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ABSTRACT

The HVE scientific visualization environment introduced motor vehicle safety researchers to a new paradigm for studying the cause of motor vehicle accidents. The open architecture of HVE provided access to several new and existing reconstruction and simulation models for both humans and vehicles. This paper provided a validation of four existing models: EDCRASH, EDSMAC, EDSVS and EDVTS. Because these EDVAP models had previous validation studies, the results obtained in the HVE environment were limited to a comparison with those previous studies. The validation of the simulation models was extended to include three-dimensional environments.

VALIDATION OF A METHOD used to analyze a motor vehicle accident provides confidence that the method's results are credible and reliable. For this reason, accident researchers depend on a validation study as a prerequisite to the use of a particular method of accident reconstruction or simulation.

Many two-dimensional (2-D) reconstruction and simulation models have been used widely over the past ten years. In 1993, the development of HVE, a general purpose, three-dimensional environment for executing reconstruction and simulation models for human and vehicle dynamics, was announced [1]. Since that time, some of the existing models, as well as several new models, have been rewritten and updated for use in the HVE three-dimensional (3-D) program environment.

This paper describes a study used to validate several reconstruction and simulation models written for HVE. This paper is another extension of previous validations studies, both published [2,3] and unpublished. The original work was based on the work conducted by CALSPAN in the late seventies, called the RICSAC (Research Input for Computer Simulation of Automobile Collisions) [4-7] study, as well as a suite of input files used for in-house testing and validation at EDC.

PURPOSE

The purpose of this paper is to validate four reconstruction and simulation models written for the HVE environment. The following models are included in this validation:

- EDSVS - A 2-dimensional single vehicle simulator extended for use in a 3-D physical environment
- EDVTS - A 2-dimensional vehicle-trailer simulator extended for use in a 3-D physical environment
- EDCRASH - A 2-dimensional, 2-car collision reconstruction model
- EDSMAC - A 2-dimensional, 2-car collision simulation model extended for use in a 3-D physical environment

These models are described in references 8 through 11.

HISTORICAL OVERVIEW

Each of the original models described in this research was originally developed for use by the National Highway Traffic Safety Administration (NHTSA) or American Automobile Manufacturer's Association (AAMA), and has one or more validation studies as a result of the original research. EDC extended these original models and provided additional validation. Now, the environment in which these

* Numbers in brackets designated references found at the end of the paper.

