2008 Joint Conference Lateral Pole Crash Test Results

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Abstract

Three lateral pole crashes were conducted as part of the 2008 Annual Joint Conference in Atlantic City, NJ on October 14, and October 15, 2008. The conference was hosted by the New Jersey Association of Accident Reconstructionists. The purpose of the tests were to determine if the CRASH3 energy equation, the Vomhof CF method, and the Morgan and Ivey equation accurately predict the impact speed of a test vehicle. The results varied depending on how the collision force was calculated. However, due to the limited number of tests, a recommendation as to which method will produce the best result is not possible. Nevertheless, some important information may be learned from these tests. Further testing must be performed and a suitable method for estimating the collision force in a lateral narrow-object impact must be found.

Introduction

Narrow-object equations based on maximum static deformation are available for collisions that involve the front of a passenger vehicle. However, most of these equations are not suitable for use in a narrow-object collision that involves the side of a passenger vehicle. Most of the equations are strictly derived or modeled for the front of the vehicle. The SAE paper authored by Morgan and Ivey, in which their equation is presented, contains the following language: "For a side impact no adjustment is warranted by the available data[1]." This infers that the authors believe their equation may be applied to side impacts. The Morgan and Ivey equation is,

$$v = d\sqrt{(395 - .062W)(1 + \Delta E)} \quad (1)$$

where,

v = kinetic energy equivalent speed (KEES)* in feet/second

d = maximum crush in feet

W = weight of the vehicle in pounds

ΔE = the increase or decrease in energy absorbed in crushing the vehicle due to impacting the pole, relative to that absorbed in an impact with a class 4-40 pole. Use ΔE of +0.25 for class-3 poles, 0.00 for class-4 poles, and -0.25 for class-5 poles.

The only other equation that estimates the KEES as a function of maximum deformation for side impacts is the Vomhof method. This method is based on the early work of Baker[2], and is essentially a use of the "slide-to-stop" equation adapted for collisions. In place of a drag factor, a crush factor is used which represents the average Gs the car is subjected to during the crash pulse. The Vomhof method is

$$v = \sqrt{30dCF(0.6)} \quad (2)$$

where,

v = KEES (mi/hr)

d = maximum crush (ft)

CF = Crush Factor (unitless)

The first approximation for the crush factor is taken to be 21 for front and side impacts[3]. Crush factors for individual vehicles may be calculated and are available through the StifCalcs® program, however, the crush factors for the three tests vehicles were very close to 21, so 21 was used to analyze these tests. When 21 is assumed to be the crush factor, equation (2) becomes,

$$v = 19.4\sqrt{d} \quad (3)$$

* For the purpose of this report, KEES is equivalent in meaning to EBS or BEV

Research has shown that the Vomhof method is accurate for frontal pole crashes when the maximum static deformation is 18 inches or more[4]. One purpose of these crash tests is to test the hypothesis that the Vomhof method will work for narrow-object impacts that involve the side of a vehicle.

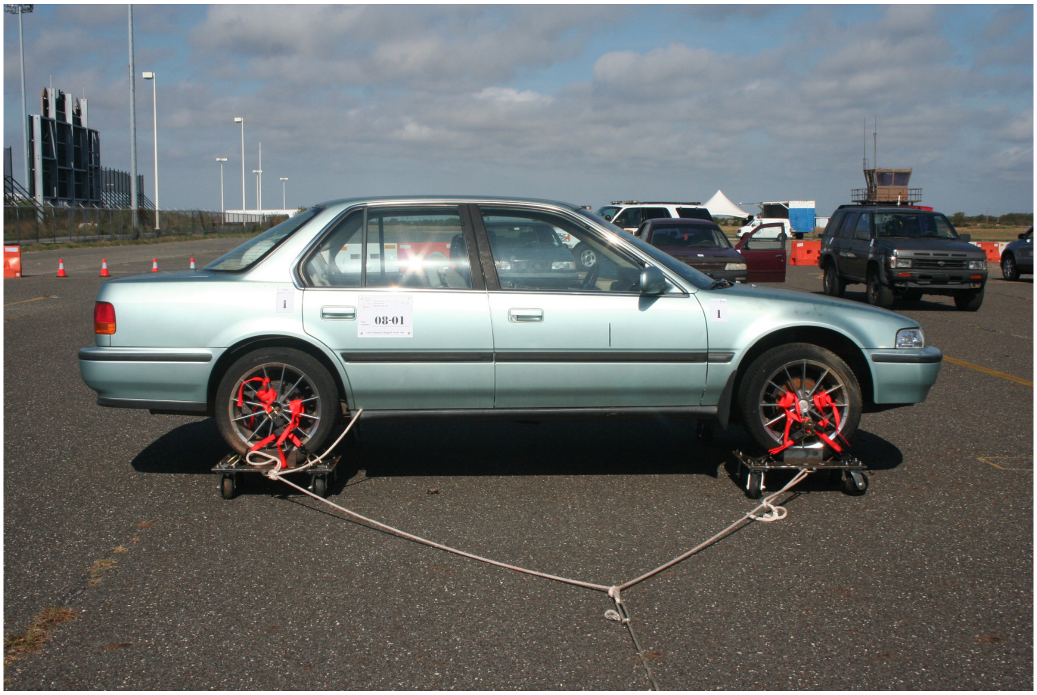
The other analysis tested was the CRASH3 energy equation. This equation is a function of NHTSA crash test derived stiffness coefficients, the length of the indentation, the location of the damage centroid, the angle the force vector makes with the undamaged surface, and the crush area. The damage centroid and the area of crush are commonly obtained by measuring the depth of crush at six equally spaced crush stations.

Procedure

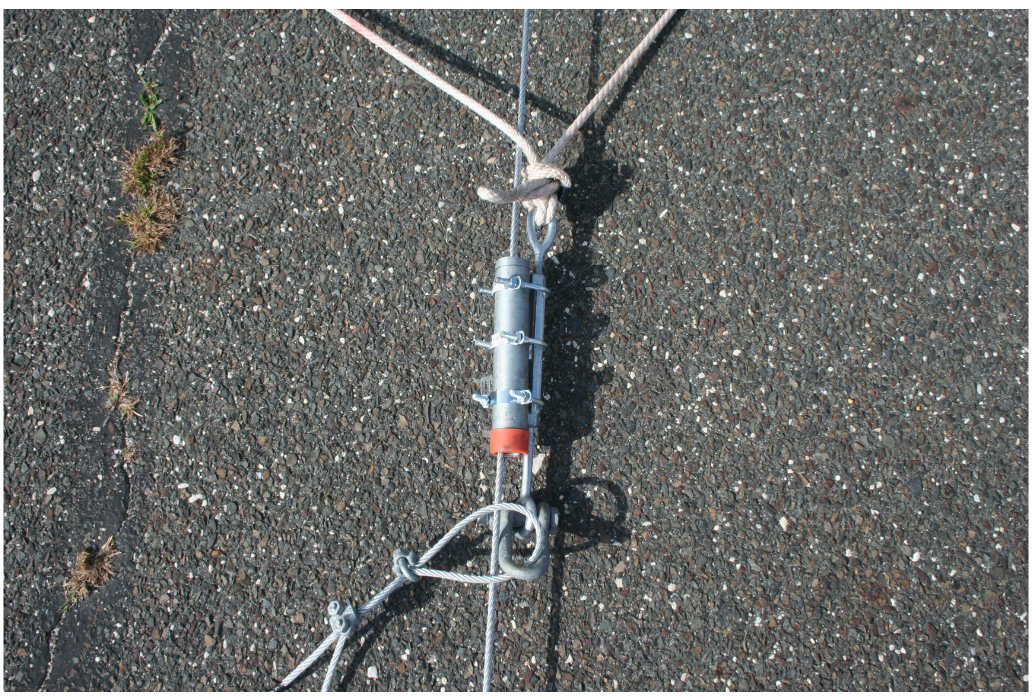
Three vehicles were set up on a dolly system (Photograph 1) and pulled sideways into class-three wooden utility poles. For safety, one end of a steel cable was attached to the pole and the other end of the cable was attached to a tow truck. The test vehicles were pulled into impact by a tow vehicle and pulley system. A pulley was attached to the pole, and the tow cable was guided along the safety cable by a steel tube (Photograph 2).

The cable that was used to pull the test car to impact was released just before the collision to eliminate the influence of external forces from the tow vehicle. The tests were set up so that the test vehicle would strike the pole near the vehicle's center-of-mass (COM). The COM was calculated by measuring the weight on each axle with Haenni WL101 wheel load scales and summing moments about the front axle. Alignment of the impact near the COM was intended to limit post-impact rotational energy. All three vehicles were instrumented with an IST model EDR-3 accelerometer, which was bolted to the floor pan opposite from the collision side of the vehicle. All of the poles were instrumented with an IST model EDR-3 accelerometer, which was bolted to the opposite side of the pole from the collision and approximately 24 inches above ground level.

