ACCURACY OF VEHICLE FRONTAL STIFFNESS ESTIMATES FOR CRASH RECONSTRUCTION

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Paper Number 07-0513

ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) estimates delta-V from detailed measurements of vehicle deformation using the WinSMASH crash reconstruction code. Previous research has shown that WinSMASH delta-V estimates underpredict true delta-V by 25% on average. One possible explanation for this error is inaccuracies in the stiffness values used in the delta-V reconstruction calculation. The accuracy of codes, such as WinSMASH, is dependent upon vehicle stiffness values computed from post-impact crush measurements in crash tests. Any error in these crush measurements will be reflected as inaccuracies in the stiffness coefficients, and ultimately as errors in WinSMASH delta-V estimates. This paper investigates the accuracy of post-impact crush measurements in 93 frontal New Car Assessment Program (NCAP) tests of model year 2005-2007 vehicles.

INTRODUCTION AND BACKGROUND

Estimating the total change in velocity or delta-V of a vehicle during a crash is a way to evaluate the severity of a motor vehicle accident. The calculated delta-V can be used as an important parameter to study the occupant injuries resulting from the crash. Therefore, the fidelity of these studies will be affected by the accuracy of the delta-V estimations.

NHTSA uses WinSMASH, a derivative of CRASH3 to estimate the delta-Vs of real-world crashes through post-crash reconstruction [1]. The algorithm of CRASH3 [2] was based on the work done by Campbell in which a linear relationship was observed between static crush and impact speed into a fixed rigid barrier [7]. The delta-V calculation is based on the estimation of the absorbed crush energy by the vehicle from the post-crash measurements of the vehicle deformation. The damage algorithm in WinSMASH uses the post-crash measurements of the vehicle to estimate the energy absorbed by the vehicle in the approach phase of the crash, which is then used to estimate the delta-V by applying the Newton's second law of motion and conservation of linear momentum.

Previous research has shown that WinSMASH delta-V estimates underpredict true delta-V by 25% on average [3, 1, 4, 5]. One possible explanation for this error is inaccuracies in the stiffness values used in the delta-V reconstruction calculation. The accuracy of codes, such as WinSMASH, is dependent upon vehicle stiffness values computed from post-impact crush measurements in crash tests. Any error in these crush measurements will be reflected as inaccuracies in the stiffness coefficients, and ultimately as errors in WinSMASH delta-V estimates.

Calculation of Delta-V

Equation 1 and Equation 2 are used by WinSMASH to calculate delta-V for one of the simplest collision configurations, a central collision, which is defined as a collision where the line of action of the collision forces passes through the centers of mass of the two vehicles. For the frontal vehicle crash with a rigid barrier, Equation 1 and Equation 2 can be simplified to Equation 3.

$$\Delta V_1 = \sqrt{\frac{2E_a m_2}{m_1(m_1 + m_2)}} \qquad (1)$$

$$\Delta V_2 = \sqrt{\frac{2E_a m_1}{m_2(m_1 + m_2)}} \qquad (2)$$

$$\Delta V = \sqrt{\frac{2E_a}{m}} \qquad (3)$$

Where ΔV_1 is the change in velocity of vehicle 1 during the approach period, ΔV_2 is the change in velocity of vehicle 2 during the approach period, E_a is the total energy absorbed during the approach period, m_1 is the mass of vehicle 1, and m_2 is the mass of vehicle 2.

The model discussed in this paper only considers the total change in velocity during the approach period, which is from the time of the initial impact to the time when the velocity of the vehicle reaches zero before it begins to rebound.

The damage algorithm, which incorporates the suggestions proposed by Prasad [2] in 1990, provides a way to describe the vehicle stiffness curve and to calculate the absorbed energy. The vehicle crush behavior, which is described by the linear relationship between $\sqrt{2E_a/w}$ and residual crush, is determined by two parameters, d_0 (the intercept of the $\sqrt{2E_a/w}$ vs. crush curve), and d_1 (the slope of the $\sqrt{2E_a/w}$ vs. crush curve.), and is shown in Figure 1. The dissipated energy is calculated by integrating this linear relationship over the crush profile of the case vehicle. Equation 5 is used for the calculation of the absorbed energy.

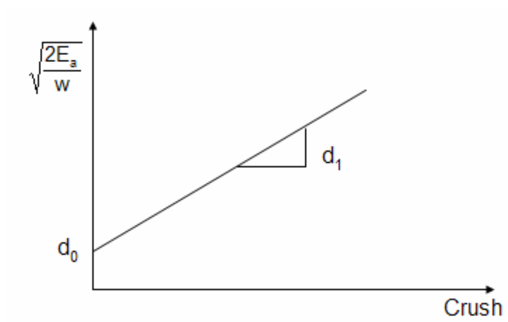

Figure 1. Linear relationship between $\sqrt{2E_a/w}$ and residual crush.

$$\sqrt{\frac{2E_a}{w}} = d_0 + d_1 c \tag{4}$$

$$\text{Or, } E_a = \frac{w}{2}(d_0 + d_1 c)^2 \tag{4'}$$

Integrating (4'), we get

$$E_a = \int_0^w 0.5(d_0 + d_1 c)^2 dw \tag{5}$$

Where E_a is total energy absorbed during approach period, m is the mass of the vehicle, w is the total length of indentation (the length of the total contact damage incurred by the vehicle), d_0, d_1 are vehicle stiffness values, and c is the post-crash crush measurements.

Calculation of Vehicle Stiffness Values d_0 and d_1

The NHTSA vehicle crash test database [8] is used to generate vehicle-specific stiffness coefficients d_0 and d_1 for accident reconstruction. The database contains the results of over 5000 crash tests conducted by NHTSA since 1979. Each test entry contains a complete description of each test which includes vehicle weight, length, center of gravity, static crush measurements, and instrumentation time histories.