TABLE 1. RICSAC STAGED Collisions

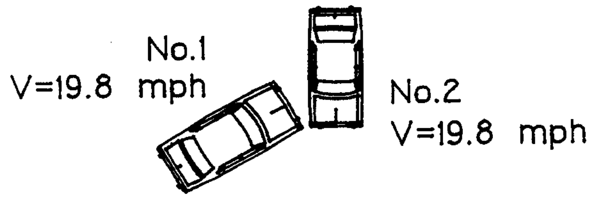
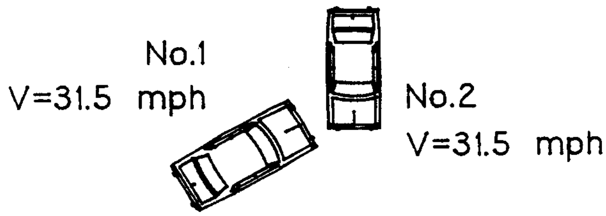
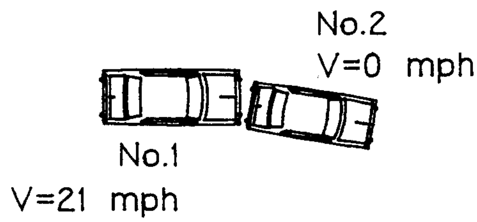
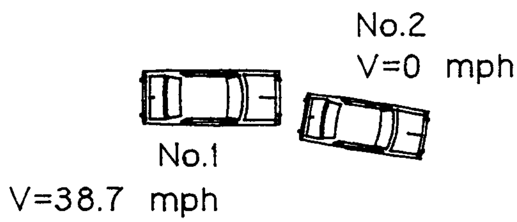
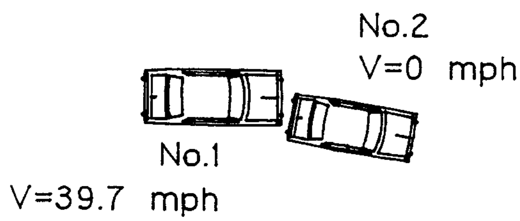
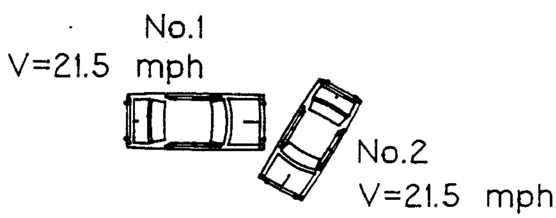
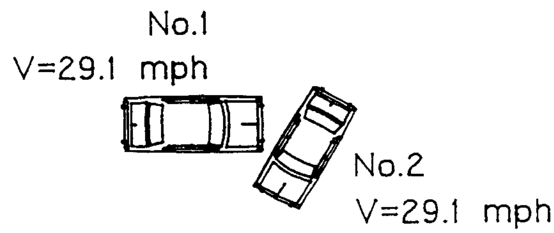
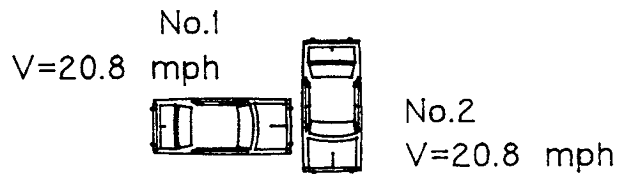
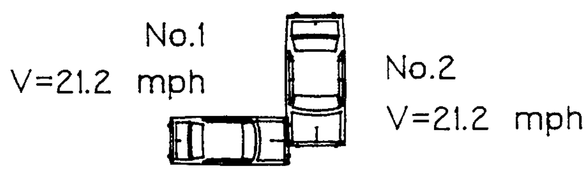
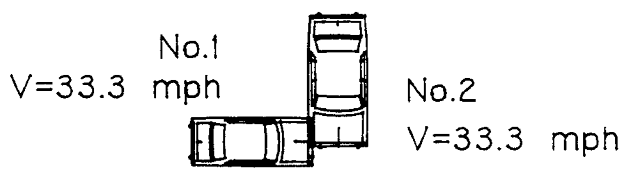
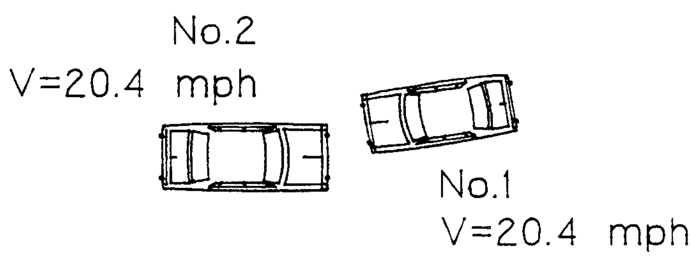
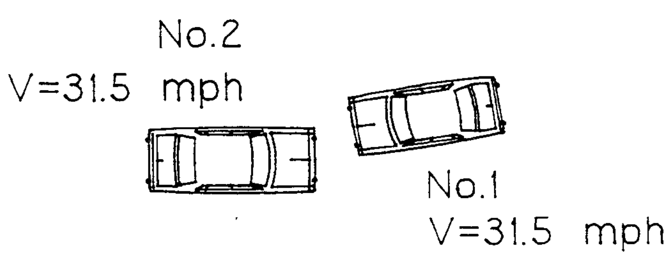
TEST No.	VEHICLES	COLLISION TYPE	CONFIGURATION at IMPACT
1	No. 1 - '74 Chevelle Malibu No. 2 - '74 Ford Pinto	Oblique	
2	No. 1 - '74 Chev Chevelle No. 2 - '74 Ford Pinto	Oblique	
3	No. 1 - '74 Ford Torino No. 2 - '74 Ford Pinto	Collinear	
4	No. 1 - '74 Ford Torino No. 2 - '74 Ford Pinto	Collinear	
5	No. 1 - '74 Ford Torino No. 2 - '74 Honda Civic	Collinear	
6	No. 1 - '74 Chev Chevelle No. 2 - '75 VW Rabbit	Oblique	

