SHORT PAPER PCB 1-2006

IN-LINE COLLISIONS

ENGINEERING EQUATIONS, INPUT DATA AND MARC 1 APPLICATIONS

By:

Dennis F. Andrews, Franco Gamero, Rudy Limpert

PC-BRAKE, INC.
2006

www.pcbrakeinc.com

PURPOSE OF PCB SHORT PAPERS

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.

Short Papers are available free of charge and can be obtained by visiting our website at

www.pcbrakeinc.com

We hope that our Short Papers will assist the practitioner in better understanding the limitations inherent in any derivation of engineering equations, to properly use critical input data, to more accurately and effectively formulate his or her case under consideration, to become a better prepared expert in the field of accident reconstruction, and to more effectively utilize the full potential of the MARC 1 computer program.

Comments and suggestions are always invited by visiting our Discussion Forum and/or by writing to:

PC-BRAKE, INC.
1071 E. Tollgate Road
Park City, Utah 84098

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 One

Single Vehicle Crashes, Test Data & Crush Energy

1. DEFINITION OF IN-LINE COLLISION

In a single vehicle collision with a fixed barrier the rotation after impact is insignificant in relationship to the crush energy. During maximum crush engagement both vehicle and barrier attain a common velocity (zero in a fixed barrier test). See ARC photographs 477, 482 through 484.

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. Two-vehicle in-line collisions with common velocity will be discussed in IN-LINE COLLISIONS, Part Two, PCB 2-2006.

In side-swipe two-vehicle (frontal or rear) collisions the approach and departure velocity vectors of both vehicles are approximately parallel. The center-of gravities of both vehicles do not reach a common velocity. In a single vehicle side-swipe the other vehicle may be stationary or a fixed object such as a wall or guard rail. In general, crush energies are minor (see ARC Section 2.4.3), but may also involved significant sheet metal deformation. See ARC Sections 2.4.1 video, and ARC 2.4.2 photographs.
Vehicle side-swipe collisions will be discussed in IN-LINE COLLISIONS, Part Three, PCB 3-2006.

2. WHAT ENGINEERING PRINCIPLES APPLY

Linear momentum equation in one direction only, energy balance, and standard velocity-after-impact run-out analysis. One direction linear momentum is discussed in detail in Sections 33-1(d) through 33-1(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 we address only those crashes that deal with crush profiles that can be reasonably accurately related to fixed barrier crash test data.

3. HEAD-ON COLLISION WITH FIXED NON-DEFORMABLE OBJECT

The fixed object could be a wall, bridge abutment, tree, or even a large truck or piece of construction equipment, that does not move and deform as a result of the impact. Fixed means it did not move after impact, that is, it did not receive any kinetic energy from the impact. Non-deformable means it did not receive any crush energy from the impact. See Section 7-4(c)(1) of the Text for some basic frontal crashworthiness discussion.

3.1. FRONTAL BARRIER OR WALL IMPACT

3.1.1 MODERATE TO HIGH IMPACT VELOCITY

Consider a car impacting a fixed wall. If the impact velocity is above approximately 20 to 30 mph, the crash will be plastic with the vehicle having no or very little rebound from the wall. Rebounding means that the car had some kinetic energy or velocity after the impact. Rebounding also means that the impact was not fully plastic, indicating a coefficient larger than zero. ARC Section 1.2.1 video shows a vehicle rebounding after a pole impact. See the discussion of elastic, plastic and real impact in Section 33-1 of the Text. MARC 1 W-2, In-Line Collisions with Restitution, may be used to evaluate the effects of restitution on rebound velocity.

For example, for a vehicle weighing 3000 lb impacting a fixed barrier (weight = 99999999 lb) at 35 mph, and a coefficient of restitution = 0.1, W-2 shows that the vehicle bounces back at -3.5 mph, a delta-V = 38.5 mph for the car, and a crush energy of 121,412 lbft. If the barrier is non-deformable, then the car will receive all the crush energy in terms of corresponding crush depth.

For plastic impact with the coefficient of restitution equal to zero, energy balance (Equation 21-6 of Text) applies, yielding that the crush energy of the vehicle after the impact equals the kinetic energy of the vehicle before impact. See Equation 21-24 where crush energy and vehicle mass (or weight) must be known in order to calculate impact velocity. Deformation or crush energy is discussed in detail in Section 21-6(f). For a constant crush depth the crush energy equation is derived, resulting in Equation 21-23. Additional crush energy equations are shown for two, four, and six crush depth measurements.

MARC 1 Program X-9 can be used to compute the crush energies corresponding to Equations 21-25 through 21-27, as well as the energy equivalent speed (EES) by use of Equation 21-24. The EES “speed” is that impact velocity against a fixed non-deformable barrier that produces the same crush energy of the subject accident vehicle under consideration.

Crush energy calculations including MARC 1 X-9 require crush depth measurements and stiffness coefficients, usually called A and B stiffness coefficients, as input data. In a head-on wall or barrier (including off-set barrier) impact the crush measurements are straight forward, usually exhibiting no vertical crush depth variations. The A and B values are frequently difficult to obtain, since they are vehicle (or at least vehicle class) specific. Often A and B stiffness coefficient ranges are published based upon wheel base and vehicle categories.

Knowledge of the Collision Deformation Classification (CDC) (SAE J440) and or the Police Damage Scale will improve the appropriate profiling of the measurements and the description of the damage.

A and B stiffness coefficient ranges, published based upon wheel base and vehicle size categories, can be obtained from sources such as the NHTSA National Accident Sampling System (NASS). The Calspan Reconstruction of Accident Speeds on the Highway program (CRASH 3), the first accident reconstruction program for Computers developed by R. R. McHenry in 1976, only accepts stiffness values (A, B, C, etc.) according to the size of the vehicle. Correspondingly, the size of the vehicle (wheel base) is also given a category code. These categories are based on the research and publications of K. L. Campbell. See the tables below (source: CRASH 3 Technical Manual).

TABLE 1.1

VEHICLE SIZE CATEGORIES BY WHEELBASE, AND DEFAULT VALUES FOR REQUIRED PARAMETERS (FOR USE IN ANSWERING QUESTION 2 OF CRASH3)

DEFAULT PARAMETER \ CATEGORY NO.	1	2	3	4	5
	Mini-car	Subcompact	Compact	Inter-mediate	Full Size
WHEELBASE (IN)	80.9-94.8	94.8-101.6	101.6-110.4	110.4-117.5	117.5-123.2
TRACK (IN)	51.1	54.6	58.9	61.8	63.7
LENGTH (IN)	159.8	174.9	196.2	212.8	223.7
WIDTH (IN)	60.8	67.2	72.6	77.0	79.8
a (IN)	45.1	46.3	51.3	54.7	58.1
b (IN)	48.1	50.1	55.5	59.2	63.0
X_F (IN)	76.0	83.3	89.8	98.8	101.8
X_R (IN)	-83.8	-91.6	-106.4	-114.0	-121.9
Y_S (IN)	30.4	33.6	36.3	38.5	39.9
RSQ (IN^2)	2006.	2951.	3324.	3741.	4040.
M ($LB\text{-}SEC^2/IN$)	5.70	7.90	9.18	10.99	12.59
CURB WT (LBS)	1902.	2753.	3247.	3947.	4565.

