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A Reevaluation of the Reference Set of Full Scale Crash Tests

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ABSTRACT

Research performed in the 1970's revealed significant limitations in the available documentation of vehicle crush information and trajectory spinout information. As a result a series of full-scale crash tests were performed which became known as the Research Input for Computer Simulation of Automobile Collisions (RICSAC) crash tests.

Previous research using the RICSAC test results, particularly in relation to the validation of accident reconstruction computer programs, has varied widely in acceptance, interpretation and presentation of the RICSAC test results.

This paper presents a detailed review and decipherment in useable form of the original 12 crash tests that were performed within the RICSAC program. A new method of analyzing accelerometer data from arbitrary sensor positions, on the basis of discrete measures of the vehicle responses rather than complete time-histories, is defined. A discussion of previous research which included reference to the RICSAC test results as a measure of the validity of reconstruction computer programs is included.

INTRODUCTION

Research performed in the 1970's to “locate, review, decipher and place in useable form available experimental data on the structural crush properties of automobiles, and on the spinout trajectories produced by measured collision conditions” [**1**][1] revealed significant limitations in the available documentation of vehicle crush information and trajectory spinout information. As a result, an initial test matrix of 12 full-scale crash tests was performed in 1978 which became known as the Research Input for Computer Simulation of Automobile Collisions (RICSAC) crash tests [**2**].

For each of the RICSAC tests, a minimum of 13 accelerometers were mounted on-board each vehicle to record acceleration components at six to seven stations. At three locations triaxial (XYZ) packages were installed ("hard mounted") to provide coverage between the front and rear of the vehicle. The front steer angles were measured on each vehicle by a linear stroke potentiometer attached to the vehicle steering linkage. The time history of the change in vehicle yaw, pitch and roll angles and yaw rate were recorded by two-degree-of-freedom, free gyroscopes and a rate gyro.

For vehicle trajectory measurement, high-speed motion picture cameras were located overhead with supporting cameras at eye level height. Also, vehicle trajectory marker systems were designed and fabricated by Calspan to spray high pressure colored water trails (using very small amounts of liquid to avoid any effects of the water on the roadway coefficient) from several locations on each of the vehicles.

Plots of the full-scale test acceleration time-histories were generated by a computer program which also integrated the acceleration time histories (using a combination of Simpson's and Newton's 3/8 methods) in order to obtain velocity time history along each of the vehicle's three axes. For most of the reported results, the ΔV values reported for the vehicle CG were based on data collected by a Firewall mounted triaxial (XYZ) accelerometer.

The time of approximate separation reported in [**3**] was based on observation of the time histories of the acceleration. The time of separation was defined as "the point at which both of the involved vehicles' accelerations reapproached 0 g's". The authors of [**3**] noted that "the separation point was not always obvious in collisions in which the two vehicles spun out together".

The components of the vehicle's change in velocity (ΔV) were computed in [**3**] "by subtracting the initial velocity at impact from the velocity at the time of separation" . The procedure was done for the X and Y velocity components separately.

The authors of [**3**] acknowledged that the "value for the separation velocity was contaminated by the effects of rotation of the vehicles between impact and separation". The problem was attributed to the post-processing integration software used for the tests which was primarily set up to integrate acceleration data for frontal collisions with barriers and therefore did not account for the rotation of the vehicle (the data reduction software assumed a constant direction

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[1] numbers in brackets [] indicate references at end of paper

cosine matrix). Errors which may occur in data collected from an accelerometer not at the center of gravity include the effects of rotation which are dependent on the magnitude of the offset of the accelerometer from the CG and the magnitudes of the vehicle's angular velocity and acceleration.

Table 1 contains best estimates of the actual accelerometer locations for the 12 RICSAC tests based on values reported by Jones [**3**]. Some of the locations have been corrected on the basis of a detailed review of the RICSAC test reports [**2**].

Table 2 contains a list of factors as reported in [**3**] which influenced the magnitude of effects of rotation on the RICSAC accelerometer data. Note that any differences in the accelerometer locations as listed in Tables 1 and 2 are due to the refinement in **Table 1** of some ambiguous dimensions reported in [2] and/or [3].

Table 1 **Firewall and Rear Deck Accelerometer Locations for RICSAC Tests (Note:Test 4(S&N 6), Veh 2 Front Deck)**

RICSAC	S&N	Accelerometer Locations							
		Vehicle No. 1				Vehicle No. 2			
[2,3]	[4]	Firewall		Rear Deck		Firewall		Rear Deck	
Test No.	Test No.	x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	x (in)	y (in)
1	1	6.9	-9	-88	0	13.5	-7	-73.5	5
2	2	8.5	-9	-86.6	0	14.6	-7	-72.5	5
3	5	15.7	0	-81.3	0	5.2	-7	-62.8	4
4	6	15.9	0	-81.1	0	3.2	-7	33.7	18
5	7	15.6	0	-81.4	0	13.1	4	-40	5
6	3	11.5	-9	-83.5	0	29	-7	-58	5
7	4	11.5	-9	-83.5	0	28.3	-7	-58.7	5
8	10	11.5	-9	-92.5	0	11.5	-10	-79.5	5
9	11	10.2	-9	-50.2	0	14.1	-7	-59.7	0
10	12	9.4	-9	-69.6	0	14.9	-7	-83.1	0
11	8	15.5	11.5	-44.4	0	14.4	1.5	-63.6	0
12	9	13.4	11.5	-48	0	15.6	1.5	-62.4	0

Table 2 **From Jones [3] Table 1-3 "Factors Influencing Magnitude of Effects of Rotation" on Accelerometer data. (Note: Contact Duration from Table 1-1 of [3])**

RICSAC [2,3] Test No.	S&N [4] Test No.	Veh No.	Heading angle Change (deg)	Angular Velocity Max (deg/sec)	Angular Velocity @Separation (deg/sec)	Distance cg to Firewall Accelerometer r_x (in)	Distance cg to Firewall Accelerometer r_y (in)	Contact Duration* (sec)
1	1	1	15	120	90	6.8	-8.9	0.225
		2	0	0	0	13.4	-6.2	
2	2	1	18	150	150	8.4	-9.6	0.225
		2	-9	-120	90	15.2	-5.5	
3	5	1	1	20	15	15.7	-0.1	0.2
		2	0	0	0	5.9	-6.8	
4	6	1	lost data	45	37	15.7	-0.1	0.275
		2	lost data	30	30	4.2	-6.2	
5	7	1	5	20	12	-15.8	-0.4	0.25
		2	lost scale factor	90	70	10.6	4.0	
6	3	1	5	45	30	6.5	-8.8	0.2
		2	20	210	180	30.4	-4.4	
7	4	1	12	65	30	6.5	-9.2	0.2
		2	22	210	192	29.8	-4.6	
8	10	1	15	135	114	11.4	-9.0	0.2
		2	0	18	18	11.2	-8.8	
9	11	1	27	210	180	10.6	-8.9	0.2
		2	-10	-45	-45	14.5	-6.7	
10	12	1	55	300	300	9.4	-8.5	0.2
		2	-12	-90	-72	14.9	-5.9	
11	8	1	-5	-45	-30	19.3	12.2	0.225
		2	0	0	0	14.4	2.8	
12	9	1	-10	-90	-90	12.4	12.1	0.225
		2	-2	-60	-60	15.6	1.9	

BACKGROUND

In 1980, Smith and Noga [**4**] created a summary of data associated with 16 full-scale crash tests (three more tests were performed as a part of RICSAC and reported in [**5**] and the other was from [**6**]). The authors "attempted to achieve corrections to acceleration and velocity data by approximating vehicle rotational velocity and rotation of the reference frame from it's orientation at impact, by making reference to multiple accelerometer outputs at different locations on the vehicles and by analysis of high speed photography." They also included an adjustment procedure for the ΔV's to insure that the momentum changes associated with the collision partners were equal and opposite (including consideration of tire forces). The adjustments were approximations to account for the effects of external tire-forces. They found that "cases number 10, 12 and 15 are believed to be in error" due to poor accelerometer data for one of the two involved vehicles. The determination of the separation velocity was not refined or presented.

In 1983, Brach [**7**] presented a table of refinements to the reported RICSAC separation velocities on the basis that: "Accelerometers used to record data on each vehicle 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." The report does not include the specific equations and the values for distances of the accelerometers from the CG and other variables used in the adjustment process (The values from Jones reported in **Table 2** were the values probably used).

In 1985, Wooley, as a part of an attack on the CRASH3 analytical procedures [**8**] and as part of a presentation and testing of the "IMPAC" computer program [**9**], included a review and analysis of the RICSAC test results as reported by Smith and Noga [**4**]. In addition to agreeing with Smith & Noga that there were problems with tests 10, 12 and 15, tests 4 and 6 were identified as having either "a typing error or reporting error." A "Data Integrity Ranking" was calculated for the tests based on Newton's 3rd Law for equal and opposite forces and the law of conservation of linear momentum. The tests utilized the post-impact velocities (the separation velocities) which were the values as reported by Jones [**3**]. The testing procedures of [**8**] and [**9**] cited many instances where the "Data Integrity Ranking" calculations revealed cases with erroneous momentum *gains* and/or instances where the forces acting on the collision partners where not equal and opposite.

