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NHTSA'S REVIEW OF A VEHICLE COMPATIBILITY PERFORMANCE METRIC THROUGH COMPUTER SIMULATION

Matthew Jerinsky
National Highway Traffic Safety Administration
Washington, D.C.

William T. Hollowell
National Highway Traffic Safety Administration
Washington, D.C.

ABSTRACT

In recent years the US fleet of passenger vehicles has seen a large increase in light trucks. This has led to concerns for occupant safety in crashes between vehicles of greatly varying size and mass. Research is ongoing in the government, industry and academic sectors to quantify a vehicle's structural performance through testing and associated evaluation criteria to ensure a balance between a vehicle's aggressivity and vulnerability in various impact scenarios. This balance is known as a vehicle's crash compatibility. In response to vehicle compatibility concerns, NHTSA is reviewing performance tests and criteria. One performance metric under investigation is known as the Average Height of Force (AHOF). AHOF is a measure of the average height from the ground that a vehicle applies force to a load cell wall in a frontal impact. NHTSA has plans underway for physical tests and computer simulations to review the robustness of AHOF when calculated after varying test parameters such as load cell wall resolution, vehicle velocity, and vehicle alignment with the load cell wall. This paper presents the computer simulation analysis and results.

NOMENCLATURE

AHOF	average height of force
HOF(t)	height of force at each time step
F	force
H	height above ground
N	number of load cells
t	time step

COMPATIBILITY CHALLENGES

Creating performance tests and performance test criteria to evaluate an automobile's ability to withstand crashes from other vehicles as well as monitoring the damage the striking vehicle imposes to the struck vehicle in a crash is not a trivial task and has spurred much debate. NHTSA along with global partners through IHRA [1] has ongoing research of test and test criteria using a global perspective in hopes of creating tests that can be used worldwide [2,3,4]. In the United States the vehicle fleet has changed in recent years with the growth of sales of light trucks over passenger cars [5]. Concern arises when such vehicles of varying mass and size interact in a crash. Research has shown that the compatibility of these vehicles to protect their occupants as well as limiting damage to the other vehicle can be controlled by a vehicle's mass, geometry, and structural interaction [6]. NHTSA is investigating a number of performance criteria as a way to improve structural interaction. One such performance criterion is known as average height of force or AHOF [7].

AHOF is calculated from a load cell wall struck by a vehicle in a full frontal impact. Each of the forces from the load cell wall is multiplied by its respective height from ground, summed, and then averaged. Figure 1 illustrates the summation of each of the load cells at each respective height.

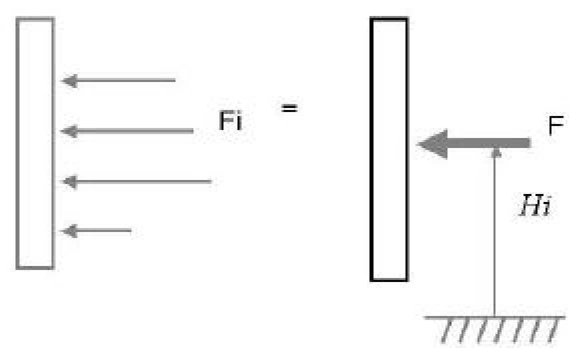

Figure 1. Average Height of Force Diagram.

The summation is calculated for each time step.

$$HOF(t) = \frac{\sum_i^N F_i \times H_i}{\sum_i^N F_i} \quad (1)$$

Finally, the height of force is averaged using the total force from each time step as a weighting function. This is done to ensure AHOF is calculated during the period the vehicle transfers load to the wall.

$$AHOF = \frac{\sum_{0}^{t} HOF(t) \times F(t)}{\sum_{0}^{t} F(t)} \qquad (2)$$

MODELS

NHTSA has a number of LS-DYNA full vehicle finite element models under development. These vehicle models are useful for investigating trends seen in performance tests and criteria. While these models are only partially representative of the full vehicle fleet in the United States, the models do allow for a preliminary understanding of the test parameters and their effects. The models were chosen for their variance in size and correlation to physical tests.

The vehicles chosen are: 1997 Geo Metro, 1998 Dodge Caravan, and 1998 Ford Econoline E-250. The relative size of the vehicle models is shown in Figure 2.

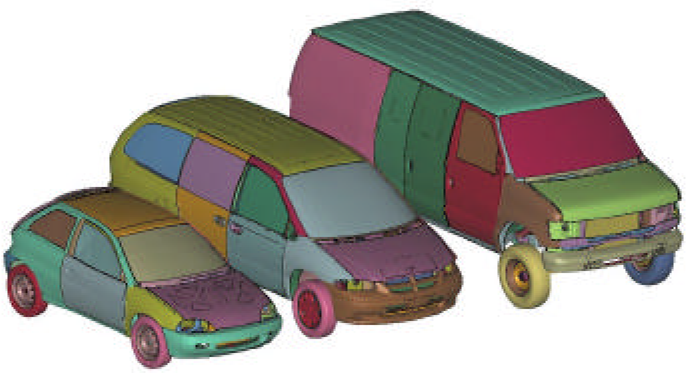

Figure 2. Vehicle Models: Metro, Caravan, Econoline (from left to right).