The impact speed was measured with dual FarmTek Polaris timer systems. One system was set up several feet in front of the poles and triggered by the test vehicle, and the second system was set up so the tow vehicle would trigger the system just as the test vehicle was released.



Photograph 1: Delivery System



Photograph 2: Safety System

Results

The following tables, charts, and photos present the data for the three crash tests:

Test #1—October 14, 2008:

Vehicle Information	
Year/Make/Model	1992 Honda Accord LX 4-Door
VIN	1HGCB7652NA102230
Weight on Front Axle	1775 lb
Weight on Rear Axle	1050 lb
Total Weight	2825 lb
Center-of-Mass from Front Axle	39.70 inches

Table 1: Test 1 Vehicle Data

Test Speed	25 mi/hr
Indentation Length	72 in
Offset (d)	+ 13 in
Contact Damage Only Offset	+ 17.25 in
C1	0.00 in
C2	5.25 in
C3	9.75 in
C4	8.00 in
C5	1.25 in
C6	0.00 in
C_{max}	14.00 in
A_D	387.6 in^2
$\overline{x}$	4.36 in
PDOF	90°
Pole Circumference	37.5 in
Pole Displacement	10.8 in
Pole Angle	9.32°

Table 2: Test 1 Damage Measurements

Chart 1 is the filtered crash pulse from the Honda-mounted accelerometer. The time of the crush pulse is approximately 0.2166 seconds and the integrated delta-v associated with this time interval is -24.88 mi/hr. It should be noted that Chart 1 displays the x-axis acceleration because the accelerometer's x-axis was aligned with the y-axis of the Honda.

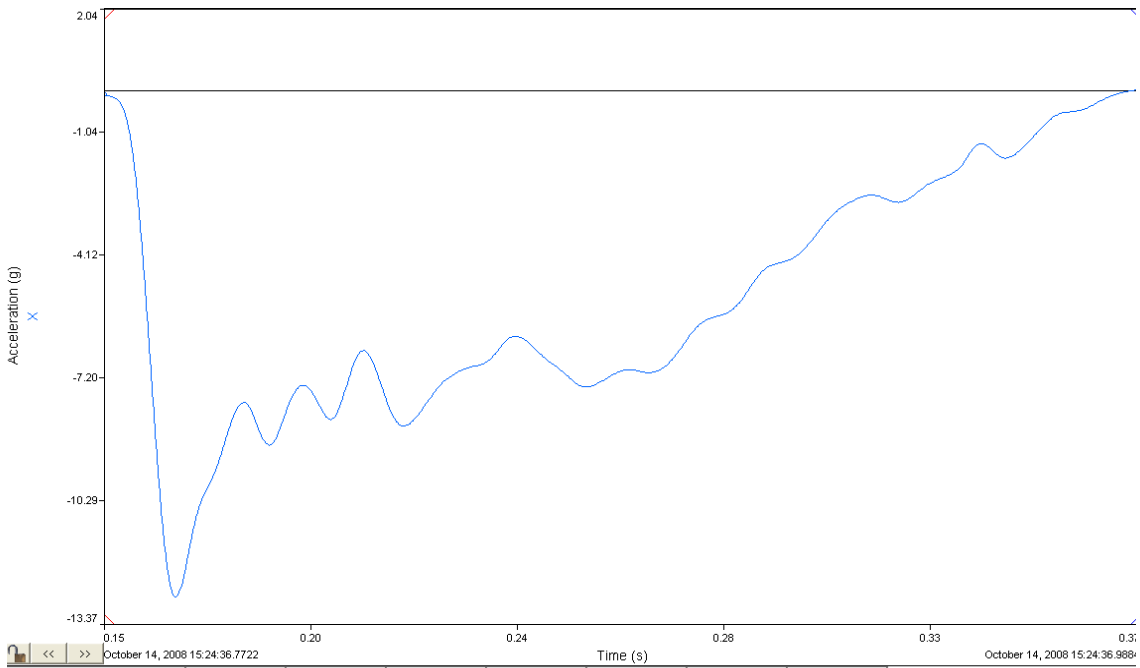


Chart 1: Test 1 IST Accelerometer Crash Pulse

The Honda was not bowed. Note that following the Tumbas-Smith damage measurement protocol missed the 14-inch maximum depth of crush. This resulted in an underestimation of the KEES and the impact speed. This will be addressed later on in this report. Also noteworthy was that the damage was measured with two different methods. The first method established a reference line by stretching a piece of masking tape from deflection point to deflection point (Photograph 3). The second method established a reference line on the ground by measuring from the undamaged side of the vehicle to the damaged side a distance equal to the undamaged width of the vehicle. Both methods rendered the same damage profile measurements.

Photograph 3: Test 1--Damaged Honda (KEES = 21.0 mi/hr) and Masking Tape Used for Crush Measurements

Test #2—October 15, 2008:

Vehicle Information	
Year/Make/Model	1994 Volvo 850 4-Door
VIN	YV1LS5511R2116003
Weight on Front Axle	1800 lb
Weight on Rear Axle	1300 lb
Total Weight	3100 lb
Center-of-Mass from Front Axle	44.28 in

Table 3: Test 2 Vehicle Data

Test Speed	35 mi/hr
Indentation Length	22.00 in
Offset (d)	0.00 in
Contact Damage Only Offset	0.00 in
C1	0.00 in
C2	4.50 in
C3	7.50 in
C4	15.50 in
C5	10.00 in
C6	0.00 in
C_{max}	21.25 in
Bowing Offset	3.25 in
A_D	963.00 in^2
$\bar{x}$	7.29 in
Bowing Constant 1	0.75 in
Bowing Constant 2	4.25 in
PDOF	270°
Pole Circumference	34.50 in
Pole Displacement	28.44 in
Pole Angle	23°

Table 4: Test 2 Damage Measurements

Chart 2 is the filtered crash pulse from the Volvo-mounted accelerometer. The time of the crush pulse is approximately 0.3197 seconds and the integrated delta-v associated with this time interval is 31.96 mi/hr. The positive y-axis of the accelerometer was aligned parallel to the lateral axis of the car and sensed to the left of the car.

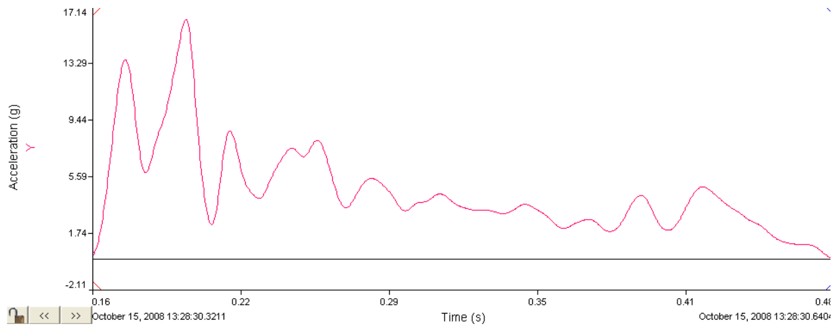


Chart 2: Test 2 IST Accelerometer Crash Pulse

The Volvo (Photograph 4) was bowed, so to account for the energy dissipated bowing the vehicle both methods described by the Tumbas-Smith protocol were used to measure the damage profile for the purpose of determining which of the two methods would render a more accurate speed estimate. Recall that these two methods are the bowing constant method and the adjusted baseline method.

Photograph 4: Test 2--Damaged Volvo (KEES = 22.5 mi/hr)

Test #3—October 15, 2008:

Vehicle Information	
Year/Make/Model	1991 Nissan Pathfinder
VIN	JN8HD17Y8MW025888
Weight on Front Axle	2100 lb
Weight on Rear Axle	1950 lb
Total Weight	4050 lb
Center-of-Mass from Front Axle	50.07 in

Table 5: Test 3 Vehicle Information

Test Speed	30 mi/hr
Indentation Length	69.00 in
Offset (d)	0.00 in
Contact Damage Only Offset	0.00 in
C1	0.00 in
C2	3.50 in
C3	6.00 in
C4	12.00 in
C5	9.00 in
C6	0.00 in
C_{max}	13.00 in
PDOF	90°
A_D	593.5 in^2
$\overline{x}$	4.88 in
Pole Circumference	34.50 in
Pole Displacement	26.64 in
Pole Angle	18.8°

Table 6: Test 3 Damage Measurements

Chart 3 is the filtered crash pulse from the Nissan-mounted accelerometer. The time of the crush pulse is approximately 0.2375 seconds and the integrated delta-v associated with this time interval is -28.60 mi/hr. The positive y-axis of the accelerometer was aligned parallel to the lateral axis of the car and sensed to the right of the car.

