ACCURACY OF AHOF400 WITH A MOMENT-MEASURING LOAD CELL BARRIER

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ABSTRACT

Several performance measures derived from rigid barrier crash testing have been proposed to assess vehicle-to-vehicle crash compatibility. One such measure, the Average Height of Force 400 (AHOF400) [1], has been proposed to estimate the height of a vehicle's primary energy absorbing structures. Previous studies have shown that the difference in AHOF measures is a significant predictor of crash partner fatality in vehicle to vehicle crashes. However, the single axis 250x250 mm and 125x125 mm size of the load cells limited the accuracy of these performance measures. The National Highway Traffic Safety Administration (NHTSA) recently purchased an advanced load cell barrier using 125 x 125 mm load cells (in a 9x16 load cell array) that measure compressive force and moments. Simulation studies predicted this should significantly improve the AHOF accuracy. This test program will evaluate this prediction. Previous studies suggest that single axis load cell measurements may not provide sufficient accuracy. This paper will evaluate the results using a rigid barrier that measures vertical and lateral moments in addition to longitudinal force. The results will be evaluated against vehicle geometry measurements. Six crash tests were conducted using an advanced load cell barrier with vertical and lateral moment capability. The test results are compared with previous single axis 125 x 125 mm rigid barrier tests. The additional accuracy resulting from the moment data is assessed. The benefits of the advanced load cell barrier in terms of amplifying and enabling compatibility criteria are discussed.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) regularly conducts crash tests of vehicles into a rigid load cell barrier. The load distribution on the load cells during the crash test provides information on the structural load paths that develop and decay during the event. In particular, the average height of force (AHOF) and the load transferred into the 49 CFR Part 581 bumper height zone can be important indicators of how effectively front end structures would manage load interaction with a crash partner. The Part 581 bumper zone is 16-20 inches (406-508 mm) above the ground as established by NHTSA federal regulation.

Traditional barrier load cells are square faceplates supported from a rigid wall through a device for measuring applied load. An inherent drawback to this approach is that the analyst is forced to assume the load is applied through the center of the cell when in fact it could be distributed in an arbitrary manner across the surface. The load distribution may well be nearly uniform across the surface of the load cell, but there is the theoretical possibility that the load is concentrated at one edge of the load cell, resulting in an error between the actual and assumed position of as much as one half of the load cell dimension [2].

In order to minimize this error, NHTSA, in conjunction with the Volpe National Transportation Systems Center (Volpe Center), developed a prototype barrier that uses 125x125 mm load cells which can also measure the moment applied about the y- (transverse) and z-axes (vertical) of the load cells mounted in the vertical y-z plane. The ability to measure the moment should reduce or eliminate the error in height of force (HOF) calculations. The additional data from advanced load cells will also increase the resolution of force distribution plots.

Six crash tests using the advanced high resolution barrier were conducted at the Transportation Research Center (TRC) of Ohio. The data from these tests are in the NHTSA crash test database as tests 6945 (2003 Honda Odyssey), 6946 (2005 Honda Odyssey), 6947 (2006 Ford F-250), 6948 (2007 Chevrolet Silverado), 6982 (2006 Honda Ridgeline), and 6983 (2002 Ford Focus). This paper assesses the results of these tests and the effect of the enhanced data on compatibility metrics.

EMPLOYING ADDITIONAL DATA IN ANALYSES

For ease of visualization and calculation, the distributed loads on a load cell surface are usually characterized by a point load of equivalent magnitude located at the center of the cell. The data from each advanced load cell are characterized by one force and two moments (F, M_y, M_z) as depicted in Figure 1. A straightforward approach to visualizing the implication of this additional data is to break the load down into an equivalent set of four point loads that yield the same total force and moment, as shown in Figure 2.

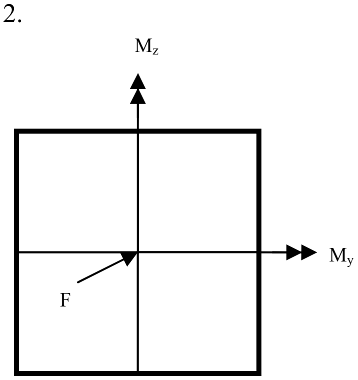


Figure 1. Load data available for advanced load cells.

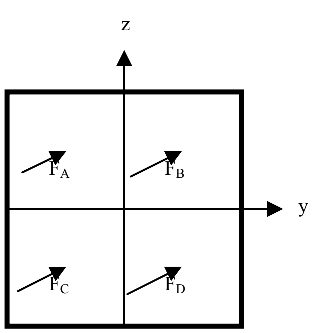


Figure 2. Equivalent force and moment through multiple loads.

