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Forensic Engineering Review of Crush Coefficients

by Joel T. Hicks, P.E. (NAFE 049F)

Abstract

Basic mathematics for computing crush coefficients from test data is presented. This information is supplemented with computer code for CRASH and SMAC coeffieients resulting form both rigid and movable barrier tests. Original CRASH3 crush data, supplemented by NHTSA test data through 1984, is tabulated and analyzed using a variety of logical and mathematical methods. The work is an extension of an analysis begun by Engineering Dynamics in 1987, where their "filtered" data has been grouped for observation. By understanding the data obtained in this earlier period of testing, the Forensic Engineer is better able to understand and use the information developed during almost ten years of subsequent testing.

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In the early 1970's, Kenneth Campbell and others observed that the vehicle crush in a series of staged frontal barrier crashes seemed to be linear with impact speed. He developed a technique to describe mathematically the relationship between kinetic energy absorption and deformation, and published the results in SAE paper 740565[1].

In the mid-1970's, R.R. McHenry provided coefficients in a revised form, which were modeled after mathematics given in Campbell's paper. The thrust of McHenry's work was a computer program, CRASH (Calspan Reconstruction of Accident Speeds on the Highway.) This technique allowed analysis of crush shapes which were neither full width nor uniformly deep nor normal.

Both techniques are attempts to correlate speed change during impact with corresponding crush. The basic idea of CRASH involves a mathematical model having one combined mass and two springs in series. The solution to the differential mathematical model of the system is a periodic function that engineers in many fields study often.

Joel T. Hicks, P.E., P.O. Box 190822, Little Rock, AR 72219-0822

Both techniques are similar, as illustrated in Figure 1. Campbell's Equivalent Barrier Speed (EBS) crush coefficients, b0 and b1, would estimate the speed loss directly using the average crush resulting from a barrier impact:

$$\text{delta-V} = b0 + cavg*b1. \qquad (1)$$

Where:

delta-V = the Equivalent Barrier Speed (EBS)

b0 = the ordinate intercept of the upper graph in Figure 1, commonly viewed as the maximum speed at which no residual deformation would occur.

b1 = the slope of the upper graph on Figure 1.

cavg = the average, reasonably uniform, residual crush.

McHenry's CRASH crush coefficients, A & B, would result in a direct measure of average force. This force could be combined with the time of impact to obtain the system impulse, or the impulse could be determined directly from the stored spring energy, which allowed a solution for delta-V:

$$I = Favg*dt = m*dV \qquad (2)$$

and

$$Favg = w*(A + cavg*B) \qquad (3)$$

Where:

I = the impulse of impact.

dt = the differential with respect to time.

m = mass of the vehicle.

dV = the differential velocity change during impact.

Favg = the average force applied during impact.

w = the width of crush.

A = the ordinate intercept of the lower graph in Figure 1.

B = the slope of the lower graph in Figure 1.

cavg = the average residual crush.

