SHORT PAPER PCB 2-2006

IN-LINE COLLISIONS

ENGINEERING EQUATIONS, INPUT DATA AND MARC 1 APPLICATIONS

By:

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To provide the accident reconstruction practitioner with a concise discussion of the engineering equations and limiting factors involved, evaluation of critical input data, and the analysis of actual cases by use of the MARC 1 computer software.

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Throughout the Short Papers we will extensively reference the 5th Edition of "Motor Vehicle Accident Reconstructions and Cause Analysis" by Rudolf Limpert, the "Accident Reconstruction Catalog" (ARC) CD, as well as the MARC 1 software.

IN-LINE COLLISIONS

Part Two

Two-Vehicle Crashes, Test Data & Crush Energy

1. DEFINITION OF TWO-VEHICLE IN-LINE COLLISION

In two-vehicle (head-on or rear-end) collisions the lines of action of both velocity vectors before impact are approximately parallel, and the rotational energies after impact are insignificant in relationship to the linear kinetic energies after impact or the crush energies of the vehicles. During maximum crush engagement the center-of gravities of both vehicles reach a nearly common velocity. See Section 33-1 of Text. See ARC photographs 486 and 487, videos of Sections 1.2.1,2.1.1,2.1.2, and 2.1.3 for examples.

2. WHAT ENGINEERING PRINCIPLES APPLY

Linear momentum equation in one direction only, energy balance, and standard velocity-after-impact run-out analysis. The final equations are discussed in Sections 33-4(a) and 33- 4(b). One direction linear momentum is discussed in detail in Sections 33-l(d) through 33-l(f) of the Text. Fundamentals of force and energy analysis including crush energy are discussed in Section 21-6. Run-out analysis is discussed in Sections 20-4(a) through 20-4(e). The most critical input data of any type of in-line collision relate to the accurate determination of crush energy. In PART ONE of IN-LINE COLLISIONS barrier crash tests were discussed in detail including crush energy.

A fundamental assumption of impulse analysis is that a body (vehicle) experiences a sudden change of its velocity state during the impact phase without changing its location. The reader is encouraged to study several of the two-vehicle crashes shown in ARC (Sections 2.1.1,2.1.2,2.1.3,2.3.1,2.3.2,2.3.6) and observe that sheet metal is being deformed before the struck vehicle actually begins to move.

3. REAR-END COLLISION WITH STRUCK VEHICLE STATIONARY

In any two-vehicle collision we have four unknowns, namely both velocities before, and both velocities after impact. Since we are considering in-line collisions only with insignificant rotation after impact, the velocity vectors remain parallel before and after impact. The velocity vector of one vehicle may change direction, that is, reverse direction, during impact. With two after-impact run-out equations (Equation 20-73b of Text), and one linear momentum equation (one direction only), and energy balance (Equation 21-6), we can calculate the velocities of both vehicle before impact.

3.1. 1980 FORD F250 REAR-ENDS 1982 CHEVROLET CAMERO

The accident occurred when the stationary Camaro was rear-ended by the Ford. Accident scene data revealed that the impact knocked the Camaro forward a distance of approximately 106 ft. The truck had its brakes locked 10 ft before impact. The after-impact distance of the Ford was 50 ft. During the impact the Camaro's driver's seat back broke, causing the driver to break his neck as the rear seat back was accelerated against the driver's head.

We must calculate the velocity change of the Camaro experienced during the impact to determine if the seat back's failure resulted from a design/manufacturing defect or excessive impact velocity of the Ford.

Since the Camaro is stopped at the moment of impact, we may be able to calculate the Ford's impact velocity, if we have accurate after-impact data to calculate after-impact velocity of the Ford and Camaro. Crush energy can be used in the energy balance as a secondary check on the accuracy of our speed calculations.

Based upon the severity of rear crush of the Camaro, the impact was clearly plastic. The discussion in Section 33-1(e) of the Text applies. In Equation 33-5, solving for velocity V11 of Vehicle 1 (Ford) with the velocity of Vehicle 2 (Camaro) V21 = 0, yields

Impact Velocity of Ford

$$V11 = Vc(m1 + m2)/(m1)$$

Consequently, if we kne the common velocity Vc, which is also the after-impact velocity of the of either the Ford or the Camaro (plastic impact), we can calculate the impact speed of the Ford. The after-impact velocity is also the velocity change or delta-V of the Camaro since it was stationary before impact.