DEFINITIONS: a = distance from c.g. to front axle

b = distance from c.g. to rear axle

X_F = distance from c.g. to front of vehicle

X_R = distance from c.g. to rear of vehicle

Y_S = distance from c.g. to side of vehicle

RSQ = radius of gyration, squared

M = vehicle mass (includes 2 passenger loading)

TABLE 1.1 (Continued)

VEHICLE SIZE CATEGORIES BY WHEELBASE, AND DEFAULT VALUES FOR REQUIRED PARAMETERS (FOR USE IN ANSWERING QUESTION 2 OF CRASH3)

CATEGORY NO. / DEFAULT PARAMETER	6 Luxury	7 Vans	8 Pick-ups	9 Jeeps	10 Movable Barrier	11 Immovable Barrier
WHEELBASE (IN)	123.2-150	109"-130"	NO DATA ARE AVAILABLE FOR CATEGORIES 8 AND 9. DO NOT USE THESE CATEGORIES.		120.0	--
TRACK (IN)	63.7	67.6"			60.0	--
LENGTH (IN)	229.4	183.6"			180.0	--
WIDTH (IN)	79.8	79."			78.0	--
a (IN)	60.1	48.5			54.0	50.
b (IN)	65.1	68.5			66.0	50.
X_F (IN)	104.2	75.6			84.0	50.
X_R (IN)	-125.2	-107."			-96.0	-50.
Y_S (IN)	39.9	39.5"			50.0	50.
RSQ (IN^2)	4229.	3713.			4024.	10^6
M ($LB\text{-}SEC^2/IN$)	13.74	11.2			10.35	10^6
CURB WT (LBS)	5009.	4300.			4000.	

DEFINITIONS:
- a = distance from c.g. to front axle
- b = distance from c.g. to rear axle
- X_F = distance from c.g. to front of vehicle
- X_R = distance from c.g. to rear of vehicle
- Y_S = distance from c.g. to side of vehicle
- RSQ = radius of gyration, squared
- M = vehicle mass (includes 2 passenger loading)

TABLE 1.2

VEHICLE STIFFNESS CATEGORIES

NOTE: Stiffness Category # is required for CRASH3 Question 5.

STIFFNESS CATEGORY 1.		1	2	3	4	5
		Mini-cars	Subcompact	Compact	Inter-mediate	Full Size
2. VEHICLE MODELS		Pinto (FRONT) Accord Honda CVCC Prelude Corolla Chevette Fiesta Bobcat Datsun 210 Datsun 310 Arrow Champ Colt Porsche 924 Mazda GLC Fiat 124 Spider Fiat X1/9 Datsun 280ZX Opel MG Midget Tri. Spitfire VW Rabbit VW Scirocco	Pinto (REAR) Chev. Monza Celica ST Celica GT Corona Spirit Pacer Gremlin VW Dasher Vega Skyhawk Omni Sunbird Starfire Mustang (78-) Horizon Fiat 128 Sedan Capri 280 ZX 2+2 Challenger BMW 320i Audi Fox Mazda Cosmo Mazda RX-7 Renault LeCar Saab 900 Saab 99 Subaru	Celica Supra Mustang (-73) AMC Concord Malibu (78-) Monarch Zephyr Fairmont Granada Firebird Cressida Datsun 810 Monte Carlo (78-) Grand Prix (78-) Cutlass (78-) Regal Aspen Peugot 604L BMW 528i Volvo (all) Audi 5000 LeMans (78-) Volare	Chevelle (-77) MonteCarlo (-77) Grand Prix (-77) Cutlass (-77) LeMans (-77) Phoenix Chev V-8 (-77) LeSabre (77-) Monaco (77-) Magnum Century LeBaron Riviera (77-) Marquis (77-) LTD (77-) Cordoba Nova Eldorado (79-) Delta 88 (77-) Diplomat T-Bird (77-) Seville Ventura Cougar	Chev V-8 (-76) LeSabre (-76) Chev V-8 (-76) Monaco (-76) Marquis (-76) LTD (-76) Delta 88 (-76) T-Bird (-76) St. Regis Newport
(F) FRONT	A	302 lb/in	259	317	356	325
	B	47 lb/in^2	43	56	34	37
	C	967 lb	778	901	1874	1429
(B) REAR	A	366	391	410	357	297
	B	38	41	44	13	70
	C	1755	1874	1931	4986	628
(R,L) SIDE	A	77	140	173	143	177
	B	37	67	57	50	47
	C	81	148	263	203	331

1. For test modes or vehicle models not listed, use a structurally similar category or choose a category by wheelbase dimension from Table 1.1. (NASS teams should consult their Zone Center if in doubt as to proper stiffness category.)
2. Includes all model years unless otherwise specified.
3. Front and rear crash modes only; for side damage, pick a category (1 to 6) by wheelbase from Table 1.1.
4. Front crash mode only; for side and rear, pick a category (1 to 6) by wheelbase from Table 1.1.

TABLE 1.2 (Continued)

VEHICLE STIFFNESS CATEGORIES

NOTE: Stiffness Category # is required for CRASH3 Question 5.

STIFFNESS CATEGORY [1]		6	7	8	9	10	11
		Luxury	Vans & 4WD [3]	Pick-up [3]	Front Drive [4]	Movable Barrier	Immovable Barrier
2. VEHICLE MODELS		Riviera (-76) Eldorado (-78) Olds 98 Brghm. DeVille Electra Fleetwood Continental Checker Cab	Ford E150 Dodge B-200 Chev G-20 Ford P-500 GMC G-3500 GMC G-1500 VW Vanagon Datsun 4x4 p/u Honcho 4x4 p/u Wagoneer Scout II Chev. Blazer	Courier Ford F150 Chev LUV Ford F250 Dodge D-100 Ford F100 1/2 ton Datsun p/u GMC 1500 Toy. SR5 long. Ranchero El Camino Sprint	Citation Phoenix Skylark Omega Reliant Aries Escort Lynx		
(F) FRONT	A	325	383	480	373	--	--
	B	37	126	50	38	--	--
	C	1429	580	2315	1849	--	--
(B) REAR	A	297	300	346	SEE	--	--
	B	70	55	25		--	--
	C	628	818	2373	NOTE 4.	--	--
(R,L) SIDE	A	177	SEE	SEE	SEE	--	--
	B	47				--	--
	C	331	NOTE 3.	NOTE 3.	NOTE 4.	--	--

1. For test modes or vehicle models not listed, use a structurally similar category or choose a category by wheelbase dimension from Table 1.1. (NASS teams should consult their Zone Center if in doubt as to proper stiffness category.)
2. Includes all model years unless otherwise specified.
3. Front and rear crash modes only; for side damage, pick a category (1 to 6) by wheelbase from Table 1.1.
4. Front crash mode only; for side and rear, pick a category (1 to 6) by wheelbase from Table 1.1.

