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Impact Analysis of Two-Vehicle Collisions

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ABSTRACT

The National Highway Traffic Safety Administration has conducted twelve staged collisions with the purpose of furnishing collision data for use with accident models. In this paper the data is fit to a two-vehicle impact model using the method of least squares. The model is based upon the equations of impulse and momentum; the computed constants are the coefficients of restitution and equivalent coefficient of friction. A gradient search technique was used to minimize the sum of squares directly.

Solutions (coefficients and velocity components) are found for 11 NHTSA collisions. The data seems to fit the model well, although deviations of 10% in impact velocity changes are not uncommon. Collisions with similar geometry but different initial velocity magnitudes do not always result in similar values of coefficients of restitution and friction. A specific parameter involving the total initial momentum, collision energy loss and velocity change, ΔV, of a single vehicle remains remarkably constant throughout all experimental collision types, speeds and vehicle mixes. This allows a simple expression to be used to predict approximately the ΔV of either vehicle in any collision.

DEVELOPMENT OF METHODS for modeling vehicle to vehicle impacts has been an active research area for over a decade. In order to provide experimental data for this area of study, the National Highway Traffic Safety Administration sponsored a series of staged collisions in the mid 1970's. A summary of collision and post impact motion data is included in one of the several report volumes (1)*. Twelve collisions are reported, but lost data from one leaves only eleven available for analysis. An analysis of these collisions is presented in this paper. Only the impacts are analyzed, that is, post impact motion (after vehicle separation) is not directly considered.

A collision of two vehicles is a complicated structural dynamics problem because of the irregularity of the shape of the vehicles' body components and because a great amount of inelastic deformation occurs. Knowledge of common characteristics of all, or classes of collisions would be convenient for many purposes, particularly for vehicle safety design. It is the intention of this paper to analyze the NHTSA Collision data to determine some of the general characteristics of vehicle to vehicle impacts. This is done by using a planar impulse/momentum model of a two vehicle impact developed earlier (2). The equations comprising this model relate the change in velocity components of each vehicle to the vehicle physical data and the impact geometry. Data from the NHTSA collisions is fitted to the model equations using the method of least squares. Details of the mathematics of the least square fitting procedure have been presented elsewhere (3); this paper emphasizes the numerical results and data trends.

One of the interesting results of the data analysis is an equation for predicting approximately the velocity change, ΔV, of a vehicle. In this expression, the velocity change depends upon the initial momentum of the colliding vehicles, their mass and the amount of kinetic energy dissipated during the impact. The availability of this equation should permit damage and injury estimates to be made simply for safety studies.

VEHICLE IMPACT MODEL

Various analytical and experimental studies have been and are being conducted of the events (forces and displacements) which occur when vehicles collide. These studies range from barrier impacts to finite element models including inelastic deformations (4). The model used in

*Numbers in parentheses designate references at end of paper.

0148-7191/83/0228-0468$02.50

this paper is based upon the fundamental laws of rigid body mechanics relating the impulse between the vehicles during contact and their resulting change in momentum. The derivation of these equations is contained in (2). The model is comprised of six algebraic equations; they are listed completely in an Appendix to this paper. Basically, these equations allow the final velocity components V_{1x}, V_{1y} and Ω_1 of vehicle 1 and V_{2x}, V_{2y} and Ω_2 of vehicle 2 to be calculated if the corresponding initial velocity components are known. In addition to the initial velocities, other information is required:

1. Vehicle inertial properties
2. Vehicle geometry
3. Collision geometry
4. Energy and friction coefficients

The collision geometry and vehicle geometry change during a collision. The impulse/momentum model ignores the details of these changes but takes their effect into account through the resultant forces and moments, overall velocity changes and energy losses. Energy losses are taken into account by the inclusion of three coefficients. These are the coefficient of restitution, e, the moment coefficient, e_m and a coefficient of equivalent friction, μ.

In order to interpret the results of the data analysis presented later, a reasonable understanding of these coefficients is required. Fig 1 shows a vehicle during a collision. A hypothetical, flat crush surface is illustrated from C' to C". Point G is the center of mass of the vehicle and point C is the location of the resultant of the intervehicular impulse. The force (and corresponding impulse) between the vehicles and velocities of the vehicles can be broken into components in the directions of crush and friction. The components then depend upon the angle Γ. The coefficient of restitution is defined as

$$|e| = \frac{\text{Relative Rebound Velocity Normal to } \Gamma}{\text{Relative Approach Velocity Normal to } \Gamma}$$

and corresponds to the classical coefficient of restitution found in mechanics texts. Its value must lie between 0 and 1. A value of 1 means a completely elastic rebound; zero means the vehicles do not move apart, perpendicular to Γ, following the impact. Other values between 0 and 1 indicate a partially elastic impact. For colinear particle impacts, e can be directly related to the energy loss. For a planar impact, e is still related to energy loss but the relationship is complicated by the presence of rotational motion and friction.

During a collision, the two vehicles do not actually "slide" along a crush surface as governed by the laws of Coulomb friction. However, an equivalent friction coefficient can still be defined:

$$\mu = \frac{\text{Impulse component along the } \Gamma \text{ line}}{\text{Impulse component normal to the } \Gamma \text{ line}}$$

With this definition, the coefficient μ can be negative or positive and can assume any magnitude, equal to or greater than zero.

The moment coefficient, e_m, is a "coefficient of restitution" for rotational motion. As defined in (2), its realistic values are $-1 < e_m < 0$ (in contrast to $0 < e < +1$), and has a similar interpretation as e. When $e_m = 0$, the two vehicles have zero relative angular velocity following impact. A value of -1, corresponds to a completely elastic angular impact. All realistic values fall between 0 and -1 with one exception. If $e_m = +1$, the moment impulse between the two vehicles is zero. In general, however, since the location of the point of application of the resultant impulse (point C, Fig 1) is not known exactly, a moment will almost always exist in the model equations.

