AWP #2013-2

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

Mike Kennedy, ACTAR, and Paul Hetherington, BTACS

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 create 3D scene models. It also incorporates a linear momentum tool which is designed to be utilized on the scene data. The results generated by that tool are often taken to both criminal and civil trials at which the accuracy of the tool will be questioned. That means the user of the system must be able to describe how the tool works in terms of foundational mathematical algorithms. Users must also give information on the accuracy of the tool in relation to staged crashes. The validation procedure must be described and documented for review by non-scientific parties.

This paper describes the way the integrated momentum solution in ARAS HD works and the method and results of the validation process. 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 within an intersection in a number of different configurations. It might be a vehicle turning left in front of a vehicle passing straight through an intersection, or it might be a car entering the intersection without stopping at a stop sign or red light. In any case, the problem is that both vehicles are in motion and therefore both speeds must be calculated simultaneously. This method, called the Conservation of Linear Momentum, has been taught at all of the various crash reconstruction training centers for the last 35 years. It is a widely accepted procedure and 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 the quality of the data. Advances in measuring procedures have improved the data quality immensely. Advances in computer software to resolve physics problems have also improved the methods considerably.

Software engineers along with reconstructionists employed by ARAS 360 Technologies Incorporated have developed a unique and useful approach to the application of the physics of linear momentum analysis. This approach allows users to generate the collision scene within ARAS 360 HD. The scene might have been generated using electronic measurements, satellite imagery, and/or hand field measurements. When the scene is complete, the user simply drops the momentum vector system onto the scene. The user then accesses grips on the system to align it to the measured evidence. This process eliminates the many errors introduced by measuring angles and distances from a scale diagram and then using those values in a purely mathematical approach. ARAS HD users are then aligning the system and getting calculation results in real time. Users get real time feedback on the sensitivity of the data.

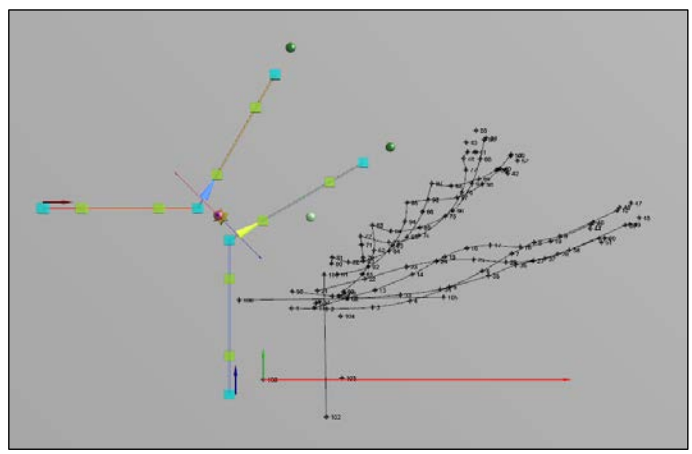

Figure 1. ARAS HD's momentum tool before alignment.

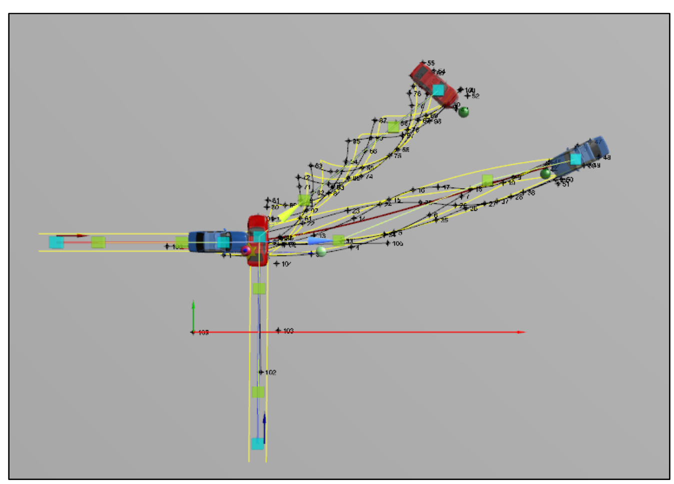

Figure 2. ARAS HD's momentum tool after alignment.

As vectors are aligned with actual scene data, departure angles and distances are captured and considered for calculations in real time.