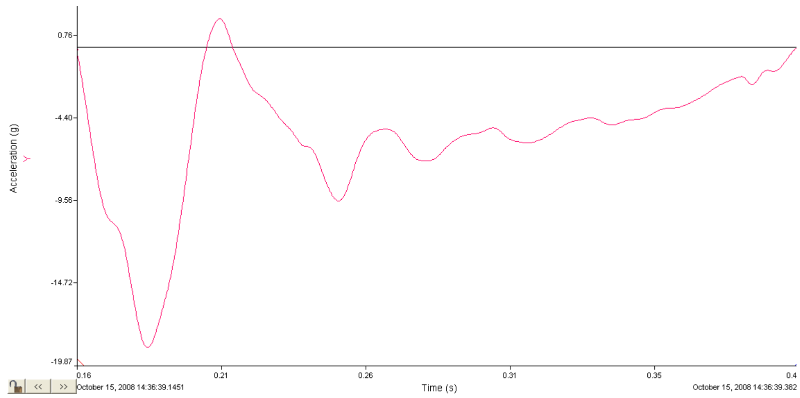


Chart 3: Test 3 IST Accelerometer Crash Pulse

The Nissan (Photograph 5) was not bowed, so a comparison of the bowing constant method and the adjusted baseline method was not possible.

Photograph 5: Test 3--Damaged Nissan (KEES = 22.5 mi/hr)

Table 7 shows the available stiffness coefficients for the three vehicles. Note that side crash tests were not available for the Nissan, so the reported stiffness coefficients were based on a class vehicle. The class vehicle will be explained later in this report.

	Honda	Volvo	Nissan
Front, Average Crush	A=336.8 lb/in B=116.4 lb/in^2	A=202.2 lb/in B=153.4 lb/in^2	A=401.6 lb/in B=114.8 lb/in^2
Side, Average Crush	A=103 lb/in B=95.5 lb/in^2	A=234.2 lb/in B=438.3 lb/in^2	A=225.2 lb/in B=419.3 lb/in^2
Side, Maximum Crush	A=64.8 lb/in B=37.9 lb/in^2	A=123.3 lb/in B=122.4 lb/in^2	A=122.9 lb/in B=121.8 lb/in^2

Table 7: Stiffness Coefficients for Test Vehicles

Discussion

Conventional Reconstruction Using CRASH3

For the first two tests NHTSA side moving barrier, and front barrier crash tests were available. The CRASH3 energy equation was used to estimate the energy deforming the vehicle. The CRASH3 force equation was then used to estimate the force acting on the car, which was related to the force acting on the pole by Newton's Third Law. The CRASH3 force equation is,

$$F_{avg} = \frac{\left(A + BC_{avg}\right)L}{2\cos\alpha} \tag{4}$$

Where,

F_{avg} = average force during the collision (lb)

A = stiffness coefficient (lb/in)

B = stiffness coefficient (lb/in^2)

C_{avg} = average crush (in)

L = length of the damage indentation (in)

α = angle the force vector makes with the normal vector to the undamaged vehicle surface (deg).

To account for rotation of the pole, the force was modified by an effective force coefficient (EFC). The EFC is a determination of the average angle of the pole during the collision. It is not a simple arithmetic average, but one that is obtained by the mean value theorem for integrals. The EFC is derived as follows:

$$EFC = \frac{1}{\theta_f - \theta_i}\int_{\theta_i}^{\theta_f} \cos\theta d\theta \tag{5}$$

where,

EFC = Effective Force Coefficient (unitless)
θ_f = The lean angle of the pole (radians)
θ_i = The initial lean angle of the pole before the collision occurred (radians)

For the assumption that the pole is perfectly vertical before the collision, this equation becomes

$$EFC = \frac{\sin\theta_f}{\theta_f} \tag{6}$$

where θ_f is measured in radians. The work moving the pole now becomes the product of the force acting on the pole, the EFC, and the distance that the pole was displaced:

$$W_{pole} = F_{avg}\left(EFC\right)d \tag{7}$$

where,

W_{pole} = work done by the car moving the pole (ft-lb)
F_{avg} = average force during the collision (lb)
d = distance the pole moved at the impact level (ft)

The work moving the pole and the work performed damaging the car were summed and related to the impact speed of the test vehicle with equation (8).

$$v = \sqrt{\frac{2gKE}{w}} \tag{8}$$

where,

v = impact velocity (ft/sec)
g = acceleration due to gravity (32.2 ft/sec^2)
KE = sum of the energy dissipated during the collision (ft-lb)
w = weight of the car (lb)

It was assumed that any other energy dissipated was negligible. This assumption may be problematic because of the safety cable that was attached to the impacted pole may not replicate real-world crash conditions. This cable dissipated energy by stretching and then returned energy after the collision by exerting a restoring force to the pole. This also complicated post-test measurements because the pole was moved back toward its original vertical position. It was also noted in the Nissan test that the 38000-pound tow truck used to anchor the other end of the cable was moved. Future testing must eliminate this energy sink.

During the initial analysis performed in Atlantic City, it was discovered that six equally spaced crush measurements did not adequately describe the damaged area of the Honda. This was because the equally distributed crush stations missed the maximum deformation. This deficiency was corrected by taking 15 crush measurements and modeling the damage in AutoCAD. Note that 15 measurements was an arbitrary number of measurements chosen to more accurately determine the KEES. More measurements may be required, and less may be sufficient depending on the damage. AutoCAD was then used to report the damaged area in square inches, and the location of the centroid from the original undamaged surface of the vehicle in inches. Equation (9) was then used, which is the general form of the CRASH3 energy equation.

$$E = \left[\frac{A^2 L}{2B} + \left(A + B\overline{x} \right) A_D \right] \left(1 + Tan^2 \alpha \right) \tag{9}$$

Where,

E = energy (in-lb)
A = stiffness coefficient (lb/in)
B = stiffness coefficient (lb/in^2)
L = indentation length including induced damage (in)
$\overline{x}$ = location of damage centroid from undamaged surface (in)
A_D = damage area (in^2)

α = angle the force vector makes with the normal vector to the undamaged vehicle surface (deg).

Side stiffness coefficients were not available for the Nissan, so a "class vehicle" filter was specified in the StifCalcs® computer program. A "class vehicle" is a feature of the StifCalcs® program that permits a search of NHTSA crash tests based on wheelbase, weight, and other criteria. The filter used for the Nissan was based on the weight and wheelbase.

Conventional Reconstruction Using Vomhof and Morgan & Ivey

The Vomhof method and the Morgan and Ivey equation rendered a KEES, which was converted to energy. To calculate the average force acting on the car during the collision for these two methods, and hence the pole, a method other than the CRASH3 force equation was used. It must be assumed that the reconstructionist may at times be using the Vomhof method or the Morgan and Ivey equation because stiffness coefficients are not available, or the reconstructionist may only have the maximum deformation measured and not the entire crush profile. Furthermore, some method to estimate force, and thus energy expended, on the pole is necessary because it is anticipated that the instrumentation of a pole in a real collision is highly unlikely.

The method used to estimate the force was derived by Andrew Rich in 2008 for frontal pole crash tests. The method is based on a geometric interpretation of the force vs. residual crush curve. This method has not yet been published, but has been peer reviewed. The application of this method to three pole crash tests conducted in 2007 at IPTM in Jacksonville, Fl and to seven crash tests conducted in 2007 in Cincinnati, Ohio show that it is an accurate method for determining the average collision force given only an estimate of the average crush, and the KEES when applied to frontal pole collisions. The technical aspects of this procedure are beyond the scope of this report. One of the measurements needed for the geometric force calculation is the average crush. To estimate the average crush, therefore, half of the maximum deformation was used. Experience with the aforementioned crash tests manifests that half of the maximum crush is a good estimator of the average crush for narrow-object collisions. Once the collision force was calculated with the geometric method, it too was adjusted by the EFC and then the work moving the pole was estimated.

Table 8 presents the results of the conventional crash test reconstruction. Chart 4 is a visual representation of Table 8.

