NHTSA'S RESEARCH PROGRAM FOR VEHICLE COMPATIBILITY

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ABSTRACT

This paper presents an overview of NHTSA's vehicle compatibility research activities. NHTSA is monitoring the changing vehicle mix in the U.S. fleet, analyzing crash statistics, and evaluating the possible effects that these changes may have on vehicle crashes in the U.S. and thus on occupant safety. NHTSA is conducting full scale crash testing to develop a better understanding of vehicle compatibility and to identify test methods to assess vehicle compatibility. All of this research is being conducted with the close cooperation of the International Harmonized Research Activities compatibility research group.

INTRODUCTION

The objective of this research program is to explore the potential for reducing injuries by improving the crash compatibility, both structural and geometric, between passenger vehicles and their potential collision partners.

PROBLEM DEFINITION

NHTSA has published several papers that describe the growing compatibility problem in the U.S. fleet [1-4]. This section provides an update of these previous reports using two additional years of data This study uses the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES) from 1995 through 2001[5]. As shown in Figure 1, the sales and registrations of light trucks and vans (LTV's) have steadily increased, as a percentage of the fleet, since 1981 [6,7]. LTV sales appear to have recently leveled off at just under half of new vehicle sales.

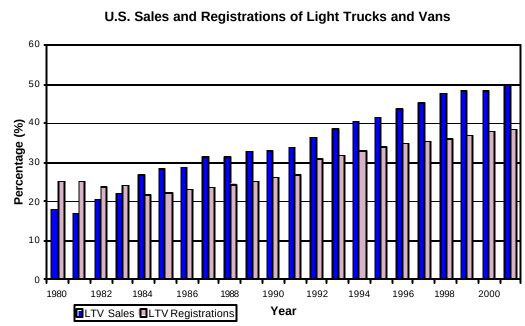

Figure 1. LTV sales and registrations

Not only are the numbers of LTV's on US roads increasing, but the average weight of LTV's has been increasing and has outpaced the weight increase of passenger cars. Figure 2 shows the average weight using the test weight and production data reported to the agency under the US Corporate Average Fuel Economy (CAFE) program [8,9]. Since 1990 the average LTV weight, using CAFE reported production data, has increased from 1868 to 2046 kg in 2000. For comparison, the average car EPA test weight has gone from 1448 to 1557 kg over the same period.

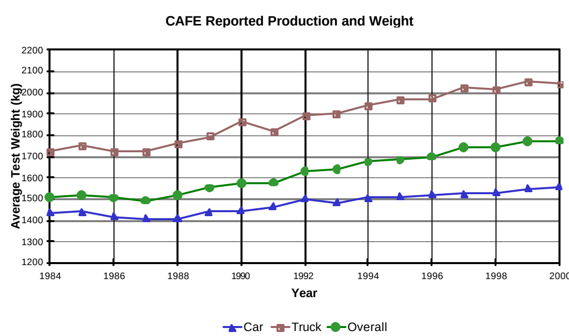

Figure 2. Annual average vehicle weights

The presence of a large number of LTV's in the fleet is leading to an increasing number of fatalities for car occupants that are struck by LTV's. Figure 3 shows the increase in passenger car fatalities that are occurring in crashes with LTV's while the fatalities for the US passenger car fleet has decreased in car-to-car crashes.

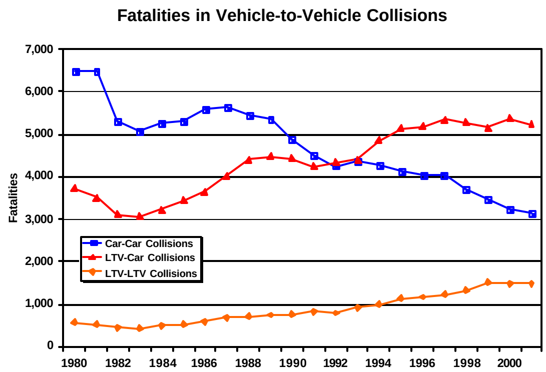

Figure 3. Occupant fatalities in 2-vehicle crashes

In order to characterize the compatibility problem, NHTSA defined an aggressivity metric based on FARS reported fatalities and GES reported crash involvements [1-4]. This aggressivity metric is defined as:

$$Aggressivity = \frac{Driver\ Fatalities\ in\ Collision\ Partner}{Number\ of\ Crashes\ of\ Subject\ Vehicle}$$

