MEASUREMENTS OF VEHICLE COMPATIBILITY IN FRONT-TO-SIDE CRASHES

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ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) routinely measures the force exerted on the barrier in NCAP crash tests. Thirty-six load cells on the face of the rigid barrier measure the distribution forces. This study examines the load cell barrier data collected during recent years of NCAP testing to determine how it can be used to assess vehicle compatibility in vehicle-to-vehicle front-to-side crashes.

The height of the center-of-force measured by the columns of load cells is proposed as a metric for quantitatively describing the geometric properties of the crash forces in the vertical direction. Another proposed metrics is the load distribution when the total force reaches 50kN. Load distribution factors are proposed, based on the number and location of load cells that carry the majority of the barrier crash forces. For front-to-side crashes, the geometric and stiffness properties of frontal structures during the early stages of crush are applicable. Consequently, compatibility measurements at a frontal crush of 125 mm or less are presented in this paper. This paper shows the values for the proposed geometric compatibility parameters measured on twenty-three late model passenger cars.

KEY WORDS BARRIERS COMPATIBILITY FORCE FULL SCALE TESTS SIDE IMPACTS

THE CRASH INCOMPATIBILITY between vehicles has been attributed to three vehicle factors: (1) mass incompatibility, (2) stiffness incompatibility, and (3) geometric incompatibility [Gabler, 1998]. The measurement of vehicle mass is relatively straightforward. However, the measurement of stiffness and geometric compatibility needs further definition.

For a stiffness metric, Gabler used the linear stiffness based on the vehicle crush at the maximum barrier force in a 35-mph crash into a rigid barrier. In survivable front-to-side collisions, the frontal crush does not produce the maximum barrier force. Consequently, the stiffness at lower values of crush is more applicable.

The Insurance Institute for Highway Safety reported a series of front-to-side crash tests to assess the influence of mass, stiffness, and vehicle ride height [Nolan, 1999]. The results were somewhat inconclusive, but suggested that the manner in which the striking vehicle deforms the struck vehicle has more influence than the vehicle stiffness alone. A significant test result was that the presence of a lower load path reduced dummy readings even for a heavy and stiff vehicle. This finding is consistent with earlier observations made by Hobbs [1989] who reported that increasing the deformation of the lower door panel so that the door does not bow inward at the shoulder level was beneficial to dummy injury measures. These investigations emphasize the importance of the geometry of the impacting vehicle in addition to its stiffness and mass. In particular, the presence of a lower load path is important.

Past studies of compatibility by the authors have addressed primarily front-to-front compatibility [Digges 1999 and 2000]. This analysis modifies the approach presented earlier to address front-to-side compatibility. In the past studies, the stiffness and geometric characteristics were examined at 250 mm and 375 mm of crush. In this study, we attempt to examine lower levels of frontal crush that are appropriate for assessing front-to-side compatibility.

BARRIER INFORMATION

The barrier used in the New Car Assessment Program (NCAP) is a rigid, fixed barrier with 36 force measuring load cells on its surface. The load cell array consists of 4 rows of 9 cells, as shown in Figure 1. The columns are numbered 1 through 9, starting at the left, facing the barrier. The array is subdivided into 6 groupings, 1 through 6, numbered left to right, and beginning with lower left grouping (see Figure 1).

The array of load cells measures the distribution of forces that the vehicle imposes on the barrier during a crash. In this study, the relationship between barrier forces and their geometric location are of particular interest. Consequently, the forces on each row and column of load cells are examined.