Also included in the reported results of [**4**] was a "velocity change" angle. The "velocity change" angle was calculated by finding the angle with tangent of the Δv (Y component) velocity change divided by the Δu (X component) velocity change. In [**8**], the "velocity change" angle reported in [**4**] was referred to as the Principal Direction of Force (PDOF).

IN 1989, as a part of a presentation of a comparison of EDCRASH program results with the RICSAC test results Day [**10**] concludes that "No general observations could be made using the RICSAC data analyzing the accuracy of the {computed} ΔV by any program because of measurement errors in the RICSAC test data." The report also states that "Previous program evaluations which used the RICSAC data as a means of validation for ΔV should be viewed as suspect."

Also in 1989, Cheng and Guenther [**11**] discussed the localized variations in speed-change (ΔV) due to rotational effects as applied to the speed-change experienced by the vehicle occupants. The paper included a discussion of the general differences in measurements produced by the various accelerometer locations in the RICSAC tests.

IN 1990, Day [**12**] as a part of a presentation of a comparison of the EDSMAC program results with the RICSAC test results included a Table of ΔV results for RICSAC which were obtained from [**1-3**] and "from personal correspondence from Dr. Russell A. Smith." . Some of the reported values are different from Smith and Noga [**4**] and may reflect refinements by Smith and Noga reported in [**13**]. The report conclusions include the observation: "The measured ΔVs were not of acceptable accuracy for use in a validation study because the motion transducers were placed at the vehicle's firewall, rather than the CG. This problem might be improved or eliminated by re-analyzing the original data with software which included a transformation matrix."

In 1996, as part of a validation effort of the PC-CRASH computer program, Cliff [**14**] used the RICSAC test results for the post-impact separation speeds as reported by Brach [**7**] for comparison "validation" purposes. They noted that "there appeared to be some error in a few of the reported post-impact speeds in [the Brach] paper when compared to the reported pre-impact speeds and vehicle weights."

Also in 1996, Bundorf [**15**] presented techniques for analysis of the CG ΔV from accelerometer data at locations other than the CG. He observed that "the potential for error is always present if yaw velocity is high and accelerometers are distant from the center of gravity." As an example, he presented a detailed analysis of RICSAC Test no. 9 (S&N Case 11).

RESEARCH APPROACH

The RICSAC tests [**1-3**] contain the most comprehensive collection of full-scale test results available to date. The test reports include objective information on the impact speeds, vehicle weights, dimensions, weight distributions, spinout trajectory and positions of rest. Some interpretation of the reported results is required, for example, to obtain speed-change (ΔV) and separation velocities from the accelerometer data. Also, some evaluations are required for the approximate extent of wheel drag and steer angles. The primary purpose of the research associated with this paper has been to develop and apply techniques for interpretation of the crash phase of RICSAC and other full-scale tests. Of particular interest are the correct values for the impact speed-changes and separation velocities effective at the centers of gravity, which can be used as an obstacle course to evaluate and/or "validate" accident reconstruction techniques.

During full-scale testing, a hard-mounted accelerometer at the CG will record the correct acceleration *including* the effects of rotation. The time integral of the accelerometer data for the X and Y directions will produce the correct vehicle-fixed X and Y components of speed-changes. However, in the RICSAC tests and in many other full-scale tests, the ΔV calculations are complicated by accelerometer data for locations other than the vehicle center of gravity. The first task of interpretation was to develop generalized analytical techniques to transform the speed-change information from arbitrary accelerometer locations to the center of gravity. A secondary task was to use the calculated CG speed-change information to calculate the vehicle separation velocities. To correctly use the CG speed-change information to calculate the separation velocities, provisions must be included for the changes in the vehicle orientation.

The technique used by Jones [**3**] for calculation of the separation speeds for the RICSAC tests is in error, primarily due to the direct subtraction of the speed-change determined by integration of accelerometer data from the initial impact speed. The u and v speed-changes computed by integration of the accelerometer X and Y data cannot be directly subtracted from the initial vehicle velocities except for the case where no rotation occurs. A secondary source of error in the calculation of separation velocities reported in [**3**] is the assumption that the acceleration and velocity data from the firewall location are equivalent to those at the vehicle center of gravity.

CG-TRANSFORM

To provide a simple approximation of the RICSAC ΔV and separation velocities at the vehicle centers of gravity, an analytical procedure was developed for transformation of accelerometer data from accelerometers not located at the vehicle center of gravity on the basis of discrete measures of the responses rather than complete time-histories.

Bundorf [**15**] presented a procedure for determination of the speed-change (ΔV) at the vehicle center of gravity (CG) using accelerometer time histories from accelerometers not located at the vehicle CG combined with rate gyro data. The technique requires either the availability of the FM data recorder tapes or a manual digitization of the accelerometer and yaw velocity traces to determine the integral of yaw velocity squared and, thereby, the speed-change (ΔV). A drawback of the procedure is that it can be time consuming for the case where there are not FM data tapes and/or processing software available. Also, possible sources of errors can occur from integrating and synchronizing randomly sampled data (the accelerations were recorded with triaxial accelerometers, the angles and yaw rates were recorded with a pair of two-degree-of-freedom, free gyroscopes and a rate gyro).

The ***CG-Transform*** analytical procedure has input requirements listed in Table 3 (for a detailed definition of ***CG-Transform*** please see **Appendix 1**).

Table 3 Information required for *CG-Transform* analytical procedure

1. Accelerometer Location on vehicle, X, Y.
2. Impact speed and heading angle.
3. Integrated speed-change from accelerometer data.
4. Duration of crash pulse.
5. Separation angular (yaw) velocity and angle.

To permit initial testing and refinement of the ***CG-Transform***, the SMAC computer program was utilized to create a set of mathematically correct "test case" reconstructions. Extensions to the SMAC program developed for the present research include a provision to monitor the acceleration for any arbitrary position on the vehicle (e.g., **Figure 1**, **Figure 2**). ***CG-Transform*** was then used to transform the data from an arbitrary accelerometer location back to the CG. Since the CG data is a direct output of the SMAC program the procedure provided a detailed check of ***CG-Transform.***

The SMAC reconstructions used for this purpose were generalized reconstructions of the RICSAC test runs. The SMAC runs were based on preliminary refinements of the original RICSAC SMAC reconstructions presented by Jones [**3**] and more recently Day [**16**] in validation studies of the SMAC and EDSMAC computer programs. The refinements of some of the inputs were required due to the questionable nature of some of the SMAC inputs used in the "validation" reconstructions (e.g., some torque and steer values were arbitrarily varied). A more detailed discussion of the rationale for the changes to the SMAC inputs and suggestions for refinement of the inputs are to be presented as part of a separate research project [**17**].

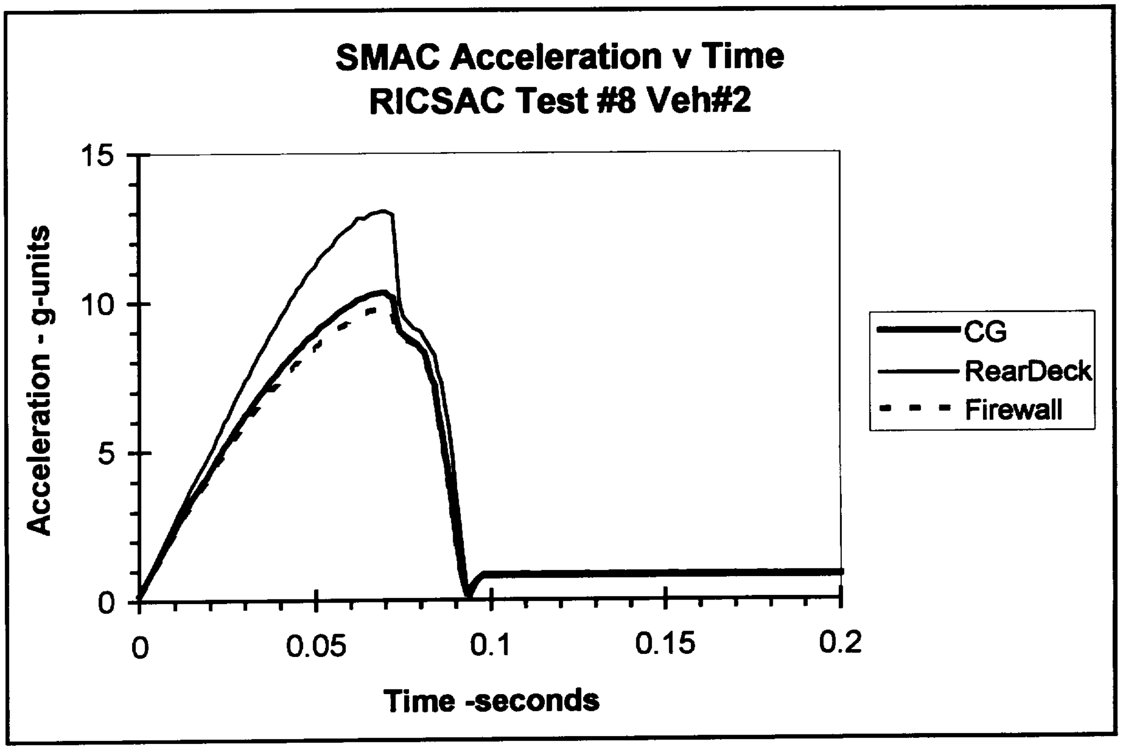

Figure 1 SMAC resultant acceleration time history at CG, Rear Deck and Firewall for RICSAC test No. 8, Vehicle No. 2