The above A and B values are subject to educated choices. They are, however, very useful for older vehicles for which no crash data may exist.

A and B values may be calculated by Equations 21-28 and 21-29, with the input data obtained from fixed barrier crash tests. See Example 21-6 of the Text for a sample A and B calculation. The A and B values may be calculated by Equations 21-28 and 21-29, with the input data obtained from fixed barrier crash tests. See Example 21-6 of the Text for a sample A and B calculation.

The National Highway Traffic Safety Administration (NHTSA) regularly publishes crash test data that allow A and B stiffness coefficient calculations. The basic frontal NCAP crash test data may be obtained from NHTSA by following these steps:

1. http://dms.dot.gov
2. Click "Simple Search"
3. Enter Docket #: 4962
4. Click "Search"
5. Choose report from "Title" column and open (PDF or TIF)
6. Go to Data Sheet: ACCIDENT INVESTIGATION DIVISION DATA

Obtain vehicle test weight, impact velocity and crush depth data required for A and B stiffness coefficient calculations. The NHTSA website www.nhtsa.gov.org may also be accessed to obtain data on crash tests, rollover testing, and vehicle ranking. Additional data are available from www-nrd.nhtsa.dot.gov/database/nrd-11/veh_db.html. Rollover ratings can be obtained via docket # 8298, side impact NCAP crash ratings via docket # 3855.

The National Crash Analysis Center (NCAC) provides (for a fee) all of NHTSA's NCAP vehicle rating reports and high speed films from George Washington University, National Crash Analysis Center Library, Suite 203, Academic Way, Ashburn, VA 22011; phone 703-726-8236, fax 703-726-8358. Their website is: www.ncac.gwu.edu/filmlibrary/index.html.

The Accident Investigation Division Data for a 2004 Ford Taurus SE and a 1999 Ford Taurus are shown below for frontal impacts at 35 mph.

DATA SHEET NO. 20

ACCIDENT INVESTIGATION DIVISION DATA

Test Vehicle: 2004 Ford Taurus SE — NHTSA No.: M40201
Test Program: 35mph Frontal Impact — Test Date: 10/16/03

VEHICLE INFORMATION

VIN: 1FAFP53U94G101400 — Wheelbase (mm) : 2755
Vehicle Size Category: Sedan — Test Weight (kg) : 1784.4

ACCELEROMETER DATA

Accelerometer Locations: As per measurements on Page 13
Cal. Procedure/Interval: MGA procedure / 6 month
Integration Algorithm: Trapezoidal — Linearity: > 99%
Impact Velocity (km/h): 55.8
Velocity Change (km/h): 63.0 — Time of Separation (msec): 108.5

CRUSH PROFILE

Collision Deformation Classification: Frontal — Midpoint of Damage: Centerline
Damage Region Length (mm): 1408 — Impact Mode: Frontal

No.	Measurement Description	Units	Pre-Test	Post-Test	Difference
C1	Crush zone 1 at left side	mm	4775	4431	344
C2	Crush zone 2 at left side	mm	4883	4405	478
C3	Crush zone 3 at left side	mm	4927	4445	482
C4	Crush zone 4 at right side	mm	4925	4454	471
C5	Crush zone 5 at right side	mm	4879	4419	460
C6	Crush zone 6 at right side	mm	4763	4360	403
L	C1 TO C6	mm	1408	1381	27

DATA SHEET 18
ACCIDENT INVESTIGATION DIVISION DATA
FOR 35 MPH FRONTAL BARRIER IMPACT

Vehicle Make/Model/Body Style: 1999/Ford/Taurus/4 Door

VIN: 1FAFP53U7XA113617

Model Year: 1999 ; Build Date: 8/98 ; Test Date: August 10, 1998

Veh. Size Category: Mid ; TEST WEIGHT: 1731.4 kg

Veh. Wheelbase: 2756 mm; Front Overhang: 1008 mm; Overall Width: 1670 mm

ACCELEROMETER DATA:

Location: As per measurements on pages 2-25

Calibration Procedure: As per MGA Calibration Procedure

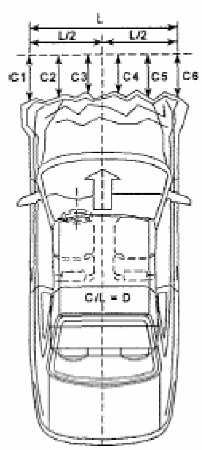
Linearity: >99.9% ; Integration Algorithm: Trapezoidal

Veh: Impact Speed: 56.3 kph ; Time Of Separation: 172 msec

Velocity Change: 66.5 kph

Collision Deformation Classification (CDC) Code: F (Frontal)

Crush Depth Dimensions: C1 = 505 mm
C2 = 494 mm
C3 = 514 mm
C4 = 5 0 2 mm
C5 = 480 mm
C6 = 4 8 3 mm



Midpoint Of Damage: D = Vehicle Centerline (Longitudinal)

Length Of Damaged Region: L = 1330 mm

Note that the dimensions follow the Collision Deformation Classification (SAE J440) protocol. This protocol must be taken into consideration when using it to calculate the stiffness coefficients.

It is of critical importance that the stiffness coefficients A and B used to calculate crush energy for a particular vehicle crush profile, and hence, impact velocity, are as reasonable accurate as possible. Check against as many independent sources as available. The following discussion will demonstrate this point.

Consider the 1984 Mercedes Benz Model 190 illustrated in Figure 1. The data were obtained from industry crash data (source: Computer Supported Reconstruction of Car/Car Accidents, Heinz Burg, (Ph.D. dissertation) published by Verlag INFORMATION Ambs GmbH, Kippenheim, Germany). The car impacted a fixed barrier in a full frontal test at a speed of 30.8 mph (49.6 km/h). The maximum permanent (static) deformation was 18.9 in (480 mm). The test weight was 3241 lb (1470 kg). In order to calculate the A and B stiffness coefficients, we must know the b(0), which is the y-axis intercept, and b(1), the slope as illustrated in Figure 21-9 of the Text. The b(0) value is that thresh-hold impact velocity at which permanent deformation begins to occur. Usually, these values are not published, but generally range between 4 and 8 ft/sec. If two or more crash tests at different impact velocities are available for the same model vehicle, b(0) may be computed more accurately. The impact velocity versus crush depth slope b(1) is calculated from the published crash data, that is, impact velocity and measured permanent crush depth, and the assumed b(0) value.

Using the 190 test weight of W = 3241 lb, b(0) = 5 ft/sec, crush width w = 65 in., crush depth c = 18.9 in. (1.575 ft), and a test velocity of 30.8 mph (45.15 ft/sec) yields with a

slope b(1) = (45.15 – 5)/(1.575) = 25.49 (ft/sec)/(ft)

the following stiffness coefficients:

A = ((3241)(5)(12)(25.49))/((32.2)(12)(65)) = 197.3 lb/in.