Other variables such as the length, d, and angle ϕ of the line between each vehicle's center of gravity and the center of impact must be estimated. This is also true for each vehicle's angle of orientation, Θ, as well as the angle, Γ, of a common crush surface discussed above. Strictly speaking, none of these is a constant for a collision. Estimates of "average" values can be made. In this study, estimates for d and ϕ were based upon each vehicle's damaged dimensions. Values for Θ and Γ at the initiation of the collision are used throughout this study. Further studies and more experience in applying the model may lead to better techniques of selecting these variables.

NHTSA STAGED COLLISIONS

Four categories of collision geometry were used and are illustrated in Fig. 2. Various initial speeds were used for the vehicles ranging from approximately 20 mph (32 kph) to 40 mph (64 kph). Table 1 gives the basic data corresponding to the RICSAC* collisions including the original collision numbers which will be followed here. The data contained in Table 1-A forms part of the input for the data analysis. Table 1-B gives the same information in metric units. The remainder of the data consists of the vehicle characteristics and the values of the velocity components at separation, that is the final impact velocities. All of this information is listed in Table 2-A and 2-B. The final velocity components listed in Table 2 are somewhat different than those listed in the RICSAC reports for the following reason. Accelerometers used to record data on each vehicle

*RICSAC is the acronym for Research Input for Computer Simulation of Automobile Collisions (1) were not located at the vehicle's center of gravity. Consequently, the final velocity data had to be corrected by the angular velocity at separation and the distance of the accelerometer from the mass center. Table 2 contains the corrected data.

While the staged collisions can be grouped into four categories, there are differences within each category . The primary difference is initial speed. Other differences are apparent from Table 2 such as vehicle size mix. Two differences of importance which do not show up in the table are evident from the photographs and diagrams in the RICSAC reports. For example, it appears from photographs that vehicle 1 struck vehicle 2 in RICSAC 1 at a different relative position than the impacts in RICSAC 6 and 7. This is illustrated in Fig. 2-a by the dashed position of vehicle 1. This may explain the notable differences in direction and magnitude of the final (separation) angular velocities between RICSAC 1 and RICSAC 6 and 7. Another notable difference within a category is the amount of damage to vehicles No. 2 in RICSAC 3 and RICSAC 4 and 5. Fig 3 shows scaled profiles, viewed from above, of the amount of damage to the vehicles in each collision. This figure shows a great difference in the amount of crush, which is shown even more dramatically in the photographs of these vehicles.

LEAST SQUARE ESTIMATION

When a mathematical model as described above is available, for a physical process, methods exist for fitting the model to experimental data (5). The most popular are based upon the classical method of least squares. A sum of squares of deviations can be defined:

$$Q = \sum_{i=1}^{6} \sum_{p=1}^{n_i} w_i \, (V_i - V_{ip})^2 \qquad (1)$$

In this equation V_i, $i = 1,2,..6$ represents the six final velocity components of impact, three from each vehicle. That is $V_1 = V_{1x}$, $V_2 = V_{1y}$, $V_3 = V_{2x}$, $V_4 = V_{2y}$, $V_5 = \Omega_1$ and $V_6 = \Omega_2$. The quantities V_{ip} represent experimentally measured values of the V_i variables. The factors w_i are weighting factors. In this study the w_i's were chosen such that translational velocity terms were unweighted and angular velocity terms weighted by a constant, 25. (This constant, 25, is a typical value for vehicles moment of inertia divided by mass. This provides each term of Q with the same units, equivalent to energy per unit mass).

In theory, Q is minimized with respect to the coefficients e, e_m and μ along with the condition that the values of V_i, $i = 1,2,...6$, satisfy the six model equations.

Experimental conditions from collision to collision varied in one way or another, such as initial speed, vehicle size and make, etc. That is, no experimental replications exist in the NHTSA collisions. As a result, only one set of final velocities is available for each collision and $n_i = 1$ in all cases.

Minimization of Q was done numerically using a direct search method and a digital computer as explained in more detail in (3). An iterative approach was used by choosing a set of values for the coefficients, calculating the final velocities and Q. New coefficients are chosen to make Q smaller using the method of gradient projection. The search is stopped when Q changes by less than 0.5%. The number of iterations ranged roughly from 4 to 24 for the eleven collisions.

RESULTS

The corrected experimental final velocity components listed in Table 2 along with the other accident data for each RICSAC collision were fit using least squares to the equations in the Appendix. As a result a set of three coefficients and another set of final velocity components were produced. The coefficients are those which minimize Q, the sum of squares. The set of final velocity components are those which correspond to those coefficients and which also satisfy the equations of impulse and momentum. Table 3 lists a summary of results for the 11 RICSAC collisions. A discussion of some of the more interesting and significant points concerning these results follows.

PERCENTAGE ENERGY LOSS -The sum of the kinetic energy of the vehicles decreases due to energy lost in the collision. The percentage change seems relatively consistent within each catagory of collision. This is dramatically illustrated by RICSAC 11 and 12 which were near head on collisions with large energy losses. A comparison can be made for collisions 8, 9 and 10 with data of Grime and Jones (6). Their values for the same type of collision (see Table 4) are 32%, 29% and 30%. These are approximately 10% lower than the NHTSA collisions, presumably due to vehicle differences. Other values from (6) are provided for information but are not directly comparable to RICSAC collisions.