It can be shown that for a square load cell of width W, the forces needed to replicate the same total force and moments would be:

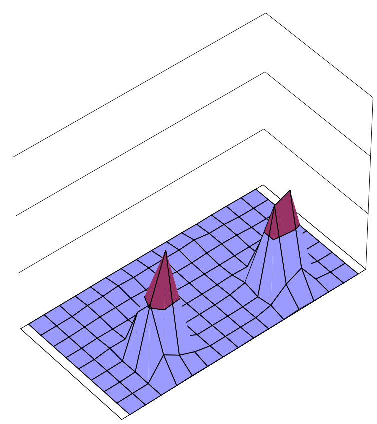
$$F_A = \frac{F}{4} - \frac{M_y}{W} - \frac{M_z}{W} \quad (1a)$$

$$F_B = \frac{F}{4} - \frac{M_y}{W} + \frac{M_z}{W} \quad (1b)$$

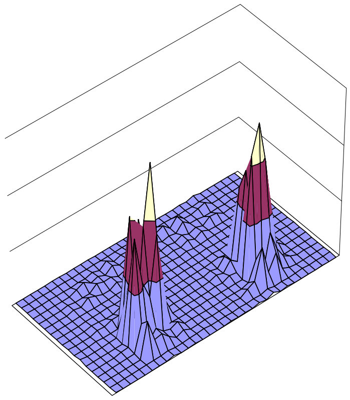
$$F_C = \frac{F}{4} + \frac{M_y}{W} - \frac{M_z}{W} \quad (1c)$$

$$F_D = \frac{F}{4} + \frac{M_y}{W} + \frac{M_z}{W} \quad (1d)$$

This representation of one force and two moments by four forces effectively doubles the resolution of the equivalent point loads in both dimensions (See Figure 3) which can yield important additional detail. This also provides a more accurate average height of force calculation than the force data alone.



(a) Load data only - 125x125 mm resolution.



(b) Load and moment data - 62.5x62.5 mm interpreted resolution.
Figure 3. Point load distribution at maximum total load for test 6947.

The addition of moment information to the load cell data gives an indication of the distribution of forces across the load cell. Of course, with only two quantities of data about the distribution in, say, the z-direction (that is, F and M_y), the best that can be asserted is a linear estimate of the force distribution. Nonetheless, given this formulation, a better estimate of the force in a specific subsection of a load cell can be made. In particular, an improved estimate of the force in the Part 581 bumper interaction zone (from 16-20 inches above the surface) can be made.

In load cell barriers with 125 x 125 mm cell dimensions, the rows of load cells are typically arrayed such that the boundary between the third and fourth row from the floor runs along the centerline of the Part 581 zone. The linear force estimate enables some of the compatibility criteria that depend on the sum of forces in the nominal[1] third and fourth rows of load cells (“F3” and “F4”) to be adjusted for the Part 581 zone itself.

It can be shown that the equation for the linear approximation of force per unit height (as a function of height) can be given as:

$$p^{linear}(z) = \frac{F}{W} + \frac{12M_y}{W^3} z \qquad (2)$$

where the origin is at the center of the load cell. If the bottom edge of a 125x125 mm load cell were at the center of the Part 581 zone, then the estimated force applied within the upper half of the Part 581 zone would be:

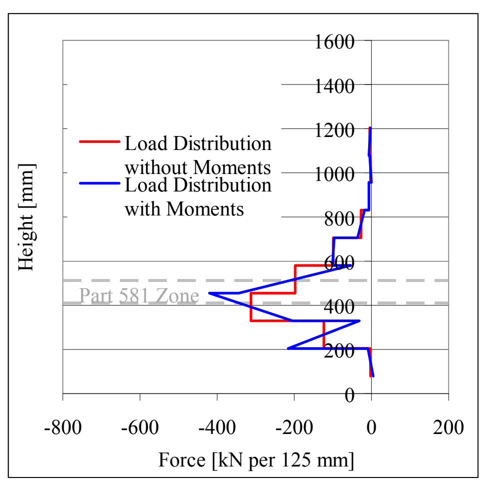
$$F^{Part581} = \int_{-62.5mm}^{-11.7mm} \left(\frac{F}{W} + \frac{12M_y}{W^3} z \right) dz \qquad (3)$$

TESTING PROGRAM

An enhanced load cell barrier with 125x125 mm load cells was constructed and used in six rigid barrier tests. There were nine rows of 16 load cells (a 9x16 array) for a total of 144 load cells. The nominal crash speed was 35 mph (56.3 kph). The vehicles tested were

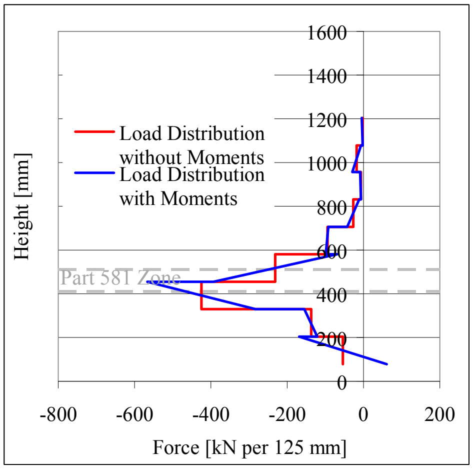
- 2003 Honda Odyssey (Test 6945)
- 2005 Honda Odyssey (Test 6946)
- 2006 Ford F-250 (Test 6947)
- 2007 Chevrolet Silverado (Test 6948)
- 2006 Honda Ridgeline (Test 6982)
- 2002 Ford Focus (Test 6983)

The presence of moment data allows for an estimate of the load distribution across the barrier rows that is piecewise linear instead of a step function. Figures 4a through 4f show the load distribution along the z-axis at the maximum total force level for each test. Each data channel from the load cell barrier was filtered with a Society of Automotive Engineers (SAE) CFC 60 filter. The lowest row often experiences load only near the top edge, leading to apparently anomalous estimated tensile loads at the bottom edge. Note that an occasional data channel yielded anomalous data. In these cases, the data was simulated either by the average of the data channels to either side of it or by the symmetric channel on the opposite side (i.e., right vs. left) of the barrier.