With the assumption of the linear relationship between $\sqrt{2E_a/w}$ and residual crush, at least two data points are required to determine the intercept d_0 and the slope d_1. The high speed data point is obtained from a rigid full frontal barrier crash test usually conducted at 56 km/h (35mph) as part of the NHTSA NCAP program. The low speed data point is obtained by assuming that 12.07 km/h (7.5 mph) is the highest full frontal barrier impact speed which will not result in any permanent vehicle deformation. The stiffness coefficients d_0 and d_1 are obtained from a linear curve fit of the two data points. Equation 6, 7, and 8 are used to calculate the vehicle stiffness values. For frontal impact tests with a rigid fixed barrier, an average of the crush measurements can be used in Equation 6 if six values of crush measurements at equally spaced intervals are available. Equation 9 is used to calculate the average crush.

$$d_1 = \frac{\sqrt{\frac{2E_2}{w_2}} - \sqrt{\frac{2E_1}{w_1}}}{C_2 - C_1} \tag{6}$$

$$d_0 = \sqrt{\frac{2E_2}{w_2}} - d_1 C_2 \tag{7}$$

$$E_1 = \frac{1}{2} m v_1^2, E_2 = \frac{1}{2} m v_2^2 \tag{8}$$

$$C = \frac{1}{5}\left(\frac{c_1}{2} + c_2 + c_3 + c_4 + c_5 + \frac{c_6}{2}\right) \tag{9}$$

Where $\sqrt{\frac{2E}{w}}$ is the energy dissipated per unit width of the crush, v_1 is the low speed (assumed to be 12.07 km/h (7.5 mph)), v_2 is the vehicle test speed, w_1 is the vehicle width, w_2 is the total length of indentation, C_1 is the zero crush intercept, and C_2 is the average of post-test crush measurements.

Sensitivity of Stiffness Coefficients to Errors in Crash Test Crush Measurements

The objective of this section is to describe the sensitivity of the WinSMASH stiffness coefficient d_1 to errors in measurement of the average crush in the high speed crash test. The coefficient d_0 is not a function of C_2 and hence is insensitive to errors in the crush measurement C_2.

By definition, C_1, the crush at the low speed impact speed, V_1, equals zero. Using Equation 6:

$$d_1 = \frac{\sqrt{\frac{2E_2}{w_2}} - \sqrt{\frac{2E_1}{w_1}}}{C_2} \tag{10}$$

Taking the derivative of this expression with respect to C_2 and approximating the infinitesimal derivatives by the finite differentials δd_1 and δC_2:

$$\delta d_1 = -\left(\frac{\sqrt{\frac{2E_2}{w_2}} - \sqrt{\frac{2E_1}{w_1}}}{C_2} \right) \frac{\delta C_2}{C_2} = -d_1 \frac{\delta C_2}{C_2} \tag{11}$$

Rewriting the expression to normalize δd_1 by d_1 and δC_2 by C_2:

$$\frac{\delta d_1}{d_1} = -\frac{\delta C_2}{C_2} \tag{12}$$

So we see that a 10% overestimate in the average crash test crush C_2 will result in a 10% underestimate of the stiffness coefficient d_1.

Sensitivity of Delta-V Estimate to Errors in Crash Test Crush Measurements

To determine the effect of errors in crash test crush measurements on delta-V calculations in the field, we consider the simple case of a real world full frontal perpendicular crash into a rigid barrier. From the preceding equations, it can be shown that

$$\Delta V = \Delta V_1 + \left(\frac{\Delta V_2 - \Delta V_1}{C_2} \right) C \tag{13}$$

Where ΔV = change of velocity of the case vehicle to be estimated and C=crush of the case vehicle. In the development of the stiffness coefficients, ΔV_1 is the change of velocity at the lowest velocity which does not result in any permanent deformation (assumed to be 7.5 mph). ΔV_2 is the change of the velocity in the high speed crash test, and C_2 is the resulting average static crush.

For mathematical convenience, we define an offset delta-V equal to $\Delta V- \Delta V_1$.

$$(\Delta V - \Delta V_1) = -(\Delta V_2 - \Delta V_1) \frac{C}{C_2} \tag{14}$$

To compute the effect of errors in C_2, we take the derivative of the expression with respect to C_2, and approximate the derivatives by finite differentials:

$$\delta(\Delta V - \Delta V_1) = -\left(\frac{\Delta V_2 - \Delta V_1}{C_2} \right) C \frac{\delta C_2}{C_2} \tag{15}$$

Rewriting the expression to normalize $\delta (\Delta V- \Delta V_1)$ by $(\Delta V- \Delta V_1)$ and δC_2 by C_2:

$$\frac{\delta(\Delta V - \Delta V_1)}{(\Delta V - \Delta V_1)} = -\frac{\delta C_2}{C_2} \tag{16}$$

Therefore, for the case of a real world full frontal perpendicular crash into a rigid barrier, a 10% overestimate in the crash test average crush C_2 will result in a 10% underestimate in the offset delta-V quantity $\Delta V- \Delta V_1$. The effect of crush measurement errors for other configurations can be computed using the relationship derived earlier showing the influence of measurement errors in C_2 on the stiffness coefficient d_1.

OBJECTIVE

The objective of this study is to determine the accuracy of post-crash test crush measurements, and their influence upon frontal stiffness coefficients used for crash reconstruction.