	Honda	Volvo	Nissan
Test Speed (mi/hr)	**24.9**	**34.8**	**30.5**
Vomhof (mi/hr)	24.8	44.0	43.9
Morgan & Ivey (mi/hr)	20.0	35.0	20.9
CRASH3 Front A&B (mi/hr)	25.5	24.8	29.5
CRASH3 Side A&B max crush (mi/hr)	13.2	21.8	28.6
CRASH3 Side A&B avg crush (mi/hr)	19.8	40.1	37.4

Table 8: Crash Test Summation Results Using Geometric Method Force Calculation and CRASH3 Force Calculation

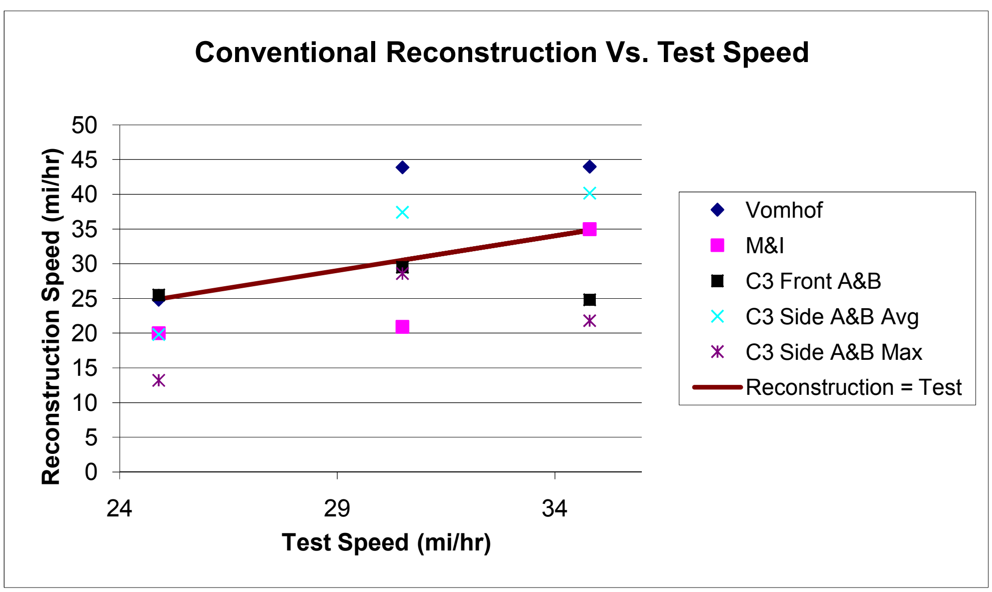


Chart 4: Crash Test Summation Results Using Geometric Method Force Calculation and CRASH3 Force Calculation

Table 9 shows the results of the collision force calculations. More comprehensive force and impact speed calculations were performed on the Nissan and are shown in Table 10. The force values for the Nissan that are reported in Table 9 come from the results in Table 10 that came closest to the test speed, and are shown in bold. The IST-calculated collision force will be explained in the next section of this report, but is presented in Table 9 for comparison purposes.

	Honda	**Volvo**	**Nissan**
Vomhof (lb)	37411	57022	93887
Morgan & Ivey (lb)	24903	39530	21005
CRASH3 Front A&B (lb)	34683	18589	38015
CRASH3 Side A&B max crush (lb)	9678	14425	34288
CRASH3 Side A&B avg crush (lb)	22216	49436	62546
IST-Calculated Collision Force (lb)	14792	14133	22214

Table 9: Results of Force Calculations

Test speed = 30.5 mi/hr	**Masking Tape Across Door**	**Baseline From Undamaged side**	**CAD Area and Centroid**
Front A&B, average crush	23.5 mi/hr 23243 lb	**29.5 mi/hr** 38015 lb	32.7 mi/hr 42176 lb
Side A&B, max crush	20.8 mi/hr 19203 lb	25.4 mi/hr 29873 lb	**28.6** mi/hr 34288 lb
Side A&B, avg crush	**37.4** mi/hr 62546 lb	45.4 mi/hr 96011 lb	51.3 mi/hr 111209 lb

Table 10: CRASH3 Results Comparison for Nissan—Impact Speed & Force Calculation

Table 11 shows the results of the equivalent speed calculations for the conventional crash test reconstruction. Again, the IST-calculated equivalent speed will be explained in the next section, but is presented in Table 11 for comparison purposes.

	Honda	Volvo	Nissan
Test Speed (mi/hr)	24.9	34.8	30.5
Vehicle Damage Energy Speed Equivalent			
Vomhof KEES (mi/hr)	21.0	25.8	20.2
Morgan & Ivey KEES (mi/hr)	13.2	19.2	9.90
CRASH3 KEES Front A&B (mi/hr)	17.9	14.2	16.0
CRASH3 KEES Side A&B Max Crush	9.10	12.4	12.8
CRASH3 KEES Side A&B Avg Crush	13.5	22.5	22.5
Pole Movement Energy Speed Equivalent Based On Geometric Method			
POLE KEES (mi/hr) Based On Vomhof KEES	13.2	35.6	39.0
POLE KEES (mi/hr) Based On Morgan & Ivey KEES	15.0	29.3	18.4
POLE KEES (mi/hr) Based On CRASH3 Force With Front A&B	18.2	20.3	18.9
POLE KEES (mi/hr) Based On CRASH3 Force With Side A&B Max Crush	9.6	18.0	26.5
POLE KEES (mi/hr) Based On CRASH3 Force With Side A&B Avg Crush	14.5	33.2	29.9
Pole Movement Energy Speed Equivalent			
Pole KEES based on IST (mi/hr)	11.9	17.8	18.9

Table 11: Crash Test Equivalent Speeds From Damage and Geometric Force Calculation or CRASH3 Force Equation

Reconstruction With IST Accelerometer Data

The results of the force calculations performed in the conventional reconstructions brought into question the CRASH3 and the geometric methodologies used to calculate the collision forces *in lateral pole impacts*. More testing and analysis is needed before any firm conclusions on limitations of these methodologies can be formed.

The IST accelerometer data was used in the impulse-momentum model to calculate the force acting during the collision. The impulse definition of momentum is,

$$F\Delta t = m\Delta v \tag{10}$$

Substitution of $m = \frac{w}{g}$ into equation (10) gives the following equation for the average force acting during the collision:

$$F_{avg} = \frac{w\Delta v}{g\Delta t} \tag{11}$$

where,

w = weight (lb)

F_{avg} = average force (lb)

Δv = change in velocity (ft/sec)

g = acceleration due to gravity (32.2 ft/sec^2)

Δt = duration of crash pulse (sec)

Table 12 is a summary of the accelerometer data along with the force as calculated from equation (11).

	Δv (mi/hr)	Δt (sec)	Force (lb)
Honda	24.9	0.2166	14792
Volvo	32.0	0.3197	14133
Nissan	28.6	0.2375	22214

Table 12: Accelerometer Data and Impulsive Force Calculation Results

All crash test results were recalculated using the force determined from the IST data and appear in Table 13. This table is presented in a visual format in Chart 5. The work deforming the car and the work moving the pole as determined by IST instrumentation were summed and the impact velocity was then estimated. It was assumed that any other energy dissipated was negligible. Again, this assumption may be problematic because of the safety cable attached to the pole. Table 14 shows the results of the equivalent speed calculations from the IST accelerometer reconstruction. The numbers in bold appear in Table 16 and in the captions of the photographs of the damaged vehicles that appeared in the beginning of this report.

	Honda	Volvo	Nissan
Test Speed (mi/hr)	**24.9**	**34.8**	**30.5**
Vomhof (mi/hr)	24.1	31.3	27.7
Morgan & Ivey (mi/hr)	17.7	25.6	21.4
CRASH3 Front A&B (mi/hr)	21.5	22.7	27.3
CRASH3 Side A&B max crush (mi/hr)	15.0	21.6	25.0
CRASH3 Side A&B avg crush (mi/hr)	18.0	28.7	29.4