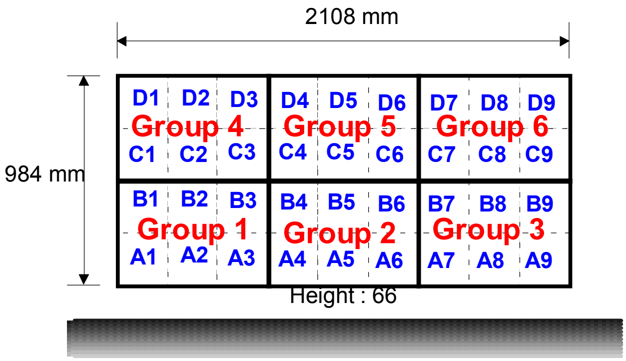

Figure 1. Configuration of Load Cells on Barrier

DATA PROCESSING PROCEDURES

In addition to load cell data, each NCAP test contains data from four or more accelerometers mounted on the vehicle. The acceleration data points used in this study were the average of two accelerometer readings. The two accelerometers selected were attached to the vehicle occupant compartment structure, close to the driver position. The purpose of the accelerometer data was to calculate the displacement vs. time of the vehicle's occupant compartment. The average of two accelerometer readings at each time point was used to reduce the effects of local vibrations of the vehicle structural elements during the crash. In the event inaccurate velocity changes of the vehicle were predicted from the two initial accelerometers, the best alternative accelerometers were selected. The raw data from all 36 load cells was processed. The raw acceleration data points were filtered according to SAE J211 Standard, with a corner frequency of 18. In earlier analyses by the authors, the barrier data was filtered in the same way as the acceleration data. This provided stiffness data that was nearly linear at crush levels of 250 mm. However, this level of filtering was found to be inappropriate for low levels of crush. Consequently, for this study, the data was filtered according to SAE J211 Standard, with a corner frequency of 90.

It was assumed that the zero time steps provided in the data were accurate, and were identical for the force and acceleration data. Beginning with the zero time step, acceleration data and barrier force data were sampled every 2 ms for 120 ms. The resulting acceleration data and load cell data were the input for subsequent analysis.

STIFFNESS AND CENTER OF FORCE CALCULATIONS

To quantify the height of the structural loading, a center of impact force was calculated for each column of cells. In addition, the height of the center of force for the total loading was calculated. For each grouping, the force on each row of cells was assumed to be uniformly distributed. The center of force in the vertical direction was determined by calculating the magnitude and height of a single force that would be required to resist the sum of the forces and moments generated by the forces on the four rows of load cells. First, the force (F) that was required to resist the sum of the load cell forces from rows A, B, C, and D was determined by static equilibrium. The height of force (F) was then found by applying moment equilibrium to the barrier forces and moment arms. The height was defined as the Center of Force. Sample calculations for the center of force for the 36 load cells are shown in Table 1.

The stiffness was calculated by dividing the force measured by the load cells at a particular time by the calculated vehicle crush at that time. The vehicle crush was determined by double integration of the longitudinal acceleration measured on a structural member close to the vehicle's center of gravity.

Table 1. Sample Calculation of Height of Center of Force, 1995 Ford Explorer

Rows	Force, N	Row Height, mm.	Force x Height
D Hi	128,985	861	$111x10^6$
C Hi	336,652	615	$207x10^6$
B Lo	104,001	369	$39x10^6$
A Lo		123	.
Total	569,638		$356 x10^6$

Barrier C of Force $(356x10^6)/(569,638)$ mm..	625.6
Ground Clearance (mm.)	66.6
Height Above Ground of Force Center, mm.	692.2

SELECTION OF BARRIER DATA

In the NCAP tests, the vehicles' frontal crush exceeds 400 mm. For survivable front-to-side impacts, the front of the striking vehicle crushes much less than 400 mm. To determine the extent of crush required, we examined the data from several sources. These sources include crush tests of the sides of vehicles to determine their stiffness, front to side vehicle to vehicle tests, and real world crashes.

There is some vehicle side crush data that has been reported in NHTSA research programs. In one research program, side crush tests were performed by mounting a vehicle in a static test fixture described in the research report (DOT 1977). Each test vehicle was positioned in a static test machine so a flat rigid platen could be forced into its side. The rigid platen had dimensions 1651 mm wide by 457 mm high and was intended to be representative of the frontal area of a midsize car. The side edge of the loading plate was 76 mm aft of the forward front door cut line. The bottom edge was positioned so that it loaded the side structure above the door sill. The loading ram was advanced in increments of 12.7 mm.

Tests of three production cars were reported. They were a 1976 Simca 1705, a 1975 Honda Civic, and a 1975 Plymouth Fury. The test results, shown in Figure 2, indicate an average initial stiffness of about 0.35 kN/mm. At forces above about 50 kN, the stiffness was reduced. At 250 mm of crush, the applied force averaged about 80 kN.