APPROACH

The mathematical methods for calculating delta-V suggest that the success of vehicle delta-V estimation will greatly rely on the accuracy of vehicle-specific stiffness coefficients which are obtained from the vehicle tests using crush measurements. This study presents the accuracy of post-test crush measurements in NCAP tests conducted from 2005-2007 using (1) double integration of accelerometers in the occupant compartment, (2) comparison of pre- and post-test vehicle length measurements, and (3) analysis of high speed videos. The paper will present and compare WinSMASH stiffness coefficients computed using each of these measurement techniques.

Double Integration of Accelerometers

The test vehicles investigated in this project were fully instrumented to measure the acceleration of the vehicles during the tests. The quality of the acceleration time history was examined before the analysis to ensure that the responses truly represent the test vehicle. The accelerometers mounted in the crush zone were not considered in this study.

The maximum static crush was calculated using the accelerometers mounted in the occupant compartment. Two accelerometers were used for each test vehicle to represent the kinematics of the occupant compartment of the vehicle. The mounting locations for the accelerometers were generally the left and right sills, the left and right floorpans, or the left and right rear seats. Any bias errors, which were caused by the accelerometers not being perfectly zeroed out before the test, were corrected before the integration. The displacement of the vehicle occupant compartment as a function of time was obtained by integrating the acceleration curve twice. The maximum static crush was achieved when the vehicle rebounded and separated from the barrier. The time of separation was defined for this study to be that time when the total force of load cells mounted on the rigid barrier reached zero.

Comparison of Pre- and Post-test Vehicle Lengths

Physically measuring the vehicle damage profile is the method currently being used by NHTSA for accident reconstruction. The techniques for field vehicle damage data collection and the detailed instructions regarding the use of these measurements are stated in the NHTSA test reference guide [6].

The NHTSA protocol estimates static crush using three methods which measure the lengths of the vehicle before and after each test. In each of the methods described below, our study uses the maximum value of the differences between pre- and post-test measurements as the maximum static crush of the vehicle.

The first method is to use six points DPD1-DPD6 (Damage Profile Distances) to determine the dimensions of the crush. The six DPD points are equally spaced along the length of the crush profile. Four points are used if the length of the damage is 400mm or less. The length of the damaged area L and the distance from the midpoint of L to the vehicle center of gravity are also calculated, and will be used in the reconstruction program. The depths of crush are measured from the original outline of the vehicle before the test to the final crushed position. For frontal damage, the DPD measurements are taken from the vehicle's left (the driver side of the vehicle) to the vehicle's right (Figure 2).

The second method is to use pre- (BX1 through BX21) and post-test (AX1 through AX21) Vehicle Measurement Data to calculate the change in length of the vehicle and distances between different vehicle components. The data BX1 through BX21 and AX1 through AX21 represent a range of vehicle measurements required for determining the extent of damage to the vehicle. The measurement most relevant to this study is the change in Total Length of Vehicle at Centerline (BX1 – AX1) (Figure 2).

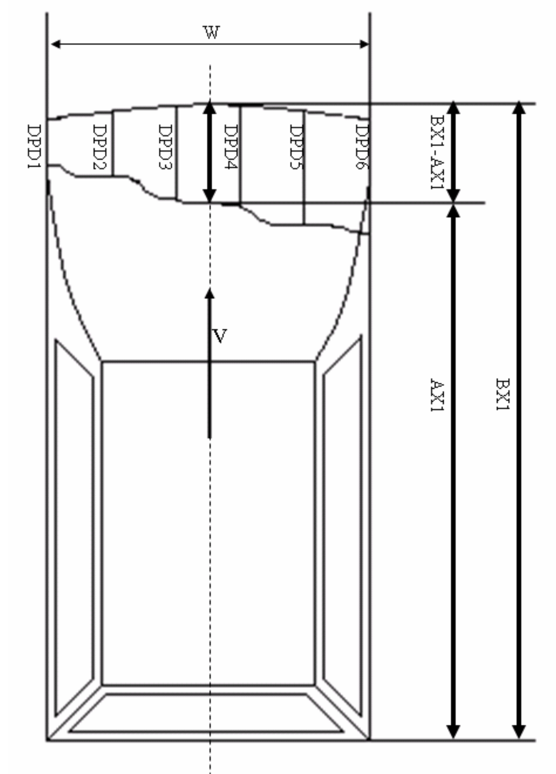

Figure 2. DPD and BX-AX crush measurements.

Finally, the maximum crush distance is recorded as CRHDST, which indicates the maximum static crush distance (damage penetration), regardless of its location. In 54 of the 93 NHTSA NCAP tests, CRHDST equaled the BX1-AX1.

Static Crush Patterns

Different post-test crush profiles were observed from the tests we investigated. Normally, a perpendicular full frontal barrier test will result in a flat post-test profile. However, during rebound from the barrier, different portions of the front structure may unload by differing amounts leading to an irregular static crush profile (Figure 3 and Figure 4). This phenomenon indicates that simply measuring static crush at the centerline of the vehicle, using for example the quantity BX1-AX1, may overestimate the average static crush.

Figure 3. Post-test right front 3/4 view of the vehicle (Test 5615).

Figure 4. Post-test front underbody of the vehicle (Test 5615).

Normally, all structural restitution ceases once barrier forces upon the vehicle drop to zero at time of separation. In unusual cases, the bumper has been observed to springback after separation. Bumper springback after separation occurs will have no effect on delta-V. Hence basing stiffness calculation on physical measurement to the bumper in these cases will introduce a bias in delta-V. These cases can be difficult to detect. Video cameras are not always in the right position to photograph structural unloading after the vehicle rebounds from the rigid wall. Because the bumper is not instrumented, this phenomenon cannot be detected with accelerometers.