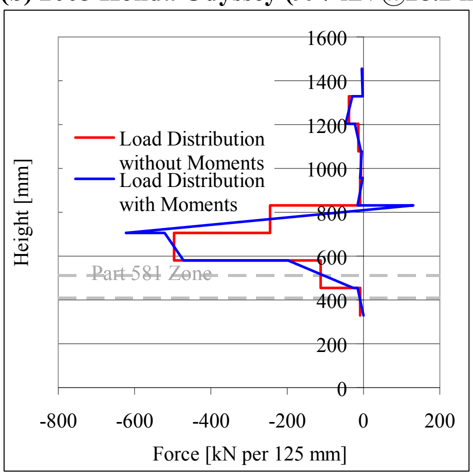


(a) 2003 Honda Odyssey (777 kN @31.4 msec).

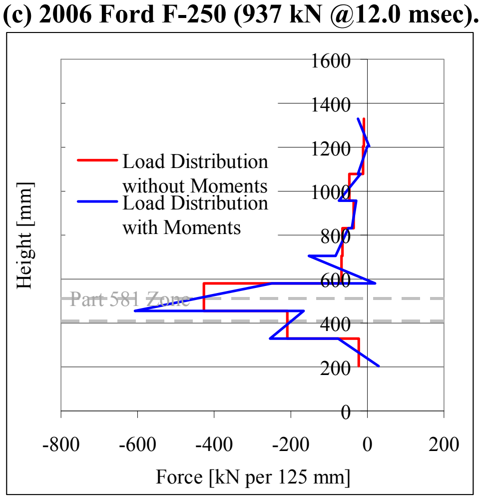
[1] Some tests of vehicles with high ground clearance and high front hood height will forgo the lowest row or two of load cells in lieu of additional rows at the top of the barrier.



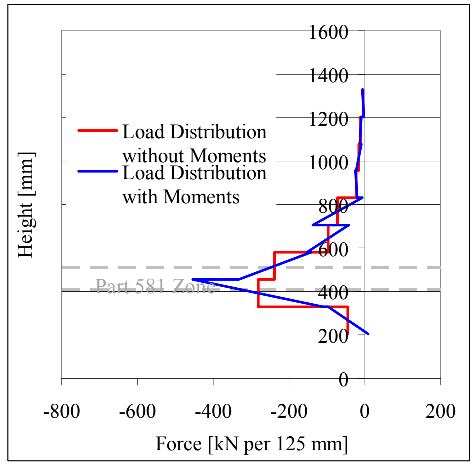
(b) 2005 Honda Odyssey (997 kN @28.2 msec).



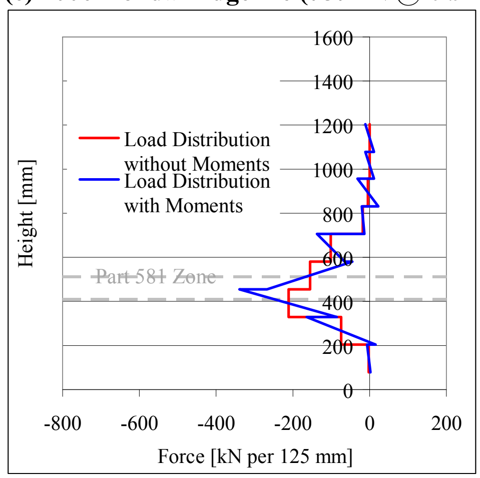
(c) 2006 Ford F-250 (937 kN @12.0 msec).



(d) 2007 Chevrolet Silverado (898 kN @48.2 msec).



(e) 2006 Honda Ridgeline (787 kN @29.9 msec).



(f) 2002 Ford Focus (566 kN @39.2 msec).

Figure 4. Load distribution at maximum total load by vertical location with and without moments.

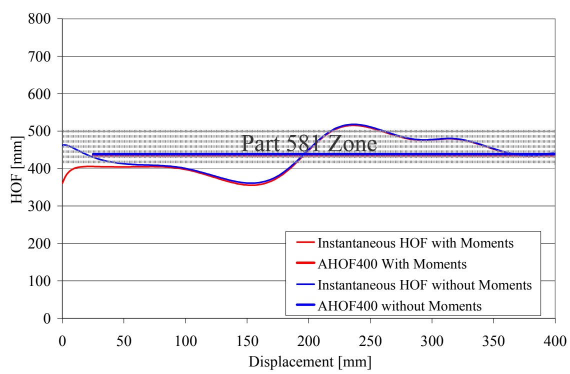
The force distributions at the time of maximum total load exhibit reasonably expected behavior in most cases, with most load being reacted in the third and fourth rows. Calculations with the moment data further imply that the load in those rows was primarily reacted in the Part 581 zone. A few anomalous negative loads are observed, but they are within the magnitude that might be expected if a major load path were temporarily aligned with the upper or lower half of a row of load cells.