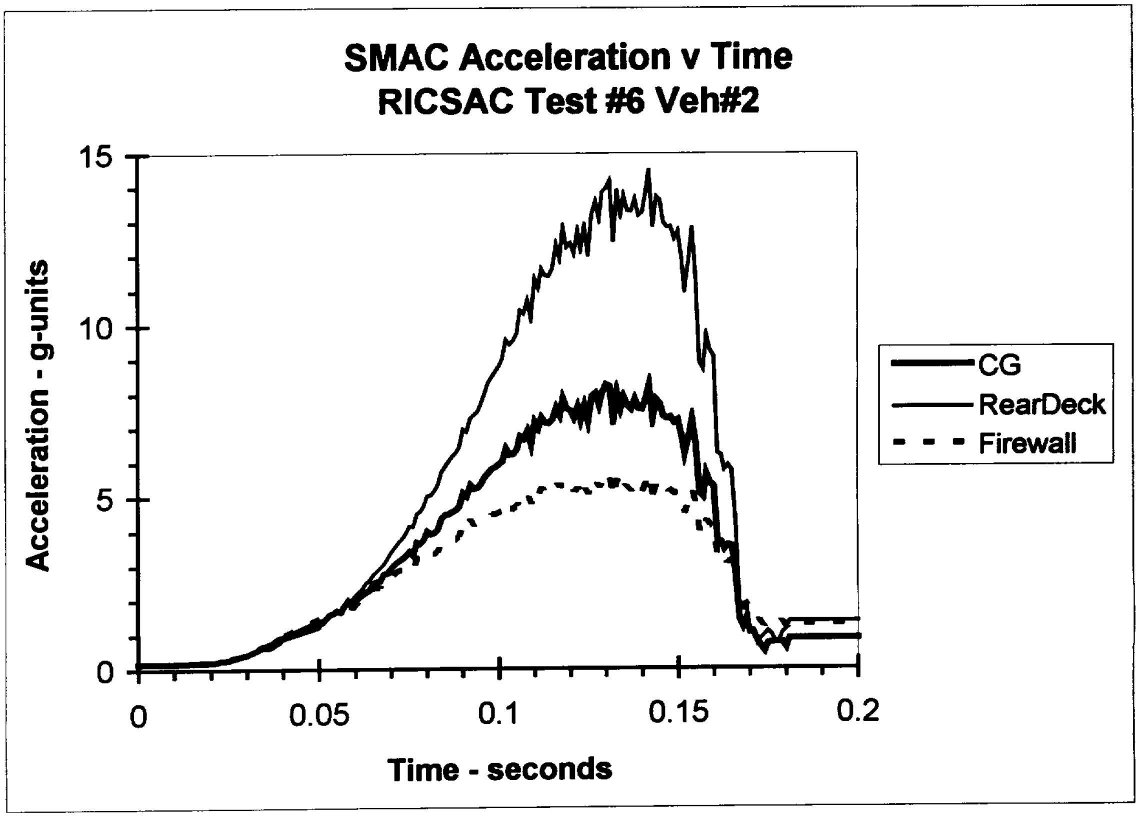

Figure 2 SMAC resultant acceleration time-history at CG, Firewall and RearDeck for RICSAC test No. 6, Vehicle No. 2

For each of the refined RICSAC SMAC runs, the acceleration was monitored for the Firewall (Cowl) and RearDeck locations as specified in the RICSAC reports. The installation locations for the Firewall and RearDeck accelerometers are included in **Table 1**. The acceleration at any given location, X_1,Y_1, can be expressed for a given time, t, as:

$$a_{xx} = \dot{u} - v * \dot{\psi} \tag{1}$$

$$a_{yy} = \dot{v} + u * \dot{\psi} \tag{2}$$

$$a_{xx1} = \dot{u} - v * \dot{\psi} - x_{a1} * \dot{\psi}^2 - y_{a1} * \ddot{\psi}^2 \tag{3}$$

$$a_{yy1} = \dot{v} + u * \dot{\psi} + x_{a1} * \ddot{\psi} - y_{a1} * \dot{\psi}^2 \tag{4}$$

$$u_{x1} = u - y_{a1} * \dot{\psi} \tag{5}$$

$$v_{x1} = v + x_{a1} * \dot{\psi} \tag{6}$$

Where, for a given time interval dt:

u, v = forward and lateral velocity componenets at cg
$\dot{u}, \dot{v}$ = change in forward and lateral velocity components at cg
a_{xx}, a_{yy} = acceleration components at cg
ψ = vehicle heading angle
$\dot{\psi}$ = yaw velocity
$\ddot{\psi}$ = yaw acceleration
x_{a1}, y_{a1} = location of accelerometer relative to cg
u_{x1}, v_{x1} = forward and lateral velocity components at x_{a1}, y_{a1}
a_{xx1}, a_{yy1} = x, y accelerations at location x_{a1}, y_{a1}

The SMAC generated acceleration time histories at the CG, Firewall and RearDeck were then integrated to determine the instantaneous velocities and resulting speed-changes. Two techniques were used to determine the impact speed-changes of the individual tests: ***Test Equivalent*** and ***SMAC Equivalent***.

TEST EQUIVALENT: For the reported RICSAC full-scale tests [**1**-**3**] the analysis of the accelerometer data to determine the vehicle speed-change consisted primarily of the integration of the vehicle a_x & a_y accelerometer traces to determine the time histories of velocities. The velocity time-history plots were then analyzed to determine the magnitude of the changes in the individual velocity components, ΔV_x and ΔV_y . The resultant speed-change and speed-change angle were determined by the following:

$$\Delta v_r = \sqrt{\Delta v_x^{\,2} + \Delta v_y^{\,2}} \tag{7}$$

Where:

Δv_r = resultant speed change
Δv_x = speed change in the vehicle x direction
Δv_y = speed change in the vehicle y direction

$$\Delta V_{angle} = \text{atan2}^{-1}\left[\frac{\Delta v_y}{\Delta v_x}\right] \tag{8}$$

Where:

ΔV_{angle} = speed change angle
Δv_x = speed change in the vehicle x direction
Δv_y = speed change in the vehicle y direction

SMAC EQUIVALENT:In the original form of the SMAC computer program, the speed-change for a given acceleration exposure was determined by the integration of the *resultant* acceleration. For each time increment, a resultant acceleration was determined by the vector sum of the x and y components of the vehicle accelerations:

$$a_c = \sqrt{a_x^{\,2} + a_y^{\,2}} \tag{9}$$

Where:

a_c = resultant acceleration, g-units

a_x = acceleration in the vehicle x direction, g-units

a_y = acceleration in the vehicle y direction, g-units

The resultant speed-change was determined by integration of the *resultant* acceleration from initial contact to separation. The initial contact is defined as the first instance where the resultant acceleration goes above 1 g-unit. The point of separation is defined as the first time that the acceleration again drops back below 1 g-unit. It was assumed that in general handling maneuvers and vehicle spinouts that the resultant acceleration would normally be below 1 g-unit (given that the nominal friction coefficient of roadways is normally less than 1 g-unit).

The Direction of Principle Force (DOPF) was determined for a given acceleration exposure in the SMAC program as the direction of the acceleration at the instance of peak *resultant* acceleration by:

$$DOPF = \text{atan2}^{-1}\left[\frac{a_y}{a_x}\right] \tag{10}$$

Where:

DOPF = direction of principal force
a_x = acceleration in the vehicle x direction
a_y = acceleration in the vehicle y direction

A summary of the steps required to create SMAC "full-scale test results" to be used for testing purposes of the ***CG-Transform*** analytical procedure was as follows:

1. A SMAC simulation was performed for each RICSAC test
2. Acceleration time histories were created for the CG and the reported Firewall and Rear Deck accelerometer locations for each vehicle of each test. **Table 1** is a list of the reported Firewall and Rear Deck accelerometer locations used in the SMAC tests.
3. The SMAC vehicle fixed X & Y acceleration time-histories were integrated for the CG, the firewall and the Rear Deck as follows:
    - 3.1. The individual speed-changes in the vehicle X and Y directions were determined by integration of the X and Y acceleration time-histories.
    - 3.2. A ***Test equivalent*** resultant speed-change was calculated.
    - 3.3. The ***SMAC equivalent*** resultant speed-change was also calculated by integration of the time-history of the resultant acceleration.