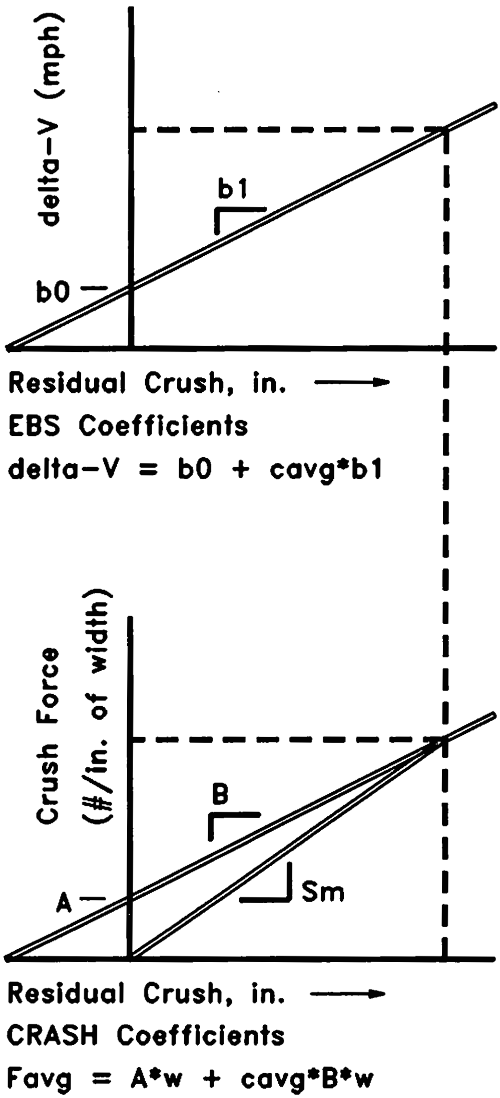

Figure 1: Comparison of EBS, CRASH and SMAC coefficients.

The analysis for SMAC (Simulation Model of Automobile Collisions) requires a single coefficient, the slope Sm in Figure 1, where b0 is set to zero. If it is desired to have SMAC and CRASH analyses agree as closely as possible, it will be desirable to use a value for the coefficient which corresponds to the crush predicted.

Equation (2) will be recognized as a form of Newton's second law, F = ma, which has been rearranged to meet the definition of impulse. Newton didn't state the law as F = ma. In differential notation, he said the sum of forces on a body is equal to its rate-of-change of momentum with respect to time. It makes a difference only if you view mass as possibly having a relationship to time or velocity, which is what Einstein did to develop his theory of relativity, "for funzies". His genius was not in the mathematics, which for him was child's play, but in recognizing what it meant.

Following through with such "what if" exercises is common for members of this Academy. It is in this vein that "research" crush coefficients are presented as a major objective of this paper.

In 1987, Engineering Dynamics Corporation (EDC) subjected test data from 1970-1984 vehicles to several "filters" to spot errors in the data. EDC then re-computed crush coefficients for the 590 surviving tests, **assuming** b0 of 5 mph for front and rear crashes and 2½ mph for side impacts[2].

Subsequently, this data was sorted again by class, and the A's and B's were **independently** averaged. Note: there is no particular technical basis for averaging them independently. The only basis was curiosity – it was a "what if" exercise.

The results, labeled here as "research coefficients", provide two benifits. There is a trend in the A's and B's with vehicle class that many expected if coefficients may be grouped by vehicle class. More importantly, these coefficients also predicted high and low impact speed crashes reasonably well, i.e., where there was other compelling evidence besides crush to suggest impact speed.

Table 1 lists the default crush coefficients published by HCCI[3], one of the first publications for this data. Tables 2-5 list the "research coefficients" for comparison, along with the count of applicable tests for each average. Use the data with reasonable caution and judgment.

In order to analyze staged crash test data, and develop appropriate crush coefficients based on them, one needs the mathematics of the model. This information is given in several sources besides the original papers and reports by

Campbell and McHenry. A computer program listing is included with this paper which is based on the publications of Engineering Dynamics Corporation[2].

The program may be keyed directly in qbasic, which is supplied with MS DOS versions 5 or later. The syntax is similar to many versions of user oriented software. Enhancements may include a data input routine to avoid altering the program steps. The math and logic may also be transferred to a spread sheet(s), if desired.

In order to compute crush coefficients from test data, one needs access to the data. Test results are available (with considerable detail, including video) from the National Highway and Traffic Safety Administration (NHTSA), and in abbreviated form in current periodicals such as *Accident Reconstruction Journal*. Some businesses offer data bases or lists for a fee.

Test reports often list the results of tests in different formats. For fixed barriers, which neither move nor absorb energy, the needed information is:

w1 = vehicle test weight, pounds.

l = width of crush, inches.

cavg = average crush depth, inches.

v = impact velocity or delta-V, mph.