The critical parameter to be determined as accurately as possible is the after-impact deceleration of the Camaro and/or the Ford. The run-out distances were 106 ft for the Camaro, and 50 ft for the braking Ford. The left rear wheel of the subject Camaro was locked into place by sheet metal crush.

The weight of the Camaro was 3630 lb, that of the Ford 5000 lb. Using a rear weight distribution of 40% for the Camaro yields a left rear normal tire load of approximately 726 lb, and with a locked wheel friction coefficient of 0.8 an after-impact deceleration 0.16g (Equation 21-3 of the Text). The after-impact velocity becomes 22.6 mph, and the impact velocity of the Ford is 39 mph.

An impact velocity of 39 mph and a corresponding Camaro delta-V = 22. 6 mph was the opinion of plaintiff's expert. The 39 mph crash test conducted by the defense is shown in ARC Section 2.1.1. In the crash test the Camaro was knocked forward approximately 103 ft, consistent with the actual scene measurements. In the crash test the longitudinal center line of the Ford was approximately 6 in. inboard of the left outside of the Camaro.

A second crash test was performed by the defense, however at an impact velocity of 49 mph and the longitudinal axis of the Ford aligned with the left outside of the Camaro, that is, less overlap. This test is shown in ARC Section 2.1.3. The test setup and final rest positions are illustrated in Figure 1. The Camaro was knocked forward approximately 139 ft after impact. The Camaro after-impact velocity was 30 mph measured at the left A-pillar approximately 170 ms after onset of the crash.

Since there was more sheet metal crush, the after-impact deceleration was expected to be greater than 0.16g by also impeding free rotation of the right rear wheel. Using 0.2g in a similar analysis yields a Ford impact velocity of 49.8 mph.

Figure 2 through 9 illustrate the rest position of the Camaro in the 49 mph crash test as well as the left rear wheel locked tire mark.

In order to use MARC 1– X2, Rear-End Collision, the crush profiles and stiffness coefficients must be known. The Neptune Tree-Ringer Binder in Appendix D page 5 provides A = 256 and B = 96 for the rear stiffness coefficients of a 1979 Camaro, and on page 19 A = 313 and B = 124 for the front stiffness coefficients of a 1978 Ford F250. The reader must ensure that these values are acceptable by investigating possible design differences based on different model years for the subject vehicles and crash test vehicles associated with the Neptune data.

The 49 mph crash test is simulated in MARC 1-X2, RUN 1 for the crush profile indicated, while RUN 2 illustrates the 39 mph crash test.

Since in the actual accident the Camaro was pushed forward approximately 106 ft, an impact velocity of 39 mph appears to be more probable than 49 mph.

3.2. 1979 INTERNATIONAL TRACTOR REAR-ENDS STATIONARY 1984 RENAULT ALLIANCE

A crash test of the two vehicles was conducted for SAE and discussed in Dr. Limpert's SAE accident reconstruction seminar. We will analyze the crash data to consider an approximate method for analyzing crush energy in over-ride rear end crashes.