TABLE 1. RICSAC STAGED Collisions (continued from previous page)

TEST No.	VEHICLES	COLLISION TYPE	CONFIGURATION at IMPACT
7	No. 1 - '74 Chev Chevelle No. 2 - '75 VW Rabbit	Oblique	
8	No. 1 - '74 Chev Chevelle No. 2 - '74 Chev Chevelle	Oblique	
9	No. 1 - '74 Honda Civic No. 2 - '74 Ford Torino	Oblique	
10	No. 1 - '74 Honda Civic No. 2 - '74 Ford Torino	Oblique	
11	No. 1 - '74 Chev Vega No. 2 - '74 Ford Torino	Collinear	
12	No. 1 - '74 Chev Vega No. 2 - '75 Ford Torino	Oblique	

models are being executed has been substantially enhanced; in particular, they are being executed in a fully three-dimensional environment which offers the opportunity for significant enhancement of the models.

In the past, the RICSAC study has been used for validating collision models (EDCRASH, EDSMAC). Vehicle and human simulators have no single study, but relied upon individual test programs created specifically for each program.

In the current validation study, the RICSAC study is used for EDCRASH and EDSMAC, while specifically developed test suites are used for the other models. A brief overview of the RICSAC study and the in-house test suites is provided below.

RICSAC Study

The RICSAC study was an analysis and reconstruction of 12 two-car staged collisions. The collision configurations are shown in Table 1. Each vehicle was fitted with a complete instrumentation package that included the following components:

- a tri-axial accelerometer mounted on the firewall (vehicle position, velocity and acceleration)
- linear stroke potentiometers mounted on the steering linkage (wheel steer angles)
- electric tachometers mounted on at least three wheels (wheel spin velocity for percent lock-up)
- crash recorders for recording the data
- ten or more high-speed cameras
- marker paint sprayed from nozzles (two per vehicle) mounted on the unsprung mass approximately 1 in. above ground level (path identification)

After each test, the site and vehicle evidence were documented by CALSPAN's professional accident investigation team. This evidence included:

- wheel positions at impact and rest
- locations of debris, skids, gouges and spilled fluids
- vehicle trajectory (spray paint)
- vehicle damage profiles

The purpose of the RICSAC study was to provide well-documented test data available for researchers to use in validating reconstruction and simulation methods involving collisions. The actual RICSAC data sets for CRASH and SMAC are published in reference 7.

In-house Validation Suites

Over the past 12 years, a set of input files has been created as part of the quality assurance program at EDC. This suite of files was designed to exercise all the available program options, and are used as part of the routine testing effort before releasing new software versions.

This validation suite was extended where necessary to exercise new program options available in the HVE environment. For the sake of brevity, the files are not included in this paper, but are available from EDC [12].

PROCEDURE

Various procedures were used in this validation. Because all the models in this study had previous validation studies, the models were first validated using previously established validation suites, including the RICSAC staged collisions. Additional validations were performed simply by ensuring the effects of gravity on sloped surfaces produced the expected levels of vehicle acceleration.

Methods

The models described in this study are of two types: reconstruction and simulation. Because of the inherent difference in reconstruction and simulation models, the validation methods employed for each type were different.

Reconstruction Model

For reconstruction models, data sets were created and executed in the HVE environment, and the computed impact velocities were compared with the speeds measured during the staged collision tests. Differences between the computed and measured results were documented.

The reconstruction model (EDCRASH) had a previously published validation study [2]. However, for the sake of completeness, the current validation provided comparison of the results obtained using EDVAP/EDCRASH Version 4.61 and HVE/EDCRASH Version 1.0 with the measured data. Absolute and percentage differences were documented for each of the test cases.

Simulation Models

For simulation models, HVE data sets were created and executed in the HVE environment, and the predicted (simulated) rest positions were compared with the rest positions obtained in earlier studies or validation suites. Differences between the predicted and measured results were documented.

Like EDCRASH, EDSMAC had a previously published validation study [3], and comparisons between measured and calculated results were presented for EDVAP/EDSMAC Version 2.51 and HVE/EDSMAC Version 1.0. For EDSVS and EDVTS, EDVAP and HVE version results were compared directly. For all programs, absolute and percentage differences were documented for each of the test cases.