Two examples of irregular post-test crush profile are NHTSA NCAP test 5615 and 5818. The pre-test and post-test frontal profile of the vehicle for test 5615 is shown in Figure 5. The detailed post-test crush patterns for 12 NHTSA NCAP tests of model year 2007 are shown in Table 1 (See Appendix).

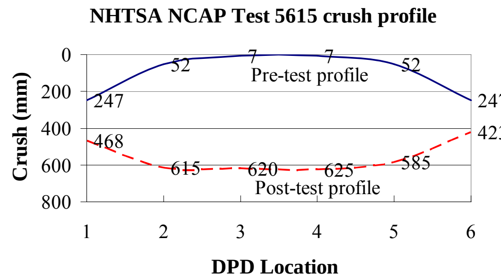

Figure 5. Pre-test and post-test frontal profile of the vehicle for NHTSA NCAP test 5615

Analysis of High-speed Videos

Real-time and high-speed cameras are used in NHTSA NCAP tests to document the frontal barrier impact events. Therefore, analysis of high speed videos provides another way to calculate the maximum dynamic crush of the vehicle in addition to the double integration of accelerometers. Maximum dynamic crush is the amount a vehicle deforms from initial impact to the point of maximum deformation. Due to the position and angle of the cameras in the tests, the maximum static crush, which is the amount a vehicle deforms from initial impact to the point of separation from the barrier, is generally difficult to obtain from the test videos.

Motion analysis software was used to identify a marker on the door of the vehicle and track its position one frame at a time throughout the image sequence. The positions of the marker at the time when the vehicle starts contacting the rigid barrier and when the vehicle fully stops were recorded and used to calculate the maximum dynamic crush.

Case Example

NHTSA NCAP test 5720 was chosen as an example to examine the accuracy of crush measurements using different methods. NHTSA Test 5720 was conducted at a speed of 56.65 km/h (35.2 mph). The test vehicle was a 2007 Mazda CX-7 having a test weight of 1968 kg. Two accelerometers were mounted on the left and right rear seat of the test vehicle. As shown in Figure 6, the time of separation was determined to be 139 ms based on the time when the total barrier forces reached zero. The maximum static crush at the time of separation was calculated as 563 mm (Figure 7) and 483 mm for the left and right rear seat of the vehicle respectively by double integration of the acceleration curves. DPDs measured from the vehicle were 127 mm, 394 mm, 559 mm, 547 mm, 350 mm, and 39 mm for DPD1 to DPD6. The values were 575 mm, 407 mm, and 454 mm for BX1-AX1, BX19-AX19, and BX20-AX20 respectively. The CRHDST recorded in the test report was 575 mm for the maximum static crush.

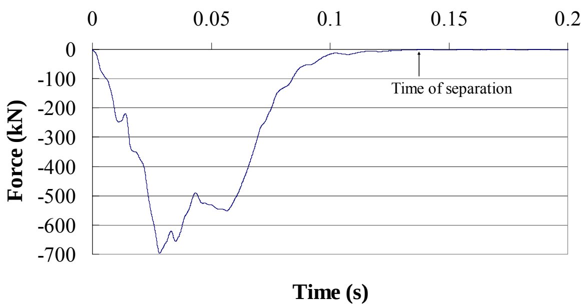

Figure 6. Total barrier forces as a function of time for NCAP Test 5720.

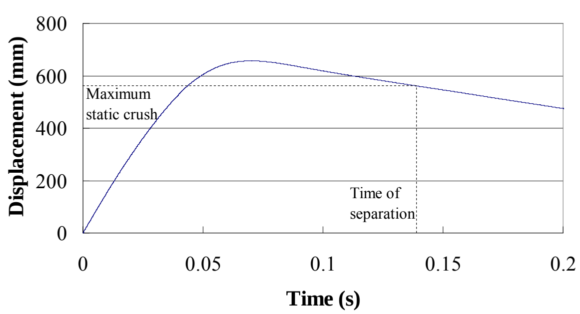

Figure 7. Displacement of the left rear seat as a function of time for NCAP Test 5720.

In the analysis of full frontal barrier tests, it is generally assumed that the left and right of the vehicle crush uniformly. In this test however, the left and right crush patterns of the front structure were not symmetrical as shown both by integration of the acceleration curves and physical measurements. Film analysis was conducted to investigate the reason for this variation. High speed videos taken from left and right side of the vehicle were analyzed to obtain the maximum dynamic crush, and results were compared to the data calculated from the accelerometers. The time of the maximum dynamic crush was 77 ms, which was determined by double integration of the accelerations. The maximum dynamic crush calculated by left and right rear seat accelerometers was 656 mm and 636 mm respectively. The maximum dynamic crushes obtained from high speed video analysis were 729 mm and 711 mm for left and right view of the videos.

Two conclusions can be drawn from the test. First, the accelerometers do not always provide an exact measurement of dynamic crush. In this test, the dynamic crush computed from accelerometers was in error by 10%. Second, even in a perpendicular full frontal barrier test, the left and right side crush may not be the same. Although the crush values obtained by film analysis were higher than accelerometer data, it was observed that the left side of the vehicle had more crush than the right side, which was consistent with the maximum static crushes.

RESULTS AND DISCUSSIONS

Maximum Static Crush by Different Methods

Ninety-three NCAP frontal barrier impact tests were investigated on the accuracy of post-test crush measurements in this project. In these tests, a vehicle impacts a rigid barrier with full frontal structure engagement with an initial velocity of around 56 km/h. The maximum static crush was calculated by double integration of the accelerometers as described above. The results were compared with the pre- and post-test measurements DPDs, BX1-AX1, and CRHDST.

