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# Accuracy Evaluation of the ARAS HD Collinear Momentum Solution in Relation to the RICSAC Staged Crash Events.

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## ABSTRACT

ARAS HD is a software application designed to allow its users to draw crash scene diagrams from electronic measurements or hand measurements, create 3D animations, and 3D scene models. It also incorporates a collinear momentum analysis tool which is designed to be utilized by matching the on- the-scene data. The results generated by that tool often lead to both criminal and civil trials at which the accuracy of that tool will be questioned. That means the user of the system must be able to describe to lay persons the basic theory of the collinear momentum calculation and also explain the accuracy possibilities in relation to staged crash events. The validation procedure must be described and documented for review by non-scientific parties.

This paper describes the way the integrated collinear momentum solution in ARAS HD functions, the foundational assumptions and algorithms as well as the method and results of validation attempts. The paper provides the output from the use of the tool and the output diagrams and charts as provided by the RICSAC tests.

## INTRODUCTION

In many crashes, vehicles collide in essentially a rear end or head on orientation. As such, the angular method of momentum analysis (also known as 360 momentum) cannot be applied because the approach angles in either orientation are collinear. Therefore the method, COLLINEAR Momentum is utilized but the user must provide more information. This method has been taught at all of the various crash reconstruction training centers for the last 40 years. It is an accepted procedure and early reference to crash tests indicates that if the procedure is used properly the results will be reliable. As is often the case, the physics model is valid but heavily dependent on quality of data. However, advances in measuring procedures have improved the data quality immensely. Advances in computer software to process complex calculation routines have also advanced exponentially.

The physics model within the ARAS HD Collinear Momentum solution has a basic design that is consistent with the method of applying collinear momentum analysis as instructed for the last 35 years at Northwestern University Traffic Institute and IPTM (Institute of Police Training and Management). This method has been used commonly by police and private collision reconstructionists in North America. The method is “collinear momentum,“ often referred to as “same direction momentum,” “inline” or “head on momentum“ which calculates the speeds of both vehicles simultaneously, when basic inputs are provided. The methods taught can be pure vector analysis done graphically or done using a purely mathematical approach.

The collinear momentum solution within the ARAS HD software is designed to be employed on the actual scene diagram so users may match evidenced positions of vehicles with the graphical vector system. In this way, not only are real time ranges of results possible, but more accurate results are gained by skipping the traditional method of gathering information from a diagram and transferring it to a calculation method or other software interface.

This solution is designed to be applied to head on or rear end configured collisions. It is best applied when the relative angle between the colliding vehicles is less than 10 degrees. When applying this solution the contributed momentum ratio between vehicles should not exceed 4:1. Therefore, if we assumed both vehicles had equal approach speeds in a head on collision, their relative mass ratio should not exceed 4:1.

Users of this tool should have received training in the theory of the conservation of momentum at specialized reconstruction training, or by university physics courses.

### Physics Theory Expressly Defined

This solution is treated as a single dimensional vector space. All motion is evaluated along the same line with the only indication of direction being the sign of the velocities. Velocities are still considered to be a VECTOR quantity. The convention used is +'ve traveling to the right and –'ve to the left. So if $v_1$ is +'ve and $v_2$ is –'ve, it is a head-on or opposing vectors scenario. If both have the same sign (+'ve) then it is a rear-end or same direction scenario.

Basic Momentum Equation

$$m_1 * v_1 + m_2 * v_2 = m_1 * v_3 + m_2 * v_4$$

(Eq. 1)

When solving for momentum, the values on the right hand side ($v_3$ and $v_4$) are determined from post-impact evidence or by some other means. Vehicle Rest Positions, Path Travelled etc… Just like with the common 360 momentum solution. Most often the 'Slide to Stop' method is used to determine the separation velocities. In the ARAS HD solution, this calculation is done automatically by the user entering the appropriate drag factor, and adjusting vehicle positions.