The aggressivity metric normalizes the fatalities in the collision partners by the number of crashes involving the subject vehicle. This normalization is intended to account for different vehicle populations and driver demographics. The aggressivity metrics were computed for vehicle categories using 1995 through 2001 FARS and GES databases. Only two-vehicle crashes where both vehicles were less than 10,000 lbs and were model years 1990 and newer were included. Previous analyses showed that model years 1990 and newer striking vehicles had substantially lower aggressivity metrics than for all model years combined [10,11]. Only struck driver fatalities are counted to remove any bias due to differing occupancy rates. Driver fatalities were also restricted to the ages of 26 to 55, inclusive, to remove the variation in injury tolerance shown by younger and older drivers. The LTV vehicle categories are a subset of the LTV categories included in FARS and GES. Passenger cars were categorized using the NCAP vehicle weight ranges. The passenger car weights were obtained by decoding VIN numbers. This requirement restricted the passenger car data to only the GES regions that report VINs. These passenger car distributions were scaled to obtain national estimates. A recent report from the University of Michigan demonstrated that national estimates for two-vehicle fatal crashes could be developed using only NASS GES regions that report VIN numbers [10]. The aggressivity metrics for all two-vehicle crashes, including front, side, and rear crashes, are shown in Figure 4. The additional two years of FARS data increased the total number of fatalities represented in Figure 4 by 71 percent over the totals reported in an earlier ESV paper [2], from 2,188 to 3,751. There was no change in the overall trend of higher aggressivity metrics for larger, heavier vehicle categories. The large vans and pickups cause over three times the fatality rate of large cars. SUV's produce around twice the fatality rate of large cars. The compact pickup category has an average weight similar to the large car category, yet it has an aggressivity metric that is over 60 percent higher. This observation indicates that something other than mass may play a role in aggressivity.

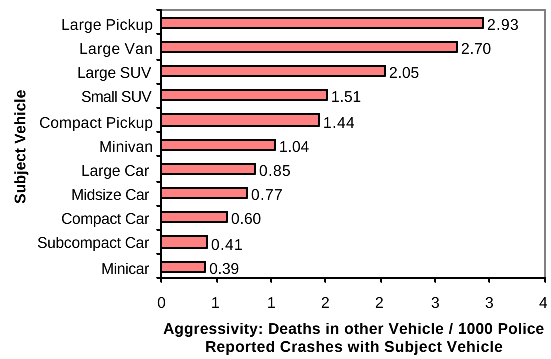

Figure 4. Aggressivity metrics for vehicle-to-vehicle crashes

Front-front crashes represent about 3.7 percent of all two-vehicle crashes, yet averaged around 4,200 annual fatalities between 1995 and 2001. The aggressivity metrics for front-front crashes are shown in Figure 5. These metrics are much higher than for all two-vehicle crashes, but the relative rankings of the vehicle categories are similar. The additional two years of data has slightly reduced the relative aggressivity of the large pickup and large van, while the aggressivity of both SUV classes has increased. [1,2]

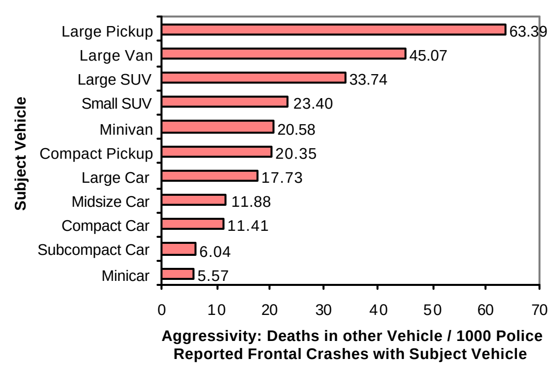

Figure 5. Aggressivity metrics for front-front crashes

Front-front crashes involve two vehicles that each experiences a frontal crash. However side impact crashes have a clear distinction between the striking and the struck vehicle. The aggressivity metrics from two-vehicle side impact crashes are shown Figure 6. The relative aggressivity of the large SUV has increased considerably from what was previously reported, while the large van and large pickup decreased slightly. The metric for the small SUV category remains about twice as large as for the large car category.