For movable barrier tests, the needed information includes the former plus:

wb = weight of barrier, pounds

and the velocities of each mass before and after impact.

One weakness in the computation of coefficients from *isolated* test results is the required selection for Campbell's b0. Modern cars tend to have b0's on the order of 4 to 5 mph, but the program's printed results provide coefficients for b0's from 0 to 10 mph. If data exists to suggest a specific b0, then that value may be used. For example, there are five tests in the literature for 1978 to 1986 Dodge vans having impact speeds between 15 and 35 mph. Plotting the data in EBS fashion suggests a b0 of 6 to 7 mph.

This weakness will have various effects on the accuracy of crash speeds computed using the coefficients developed. If the crush in a case is close to the test crush, there will be little effect. If the crush is significantly different, the accuracy of the results may depend significantly on the selection of a representative value of b0.

The CRASH model does NOT consider the **conservation** of energy. Hence, one of the practical tests of the reasonableness of results is a comparison of kinetic energy (Ek) with crush energy (Ec). Be aware that the energy reported by crash software is the energy stored in the modeled springs, which extend out beyond the vehicle's skin. This energy includes the little triangle at the left of the origin in Figure 1, where the area is:

$$G = (A^2 / 2*B) * (\text{crush width})$$

The program provided may be modified to print such an energy comparison for the test results. Expect Ek/Ec to be 1 if G is included in Ec. The ratio is expected to be different if G is ignored. Many will be tempted to view the latter more as the work done on the vehicle rather than crush energy. Modifying the program and studying this issue will obviously require some time and effort. The only reward promised for such an exercise is a better understanding and appreciation for the dynamics of vehicle crashes.

The principal purposes of this paper have been to provide a model computer program for computing crush coefficients, and to provide a series of crush coefficients which have been independently averaged. There may be other ways to look at the data at hand, and thereby understand it better. It is hoped that the material will stimulate your interest and participation in the exchange of knowledge.

TABLE 1
(HCCI) Crash/Trajectory Default Data

Class	1	2	3	4	5	6	7
Wheel Base	80.0	94.8	101.6	110.4	117.5	123.2	109.0
to	94.8	101.6	110.4	117.5	123.2	150.0	130.0
Data	Mini	SubC	Comp	Intm	Full	Larg	Van
Trajectory:							
Weight	2202	3053	3547	4247	4865	5309	4300
K^2 (in^2)	2006	2951	3324	3740	4040	4229	3737
K^2/Weight	.91	.97	.94	.88	.83	.80	.87
A (.48*Wb)	45.1	46.3	51.3	54.7	58.1	60.1	48.5
B	48.1	50.1	55.5	59.2	63.0	65.1	68.5
A+B(Avg Wb)	93.2	96.4	106.8	113.9	121.1	125.2	117.0
T (.5*Tw)	25.6	27.3	29.5	30.9	31.8	31.8	33.8
Tire C's f	5374	7500	8714	10434	11964	13051	11964
Tire C's r	5039	6931	8055	9641	11033	12049	11033
Crash (I = K^2*Wt/386.4 slugs/in^2):							
I(slg/in^2)	11434	23313	30514	41114	50864	58160	41586
A	76.0	83.3	89.8	98.8	101.8	104.2	75.6
B	83.8	91.6	106.4	114.0	121.9	125.2	107.0
A+B (OAL)	159.8	174.9	196.2	212.8	223.7	229.8	182.6
T (.5*OAW)	30.4	33.6	36.3	38.5	39.9	39.9	39.5
CRASH3 Crush Coefficients:					— 5 & 6 —		
Front Offset	301.5	259.4	317.4	355.9	325.2	325.2	383.0
Front Slope	47.0	43.2	55.9	33.8	37.0	37.0	125.0
Side Offset	77.2	140.4	173.3	143.0	176.5	176.5	–
Side Slope	36.7	66.7	57.1	50.4	47.1	47.1	–
Back Offset	365.7	390.5	410.3	356.6	296.8	296.8	300.0
Back Slope	38.1	40.7	43.6	12.8	70.1	70.1	55.0