For some of the RICSAC tests the values for the ***Test equivalent*** speed-change was found to be less than the ***SMAC equivalent*** speed-change (ΔV) by as much as 10%-15%. The difference is due to the following:

When we use integration to find the velocity change produced by an acceleration curve, we are finding the equivalent velocity that is produced by the variation of the acceleration over a fixed interval of time. In full scale tests, the accelerometers measure the acceleration for the X and Y directions separately. Therefore, the integration of these acceleration time-histories produce separate velocities (areas) for the X and Y directions. The *resultant* speed-change velocity from full-scale tests is determined by finding the square root of the sum of the squares for the X and Y velocities. In the SMAC program, in addition to the separate X and Y acceleration time-histories, we also have available the resultant acceleration. Therefore, to determine the *resultant* speed-change we can integrate directly the resultant acceleration vs. time curve. In a motor vehicle full-scale test, the vehicle and occupants experience the resultant acceleration, not individually the X and Y components. The possibility of differences in the resultant speed-change by these two methods reveals a need for accident reconstruction simulation programs to individually calculate the speed-changes in the X and Y directions for comparisons with full-scale tests, while also calculating and reporting the resultant speed-change determined by integration of the resultant acceleration over time.

For testing and comparison purposes of the ***CG-Transform*** analytical technique, reconstructions were performed of the collision phase of the 12 RICSAC tests with the SMAC computer program. **Table 4** contains a summary of the RICSAC SMAC impact speed-change (ΔV) for the CG, Firewall and Rear Deck, **Table 5** contains the impact conditions, and **Table 6** contains the separation conditions.

The results of the SMAC reconstructions of the RICSAC tests were used in an evaluation of the ***CG-Transform*** analytical technique. The integrated speed-change for the Firewall and Rear Deck accelerometer locations were used with the other items per **Table 3** in an application of the ***CG-Transform*** analytical procedure to determine the speed-change at the center of gravity and the separation velocity. The results for the speed-change (ΔV) and separation velocity for each of the 12 RICSAC tests were calculated. For all cases the speed-change and separation velocity calculated for the CG based on the Firewall and Rear Deck accelerometer data was less then 1 mph maximum error, with an average error of ±0.1 MPH and a standard deviation of 0.30 MPH. The comparison gave a good indication that the ***CG-Transform*** analytical procedure properly approximates the CG speed-change and separation speed from speed-change data at arbitrary accelerometer locations combined with discrete measures of the yaw responses.

A dramatic demonstration of the positional differences in accelerations and therefore the corresponding differences in the integrated speed-change calculations is illustrated in **Figure 3** and **Table 7**. **Figure 3** is the resultant acceleration time-history for the CG, Firewall and RearDeck for the SMAC reconstruction for vehicle number 1 of RICSAC Test No. 10. The full scale test and the SMAC simulation of RICSAC 10 each contained a “sideslap” impact of the vehicles subsequent to the primary impact. In **Figure 3** there are two peaks in the acceleration time histories, particularly at the RearDeck location. **Table 7** contains the integrated speed-changes calculated for the primary impact, the side-slap and for the total duration. The speed-change calculated by components (***Test equivalent***) and based on the resultant acceleration (***SMAC equivalent***) for vehicle No. 1 illustrates a problem which can occur when integrating individual acceleration components. **Figure 4** is the X-Y acceleration components for vehicle number 1 of RICSAC Test No. 10. The X-acceleration for the RearDeck location in **Figure 4** reverses sign after the primary impact which acts to reduce and *reverse* the calculated X component of speed-change for the ***Test equivalent*** integration technique (The reported time-histories of the velocity components produced by integration of the RICSAC accelerations contain this anomaly, e.g., p 16-41,[**2**]). Determining the speed-change based on the resultant acceleration per the ***SMAC equivalent*** technique eliminates the directional sensitivity.

The side-slap acceleration of RICSAC Test 10 also reveals a problem of determining which speed-change and/or separation velocity should be reported when a sideslap occurs. Note that the ***SMAC Equivalent*** resultant speed-change for the Rear Deck calculated from the initial impact through the end of the sideslap (from 0.50 to 0.862 sec.) is dramatically higher (63 mph) than the sum of the individual speed-changes for the primary impact (25.5 mph) and sideslap impact (17.5 mph). The difference is due to the integration of the acceleration (> 5 g's) which occurs at the RearDeck (due to it's offset from the center of gravity) during the rapid rotation of the vehicle between the primary and sideslap impact (approximately 0.20 seconds).

It is herein proposed that all test reports include provisions to indicate a "side-slap" impact. The post-processing analysis of the acceleration data should also integrate and report the speed-change for the primary and secondary impacts separately.

Large accelerations that can occur at locations other than the center of gravity, as demonstrated at the RearDeck for RICSAC Test 10 vehicle 1, should not be included in the speed-change calculations for the individual vehicles since the vehicles are not in contact during this time period. However, the additional accelerations due to offset from the center of gravity and rotational velocity may have dramatic effects on the magnitude of occupant exposure and consideration should be given to localized ΔV calculations as suggested in [**11**].

Table 4 SMAC RICSAC reconstructions predicted ΔV's for CG, Firewall and Rear Deck accelerometer locations

SMAC RICSAC Reconstruction Results for Speed-change at CG, Firewall and Rear Deck

RICSAC Test No.	S&N Test No.	Location	Vehicle1 Delta-V				Vehicle2 Delta-V			
			Components		*Test Equiv*	*SMAC Equiv*	Components		*Test Equiv*	*SMAC Equiv*
			X (mph)	Y (mph)	Resultant (mph)	Resultant (mph)	X (mph)	Y (mph)	Resultant (mph)	Resultant (mph)
1	1	*cg*	-13.2	3	13.5	13.6	-12.7	-12.8	18.1	18.2
		firewall	-12.3	3.7	12.9	13	-12.5	-12.4	17.6	17.8
		reardeck	-12.5	-6	13.8	14.1	-12.9	-14.9	19.7	20.1
2	2	cg	-19.9	5	20.5	21.3	-20.7	-20.8	29.4	30.9
		firewall	-18.7	6.7	19.8	21	-20.3	-19.8	28.4	29.9
		reardeck	-17.5	-8.8	19.6	21.2	-20.9	-25.7	33.1	34.6
3	5	cg	-9.7	-1.1	9.8	9.9	15.4	0.2	15.4	15.5
		firewall	-9.7	-1.2	9.8	9.9	15.5	0.3	15.5	15.6
		reardeck	-9.7	-1	9.8	10	15.4	-1.1	15.4	16.4
4	6	cg	-16.3	-2.3	16.5	16.7	24.7	0.3	24.7	25.4
		firewall	-16.3	-2.1	16.4	16.7	25	0.5	25	25.8
		reardeck	-16.3	-2.8	16.5	17	23.6	2	23.7	23.7
5	7	cg	-14.8	-2.2	15	15.2	26.6	-0.5	26.6	27.2
		firewall	-14.8	-2.1	15	15.3	26.3	0.4	26.3	26.5
		reardeck	-14.8	-2.8	15.1	15.4	26.5	-3.3	26.7	28.3
6	3	*cg*	-10	1.9	10.2	10.2	-11.8	-9.8	15.3	15.4
		firewall	-9.4	2.8	9.8	9.8	-11.1	-4.7	12	12.2
		reardeck	-9.6	-4.6	10.7	10.8	-11.7	-19.8	23	23.1
7	4	cg	-12.9	0.8	12.9	12.9	-12.2	-15.9	20.7	20.2
		firewall	-12.3	1.5	12.4	12.4	-11.5	-11.2	16	16.2
		reardeck	-12.7	-4.4	13.4	13.5	-12.3	-25.6	28.4	28.8
8	10	cg	-13.1	5.2	14.1	15	-5	-10.8	11.9	13
		firewall	-12.3	6.4	13.9	15.4	-4.5	-10.1	11.1	12
		reardeck	-12.1	-4	12.7	14.1	-5.1	-15.4	16.2	16.9
9	11	cg	-17.2	9.8	19.8	20.1	-4.5	-6.3	7.8	8.2
		firewall	-16	11.9	20	20.5	-4.9	-7	8.5	8.9
		reardeck	-15.3	0.8	15.3	16.2	-4.4	-3.5	5.6	5.9
10*	12	cg	-24.1	16.4	29.2	30.4	-7.3	-11.3	13.5	14.1
		firewall	-22.1	20.6	30.3	31.4	-8.1	-12.6	15	15.7
		reardeck	-16.4	-7.2	17.9	25.5	-6.3	-4	7.5	7.9
11	8	*cg*	-27.8	2.2	27.9	28.1	-16.9	3.4	17.3	17.4
		firewall	-27.4	1.6	27.4	27.4	-16.9	3.5	17.3	17.5
		reardeck	-27.7	3.8	27.9	28	-16.9	3	17.2	17.5
12	9	cg	-38.7	2.1	38.7	39.5	-26.4	5.5	27	27.4
		firewall	-38.6	1	38.6	39.7	-26.4	5.2	26.8	27.5
		reardeck	-38.4	6.2	38.9	39.2	-26.4	7	27.3	27.5

***Note: Reported test #10 results are for primary collision only. Please see discussion in text.**

Table 5 SMAC RICSAC reconstructions Impact Conditions

			SMAC Impact Conditions			
RICSAC Test No.	S&N Test No.	Veh No.	x (ft)	y (ft)	psi (deg)	u (mph)
1	1	1	-11	1.2	-30	19.8
		2	0	6.3	90	19.8
2	2	1	-11.1	7.8	-30	31.8
		2	0	-0.5	90	31.8
3	5	1	-0.1	0	0	21.2
		2	16.2	3.6	10	0
4	6	1	0.1	0	0	38.7
		2	16.4	3.5	10	0
5	7	1	-14.9	0	0	39.3
		2	0	3.1	10	0
6	3	1	4.5	0.6	0	21.5
		2	16.4	1.4	120	21.4
7	4	1	5.4	0	0	29.1
		2	17.5	0.4	120	29.1
8	10	1	-11.1	1.3	0	20.3
		2	0	1	90	20.5
9	11	1	0	0	0	21
		2	8.5	-5.4	90	21
10	12	1	0	0	0	33.3
		2	8.4	-6.7	90	33.3
11	8	1	15.7	-4.1	170	20.4
		2	0	0	0	20.4
12	9	1	15.6	-4.2	170	31.5
		2	0	0	0	31.5