Definition of Error

The primary goal of a validation study is to determine the amount of error inherent to a particular analysis method. Two potential sources of error exist:

- *Program* error
- *Data* Error

The value of using staged collisions in a validation study lies in the fact that one of the sources of error (i.e., error in the data) is virtually eliminated. Thus, it is reasoned that any errors found in the program results are attributable only to the program.

The error criteria used in the current study are the same as those used in previous studies [2,3], and are described below.

Reconstruction Models

As in previous validation studies for reconstruction programs, the error is calculated as a percentage of combined impact speed. The selection of combined impact speed avoids the problem of calculating the error for a vehicle having no initial velocity (the classic approach of comparing the calculated vs actual speed for this vehicle alone would find an infinite percentage of error associated with even the smallest non-zero calculated speed). Error was calculated as follows:

$$E_1 = (\delta V_1/CS)*100 \qquad (\%)$$

and

$$E_2 = (\delta V_2/CS)*100 \qquad (\%)$$

where

E_n = *percentage error for vehicle n*

δV_n = *difference between measured and calculated impact velocity for vehicle n*

CS = *combined impact speed,* $V_{1,imp} + V_{2,imp}$ *(measured)*

Simulation Models

Error in the rest positions were calculated according to the distance from the predicted rest position to the actual rest position. This range error was calculated as follows:

$$error = \Delta(X,Y) / L_{act} * 100 \qquad (\%)$$

where

$\Delta(X,Y)$ = difference between predicted and measured rest position

$$= \sqrt{(X_{pred} - X_{act})^2 + (Y_{pred} - Y_{act})^2} \quad \text{(ft)}$$

$$L_{act} = \sqrt{(X_{rest} - X_{imp})^2 + (Y_{rest} - Y_{imp})^2} \quad \text{(ft)}$$

TABLE 2. Descrition of Validation Test Suites for EDSVS and EDVTS

EDSVS, Test 1	*Passenger Car, 50 mph, Reverse Turn (default input file)*
EDSVS, Test 2	*Passenger Car, 50 mph, Steering and Braking (EDSVS Tutorial)*
EDSVS, Test 3	*Truck, 50 mph, Steering and Braking, Wheel Lift-off*
EDSVS, Test 4	*Passenger Car, Lab Exercise #1 (Extra-long Run)*
EDSVS, Test 5	*Passenger Car, Steering, Braking and Accelerating on a Rainy Road*
EDSVS, Test 6	*Passenger Car, V_0=35 mph down a 5% grade for 2.0 seconds (No Driver Inputs)*
EDSVS, Test 7	*Truck, V_0=35 mph, up a 5% grade for 2.0 seconds (No Driver Inputs)*
EDSVS, Test 8	*Passenger Car, V0=25 mph on a 5% cross-slope for 2.0 seconds (No Driver Inputs)*
EDVTS, Test 1	*Passenger Car, Small Trailer, 50 mph, Steering and Braking (Default Input File)*
EDVTS, Test 2	*Tractor/Trailer, 35 mph, Braking and Steering Resulting in Jackknife (EDVTS Tutorial)*
EDVTS, Test 3	*Tractor/Trailer, 50 mph, Steering and Braking, Wheel Lift-off)*
EDVTS, Test 4	*Tractor/Trailer, 50 mph, Accelerating and Steering*
EDVTS, Test 5	*Passenger Car, Small Trailer, 30 mph Slalom*
EDVTS, Test 6	*Passenger Car, Small Trailer, V_0=35 mph down a 5% grade for 2.0 seconds (No Driver Inputs)*
EDVTS, Test 7	*Tractor/Trailer, V_0=35 mph, up a 5% grade for 2.0 seconds (No Driver Inputs)*
EDVTS, Test 8	*Tractor/Trailer, V0=25 mph on a 5% cross-slope for 2.0 seconds (No Driver Inputs)*

For the difference in heading angle, the error was calculated as follows:

$$error = ((\Delta\Psi_{pred} - \Delta\Psi_{act}) / 360) * 100 \qquad (\%)$$

where

$\Delta\Psi_{pred}$ = $(\Psi_{rest} - \Psi_{imp})_{pred}$ (deg)

$\Delta\Psi_{act}$ = $(\Psi_{rest} - \Psi_{imp})_{act}$ (deg)

An important discussion of the term *accuracy* as it relates to simulation programs is found in the *General Discussion* section of this paper.