TABLE 2
RESEARCH Crush Coefficients (1970-84) *

EDC Filtered Data, 5mph Offset, All Data where Wb>=80:

Class	1	2	3	4	5	6
Count (446)	82	134	110	60	25	35
Avg Wb	92.7	97.9	106.5	114.4	120.1	129.6
Front Offset	256.0	262.7	294.4	295.0	305.5	380.3
Front Slope	75.1	74.3	82.7	76.6	85.5	111.6
Count (10)	3	2	5			
Avg Wb	94.8	97.9	105.1			
Side Offset	152.9	117.2	110.6			
Side Slope	141.7	76.2	56.2			
Count (106)	31	32	20	18	5	
Avg Wb	92.0	97.7	106.6	113.8	118.7	
Rear Offset	259.8	305.5	275.0	288.5	250.0	
Rear Slope	82.2	95.8	74.7	69.6	47.2	

TABLE 3
RESEARCH Crush Coefficients (1970-84) *

EDC Filtered Data, 5mph Offset, Cars only, not vans, LT, 4WD:

Class	1	2	3	4	5	6	5 & 6
Count (350)	75	121	80	48	23	3	26
Avg Wb	92.8	97.9	106.2	114.6	120.0	126.5	120.8
Front Offset	244.6	257.8	276.2	283.6	293.7	320.8	296.8
Front Slope	71.2	72.1	73.4	69.1	81.1	69.1	79.7
Count (10)	3	2	5				
Avg Wb	94.8	97.9	105.1				
Side Offset	152.9	117.2	110.6				
Side Slope	141.7	76.2	56.2				
Count (94)	30	28	15	16	5		
Avg Wb	91.9	97.6	106.2	113.8	118.7		
Rear Offset	256.6	286.7	266.5	287.9	250.0		
Rear Slope	80.0	84.8	68.1	68.8	47.2		

TABLE 4
RESEARCH Crush Coefficients (1970-84) *

EDC Filtered Data, 5mph Offset, Light Trucks only:

Count (47)	1	3	21	7	1	14	15
Avg Wb	94.4	99.5	106.9	113.6	118.8	132.3	131.4
Front Offset	244.2	379.5	321.7	306.4	549.3	314.5	330.2
Front Slope	63.3	130.0	103.5	87.8	182.8	79.6	86.5

TABLE 5
RESEARCH Crush Coefficients (1970-84) *

EDC Filtered Data, 5mph Offset, 4WD only:

Count (19)	5	9	5
Avg Wb	91.7	97.7	107.6
Front Offset	381.4	268.1	365.4
Front Slope	114.2	73.5	105.1

* [2], EDC Data Grouped and Averaged by Joel T. Hicks, P.E.