That leaves two unknowns on the left hand side ($v_1$ and $v_2$). Unlike 360 momentum, we cannot create a system of linear equations to solve. Therefore the user must provide additional information. In the ARAS HD system, that means either:

1. Velocity of vehicle 1
2. Velocity of vehicle 2
3. Relative velocity ( closing velocity)

In order to solve the system we need to know either $v_1$, or $v_2$, or the difference relative velocity of $v_2$ compared to $v_1$.

The convention used in ARAS HD is vehicle 1 is always treated as the bullet vehicle, and vehicle 2 the target.

So in an "at-rest" or "rear-end" scenario vehicle 2 is always the slower or "at-rest" vehicle.

If $v_2$ is known, we solve for $v_1$.

$$v_1 = \frac{(m_1 * v_3 + m_2 * v_4) - (m_2 * v_2)}{m_1}$$

(Eq. 2)

Similarly if $v_1$ is known, we solve for $v_2$

$$v_2 = \frac{(m_1 * v_3 + m_2 * v_4) - (m_1 * v_1)}{m_2}$$

(Eq. 3)

If $v_2$ is at rest (its velocity is 0) we use the option to solve for $v_1$, using 0 for $v_2$

If the relative velocity between vehicle 1 and vehicle 2 is known, we use substitution. Remember that $v_1$ is always treated as > $v_2$. (Note: $v_1 = v_2$ is a situation where NO collision would occur.)

$$\delta v = absolute\ relative\ velocity\ (v_1 being > v_2)$$

$$v_2 = v_1 - \delta v$$

(Eq. 4)

$$m_1 * v_1 + m_2 * (v_1 - \delta v) = m_1 * v_3 + m_2 + v_4$$

(Eq. 5)

Solve for $v_1$

$$v_1 = \frac{\left((m_1 * v_3) + \left(m_2 * (v_4 + \delta v)\right)\right)}{(m_1 + m_2)}$$

(Eq. 6)

Then solve $v_2$ using (Eq. 4) from above

## Summary:

### $v_2$ Is known

$$v_1 = \frac{(m_1 * v_3 + m_2 * v_4) - (m_2 * v_2)}{m_1}$$

### $v_1$ Is known

$$v_2 = \frac{(m_1 * v_3 + m_2 * v_4) - (m_1 * v_1)}{m_2}$$

**Relative Absolute Velocity between vehicle 1 and vehicle 2 is known (δv)**

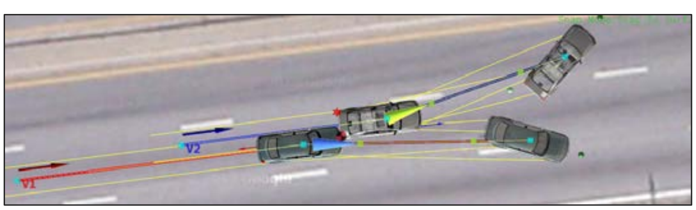
Assuming that $v_1 > v_2$

$$v_1 = \frac{\left((m_1 * v_3) + \left(m_2 * (v_4 + \delta v)\right)\right)}{(m_1 + m_2)}$$

$$v_2 = v_1 - \delta v$$

**Limited Orientation of Engagement**

The vehicle alignment possibilities are simply rear end or head on orientation and the angle differential in either case should not exceed 10 degrees.

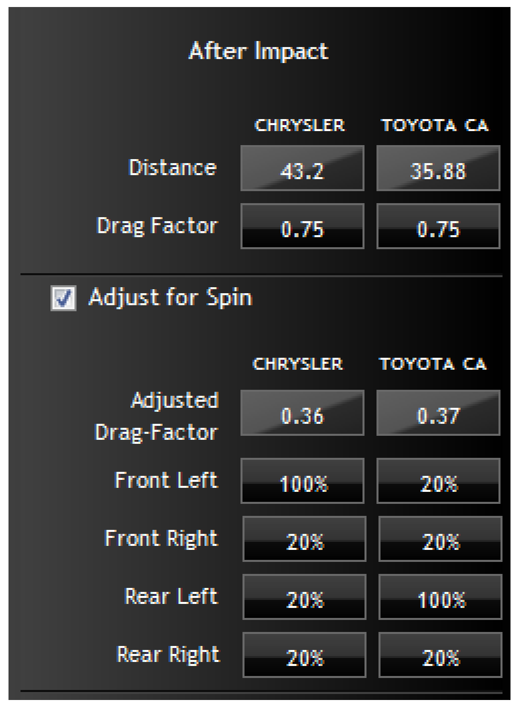



The vehicle overlap can be offset as shown above and the physics are still valid.