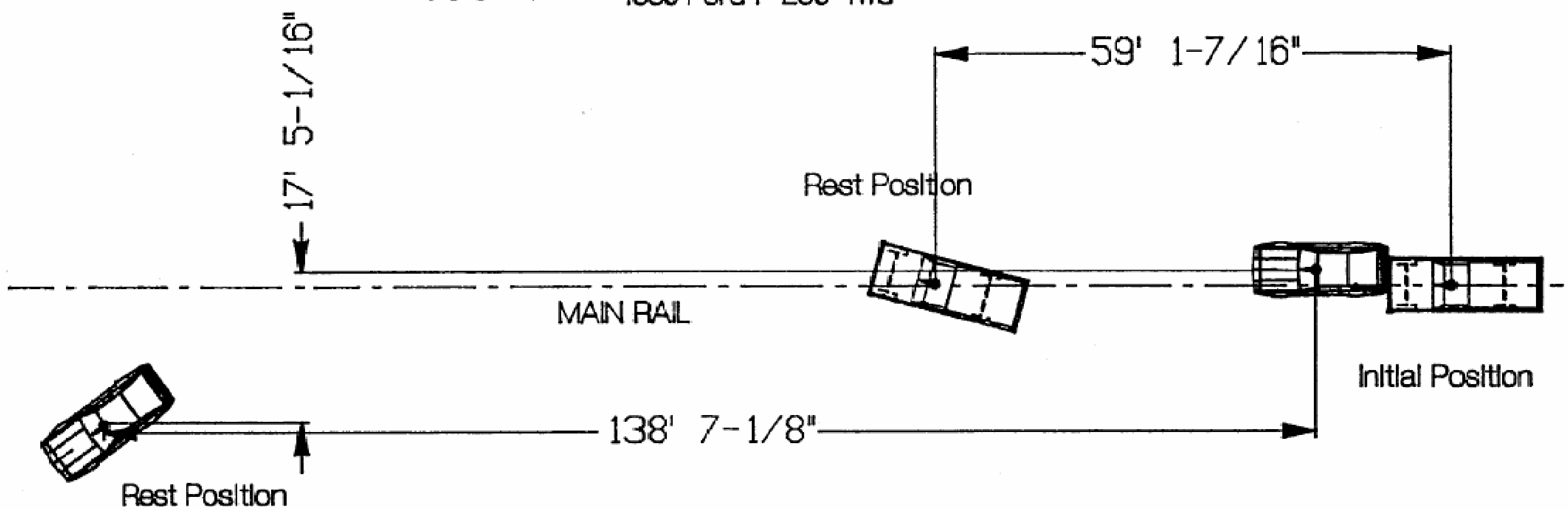
A brief clip of the crash itself and some crush damage photographs are shown in ARC Sections 2.1.6 and 2.1.7. The 1984 Renault Alliance appears totally destroyed.

The weights of the vehicles are: Tractor 15,500 lb, car 2220 lb. The impact velocity was 36 mph. As a careful review of the video clip reveals, the right front tire of the tractor over-rode the floor of the car, indicating that no primary impact load carrying

VEHICLE POSITIONS

Target Vehicle 1982 Chevrolet Camaro Berlinetta

Bullet Vehicle 1980 Ford F-250 4wd



Oakes Research
AZ04090
Test Date: May 13, 1991

Figure 1

2

3

4

5

Figures 2-5: 49mph test, 82 Camaro

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MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-2' RUN FOR PCB 2-2006, RUN 1 ********
REAR-END COLLISION

Information For Vehicles		1980 FORD F250	1982 CHEVROLET CAMARO
Vehicle Weight, LBS:	===>	5000.00	3630.00
NO BEFORE IMPACT SURFACE DATA			
Surface #1			
Distance Traveled After Impact, FT:	===>	59.00	138.60
After-Impact Deceleration, g-UNITS:	===>	0.45	0.19
Max. Force Not Causing Damage, LBS/IN:	==>	313.00	256.00
Stiffness/Inch of Width, PSI:	===>	124.00	96.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	30.00	44.00
Number of Crush Measurements:	===>	2	2
Crush Measurement #1, IN:	===>	7.00	33.00
Crush Measurement #2, IN:	===>	7.00	20.00
Energy from Secondary Impacts, FT·LBS:	==>	0.00	0.00

Pre-Impact Speed, MPH:	===>	48.59	0.02
Speed at Impact, MPH:	===>	48.59	-0.02
After-Impact Speed, MPH:	===>	28.19	28.08
Crush Energy, FT·LBS:	===>	14060.09	152200.89
EES Speed, MPH:	===>	9.18	35.43

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MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS

******** PROGRAM 'X-2' RUN FOR PCB 2 - 2006, RUN 2 ********

REAR-END COLLISION

Information For Vehicles		1980 FORD F250	1982 CHEVROLET CAMARO
Vehicle Weight, LBS:	===>	5000.00	3630.00
NO BEFORE IMPACT SURFACE DATA			
Surface #1			
Distance Traveled After Impact, FT:	===>	38.00	103.00
After-Impact Deceleration, g-UNITS:	===>	0.45	0.16
Max. Force Not Causing Damage, LBS/IN:	==>	313.00	256.00
Stiffness/Inch of Width, PSI:	===>	124.00	96.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	30.00	48.00
Number of Crush Measurements:	===>	2	2
Crush Measurement #1, IN:	===>	5.00	28.00
Crush Measurement #2, IN:	===>	5.00	10.00
Energy from Secondary Impacts, FT·LBS:	==>	0.00	0.00