The physics model within the ARAS HD linear momentum solution has a basic design that is completely consistent with the method of applying linear momentum analysis as instructed in the industry for the last 35 years. This method is instructed at Northwestern University Traffic Institute and IPTM (Institute of Police Training and Management) and is also commonly used by police and private collision reconstructionists in North America. This method, commonly referred to as “360 momentum,” calculates the speeds of both vehicles simultaneously. The specific methods taught are generally graphical vector analysis or the trigonometric mathematical approach.

The mathematical solution uses the equations for solving the impact speeds as follows:

Impact Speed V1 - Vehicle 1*

$$v_1 = \frac{(m_1 * v_3 * \cos(\theta_3)) + (m_2 * v_4 * \cos(\theta_4)) - (m_2 * v_2 * \cos(\theta_2))}{m_1}$$

v_1	Pre-Impact Velocity Vehicle 1
Value (mph)	33.43
m_1	Mass / Weight Vehicle 1
Value (lbs)	2500.00
v_3	Post-Impact Velocity Vehicle 1
Value (mph)	24.47
θ_3	Departure Angle Vehicle 1
Value (deg)	60.00
m_2	Mass / Weight Vehicle 2
Value (lbs)	2500.00
v_4	Post-Impact Velocity Vehicle 2
Value (mph)	24.47
θ_4	Departure Angle Vehicle 2
Value (deg)	30.00
v_2	Pre-Impact Velocity Vehicle 2
Value (mph)	33.43
θ_2	Approach Angle Vehicle 2
Value (deg)	90.00
Result (mph)	
33.43	

Figure 3. An excerpt from the ARAS HD Momentum Report showing the solution for calculating the impact speed of vehicle 1.

The speed changes or delta V’s are calculated as follows:

Delta V1 - Vehicle 1*

$$\Delta V_1 = \sqrt{((v_1^2 + v_3^2) - 2 * v_1 * v_3 * \cos(\theta_3))}$$

ΔV_1	Delta V1
Value (mph)	29.97
v_1	Initial Velocity Vehicle 1
Value (mph)	33.43
v_3	Final Velocity Vehicle 1
Value (mph)	24.47
θ_3	Departure Angle Vehicle 1
Value (deg)	60.00
Result (mph)	
29.97	

The Principal Direction of Force(s) is solved as follows:

Principal Direction of Force 1*

$$p_1 = -1 * \sin^{-1}\left(\frac{v_3 * \sin(-\theta_3)}{\Delta v_1}\right)$$

p_1	PDOF 1
Value (deg)	45.00
v_3	Post-Impact Velocity Vehicle 1
Value (mph)	24.47
$-\theta_3$	Departure Angle Vehicle 1
Value (deg)	60.00
Δv_1	Delta V1
Value (mph)	29.97
Result (deg)	
45.00	

The separation speed(s) are resolved as follows:

Post-Impact Separation Velocities V2

$$v = \sqrt{(v_0^2 + 2 * a * d)}$$

v	Final Velocity
Value (mph)	35.89
v_0	Initial Velocity
Value (mph)	0.00
a	Acceleration
Value (ft/s²)	12.88
d	Distance Travelled
Value (ft)	50.00
Result (mph)	
35.89	

The separation velocities are solved by an automatic measurement of the post impact departure trajectory(s) and a user assigned deceleration rate or drag factor. The automatically generated vector diagram explains the angles and distances found in the mathematical procedures which form part of the ARAS HD Momentum Report.

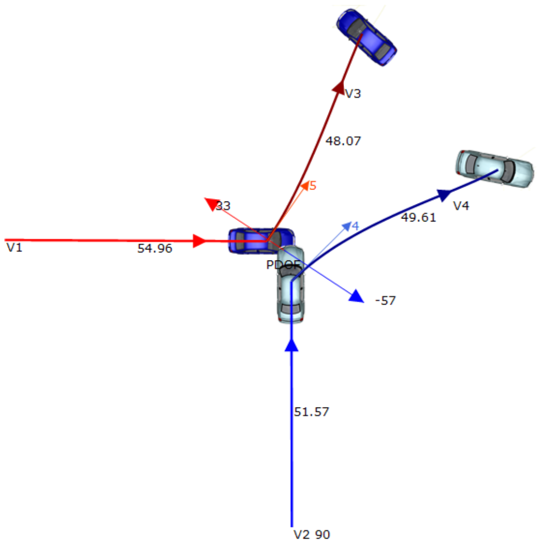

Figure 4. A Vector Diagram generated in ARAS HD.