The Ford F-250 and Chevrolet Silverado exhibited most of their crushing load above the Part 581 zone. This is indicative of potential problems with geometric compatibility. For this reason, these vehicles have been equipped by their manufacturers with Secondary Energy Absorbing Structures (SEAS). These components mounted below and behind the bumper structure provide a means for interaction between the vehicle and other lower vehicles which may have begun to ride under their primary structure.

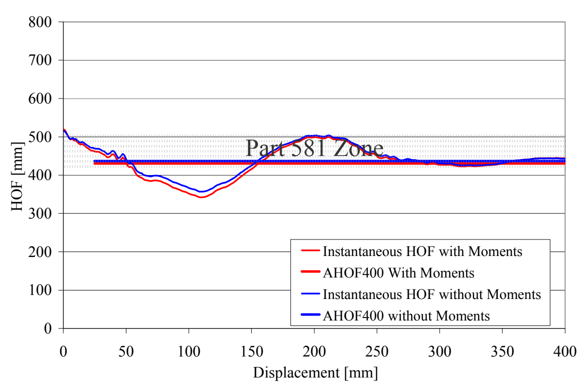
AVERAGE HEIGHT OF FORCE (AHOF400)

The height of force (HOF) can be computed at any instant by summing the product of applied force and the central height for all load cells and dividing by the total load. AHOF400 is the value of the instantaneous HOF for each data point weighted by the distance the occupant compartment travels over the associated data acquisition interval for the total displacement range 25 mm to 400 mm [1]. AHOF400 was first computed for the tests in the normal manner. It was then recomputed using the enhancement enabled by the moment data.

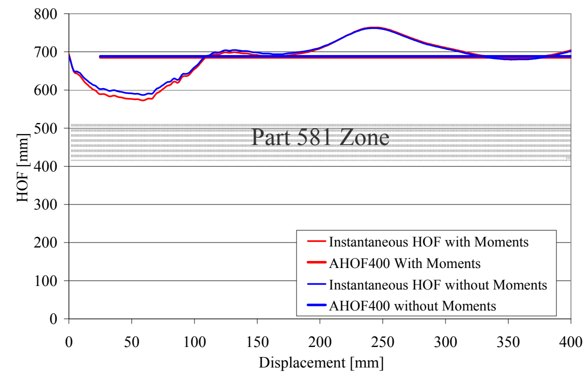
Figures 5(a) through 5(f) show the progression of HOF through the test for the two calculation methods. The calculated AHOF400 is also shown for reference.



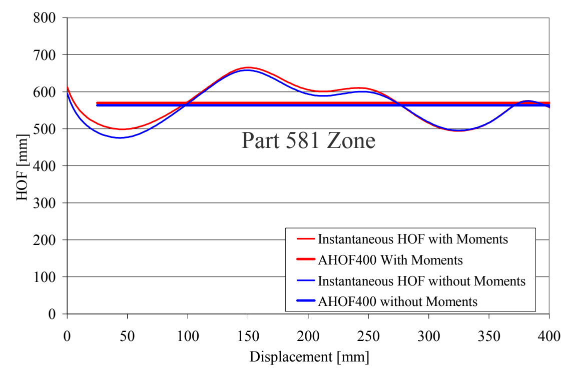
(a) 2003 Honda Odyssey.



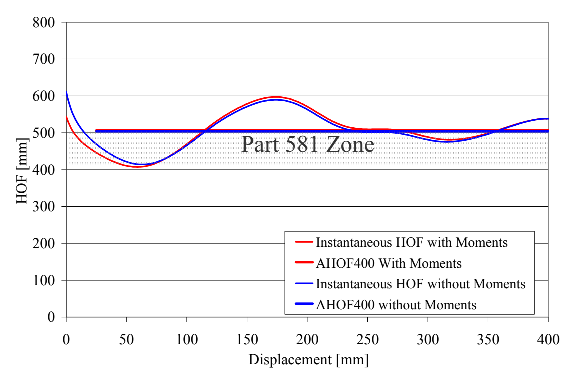
(b) 2005 Honda Odyssey.



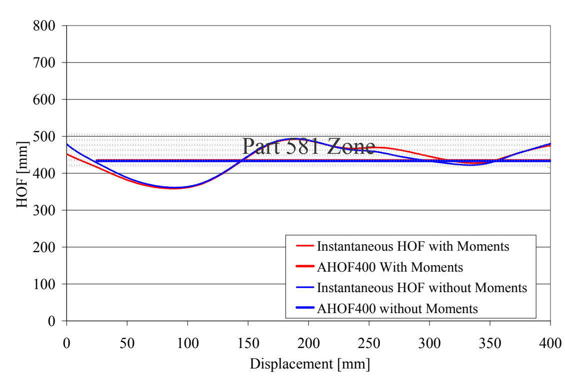
(c) 2006 Ford F-250.