COEFFICIENT OF RESTITUTION -The coefficients of restitution, e, are all quite low, from 0.000 to 0.258. These quantities represent the relative rebound of the vehicles at the common crush surface, perpendicular to the crush line. There is a consistent set of low values from the 60° FRONT-TO-SIDE impacts. All are near zero indicating almost perfectly inelastic impacts. (In the context of vehicle impacts this means that the common surfaces of each vehicle had nearly the same final velocity components of rebound.) The consistency found in this collision category does not carry over to the others. The 90° FRONT-TO-SIDE collision e values are .043, .245 and .258, for collisions 8, 9, and 10 respectively. Collision 8 had a different vehicle mix (two intermediates) than 9 and 10. In addition, the post impact travel of both vehicles of collision 8 was much less.

This may indicate some interlocking of parts during contact and a consequent small coefficient e.

For collisions 3, 4, and 5, the respective coefficients are .221, .071 and .075, showing a notable difference between the first and the others. A major difference betweeen RICSAC 3 and RICSAC 4 and 5 is the initial speeds and the amount of damage. The damage to the target cars (vehicles 2) was much greater in collisions 4 and 5. Fig 3 shows the extent of permanent damage to the vehicles for these three collisions. Apparently, the extent of crush influences the value of the coefficient. Another possibility, however, is the choice of the angle Γ chosen for the analysis. For all three collisions, Γ was kept at -10°, the angle of initial surface contact. However, changing the angle, from -10° to -20° to conform more to the damaged surface rather than the original surface of contact does not increase e for collisions 4 and 5. Table 5 instead shows that the coefficient e becomes somewhat smaller. This seems to indicate that the lower initial speed in collision 3 caused less damage and less relative velocity changes and consequently a higher coefficient e. This indicates that for vehicular collisions, e may depend significantly upon initial velocities; its value is not solely dependent upon the structural parameters and collision geometry. Note also that changing Γ from -10° to 0° for RICSAC 3 has a very small effect on e.

MOMENT COEFFICIENT -The moment coefficient, e_m, must have a value of +1 (no moment between vehicles during impact) or $-1 < e_m < 0$. In all of the least square solutions, a value of +1 was not permitted. This choice was made since in a general formulation, some moment must always exist, however small. The values of e_m range between -.914 to -.430; the majority are very near -0.5 however. This indicates that the relative angular velocity changes between vehicles were neither predominantly inelastic nor elastic. Exceptions are collisions 9 and 10 with e_m = -.914 for both. The final relative angular velocities of these vehicles is the largest of all collisions, namely 3.927 and 6.493 rad/s, respectively. These exceptional values of e_m seem to be a consequence.

EQUIVALENT COEFFICIENT OF FRICTION -The equivalent coefficient of friction is the ratio of the intervehicular impulse components along and perpendicular to the crush line defined by Γ. It is not necessarily a measure of an actual sliding coefficient but is a measure of the ratio of impulse components. There is a definite trend to these values. For nearly colinear ("head-on") impacts, the magnitude of the coefficients is small, less than 0.1. See collisions 11, 12, 3, 4, and 5. For the rest of the collisions, the coefficient magnitude is much larger and indicates sliding penetration of one vehicle into or along the other. This is born out by the crush surface extent and appearance in photographs. Relative sliding along the Γ line is of course due to the large initial relative velocity components tangent to this line.

Both e and μ have a noticable dependence upon the choice of the angle Γ for a given collision. At this time, Γ is determined by the analyst's judgement and treated as an input to the least square procedure. Further research may permit the value of Γ to be computed from the data during the minimization of Q.

VELOCITY CHANGES, ΔV -A pair of columns of Table 3 shows the velocity change magnitude of each vehicle for each collision. Two values are given, the value calculated from the corrected experimental velocity components and the value calculated from the least square solution. By and large, these differ by a few ft/s or less with one exception. The values of ΔV for vehicle 2 of RICSAC 10 are 19.1 and 25.2 ft/s. This particular collision also has the largest sum of squares of deviations which is discussed in the next section.

Velocity changes are currently used as a guide to the severity of collisions. Although the statistical correlation of occupant injury (severity) and ΔV is not as good as desired (7), to a large extent, ΔV is still used (8). Consequently, this quantity is examined here in more detail. Rather than viewing ΔV alone, it is converted to momentum and normalized to the initial momentum, that is

$$L_i = \frac{m_i \Delta V_i}{[(m_1 v_1)^2 + (m_2 v_2)^2]^{1/2}} \qquad (1)$$

where i = 1 or 2, depending on which vehicle is chosen. Since the product of mass and velocity is momentum, L is the magnitude of normalized momentum change for a vehicle. Values of L_i for the computed velocity changes are listed in Table 3 under the heading of Normalized Speed Change. These numbers range from .3520 (RICSAC 5) to .7364 (RICSAC 12). There seems to be a negative correlation between the values of L_i and the kinetic energy loss, so a new quantity is calculated. The new quantity is $L'_i = L_i/\sqrt{\Delta T}$, where ΔT is the fraction of energy lost.

$$L'_i = \frac{m_i \Delta V_i}{\sqrt{\Delta T}\,[(m_1 v_1)^2 + (m_2 v_2)^2]^{1/2}} \qquad (2)$$

Values of this quantity are also listed in Table 3. It is rather interesting to note that the values of L'_i remain relatively constant within each accident category, as did L_i. The values of L'_i lie between .5641 and .7787 and surprisingly are much more constant over all impact speeds, collision geometries, vehicle mixes, etc. If a linear regression is performed between log(L') and log(ΔT), the regression coefficient is 0.5237 and the intercept is 0.6752. If these are generously rounded to 1/2 and 2/3, respectively, the resulting relationship is

$$\Delta V_i = \frac{2}{3} [(m_1 v_1)^2+(m_2 v_2)^2]^{1/2} (\Delta T)^{1/2}/m_i \quad (3)$$

The corresponding values of ΔV_i computed with Eq. 3 are shown in the last column of Table 3. There is little question that Eq. 3 is only approximate, but the fact that it applies to such a wide range of conditions indicates a potential usefullness. Perhaps data from more experimental collisions other than those presented here can be used to shed more light on the validity, accuracy and applicability of Eq. 3.