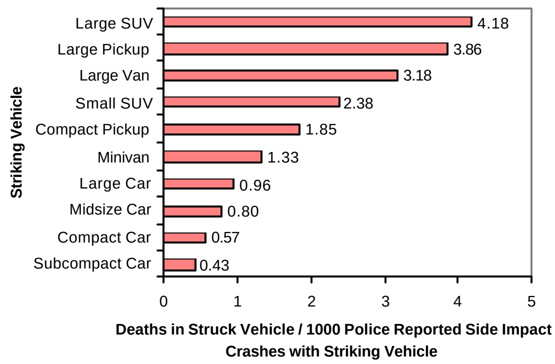

Figure 6. Aggressivity metrics for side impact crashes

For side impact crashes, it is possible to evaluate the number of fatalities in the struck vehicle per 1,000 NASS GES reported crashes, as shown in Figure 7. This "vulnerability metric" shows the number of fatalities in the struck vehicle when any vehicle strikes it. This metric has some surprising results. The minicar category has a very high vulnerability metric, but it also has the smallest number of GES reported crashes of any category. The compact pickup category is very similar to the large car category, despite a substantial difference between the aggressivity metrics of the two categories. The large SUV category had only one struck-vehicle driver fatality and was omitted from Figure 7.

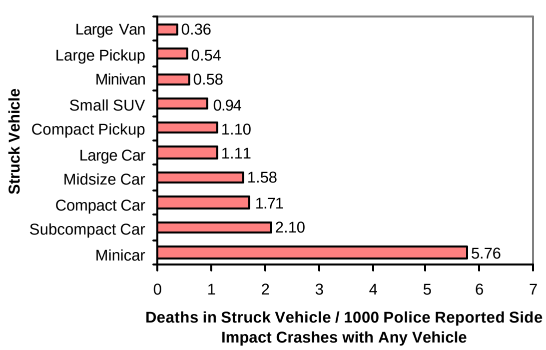

Figure 7. Vulnerability metric for side impact crashes

Europe and other regions of the world are concerned with compatibility in car-to-car crashes. Restricting the crash population to all crashes where both vehicles are passenger cars and including the same constraints on driver age and model years, the aggressivity metrics based on only driver fatalities are shown in Figure 8. The aggressivity metrics for car-to-car crashes are only slightly higher than the aggressivity metrics for the cars striking any vehicle shown in Figure 4.

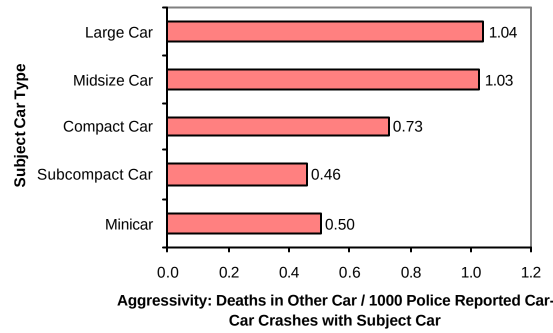

Figure 8. Aggressivity metrics for car-to-car crashes

These aggressivity metrics have established, by vehicle category, the aggressivity of the vehicle as it strikes any other vehicle in a given configuration. It is desired to examine the compatibility between specific vehicle categories, e.g., LTV into large car, rather than evaluating the aggressivity of a vehicle category striking any other vehicle. However due to data limitations, the aggressivity metrics for specific vehicle category-to-category crash configurations do not produce reliable estimates. Instead fatality ratios, which are not subject to sampling errors, can be used to study the aggressivity of vehicle category-to-category crashes. Figure 9 shows the driver fatality ratios for all passenger cars struck by five LTV categories. For consistency, these ratios were computed using the same criteria as the aggressivity metrics, two-vehicle crashes where both vehicles were model year 1990 or newer and both drivers were between ages 26 to 55, inclusive. These driver fatality ratios have not changed substantially from what was previously reported [1,2].