Cross sections of each of the vehicles in the same scale are shown in Figure 3. These cross sections demonstrate the variance in size and height of the vehicles and the height of their structural members in relation to each vehicle.

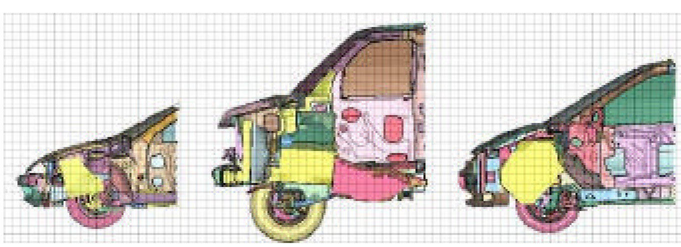

Figure 3. Vehicle Side Section Cuts: Metro, Econoline, Caravan.

A load cell wall was created using the rigid wall option in LS-DYNA. The wall was separated into load cells reflecting the size of each of the test conditions. The US NCAP load cell wall is assembled from a matrix of 4 by 9 load cells. The two lower row heights are 229 mm while the two upper rows are 254 mm in height. Each of the load cells is 229 mm in width, and the total wall is 66.675 mm from ground. For convenience of this study and to match future physical tests at NHTSA, the barrier used for this study was created from uniform 250 mm x 250 mm load cells at a distance of 50 mm from ground. This change created a 4x8 load cell wall. The differences in the load cell walls can be seen in Figure 4.

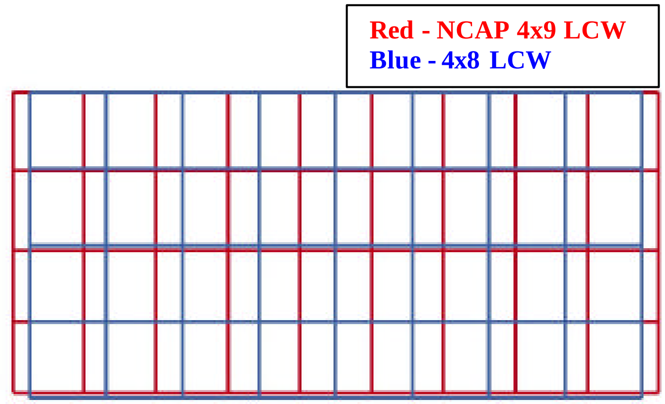

Figure 4. NCAP and 4x8 Load Cell Walls.

Subsequent load cells in this study were based on the 4x8 LCW and were simply halved and then halved again as seen in Figure 5.

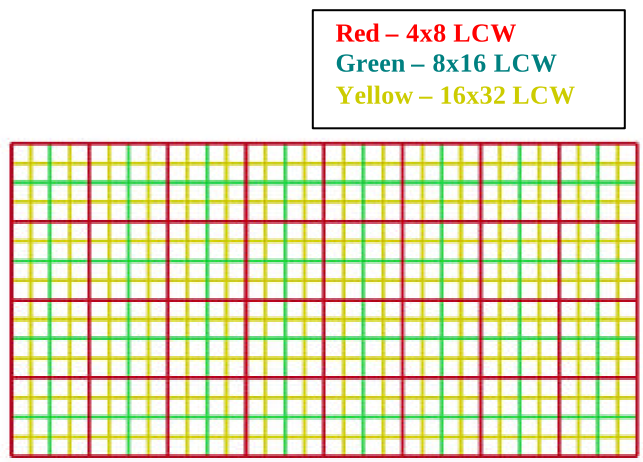

Figure 5. Load Cell Wall with Increasing Resolution.

Model Correlation

The models have undergone various levels of correlation to frontal impact tests including full frontal impact, offset deformable barrier impact, and frontal movable deformable barrier impact. Here the correlation is discussed in limited detail since this paper is reviewing trends of the effects caused by the test parameters on AHOF and not the effects of the tests on the specific vehicles.

Each of the vehicles is crashed into the US NCAP rigid wall at US Frontal NCAP test conditions. These conditions are: vehicle speed of 56 km/h, full frontal overlap, and rigid barrier. The HOF is calculated for the physical and simulation NCAP cases and plotted in Figures 6, 7, and 8. The 4x8 load cell wall is included for comparison. The Caravan, Metro, and Econoline follow the test curves until 60 msec., 45 msec., and 55 msec., respectively. Since the AHOF is weighted by the force when the vehicle is loading the wall, and the maximum loading from the vehicle is before the divergent curves, the models are deemed acceptable for a review of test parameters on AHOF. Interestingly, the 4x8 load cell wall simulations for the Caravan and Metro predict close to the same results of the NCAP wall with less than a 5% difference in AHOF.