SUMS OF SQUARES -The magnitude of the sum of squares is a measure of how well the experimental data fits the model equations. The dimensional weighting is the same for all collisions so the sums of squares can be compared directly. The range is fairly broad, from 6.3 to 240.4. Many possible reasons exist for a large sum of squares when fitting experimental data. Some of these are:

1. Applicability of the model equations
2. Accuracy of experimental data
3. Choice of geometrical parameters (such as angles Γ and ϕ and distances d)

Implicit in item 2 above is that only one collision was conducted for each set of experimental conditions. Consequently n_i = 1 in the fitting procedure and no direct assessment of experimental error is possible.

One measurement made during the collisions and reported (1) was the angular rotation of the vehicles during contact. The impulse/momentum model assumes short durations of contact, relatively high forces between vehicles and negligible changes in position (including angular position) during contact. For some collisions, the angular rotation measured was significant. The values ranged from 0° for at least one vehicle in several collisions to as high as 55° for vehicle 1 in collision 10. Collision 10 happens to have the largest sum of squares. The correlation coefficient was computed between the sum of squares for each collision and (the square root of the sum of squares of) the vehicles' angular rotations for that same collision. The correlation coefficient is 0.87. This seems to indicate that the amount of rotation during contact may significantly affect the degree of fit of the equations. It must be pointed out however that despite large sums of squares, other quantities agree quite well. For example, the second highest sum of squares is 182.0 for RICSAC 7 yet the agreement between the measured and calculated ΔV's is rather good. Effects other than angular rotation seem to be present.

CONCLUSIONS

In many areas of engineering and science, modeling of a process can often yield results to within a few percent of experimentally measured values. This is certainly not true for modeling of collisions, at least for the results obtained here. On the average, computed velocity changes from the least square solution deviated by about 3.35 ft/s (2.28 mph, 3.68 kph) from the measured values. Since the average ΔV is 27.3 ft/s (18.6 mph, 30.0 kph), a 12% deviation typically occurs. Since collision dynamics is such a highly nonlinear problem, and since staged collisions are extensive experiments, perhaps a 12% deviation is not too bad.

Some noticible trends did occur from the fitting of the data and are summarized:

1. Energy loss expressed in percent, seemed relatively consistent within each category of collision but did differ somewhat from the results of others.

2. All values of the coefficient of restitution, e, were less than 0.3 but not very consistent within each category. Values seem dependent upon initial velocities (and subsequent damage).

3. Velocity changes do not seem to correlate to the coefficient of restitution.

4. The equivalent coefficient of friction varied considerably. For front-to-front or front-to-rear collisions, its magnitude was always less than 0.1. For front-to-side collisions, its magnitude ranged from about 0.5 to 0.9.

One of the interesting results was the observation that the value of normalized velocity change divided by the square root of kinetic energy loss remained relatively constant for all of the staged collisions. Because of this, an equation giving the approximate velocity change of a vehicle in a collision is available. A comparison of values predicted with this equation with measured velocity changes shows an average deviation of 3.27 ft/s (2.23 mph, 3.59 kph). This is the same magnitude as the experimental-fit deviation seen above. This equation appears to yield fairly good results. In non-experimental situations where the actual energy loss value is not available, typical values can be used for the corresponding category of collision.

APPENDIX: EQUATIONS OF IMPULSE/MOMENTUM MODEL

The equations comprising the model being fit by the method of least squares are summarized here. The derivation is presented in (2).

1. Conservation of momentum along the x axis: $m_2(V_{2x}-v_{2x}) + m_1(V_{1x}-v_{1x}) = 0$

2. Conservation of momentum along the y axis: $m_2(V_{2y}-v_{2y}) + m_1(V_{1y}-v_{1y}) = 0$

3. Conservation of Angular Momentum:
$I_2(\Omega_2-\omega_2) + I_1(\Omega_1-\omega_1)$
$+ m_2(d_a+d_c)(V_{2x}-v_{2x})$
$+ m_1(d_b+d_d)(V_{1y}-v_{1y}) = 0$

4. Restitution Normal to the Crush Line at Angle Γ:
$(V_{1y}-d_d\Omega_1-V_{2y}-d_b\Omega_2)\sin\Gamma$
$+ (V_{1x}+d_c\Omega_1-V_{2x}+d_a\Omega_2)\cos\Gamma$
$= -e[(v_{1y}-d_d\omega_1-v_{2y}-d_b\omega_2)\sin\Gamma$
$+ (v_{1x}+d_c\omega_1-v_{2x}+d_a\omega_2)\cos\Gamma$

5. Friction Along Crush Line at Angle Γ:
$m_1 (V_{1y}-v_{1y})(\cos\Gamma-\mu\sin\Gamma) +$
$m_2(V_{2x}-v_{2x})(\sin\Gamma + \mu\cos\Gamma) = 0$

6. Moment Resitution at Impact Surface:
$(\Omega_2-\Omega_1)(1-e_m)$
$= -e_m [(\Omega_1-\omega_1) - m_1d_c(V_{1x}-v_{1x})/I_1$
$+ m_1d_d(V_{1y}-v_{1y})/I_1 - (\Omega_2-\omega_2)$
$- m_2d_a (V_{2x}-v_{2x})/I_2 + m_2d_b (V_{2y}-v_{2y})/I_2]$

In the above

$d_a = d_2 \sin(\Theta_2+\phi_2)$ $d_b = d_2 \cos(\Theta_2+\phi_2)$
$d_c = d_1 \sin(\Theta_1+\phi_1)$ $d_d = d_1 \cos(\Theta_1+\phi_1)$