Table 6 SMAC RICSAC reconstructions Separation Conditions

				SMAC Separation Conditions						
RICSAC Test No.	S&N Test No.	Veh No.	Contact Duration (sec)	x (ft)	y (ft)	psi (deg)	Psi (deg)	u (mph)	v (mph)	PsiD (deg/sec)
1	1	1	0.168	-7.6	-0.47	-23	-23.4	6.62	1.66	102
		2	0.168	1	-2.5	90	90.2	6.86	-12.8	30
2	2	1	0.135	-6.7	5.7	-19	-19	11.94	1.54	164
		2	0.135	1.3	4.1	92	92.5	10	-21.5	69
3	5	1	0.119	2.9	0	1	0.5	11.5	-1.3	-1
		2	0.119	17.3	3.7	12	12	15.4	-0.22	22
4	6	1	0.13	6	-0.2	1	1.2	22.3	-2.9	6.9
		2	0.13	18.6	3.8	14	14.4	24.8	-1	51
5	7	1	0.119	-9.2	-0.2	1	1	24.4	-2.8	5.5
		2	0.119	2	3.4	15	14.9	26.6	-1.8	64.5
6	3	1	0.126	8.6	0.7	5	4.7	11.3	0.7	79.5
		2	0.126	15.1	5.2	128	128	8.3	-11.7	176.5
7	4	1	0.125	9.8	0	3	3.4	16	-0.4	63.5
		2	0.125	16.3	4.8	126	125.9	15.1	-18.1	172
8	10	1	0.091	-9.1	1.8	7	6.5	7.6	3.8	102
		2	0.091	0.6	3.3	93	92.8	15.1	-11.6	58.1
9	11	1	0.118	2	0.9	14	14.4	5.1	7.9	191
		2	0.118	9	-2.2	88	88	16.6	-5.3	-42
10*	12	1	0.134	3.7	1.4	24	24	12.5	10.5	350
		2	0.134	9.7	-0.9	81	81.5	26.9	-7.2	-91.1
11	8	1	0.125	14.1	-4	166	166	-7.4	2	-45
		2	0.125	2.5	0.2	-0.5	-0.4	3.4	3.3	2.2
12	9	1	0.105	13.3	-3.9	165	165	-7.6	2.9	-77.2
		2	0.105	3.1	0.3	-1.4	-1.4	4.9	6.1	-20
10**	12	1	0.059	5.7	6.4	88	87.8	16.9	-1.2	88.5
		2	0.059	13.2	7.4	68	67.5	25.8	-1.9	20.1

Test#10: * Primary impact, ** Secondary impact

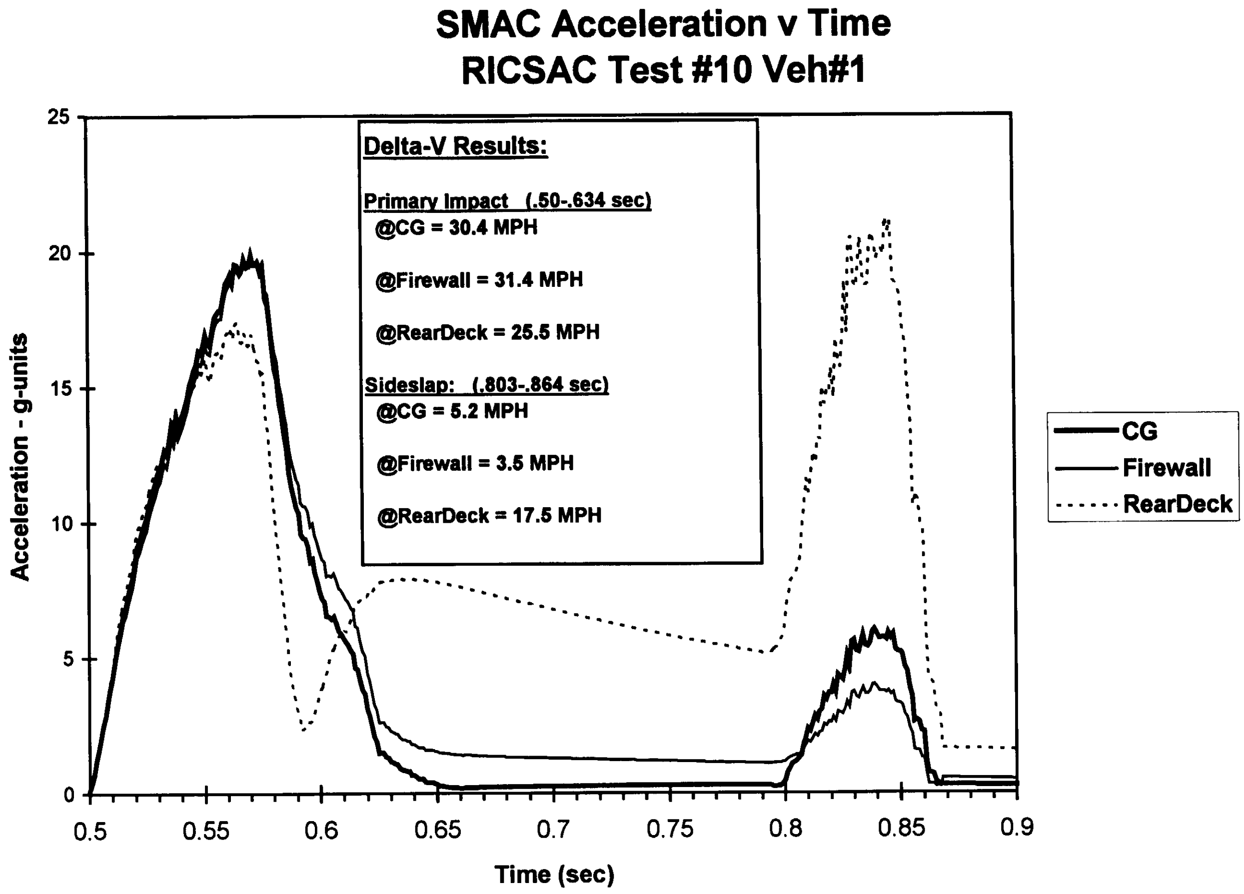

Figure 3 Resultant Acceleration time histories for RICSAC Test No. 10, Veh#1 for CG, Firewall and RearDeck

Table 7 Comparison of Calculated Speed-changes for RICSAC test No.10 for CG, Firewall and RearDeck.

Location	Vehicle1 Delta-V				Vehicle2 Delta-V			
	Components		*Test Equiv*	*SMAC Equiv*	Components		*Test Equiv*	*SMAC Equiv*
	X (mph)	Y (mph)	Resultant (mph)	Resultant (mph)	X (mph)	Y (mph)	Resultant (mph)	Resultant (mph)
	Delta-V's for primary event: (T=0.50 to 0.634):							
cg	-24.1	16.4	29.2	30.4	-7.3	-11.3	13.5	14.1
firewall	-22.1	20.6	30.3	31.4	-8.1	-12.6	15	15.7
reardeck	-16.4	-7.2	17.9	25.5	-6.3	-4	7.5	7.9
	Delta-V's for sideslap:(T=0.803-862 sec):							
cg	2.1	4.7	5.1	5.2	-0.8	-2.1	2.2	2.2
firewall	0.1	3.4	3.4	3.5	-0.3	-1	1	1.1
reardeck	4.7	16.8	17.4	17.5	-0.7	-8.1	8.1	8.1
	Delta-V's for total event:(T=0.50-862 sec):							
cg	-22.9	21.1	31.2	36.7	-9.2	-12.5	15.5	17.8
firewall	-26.2	26	36.9	39.7	-9.6	-12	15.4	18.7
reardeck	7.6	14.9	16.7	63.1	-6.7	-14.1	15.6	18.2