Another series of tests measured the door stiffness of seven different passenger cars, model year 1980. The results of the door tests found an average initial stiffness was 0.25 kN/mm. However, the stiffness decreased after about 75 mm of crush. The results are reported in Digges 1999.

By contrast, the NCAP tests show that most passenger cars apply 50kN of force to the barrier at about 100 mm of frontal crush. This frontal crush data suggests that the geometry of the force generated by a vehicle's front structure during the initial period of frontal crush is most influential in controlling the side crush of the struck vehicle. The side crush data indicates that force levels of 30 to 70 kN produce significant crush to the side structures of the vehicles tested.

NHTSA has not reported more recent static crush data on vehicle side strength. However, in 1998, NHTSA conducted four vehicle-to-vehicle front-to-side tests and reported the crush information on both vehicles (TRC, 1998). One test was of a passenger car and three were of light trucks. The test configuration replicated the crash direction of the FMVSS 214 Side Impact

Protection Standard with the impact speed of 53 kph. The passenger car test was of a 1995 Chevrolet Lumina into the side of a 1993 Honda Accord.

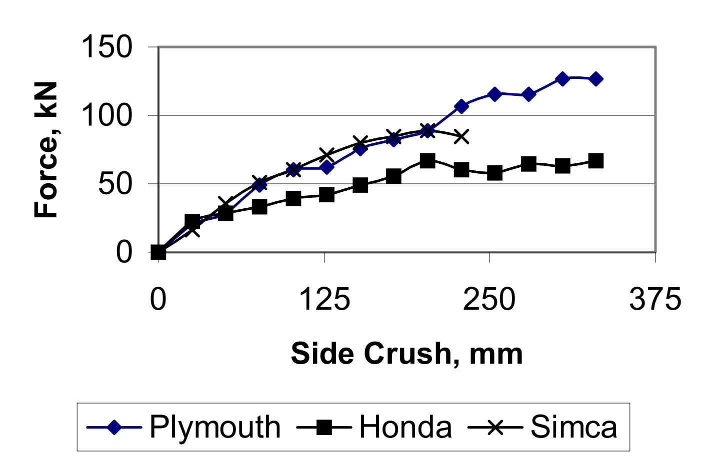

Figure 2. Static Crush Tests of Vehicle Side Stiffness

In the FMVSS 214 test, the front of the barrier is parallel to the side of the car at the time of initial impact. However, the lateral velocity and impact location causes the struck vehicle to rotate about the edge of the barrier that engages the rear door. Maximum side crush frequently occurs at this location. The loading of the front door was assumed to be more comparative with the static crush tests reported earlier. In the Lumina to Accord test, the maximum crush for the Lumina was 73 mm and the maximum front door crush for the Accord was 420 mm. The Lumina bumper is composed of a metal bar positioned 100 to 170 mm behind a fascia that resists damage. The 73 mm crush was the deformation of the metal bumper bar. The total elastic and plastic crush was in the order of 250 mm.

The load cell barrier readings for the Lumina are shown in Figure 3. Figure 3 shows that during the initial 125 mm of crush, virtually all the loads is on the B row of load cells. The force builds to 92 kN during this period. Above 125 mm of crush, force is exerted on the C rows, as well.