**The Tire Road Model**

The ARAS model allows the final position of the vehicles to be rotated to match evidenced tire marks and final rest orientations. When this is chosen a tire road model is utilized which will adjust the roadway drag factor based on wheel by wheel braking percentage and the vehicle spin. Based on the result of this calculation and the post impact distance as defined by vehicle placement on the scene diagram; the post impact speed is calculated.

The image below shows the software interface for ARAS users to input the data and review the resulting adjusted drag factor in real time.




Note: the ARAS Collinear Momentum model has default braking percentages of 20% and the default drag factor is 0.4 g's. These must always be corrected by the user.

Calculating friction based on vehicle angle based on the friction circle concept. The effective friction acting on a vehicle is a combination of its sideways (lateral) friction combined with its forward/roll (longitudinal) friction.

At any given angle the friction can be calculated thus:

$$f_{lat} = f * \sin(\theta) \quad (Lateral\ Friction)$$

$$f_{long} = f_{roll} * \cos(\theta) \quad (Longitudal\ Friction)$$

$$f_c = \sqrt{f_{lat}^2 + f_{long}^2} \quad (Combined\ Friction)$$

$$f == roadway|surface\ friction\ co - efficient$$

$$f_{roll} = \frac{1}{2}\Big(W_f * (R_1 + R_2) + W_r * (R_3 + R_4)\Big)$$

$$W_f == \%\ of\ weight\ on\ front\ axle$$

$$W_r == \%\ of\ weight\ on\ rear\ axle$$

$$R_1 == Min\ (\ Roll\ Resitance\ Front\ Left\ Tire\ , f)$$

$$R_2 == Min(Roll\ Resistance\ Front\ Right\ Tire, f)$$

$$R_3 == Min(Roll\ Resistane\ Rear\ Left\ Tire, f)$$

$$R_4 == Min(Roll\ Resistance\ Rear\ Right\ Tire, f)$$

To get an average value as the vehicle rotates from an initial angle to a final angle you Sum up the incremental angles and average them out.

$$f_{avg} = \frac{\sum f_c}{n}$$

n= the number of iterations between initial angle and final angle.

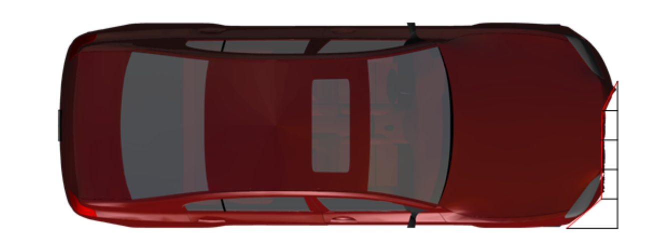
### Damage Simulation from Momentum Results

Within the ARAS solution there is an option to simulate the damage profiles or crush based on input speeds from the momentum output. These speeds provide the input speed for a SMAC based simulation. The collision routine from SMAC is used for this process and specifically as refined for EDSMAC 4. The resulting damage when applied is to be used for comparison purposes to validate the results. In other words the users will compare the simulated damage to the real world damage as a check for accuracy.

Damage was verified via RICSAC test 3, 5, 11.