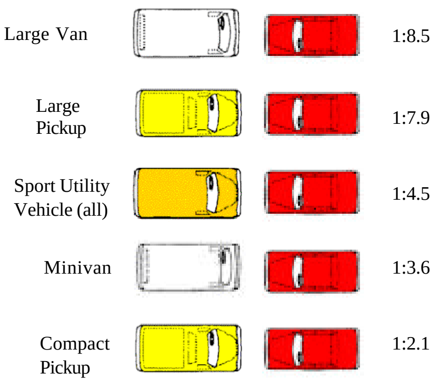

Figure 9. Driver fatality ratios for frontal-frontal LTV-to-car crashes

Driver fatality ratios were similarly computed for the side crashes, as shown in Figure 10. In side impacts, the drivers of the struck passenger cars are much more likely to be killed. It is important to remember that the 8.2 passenger car fatality ratio is the appropriate baseline for comparing the LTV-to-car fatality ratios. The side impact driver fatality ratios are based on small sample sizes and are somewhat unreliable as the large pickup and sport utility vehicle ratios are based on only 8 and 10 LTV driver fatalities, respectively.

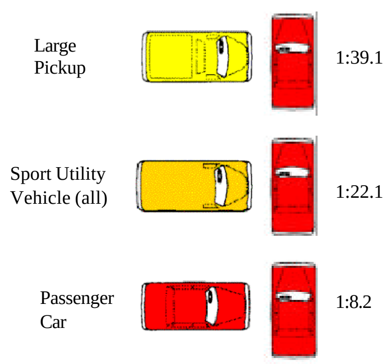

Figure 10. Driver fatality ratios for side impact crashes into passenger cars

Analysis of the FARS and GES crash data from 1995 to 2001 shows that a consistent and significant compatibility problem exists in the U.S. fleet. The passenger car occupants incur a disproportionate number of the fatalities in LTV-car crashes. The aggressivity estimates are strongly, but not entirely, related to the weight differences in the vehicles. Vehicle crash compatibility continues to be a significant concern for occupant safety in the U.S. fleet.

RESEARCH APPROACH

The compatibility of a vehicle is a combination of its crashworthiness, its ability to protect occupants within the vehicle, and its aggressivity, its potential to cause injury to the occupants within the collision partner vehicle. This research program pursues an analytical investigation of vehicle performance in vehicle-to-vehicle crashes and seeks to identify the causes of incompatibility, potential countermeasures, and to develop or evaluate performance tests for assessing vehicle compatibility. An important long-term goal is the development of a fleet wide analysis methodology that can be used to understand how the design or purchase trends in one segment of the fleet affect the safety of all occupants in the US fleet. This fleet simulation model should provide the basis for a fleet wide optimization approach.

The initial focus of the program is to identify and quantify the safety issues associated with vehicle compatibility. NHTSA has conducted numerous studies to better understand the compatibility problem and to identify vehicle characteristics associated with aggressive vehicle behavior.[1-4] Additionally, since 1997 NHTSA has sponsored a series of studies at the University of Michigan to quantify the growing compatibility problem.[10,11]

Once the compatibility problem is identified, the next task is to identify performance test(s) that can measure or predict a vehicle's crash compatibility. However, since a vehicle's compatibility performance can only be demonstrated using historical fleet crash data, any new compatibility performance test procedure will have to conduct considerable testing to demonstrate a correlation with real world performance. A second option is to rely on historical test data for real world correlation. For this reason, the development of compatibility performance test procedure(s) is initially focused on the evaluation of load cell data collected in full frontal rigid barrier testing. Load cell data have been electronically recorded for over 20 years of NCAP testing. These data are being evaluated to develop performance measures regarding the force level, distribution of force, and energy absorption. These performance measures are being fed back into the fleet studies to examine whether the performance measures are correlated with improved real world crash behavior. Initial evaluations of the NCAP data, coupled with finite element simulations [12] have been encouraging enough that NHTSA has initiated the procurement of a high resolution load cell barrier. Initial tests using the new load cell are planned for Summer 2003.