NOTATION

e coefficient of restitution

e_m moment coefficient of restitution

d distance between mass center and crush center

I vehicle yaw inertia about its mass center

m mass of vehicle

V velocity component of a vehicle following impact

v velocity component of a vehicle before impact

μ equivalent coefficient of friction along the impact surface

Θ heading angle of vehicles relative to the x axis

Γ angle of impact surface relative to the y axis

Ω angular velocity of a vehicle following impact

ω angular velocity of a vehicle before impact

ϕ angle between the length axis of a vehicle and a line between its center of gravity and the center of impact

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Table 1-A, RICSAC Collision/Vehicle Data

RICSAC COLLISION NUMBER	IMPACT CONFIGURATION	VEHICLE SIZE	VEHICLE MAKE	VEHICLE MASS $lb\text{-}s^2/ft$	MOMENT OF INERTIA $ft\text{-}lb\text{-}s^2$	DISTANCE d, CG TO IMPACT CTR, ft	ANGLE ϕ OF IMPACT CTR DEG	VEHICLE ORIENTATION ANGLE, DEG	ANGLE, Γ OF CRUSH SURFACE DEG
1	60° Front to Side	I	Chev	143.52	3728.25	7.59	-19.8	0	-30
		SC	Pinto	95.76	1961.42	3.44	-38.7	60	
6		I	Chev	133.56	3469.25	8.41	-17.9	0	-30
		SC	VW	81.48	1669.33	2.0	-90.0	60	
7		I	Chev	114.96	2985.17	8.41	-17.9	0	-30
		SC	VW	81.12	1081.92	2.0	-90.0	60	
8	90° Front to Side	I	Chev	139.08	3613.67	7.90	0.0	0	0
		I	Chev	146.28	3800.00	2.77	-68.8	90	
9		M	Honda	70.08	976.00	4.80	6.0	0	0
		I	Ford	152.16	3953.33	5.20	-29.7	90	
10		M	Honda	71.64	997.58	5.20	0.0	0	0
		I	Ford	146.64	3808.17	5.29	-29.2	90	
11	10° Front to Front	SC	Vega	94.44	1935.42	6.14	9.4	0	0
		I	Ford	150.60	3913.00	7.66	11.3	-10	
12		SC	Vega	97.20	1992.00	5.90	9.6	0	0
		I	Ford	140.16	3640.33	7.28	10.3	-10	
3	10° Front to Rear	I	Ford	153.72	3992.92	8.83	-17.0	0	-10
		SC	Pinto	96.96	1985.67	7.63	171.4	170	
4		I	Ford	154.68	4017.92	8.02	-18.2	0	-10
		SC	Pinto	99.12	2031.83	6.94	171.7	170	
5		I	Ford	142.92	3711.33	8.08	-20.7	0	-10
		M	Honda	78.60	1094.58	5.75	168.0	170	

I: Intermediate SC: Sub Compact M: Minicar

Table 1-B, RICSAC Collision/Vehicle Data (Metric Units)

RICSAC COLLISION NUMBER	IMPACT CONFIGURATION	VEHICLE SIZE	VEHICLE MAKE	VEHICLE MASS kg	MOMENT OF INERTIA $kg\text{-}m^2$	DISTANCE d, CG TO IMPACT CTR, m	ANGLE ϕ OF IMPACT CTR DEG	VEHICLE ORIENTATION ANGLE, DEG	ANGLE, Γ OF CRUSH SURFACE DEG
1	60° Front to Side	I	Chev	2095	5055	2.31	-19.8	0	-30
		SC	Pinto	1398	2659	1.05	-38.7	60	
6		I	Chev	1949	4704	2.56	-17.9	0	-30
		SC	VW	1189	2263	0.61	-90.0	60	
7		I	Chev	1678	4047	2.56	-17.9	0	-30
		SC	VW	1184	1467	0.61	-90.0	60	
8	90° Front to Side	I	Chev	2030	4899	2.41	0.0	0	0
		I	Chev	2135	5152	0.84	-68.8	90	
9		M	Honda	1023	1323	1.46	6.0	0	0
		I	Ford	2221	5360	1.58	-29.7	90	
10		M	Honda	1046	1353	1.58	0.0	0	0
		I	Ford	2140	5163	1.61	-29.2	90	
11	10° Front to Front	SC	Vega	1378	2624	1.87	9.4	0	0
		I	Ford	2198	5305	2.33	11.3	-10	
12		SC	Vega	1419	2701	1.80	9.6	0	0
		I	Ford	2045	4936	2.22	10.3	-10	
3	10° Front to Rear	I	Ford	2243	5414	2.69	-17.0	0	-10
		SC	Pinto	1415	2692	2.33	171.4	170	
4		I	Ford	2257	5448	2.44	-18.2	0	-10
		SC	Pinto	1447	2755	2.12	171.7	170	
5		I	Ford	2086	5032	2.46	-20.7	0	-10
		M	Honda	1147	1484	1.76	168.0	170	