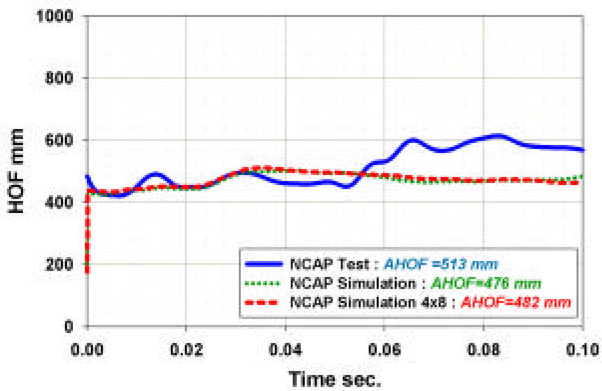

Figure 6. Caravan HOF : Test and Simulation.

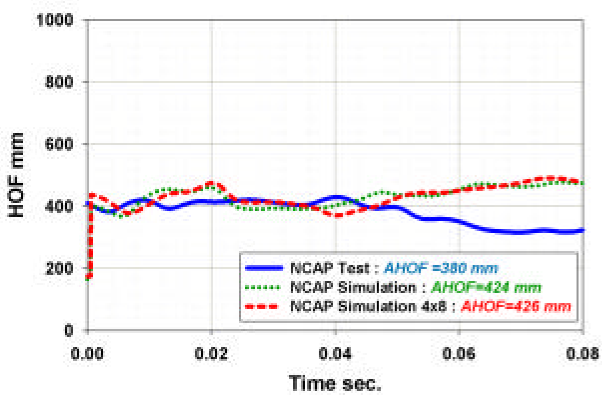

Figure 7. Metro HOF : Test and Simulation.

In the case of the Econoline, the dominant members of the structure do not bridge the second and third row of load cells in the 4x8 load cell wall case. This does happen with the NCAP load cell wall and the effects on HOF can be seen in Figure 8.

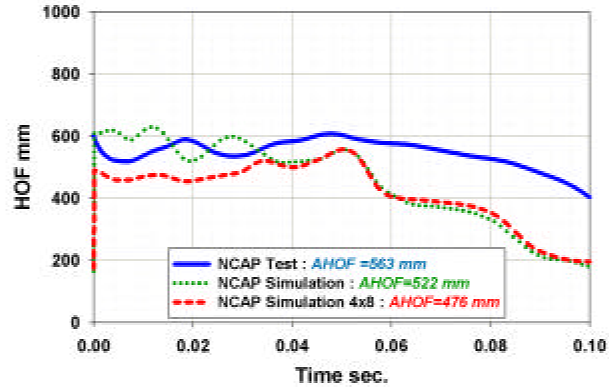

Figure 8. Econoline HOF : Test and Simulation.

This suggests caution in switching load cell wall resolution and in aligning vehicles to the load cell wall. Therefore, these two test parameters are chosen for investigation. Also, the vehicle's velocity can influence the crush deformation and ultimately the intrusion of the structure into the occupant compartment. This deformation might affect AHOF, and is chosen as the third parameter to review.

SIMULATION MATRIX AND RESULTS

The US Frontal NCAP was used as the initial test condition for the three vehicles. This simulation matrix was expanded to include studies of the load cell wall resolution, vehicle velocity, and vehicle alignment to the load cell wall. Table 1 summarizes the completed simulation matrix and calculated AHOF for each of these cases.

Table 1. Simulation Matrix.

LC Resolution	4x8				8x16				16x32			
Velocity km/h	40	56			40	56			40	56		
Vehicle Alignment	0	+30mm	0	-30mm	0	+30mm	0	-30mm	0	+30mm	0	-30mm
Vehicle	AHOF mm											
Caravan	540	585	558	535	509	545	520	488	478	515	491	455
Econoline	575	623	550	528	548	559	540	505	503	528	500	473
Metro	485	510	503	478	454	490	475	435	403	439	421	384

AHOF Results and Discussion

Load Cell Size

AHOF is dependent on the use of a load cell wall in testing, so the US Frontal NCAP test parameters are simulated.

The effects of load cell wall resolution can be quite significant in calculating AHOF. Choosing a load cell size is a balance between AHOF convergence and load cell costs.

AHOF is calculated based on assuming the reading from the load cell is applied evenly across the load cell face, which is then averaged to the center of the load cell. For numerical convenience the AHOF in Figure 9 is calculated by giving each load cell a height of 1 unit and multiplied by the load cell height rather than first splitting the load cell in the middle. This offsets the calculated AHOF by half a load cell height when compared to the NCAP data, but is numerically convenient in comparing load cells of different resolution.