In many cases, users of the ARAS HD software suite are asked to explain how the software functions and how it has been validated.

Methods by which an ARAS HD momentum user can convey this information might include verbal description, static diagrams, imagery, or animations. The ARAS HD momentum system automatically animates the momentum results in 3D in real time and generates an AVI movie as the deliverable output.
In addition, a mathematical explanation is often necessary for court acceptance and the automatically generated mathematics report from ARAS HD is helpful. This report is comprised of 20 pages (if all pages are included) and completely describes the method as well as breaking down the mathematical solution steps.
The accuracy or validation of the program is necessary to satisfy the litigants as well as potential users of the software.

The mathematics of momentum is based on the tried and true concept of Conservation of Linear Momentum which states simply that the post impact motion (direction and distance) of the vehicles will be an indication in terms of direction and magnitude of the contributing momentums. The solution simply examines the angles and distances, and assigns the contributing momentum to each vehicle by vector analysis. Dividing by the masses, the speed of each vehicle is determined.

VALIDATION STUDIES

Validation of the system is done by comparing speeds calculated with the ARAS HD momentum system to the actual speeds of vehicles in instrumented crash tests.
One such group of tests against which ARAS HD 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 to “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. The diagrams have simply been scanned and inserted as images into the ARAS HD program. The diagrams have been appropriately scaled using the scale symbol on each of the test schematics.

Many of the RICSAC tests were head on and rear end or collinear engagements and, as such, they are eliminated as relevant tests upon which to validate the tool. Therefore, in the table below you will see that many of the RICSAC tests are not represented.

The other instrumented crash test used for comparison in this paper is the Exponent Failure Analysis crash test completed in 2004. The Exponent test was far more relevant in terms of quality data.

Linear Momentum Limitations

1. Normally it is assumed that angles of attack >30 degrees will yield inconsistent results. In other words, essentially collinear impacts cannot be accurately assessed using the 360 momentum method of solving for Conservation of Linear Momentum.

2. When the contributing momentum of one vehicle is more than 4 times that of the other vehicle the results will be unreliable.

3. If the colliding vehicles do not fully engage or fully exchange momentum, like in a sideswipe, the results will be suspect.

Furthermore, certain information must be known about a crash incident before the linear momentum solution may be applied. This information includes:

- *Impact and rest locations.*
- *Impact and rest orientations.*
- *Impact to rest trajectories.*
- *Braking percentage on each wheel.*
- *Roadway friction.*
- *Vehicle weights.*
- *Vehicle weight distribution.*
- *Departure angles (normally the tire marks shown as the vehicles disengage).*

In many cases, not all of this information is known. The solution might still be possible using momentum analysis, but in those cases it would be important to know the speed changes from another calculation process like crush, or a CDR report.

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

RICSAC Test no.	**Real speed V1**	**Real speed V2**	**ARAS speed V1**	**ARAS speed V2**	**% accu-rate***
1	19.5	19.5	20.4	19.2	97
2	31.5	31.5	32.4	31.16	98
6	21.5	21.5	21.9	22.5	97
7	29.5	29.5	30.5	31.2	96
8	20.6	20.6	19.9	20.9	98
9	21.2	21.2	20.4	22	96
Exponent	59.7	19.7	59.2	20.4	98
Overall					97%

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

In each case, the tester used the tool best suited for the test configuration to determine the post impact drag factor. In some cases, the tester simply assigned a reasonable value based on estimated rotation and overall friction. In other tests, the built in spin analysis was employed to calculate the drag factor. It seems the longer the post impact distance, the more necessary it was to employ spin analysis.

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 thoroughly the use of the specific options within the momentum tool.

The physics modules within the ARAS HD momentum and simulation environment have been validated against full-scale vehicle tests not mentioned in this paper and will be reviewed in upcoming publications.

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

Sensitivity to Data

Using the Exponent test as an example, one can see from the survey data that the east bound vehicle initially departed almost directly eastbound, but then as momentum dissipated and tire forces became a factor, moved more northbound.