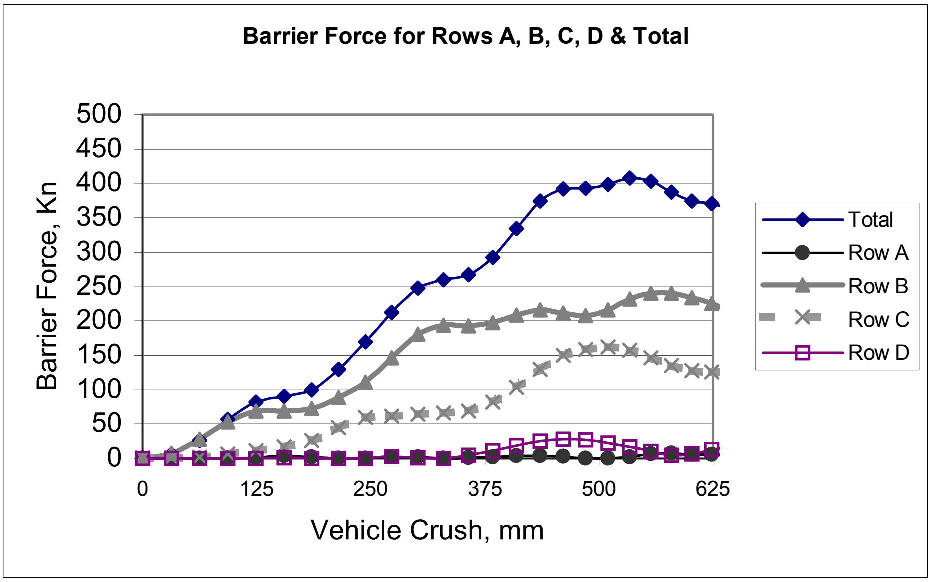

Figure 3. Force Deformation of the Chevrolet Lumina, Based on Load Cell Readings

Figure 4 shows how the force is distributed across the barrier face at three levels of vehicle crush. The crush levels are 75 mm, 125 mm, and 250 mm. At 75 mm of crush, the total barrier force is 55 kN which is almost equally distributed across the three center columns of load cells. The loading is primarily from the bumper. At 125 mm of crush, the loading on columns C4 and C6 increases more than C5. At 250 mm, the maximum forces move to L3 and R7. This indicates that the stiff frame on each side of the vehicle is loading the barrier.

An examination of the barrier force characteristics of other passenger cars indicates a similar loading pattern to that in Figure 4. The load distribution during the bumper loading has a more uniform pattern than occurs after frame loading begins.

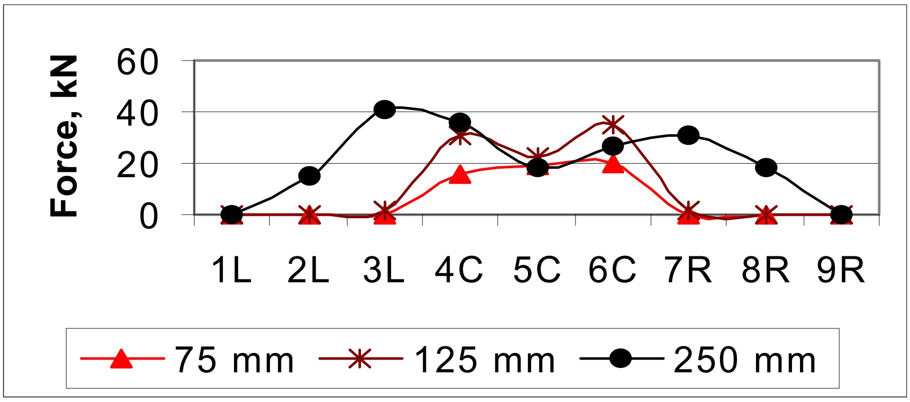

Figure 4. Force Distribution Across the Barrier for the Lumina Crash Test Measured at 75 and 125 and 250 mm of Crush

Others have reported that more than 50% of the serious injuries in side impacts occur in crashes more severe than the tests specified by US and European Standards [Thomas, 1999]. Consequently, the test Lumina to Accord test conducted by NHTSA may not be representative of real world side impacts that produce injury. The 1997 to 1999 data from National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) was examined for cases that involved the Chevrolet Lumina impacting the driver's side of other passenger cars. A total of three Lumina cases were found in which the impact was at the occupant compartment of the struck car and the crash severity was sufficient to cause an AIS 1+ injury to the driver of the struck vehicle. The maximum AIS in the cases was 3. In all three cases, the measured deformation for the Lumina exceeded 125 mm. The loading on the Lumina was more complex than the car-to-car tests that produced only 75 mm of crush.

A crush level of 125 mm was selected as a basis for comparing the frontal stiffness and geometry of vehicles in front to side collisions. This lower crush level was selected in order to examine the height and uniformity of loading produced by the front of the vehicle before its frame is engaged.