(d) 2007 Chevrolet Silverado.



(e) 2006 Honda Ridgeline.



(f) 2002 Ford Focus.
Figure 5. HOF vs Displacement.

Table 1 gives the calculated AHOF400 of each test for the two computation methods, as well as the measured structural height (longitudinal bottom and top heights) at the test facility. In five of the six cases, the value of AHOF400 was comfortably in the range of heights of the bumper structure. For the Chevrolet Silverado, the AHOF400 was above the measured top of the bumper structure implying that significant load paths had developed above that structure during the first 400 mm of crush of the vehicle.

Note that the instantaneous HOF values are most disparate for low displacements. This might be expected, as the effects of minor noise in the moment channel or off-center load concentrations will be most visible in the HOF calculations when the overall force level is low. It is also notable that the AHOF400 changes by less than 10 mm with the inclusion of moment data. Recall that the maximum theoretical error in HOF is one half of the load cell size. The observed discrepancy is usually an order of magnitude lower. Despite significant load concentrations in the bumper regions (as evidenced by the force gradients visible in Figure 4), the net effect of the moments in opposite directions across the adjoining rows seems to be minimal.

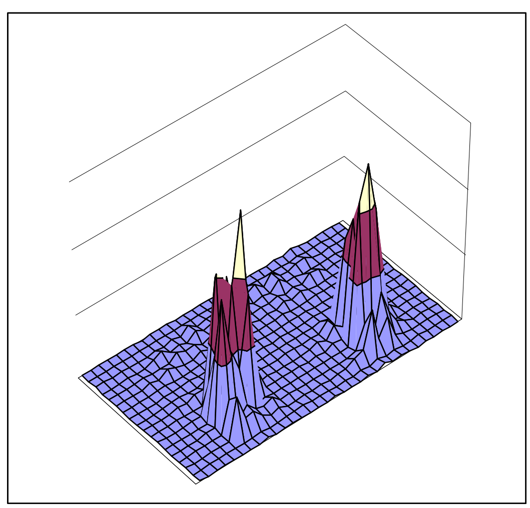
Table 1: AHOF400 parameters by Calculation Method

Vehicle	AHOF400 without Moments	AHOF400 with Moments	Difference with Moments	Measured Structure Height
2003 Honda Odyssey	438.5 mm	434.9 mm	-3.6 mm	390 - 498 mm
2005 Honda Odyssey	436.7 mm	430.5 mm	-6.2 mm	400 - 500 mm
2006 Ford F-250	688.3 mm	685.7 mm	-2.6 mm	630 - 765 mm
2007 Chevrolet Silverado	563.3 mm	570.1 mm	+6.8 mm	444 - 544 mm
2006 Honda Ridgeline	503.8 mm	506.9 mm	+3.1 mm	487 - 578 mm
2002 Ford Focus	433.4 mm	435.0 mm	+1.6 mm	423 - 531 mm

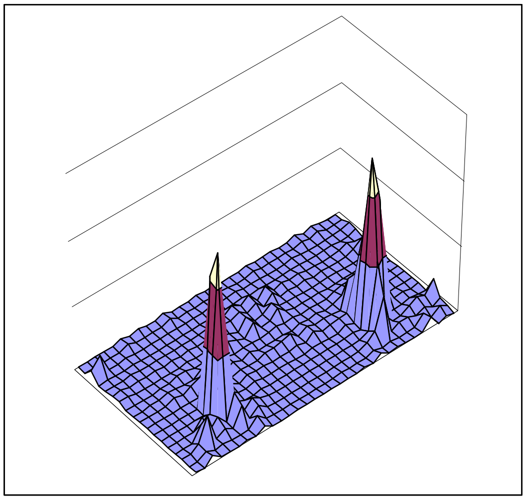
For four of the six vehicles, the value of AHOF400 is within the Part 581 zone, mostly quite close to its center. Admittedly, the value for the Honda Ridgeline is close to the edge (within 5 mm). The values for the Chevrolet Silverado and Ford F-250 are again above the Part 581 zone. This is another indication that the vehicle structures may be too high to adequately engage the bumper structures of most vehicles in its early crush stages.

As mentioned, the Ford F-250 and Chevrolet Silverado (as well as the Honda Ridgeline) do have secondary energy absorbing structures (SEAS) which are intended to interact with a partner vehicle and share crash forces in the Part 581 zone. Nonetheless, due to their position in these vehicles (behind and below the bumper structure), the forces from these SEAS are arise only when the structure crushes to the point where load paths can develop at that height. In a deformable barrier test (and in a crash against a deformable vehicle), there is the possibility of a load path developing from these SEAS before the upper structure is fully crushed. In these rigid barrier crash tests, however, the development of a load path through the SEAS required significant crush of that structure.