Results of the maximum static crush obtained from the accelerometers and physical measurements are shown in Figure 8 to Figure 13. In each graph, the maximum static crush computed from the accelerometers is plotted on the horizontal axis. The dotted 45 degree diagonal lines indicated the perfect agreement between the horizontal and vertical axis values. Trendlines were created to compare the physical measurements to the accelerometers. R^2 is a measure of goodness of fit surrounding the trendlines. It was observed from Figure 8 to Figure 13 that the physical measurements of the maximum static crush were on average 6 % less than the values calculated using the accelerometers. The values of the goodness of fit (R^2) for each comparison showed considerable scattering. The maximum static crush based on the maximum DPDs had a slightly better fit to the values calculated using the accelerometers than the other measurements. No significant difference was noticed between the left and right accelerometers comparing with the same physical measurements, as similar values of the goodness of fit were obtained.

Direct comparison was also completed between the accelerometer data obtained from the left and right side of the occupant compartment, and the results are plotted in Figure 14. It was found that the acceleration data obtained from both sides of the vehicle occupant compartment were very consistent with each other, which was indicated by the goodness of fit value (R^2) of 0.82.

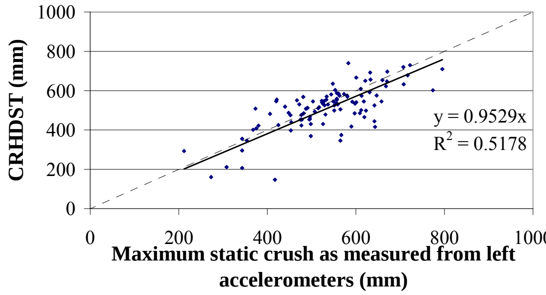

Figure 8. Comparisons of the maximum static crush computed from CRHDST and left accelerometers.

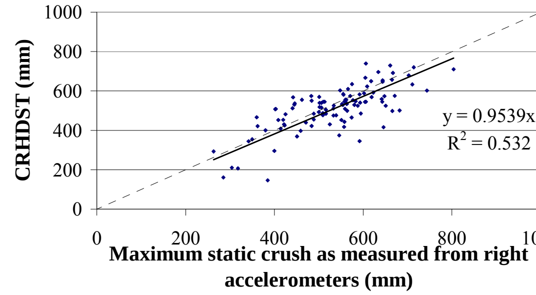

Figure 9. Comparisons of the maximum static crush computed from CRHDST and right accelerometers.

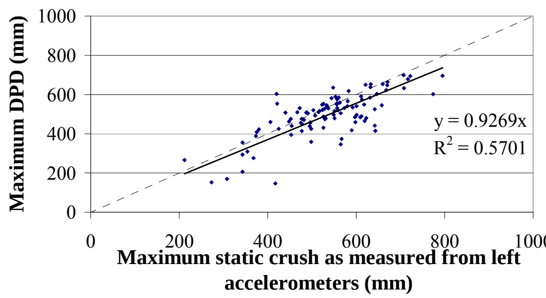

Figure 10. Comparisons of the maximum static crush computed from maximum DPDs and left accelerometers.

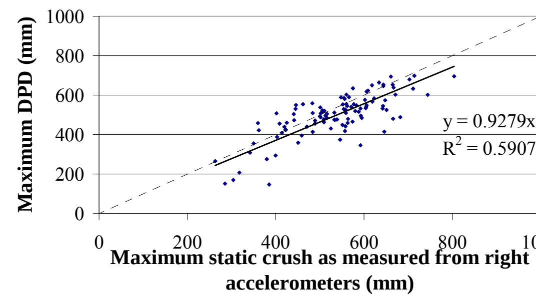

Figure 11. Comparisons of the maximum static crush computed from maximum DPDs and right accelerometers.

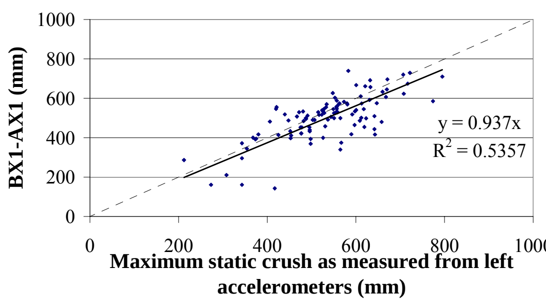

Figure 12. Comparisons of the maximum static crush computed from BX1-AX1 and left accelerometers.

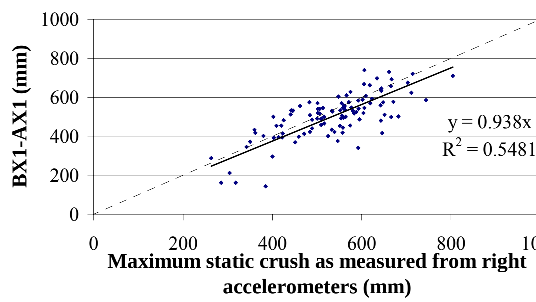

Figure 13. Comparisons of the maximum static crush computed from BX1-AX1 and right accelerometers

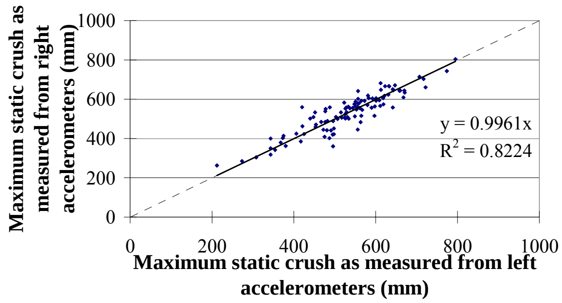

Figure 14. Comparisons of the maximum static crush computed from left and right side accelerometers.