TABLE 3. EDSVS Simulation Validation Results

TEST No.	METHOD	REST POSITION X (ft.)	REST POSITION Y (ft.)	REST POSITION PSI (deg.)	ERROR Range (ft.)	ERROR Range (%)	ERROR Heading (deg.)	ERROR Heading (%)
1	EDVAP	157.5	141.7	-104.7				
	HVE	157.6	141.0	-104.9	0.7	0.4	0.2	0.1
2	EDVAP	252.3	75.3	41.2				
	HVE	252.3	75.3	41.2	0.0	0.0	0.0	0.0
3	EDVAP	341.2	20.6	-24.1				
	HVE	343.4	18.5	-25.2	3.0	0.9	1.1	0.3
4	EDVAP	-224.3	-0.3	180.5				
	HVE	-225.2	-0.5	180.5	0.9	0.4	0.0	0.0
5	EDVAP	-243.5	-8.2	-0.3				
	HVE	-245.9	-9.8	-6.2	2.9	1.2	5.9	1.6
6	CALC	0.0	105.9	90.0				
	HVE	0.0	105.9	90.0	0.0	0.0	0.0	0.0
7	CALC	0.0	99.5	-90.0				
	HVE	0.0	99.5	-90.0	0.0	0.0	0.0	0.0
8	HVE*	73.3	0.6	0.7	N/A	N/A	N/A	N/A
				HVE Average Error	1.51	0.57	1.44	0.40
				Standard Deviation	1.16	0.37	1.78	0.50

TABLE 4. EDVTS Simulation Validation Results (error data for tow vehicle only)

TEST No.	METHOD	REST POSITION X (ft.)	REST POSITION Y (ft.)	REST POSITION PSI (deg.)	REST POSITION Gamma (deg.)	ERROR Range (ft.)	ERROR Range (%)	ERROR Heading (deg.)	ERROR Heading (%)
1	EDVAP	107.7	113.0	153.8	4.8				
	HVE	107.7	112.9	152.7	4.6	0.1	0.1	1.1	0.3
2	EDVAP	75.3	11.9	61.3	-50.7				
	HVE	75.3	11.9	61.3	-50.7	0.0	0.0	0.0	0.0
3	EDVAP	-113.0	-37.3	163.7	10.3				
	HVE	-113.0	-37.2	163.4	10.0	0.1	0.1	0.3	0.1
4	EDVAP	-234.9	-277.1	231.7	0.0				
	HVE	-234.6	-276.7	230.7	0.0	0.5	0.1	1.0	0.3
5	EDVAP	32.7	253.2	27.3	50.4				
	HVE	31.7	252.3	28.3	49.9	1.3	0.7	-1.0	-0.3
6	CALC	0.0	105.9	90.0	0.0				
	HVE	0.0	105.9	90.0	0.0	0.0	0.0	0.0	0.0
7	CALC	0.0	99.5	-90.0	0.0				
	HVE	0.0	99.5	-90.0	0.0	0.0	0.0	0.0	0.0
8	HVE*	73.3	0.4	0.0	0.3	N/A	N/A	N/A	N/A
					HVE Average Error	0.41	0.20	0.28	0.08
					Standard Deviation	0.41	0.19	0.62	0.17

* No comparisons available.

VALIDATION RESULTS

The specific results for each program are provided below.

EDSVS and EDVTS

The suite of five input data sets used to validate EDSVS and EDVTS are described in Table 2 (reference [12]); the data sets are also shipped with the software. The resulting path rest positions for the EDVAP and HVE versions of EDSVS are shown in Table 3; EDVTS results are shown in Table 4.

Extensions

EDSVS and EDVTS already included quasi-static roll and pitch load transfers due to lateral and longitudinal acceleration. In HVE, these programs were extended to take advantage of the three-dimensional HVE environment. Two functions were added to EDSVS and EDVTS:

- `GetSurfaceInfo()` is called by the tire model for each tire to obtain the tire contact patch elevation, surface normal and friction for the current timestep.
- `AutoPosition()` is called by the routine that calculates derivatives to include the current roll and pitch orientations used to calculate the gravity force vector for the current timestep.