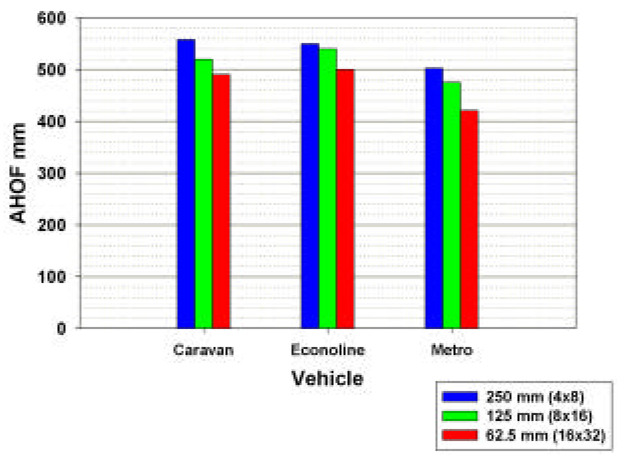

Figure 9. Summary of AHOF for each vehicle.

From Figure 9, the AHOF calculations start to converge with increasing load cell wall resolution. Future work will be completed to ensure convergence by studying more vehicle models and higher resolution load cell walls.

The HOF is plotted for the time duration of the impact in Figures 10, 11, and 12. In the case of the Caravan the resolution does not change HOF at the initial impact, while the Econoline and the Metro show a change of the initial impact HOF with decreasing load cell resolution. The shape of the Metro's and Econoline's front end causes this variance.

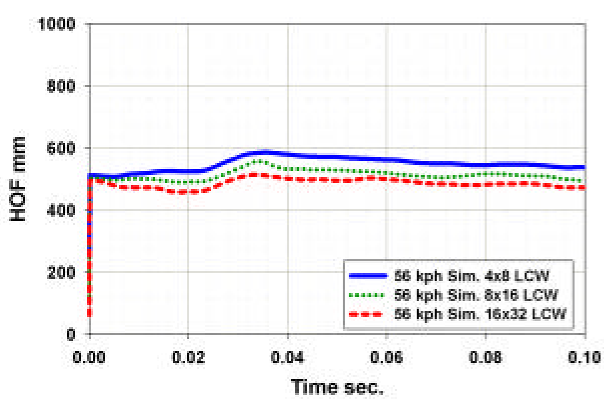

Figure 10. Caravan HOF by Load Cell Size.

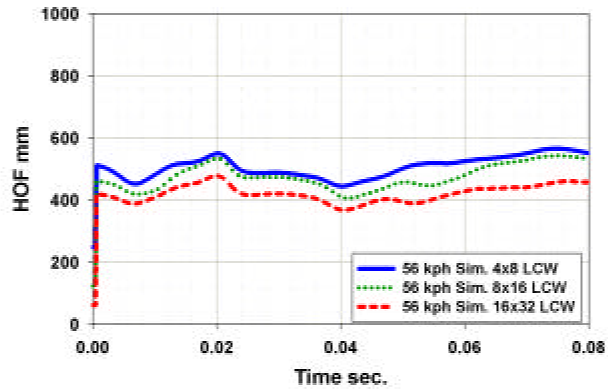

Figure 11. Metro HOF by Load Cell Size.

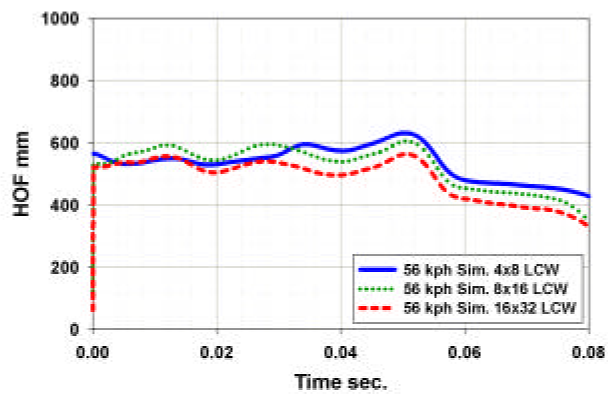

Figure 12. Econoline HOF by Load Cell Size.

From Figures 9 thru 12, it can be seen that further research is needed to obtain convergence of AHOF. Convergence would lead to higher resolution and more costly load cell walls. Since costs may prevent true convergence, care must be taken to choose a load cell resolution that is unbiased to any particular vehicle class. One solution may be adding higher resolution load cells within the wall's height where the US requires passenger car bumpers to align. This would aid in good structural interaction between vehicles of different classes since the goal would be to focus the highest vehicle loads to this height in order to lower AHOF.

Alignment

In setting up a physical test, many factors such as a vehicle's option list can affect a vehicle's ride height. AHOF needs to be able to capture these differences to ensure test repeatability. One challenge is selecting a sufficient load cell wall resolution to ensure enough data can be measured for an accurate AHOF calculation. This is especially true when comparing a vehicle's initial alignment to the load cell wall between tests.