B = ((3241)(25.49)^2)/((32.2)(12)(65)) = 83.8 lb/(in^2)

Using these values in MARC 1 X-9, Crush Energy/EES Values, yields the output data shown in RUN 1. Using MARC 1 X-1, Head-On Collision, will yield the same result by making the input data of vehicle 2 correspond to those of a fixed barrier, namely very large weight for "vehicle 2", zero crush width, etc. resulting in no energy delivered to vehicle 2, the "fixed barrier".

Neptune Engineering in "Crush Stiffness Coefficients for Vehicle Model Years 1960 – 1992" (Three-Ring Binder) publishes frontal stiffness coefficients A = 315 and B = 150 for a 1989 Mercedes 190 E, and A = 431 and B = 278 for a 1990 Mercedes 190 E. The question to be answered is: Why is there such significant difference in stiffness coefficients for the 1984 Mercedes 190 versus model years 89 and 90, and in particular, between the 89 and 90 model years?

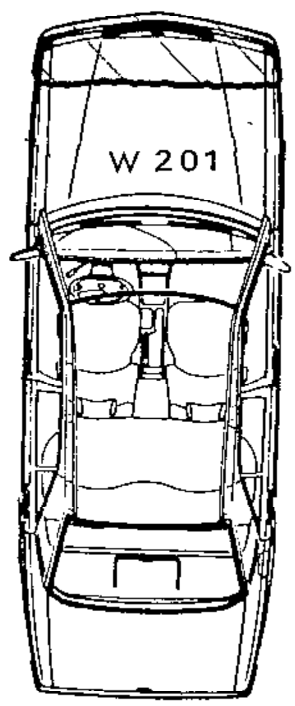


Figure 1

1984 Mercedes Benz 190
Full Frontal Fixed Barrier Test
Velocity 30.8 mph
Weight 3241 lb
Maximum uniform permanent crush 18.9 in.

Monday, February 13, 2006

MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-9' RUN FOR PCB 1-2006/RUN 1 ********
CRUSH ENERGY/EES VALUES

Information For Vehicles		1984 MERCEDES BENZ 190	2000 Barrier N/A
Vehicle Weight, LBS:	===>	3241.00	99999999.00
Max. Force Not Causing Damage, LBS/IN:	===>	197.30	1.00
Stiffness/Inch of Width, PSI:	===>	83.80	1.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	65.00	0.00
Number of Crush Measurements:	===>	2	2
Crush Measurement #1, IN:	===>	18.90	1.00
Crush Measurement #2, IN:	===>	18.90	1.00
Crush Energy, FT·LBS:	===>	102528.47	0.00
EES Speed, MPH:	===>	30.77	0.00

Review of the detailed crash data reveals that the 89 MB190 produced an average crush depth of 13.2 in. for an impact velocity of 29.2 mph and test weight of 3450 lb (test # 1354), versus 11.9 in., 34.8 mph, and 3492 lb for the 90 MB190 (test # 1459). The b(0) values are identical for both (5.86 ft/sec). The crush width is 67 in. for both vehicles. This might not the actual crush width since 67 in. is the overall width of the MB190.

The question raised is, how can a 29 mph impact velocity produce an average crush depth of 13.2 in., while 35 mph produce only 11.9 in. in spite of the fact that the that there is only a 42 lb weight difference?

A detailed review of appropriate literature such as repair manuals and trade publications does not reveal any design or manufacturing changes by Mercedes Benz that what warrant significant differences in stiffness characteristics between the 89 and 90 model years. Detailed review of the six crush depth measurements reveals that only three crush points were recorded for the 89 MB versus six for the 90 MB. The three values were averaged by Neptune Engineering to yield 13.2 in. versus the six point average of 11.9 in. Unless a review of test details provides more information for the 89 MB190, any conclusions reached by use of the associated A and B values may be questionable and will certainly provide for serious cross examination.

The difference between the 84 and 89/90 MB190 can only be explained by design changes that affect the crashworthiness, and possibly by differences in test procedures.

Figure 2 illustrates the crush profile of a 1984 Mercedes 190 after impacting a fixed barrier in a 40% overlap crash test. The maximum permanent crush depth was 33.5 in. Assuming that the crush profile as depicted in Figure 2 is correct, we may be able to approximate the six-point crush profile for every 13 in. (65/5) by scaling (over-all length of vehicle is 174.4 in.) as follows: 33.5 in. (test measurement), 32, 30, 3, 2, 0 inches. Substituting the same values of RUN 1 including the A and B values established in the fixed barrier test above, except for the different crush depth values, yields the output data shown in RUN 2. The calculated impact velocity is 34.24 mph, while the actual test velocity was 34.18 mph (55 km/h).

Using the 1990 MB190 stiffness coefficients of A = 431 and B = 278 from Neptune Engineering in our MB190 off-set crash yields an impact velocity of 60.67 mph. The error is unacceptably high, suggesting incorrect test data. The mathematical procedure carried out by Neptune Engineering apparently were correct.

The results indicate that our A and B stiffness values are more realistic. This should be the case since solid barrier test crush depth values vary very little as a function of height resulting crush energy calculations that are consistent with energy levels “exhibited” by crashed test vehicle. In vehicle-to-vehicle crashes the crush profiles are not uniform over the height of the frontal area of the vehicle. In other words, real world crashes produce crush profiles in both the horizontal plane (as it was the case in RUN 1 and RUN 2) and the vertical plane.

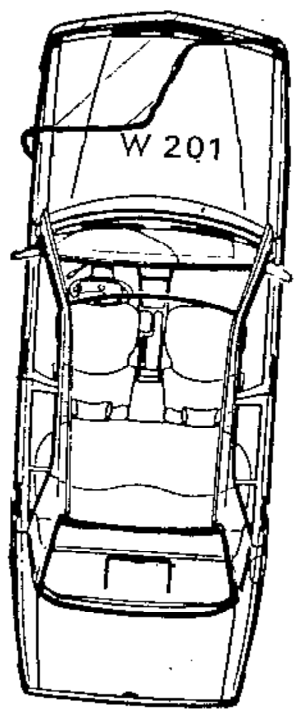


Figure 2

1984 Mercedes Benz 190
40% Overlap Frontal Fixed Barrier Test
Velocity 34.18 mph
Weight 3241 lb
Maximum permanent crush 33.5 in.