Results of High-speed Video Analysis

In addition, video analysis was completed for 13 NHTSA NCAP tests of model year 2007. Test videos were not available for Test 5818, a 2007 Nissan Versa. The results were compared to the maximum dynamic crush calculated by accelerometers and illustrated in Figure 15 and Figure 16. These figures show that the maximum dynamic crush obtained from the acceleration curves were on average 3% less than the value estimated by the analysis of high-speed videos. The goodness of fit values suggest that the left side accelerometers had a better correlation with the videos ($R^2 = 0.82$) than the right side accelerometers ($R^2 = 0.65$). It was concluded from the figures that when video analysis was unavailable, utilizing accelerometers was a good alternate method to estimate the vehicle maximum dynamic crush accurately.

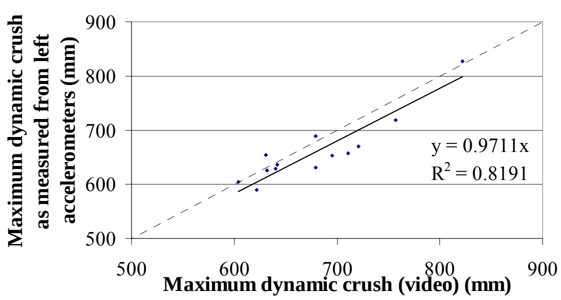

Figure 15. Comparisons of the maximum dynamic crush between video analysis and left side accelerometers in 13 model year 2007 vehicles.

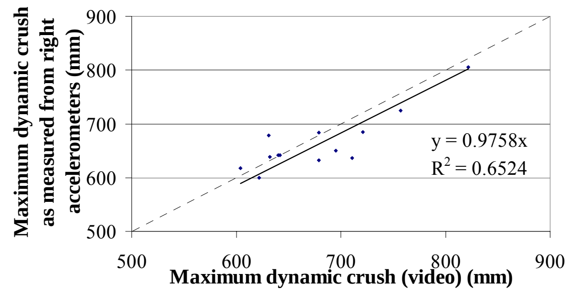

Figure 16. Comparisons of the maximum dynamic crush between video analysis and right side accelerometers in 13 model year 2007 vehicles.

Study of Vehicle Stiffness Coefficients and Delta-V Estimations Using Different Measurements

Accurate crush measurements are the basis for WinSMASH reconstruction of delta-V in real world crashes. Errors in static crush measurements will be reflected as inaccuracies in the stiffness coefficients, and ultimately as errors in WinSMASH delta-V estimates. The effects of vehicle crush measurements using different methods on vehicle stiffness coefficients and delta-V estimations will be discussed in the following section.

The investigation was conducted on 14 NHTSA NCAP tests of model year 2007 vehicles. Estimates of average crush obtained by different post-test crush measurements (DPDs, BX1-AX1, and the accelerometers) were used to calculate the vehicle stiffness coefficients. The comparisons of different crush measurements were completed in two steps. First, the average crush calculated using different crush measurements was compared, and the results are illustrated in Figure 18. Second, vehicle stiffness coefficients were calculated using the average crushes. The comparison between different methods was shown in Figure 19.

Equation 9 was used to calculate the average crush. Value c1 to c6 were the crush measurements along the damage profile. The average crush was calculated in three different methods. For the first method (denoted as DPDs in figures), original DPD measurements were used in the equation. For the second method, it was noticed that the post-test damage profile of the vehicle was nonuniform along the vehicle width. Large variations were also observed in different test vehicles. Our concern was that the post-test measurements may not really represent the true deformation of the vehicle during the test. Therefore, for the second method (denoted as

DPDs' in figures), it was assumed that the vehicle had a uniform post-test damage profile. The average of DPD3 and DPD4 was used as the maximum static crush, and was subtracted from the original profile (six equally spaced points along the vehicle) of the vehicle to calculate the average crush. For the third method, the change in Total Length of Vehicle at Centerline (BX1 – AX1) was subtracted from the pre-test profile of the vehicle, and then used in Equation 9. As an example, the average crush computed using these three methods is plotted in Figure 17 for NHTSA NCAP test 5615. Along the same line, the average of maximum crushes by right and left accelerometers was used as the post-test profile, and was subtracted from the pre-test profile of the vehicle to calculate the average crush.

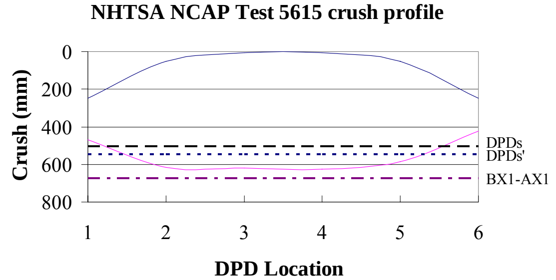

Figure 17. The average crush computed using three methods for NHTSA NCAP test 5615.

For 13 NHTSA NCAP tests of model year 2007, accelerometers were corrected to agree with the video dynamic crush. The accelerometer static crush was recomputed, and is shown in Table 2. Vehicle stiffness coefficients calculated using the corrected accelerometer static crush are also tabulated in Table 2.

It was observed from Figure 18 that the average crush calculated by physical measurements was generally 5% less than the value predicted by the accelerometers. The reason for this difference could be the continued expansion of the vehicle after its separation from the barrier or errors in measurement. Also from the figure, no significant difference was noticed between the average crush calculated by the first two methods mentioned above (DPDs and DPDs') despite the concern we had before the analysis.