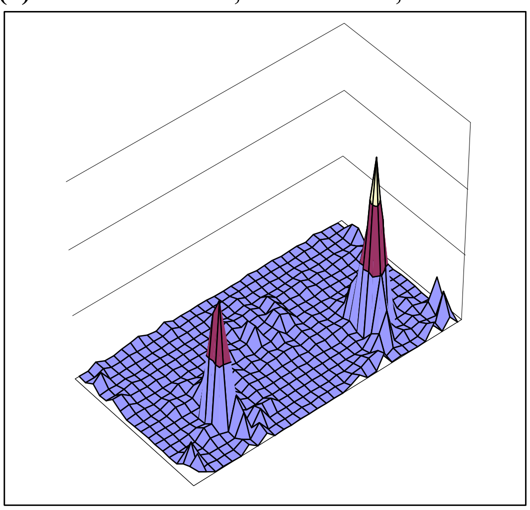
As an example, evidence of the Ford F-250's SEAS structure can be seen later in its test. Although the total force in that test peaks at 937 kN at 12.0 msec after contact, the total force in the nominal third row does not exceed 15 kN until 46.8 msec, when the vehicle displacement is approximately 528 mm. After that load path is established however, the row load quickly passes 50 kN (53.4 msec /576 mm) on its way to a maximum of 78 kN (72.1 msec/650 mm). Even at the 100 msec point (while the vehicle still maintains contact with the barrier but after it has started its elastic rebound), the row load maintains a level of 41 kN. Figure 6 shows high-resolution force distribution plots at each of these times to illustrate this progression.



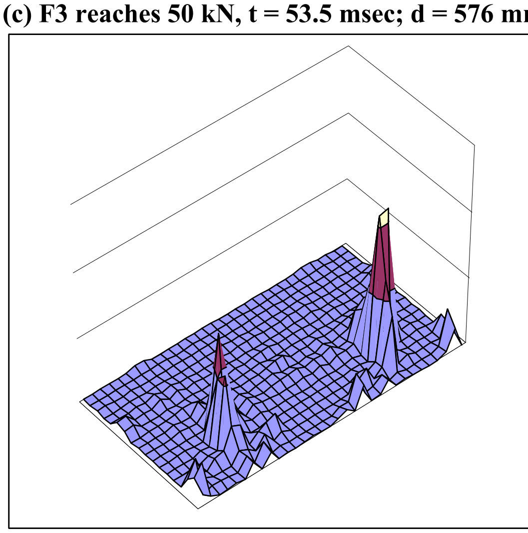
(a) Maximum Ftotal, t = 12.0 msec; d = 182 mm.



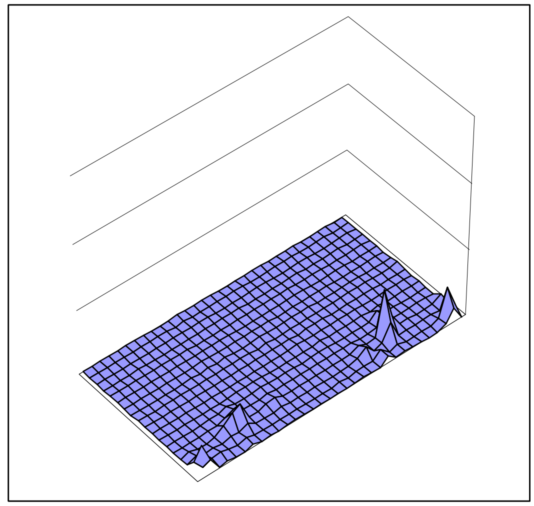
(b) F3 reaches 15 kN, t = 46.8 msec; d = 528 mm.



(c) F3 reaches 50 kN, t = 53.5 msec; d = 576 mm.



(d) Maximum F3, t = 72.1 msec; d = 650 mm.



(e) During rebound, t = 100.0 msec; d = 638 mm.
Figure 6. Load distribution plots for test 6947 – 2006 Ford F-250.

GEOMETRIC COMPATIBILITY METRICS

There are several metrics other than AHOF400 that attempt to assess the geometric compatibility of automobile structures. There have been several developed that are based on a load cell barrier with 125x125 mm load cells with the boundary between two rows (nominally rows 3 and 4) set at the centerline of the Part 581 zone. The bottom of the 144 load cell array (nine rows by 16 columns) is nominally 80 mm above the ground surface. The criteria associated with these metrics usually dictate whether a secondary energy absorbing structure (SEAS) is recommended.

Nagoya Criterion

Nagoya University [3] proposed a compatibility criterion for the 144 load cell array. Under the assumption that the engine does not affect the distribution of impact forces until after the total force reaches 200 kN, the criterion evaluates the total load in the nominal third and fourth rows of the load cell barrier (F3 and F4) at the point when the total barrier load first reaches 200 kN. The criterion first requires that the sum of F3 and F4 exceed 80 kN. It then requires that the ratio of F3 to (F3+F4) be between 0.2 and 0.8, which nearly assures that the center of force for these rows is in the Part 581 zone. If these two conditions are met, the criterion indicates that the structure does not require a secondary energy absorbing structure (SEAS).

As part of the analysis of the tests with the enhanced load cell barrier, the load within the Part 581 zone (F581) was explicitly estimated using the method described by Equation 3 above. Table 2 exhibits the calculated Nagoya Criterion parameters for the enhanced load cell barrier tests.