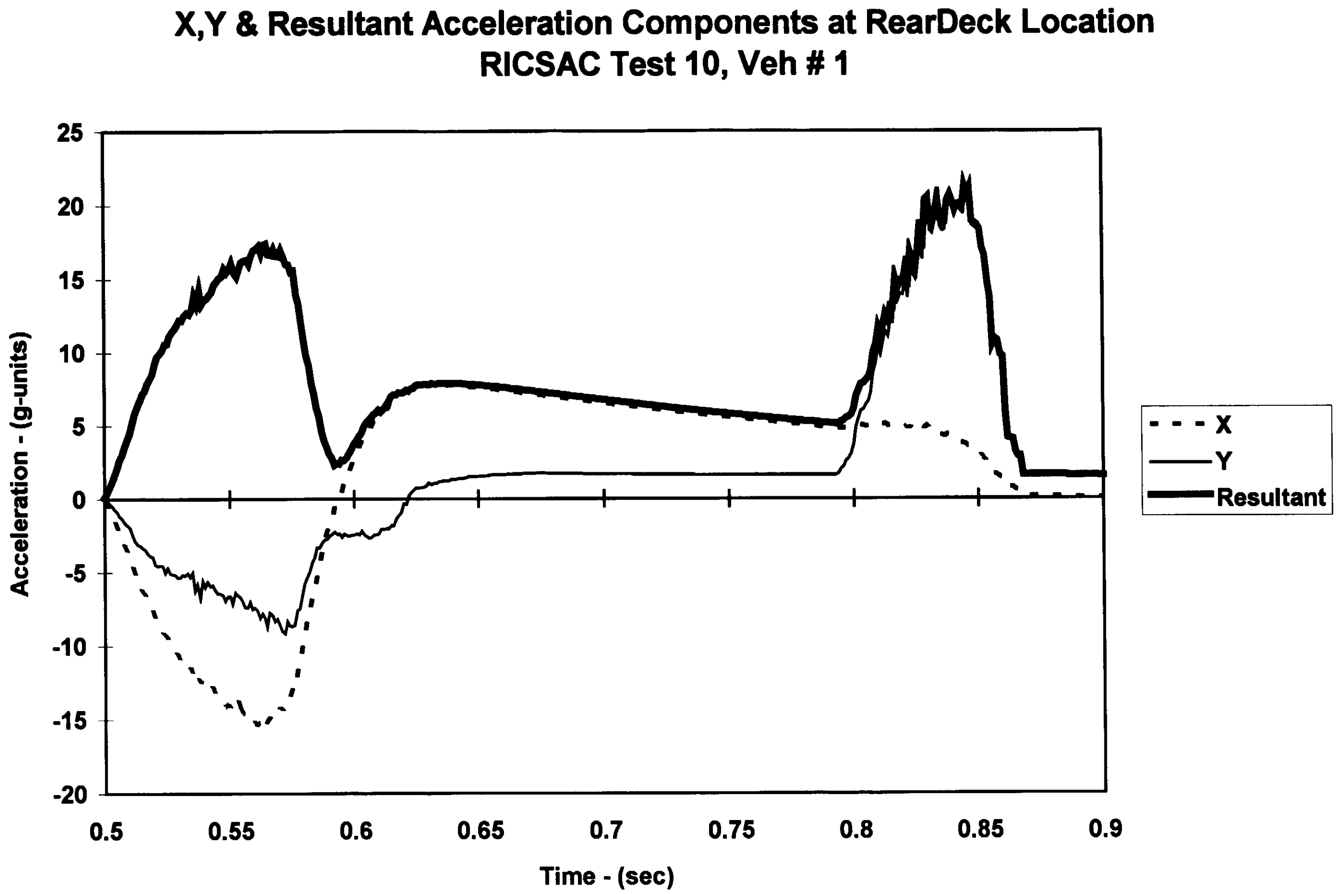

Figure 4 **Acceleration components at RearDeck Location for RICSAC Test 10, Vehicle No. 1**

Another check of the ***CG-Transform*** was to perform a comparison of the calculated results with results reported by Bundorf in [**15**]. Bundorf included a procedure for transformation of accelerometer information from locations other than the vehicle center of gravity to the CG. The procedure presented by Bundorf includes digitizing and analyzing the acceleration and angular velocity time-history data. The reported results by Bundorf were compared with results calculated with the ***CG-Transform*** procedure. The results of the comparison are contained in Table **8**. The results of the ***CG-Transform*** procedure correlate well with the results of the Bundorf analysis procedure. The average result and standard deviation are nearly identical. Some small differences did occur between the different accelerometer locations.

The results of application of ***CG-Transform*** analytical procedure to the various locations tested demonstrate the ability of the ***CG-Transform*** procedure to accurately calculate the speed-change at the center of gravity for any arbitrary accelerometer location.

Table 8 **Comparison of Bundorf [15] with *CG-Transform* results for RICSAC Test 9**

Delta-V (MPH) for RICSAC Test 9 (S&N 11), Vehicle 1

Description	Location		Measured @Location			Calculated for CG per Bundorf			Calculated for CG with CG-Transform		
	X (in)	Y (in)	X (mph)	Y (mph)	Res (mph)	X (mph)	Y (mph)	Res (mph)	X (mph)	Y (mph)	Res (mph)
LF	-3.3	-21	-9.8	11.0	14.7	-14.6	10.9	18.2	-14.6	10.9	18.3
RSide	-41.8	21	-17.8	0.4	17.8	-14.7	10.9	18.3	-14.7	10.8	18.3
Cowl	10.2	-9	-16.4	15.0	22.2	-17.8	11.3	21.1	-18.0	12.3	21.8
Rear Deck	-64.3	0	-12.2	-3.4	12.7	-15.2	11.4	19.0	-14.8	11.3	18.6
Average Result						**-15.6**	**11.1**	**19.2**	**-15.5**	**11.3**	**19.3**
Std Deviation						**1.5**	**0.3**	**1.3**	**1.7**	**0.7**	**1.7**

EVALUATION OF THE "RAW" RICSAC DATA

The task of evaluating and transforming the accelerometer data for the RICSAC full scale tests was undertaken to determine the CG speed-change and separation velocity for each test. A few possible problem areas which might affect the correlation are:

Source of Raw Data.

Acceleration Time-history Oscillations.

Excessive Collision Duration.

SOURCE OF RAW DATA: The raw ΔV values as reported in [**3**] were used for the comparison. A brief visual check of the time-history plots vs. the reported values was performed to check for any major differences. The reason the other reported refinements of the values could not be used was that the other reported values contained adjustments and corrections to transform the results from the Firewall accelerometer locations to the CG, the very task our ***CG-Transform*** is to perform.

ACCELERATION TIME-HISTORY OSCILLATIONS: Some of the acceleration time traces contained in the RICSAC reports [**2**] appear to have excessive oscillations (e.g., RICSAC Tests.Veh: 2.1,2.2,5.1,5.2,8.2,11) and some have resultant accelerations exceeding 40 g's (e.g., RICSAC Test.Veh: 10.1,12.1,7.2). These results may either reflect a possible problem with the accelerometers or with the choice in cutoff frequency filter. Sample oscillograph data from Mayor and Naab [**18**] contained in [**19**] illustrates the differences between unfiltered and filtered acceleration data for a 20 mph lateral impact. Peak accelerations vary from approximately 100 g's for unfiltered data to 40 g's for 50 Hz cutoff frequency to 28 g's for 25 Hz cutoff frequency. Also a dramatic reduction in the amount of oscillation occurs with increased filtering.

EXCESSIVE COLLISION DURATION: The collision contact duration reported by Jones (see **Table 2**) appears to be excessive. For example, Bundorf [**15**] determined the pulse duration for RICSAC Test 9 to be approximately 0.125 seconds whereas Jones reported the duration to be 0.200 seconds. Generally for car-to-car collisions, a normal range of pulse duration is 0.075 to 0.125. A review of the time-history accelerometer traces and the integrated velocity traces contained in the original RICSAC test reports also appears to indicate that the durations of the pulses reported by Jones are excessive. A comparison of the SMAC reconstruction pulse durations indicates that an average adjustment of the duration of approximately 0.090 seconds would be appropriate. For the purposes of this reported research, an approximate adjustment of 0.0825 was used (the average of .075 + .09).

RESULTS

The inputs for the reported raw RICSAC data [2, 3] which were used with the *CG-Transform* analytical technique are contained in ***Table 9***. A comparison of the *CG-Transform* calculated results with the speed-change at the CG as predicted by the SMAC program is contained in Table 10. A comparison of the *CG-Transform* calculated separation velocities with the separation velocities predicted by the SMAC program is contained in **Table 11**.

Given the possible variations and problems which can occur in full-scale test measurements the correlation of the ***CG-Transform*** calculated results and the SMAC results for most of the RICSAC tests appears very good. In all cases the cited correlation of ***CG-Transform*** with the mathematically correct SMAC results is within ±10% for ΔV and within ±13% for the separation velocity for at least one of the vehicles. This gives a good indication that properly interpreted results of all the tests are in complete agreement with Newton's Laws.