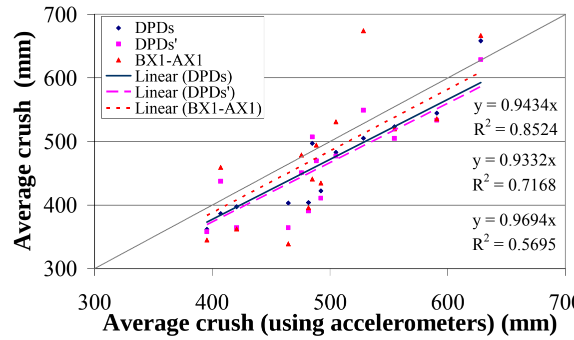

Figure 18. Comparisons of the average crush computed from physical measurements and accelerometers.

When the average crush was used to compute the vehicle stiffness coefficients (as shown in Figure 19), vehicle stiffness coefficient d_1 (the slope of the stiffness curve) calculated using physical measurements was approximately 7% greater than the value calculated using accelerometers. This discrepancy in stiffness coefficients indicated that the physical measurements estimated the test vehicle had a stiffer structure than predicted by the accelerometers.

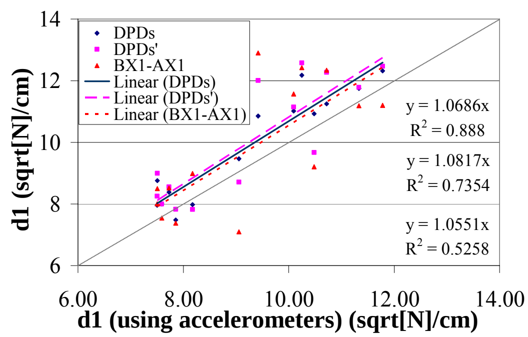

Figure 19. Comparisons of the vehicle stiffness coefficient computed from physical measurements and accelerometers.

Implications of the Results

Accelerometers can be used as an upper bound on crush. We originally thought that accelerometers might provide a true measure of crush. This was based heavily on the belief that all restitution of the front structure ended after the vehicle separated from the wall. Examination of high speed videos however shows that the bumper can spring back somewhat after separation from the wall. Despite the fact that bumper springback has no effect on delta-V, post-test measurements of frontal deformation use this final bumper position to compute static crush.

From the comparisons of the maximum static crush computed from physical measurements and accelerometers, 27 cases in the 93 case data set appeared to show physical measurements in error. These would be cases in which physical measurements of static crush exceeded the static crush computed using the accelerometers. This situation is not possible in a rigid full frontal barrier test. For the 27 cases, the maximum static crush from DPD measurements exceeded the static crush computed from the accelerometers by 9% on average, with a range from 0.2% to 25%. As shown in the derivation in the previous section, a 9% overestimate in crush will lead to a 9% underestimate in d_1 and also a 9% underestimate in ΔV- 7.5 mph in full frontal rigid barrier crashes.

Therefore, our recommendations for the post-test measurements are that: (1) all physical measurements should be checked against accelerometers; (2) all accelerometers should be checked against high speed videos and corrected if necessary. It should be noted that this does not guarantee that the physical measurements which have lower crush than accelerometers are correct, but this procedure does catch some measurement problems.

LIMITATIONS

Several limitations were found for the three different methods to obtain the maximum crush. Although the data calculated by left and right side accelerometers were generally very close, relatively large discrepancies were observed in some test cases. The differences could be the result of failure and errors by the accelerometers or the variation of the vehicle impact angle during the test. The limitation for video analysis was that the marker tracked in the videos was on the door of the vehicle instead of the floor of the occupant compartment, and it could only be used to calculate maximum dynamic crush to help examine the accuracy of accelerometers since the time of separation was difficult to determine in videos.

CONCLUSIONS

This paper has presented the accuracy of vehicle crush measurements in 93 NCAP frontal impact tests conducted from 2005-2007 and the WinSMASH stiffness coefficients as well as the delta-V estimates computed using different measurement techniques.

- The results from comparing the maximum static crush by different methods showed that the physical measurements of the maximum static crush were on average 6 % less than the values calculated using the accelerometers.

- The comparison of the accelerometer data obtained from the left and right side of the occupant compartment demonstrated that acceleration data obtained from both sides were very consistent with each other.

- Results of high-speed video analysis indicated that utilizing accelerometers to estimate the vehicle maximum dynamic crush was a good alternate method in addition to the video analysis. The maximum dynamic crush obtained from the acceleration curves were on average 3% less than the value estimated by analysis of high-speed videos.

- Study of vehicle stiffness coefficients and delta-V estimations using different measurements showed that the average crush calculated by physical measurements was 5% less than the value computed by the accelerometers. As a result, vehicle stiffness coefficient d1 calculated using physical measurements was mostly 7% greater than the value calculated using accelerometers.

- The comparisons of the maximum static crush computed from physical measurements and accelerometers showed that in 27 cases of the 93 case data set DPD measurements exceeded accelerometers by 9% on average. A 9% overestimate in crush will lead to a 9% underestimate in d_1 and also a 9% underestimate in ΔV- 7.5 mph in full frontal rigid barrier crashes.

- Physical measurements of static crush in crash tests should be checked against high speed videos and accelerometers prior to computation of vehicle stiffness coefficients. When physical measurements are found to be in error and cannot be repeated, the maximum static crush computed from accelerometers in the occupant compartment or measured from high speed videos can be used as an upper bound on static crush.