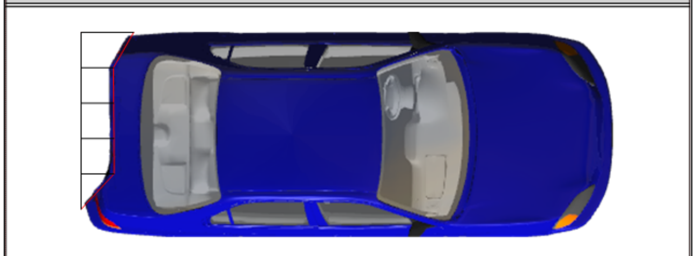
**Damage Report**

**Vehicle 1: FORD Torino 2d**



| | | | |
|---|---|---|---|
| **Location** | Front | **C1 (inch)** | 0 |
| **Width (inch)** | 55.89 | **C2 (inch)** | 5.84 |
| **Offset (inch)** | -11.03 | **C3 (inch)** | 6.01 |
| **Yaw Moment (lb-sec^2-ft)** | 2311.263 | **C4 (inch)** | 6.12 |
| **A Stiffness (lb / in)** | 575 | **C5 (inch)** | 6.16 |
| **B Stiffness (lb / in^2)** | 153 | **C6 (inch)** | 19.38 |

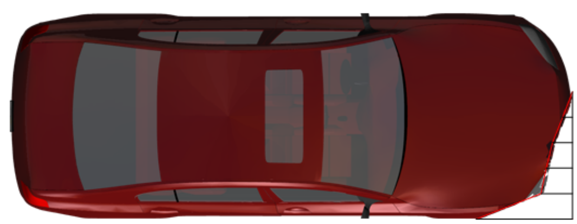
**Vehicle 2: FORD Pinto 2d**



| | | | |
|---|---|---|---|
| **Location** | Rear | **C1 (inch)** | 16.62 |
| **Width (inch)** | 55.93 | **C2 (inch)** | 10.23 |
| **Offset (inch)** | 4.51 | **C3 (inch)** | 10.31 |
| **Yaw Moment (lb-sec^2-ft)** | 1471.337 | **C4 (inch)** | 10.41 |
| **A Stiffness (lb / in)** | 112 | **C5 (inch)** | 10.45 |
| **B Stiffness (lb / in^2)** | 90 | **C6 (inch)** | 0 |

**Damage Report**

**Vehicle 1: FORD Torino 2d**



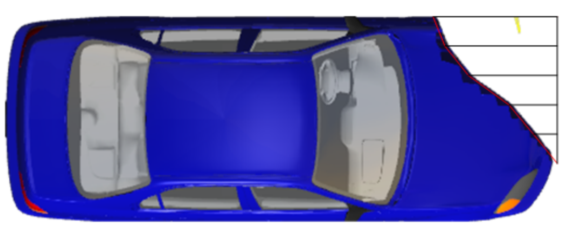
| | | | |
|---|---|---|---|
| **Location** | Front | **C1 (inch)** | 0 |
| **Width (inch)** | 48.32 | **C2 (inch)** | 3.72 |
| **Offset (inch)** | -14.82 | **C3 (inch)** | 7.59 |
| **Yaw Moment (lb-sec^2-ft)** | 2311.263 | **C4 (inch)** | 9.96 |
| **A Stiffness (lb / in)** | 545 | **C5 (inch)** | 11.93 |
| **B Stiffness (lb / in^2)** | 153 | **C6 (inch)** | 36.52 |

**Vehicle 2: HONDA Civic 2d**

| | | | |
|---|---|---|---|
| **Location** | Rear | **C1 (inch)** | 28.99 |
| **Width (inch)** | 49.92 | **C2 (inch)** | 25.73 |
| **Offset (inch)** | 4.57 | **C3 (inch)** | 23.06 |
| **Yaw Moment (lb-sec^2-ft)** | 1125.642 | **C4 (inch)** | 23.13 |
| **A Stiffness (lb / in)** | 112 | **C5 (inch)** | 16.39 |
| **B Stiffness (lb / in^2)** | 67 | **C6 (inch)** | 0 |