These functions are described further in references 13 and 14.

To validate EDSVS and EDVTS on sloped surfaces, three new data sets were added to each program's test suite, as described in Table 2. The results of these additional tests are also shown in Tables 3 and 4.

Discussion

Minor differences were observed between EDVAP and HVE results. The differences were found to be attributable to rounding of the input that occurs during conversion from the user's system of units to the program's system of units. The differences were generally less than 1 % of both path and heading angle change.

As expected, the validations on a 5% upgrade and downgrade matched hand calculations for tests 6 and 7 (which included no braking or steering). The vehicle accelerates at ± 0.05 g. The cross slope test was provided as an example of how the gravity force vector affects the tire model. Note the vehicle assumes a slight yaw angle because the CG is not in the m iddle of the vehicle; thus the gravity vector produces a small yaw moment (again, this is consistent with normal vehicle behavior). Additional testing has also shown that on-grade vehicles with simulated braking and throttle inputs experience a ± 0.05 g change due to the grade.

A detailed, well-documented set of handling tests for vehicles travelling on sloped surfaces has not been found. Therefore, a rigorous validation of EDSVS and EDVTSfor combined braking and steering on sloped surfaces was not performed in this study.

EDCRASH

EDCRASH was the only reconstruction-type program in the current validation study. The RICSAC input data sets were used to validate EDCRASH (the actual data sets are included in Reference 7 and are shipped with the software). The results for EDVAP/EDCRASH and HVE/EDCRASH are shown in Table 5.

Extensions

EDCRASH was extended to allow up to nine crush zones. Because all the input data sets were predefined with one, three or five crush zones, this extended feature was not exercised in the current validation. However, it should be expected to show minor improvements for extremely irregular damage patters.

Discussion

As expected, comparison of the results reveals close agreement between EDVAP/EDCRASH and HVE/EDCRASH, as shown in Table 5. The average error was about 5 percent of combined impact speed for all runs, with a standard deviation of about 6 percent. It should be noted this validation did not use the Trajectory Simulation option.

EDSMAC

The RICSAC input data sets were used to validate EDSMAC (the actual data sets are included in Reference 7 and are shipped with the software). The validation results from the RICSAC tests and for EDVAP/EDSMAC and HVE/EDSMAC are shown in Table 6.

Extensions

Like EDSVS and EDVTS, EDSMAC was also extended to include gravitational forces resulting from travel on sloped surfaces (see the previous discussion of `GetSurfaceInfo()` and `AutoPosition()` functions). Preliminary validations have confirmed behavior identical to EDSVS Validation Tests 6, 7 and 8 (described earlier). These results are also shown in Table 6 (see Tests 13 and 14).

Discussion

As expected, comparison of the results reveals close agreement between EDVAP/EDSMAC and HVE/EDSMAC, as shown in Table 6. The difference in rest position was less than 1 foot and 1 degree in most cases. Again, the difference was attributable to rounding.