Table 2-A, RICSAC Collision Velocity Data

RICSAC COLLISION NUMBER	IMPACT CONFIGURATION	VEHICLE SIZE	VEHICLE MAKE	INITIAL SPEED, MPH	v_x, INITIAL SPEED COMPONENT, ft/s	v_y, INITIAL SPEED COMPONENT, ft/s	V_x, MEASURED FINAL SPEED COMPONENT, ft/s	V_y, MEASURED FINAL SPEED COMPONENT, ft/s	MEASURED FINAL ANGULAR VELOCITY, rad/s
1	60° Front to Side	I	Chev	19.8	-29.04	0.0	-12.330	7.905	-1.571
		SC	Pinto	19.8	14.52	25.15	- 6.803	16.697	0.0
6		I	Chev	21.5	-31.53	0.0	-18.684	4.117	-0.524
		SC	VW	21.5	15.29	27.31	- 4.196	18.016	-3.142
7		I	Chev	29.1	-42.68	0.0	-25.410	4.850	-0.524
		SC	VW	29.1	21.34	36.96	- 7.631	28.339	-3.351
8	90° Front to Side	I	Chev	20.8	-30.51	0.0	-10.241	10.723	-1.990
		I	Chev	20.8	0.0	30.51	-12.025	19.718	-0.314
9		M	Honda	21.2	-31.09	0.0	- 2.808	14.835	-3.142
		I	Ford	21.2	0.0	31.09	- 9.903	24.200	0.785
10		M	Honda	33.3	-48.84	0.0	- 5.082	28.183	-5.236
		I	Ford	33.3	0.0	48.84	-14.574	36.549	1.257
11	10° Front to Front	SC	Vega	20.4	-29.92	0.0	5.814	2.017	0.524
		I	Ford	20.4	29.47	-5.20	6.424	-4.111	0.0
12		SC	Vega	31.5	-46.20	0.0	-14.054	-1.609	1.571
		I	Ford	31.5	45.50	-8.02	6.321	-9.645	1.047
3	10° Front to Rear	I	Ford	21.2	-31.09	0.0	-17.157	0.244	-0.262
		SC	Pinto	0.0	0.0	0.0	-22.872	3.735	0.0
4		I	Ford	38.7	-56.76	0.0	-29.327	-1.433	-0.646
		SC	Pinto	0.0	0.0	0.0	-32.542	1.381	-0.524
5		I	Ford	39.7	-58.23	0.0	-34.314	0.569	-0.209
		M	Honda	0.0	0.0	0.0	-37.152	2.778	-1.222

Table 2-B RICSAC Collision Velocity Data (Metric units)

RICSAC COLLISION NUMBER	IMPACT CONFIGURATION	VEHICLE SIZE	VEHICLE MAKE	INITIAL SPEED, kph	v_x, INITIAL COMPONENT, m/s	v_y, INITIAL COMPONENT, m/s	V_x, MEASURED FINAL SPEED COMPONENT, m/s	V_y, MEASURED FINAL SPEED COMPONENT, m/s	MEASURED FINAL ANGULAR VELOCITY rad/s
1	60° Front to Side	I	Chev	31.9	- 8.85	0.0	-3.76	2.41	-1.571
		SC	Pinto	31.9	4.43	7.67	-2.07	5.09	0.0
6		I	Chev	34.6	- 9.61	0.0	-5.69	1.25	-0.524
		SC	VW	34.6	4.66	8.32	-1.28	5.49	-3.142
7		I	Chev	46.8	-13.01	0.0	-7.74	1.48	-0.524
		SC	VW	46.8	6.50	11.27	-2.33	8.64	-3.351
8	90° Front to Side	I	Chev	33.5	- 9.30	0.0	-3.12	3.27	-1.990
		I	Chev	33.5	0.0	9.30	-3.67	6.01	-0.314
9		M	Honda	34.1	- 9.48	0.0	-0.86	4.52	-3.142
		I	Ford	34.1	0.0	9.48	-3.02	7.38	0.785
10		M	Honda	53.6	-14.89	0.0	-1.55	8.59	-5.236
		I	Ford	53.6	0.0	14.89	-4.44	11.14	1.257
11	10° Front to Front	SC	Vega	32.8	- 9.12	0.0	1.71	0.61	0.524
		I	Ford	32.8	8.98	-1.58	1.96	-1.25	0.0
12		SC	Vega	50.7	-14.08	0.0	-4.28	-0.49	1.571
		I	Ford	50.7	13.87	2.44	1.93	-2.94	1.047
3	10° Front to Rear	I	Ford	34.1	- 9.48	0.0	-5.23	0.07	-0.262
		SC	Pinto	0.0	0.0	0.0	-6.97	1.14	0.0
4		I	Ford	62.3	-17.30	0.0	-8.94	-0.44	-0.646
		SC	Pinto	0.0	0.0	0.0	-9.92	0.42	-0.524
5		I	Ford	63.9	-17.75	0.0	-10.46	0.17	-0.209
		M	Honda	0.0	0.0	0.0	-11.32	0.85	-1.222

Table 3, Results of Least Square Impact Analysis

RICSAC COLLISION NUMBER	FINAL SUM OF SQUARES	ENERGY LOSS PERCENT	SPEED CHANGE, $\lvert\Delta V\rvert$, EXPERIMENTAL ft/s	SPEED CHANGE $\lvert\Delta V\rvert$, COMPUTED ft/s	COEFF OF RESTITUTION, e	MOMENT COEFFICIENT, e_m	FRICTION COEFFICIENT, μ	NORMALIZED SPEED CHANGE, L	NORMALIZED SPEED CHANGE DIVIDED BY ENERGY, L'	PREDICTED SPEED CHANGE, ft/s
1	52.8	57.5	18.5	16.1	.005	-.715	.911	.4613	.6084	17.6
			22.8	24.2				.4626	.6101	26.4
6	154.1	48.4	13.5	14.7	.000	-.430	.797	.3980	.5721	17.1
			21.6	24.1				.3981	.5722	28.1
7	182.0	47.9	17.9	20.4	.003	-.505	.656	.3905	.5641	24.1
			30.2	28.9				.3904	.5641	34.2
8	51.0	38.9	22.9	19.3	.043	-.705	.553	.4359	.6987	18.4
			16.2	18.4				.4371	.7009	17.5
9	75.3	40.0	31.9	32.0	.245	-.914	.714	.4306	.6810	31.3
			12.1	14.7				.4295	.6795	14.4
10	240.4	41.5	52.0	51.6	.258	-.914	.822	.4638	.7201	47.8
			19.1	25.2				.4636	.7196	23.3
11	6.3	92.0	35.8	36.6	.008	-.504	.049	.6499	.6776	36.0
			23.1	22.9				.6484	.6760	22.6
12	10.3	92.9	60.3	59.3	.112	-.499	-.009	.7315	.7589	52.1
			39.2	41.4				.7364	.7640	36.1
3	23.2	34.0	13.9	14.1	.221	-.489	-.069	.4535	.7778	12.1
			23.2	22.4				.4545	.7787	19.2
4	83.4	36.1	27.5	22.4	.071	-.489	-.008	.3946	.6567	22.7
			32.6	34.9				.3940	.6556	35.5
5	96.4	32.1	23.9	20.5	.075	-.475	-.034	.3520	.6214	22.0
			37.3	37.3				.3523	.6220	40.0