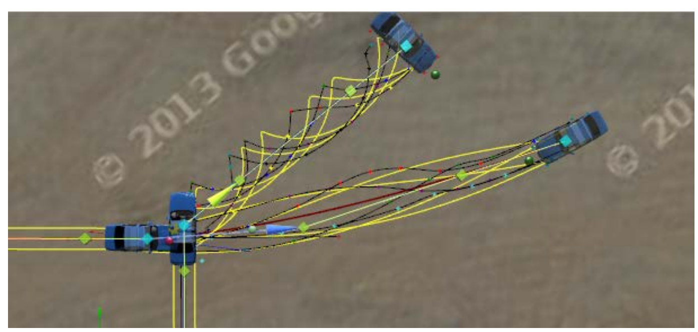

Figure 5. The Exponent test results as seen in ARAS HD.

The ARAS HD momentum solution allows the user to set a departure angle which is different than the angle between impact and rest. In the Exponent crash test above, if the user did not adjust using the blue arrow grip and set the true departure, the calculated impact speed is incorrect by 7 mph (or is approximately 26% too high).

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 for much more accurate analyses include:

1. Allowing for the changing of friction values during the 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. Allowing for adjustment of drag factor in relation to vehicle spin.
5. Simulating damage based on momentum results.

The ARAS HD momentum tool allows users to set multiple friction zones, curvilinear trajectories, and considers spin analysis. These features allowed the calculated speeds using the test data above to be far more accurate.

Crucial Data Issues

One of the key components of 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. It was our experience that, in most cases during the validation process, choosing the "Adjust for Spin" option in ARAS HD momentum generated more accurate results.

SMAC Collision Model

The advanced momentum system within ARAS HD is called SAMI (Simulated Angular Momentum Interactive). This advanced physics model has two functions not found within the ARAS HD basic momentum system:

1. Simulated spin: This tool allows users to predict the amount and direction of spin when it may not be known from field data. The mathematical procedure for generating the simulated spin is based on rigid body dynamics. The force from the collision is applied through the damage centroid specified by the user in the direction of the PDOF determined from the momentum solution. Alternatively, the user may specify to use the damage centroids determined by the simulated damage system rather than the common damage centroid that was manually positioned. Note that the vehicle is constrained to the user defined post impact trajectory and indicates spin magnitude and direction only.

2. Simulated 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 then click a button. After brief processing the damage will be displayed and will also be included in the momentum report.

3. The damage calculations are based on the SAE paper by Terry Day of Engineering Dynamics Corporation entitled "An Overview of the EDSMAC4 Collision Simulation Model."

SUMMARY AND CONCLUSION

- ARAS HD momentum results were compared to RICSAC tests 1, 2, 6, 7, 8, 9 as well as the Exponent crash test.

- The output comparisons for the determination of accuracy were the impact speeds only. Further studies will examine delta v's and damage comparisons.

- No more than 5 minutes was dedicated to adjusting the momentum data using the ARAS HD momentum function.

- The resulting accuracy averaged from all tests yielded 97%.

- The RICSAC staged collision data was quite crude 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 hoped that the methods discussed in this paper provide useful information for other researchers interested in comparing the results of computer-generated vehicle impact speeds against full-scale crash tests. It is also hoped that the comparison results created in this particular study can be relied upon by other ARAS HD users as well as general users of various tools that support the Conservation of Linear Momentum calculations.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of the staff of ARAS 360 Technologies as well as the many contributing authors over the years that have discussed the RICSAC tests and the results from those tests. Additionally, we acknowledge the training classes at both Northwestern University Traffic Institute and IPTM in crash reconstruction techniques.

REFERENCES

ARAS 360 HD User Manual, Version 2.0.6, ARAS 360 Technologies Inc., B.C., Canada 2013.

"Crash Survival/ROVs/Video Surveillance." *Tactical to Practical*. History Channel. Phoenix, AZ. 22 June 2004.

Day, T.D., "An Overview of the EDSMAC4 Collision Simulation Model," SAE Paper No. 1999-01-0102, Engineering Dynamics Corporation, Detroit, MI 1999.

Jones, I., Baum, A., "Research Input for Computer Simulation of Automobile Collisions" Volume IV, DOT HS-805-040, 1978.

Parkka, D.J., *Equation Directory for the Reconstructionist*. Institute of Police Technology and Management, Jacksonville, FL 1996.

Shoemaker, N.E., "Research Input for Computer Simulation of Automobile Collisions" Volumes II - III, DOT HS-805 038/DOT HS-805 039, Buffalo, NY 1978.