TABLE 5. EDCRASH Reconstruction Validation Results

TEST No.	METHOD	IMPACT SPEED Veh #1 (mph)	IMPACT SPEED Veh #2 (mph)	ERROR (Combined Speed) Veh #1 (mph)	Veh #1 (%)	Veh #2 (mph)	Veh #2 (%)
1	Measured	19.8	19.8				
	EDVAP	20.7	22.3	0.9	2.3	2.5	6.3
	HVE	20.6	22.2	0.8	2.0	2.4	6.1
2	Measured	31.5	31.5				
	EDVAP	27.9	32.7	-3.6	-5.7	1.2	1.9
	HVE	28.6	32.6	-2.9	-4.6	1.1	1.7
3	Measured	21.0	0.0				
	EDVAP	19.7	5.1	-1.3	-6.2	5.1	24.3
	HVE	18.3	5.5	-2.7	-12.9	5.5	26.2
4	Measured	38.7	0.0				
	EDVAP	33.3	-6.0	-5.4	-14.0	-6.0	-15.5
	HVE	35.3	3.4	-3.4	-8.8	3.4	8.8
5	Measured	39.7	0.0				
	EDVAP	41.1	-2.6	1.4	3.5	-2.6	-6.5
	HVE	42.0	0.0	2.3	5.8	0.0	0.0
6	Measured	21.5	21.5				
	EDVAP	24.4	24.5	2.9	6.7	3.0	7.0
	HVE	24.4	24.5	2.9	6.7	3.0	7.0
7	Measured	29.1	29.1				
	EDVAP	25.9	34.7	-3.2	-5.5	5.6	9.6
	HVE	25.6	34.8	-3.5	-6.0	5.7	9.8
8	Measured	20.8	20.8				
	EDVAP	16.8	25.7	-4.0	-9.6	4.9	11.8
	HVE	16.9	25.8	-3.9	-9.4	5.0	12.0
9	Measured	21.2	21.2				
	EDVAP	19.6	21.6	-1.6	-3.8	0.4	0.9
	HVE	22.6	23.7	1.4	3.3	2.5	5.9
10	Measured	33.3	33.3				
	EDVAP	31.1	33.7	-2.2	-3.3	0.4	0.6
	HVE	30.6	32.0	-2.7	-4.1	-1.3	-2.0
11	Measured	20.4	20.4				
	EDVAP	16.9	16.5	-3.5	-8.6	-3.9	-9.6
	HVE	16.9	17.8	-3.5	-8.6	-2.6	-6.4
12	Measured	31.5	31.5				
	EDVAP	17.8	29.0	-13.7	-21.7	-2.5	-4.0
	HVE	17.7	29.0	-13.8	-21.9	-2.5	-4.0
	HVE Average Error			-2.42	-4.86	1.85	5.43
	Standard Deviation			2.84	6.39	2.43	6.28

Comparison of the simulation results with the measured RICSAC data requires a careful review of the tests and the RICSAC data sets themselves. For example, in some cases, the simulations terminated at tmax before the vehicles had stopped. In one case, the actual vehicle was stopped by its data umbilical. These important issues are addressed in detail in references 3 and 7.

This validation did not include of simulated and actual damage profiles or CDC's. Preliminary, in-house validation has confirmed HVE/EDSMAC results substantially similar to EDVAP/EDSMAC.

GENERAL DISCUSSION

In a previous validation study [3], we discussed the term accuracy as it relates to simulations. This issue is so fundamental to the use and acceptance of simulations, it is included again.

The term 'accuracy' is felt to be somewhat misleading when applied to simulations of motor vehicle crashes. This is true for several reasons. The investigator is normally interested in the accuracy of speed estimates. However, for simulations, speed is an *input* quantity. The true purpose of a simulation is to predict the outcome of an event - in this case, the resulting vehicle paths and damage profiles. Given enough time, the investigator can adjust the program parameters until the simulated paths and damage profiles match the measured results nearly perfectly. One must then address the accuracy of the individual input parameters (some of which are rather crude estimates) used to achieve the match.

A match between simulated and measured paths and damage profiles can normally be achieved using a variety of data combinations. Therefore, if speed is an issue, a range of speed estimates should be examined and matches should be attempted. The minimum and maximum limits of the speed range are found when the known evidence can no longer be matched using reasonable input parameters.

This validation included no to attempt to optimize the inputs to improve the match between simulated and actual vehicle paths. Optimization is certainly possible and, in fact, recommended when initial attempts to model an accident sequence result in a poor match. Methods for optimization were addressed in an earlier validation [3]; researchers are encouraged to review that process.

Readers of this research are encouraged to review earlier validations [2,3,4,5,6,7] to gain learn how the RICSAC testing was performed, and to learn about the applications and limitations of the RICSAC data. In particular, the current study should be viewed as an extension of references 2 and 3. Several important issues were addressed in that research that were not included here.