Some areas of difference can be explained as follows:

- For the ΔV values from the full-scale tests, differences in the individual components may be attributable to possible accelerometer calibration errors. Errors also can be caused by cross-coupling problems with gyros which can occur due to vehicle roll and pitch angles. Larger errors may be produced by problems with the individual accelerometers either in the crush zone or on components possibly affected by the impact configuration.
- For the separation velocity, differences in the individual components and resultant are produced by any of the following possibilities:
  - possible errors in determination of the time of separation in the full-scale tests
  - possible errors in the reported orientation of the vehicle at the time of separation
  - possible synchronization problems between the triaxle accelerometers and the gyros

Table 9 ***CG-Transform*** **inputs for the 12 RICSAC full-scale tests raw data**

RICSAC	S&N		Impact		Impact Speed Change			Reported	Adj	Sep	Sep	Sep
Test No.	Test No.	Veh No.	Speed (mph)	Heading Angle (deg)	u (mph)	v (mph)	Res (mph)	Pulse Width (sec)	Pulse Width (sec)	Angular Velocity (deg/sec)	Heading Change (deg)	Heading Angle (deg)
1	1	1	19.7	-30.0	-10.6	6.0	12.1	0.225	0.143	90	15	-15
		2	19.7	90.0	-12.1	-9.8	15.5	0.225	0.143	0	0	90
2	2	1	31.3	-30.0	-16.5	10.5	19.6	0.225	0.143	150	18	-12
		2	31.3	90.0	-20.1	-19.2	27.8	0.225	0.143	90	2.5	93
3	5	1	21.1	0.0	-9.5	-0.4	9.5	0.2	0.118	15	1	1
		2	0.0	10.0	15.8	-0.2	15.8	0.2	0.118	0	0	10
4	6	1	38.5	1.0	-18.7	0.4	18.7	0.275	0.193	37	0	1
		2	0.0	10.0	22.2	-2.8	22.4	0.275	0.193	30	0	10
5	7	1	39.5	0.0	-16.3	0.2	16.3	0.25	0.168	12	5	5
		2	0.0	10.0	25	-1.8	25.1	0.25	0.168	70	0	10
6	3	1	21.4	0.0	-8.5	3.0	9.0	0.2	0.118	30	5	5
		2	21.4	120.0	-11.5	-3.2	11.9	0.2	0.118	180	20	140
7	4	1	29.0	0.0	-11.5	3.5	12.0	0.2	0.118	30	12	12
		2	29.0	120.0	-14.1	-8.5	16.5	0.2	0.118	192	22	142
8	10	1	20.6	0.0	-12.7	8.6	15.3	0.2	0.118	114	15	15
		2	20.6	90.0	-7.2	-8.0	10.8	0.2	0.118	18	0	90
9	11	1	21.1	0.0	-17.7	12.0	21.4	0.2	0.118	180	27	27
		2	21.1	90.0	-5.0	-7.4	8.9	0.2	0.118	-45	-10	80
10	12	1	33.1	0.0	**-27.3**	**22.0**	35.1	0.2	0.118	300	25	**25**
		2	33.1	90.0	-8.8	-11.0	14.1	0.2	0.118	-72	-12	78
11	8	1	20.3	171.0	-24.0	0.8	24.0	0.225	0.143	-30	-5	166
		2	20.3	0.0	-15.6	2.0	15.7	0.225	0.143	0	0	0
12	9	1	31.3	171.0	-40.0	-2.2	40.1	0.225	0.143	-90	-10	161
		2	31.3	0.0	-26.0	4.8	26.4	0.225	0.143	-60	-2	-2

Table 10 **Comparison of ΔV at the CG based on *CG-Transform* calculated results and SMAC reconstructions for the 12 RICSAC full-scale tests**

			CG-Transform Results Delta-V at CG			Difference from SMAC Results				
						Components		Resultant		Direction
RICSAC Test No.	S&N Test No.	Veh No.	X (mph)	Y (mph)	Res (mph)	X (mph)	Y (mph)	(mph)	(%)	diff (deg)
1	1	1	-11.3	4.8	12.3	**1.9**	**1.8**	**-1.2**	**-9**	**-10**
		2	-12.6	-11.2	16.9	**0.1**	**1.6**	**-1.2**	**-7**	**-4**
2	2	1	-17.4	8.8	19.5	**2.5**	**3.8**	**-1.0**	**-5**	**-13**
		2	-18.8	-17.7	25.8	**1.9**	**3.1**	**-3.5**	**-12**	**-2**
3	5	1	-9.5	-0.7	9.5	**0.2**	**0.4**	**-0.2**	**-3**	**-2**
		2	15.8	-0.2	15.8	**0.4**	**-0.3**	**0.4**	**3**	**-1**
4	6	1	-18.7	-0.3	18.7	**-2.4**	**2.0**	**2.2**	**14**	**-7**
		2	22.0	-2.9	22.2	**-2.7**	**-3.1**	**-2.5**	**-10**	**-8**
5	7	1	-16.2	-0.1	16.2	**-1.4**	**2.1**	**1.3**	**9**	**-8**
		2	25.4	-3.0	25.6	**-1.2**	**-2.5**	**-1.0**	**-4**	**-6**
6	3	1	-8.8	2.4	9.2	**1.2**	**0.5**	**-1.0**	**-10**	**-5**
		2	-10.5	-9.8	14.4	**1.3**	**0.0**	**-1.0**	**-6**	**3**
7	4	1	-11.7	2.5	11.9	**1.2**	**1.7**	**-1.0**	**-8**	**-8**
		2	-12.8	-15.1	19.8	**-0.6**	**0.8**	**-0.3**	**-1**	**-3**
8	10	1	-13.4	6.6	14.9	**-0.3**	**1.4**	**0.8**	**6**	**-5**
		2	-7.4	-8.2	11.0	**-2.4**	**2.6**	**-0.9**	**-7**	**-17**
9	11	1	-18.0	8.5	20.0	**-0.8**	**-0.7**	**0.5**	**2**	**3**
		2	-4.4	-6.9	8.2	**-0.2**	**-0.6**	**0.6**	**8**	**1**
10	12	1	-28.8	18.1	34.0	**-4.7**	**1.7**	**4.9**	**17**	**2**
		2	-7.7	-9.9	12.5	**-0.4**	**1.4**	**-0.9**	**-7**	**-5**
11	8	1	-24.4	1.6	24.5	**3.4**	**-0.6**	**-3.4**	**-12**	**1**
		2	-15.6	2.0	15.7	**1.3**	**-1.4**	**-1.5**	**-9**	**4**
12	9	1	-40.8	-0.8	40.8	**-2.1**	**-2.9**	**2.1**	**5**	**4**
		2	-26.1	5.7	26.7	**0.3**	**0.2**	**-0.3**	**-1**	**-1**

Table 11 **Comparison of Separation velocities based on *CG-Transform* calculated results and SMAC reconstructions for the 12 RICSAC full-scale tests**

			***CG-Transform* RESULTS**			**Difference from SMAC Results**				
RICSAC	**S&N**		**Separation Velocity**			**Components**		**Resultant**		**Direction**
Test No.	**Test No.**	**Veh No.**	**X (mph)**	**Y (mph)**	**Res (mph)**	**X (mph)**	**Y (mph)**	**(mph)**	**(%)**	**diff (deg)**
1	1	1	8.5	1.6	8.6	**1.8**	**-0.1**	**1.7**	**25**	**-4**
		2	7.1	-10.5	12.7	**0.2**	**2.3**	**-1.9**	**-13**	**6**
2	2	1	14.2	2.2	14.4	**2.2**	**0.7**	**2.3**	**19**	**2**
		2	11.4	-20.6	23.5	**1.4**	**0.9**	**-0.2**	**-1**	**4**
3	5	1	11.6	-0.9	11.6	**0.1**	**0.4**	**0.0**	**0**	**2**
		2	15.8	-0.2	15.8	**0.4**	**0.0**	**0.4**	**3**	**0**
4	6	1	19.8	-0.2	19.8	**-2.5**	**2.7**	**-2.7**	**-12**	**7**
		2	21.9	-3.2	22.2	**-2.9**	**-2.2**	**-2.6**	**-11**	**-6**
5	7	1	23.2	-2.4	23.3	**-1.2**	**0.4**	**-1.3**	**-5**	**1**
		2	25.3	-3.8	25.5	**-1.3**	**-2.0**	**-1.1**	**-4**	**-5**
6	3	1	12.6	1.2	12.6	**1.3**	**0.5**	**1.3**	**12**	**2**
		2	9.1	-14.6	17.2	**0.8**	**-2.9**	**2.8**	**20**	**-3**
7	4	1	17.2	-1.5	17.3	**1.2**	**-1.1**	**1.3**	**8**	**-4**
		2	13.2	-22.4	26.0	**-1.8**	**-3.9**	**2.2**	**9**	**-8**
8	10	1	7.5	3.3	8.2	**-0.1**	**-0.5**	**-0.3**	**-3**	**-3**
		2	13.2	-8.2	15.6	**-1.9**	**3.5**	**-3.5**	**-19**	**6**
9	11	1	3.4	2.9	4.5	**-1.7**	**-5.0**	**-4.9**	**-52**	**-17**
		2	16.8	-4.1	17.3	**0.2**	**1.2**	**-0.1**	**0**	**4**
10	12	1	6.0	10.1	11.8	**-6.5**	**-0.5**	**-4.6**	**-28**	**19**
		2	25.7	-4.8	26.1	**-1.1**	**2.4**	**-1.6**	**-6**	**4**
11	8	1	-4.2	2.3	4.8	**3.2**	**0.3**	**-2.9**	**-37**	**-13**
		2	4.7	2.0	5.1	**1.3**	**-1.3**	**0.3**	**7**	**-21**
12	9	1	-9.6	1.2	9.6	**-2.0**	**-1.7**	**1.5**	**19**	**14**
		2	5.1	6.2	8.0	**0.2**	**0.1**	**0.2**	**2**	**-1**

CONCLUSIONS

1. The RICSAC data, when interpreted with the ***CG-Transform*** procedure, are reasonably accurate and are suitable for their intended purpose of testing the validity of reconstruction techniques.
2. Previously reported findings of gross errors and violations of Newton's laws in the reported RICSAC data are erroneous.
3. The SMAC program has been demonstrated to correlate well with properly analyzed full-scale test results