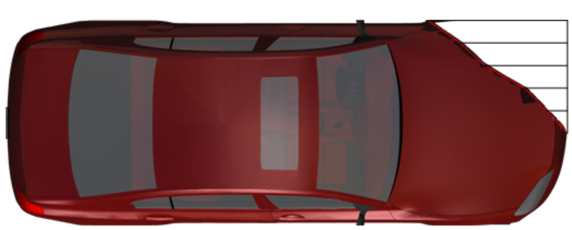
**Damage Report**

**Vehicle 1: CHEVROLET Vega 2d H**



| | | | |
|---|---|---|---|
| **Location** | Front | **C1 (inch)** | 38.81 |
| **Width (inch)** | 45.84 | **C2 (inch)** | 35.15 |
| **Offset (inch)** | 9.16 | **C3 (inch)** | 27.79 |
| **Yaw Moment (lb-sec^2-ft)** | 1457.769 | **C4 (inch)** | 15.13 |
| **A Stiffness (lb / in)** | 395 | **C5 (inch)** | 7.47 |
| **B Stiffness (lb / in^2)** | 60 | **C6 (inch)** | 0 |

**Vehicle 2: FORD Torino 2d**



| | | | |
|---|---|---|---|
| **Location** | Front | **C1 (inch)** | 53.04 |
| **Width (inch)** | 42.78 | **C2 (inch)** | 40.7 |
| **Offset (inch)** | 17.59 | **C3 (inch)** | 31.4 |
| **Yaw Moment (lb-sec^2-ft)** | 2311.263 | **C4 (inch)** | 16.27 |
| **A Stiffness (lb / in)** | 395 | **C5 (inch)** | 7.9 |
| **B Stiffness (lb / in^2)** | 60 | **C6 (inch)** | 0 |

**Crush Simulation Report, Test 12**

## VALIDATION STUDIES

Validation of the system is done by comparing speeds calculated with the ARAS HD Collinear Momentum system to the actual speeds of vehicles in instrumented crash tests.

One such group of tests against which ARAS MOMENTUM modules have been validated is the RICSAC test series. With the title of "**Research Input for Computer Simulation of Automobile Collisions**," these twelve tests were performed by Calspan Corporation in the late 1970's under the auspices of the **National Highway Traffic Safety Administration** (**NHTSA**). The object of these tests was "develop a library of experimental data which could be used to validate accident reconstruction techniques such as **SMAC** and **CRASH**" (Shoemaker, 1978).

The authors of this paper have relied upon diagrams supplied with the **RICSAC** test data and simply scanned the diagrams and inserted them as images in the ARAS HD program, by scaling them appropriately using the scale symbol on each of the test schematics.
Only 4 of the 12 **RICSAC** tests were head on and rear end or collinear engagements so they were chosen as tests upon which to validate the tool. Therefore, in the table below you will see many of the **RICSAC** tests are not represented.

The method of accuracy evaluation was to compare the % accuracy of V1 and V2, and find the average between them.

Most recently, the authors of this paper have developed a series of ARAS validation movies which provide a real time depiction of the use of the ARAS HD momentum tool with the **RICSAC** and other crash tests. Viewers of this movie series will understand more closely the use of the specific options within the momentum tool. Any ARAS users wishing to perform validation studies must be prepared to carefully analyze the post impact friction values and use of the damage simulation is an important check to determine the correct values. In essence, the damage simulation has a very important role in determining the accuracy of a collinear momentum analysis, and much more than the authors had predicted when initiating the validation.

Further validation will be conducted in the same manner in the future using the crash test data from the various ARC/CSI crash reconstruction conferences.

## METHOD

The authors were provided by ARAS 360 Technologies Incorporated (ARAS) with a digital version of a selection of RICSAC crash test films contained within ARAS's reference library. These were films which documented RICSAC Tests 3, 5, 11, and 12. These films contained footage collected with film-based motion picture cameras shot from a variety of angles and at varying film speeds. The RICSAC test reports contain information regarding the location of many of the cameras as well as technical specifications such as frame rates and lens focal lengths.