COMPATIBILITY MEASUREMENT FOR VEHICLES IN NCAP TESTS

The barrier data for NCAP tests of passenger cars conducted between 1995 and 1999 were reviewed for applicability to the analysis outlined earlier. Some tests were rejected because complete load cell data was not collected. Others were rejected because the barrier was different in configuration from that in Figure 1 or because the measured forces and resulting vehicle accelerations were not in agreement. A total of 23 tests of different makes and models of passenger cars were analyzed and the results are reported in Table 2.

Table 2 shows the vehicle make and model, its weight (Weight) in Kg, and the center of force height (COF) in mm, measured at 125 mm of crush. Several other parameters are also reported. One is the extent of crush in mm when the force reached 50kN (Crush 50 kN). This parameter is inversely related to the stiffness.

Table 2. Geometric Compatibility Metrics for Passenger Cars in Front-to-Side Crashes

Test No.	Mode Year	Vehicle Make	Model	Weight Kg	COF mm	Crush 50kN	No. Lo	No. Hi	No. > 15kN
2239	1995	Geo	Metro	1125	431	116	4		1
2372	1996	Mitsubishi	Mirage	1185	440	114	3		2
2968	1999	Saturn	SL1	1255	440	114	3		2
2993	1999	Honda	Civic	1259	444	113	3		1
2257	1995	Kia	Sephia	1290	442	113	4		1
3001	1999	Mazda	323-Protégé	1321	456	110	3		2
2320	1996	Dodge	Neon	1354	442	113	3		2
2398	1996	Hyundai	Elantra	1422	485	103	5		1
3009	1999	Mazda	626	1459	434	115	5		1
2232	1995	Mitsubishi	Eclipse	1490	471	106	5		
2221	1995	Dodge	Avenger	1516	483	103	3		1
3051	1999	VW	Beetle	1573	432	116	3		1
2806	1998	Ford	Mustang	1585	534	94	3	1	
2967	1999	Pontiac	Grand Am	1618	523	96	3	1	1
2252	1995	Dodge	Stratus	1626	501	100	3		
3031	1999	Subaru	Forester	1654	462	108	4		
2250	1995	BMW	325 I	1717	488	102	2		1
2222	1995	Chevrolet	Lumina	1741	468	107	3		1
2454	1997	Pontiac	Grand Prix	1753	482	104	3		
2342	1996	Lexus	ES300	1759	490	102	3		1
2312	1996	Ford	Taurus	1764	480	104	3	1	
3005	1999	Dodge	Intrepid	1770	465	108	2		1
3007	1999	Oldsmobile	Intrigue	1783	491	102	3		2

Two other factors were proposed as load distribution and concentration factors. The load distribution factor is the number of load cells that register more than 5kN of the load when the total load is 50kN. The IIHS tests suggest that for pickup trucks with high fronts, some load concentrations at the bumper level may reduce dummy readings (Nolan, 1999). Load distribution, in the A and B rows may be more favorable than load distribution in the C and D rows. Consequently, the load distribution factor is reported separately by lower (A&B) and upper (C&D) rows. In Table 2, these factors are designated as "No. Lo", and "No. Hi", respectively.

The load concentration factor is the number of load cells that register more than 15kN when the total load is 50 kN. This factor is designated as "> 15 kN". in Table 2.

DISCUSSION

The Center of Force, measured at 125 mm of crush varied from 431mm to 534 mm. This parameter shows a significant difference in the geometric height of the frontal loading of different passenger cars. However, the Center of Force does not give an indication of whether or not a load path exists at the level of the struck vehicle's lower door sill. For the Honda Accord, the top of the door sill was 320 mm above the ground. A striking vehicle would have to engage the "A" row of load cells in order to directly load the sill of the Accord. At crush levels that only engage the bumper, the lower height of the bumper structure may be a better indicator of the geometric compatibility than the Center of Force, as measured by the NHTSA barrier. The reason for this observation is discussed in the paragraphs to follow.