One of the shortcomings of a rigid barrier test procedure is that the barrier is infinitely heavy relative to the weight of the test vehicle. The test results from testing a heavy vehicle are not directly comparable to the test results for testing a light vehicle due to the higher energy involved in the crash of the heavy vehicle. One simple way around this energy constraint would be to run the rigid barrier tests at different impact speeds depending upon the mass of the test vehicle. This protocol is technically feasible, but leads to the requirement that small passenger cars are tested at considerable higher speeds than heavier LTV's. An alternate test procedure that can reduce, but not eliminate, the energy inequity is to mount the load cells on a Moving Deformable Barrier (MDB). In this test procedure, the change in velocity of the test vehicle depends upon its relative weight to that of the MDB. Additionally, the MDB can be designed to represent a typical collision partner in terms of weight, size, and energy absorption [13]. This type test procedure is being evaluated using similar performance measures as the rigid barrier test. The use of an MDB also introduces considerable complications in the repeatability and reproducibility of the test procedure and these concerns must be researched as well.

NHTSA's compatibility research program also explores the fleet wide evaluation of vehicle designs as a means of minimizing injuries in the US fleet. Finite element and lumped parameters simulations are utilized to model the US vehicle-to-vehicle crash environment and to predict trends in safety outcomes [14,15]. This fleet system model is intended to support benefit estimation and fleet wide safety optimization studies.

FULL VEHICLE TESTING

Recently automotive manufacturers have begun to consider vehicle compatibility in the design of new vehicles. NHTSA initiated a research program to evaluate the compatibility of the redesigned Lincoln Navigator. This vehicle and its corporate twin the Ford Expedition were redesigned for model year 2003 and include a lower front-end bumper and frame structure. The research program is intended to evaluate the effect of this vehicle redesign in vehicle-to-vehicle and vehicle-to-barrier test configurations. These tests should evaluate the performance of the compatibility countermeasures included in the redesigned vehicle and whether the proposed test procedures and test criteria reflect the vehicle redesign.

NHTSA has conducted two vehicle-to-vehicle full frontal crash tests between 2003 and 1999 Lincoln Navigators and 1996 Dodge Neon vehicles. These tests were run with both vehicles moving at 48 kmph with a 50^{th} percentile male driver and a 5^{th} percentile female frontal passenger. The vehicles descriptions are shown in Table 1 below.

Test Number	Vehicle Descriptions
4429	1999 Lincoln Navigator (2873 kg, 48.5 kmph)
	1996 Dodge Neon (1377 kg, 48.5 kmph)
4430	2003 Lincoln Navigator (3027 kg, 48.2 kmph)
	1996 Dodge Neon (1398 kg, 48.3 kmph)

Table 1. Vehicle Selections

In the redesign of the Lincoln Navigator, Ford lowered the bumper and frame rail elements for better interaction with passenger cars. This can clearly be seen in the pre test alignment photos shown in Figures 11 and 12 below.

Figure 11. 2003 Navigator pre test alignment

Figure 12. 1999 Navigator pre test alignment

The crash test kinematics for the 1999 Navigator demonstrated significant override with the top of the grill contacting the windshield of the Neon. The overriding did not occur for the 2003 Navigator. The post-test photos for the two tests can be seen in Figures 13 and 14. Here the override of the 1999 Navigator can be easily observed. It is also important to notice the increased front end crush of the Neon that impacted the 2003 Navigator. The lower design of the 2003 improved the crash interaction at the expense of increased energy absorption of the Neon structure.

Figure 13. 2003 Navigator post-test

Figure 14. 1999 Navigator post-test

The driver side toepan intrusion measurements from the Neon vehicles are higher for the Neon struck by the 2003 Navigator, see Figure 15. Conversely the steering column and instrument panel intrusions are higher for the Neon struck by the 1999 Navigator. Additionally, while the toepan intrusions in both the Navigators were low, the 1999 Navigator had consistently larger toepan intrusions than the 2003 Navigator.