The following table summarizes the calculated speeds using ARAS HD Momentum and the speeds reported by the **RICSAC** test crashes.

| RICSAC Test no. | Real speed V1 | Real Speed V2 | ARAS speed V1 | ARAS speed V2 | % accu rate * |
|---|---|---|---|---|---|
| **3** | 21.2 | 0 | 23.5 | 0 | 90 |
| | | | | | |
| **5** | 39.5 | 0 | 41 | 0 | 96 |
| | | | | | |
| **11** | 20.4 | 20.4 | 20.4 | 22.5 | 95 |
| | | | | | |
| **12** | 20.4 | 20.4 | 20.4 | 19.32 | 95 |
| | | | | | |
| **Overall** | | | | | 94 |

**Sensitivity to Data**

Overall the reliability of the RICSAC input parameters for vehicle positions, weights and the general test scenes are within reason. However, the estimation of the post impact resisting forces is somewhat suspect. In most cases the reports state the vehicles had the transmissions engaged and the wheels were free-wheeling. We have some suspicions that in some cases the transmissions were either not engaged or slipped out of gear from the impact.

In many cases the accuracy of the calculation tool is dependent on the features within the tool or calculation procedure to allow for circumstances that are the reality of modern day crash investigations.

The considerations that allow much more accurate analyses include:

1. Allowing for changing friction values during post impact phase.
2. Allowing for secondary impacts or sudden speed loss during the post impact phase.
3. Allowing for non-linear or curved post impact trajectories.
4. Adjustment of drag factor in relation to vehicle spin.
5. Simulating damage based on momentum results.

*The ARAS HD Collinear Momentum tool allows users to set multiple friction zones, curvilinear trajectories, and considers spin analysis for adjustment of drag factors. These features allowed the calculated speeds using the test data above to be far more accurate.*

**Crucial Data Issues**

One of the key ingredients to accurate momentum analysis, no matter the software or specific method, is an accurate drag factor. The problem with the RICSAC test data is that the information about the post impact deceleration is, in many cases, very crude and that might lead to inaccurate analysis. In real world crashes it is imperative to know as much as possible about the wheel by wheel braking during the post impact phase, as well as the value(s) of the surface friction. In most cases, it was our experience during the validation process, that choosing the "adjust for spin" option in ARAS HD momentum generated more accurate results.

**SMAC Collision Model**

The Advanced Collinear Momentum system within HD is called SCMI (Simulated Collinear Momentum Interactive). The collision model portion of SMAC is applied by ARAS users as a method of checking or accuracy. Simply put, the user visually and with reference to crush measurements, compares the simulated damage to the real damage – this tool uses the impact configuration and impact speeds calculated by momentum to generate a 6 zone damage profile. The user must enter the A and B stiffness values for both vehicles and drag the center of impact (common damage centroid) to the likely position and click a button. After brief processing the damage will display and will also be included in the Momentum report.
The damage calculations are based on the original SMAC collision model with refinements as outlined in the SAE paper by Terry Day of Engineering Dynamics Corporation entitled "An Overview of the ESMAC4 Collision Simulation Model."

## SUMMARY AND CONCLUSION

- ARAS HD Collinear Momentum results were compared to RICSAC tests 3, 5, 11, 12.

- The output comparisons for accuracy determination were the impact speeds, and basic damage profiles.

- No more than 15 minutes was dedicated to adjusting the momentum data using the ARAS HD Collinear Momentum function.

- The resulting accuracy averaged from all tests yielded 94%.

- The RICSAC staged collision data was insufficient in terms of scene measurements. If the scenes were inaccurate in terms of the supplied schematics, the overall assessed accuracy would be in error as well.

- It is believed that the methods discussed in this paper provide useful techniques for researchers interested in comparing the results of computer-simulated vehicle motions against full-scale crash tests, and that the comparison videos created in this particular study can be relied upon by other ARAS Collinear Momentum users when describing the validation of ARAS Momentum software modules against full-scale vehicle tests.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of the staff of ARAS 360 Technologies as well as the many contributing authors over the years discussing the RICSAC tests and results from those tests.

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