Table 4 Percentage Energy Losses

For 30 MPH (48 KPH) Collisions Reported by Grime & Jones (6)

Collision Geometry	Vehicle Types Veh 1 / Veh 2	Percentage Energy Loss
90°	Plymouth/Plymouth	32
Front to	Standard/Standard*	29
(Front) Side	Mini/Standard*	30
90°	Plymouth/Plymouth	35
Front to	Standard/Standard*	35
(Center) Side	Mini/Standard*	33
90°	Plymough/Plymouth	23
Front to	Standard/Standard*	23
(Rear) Side	Mini/Standard*	23

*Individual Vehicle Mfg. not identified

Table 5, Effect of Changing Angle Γ

Collision Number	Γ Deg	SSQ	ΔT %	|ΔV| ft/s	Coefficients e	e_m	μ
3	-10	23.0	34.2	14.3 22.6	.221	-.489	-.069
	0	23.2	34.0	14.1 22.4	.227	-.486	-.242
4	-10	83.4	36.1	22.4 34.9	.071	-.489	-.008
	-20	83.2	36.2	23.0 37.8	.046	-.492	+.164
5	-10	96.4	32.1	20.5 37.3	.075	-.475	-.034
	-20	96.8	32.1	20.8 37.8	.068	-.485	+.138

