA's Compatibility Research Program", SAE Paper 01B-257, March 1999

6. K. Digges, A. Eigen, J. Harrison, "Application of Load Cell Barrier Data to Assess Vehicle Crash Performance and Compatibility", SAE Paper 1999-01-0720, March 1999

7. H. Joksch, "Vehicle Design versus Aggressivity", *To be published*

8. Trella, Samaha, Fleck, Strassburg, "A FMVSS 214 Moving Deformable Barrier with Dynamic Force and Deflection Spatial Measurement Capabilities for Full Scale Tests", SAE Paper 2000-01-0637, March 2000