The main criterion (that F3+F4 is greater than 80 kN at the point when total load is 200 kN) is easily met for five of the six vehicles. Further, in four of these cases, the value is in fact more than 90% of the total load. In fact, in these four cases, moment calculations imply that more than half of the total load is reacted within the Part 581 zone itself. The Chevrolet Silverado exhibits a concentration of load in Row 4, indicating insufficient alignment of the load with the Part 581 zone.

Table 2. Nagoya Criterion Parameters for Enhance Load Cell Barrier Tests.

Test	6945	6946	6947	6948	6982	6983
Vehicle	2003 Honda Odyssey	2005 Honda Odyssey	2006 Ford F-250	2007 Chevrolet Silverado	2006 Honda Ridgeline	2002 Ford Focus
Time to 200 kN [sec]	0.01200	0.00984	0.00640	0.00672	0.00736	0.00848
Total Force [kN]	201.7	203.7	204.1	200.7	204.8	201.9
F3+F4 [kN]	193.4	184.4	45.9	97.9	187.0	199.3
F3/(F3+F4)	0.469	0.537	0.213	0.017	0.297	0.579
$F581^{total}$ [kN]	133.7	130.4	19.8	*	123.3	116.0
$F581^{lower}/F581^{total}$	0.410	0.409	0.291	*	0.437	0.550
SEAS needed?	No	No	Yes	Yes	No	No

*Moments at this point implied a small tensile value for $F581^{upper}$ for the Chevrolet Silverado, indicating a concentrated load just above the Part 581 zone.

The Nagoya criterion asserts that there is a necessity for a SEAS for the Ford F-250 and the Chevrolet Silverado. Only a small fraction of the load is reacted in Rows 3 and 4 or the Part 581 zone. A SEAS is necessary to provide some measure of compatibility between these models and most other vehicles. These vehicles do in fact have a SEAS, but, as mentioned earlier, it is difficult to evaluate the effectiveness of these SEAS structures through a rigid barrier crash test.

The Nagoya criterion could easily be modified for use with a moment-measuring load cell barrier. Rather than requiring a certain fraction of the total load (40%) to be in the measurable vicinity of the Part 581 zone and an indication that the geometric center of that load be within the Part 581 zone, the criterion could be simplified to require a specific fraction of the load to be reacted in that zone. Further research could be conducted to recommend a particular threshold, most likely in the 20% to 50% range.

Japanese Automobile Manufacturers Association (JAMA) Criterion

The Japanese Automobile Manufacturers Association (JAMA) also proposed a criterion [4] to evaluate the necessity of SEAS. The JAMA criterion evaluates the total force level in the nominal third and fourth rows (F3+F4) once the “central column force”, F_c, reaches a critical value. F_c is defined as the sum of all forces in the four central columns of load cells. Once again, the F3+F4 quantity appears to be a proxy for the Part 581 load, which can be estimated far more accurately with a moment-measuring load cell barrier. JAMA did not propose a critical value for F_c.

In the crash tests, the value of F_c generally tracked the F3+F4 parameter closely until a certain load level and then stabilized or decreased while the F3+F4 rose substantially. The behavior observed for the Honda Ridgeline (Figure 7) is typical. The maximum value of F3+F4 at the critical value of F_c depended strongly on whether that critical value of F_c was greater than the local maximum of F_c experienced in the early segment of the test. For example, it can be seen in Figure 7 that F3+F4 would be close to F_c, if F_c were less than about 75 kN, but if a larger value of F_c were used, F3+F4 would be in the 400 to 500 kN range.

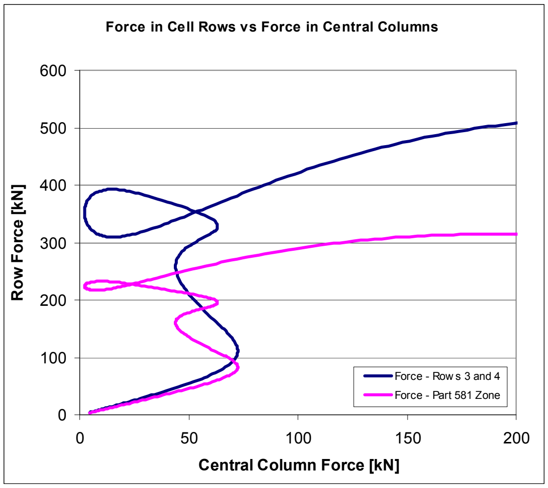


Figure 7. Row forces in the Part 581 region vs. central column force for the 2006 Honda Ridgeline.

The load-vs.-load curves in Figure 7 can be difficult to interpret. In general, the close correlation at low loads (less than about 50 kN) implies that the load in Rows 3 and 4 is primarily in the Part 581 zone. The fact that F581 and F3+F4 track F_c implies the load in the central columns above and below the considered rows is on the same order of magnitude as the load in those rows to either side of the center. This is not surprising, as one can imagine that at these low loads, the central section of the Part 581 structure reacts virtually all of the crushing loads. Eventually, significant loads are reacted by all components of the vehicle front structure. It is not surprising that during the intense crushing segment of the crash event, the load cells in the third and fourth rows pick up significant load outside the Part 581 zone (eventually including engine deceleration load) and therefore F3+F4 starts to exceed F581 by a significant factor. Nonetheless, even though the Part 581 zone is approximately 40% of the area of Rows 3 and 4, it is often calculated to react more than half of the F3+F4 load.