Program Listing

```
'cracoef.bas: Compute A & B from barrier crush data

GOSUB 5000 ' establish output device = #p9

t$ = " '84 Pontiac 4dr Wagon rear barrier test"
v1$ = " b0   b1    A    B"
v2$ = " mph mph/in  #/in #/in^2  "
k1 = 17.6 ' in/sec / mph (constant)
g = 386.04 ' in/sec*sec (constant)
w1 = 4472 ' test vehicle weight lb
cavg = 13.83 ' average crush in
l = 73.5 ' crush width or length in

' ***  vehicle into barrier speed ***
v = 35! ' vehicle impact speed mph, ignored if barrier into vehicle

' ***  barrier into vehicle data  ***
wb = 3987 ' if barrier wt not 0, then use movable barrier calculations
vb = 29.54 ' barrier impact vel mph
vbs = 14.02: ubs = 1 ' barrier sep vel mph, ubs=-1 for direction change
vv = 0: uvi = 1 '   veh imp vel mph, uvi=-1 for direction change
vvs = 14.96: uvs = 1 ' veh sep vel mph, uvs=-1 for direction change
' Note: vb assumed positive, analyze carefully for direction changes!
PRINT #p9, t$
IF wb = 0 THEN
  PRINT #p9, USING " cavg=###.##, vimp=###.##, w=####"; cavg; v; w1
ELSE
  PRINT #p9, USING " cavg=###.##, dv=###.##, w=####"; cavg; vvs - vv
* uvs; w1
END IF
PRINT #p9, v1$: PRINT #p9, v2$' : PRINT #p9,
FOR b0 = 0 TO 10 ' zero crush intercept mph
IF wb > 0 THEN GOTO mov:
b1 = (v - b0) / cavg ' slope
GOTO AB

mov:
bx = SQR(wb / w1 * (vb ^ 2 - vbs ^ 2 * ubs) + (vv ^ 2 * uvi - vvs ^ 2 *
uvs))
b1 = (bx - b0) / cavg
```

```
AB:
A = w1 * b0 * k1 * b1 * k1 / (g * l)
B = w1 * (b1 * k1) ^ 2 / (g * l)
PRINT #p9, USING " ##.# ###.## ####.# ####.#"; b0; b1; A; B
IF b0 = 3 OR b0 = 4 OR b0 = 5 THEN
  PRINT #p9, "                Vimp Cavg   Sm"
  GOSUB smack
END IF
NEXT b0
IF nm = 2 OR nm = 3 THEN PRINT #p9, CHR$(12);
END

smack:
FOR v2 = 20! TO 50! STEP 5
cr = (v2 - b0) / b1
sm = w1 * (v2 * k1 / cr) ^ 2 / (g * l)
PRINT #p9, SPC(34); : PRINT #p9, USING "##.# ##.# ####.#"; v2; cr;
sm
NEXT v2
RETURN

5000 REM SET UP OUTPUT FILE      ***
5010 CLS : PRINT "OUTPUT IS TO BE DIRECTED TO:"
5020 PRINT "1. SCRN:"
5030 PRINT "2. LPT1:"
5040 PRINT "3. COM2:"
5050 PRINT "4. DISK FILE"
5060 PRINT : BEEP: INPUT "YOUR SELECTION "; A: IF A > 4 OR A <
1 THEN 5060
5070 IF A <> 4 THEN 5090
5080 BEEP: INPUT "ENTER THE FILE NAME W/ DRIVE & EXT
(B:FNM.EXT) ", nm$
5090 IF A <> 3 THEN 5100 ELSE nm$ = "COM2:9600,n,8,1"
5100 IF A <> 2 THEN 5110 ELSE nm$ = "LPT1:"
5110 IF A <> 1 THEN 5120 ELSE nm$ = "SCRN:"
5120 p9 = 5: OPEN nm$ FOR OUTPUT AS p9: nm = A
5130 CLS : RETURN
```

Program Sample Output – Moving Barrier

'84 Pontiac 4dr Wagon Rear Barrier Test

cavg= 13.83, dv= 14.96, w=4472

b0	b1	A	B			
mph	mph/in	#/in	#/in^2			
0.0	1.41	0.0	96.7			
1.0	1.34	65.2	87.0			
2.0	1.26	123.3	77.9			
3.0	1.19	174.4	69.2			
				Vimp	Cavg	Sm
				20.0	14.3	95.8
				25.0	18.5	89.4
				30.0	22.7	85.4
				35.0	26.9	82.8
				40.0	31.1	80.9
				45.0	35.3	79.4
				50.0	39.5	78.3
4.0	1.12	218.4	61.1			
				Vimp	Cavg	Sm
				20.0	14.3	95.4
				25.0	18.8	86.5
				30.0	23.2	81.3
				35.0	27.7	77.8
				40.0	32.2	75.4
				45.0	36.7	73.6
				50.0	41.1	72.1
5.0	1.05	255.3	53.4			
				Vimp	Cavg	Sm
				20.0	14.3	95.0
				25.0	19.1	83.5
				30.0	23.9	76.9
				35.0	28.7	72.7
				40.0	33.5	69.8
				45.0	38.2	67.6
				50.0	43.0	65.9
6.0	0.97	285.2	46.3			
7.0	0.90	308.0	39.7			
8.0	0.83	323.8	33.6			
9.0	0.76	332.5	28.0			
10.0	0.68	334.2	22.9			