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APPENDIX

Table 1.
Crush patterns of 12 NHTSA NCAP tests of model year 2007
(solid lines represent pre-test profiles, dash lines represent post-test profiles)

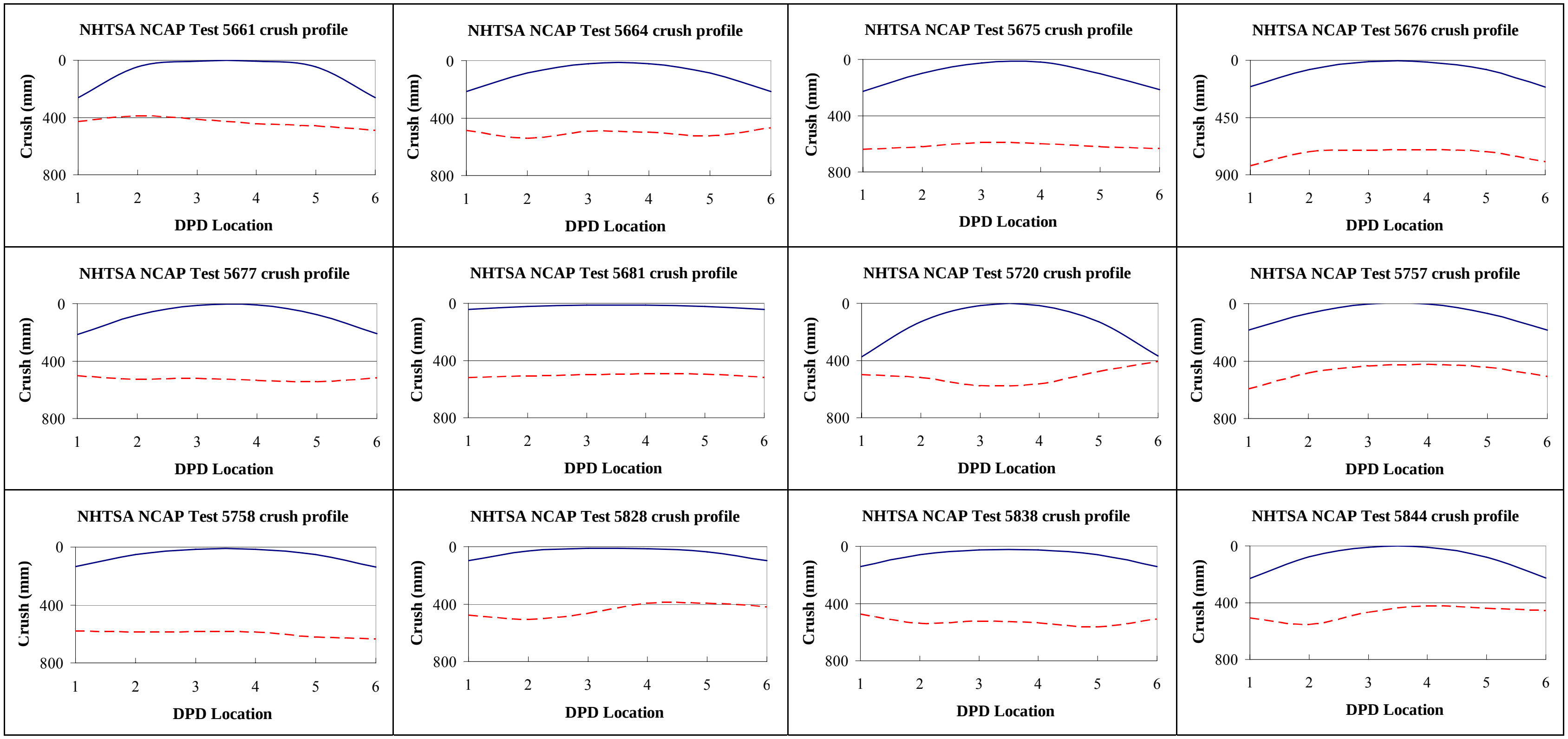

Table 2.
Summary of the data presented in Figure 18 and Figure 19

Test	Make	Model	Year	Average static crush (mm)		Stiffness coefficient d0 ($\sqrt{N}$)	Stiffness coefficient d1 ($\sqrt{N}/cm$)				
				Accelerometer (uncorrected)	Accelerometer (corrected)		Accelerometer (uncorrected)	Accelerometer (corrected)	DPDs	DPDs'	BX1-AX1
5615	CHEVROLET	TAHOE	2007	528.5	557.5	123.25	9.06	8.58	9.47	8.71	7.10
5661	DODGE	CALIBER	2007	395.5	416.5	101.10	10.10	9.58	11.02	11.15	11.57
5664	HONDA	FIT	2007	492.3	497.8	95.41	7.51	7.43	8.76	9.00	8.50
5675	TOYOTA	CAMRY	2007	554.8	548.8	102.08	7.51	7.59	7.96	8.25	8.01
5676	CHEVROLET	SUBURBAN	2007	628.1	633.1	128.23	7.86	7.79	7.48	7.83	7.38
5677	TOYOTA	YARIS	2007	475.7	478.7	91.81	7.59	7.54	8.00	8.00	7.54
5681	TOYOTA	FJ CRUISER	2007	505.0	539.5	115.88	11.78	11.03	12.32	12.47	11.20
5720	MAZDA	CX-7	2007	407.2	461.2	109.71	10.48	9.21	10.93	9.67	9.21
5757	LEXUS	ES 350	2007	464.6	507.1	107.39	9.42	8.63	10.85	12.01	12.90
5758	FORD	RANGER	2007	590.9	557.4	111.23	7.73	8.19	8.38	8.55	8.52
5818	NISSAN	VERSA	2007	485.0	485.0	96.94	8.18	8.18	7.98	7.82	8.99
5828	JEEP	COMPASS	2007	481.8	476.3	105.75	10.25	10.35	12.18	12.58	12.42
5838	HYUNDAI	SANTA FE	2007	488.4	485.9	118.40	11.33	11.39	11.75	11.78	11.19
5844	SATURN	AURA	2007	420.8	452.8	107.32	10.72	9.94	11.25	12.27	12.34