Table 13: IST Accelerometer Reconstruction Results

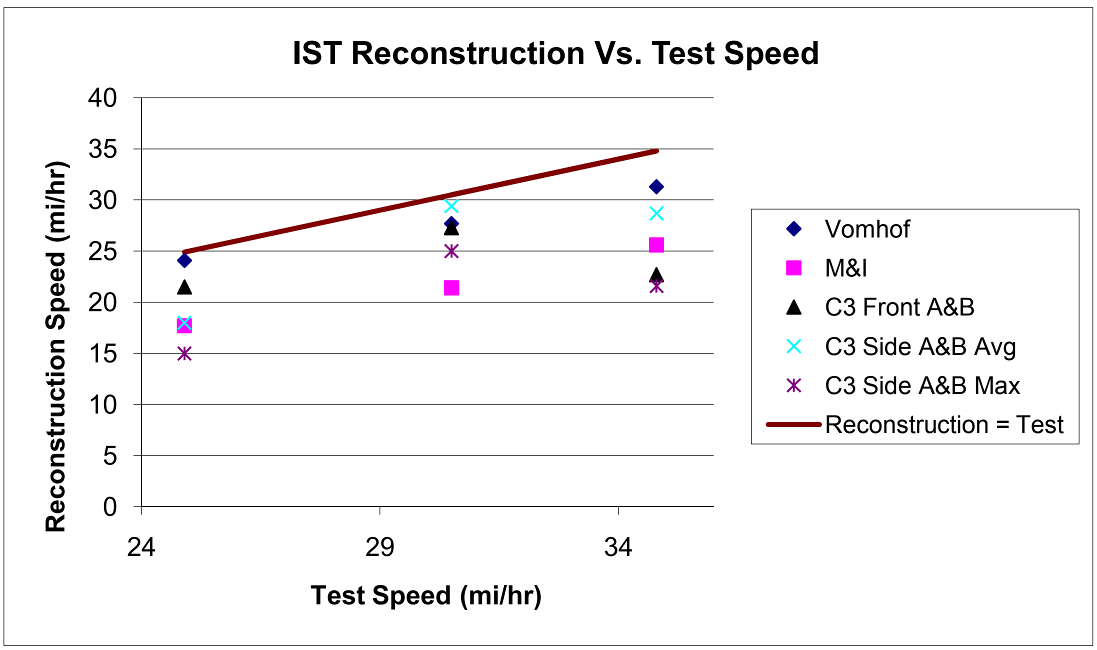


Chart 5: Results From IST Accelerometer Reconstruction

	Honda	Volvo	Nissan
Test Speed (mi/hr)	24.9	34.8	30.5
Vehicle Damage Energy Speed Equivalent			
Vomhof KEES (mi/hr)	**21.0**	**25.8**	20.2
Morgan & Ivey KEES (mi/hr)	13.2	19.2	9.9
CRASH3 KEES Front A&B (mi/hr)	17.9	14.2	16.0
CRASH3 KEES Side A&B Max Crush (mi/hr)	9.1	12.4	12.8
CRASH3 KEES Side A&B Avg Crush (mi/hr)	13.5	22.5	**22.5**
Pole Movement Energy Speed Equivalent			
Pole KEES based on IST (mi/hr)	11.9	17.8	18.9

Table 14: Crash Test Equivalent Speeds From Damage and IST Pole Movement

Nine different combinations of calculating the CRASH3 results for the Nissan were tried and are tabulated in Table 15. The results in Table 15 that were closest to the test speed are shown in bold and are reported in Table 13.

Test speed = 30.5 mi/hr	**Masking Tape Across Door**	**Baseline From Undamaged side**	**CAD Area and Centroid**
Front A&B, average crush	23.9 mi/hr	24.8 mi/hr	**27.3** mi/hr
Side A&B, max crush	21.9 mi/hr	22.9 mi/hr	**25.0** mi/hr
Side A&B, avg crush	27.3 mi/hr	**29.4** mi/hr	34.5 mi/hr

Table 15: CRASH3 Results Comparison for Nissan Using IST-Calculated Collision Force

Test Summaries

Test #1 Summary (Honda)

The best predictor of speed for this test was the Vomhof method when used with the geometric force calculation. The Honda was not bowed, so it was not possible to test the two different methods for bowing compensation. The lesson learned from this test is that the maximum crush must be included in the damage measurements or the crushed area will be underestimated. This will result in an underestimation of the KEES. The best CRASH3 estimate was achieved by taking 15 crush measurements and plotting the damage in AutoCAD.

The CRASH3 analysis performed well when frontal stiffness coefficients were employed with the IST-calculated collision force. The use of side stiffness coefficients for this vehicle underestimated the impact speed of the Honda.

Test #2 Summary (Volvo)

The best predictor of impact speed for this test was the Morgan and Ivey equation when used with the geometric force calculation. The Vomhof method significantly overestimated the impact speed when combined with the geometric force calculation. The Volvo was bowed, so both methods described by the Tumbas-Smith protocol were used to measure the damage profile for use in the CRASH3 analysis. Results using the bowing constant method are reported in Table 8 and Table 13. The adjusted baseline results were 1 to 2 mi/hr higher than the bowing constant method. The CRASH3 analysis overestimated the impact speed when calculated with side stiffness coefficients calculated from the average crush of the NHTSA test vehicle. The impact speed was underestimated when calculated from frontal stiffness coefficients and side coefficients based upon the maximum crush of the NHTSA tests vehicle.

When the analysis was recalculated with the IST-determined force, the Vomhof method worked well as did the CRASH3 analysis based on frontal stiffness coefficients.

Test #3 Summary (Nissan)

The best predictor for this test was the CRASH3 analysis based upon frontal stiffness coefficients combined with the crush measurements taken from a reference line established from the undamaged side of the vehicle. Side stiffness coefficients calculated from the maximum crush of the NHTSA test vehicle combined with AutoCAD-provided damage area and centroid location also performed well. The Vomhof method, when combined with the geometric force calculation, significantly overestimated the impact speed of the vehicle. The Morgan and Ivey equation, when combined with the geometric force calculation, significantly underestimated the impact speed of the vehicle.

When the IST-calculated collision force was used, the CRASH3 method that worked the best was the baseline established from the undamaged side of the vehicle combined with side stiffness coefficients calculated from the average crush of the NHTSA test vehicle. The Vomhof method also provided acceptable results when combined with the IST-calculated collision force.

Concluding Vehicle KEES Estimators

Using the IST reconstruction results that most accurately predicted the impact speed, Table 16 is a tabulation of the estimated KEES for each test vehicle. It is these KEESs that are reported in the caption of the photographs of the damaged vehicles that were shown earlier in this report.

Honda	Volvo	Nissan
21.0 mi/hr	22.5 mi/hr	22.5 mi/hr

Table 16: Best Estimators of KEESs Calculated From IST Accelerometer Reconstruction

Conclusions

With only three crash tests to analyze, it is not possible to make any sound conclusions as to the efficacy of the methods used in this report to analyze lateral pole impacts. No pattern is apparent that would suggest that one method is better than the others. However, it is appropriate at this time to offer the following:

- One lesson learned from these tests was that it is important to include the maximum deformation when measuring the damage profile according to the Tumbas-Smith Protocol. To accomplish this task, the reconstructionist may use unequal crush station intervals, take more than six crush measurements, or measure the damage with a total station and determine the damaged area in a CAD program. The latter method would of course require the additional step of measuring an undamaged exemplar vehicle if the accident vehicle is bowed.
- Frontal stiffness coefficients may be appropriate for use in narrow-object lateral impacts.
- Another complicating issue with side impacts is varying areas along the side of the vehicle that may differ in stiffness. For example, the Honda was struck on the firewall, while the Volvo and the Nissan were struck between the pillars. Only a substantial amount of future crash testing will assist in this endeavor.
- A baseline established with masking tape between deflection points, as well as a baseline established from the undamaged side of the vehicle worked well on the two vehicles that did not bow. Both methods produced the same crush measurements for the Honda. Measurements taken from the baseline established from the undamaged side of the Nissan worked better than the masking tape.
- A determination cannot be made at this time as to the best method for measuring damage when the vehicle is bowed; however, the difference

seen in the one test where the vehicle was bowed was approximately 1 to 2 mi/hr. The adjusted baseline method rendered the higher impact speed.

- The Vomhof method worked well in the Honda test with the geometric force calculation.
- When combined with the IST-calculated collision force, both the Vomhof method and the CRASH3 impact model showed promise across all three tests.
- When combined with the IST-calculated collision force, the Morgan and Ivey equation significantly underreported the impact speed across all three tests.
- Examination of the accelerometer data revealed that the time of the crash pulses exceeded that of a car-to-car crash pulse by two to three times. This is good news for occupants sitting on the opposite side of the collision. Because acceleration is inversely proportional to time, the increased delta-t means a reduced chance for acceleration-induced injuries.
- Further testing must be done to determine which method(s) perform best. Future tests must dispense with any guide cables that are connected to the struck pole.
- Further research must be performed to determine an acceptable method to estimate the collision force in side impacts. Neither the CRASH3 method or the geometric method agreed with the IST-calculated force within a reasonable degree of certainty.