Figures 13 thru 15 are plots of the AHOF for each vehicle with regard to increasing load cell resolution and vehicle alignment to the wall. The center or red bar for each load cell resolution is the vehicle in its nominal position. The vehicle was then raised 30 mm and lowered 30 mm to determine if the load cell wall would accurately record the 30 mm difference. The error bar on the nominal case for each load cell illustrates the 30 mm difference in AHOF that should be recorded by the load cell wall if it were accurate. 30 mm was chosen since it is less than half the 62.5 mm load cell height in the 16x32 load cell wall case and not a multiple of any of the load cell heights.

The Caravan case shows a 20% or less difference between the 30 mm height difference and the recorded AHOF. This does not change with load cell resolution.

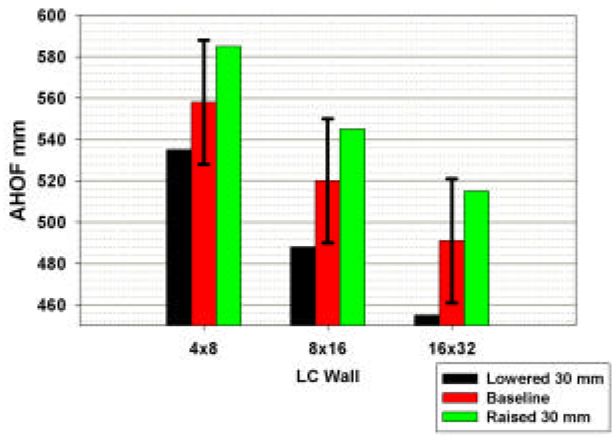

Figure 13. Caravan AHOF by Alignment Height.

In the case of the Metro, raising the vehicle does show that increasing the load cell wall resolution improves the recorded AHOF. However, even at the 16x32 resolution the raised vehicle AHOF is off 40% or 12 mm. The lowered vehicle does not show the same trend, and increasing load cell resolution increases the error in the AHOF measured.

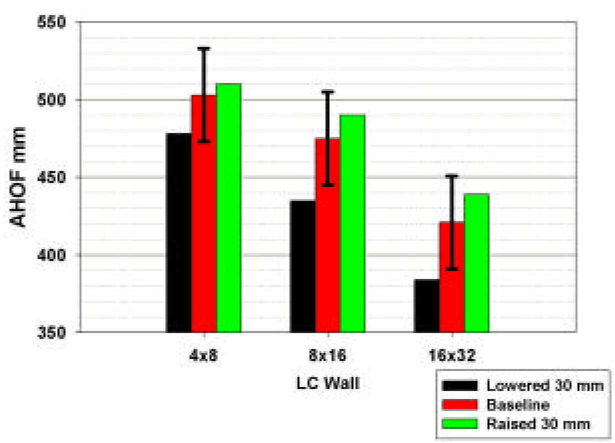

Figure 14. Metro AHOF by Alignment Height.

Only in the case of the Econoline, Fig 15 does increasing the load cell resolution yield decreasing error in predicting the 30 mm ride height adjustment. The Econoline case also stresses the need for a higher resolution wall as the 4x8 load cell wall over records the raised 30 mm by 143% or 42 mm.

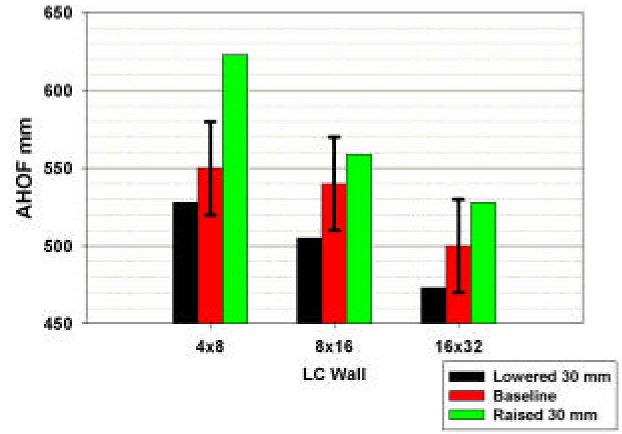

Figure 15. Econoline AHOF by Alignment Height.

From this study a load cell wall's accuracy in measuring small changes in a vehicle's height and alignment seems to be based on the vehicle's design as well as the load cell wall's resolution. AHOF may be influenced by a vehicle design's ability to spread the structural loading over as many load cells as possible. A concentrated load would be more likely to influence AHOF especially if the load falls near the edge of a load cell. The load may randomly bridge load cells when using different load cell wall resolutions and this could cause differences in the calculated AHOF. Also, even when using the same load cell resolution the vehicle's structure could randomly bridge adjacent load cells from test to test causing differences in the calculated AHOF. A very high-resolution load cell wall may address this, but is cost prohibitive.