Pre-Impact Speed, MPH:	===>	38.63	0.16
Speed at Impact, MPH:	===>	38.63	0.16
After-Impact Speed, MPH:	===>	22.63	22.21
Crush Energy, FT·LBS:	===>	8775.09	95317.33
EES Speed, MPH:	===>	7.25	28.04

components were crushed. Neither the left nor the right wheel base of the car was shortened, as the following crush measurement table reveals:

Location	Crush (in.)
Left Wheelbase	0
Right Wheelbase	0
LR Quarter Panel	62.5
RR Quarter Panel	3.8
LR Corner of Trunk Lid	69.3
Left Lower C-Pillar	46.8
Right Lower C-Pillar	1.1

Using MARC 1 W-2 with the proper weights and impact velocity of 36 mph yields a total crush energy of 83,986 lbft for a plastic impact. Consequently, we immediately learn that the crush energy of the Renault Alliance can not exceed 83,986 lbft, regardless of the total "destruction of the Renault.

Using average rear stiffness coefficients (SAE 960897) for the wheelbase of the Renault of A = 162 and B = 49 in MARC 1 X-9 with a maximum crush profile of 62.5 and 3.8 in. over a crush width of 65.3 in. calculates a theoretical "crush energy" of 215,471 lbft. Of course, this crush energy only provides an upper limit if the entire rear end of the Renault had been crushed forward without any over-ride by the tractor.

The frontal stiffness coefficients of the tractor were obtained from limited German test data.

Since the actual crush energy delivered to the Renault in the crash test was 84,000 lbft, the ratio of actual to maximum can be expressed as 84,000/215,000 = 0.39, assuming the average stiffness coefficients apply. Consequently, only approximately 39% of the maximum crush energy was delivered to the Renault in the over-ride crash test. In general, an upper and lower range of 40 to 50% should be used depending upon the maximum over-ride crush depth produced in the crash.

The crash test reconstruction is shown in RUN 3 where the Renault crush depth data were "adjusted" until approximately 84,000 lbft of crush energy was delivered to the Renault. The crush energy of the tractor was assumed to be zero. Inspection of RUN 3 shows that a crush energy of approximately 84,000 lbft with the after-impact distances of 104 ft and decelerations of 0.32g calculates an impact velocity of 36 mph with the car stationary (0.07 mph) .

4.0 FRONTAL COLLISIONS - BOTH VEHICLES MOVING

4.1 MERCEDES 230E HEAD-ON COLLISION WITH MERCEDES 230E

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MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-2' RUN FOR PCB 2-2006 RUN 3 ********
REAR-END COLLISION

Information For Vehicles		1979 INTERNATIONAL Transtar	1984 RENAULT ALLIANCE
Vehicle Weight, LBS:	===>	15550.00	2220.00
NO BEFORE IMPACT SURFACE DATA			
Surface #1			
Distance Traveled After Impact, FT:	===>	104.00	104.00
After-Impact Deceleration, g-UNITS:	===>	0.32	0.32
Max. Force Not Causing Damage, LBS/IN:	==>	1110.00	162.00
Stiffness/Inch of Width, PSI:	===>	574.00	49.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	0.00	49.00
Number of Crush Measurements:	===>	2	2
Crush Measurement #1, IN:	===>	1.00	25.70
Crush Measurement #2, IN:	===>	1.00	25.70
Energy from Secondary Impacts, FT·LBS:	==>	0.00	0.00

Pre-Impact Speed, MPH:	===>	36.06	0.07
Speed at Impact, MPH:	===>	36.06	0.07
After-Impact Speed, MPH:	===>	31.56	31.56
Crush Energy, FT·LBS:	===>	0.00	84170.57
EES Speed, MPH:	===>	0.00	33.69

The crash test details are discussed in Section 40-2(a) of the Text including some of the measured injury data. The crash test reconstruction is shown in RUN 4.
Assume the two vehicles had an actual head-on crash on the highway with Vehicle 1 pushing Vehicle 2 back approximately 48 feet (drag factors 0.5g), and Vehicle 1 braking for 67 ft at 0.85g before impact. You are asked to calculate the impact velocities of each vehicle and the pre-braking velocity of Vehicle 1. The wheelbase is 110.2 in. (2800 mm).