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Contact

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APPENDIX
Full Size IST Charts

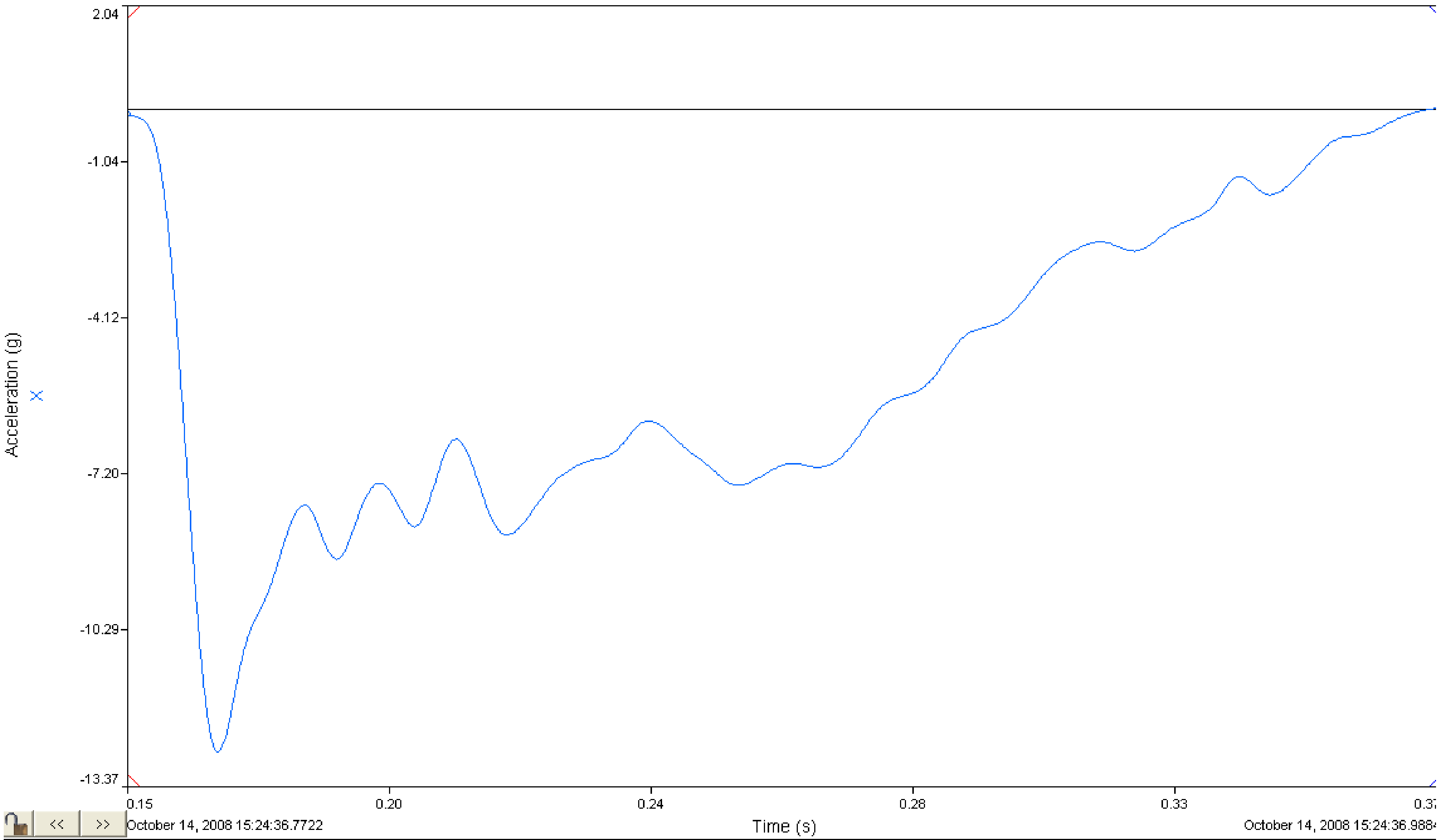


Chart 1: Test 1 IST Accelerometer Crash Pulse

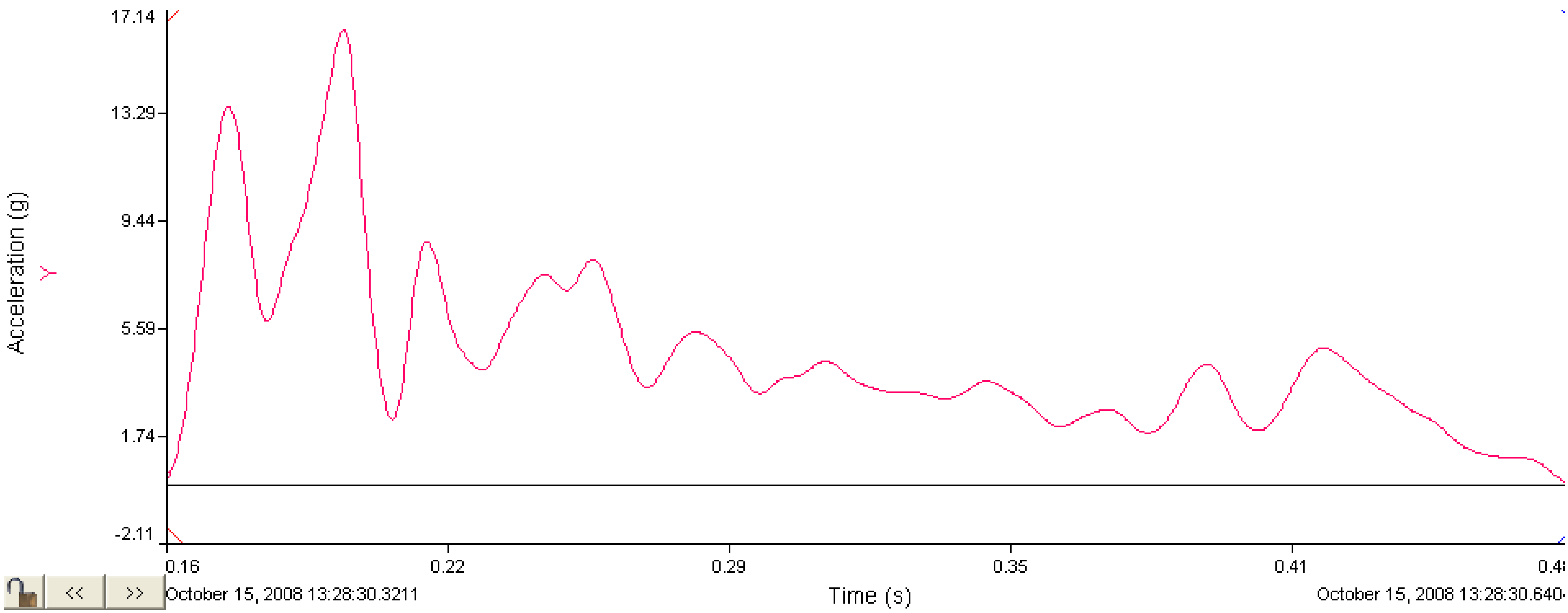


Chart 2: Test 2 IST Accelerometer Crash Pulse

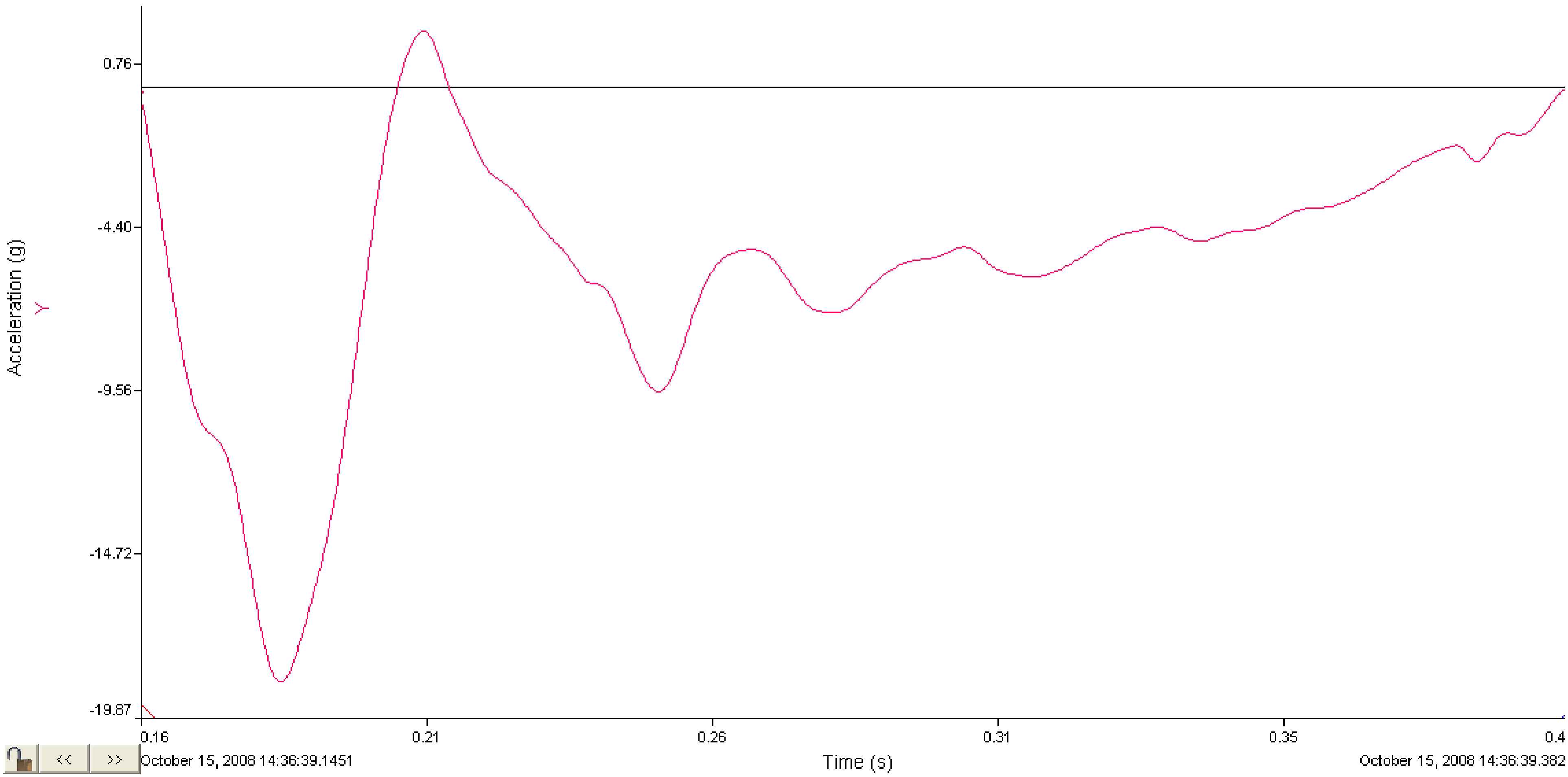
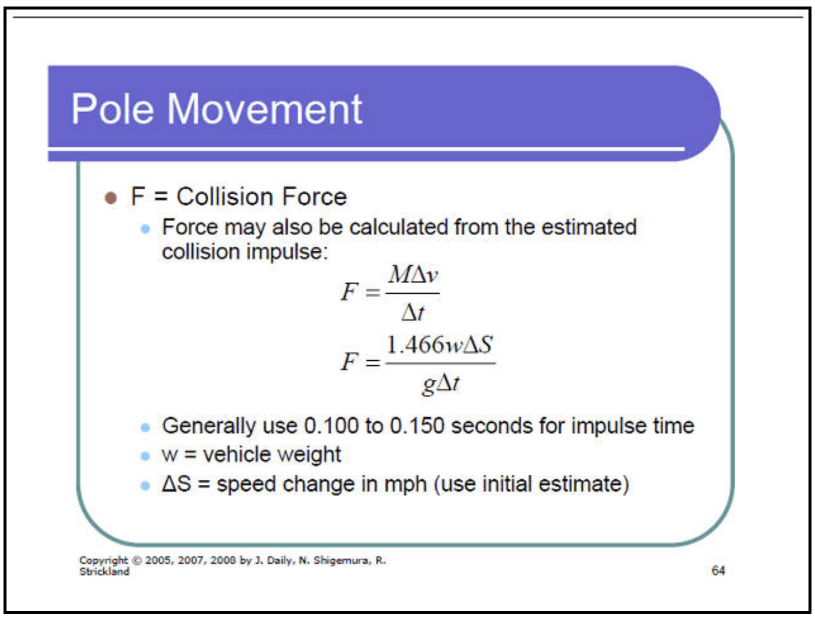


Chart 3: Test 3 IST Accelerometer Crash Pulse

2008 Joint Conference Lateral Pole Crash Tests
One Possible Method for the Estimation of the Pole Energy
a Supplement to
2008 Joint Conference Lateral Pole Crash Tests Results
Supplement prepared by Daniel W. Vomhof III

When analyzing the data from the three pole impact tests conducted at the 2008 Joint Conference, it became apparent that a method to form an estimation of the pole energy contribution was needed for real world (as opposed to test) collisions, and that the available methods need further study with their application to lateral impact pole collisions. This paper is intended as a summary of one method's application to the pole energy estimation problem, and is not meant to stand alone without the data and analysis provided in the primary paper. Thus, much of the detail which might normally be provided in a paper of this sort has been left to the primary paper. A glossary of terms is located at the end of this paper.

A method proposed by John Daily, with limitations, to accomplish this is shown below:



Page 64 from John Daily handout on Pole and Narrow Object Collisions.

When using this method, the delta-v or delta-S is determined from the EBS (also notated as KEES in this and the primary paper) of the damage to the vehicle and in John's words "...and it only works if the EBS and delta-V are reasonably close." The key words here are "***reasonably close***". Some discussion of this will follow later in the paper.

Using John Daily's proposed method at several delta-t's, an estimation of pole movement energy and impact speeds for each proposed vehicle damage Kinetic Energy Equivalent Speed (KEES) calculation method was completed. In each case, the KEES calculated from damage was used as the delta-S in the proposed Force equation. The result of the calculation was then used as the F_{avg} value in equations 7 & 8 from the primary paper to calculate the Pole Energy Equivalent Speeds (PEES) values. These values are displayed in Table 1 and Table 2 below. The equation 8 velocity result was converted from feet per second to miles per hour for entry into the tables.

Table 1, **Crash Test Equivalent Speeds**, shows the following:
- the measured test impact speeds,
- the calculated vehicle damage speeds from crush,
- the Pole Energy Equivalent Speeds (PEES) determined from the IST instrumentation is shown for comparison purposes, and