For many of the passenger cars reported in Table 2, the force was concentrated on only the "B" row of load cells. Additional resolution would be desirable to improve the accuracy of the center of force calculation. It would be particularly desirable to have better resolution of the B row level. The bottom of the B row is positioned 312 mm above the ground. The ground clearance of NHTSA barrier is 280 mm. and the lower edge of the bumper is at 330 mm. Tests reported in the literature indicate that increases in the barrier ground clearance of 50 to 100 mm result in large increases in struck vehicle deformation [Terrell, 2001]. Dummy injury measures also increase [Terrell, 2001]. The force distribution just above and below the intersection of the A and B rows of load cells appears to be a critical geometric compatibility parameter. Consequently, additional resolution of the force distribution in this region is warranted.

The vehicle frontal crush that resulted in 50 kN of barrier force ranged from 94 mm to 116 mm. The loading at this level of crush was primarily by the bumper. However, the accuracy of the data at these low load levels needs further investigation.

Measurements of geometric and stiffness properties at low values of crush requires accuracy of the load cells at low load values. In addition, it requires precision in the determination of time zero for the acceleration and the barrier data. To date, the barrier data has been used primarily for assessing the maximum loads and the stiffness based on large amounts of crush. Consequently, accuracy at low loads has not been a major concern. If measurements at low loads become important, additional calibration may be required to assure the accuracy of the data.

Other researchers have reported that maintaining a low but distributed load on the vehicle side is beneficial to side impact protection [Hobbs, 1989]. To assess uniformity of the barrier loading, the number of load cells that register more than 10% of the load and more than 30% of the load are reported. For uniform loading, the number with more than 10% should be large and the number with more than 30% should be small. Seventeen of the vehicles had one or more load cells that registered more than 30% of the load, and five had two load cells that totaled more than 60% of the load. Three of the vehicles had load cells in the "C" row (above 558 mm) that measured more than 10% of the load.

The degree to which compatibility is influenced by loading uniformity across the vehicle width has not been established. As reported earlier, IIHS tests found benefit from load concentrations when they were at a low level [Nolan 1999]. For the twenty three vehicles analyzed in Table 2, three had five load cells that registered more than 10% of the load, and two had only 2 load cells that registered more than 10% of the load. The Lumina, for which there is test data, had three calls in the B row that registered more than 10% of the load, one of which registered more than 15% of the load.

The results of the barrier data analysis provide useful insights into the geometry and stiffness of vehicle frontal structure in a barrier crash. It should be noted that the data presented is restricted to passenger cars. Additional metrics may be applicable to light trucks. The selection of 50 kN as the force level for reporting barrier load distribution was partially based on static testing of older models of vehicles. A higher force may be more appropriate for newer vehicles that have been designed to meet more comprehensive side impact standards. . A combination of the bumper height, the center of force and the force distribution may be required to adequately assess front-to-side compatibility.

The proposed metrics need to be evaluated further. The evaluation should include the assessment of a larger number of static tests and crash tests, as soon as they are conducted and reported. In addition, the metrics should be evaluated by determining the extent to which they explain the differences in vehicle aggressiveness characteristics observed in the on-the-road crash data.

CONCLUSIONS

The load cell barrier data from NHTSA's NCAP tests provides a basis for measuring the forces exerted by the front of vehicles during the crash. For front-to-side crashes, the distribution of forces at low levels of frontal crush are most influential on the side impact compatibility. In NHTSA's Lumina to Accord crash test simulating the FMVSS 214 crash configuration, the crush of the bumper bar was less than 75 mm. For NASS/CDS real world injury producing crashes involving the Lumina as the bullet vehicle, the frontal crush was larger than 100 mm. The vehicle stiffness and geometric measurements during the initial 125 mm of frontal crush are essential for evaluating front-to-side compatibility.

The accuracy of the barrier forces at low loads is critical to the measurement of front-to-side compatibility from NCAP load cell barrier data. Additional force resolution at the height of 300 to 350 mm would permit better assessment of the lower load path loading of the vehicle frontal structures. The lower load path loading appears to be a critical parameter in front-to-side compatibility.

The 23 vehicles analyzed varied by a range of 103 mm in the height of the center of force measured at 125 mm of crush. Differences were also identified in the uniformity of loading.

ACKNOWLEDGMENTS

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