Monday, February 13, 2006

MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-9' RUN FOR PCB 1-2006/RUN 2 ********
CRUSH ENERGY/EES VALUES

Information For Vehicles		1984 MERCEDES BENZ 190	2000 Barrier N/A
Vehicle Weight, LBS:	===>	3241.00	99999999.00
Max. Force Not Causing Damage, LBS/IN:	===>	197.30	1.00
Stiffness/Inch of Width, PSI:	===>	83.80	1.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	65.00	0.00
Number of Crush Measurements:	===>	6	2
Crush Measurement #1, IN:	===>	33.50	1.00
Crush Measurement #2, IN:	===>	32.00	1.00
Crush Measurement #3, IN:	===>	30.00	0.00
Crush Measurement #4, IN:	===>	3.00	0.00
Crush Measurement #5, IN:	===>	2.00	0.00
Crush Measurement #6, IN:	===>	0.00	0.00
Crush Energy, FT·LBS:	===>	126952.82	0.00
EES Speed, MPH:	===>	34.24	0.00

As was discussed above, difficulties may arise when the stiffness characteristics from one vehicle (such as the Mercedes Benz 190) are used in the crash analysis of a different Mercedes Benz model or for a similar vehicle of a different manufacturer. To investigate potential differences between models of the same manufacturer, consider the crash test discussed next.

A Mercedes Benz S Model (W126) was 40% overlap crash tested at 35.7 mph yielding a maximum permanent crush depth of 39.7 in. with a vehicle test weight of 4275 lb. The crush profile was measured as: 39.7, 38, 9.5, 6.7, 3, 0 in. over a crush width of 71.6 in. Using these data and A = 197.3 and B = 83.8 of the Mercedes 190 yields with MARC 1 X-9 an impact velocity of 30.32 mph instead of a test velocity of 35.7 mph. Inspection of the results shows that the MB190 stiffness coefficients are not valid for use in a MB S model frontal crash.

The proper stiffness coefficients A and B may be calculated from the following MB S model full frontal crash test data: Weight 4256 lb, impact velocity 30.9 mph, maximum permanent uniform crush deformation of 21.4 in. With b(0) = 5, and b(1) = 22.6, the stiffness coefficients are A = 208.6 and B = 78.6. With these proper data MARC 1 X-9 calculates an impact velocity in the 40% overlap test of 30.8 mph indicating excellent agreement with the stiffness coefficients obtained from full frontal crash test data.

To assess the potential difference between manufacturers, consider the following full frontal crash test of a close competitor to the MB 190. A 1984 BMW Type 3 weighing 2983 lb was solid-barrier crash tested at 30.26 mph, yielding a maximum permanent uniform crush depth of 17.76 in. Performing a stiffness coefficient calculation yields A = 192.5 and B = 85.3. The frontal stiffness characteristics are similar for both vehicles, as one would expect, since both are rear wheel drives with the 190 having a wheel base of 104.9 in. versus the BMW with 101.1 in. Neptune Engineering publishes A = 245 and B = 104 for a 1985 BMW 318i.

Consider the full frontal fixed barrier crash test data of a 1984 VW Golf Cabrio. For an impact velocity of 31.26 mph, test weight of 2090 lb, and permanent crush depth values of 16.9, 15.5, and 14.9 in. left to right (driver to passenger), the stiffness coefficients are equal to A = 159.2 and B = 82.5 for an average crush depth of 15.7 in.

If we did not have access to the VW Golf specific crash data, and had used the values for the Mercedes Benz 190, MARC 1 X-9 would have calculated an impact velocity of 32.33 mph instead of a test velocity of 31.26 mph. The correlation is good, indicating that at times we may cautiously apply A and B values across manufacturers and front and rear wheel drive models.

In some cases, where neither government testing nor other test data are available, use of average values for A and B stiffness coefficients may become necessary. A Society of Automotive Engineers paper SAE 960897 presents a listing of stiffness coefficients grouped by vehicle type (passenger cars, SUVs, pickup trucks, vans), and by wheel base.

For the Mercedes Benz 190, having a wheel base of 104.9 in., SAE 960897 shows A = 207 and B = 70 for Class 3 passenger cars (wheel base 101.6 to 110.4 in.). Using these values in RUN 2 yields an impact velocity of 31.95 mph instead of 34.2 mph, still indicating good accuracy. The A and B stiffness coefficients shown in SAE 960897are an upgrade over those shown in the tables reprinted above from the Crash 3 manual.

3.1.2. LOW IMPACT VELOCITY – MINOR OVERLAP, POLE IMPACT

A frontal solid barrier impact with 40% overlap is illustrated in Figure 3. The vehicle is a Mercedes Bens S model, weighing 4009 lb, impacting with 12.9 mph. The maximum permanent crush is 10.7 in. as shown. Scaling the crush profile yields four crush depth values of 10.7, 10.7, 10.7 and 3 in. over a crush width of 29 in. Using A = 208.6 and B = 78.6 from the earlier example in MARC 1 X-9 yields an impact velocity of 10.34 mph. The calculated velocity is only 80% of the actual test velocity. This finding indicates that stiffness coefficients determined from moderate to high impact velocities may not be directly applicable to low impact velocity cases, indicating a bi-linear relationship with higher stiffness for lower impact speeds as indicated by Figure 33-9 of the Text.

A frontal central pole impact is illustrated in Figure 4 for a Mercedes Benz S model. The test weight is 4072 lb, the maximum permanent crush depth is 14.45 in., the impact velocity is 18.3 mph. Scaling the crush profile yields a four-point crush profile of 2, 14.45, 14.45, and 2 in. over a crush width of 30 in. Using MARC 1 X-9, results in an impact velocity of 11.58 mph. The calculated velocity is lower then the actual test impact velocity by approximately 37%.

The empirical pole relationship Equation 33-22 of the Text with the input data of the Mercedes Benz S model yields an impact velocity of:

$$V = ((395- (0.065)(4072))((14.45/12)^2))^{0.5} = 14.4 \text{ mph.}$$

In the frontal MB pole impact test the kinetic, and hence, the crush energy of the test car equals 45,370 lbft. We can use MARC 1 X-9 to determine what b(1) value is required to yield the proper A and B values to produce a crush energy of 45,370 lbft for the given crush profile produced in the pole impact.

In MARC 1 X-9 as shown in RUN 3 we use the proper input data for crush profile and weight. By trial and error we use different A and B values to determine a crush energy of approximately 45,000 lbft, keeping in mind that the A and B values need to increase over those of the moderate to high velocity crash tests. Having obtained reasonable values, we check by use of Equations 21-28 and 21-29 with b(0) between 3 and 7 ft/sec what b(1) value is required. For b(0) = 4.5 and b(1) = 24.3, A = 459 and B = 206.7. Inspection of RUN 3 shows a calculated impact velocity of 18.21 mph, as compared with a test velocity of 18.27 mph. Of course, the correlation is excellent since we used MARC 1 to calculate the A and B values to yield the required test crush energy.

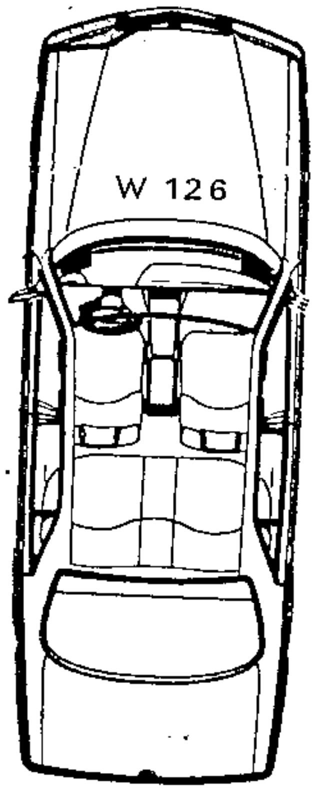


Figure 3

1984 Mercedes Benz S Model
40% Overlap Frontal Fixed Barrier Test
Velocity 12.9 mph
Weight 4009 lb
Maximum permanent crush 10.7 in.