The reconstruction is illustrated in RUN 5. The formulation underlying MARC 1 X-1 requires that Vehicle 1 is that vehicle that pushes Vehicle 2 back, or both vehicles stop at the point of impact as it was the case in the crash test (see Section 33-4(a) of the Text). Inspection of RUN 5 shows that Vehicle 1 traveled approximately 71 mph at begin of braking, and 58 mph at impact, Vehicle 2 approximately 10 mph at impact. The delta-V of Vehicle 1 is 57.55 – 23.97 = 33.58 mph (V1 continues in the same direction), of Vehicle 2 is 23.97 + 9.60 = 33.57 mph (V2 is stopped first and then pushed back at 23.97 mph). The delta-Vs also equal the EES velocities since both vehicle weights are equal.

If no vehicle specific stiffness coefficients are available, SAE 960897 provides A = 207 and B = 70 (101.6 to 110.4 in.) and A = 215 and B = 67 (110.4 to 117.5 in.). Using these values in MARC 1 X-1 yields the results that follow:

	A/B	V11	V21	V1b	Delta-V	
1.	249/92	57.55	9.60	70.84	33.57	mph
2.	215/67	53.21	5.26	67.37	29.24	mph
3.	207/70	53.61	5.61	67.64	29.56	mph

Inspection of the results indicates minor differences between Rows 2 and 3, most likely explained by the offsetting relationships between the A and B values (A decreases while B increases). Even the Row 1 delta-V value differs only by approximately 13%, a value well within expected accuracy variation.

4.2 MERCEDES BENZ S300 HEAD-ON COLLISION WITH OPEL CORSA

The crash test details are discussed in Section 40-2(b) of the Text including measured injury data and reconstruction data. A 1995 Mercedes Benz S 300 traveling at 31.30 mph crashes head-on against a 1995 Opel Corsa also traveling at 31.20 mph. The crash sequence photographs are shown in ARC Section 2.2.3. Figure 40-3 of the Text illustrates the rest positions and distances traveled after impact.

With the wheelbases of 119.7 and 96.1 in., SAE Paper 960897 shows A/B = 289/113 and A/B = 185/66, respectively. MARC 1 X-9, RUN 6 is a rerun of Figure 40-4 on page 624 of the Text. Inspection shows impact velocities of 31.7 and 30.2 mph for the Mercedes and Opel, respectively. Using the average A and B values in MARC 1 X-9 RUN 7, results in impact velocities of 28.17 mph for the Mercedes and 23.62 mph for the Opel.

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MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-1' RUN FOR PCB 2 - 2006, RUN 4 ********
HEAD-ON COLLISION

Information For Vehicles		1991 MERCEDES BENZ 230 E	1991 MERCEDES BENZ 230 E
Vehicle Weight, Lbs:	===>	3425.00	3425.00
Max. Force Not Causing Damage, LBS/IN:	===>	249.00	249.00
Stiffness/Inch of Width, PSI:	===>	92.00	92.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	68.00	68.00
Number of Crush Measurements:	===>	6	6
Crush Measurement #1, IN:	===>	31.00	31.00
Crush Measurement #2, IN:	===>	28.00	28.00
Crush Measurement #3, IN:	===>	23.00	23.00
Crush Measurement #4, IN:	===>	12.00	12.00
Crush Measurement #5, IN:	===>	7.00	7.00
Crush Measurement #6, IN:	===>	4.00	4.00
Energy from Secondary Impacts, FT·LBS:	===>	0.00	0.00

Pre-Impact Speed, MPH:	===>	33.57	33.57
Speed at Impact, MPH:	===>	33.57	33.57
After-Impact Speed, MPH:	===>	0.00	0.00
Crush Energy, FT·LBS:	===>	128939.68	128939.68
EES Speed, MPH:	===>	33.57	33.57

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MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-1' RUN FOR PCB 2 - 2006, RUN 5 ********
HEAD-ON COLLISION