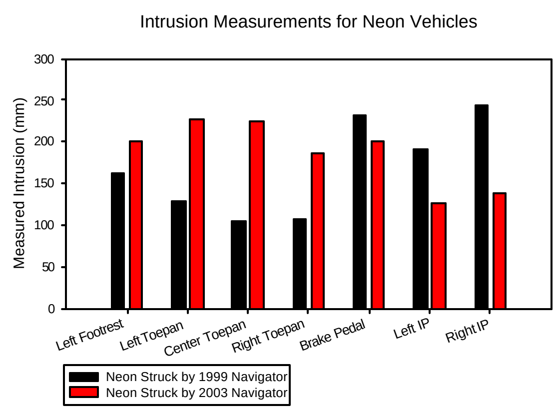

Figure 15: Neon Intrusion measurements

Despite the difference in intrusion levels the acceleration profiles measured in the occupant compartment of the Neon are remarkably similar, as shown in Figure 16. Examining the velocity profiles shown in Figure 17 indicates that the 2003 Navigator did generate an earlier change in velocity for the struck Neon.

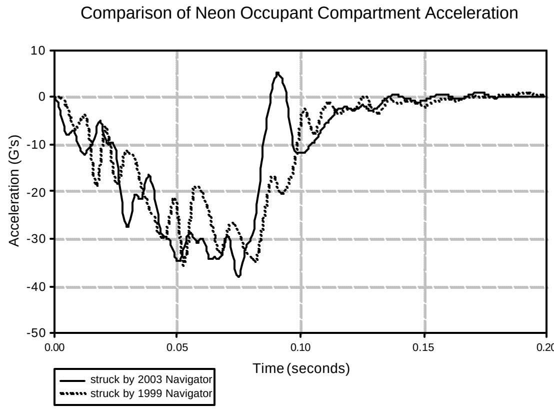

Figure 16. Neon Occupant Compartment Acceleration

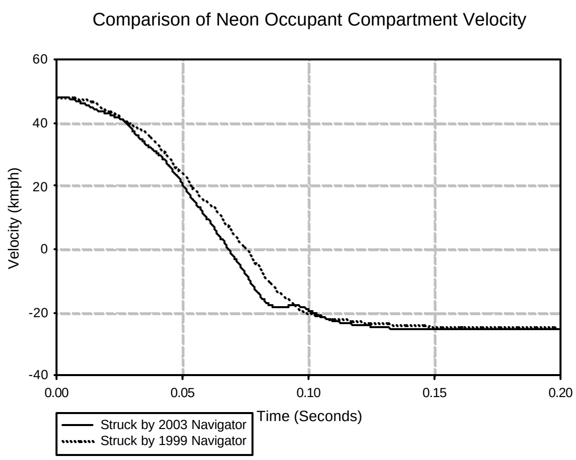

Figure 17. Neon Occupant Compartment Velocity

The injury criteria for the drivers of the Neon vehicle are shown in Table 2 below. Despite the contact between the 1999 Navigator and the Neon windshield, the HIC for the Neon driver struck by the 1999 Navigator was less than half than for the Neon driver struck by the 2003 Navigator. The chest deflection and peak femur loads were lower for the driver of the Neon struck by the 2003 Navigator. The tibia index was higher for the driver struck by the 2003 Navigator. Overall, improved crash interaction between the 2003 Navigator and the Neon did not translate into reduced injury criteria measured by the driver dummy of its crash partner.

Injury Criteria	Struck by 1999 Navigator	Struck by 2003 Navigator
15ms HIC	327	740
Max Nij	0.37	0.4
Chest G	64.4	67.9
Chest Deflection	42.8	28.0
Femur Load	10,095 (left)	7,044 (left)
Tibia Index	0.9 (left upper)	1.33 (right upper)

Table 2. Injury Criteria for Neon Drivers

DISCUSSION

The increased weight of the 2003 Navigator, certainly contributed to the increased injury criteria measured in the Neon driver. However, the vehicle redesign seems to have involved much more that just lowering the vehicle frame structure. Using the INSIA measurement protocols developed by the IHRA compatibility group [16], the minimum height of the longitudinal member went from 463 to 362 mm, a decrease of 101 mm.

NHTSA has not conducted any frontal NCAP tests for the Lincoln Navigator, but has conducted several frontal NCAP tests of the Ford Expedition, which is built on the same platform. Figure 18 shows the force-deflection profile for the 2003 Expedition compared with the results from previous NCAP tests. Clearly the 2003 model is significantly stiffer than the previous models. The 2003 Expedition was tested using a low-resolution load cell array, which prevents a comparison of the average height of force for these tests.