The stabilization or reduction of F_c is indicative of the transfer of load into the stiffer load paths through the vehicles side rail structure. Thus, the selection of a critical value of F_c implies an acceptable amount of central load that should be attained before this transition commences. The consequence of choosing a consistent value or a vehicle mass-specific value should be carefully considered.

CONSISTENCY OF AHOF400 RESULTS

Five of the six advanced load cell barrier tests were completed for virtually the same vehicles used in previous 125x125 mm single axis high resolution barrier cases. A 2007 Chevrolet Silverado was previously tested against a rigid barrier with 250x250 mm single axis load cells and yielded some anomalous data. Thus, no direct comparisons were possible for that model. The values of the AHOF400 for the remaining vehicles are given in Table 3. The two virtually identical high-resolution barrier test series provide an opportunity to evaluate the consistency of AHOF400.

Table 3. Comparison of AHOF400 in Similar Crash Tests.

Vehicle	Test No.	4x9 Single Axis 250x 250 mm Barrier AHOF 400	Test No.	9x16 Single Axis 125x 125 mm Barrier AHOF 400	Measured Height of Top and Bottom of Structure	Test No.	9x16 125x125 mm Barrier With Moments AHOF 400		Measured Height of Top and Bottom of Structure
							Without Moment	With Moment	
2002 Ford Focus	4216	436 mm	5712	448 mm	512-402 mm	6983	433.4 mm	435.0 mm	531-423 mm
2003* Honda Odyssey	4463	443 mm	5144	454 mm	508-388 mm	6945	438.5 mm	434.9 mm	498-390 mm
2005 Honda Odyssey	5273	450 mm	5714	451 mm	486-382 mm	6946	436.7 mm	430.5 mm	500-400 mm
2006 Honda Ridgeline	-	-	5715	548 mm	553-529 mm	6982	503.8 mm	506.9 mm	578-487 mm
2006 Ford F-250	-	-	5820	693 mm	742-611 mm	6947	688.3 mm	685.7 mm	765-630 mm
2007 Chevrolet Silverado	-	-	-	-	-	6948	563.3 mm	570.1 mm	544-444 mm

* Test 5144 was of a 2004 Honda Odyssey.

The AHOF400 values do not agree as closely as one might hope between the two sets of tests. In three of the five cases, the additional moment data reduces the discrepancy. The Honda Ridgeline experienced a difference in AHOF400 of 44 mm, which is a significant fraction of the height of the Part 581 zone (102 mm). In the remaining cases, the difference in (non-moment adjusted) AHOF400 between the two tests was 15 mm or less. This result leads to several questions. First, would the consistency have been enhanced if the moment adjustment had been available in all test series? Second, is 15 mm within the normal variability one can expect for AHOF400 in this type of test? And third, what factors can lead to the discrepancy on the order of magnitude observed for the Honda Ridgeline?

CONCLUSIONS

The addition of moment channels to the high resolution load cell barriers yields more information about the structural response of a vehicle in a vehicle-to-barrier crash test. In particular, it theoretically eliminates error in the AHOF400 calculation and it allows a more direct estimate of the forces directly in the Part 581 zone. The better representation of the Part 581 load could aid in the enhancement of the various compatibility criteria (e.g., Nagoya, JAMA, VNT) by the reduction of uncertainties from the non-Part 581 zone loads in the total row loads for the third and fourth rows (F3 and F4).

The ability to visualize an even higher resolution force pattern further aids assessment of the structural interaction during the crash event. In particular, it helped with the visualization of the effect of the SEAS late in some of the rigid barrier tests. Nonetheless, the effectiveness of SEAS devices that are displaced behind the primary energy absorbing structures may be easier to assess in vehicle-to-vehicle and vehicle-to-deformable barrier tests.

Other than visual enhancement and in the local region of the side rail impingement, the data for the moment about the vertical axis (M_z) does not significantly improve the understanding of the crash event and, in situations in which data acquisition resources are limited, might be comfortably sacrificed in lieu of redundancies for more important data channels.

In the analysis of the current tests, the calculated value of AHOF400 did not change substantially (less than 7 mm) as a result of the additional moment data.

Nonetheless, the 125x125 mm load cells do provide a smaller theoretical maximum error in computed AHOF400 than 250x250 mm load cells. Therefore, any further improvement is notable.

For all of the vehicles except the Chevrolet Silverado, the values of AHOF400 found with and without using the moment data were within the range of actual measured heights of the bumper structure.

When AHOF400 was evaluated over two sets of virtually identical tests, there was some lack of consistency. The discrepancies (on the order of 15 mm) may simply be the normal scatter in an assessment of this type. The additional accuracy derived from the moment data should minimize this test-to-test variation. Nonetheless, an improvement of 7 mm in measurement for which 15 mm of scatter is typical will be helpful but will not define system accuracy.

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