A solution may be to spread the vehicle loading over a number of load cells on a load cell wall with sufficient resolution. Spreading the load over a number of load cells would lead to better structural interaction since designing one stiff structural member such as the rails designed for a large vehicle could overwhelm rails designed for a small car. Therefore, coupling AHOF with a performance criterion that measures a vehicle's design in spreading the load across the load cell wall face such as Transport Research Lab's (TRL) Homogeneity Criterion [8] and a high resolution load cell in the area of bumper height could lead to better structural interaction between different vehicle classes. More research of TRL's Homogeneity Criterion and a load cell wall with sufficient resolution in the bumper area is needed to fully understand this possible solution for a more robust AHOF.

Velocity

The simulation cases discussed up this point have all held the vehicle velocity at 56 km/h. A vehicle's structure will deform differently based on the energy involved in the impact. This deformation can affect the AHOF, which is critical since crashes occur at a range of vehicle speeds. AHOF needs to be able to predict a vehicle's AHOF for a portion of this range.

Figures 16, 17, and 18 are plots of each vehicle's total wall force throughout the impact. With these plots and review of the vehicle's kinematics during the 56 km/h crash, the maximum peak is recorded when the vehicle's engine hits the wall. Force before that peak is assumed to be from the structure. 40 km/h impacts are also plotted in these figures. 40 km/h was chosen as a comparison for AHOF at lower velocities where the vehicle's engine would play less of a role. After reviewing the wall force for each vehicle at 40 km/h, it is found true for the Caravan and the Econoline but not the Metro. This is a factor of the vehicle's mass. A vehicle's front structure is designed based on its mass, and a smaller vehicle could have a weaker front structure in relation to the engine load when compared to a heavier vehicle's design.

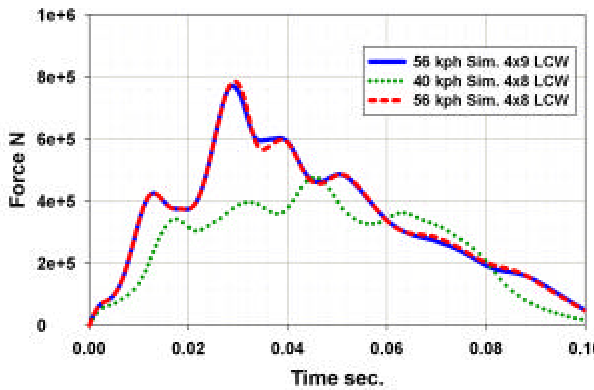

Figure 16. Caravan Load Cell Wall Total Force.

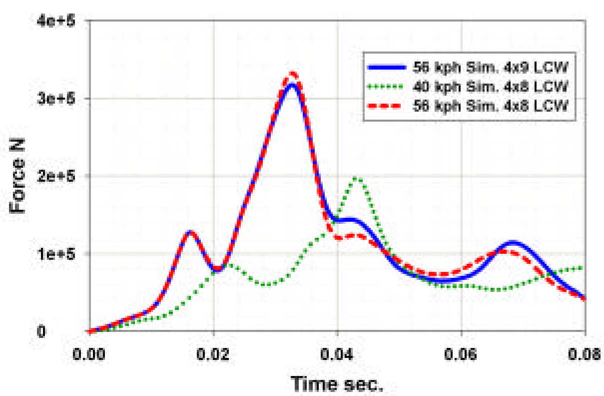

Figure 17. Metro Load Cell Wall Total Force.

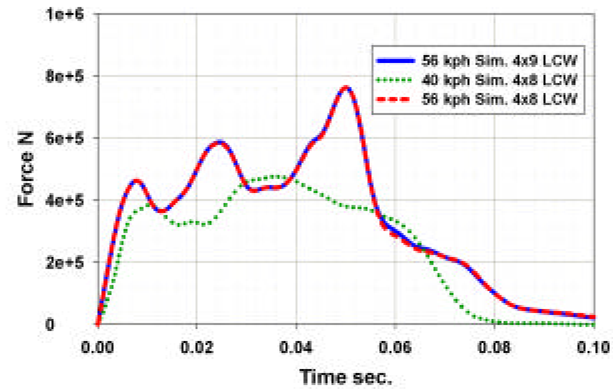

Figure 18. Econoline Load Cell Wall Total Force.

In an attempt to concentrate on the vehicle structure deformation loads and not the engine loading, 20 msec. is chosen as a window to calculate AHOF for the 56 km/hr case. Based on the vehicle loading seen in the total wall force HOF should maintain similar results at both speeds up to 20 msec. since the structural members under load should not change even if their deformation may change. The Caravan and Metro show this to be true as seen in Figures 19 and 20.