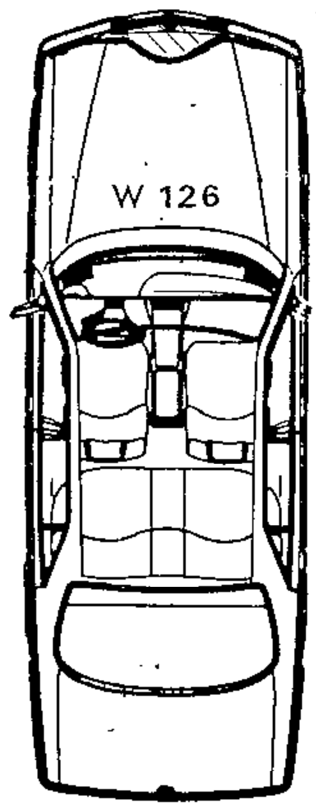


Figure 4

1984 Mercedes Benz S Model
Central Pole Impact
Velocity 18.3 mph
Weight 4057 lb
Maximum permanent crush 14.4 in.

Monday, February 13, 2006

MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-9' RUN FOR PCB 1 - 2006/RUN 3 ********
CRUSH ENERGY/EES VALUES

Information For Vehicles		1984 MERCEDES BENZ S Model	2000 Barrier N/A
Vehicle Weight, LBS:	===>	4057.00	99999999.00
Max. Force Not Causing Damage, LBS/IN:	===>	459.00	1.00
Stiffness/Inch of Width, PSI:	===>	206.70	1.00
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	30.00	0.00
Number of Crush Measurements:	===>	4	2
Crush Measurement #1, IN:	===>	2.00	1.00
Crush Measurement #2, IN:	===>	14.45	1.00
Crush Measurement #3, IN:	===>	14.45	0.00
Crush Measurement #4, IN:	===>	2.00	0.00
Crush Energy, FT·LBS:	===>	44954.19	0.00
EES Speed, MPH:	===>	18.21	0.00

4.0 REAR-END MOBILE BARRIER CRASH TEST

See Section 7-4(c)(2) of the Text for some basic rear-end crashworthiness discussion.

The non-deformable mobile barrier rear-end crash test is a two-vehicle test used to determine the rear-end crash characteristics of cars. We use this test in our single vehicle collision discussion to determine rear-end stiffness coefficients A and B.

The rear crash test data of a Mercedes Benz 190 are as follows: Weight of test car 3407 lb, weight of mobile barrier 4000 lb, impact velocity of barrier 30 mph, maximum permanent crush depth 23.62 in. uniform across full rear width and height of car.

In this crash test both vehicles attain a common after-impact velocity, since a fully plastic impact is assumed. We use MARC 1 W-2, In-Line Collisions with Restitution, RUN 4 to analyze the crash. Inspection of MARC 1 RUN 4 reveals a crush energy of 55,260 lbft for a coefficient of restitution e = 0. Even for e = 0.1 the crush energy decreases only insignificantly to 54,707 lbft. The reader is reminded that MARC 1 W-2 requires that Vehicle 1 is that vehicle that rear-ends Vehicle 2. See Figure 33-2 of the Text.

Since all crush energy is absorbed by the MB 190, the EES velocity can be obtained from Equation 21-24 as follows:

V = EES = ((2)(55,269)/(105.8))^2 = 32 ft/sec or 22 mph.

If the MB190 had been driven backwards against a fixed barrier at a test velocity of 22 mph, it would have produced the same rear-end damage as the mobile barrier did at an impact velocity of 30 mph against the stationary MB190.

As an inspection of RUN 4 shows, the EES = 22 mph is different from the velocity change or delta-V of the car which is 16.2 mph.

We now want to determine the A and B stiffness coefficients of the rear damage sustained by the MB190 in the mobile barrier crash test. Since this test is equivalent to a rear-end wall crash test with the Mercedes traveling backwards at 20 mph, we simply use the stiffness coefficient equations as before. Making the assumption that b(0) ranges between 3 to 7 ft/sec we can calculate slope b(1), and hence, A and B values.

The slope is calculated as b(1) = ((22)(1.466) – 5)/(1.96) = 13.9 (ft/sec)/(ft). Using b(0) = 5 ft/sec in Equations 21-28 and 21-29 yields A = 113 and B = 26.2.

SAE Paper 960897 specifies average values of A = 190 and B = 52 for a wheel bases ranging between 101.6 and 110.4. Neptune Engineering publishes rear-end stiffness coefficients of A = 177 and B = 53 for a 1978 BMW 320i.

Monday, February 13, 2006

MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'W-2' RUN FOR PCB 1 -2006/RUN 4 ********
TWO VEHICLE IN-LINE COLLISION

Information For Vehicles		2000 MObile Barrier N/A	1984 MERCEDES BENZ 190
Before Impact Speed of Vehicle, MPH:	===>	30.00	0.00
Vehicle Weight, LBS:	===>	4000.00	3407.00
Coefficient of Restitution, D'LESS:	===>	0.00	
After Impact Speed of Vehicle, MPH:	===>	16.20	16.20

Delta-V for Vehicle 1, MPH:	===>	-13.80
Delta-V for Vehicle 2, MPH	===>	16.20
Crush Energy, FT·LBS:	===>	55260.44

Using MARC 1 X-2, Rear-End Collisions, we can rerun the mobile barrier crash test in the computer. X-2 requires the after-impact distances and decelerations of each vehicle. Since no after-impact data were measured, we utilize the data from RUN 4, which indicates an after-impact velocity of 16.2 mph for both vehicles (plastic impact). Assuming an after-impact deceleration of 0.35g for each vehicle, the distance traveled must be 25 ft to yield 16.2 mph after impact velocity. Using these and the other proper data in MARC 1 X-2 yields the output data of RUN 5. Inspection of RUN 5 shows Vehicle 2 (MB190) was stopped prior to impact and the mobile barrier's impact velocity at approximately 30 mph. The reader is reminded that Vehicle 1 (mobile barrier) is the vehicle that rear-ends Vehicle 1 (MB 190).

Similar to the rear-end stiffness coefficient determination for a MB190, the mobile non-deformable barrier test with a 1980 BMW 3-Series resulted in the following crash data: Mobile barrier weight 4000 lb, car weight 2983 lb, impact velocity 29.8 mph, maximum permanent uniform crush depth 11.1 in. Performing an analysis similar to the one for the MB190 yields the following for the BMW:

MARC 1 W-2 yields the crush energy of 50,741 lbft. With Equation 21-24 the energy equivalent speed EES = 22.6 mph. With b(0) = 5 ft/sec, slope b(1) = ((22.6)(1.466) – 5)/(0.925) = 30.4 (ft/sec)/(ft), and width of 64.7 in. Equations 21-28 and 21-29 yield A = 217.6 and B = 110.3.