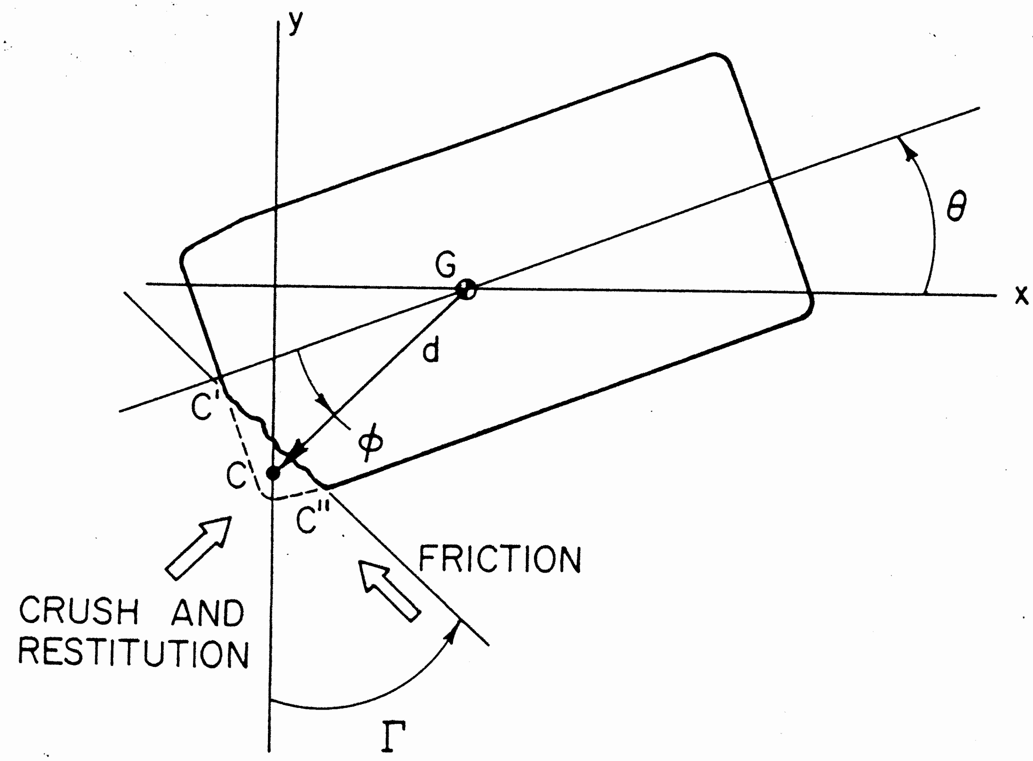

Fig. 1. Vehicle Coordinates and Configuration During Collision

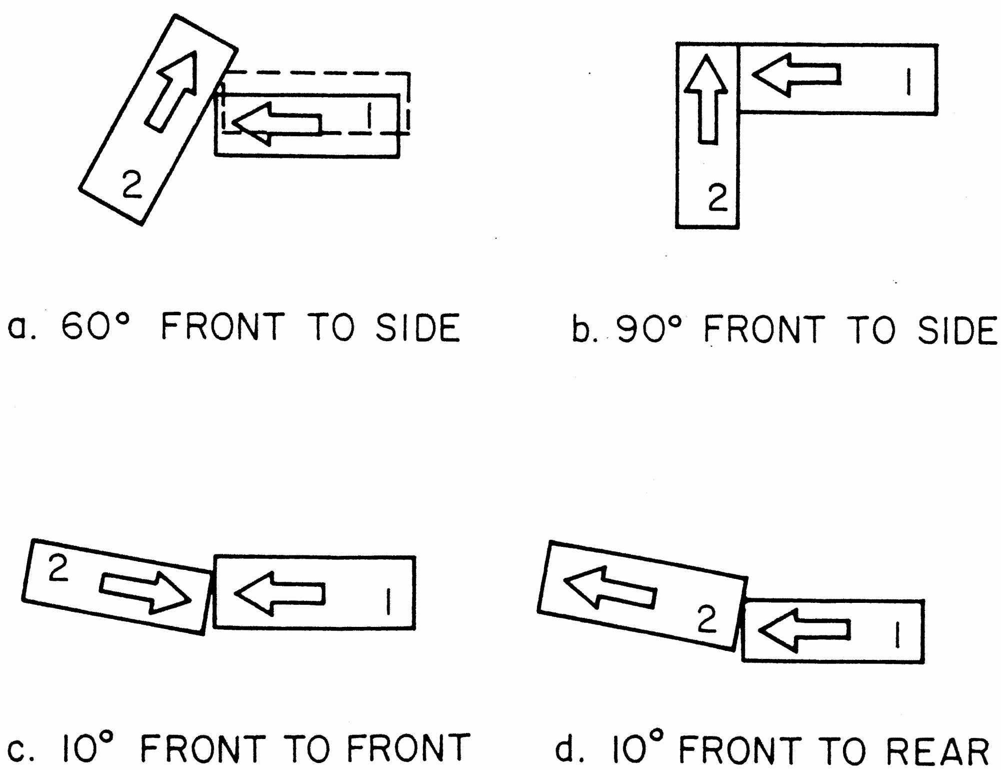

Fig. 2. RICSAC Collision Catagories

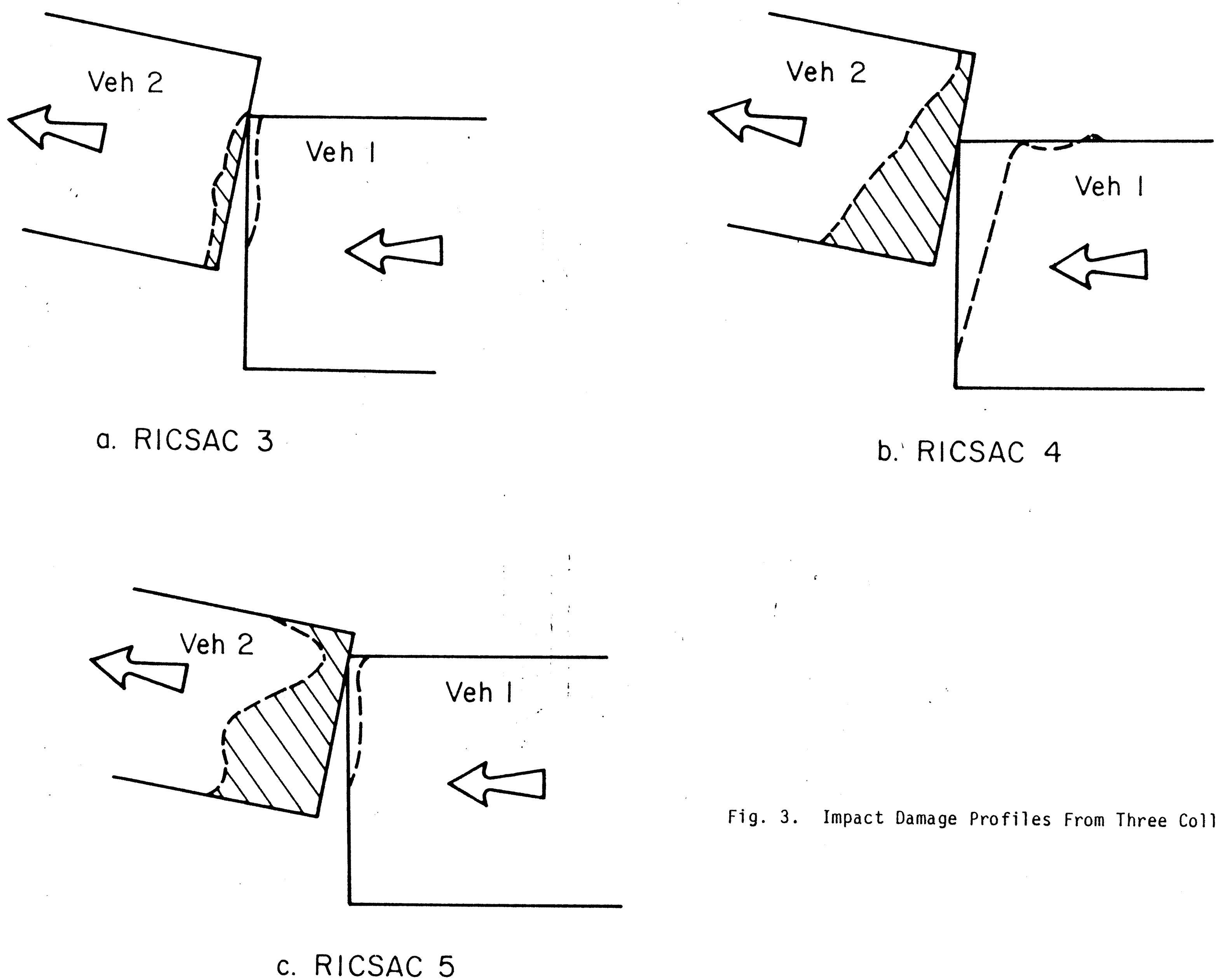

Fig. 3. Impact Damage Profiles From Three Collisions