- the Pole Energy Equivalent Speeds (PEES) determined from the calculated vehicle damage speeds using the varying delta-t's of 0.10 seconds, 0.15 seconds, 0.20 seconds and 0.30 seconds.

The first two delta-t's are those suggested by John Daily in his handout and are presumed to be derived from the time frames experienced in the typical vehicle-to-vehicle collision. The last two delta-t's were added based upon the instrumentation of the three subject crash tests.

Crash Test Equivalent Speeds			
	Honda	Volvo	Nissan
Measured Test Impact Speed	**24.9**	**34.8**	**30.5**
Kinetic Energy Equivalent Speed (KEES) from Vehicle Damage			
Vomhof KEES (mi/hr)	21.0	25.9	20.2
Morgan & Ivey KEES (mi/hr)	13.2	19.2	9.9
CRASH3 KEES - Frontal A & B (mi/hr)	18.0	26.0	19.7
CRASH3 KEES - Side A & B from MAX Crush (mi/hr)	9.1	21.8	12.8
CRASH3 KEES - Side A & B from AVG Crush (mi/hr)	13.5	39.6	22.5
Pole Energy Equivalent Speed (PEES) from IST Instrumentation			
PEES from IST	**11.9**	**17.8**	**18.9**
Pole Energy Equivalent Speed (PEES) estimated from DAMAGE KEES			
Force Calculated from Vehicle Damage - delta-t = 0.10 seconds			
PEES from Vomhof KEES (mi/hr)	16.0	28.6	24.6
PEES from Morgan & Ivey KEES (mi/hr)	12.7	24.6	17.2
PEES from CRASH3 KEES - Frontal A & B (mi/hr)	14.8	28.6	24.2
PEES from CRASH3 KEES - Side A & B from MAX Crush (mi/hr)	10.6	26.2	19.5
PEES from CRASH3 KEES - Side A & B from AVG Crush (mi/hr)	12.9	35.3	25.9
Force Calculated from Vehicle Damage - delta-t = 0.15 seconds			
PEES from Vomhof KEES (mi/hr)	13.1	23.2	20.0
PEES from Morgan & Ivey KEES (mi/hr)	10.4	20.1	14.0
PEES from CRASH3 KEES - Frontal A & B (mi/hr)	12.1	23.4	19.8
PEES from CRASH3 KEES - Side A & B from MAX Crush (mi/hr)	8.6	21.4	15.9
PEES from CRASH3 KEES - Side A & B from AVG Crush (mi/hr)	10.5	28.8	21.1
Force Calculated from Vehicle Damage - delta-t = 0.20 seconds			
PEES from Vomhof KEES (mi/hr)	11.3	20.2	17.4
PEES from Morgan & Ivey KEES (mi/hr)	9.0	17.4	12.1
PEES from CRASH3 KEES - Frontal A & B (mi/hr)	10.5	20.2	17.1
PEES from CRASH3 KEES - Side A & B from MAX Crush (mi/hr)	7.5	18.5	13.8
PEES from CRASH3 KEES - Side A & B from AVG Crush (mi/hr)	9.1	25.0	18.3
Force Calculated from Vehicle Damage - delta-t = 0.30 seconds			
PEES from Vomhof KEES (mi/hr)	9.3	16.5	14.2
PEES from Morgan & Ivey KEES (mi/hr)	7.3	14.2	9.9
PEES from CRASH3 KEES - Frontal A & B (mi/hr)	8.6	16.5	14.0
PEES from CRASH3 KEES - Side A & B from MAX Crush (mi/hr)	6.1	15.1	11.3
PEES from CRASH3 KEES - Side A & B from AVG Crush (mi/hr)	7.4	20.4	14.9

Table 1

An examination and comparison of the data contained in Table 1 shows that the instrumented PEES is generally most closely approximated by the force calculation when a delta-t of 0.15 to 0.20 seconds is used.