A comparison of the rear-end stiffness characteristic reveals that for essentially identical crash test conditions, the MB190 has a significantly softer rear-end than the BMW 3 Series, shown by 23.62 versus 11.1 in. crush depths. For the MB190 the entire trunk was pushed to nearly the bottom of the rear window glass, while in the case of the BMW Type 3 only approximately 50% of the trunk was pushed forward.

5.0. SUMMARY CONCLUSIONS

As is evident from the discussion above, the engineering formulation in terms of governing equations is fairly straight forward. The input data, and then in particular, the stiffness coefficients frequently involve curve fitting procedures which do not involve any fundamentals of physics. For example, if the A and B values are wrong, the reconstruction analysis is wrong. If the crash test procedure is wrong, the A and B values are wrong. If the test procedure is correct, however the curve fitting is wrong, the A and B values are wrong. If the test procedure is correct and the curve fitting is correct, however the empirical relationship describing the curve fit is wrong, the A and B values are wrong. The reader is referred to the assumptions made in deriving energy from crush depth measurements including the linear relationships between impact velocity and crush as well as force crush as discussed in Section 2.1.of the Text.

Consequently, careful attention must be paid to all aspects of crush energy analysis. If no reasonably accurate stiffness coefficients are available, always use meaningful upper and lower bounds for A and B values to obtain a reasonable range of impact velocities. Often secondary accident reconstruction principles are available that may assist in determining

Monday, February 13, 2006

MOTOR VEHICLE ACCIDENT RECONSTRUCTION AND CAUSE ANALYSIS
******** PROGRAM 'X-2' RUN FOR PCB 1 - 2006/RUN 5 ********
REAR-END COLLISION

Information For Vehicles		2000 BARRIER N/A	1984 MERCEDES BENZ 190
Vehicle Weight, LBS:	===>	4000.00	3408.00
NO BEFORE IMPACT SURFACE DATA			
Surface #1			
Distance Traveled After Impact, FT:	===>	25.00	25.00
After-Impact Deceleration, g-UNITS:	===>	0.35	0.35
Max. Force Not Causing Damage, LBS/IN:	===>	1.00	113.00
Stiffness/Inch of Width, PSI:	===>	1.00	26.20
Force Angle Offset from Perpendicular, DEG:	===>	0.00	0.00
Width of Crush Region, IN:	===>	0.00	65.00
Number of Crush Measurements:	===>	2	2
Crush Measurement #1, IN:	===>	1.00	23.62
Crush Measurement #2, IN:	===>	1.00	23.62
Energy from Secondary Impacts, FT·LBS:	===>	0.00	0.00

Pre-Impact Speed, MPH:	===>	29.98	0.01
Speed at Impact, MPH:	===>	29.98	-0.01
After-Impact Speed, MPH:	===>	16.18	16.18
Crush Energy, FT·LBS:	===>	0.00	55365.33
EES Speed, MPH:	===>	0.00	22.05

the probable impact velocity within that range.

When we have given any numerically calculated values for such parameters as impact velocity or A and B stiffness coefficients, we did not intend to demonstrate that this accuracy actually exists. This was done to allow the reader in his/her own calculations to check for mathematical correctness. For example, a calculated A = 151. 8 becomes 152, or an impact velocity of 34.43 mph becomes 34 mph. Vehicle crush measurements should be carried out within one-half inch accuracy, if possible.

Always ask yourself the following questions: Does the calculated numerical result make sense? What obvious laws of physics are violated? Is energy balance satisfied? What generally accepted concepts apply to my case? What is shown in the published literature? What case-specific tests can be conducted to support theoretical results?

6.0. APPLICATIONS TO SINGLE VEHICLE FIXED OBJECT CRASHES

6.1. HONDA CIVIC REAR-ENDS POWER POLE IN SECONDAY COLLISION

A 1981 Honda Civic 1300 Hatchback was impacted in the right side by a 1971 GMC pickup truck. The intersection impact spun the Honda around crashing into a power pole where it came to rest. We must calculate the rear-end crush energy of the Honda and the rear crush EES velocity.

The subject Honda Civic rest position is illustrated in Figures 4 through 11. The maximum permanent rear crush depth is 21 in. with a crush width of 58 in. measured at the outboard positions of the rear tail light lenses. The pole diameter is 11 in.

Mobile barrier rear-end crash test data show the following for a 81 Honda Civic Hatchback: Mobile barrier weight 3977 lb, impact velocity 35 mph, Honda Civic test weight 2386 lb, maximum permanent uniform rear-end crush depth 23.4 in.

Solution:

MARC 1 – W2 yields a common velocity (after-impact velocity of each vehicle) in the mobile barrier test of 18.79 mph with a coefficient of restitution e = 0. The stiffness coefficient analysis yields with b(0) = 4 ft/sec and b(1) = (27.55 – 4)/(1.95) = 12.1ft/(sec-ft) the stiffness coefficients A = 86.8 and B = 14.6. Estimating the crush profile from the known maximum depth of 23.4 in. as well as those located at six equally spaced (11.8 in. apart) depth measurements yields the following approximate crush depth data: 2, 14, 23.4, 23.4, 14 and 2 in. MARC 1 X-9 yields an impact velocity of 14.9 or approximately 15 mph against the pole.

Close inspection of the crush damage shown in Figures 4 and 5 reveals that the left and right rear corners (tail light lenses) are not crushed forward in any significant manner. This observation suggests that no major longitudinal load carrying components of the rear of the car were participating in absorbing crush energy. An in-depth inspection of the