Information For Vehicles		1991 MERCEDES BENZ 230 E	1991 MERCEDES BENZ 230 E
Vehicle Weight, Lbs:	===>	3425.00	3425.00
Surface #1			
Pre-Impact Braking Distance, FT:	===>	67.00	0.00
Pre-Impact Deceleration, g-UNITS:	===>	0.85	0.00
Surface #1			
Distance Traveled After Impact, FT:	===>	48.00	48.00
After-Impact Deceleration, g-UNITS:	===>	0.40	0.40
Max. Force Not Causing Damage, LBS/IN:	===>	249.00	249.00
Stiffness/Inch of Width, PSI:	===>	92.00	92.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	68.00	68.00
Number of Crush Measurements:	===>	6	6
Crush Measurement #1, IN:	===>	31.00	31.00
Crush Measurement #2, IN:	===>	28.00	28.00
Crush Measurement #3, IN:	===>	23.00	23.00
Crush Measurement #4, IN:	===>	12.00	12.00
Crush Measurement #5, IN:	===>	7.00	7.00
Crush Measurement #6, IN:	===>	4.00	4.00
Energy from Secondary Impacts, FT·LBS:	===>	0.00	0.00

Pre-Impact Speed, MPH:	===>	70.84	9.60
Speed at Impact, MPH:	===>	57.55	9.60
After-Impact Speed, MPH:	===>	23.97	23.97
Crush Energy, FT·LBS:	===>	128939.68	128939.68
EES Speed, MPH:	===>	33.57	33.57

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MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-1' RUN FOR PCB 2 - 2006 RUN 6 ********
HEAD-ON COLLISION

Information For Vehicles		1995 MERCEDES BENZ 300 S	1995 OPEL Corsa
Vehicle Weight, Lbs:	===>	4884.00	2624.00
Surface #1			
Pre-Impact Braking Distance, FT:	===>	0.00	0.00
Pre-Impact Deceleration, g-UNITS:	===>	0.00	0.00
Surface #1			
Distance Traveled After Impact, FT:	===>	18.00	15.00
After-Impact Deceleration, g-UNITS:	===>	0.20	0.20
Max. Force Not Causing Damage, LBS/IN:	===>	350.00	250.00
Stiffness/Inch of Width, PSI:	===>	161.00	100.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	74.30	63.30
Number of Crush Measurements:	===>	4	4
Crush Measurement #1, IN:	===>	19.70	28.30
Crush Measurement #2, IN:	===>	13.00	24.00
Crush Measurement #3, IN:	===>	4.00	18.00
Crush Measurement #4, IN:	===>	0.00	3.00
Energy from Secondary Impacts, FT·LBS:	===>	0.00	0.00

Pre-Impact Speed, MPH:	===>	31.70	30.20
Speed at Impact, MPH:	===>	31.70	30.20
After-Impact Speed, MPH:	===>	10.38	9.48
Crush Energy, FT·LBS:	===>	80797.61	137621.53
EES Speed, MPH:	===>	22.25	39.62

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MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-1' RUN FOR PCB 2 - 2006, RUN 7 ********
HEAD-ON COLLISION

Information For Vehicles		1995 MERCEDES BENZ 300 S	1995 OPEL Corsa
Vehicle Weight, Lbs:	===>	4884.00	2624.00
Surface #1			
Pre-Impact Braking Distance, FT:	===>	0.00	0.00
Pre-Impact Deceleration, g-UNITS:	===>	0.00	0.00
Surface #1			
Distance Traveled After Impact, FT:	===>	18.00	15.00
After-Impact Deceleration, g-UNITS:	===>	0.20	0.20
Max. Force Not Causing Damage, LBS/IN:	===>	289.00	185.00
Stiffness/Inch of Width, PSI:	===>	113.00	66.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	74.30	63.30
Number of Crush Measurements:	===>	4	4
Crush Measurement #1, IN:	===>	19.70	28.30
Crush Measurement #2, IN:	===>	13.00	24.00
Crush Measurement #3, IN:	===>	4.00	18.00
Crush Measurement #4, IN:	===>	0.00	3.00
Energy from Secondary Impacts, FT·LBS:	===>	0.00	0.00

Pre-Impact Speed, MPH:	===>	28.17	23.62
Speed at Impact, MPH:	===>	28.17	23.62
After-Impact Speed, MPH:	===>	10.38	9.48
Crush Energy, FT·LBS:	===>	59745.97	93137.30
EES Speed, MPH:	===>	19.14	32.60

Unless specific test data are available to fine tune the frontal stiffness coefficients used, an impact velocity range of 28 to 31 mph, and 24 to 31 mph for the Mercedes and Opel, respectively, should be stated.