Table 2, **Crash Test Calculated Impact Speed Results**, shows the following:

- the measured test impact speeds,
- the calculated resultant impact speed obtained by combining the vehicle damage KEES with the pole PEES speeds determined from the IST measurements,
- the calculated resultant impact speeds obtained by combining the vehicle damage KEES with the pole PEES speeds determined by the F= (1.466*Wt*delta-S)/(g*delta-t) method using the varying delta-t's of 0.10 seconds, 0.15 seconds, 0.20 seconds and 0.30 seconds.

Crash Test Calculated Impact Speed Results			
	Honda	Volvo	Nissan
Measured Test Impact Speed	**24.9**	**34.8**	**30.5**
KEES Combined with PEES Resultant Speeds			
Resultant Impact Speed when PEES is Determined from IST Instrumentation			
Vomhof KEES method (mi/hr)	24.1	31.4	27.7
Morgan & Ivey KEES method (mi/hr)	17.7	26.2	21.4
CRASH3 KEES - Frontal A & B method (mi/hr)	21.5	30.7	24.8
CRASH3 KEES - Side A & B from MAX Crush method (mi/hr)	15.0	28.1	22.9
CRASH3 KEES - Side A & B from AVG Crush method (mi/hr)	18.0	43.4	29.4
Resultant Impact Speed when PEES is Calculated from Vehicle Damage KEES using delta-t = 0.10 seconds			
Vomhof KEES method (mi/hr)	26.4	38.5	31.8
Morgan & Ivey KEES method (mi/hr)	18.3	31.2	19.8
CRASH3 KEES - Frontal A & B method (mi/hr)	23.3	38.7	31.2
CRASH3 KEES - Side A & B from MAX Crush method (mi/hr)	13.9	34.1	23.3
CRASH3 KEES - Side A & B from AVG Crush method (mi/hr)	18.6	53.1	34.3
Resultant Impact Speed when PEES is Calculated from Vehicle Damage KEES using delta-t = 0.15 seconds			
Vomhof KEES method (mi/hr)	24.7	34.8	28.5
Morgan & Ivey KEES method (mi/hr)	16.8	27.8	17.2
CRASH3 KEES - Frontal A & B method (mi/hr)	21.7	35.0	27.9
CRASH3 KEES - Side A & B from MAX Crush method (mi/hr)	12.5	30.6	20.4
CRASH3 KEES - Side A & B from AVG Crush method (mi/hr)	17.1	49.0	30.9
Resultant Impact Speed when PEES is Calculated from Vehicle Damage KEES using delta-t = 0.20 seconds			
Vomhof KEES method (mi/hr)	23.9	32.8	26.7
Morgan & Ivey KEES method (mi/hr)	16.0	25.9	15.7
CRASH3 KEES - Frontal A & B method (mi/hr)	20.8	33.0	26.1
CRASH3 KEES - Side A & B from MAX Crush method (mi/hr)	11.8	28.6	18.9
CRASH3 KEES - Side A & B from AVG Crush method (mi/hr)	16.3	46.8	29.0
Resultant Impact Speed when PEES is Calculated from Vehicle Damage KEES using delta-t = 0.30 seconds			
Vomhof KEES method (mi/hr)	23.0	30.7	24.7
Morgan & Ivey KEES method (mi/hr)	15.1	23.9	14.0
CRASH3 KEES - Frontal A & B method (mi/hr)	19.9	30.8	24.2
CRASH3 KEES - Side A & B from MAX Crush method (mi/hr)	11.0	26.5	17.1
CRASH3 KEES - Side A & B from AVG Crush method (mi/hr)	15.4	44.5	27.0

Table 2

An examination and comparison of the data in Table 2 shows that in general, a time frame of 0.10 seconds over estimates the collision speed, while time frames of 0.20-0.30 seconds under estimates the collision speed. It can also be seen that a poor damage speed estimate provides a poor resultant impact speed estimate. A statement of the obvious? Perhaps, but also a statement that needs to be emphasized for this type of collision. A review of the overall procedure quickly shows why this is a true statement: (1) calculate vehicle damage speed, (2) feed the result of step 1 into the calculation of the force on the pole to determine the pole energy speed, and (3) combine the two speeds. Thus, the determination of the vehicle damage speed is the point from which everything else flows. Further, any differences in the damage speed estimate from the actual delta-v will be accentuated with this calculation procedure. A high damage speed estimate will result in an exaggerated calculated impact speed result, as can be seen in the

Volvo test where the average A-B values were used in the CRASH 3 impact model. Conversely, a significantly low damage speed estimate will result in a greatly depressed calculated impact speed result, as can be seen in the Honda test where the Morgan & Ivey calculation was used.

This brings us back to the "*it only works if the EBS and delta-V are reasonably close*" limitation, and a definition of what is "reasonably close". For this discussion, initially consider only the Honda test and compare the Vomhof method with the Morgan & Ivey calculation, at the IST PEES and delta-t=0.10 seconds PEES points. At these points we see the following:

- Looking at Table 1, the Vomhof method KEES value more closely approximates the measured impact speed, while the Morgan & Ivey calculation results in a KEES that is just over half of the measured impact speed.
- Looking at Table 1, the PEES from the Vomhof method over estimates the IST PEES by just over 4 mph, while the PEES from Morgan & Ivey over estimates the IST PEES by less than 1 mph. In other words, the Morgan & Ivey calculation results in a near match to the IST PEES, which indicates a good match to the limitation.
- However, when we look at Table 2, while the Vomhof method over estimates the impact speed by about 1.5 mph, the Morgan & Ivey calculation results in an under estimation of the impact speed by more than 6.5 mph.

If we broaden our view slightly and look at all three tests across all methods using the delta-t values of 0.10 seconds and 0.15 seconds, it is seen that:

- The "best" resultant speeds at the delta-t = 0.10 seconds level are obtained when the vehicle KEES is in the range of 63%-72% of the impact speed.
- The "best" resultant speeds at the delta-t = 0.15 seconds level are obtained when the vehicle KEES is in the range of 74%-84% of the impact speed.

These observations could lead to several conclusions. The most correct conclusion, however, is that further research is needed to clearly define the parameters of this limitation, as well as the dynamics of a vehicular lateral pole collision. Further, as has been already stated in the primary paper, these three tests may not be the best basis for such a definition due to the test protocol used with its resulting undocumented energy sinks.

Based upon the three tests at the conference, the following preliminary conclusions are offered for consideration -

1) Much more testing of lateral pole collisions needs to be conducted.
2) The additional testing should include the following scenarios :
   A - No pole movement, similar to hitting a tree, or possibly a utility pole in frozen ground or in a concrete sidewalk
   B - Pole movements of varying degrees
   C - Pole movement combined with pole breakage and post impact vehicle movement
3) Within the limited constraints of these three tests: Lateral impact into a wooden pole, pole movement with no breakage, and minimal or no post impact vehicle movement, the pole energy estimation method suggested by John Daily shows promising potential as a method to estimate the pole

energy in a lateral vehicle-into-pole collision.

4) A very preliminary conclusion based upon these three tests is that within the restrictions of this method of estimating the pole movement energy, the Morgan & Ivey method tends to give a conservative estimate of the collision speed, the Vomhof method tends to approximate the collision speed, and the CRASH 3 method (as presented) can be highly accurate, or wildly inaccurate, depending upon the choice of stiffness coefficients used.

GLOSSARY

EBS - Equivalent Barrier Speed. The energy required to damage a vehicle that is equivalent to the speed at which a vehicle would hit a non-moving, non-deformable barrier to do the same amount of damage.

KEES - Kinetic Energy Equivalent Speed. The Kinetic Energy, most specifically that absorbed in damaging a vehicle, expressed as a speed, rather than in ft-lbs or joules. Similar to EBS.

PEES - Pole Energy Equivalent Speed. The Kinetic Energy absorbed by the pole movement in the collision, expressed as a speed, rather than in ft-lbs or joules. Similar to EBS.

delta-v - the change in velocity. This is typically used in its scalar rather than vector form, and in units of feet per second. In the scalar form, it is calculated as the absolute value of [ending velocity - starting velocity]. Similar to this is delta-S: the change in speed expressed in miles per hour. The only time the delta-v is equivalent to the EBS or KEES value is when the last event in the collision sequence is the damage made to the vehicle. This can be verified in the following manner: Calculate the EBS for 12 inches of crush (roughly, 25 mph). If this was caused by a vehicle hitting a building with no post impact movement, the delta-v would be essentially equal to the EBS. If, however, there was 50 feet of post impact 4 wheel skid, the impact speed into the building would be approximately 40-41 mph, the post impact skid would be approximately 32-33 mph, and the crush delta-v becomes 8-9 mph, while the damage EBS is still 25 mph. Further discussion of this is left to another time and place.

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