Figure 4

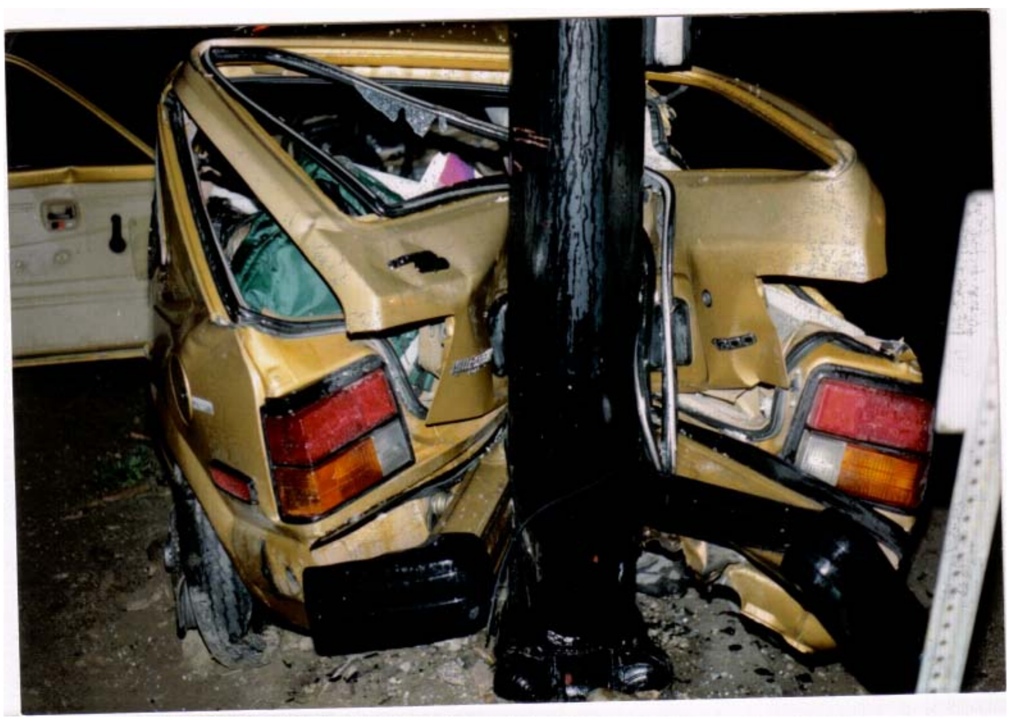


Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

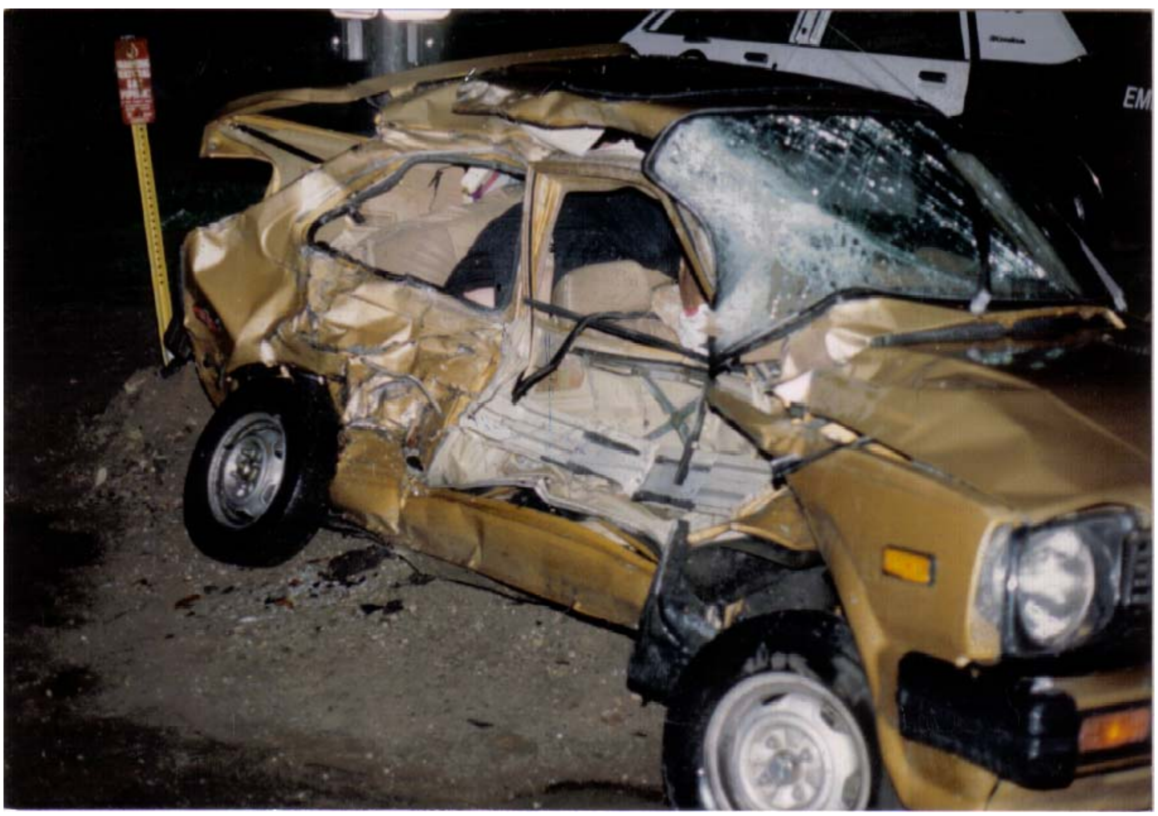


Figure 11

subject vehicle may reveal if any major load carrying components were participating in absorbing crush energy. An initial “interpretation” of the photographic data of Figures 4 and 5 appears to indicate a fairly “soft” pole crash.

6.2. FORD TAURUS TREE IMPACT

You have been asked by the attorney who retained you to check the accuracy of another expert’s work. Accident details including the expert’s reconstruction are shown in ARC Section 1.2.2. Photo 538 shows the rest position of the Taurus (below the MARC 1 X-9 computer run). In particular, you must determine through your own analysis, if the frontal stiffness coefficient A = 274 and B = 104 are correct.

Your attorney provided you with two different 1986 Taurus fixed barrier crash test data. The test weight of 3507 lb and crush width of 71 in. are the same for each test. The first test yielded a maximum uniform crush depth of 18.3 in. for an impact velocity of 18.6 mph, the second test 14.1 in. for 20.1 mph. Use the two crash test data points to calculate an accurate value for b(0), if possible.

Solution:

An obvious question is why a lower impact velocity produces more crush depth? Consequently, the data of one of the tests are highly questionable. The slope b(1) would be negative, meaning as impact velocity increases, crush depth decreases. Without more detailed information about test specifics it is meaningless to use both tests to establish the b(0) value of the 1986 Taurus.

The reader is reminded here, that if something is wrong with the crash test, the A and B values will be wrong also.

The first crash test data (18.6 mph) with b(0) = 6 ft/sec yield b(1) = 14.2 (ft/sec)/ft A = 130.7 and B = 25.8, the second test (20.1 mph) with b(1) = 20 yields A = 184.1 and B = 51.1. Which ones are correct cannot be answered without additional detailed test information, except that the 18.6 mph test may be unacceptable.

Inspection of the Neptune Three-Ring Binder reveals that the expert used A = 274 and B = 109 as determined from the 18.6 mph impact test. The slope used by Neptune Engineering in the 18.6 mph test was b(1) = 29.2 (ft/sec)/ft (or 1.66 mph/in.). Using their data to calculate the stiffness coefficients yields A = 274 and B = 109 as published in the Neptune Engineering Three-Ring Binder and used by the opposing expert. However, using the crash test point of 20.1 mph and the associated crush depth of 14.1 in yields a slope b(1) of approximately 20, and not 29.2 as used by Neptune Engineering.

SAE 960897 shows A = 207 and B = 70 for an average passenger car with a wheelbase of 106 in. Using all three sets of A and B values in MARC 1 X-9 yields EES velocities of 30.64, 25 and 22 mph, respectively. Using the empirical relationship Equation 33-22 of the Text yields an approximate impact velocity of 24 mph.