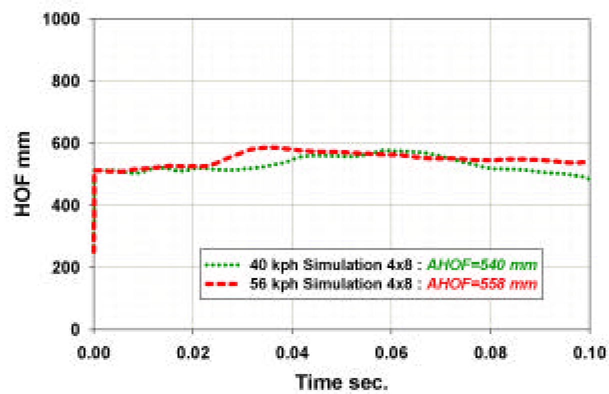

Figure 19. Caravan HOF by Vehicle Speed.

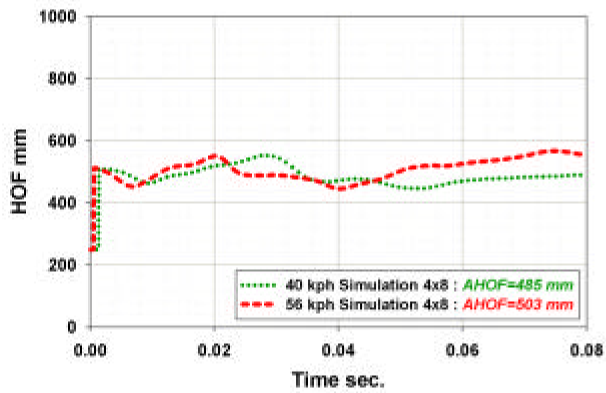

Figure 20. Metro HOF by Vehicle Speed.

The Econoline defies this statement as seen in Figure 21, but as reviewed in Figure 12, the initial HOF for the Econoline is different for the 4x8 load cell wall case when compared to the 8x16 and 16x32 load cell wall. It does not follow the same trend for the 4x8 load cell wall, so the 8x16 load cell wall is plotted in Figure 22.

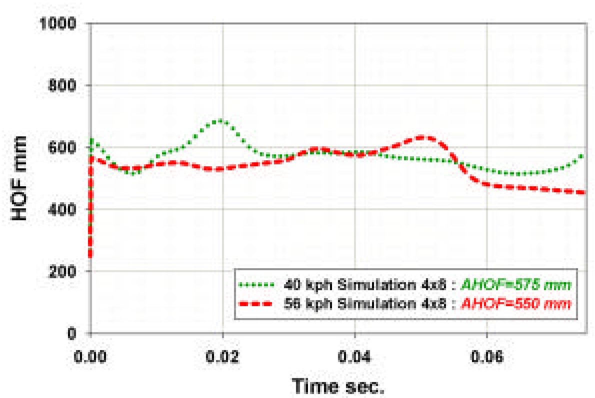

Figure 21. Econoline HOF by Vehicle Speed.

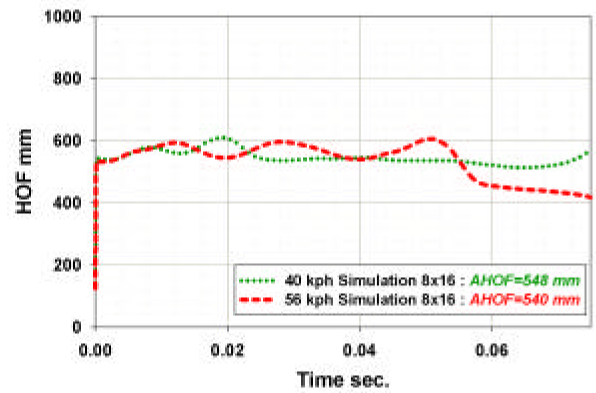

Figure 22. Econoline HOF by Vehicle Speed for 8x16 LCW.

Here the initial 15 msec. of HOF follow closely, but diverge after that. This could be caused by insufficient crushing of the Econoline's structural members when comparing the 40 km/h impact to the 56 km/h impact.

The AHOF of the three vehicles are summarized in Figures 23 thru 25. For each load cell resolution the AHOF is plotted for the 56 km/h and 40 km/h impact. Also included is the 56 km/h impact with AHOF calculated for the first 20 msec.

The Caravan's AHOF shows the same trend in each of the load cell cases. The higher AHOF in the 56 km/h impact is caused by the engine load, which is higher from ground than the rail structure as seen in Figure 3. The 56 km/h case up to 20 msec. drops the AHOF closer to the 40 km/h impact since the engine load is reduced.