Revisions to Program Listing for Fixed Barrier

```
'cracoef.bas: Compute A & B from barrier crush data

GOSUB 5000 ' establish output device = #p9

t$ = " '84 Chevrolet Light Truck Fixed Barrier Test"
v1$ = " b0   b1    A    B"
v2$ = " mph mph/in  #/in #/in^2  "
k1 = 17.6 ' in/sec / mph (constant)
g = 386.04 ' in/sec*sec (constant)
w1 = 4839 ' test vehicle weight lb
cavg = 26.25 ' average crush in
l = 77.5 ' crush width or length in

' ***  vehicle into barrier speed ***
v = 35.2 ' vehicle impact speed mph, ignored if barrier into vehicle

' ***  barrier into vehicle data  ***
wb = 0  ' if barrier wt not 0, then use movable barrier calculations
```

Changes to the program steps for the following variables:

```
t$ = " '84 Chevrolet Light Truck Fixed Barrier Test"
w1 = 4839 ' test vehicle weight lb
cavg = 26.25 ' average crush in
l = 77.5 ' crush width or length in
v = 35.2 ' vehicle impact speed mph, ignored if barrier into vehicle
wb = 0  ' if barrier wt not 0, then use movable barrier calculations
```

results in the output that follows:

Program Sample Output – Fixed Barrier

'84 Chevrolet Light Truck Fixed Barrier Test

cavg= 26.25, vimp= 35.20, w=4839

b0	b1	A	B	Vimp	Cavg	Sm
mph	mph/in	#/in	#/in^2			
0.0	1.34	0.0	90.1			
1.0	1.30	65.3	85.0			
2.0	1.26	126.7	80.1			
3.0	1.23	184.4	75.4			
				Vimp	Cavg	Sm
				20.0	13.9	104.3
				25.0	17.9	97.3
				30.0	22.0	93.1
				35.0	26.1	90.2
				40.0	30.2	88.1
				45.0	34.2	86.5
				50.0	38.3	85.3
4.0	1.19	238.2	70.8			
				Vimp	Cavg	Sm
				20.0	13.5	110.6
				25.0	17.7	100.3
				30.0	21.9	94.2
				35.0	26.1	90.2
				40.0	30.3	87.4
				45.0	34.5	85.3
				50.0	38.7	83.6
5.0	1.15	288.2	66.3			
				Vimp	Cavg	Sm
				20.0	13.0	117.9
				25.0	17.4	103.6
				30.0	21.7	95.5
				35.0	26.1	90.3
				40.0	30.4	86.6
				45.0	34.8	83.9
				50.0	39.1	81.9
6.0	1.11	334.4	62.0			
7.0	1.07	376.8	57.8			
8.0	1.04	415.3	53.8			
9.0	1.00	450.1	49.9			
10.0	0.96	481.0	46.2			

References

[1] Kenneth L. Campbell, Energy Basis for Collision Severity, SAE 740565. Society of Automotive Engineers, 400 Commonwealth Dr., Warrendale, PA 15096.

[2] Terry D. Day, et al, Vehicle Crush Stiffness Coefficients, Engineering Dynamics Corporation, Library Reference Number 1042. EDC, 8625 SW Cascade Blvd., Suite 200, Beaverton, OR 97005.

[3] Robert L. Hess, Ph.D., Operator's Manual for HCCI CRASH/TRAJECTORY System of Programs. Hess Computing Co., Inc., 2629 Danbury Lane, Ann Arbor, MI 48103.