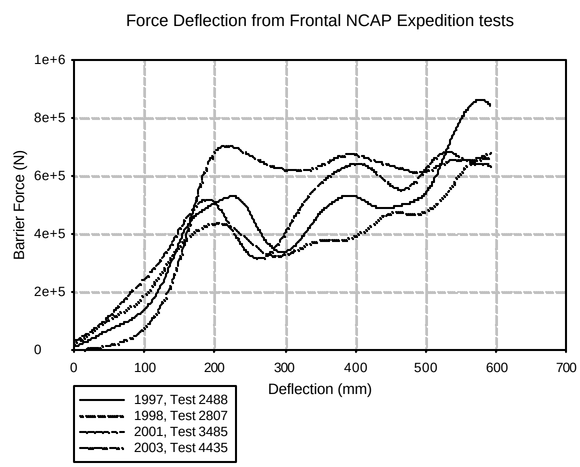

Figure 18. Force-deflection profiles for NCAP tests of the Ford Expedition

NHTSA has also conducted 40% offset barrier tests using the 2000 Ford Expedition. These tests are not directly comparable as shown in Table 3 below.

Test	Vehicle	Speed	Barrier
3441	2000 Ford Expedition	60.3	European
4441	2003 Lincoln Navigator	56.0	FMVSS 208

Table 3. 40 percent offset barrier tests

The 2003 Lincoln Navigator was 307 kg heavier than the 2000 Ford Expedition. As a result, the initial kinetic energy of the Navigator test was about 96 percent of the energy for the Expedition test. The toepan intrusions measured on the 2000 Ford Expedition are generally twice the comparable intrusions measured on the 2003 Lincoln Navigator. These offset tests support the conclusion that the redesigned Navigator is stiffer than the previous versions.

FUTURE RESEARCH

This research effort is part of a larger cooperative research program between Ford, MIRA, and NHTSA. MIRA is conducting full frontal barrier testing of 2003 and 1999 Lincoln Navigators using their ultra-high resolution load cell barrier, 50 by 50 mm sensor size. This test series will provide an exceptionally detailed comparison of the load cell data before and after redesign. This testing is intended to evaluate whether load cell data can distinguish between the designs and to provide some insight into the minimum required load cell resolution to evaluate vehicle compatibility.

NHTSA plans to follow up the high-resolution load cell barrier tests with a pair of Navigator-to-load cell MDB frontal tests. These tests are intended to determine whether the MDB-to-vehicle tests can replicate the vehicle-to-vehicle test behavior and whether the load cell instrumentation on the MDB can provide performance metrics similar to those measured on a fixed load cell barrier.

CONCLUSIONS

Light trucks and vans are continuing to increase as a percentage of the U.S. fleet. The number of occupant fatalities in cars struck by LTVs has stopped increasing in recent years. However, there still remains a significant difference in the fatality rates between LTVs and passenger cars. Large vans and large pickups are over three times more aggressive than passenger cars in all vehicle-to-vehicle crash configurations. Sport utility vehicles are over twice as aggressive as passenger cars for all vehicle-to-vehicle crash configurations. The compatibility measures for the 1995 to 2001 time period are similar to the measures previously reported for the 1995 to 1999 time period.

The vehicle factors involved in compatibility are very complex. While lowering the structural height of a vehicle could greatly improve the crash kinematics, it may not immediately translate into improved injury criteria in the collision partner. Other vehicle factors such as increased weight and stiffness of a vehicle appear to play a role in the overall compatibility performance of a vehicle in front-front crashes. More research is necessary to better understand the tradeoffs and issues involved in improving crash compatibility.

ACKNOWLEDGEMENTS

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ADDITIONAL INFORMATION

NHTSA test reports, photos, data, and video can be obtained from http://www-nrd.nhtsa.dot.gov/database/nrd-11/asp/QueryTestTable.asp

Additional NHTSA reports on compatibility research are available from http://www-nrd.nhtsa.dot.gov/departments/nrd-11/aggressivity/ag.html

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