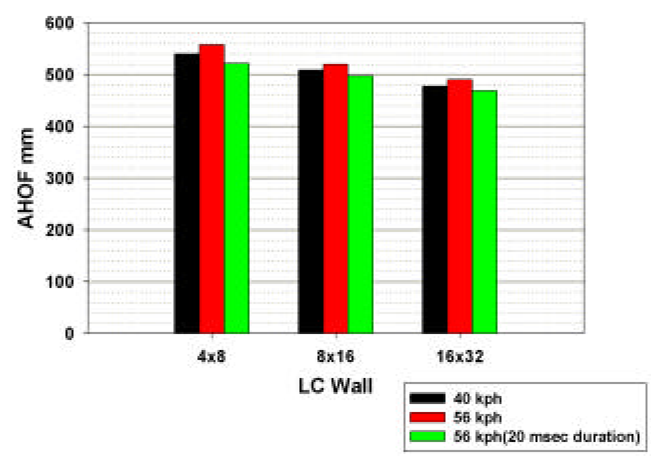

Figure 23. Caravan AHOF by Vehicle Speed.

The Metro shows the same trend for each of the load cell walls, as with the Caravan, but the 56 km/h case up to 20 msec. raises AHOF. The Metro's raised bumper in relation to the front rail structure may cause this. With decreasing vehicle crush as in the 20 msec. case, the rail section and the engine sub-frame located below the front bumper height have not fully engaged and have not fully loaded the wall. In the 40 km/h impact both of these members have loaded the wall, but the engine has not loaded the wall enough to increase the AHOF to the level of the 56 km/h impact.

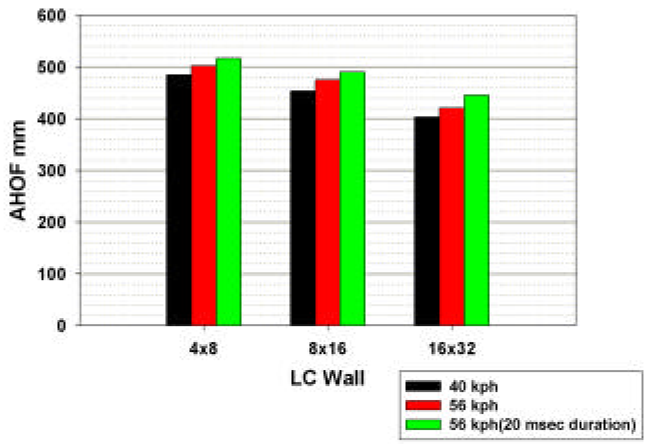

Figure 24. Metro AHOF by Vehicle Speed.

The Econoline's AHOF for the 40 km/h and 56 km/h impacts converges with increasing load cell resolution. As shown in Figure 15, the Econoline is sensitive to the load cell resolution and that would explain why the same trend is not seen in AHOF for each of the load cell wall cases. This is especially true for the 4x8 case. Reviewing the 8x16 and 16x32 walls, the 56 km/h and 40 km/h impacts show less than a 5% difference in respect to each other.

Load cell resolution does show a convergence of calculated AHOF for these three vehicles when vehicle velocity is varied. However, velocity by itself does affect AHOF. The vehicle's velocity influences the vehicle's deformation. From this study AHOF can be dependent on the vehicle's deformation, but more research is needed to fully understand the effects of the vehicle's crush on AHOF.

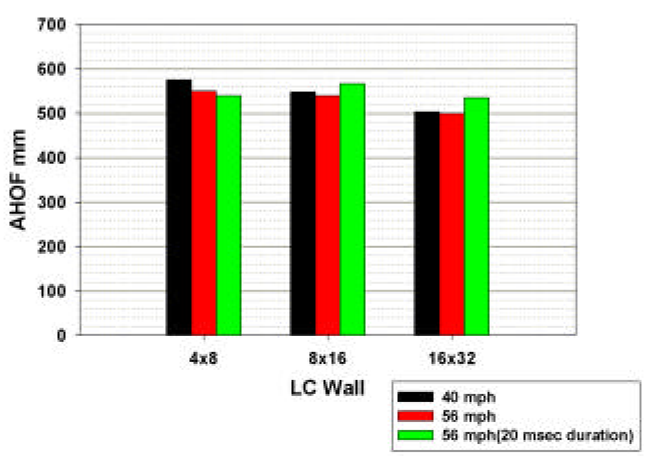

Figure 25. Econoline AHOF by Vehicle Speed.

RECOMMENDATIONS AND FUTURE STUDY

Vehicle compatibility is a difficult performance assessment to make based on one criterion. AHOF does not answer all the needs to ensure vehicle compatibility between vehicle classes, but it is one candidate criterion under review. There may be other significant parameters that may supplement AHOF to ensure vehicle compatibility between vehicle classes. The method of AHOF measurement needs to be robust and nonbiased in order to be applied across different vehicle classes and under various test conditions with good test repeatability. This study needs to be supplemented with more vehicle classes from simulation and test; however, it does demonstrate that AHOF can be used across vehicle classes as long as the same load cell wall with sufficient resolution is used for all vehicles.

The next step is to determine the load cell wall resolution and to couple a performance criterion with AHOF that measures a vehicle design's ability to disperse the load over a number of load cells. Lastly, more study into the vehicle's initial velocity, vehicle crush, and vehicle crash environment must be completed to choose a vehicle test velocity.

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