RECOMMENDATIONS

1. Future "validation" comparisons with the RICSAC full-scale tests should also give consideration to utilizing the mathematically correct SMAC results presented herein. Use of the SMAC program results for comparisons avoids the variability that normally occurs in full-scale tests. Without direct measures of the variability of experimental responses, by means of repeated runs of tests, the accuracy of analytical predictions cannot be properly evaluated.
2. Future full-scale tests should utilize a time-history simulation program like SMAC or a three-dimensional equivalent to permit a check of results and conversion procedures for data from accelerometers not located at the CG.
3. Any integration analysis of accelerometer data should include consideration for possible directional changes of individual components. This can be accomplished by direct analysis of the resultant acceleration to avoid the possibility of a reduction in the reported values for individual component velocities due to acceleration directional reversals.
4. Full-scale tests should include provisions for separately reporting and analyzing the occurrence of "side-slap" types of collisions
5. Full-scale test reporting and subsequent analysis should be in a coordinate system in conformity with standard SAE J670e

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APPENDIX 1: *CG-TRANSFORM* PROCEDURE

In the following, a procedure is defined whereby accelerometer measurements taken at locations away from the CG are transformed into impact speed-changes at the center of gravity and into separation velocities on the basis of discrete measures of the vehicle responses rather than complete time-histories. The procedure, entitled ***CG-Transform***, is validated by means of applications to SMAC runs in which the outputs include acceleration components at selected locations on the simulated vehicles.

DEFINITION OF SYMBOLS

OXY =	Vehicle-fixed coordinate system with origin at the center of gravity.
O'X'Y'=	Space-fixed coordinate system.
ψ =	Heading angle of vehicle relative to space-fixed system.
u, v =	Components of velocity in the directions of the vehicle-fixed X and Y coordinates respectively, inches/second.
u', v' =	Components of velocity in the directions of the space-fixed X' and Y' coordinates respectively, inches/second.
x1, y1 =	Coordinates of accelerometer location in vehicle-fixed system, inches.
ax1, ay1 =	Components of acceleration at point 1 relative to the vehicle-fixed system, inches/sec^2.
a_x, a_y =	Components of acceleration at the center of gravity relative to the vehicle-fixed system, inches/sec^2.
Δu, **Δv** =	Changes in velocity in the directions of the vehicle-fixed X and Y coordinates respectively, inches/sec.

In the following pages, a dot over a symbol is used to indicate a time derivative.

The subletter **1** indicates the value of a variable at point **1**

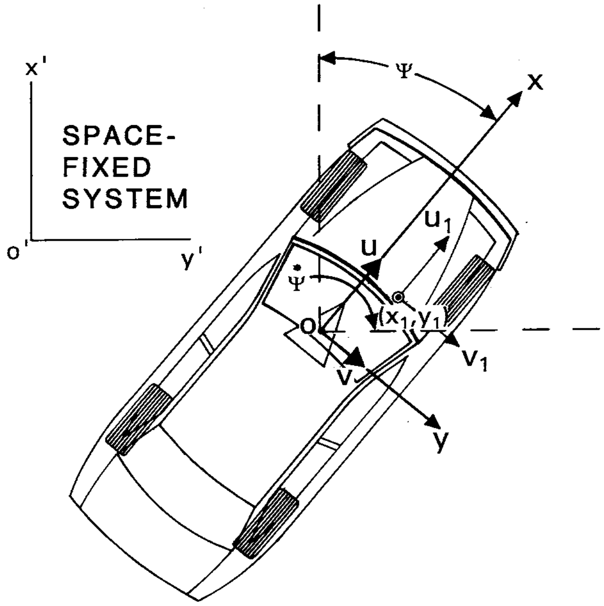

Figure 5 Velocity components of a Point on a vehicle

In ***Figure*** 5, velocity components of point **1** relative to the vehicle-fixed coordinate system are defined by:

$$u_1 = u - y_1\dot{\psi} \qquad (11)$$

$$v_1 = v + x_1\dot{\psi} \qquad (12)$$

The velocity components of point P relative to the space-fixed coordinate system may be expressed as:

$$u_1' = u_1 \cos \psi - v_1 \sin \psi \qquad (13)$$

$$v_1' = u_1 \sin \psi + v_1 \cos \psi \qquad (14)$$

Substitution of (11) and (12) into (13) and (14) and differentiation of the resulting equations yields the following components of acceleration relative to the vehicle-fixed system:

$$a_{x1} = \dot{u} - v\dot{\psi} - y_1\ddot{\psi} - x_1\dot{\psi}^2 \qquad (15)$$

$$a_{y1} = \dot{v} + u\dot{\psi} + x_1\ddot{\psi} - y_1\dot{\psi}^2 \qquad (16)$$

From (15) and (16), the components of acceleration relative to the vehicle-fixed system at the center of gravity of the vehicle (i.e., $x_1 = y_1 = 0$) may be expressed:

$$a_x = \dot{u} - v\dot{\psi} \qquad (17)$$

$$a_y = \dot{v} + u\dot{\psi} \qquad (18)$$

Thus, the ΔV components at the center of gravity relative to the vehicle-fixed system, including rotational effects, may be obtained by integration of (15) and (16):

$$\int_o^t a_x dt = \int_o^t a_{x1} dt + y_1 \int_0^t \ddot{\psi} dt + x_1 \int_o^t \dot{\psi}^2 dt \quad (19)$$

$$\int_o^t a_y dt = \int_o^t a_{y1} dt - x_1 \int_o^t \ddot{\psi} dt + y_1 \int_o^t \dot{\psi}^2 dt \quad (20)$$

To obtain the components in the vehicle-fixed system, of the separation velocity (i.e., the velocity at the end of a period of acceleration) it is necessary to integrate (17) and (18) in the following manner:

$$u_f = u_o + \int_o^t \dot{u} dt = u_0 + \int_o^t a_x dt + \int_o^t v\dot{\psi} dt \quad (21)$$

$$v_f = v_o + \int_o^t \dot{v} dt = v_o + \int_o^t a_y dt - \int_o^t u\dot{\psi} dt \quad (22)$$

From the preceding, it may be seen that the following integrations are required to correct readings obtained from accelerometers at point **1**:

$$\int_o^t \ddot{\psi} dt \qquad (23)$$

$$\int_o^t \dot{\psi}^2 dt \qquad (24)$$

$$\int_o^t v\dot{\psi} dt \qquad (25)$$

$$\int_o^t u\dot{\psi} dt \qquad (26)$$

Reasonable approximations of the values of the integrals listed as equations (23) through (26) can be obtained by the use of analytical functions fitted to test data:

$$\ddot{\psi} = Q_1 \sin \omega t - Q_2 \sin 3\omega t \qquad (27)$$

$$u = u_f - (\Delta u) \cos \omega t \quad (28)$$

$$v = v_f - (\Delta v) \cos \omega t \quad (29)$$

Integration of equations (23) through (26) using the functional relationships defined by (27), (28) and (29) and application of the results to equations (19), (20), (21) and (22) yields the following relationships:

$$\omega = \frac{\pi}{2(\Delta t)} \quad (30)$$

$$Q_1 = \frac{3\omega}{4}\left[\frac{\pi}{2}\dot{\psi}_f + \frac{\Delta\dot{\psi}}{3} - \omega\Delta\psi\right] \quad (31)$$

$$Q_2 = 3\left[Q_1 - \omega\Delta\dot{\psi}\right] \quad (32)$$

$$A = \frac{1}{\omega}\left(\frac{\pi}{2}\dot{\psi}_f^{\,2} + \frac{Q_1}{\omega}\left[\frac{Q_1\pi}{4\omega} - 2\dot{\psi}_f\right] + \frac{Q_2}{9\omega}\left[\frac{Q_2\pi}{4\omega} - 2\dot{\psi}_f\right]\right) \quad (33)$$

$$\Delta V_x = \int_o^t a_x dt = \int_o^t a_{x1} dt + y_1\Delta\dot{\psi} + x_1 A \quad (34)$$

$$\Delta V_y = \int_o^t a_y dt = \int_o^t a_{y1} dt - x_1\Delta\dot{\psi} + y_1 A \quad (35)$$

$$B = \frac{1}{\omega}\left(\frac{\pi}{2}\dot{\psi}_f - \frac{Q_1}{\omega} - \frac{Q_2}{9\omega^2}\right) \quad (36)$$

$$C = \frac{1}{\omega}\left(\frac{\pi}{4}\frac{Q_1}{\omega} - \dot{\psi}_f\right) \quad (37)$$

$$D = \int_o^t a_x dt + Bv_0 \quad (38)$$

$$E = \int_o^t a_y dt - Bu_0 \quad (39)$$

$$delu = \Delta u = \left(\frac{D + (B+C)E}{1 + (B+C)^2}\right) \quad (40)$$

$$delv = \Delta v = \frac{\left(E - (B+C)D\right)}{\left(1 + (B+C)^2\right)} \quad (41)$$

$$u_f = u_0 + \Delta u \quad (42)$$

$$v_f = v_0 + \Delta v \quad (43)$$

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