TABLE 6. EDSMAC Simulation Validation Results

TEST No.	METHOD	REST POSITION						ERROR							
		Veh #1			Veh #2			Veh #1				Veh #2			
		X (ft)	Y (ft)	PSI (deg)	X (ft)	Y (ft)	PSI (deg)	Range (ft)	Range (%)	Heading (deg)	Heading (%)	Range (ft)	Range (%)	Heading (deg)	Heading (%)
1	Measured	-1.0	5.4	-1.5	8.5	7.8	105.0								
	EDVAP	-1.0	5.5	1.3	8.8	7.2	92.1	0.1	0.6	2.8	0.8	0.7	4.3	-12.9	-3.6
	HVE	-1.0	5.5	1.2	8.7	7.1	91.8	0.1	0.6	2.7	0.8	0.7	4.6	-13.2	-3.7
2	Measured	11.0	9.4	55.0	23.6	12.5	134.0								
	EDVAP	4.4	3.5	78.5	22.2	14.9	177.6	8.9	33.2	23.5	6.5	2.8	9.4	43.6	12.1
	HVE	4.4	3.5	78.3	22.4	14.9	178.7	8.9	33.2	23.3	6.5	2.7	9.0	44.7	12.4
3	Measured	111.4	2.0	-4.0	181.5	-6.3	-19.0								
	EDVAP	118.2	3.7	-4.6	192.5	-0.6	-22.5	7.0	6.8	-0.6	-0.2	12.4	7.8	-3.5	-1.0
	HVE	114.6	4.2	-4.3	190.8	-1.0	-22.4	3.9	3.8	-0.3	-0.1	10.7	6.8	-3.4	-0.9
4	Measured	42.8	54.5	137.5	63.9	62.5	88.0								
	EDVAP	36.4	58.1	137.5	79.4	60.1	54.6	7.3	10.6	0.0	0.0	15.7	20.7	-33.4	-9.3
	HVE	36.6	57.8	136.7	80.3	60.1	54.5	7.0	10.1	-0.8	-0.2	16.6	21.9	-33.5	-9.3
5	Measured	252.0	0.0	0.0	59.0	35.0	282.0								
	EDVAP	175.6	-30.0	-10.6	83.4	30.5	243.5	82.1	32.6	-10.6	-2.9	24.8	45.9	-38.5	-10.7
	HVE	174.7	-29.9	-10.6	83.7	30.7	237.0	82.9	32.9	-10.6	-2.9	25.1	46.4	-45.0	-12.5
6	Measured	60.0	11.0	15.0	20.0	21.0	242.0								
	EDVAP	35.1	17.7	33.2	20.7	28.5	244.8	25.8	42.3	18.2	5.1	7.5	35.1	2.8	0.8
	HVE	34.4	17.4	33.5	21.2	29.6	245.5	26.4	43.3	18.5	5.1	8.7	40.4	3.5	1.0
7	Measured	84.5	18.2	16.5	22.9	41.4	262.0								
	EDVAP	96.2	7.3	5.0	2.3	47.1	285.3	16.0	18.5	-11.5	-3.2	21.4	50.9	23.3	6.5
	HVE	93.8	7.3	5.1	2.5	47.5	285.8	14.3	16.6	-11.4	-3.2	21.3	50.7	23.8	6.6
8	Measured	0.0	10.8	45.0	6.3	19.2	130.0								
	EDVAP	0.7	10.8	41.9	3.8	22.0	133.7	0.7	5.0	-3.1	-0.9	3.8	18.6	3.7	1.0
	HVE	0.9	10.5	39.3	0.5	26.1	130.9	0.9	6.8	-5.7	-1.6	9.0	44.6	0.9	0.3
9	Measured	4.0	35.5	104.0	-5.0	49.5	152.0								
	EDVAP	7.7	16.9	73.8	-17.9	57.3	166.6	19.0	53.1	-30.2	-8.4	15.1	26.7	14.6	4.1
	HVE	7.7	16.9	73.9	-17.7	57.3	166.6	19.0	53.1	-30.1	-8.4	14.9	26.4	14.6	4.1
10	Measured	5.0	43.0	87.0	0.0	99.5	128.5								
	EDVAP	-4.5	25.7	148.5	5.5	103.2	117.8	19.7	45.6	61.5	17.1	6.6	6.3	-10.7	-3.0
	HVE	-6.0	27.5	141.8	1.9	99.4	120.6	19.0	43.9	54.8	15.2	1.9	1.8	-7.9	-2.2
11	Measured	25.6	-6.4	170.0	8.6	0.4	0.0								
	EDVAP	19.0	-6.0	164.1	5.0	0.7	0.3	6.6	65.1	-5.9	-1.6	3.6	42.0	0.3	0.1
	HVE	19.1	-6.1	164.0	4.9	0.7	0.3	6.5	64.0	-6.0	-1.7	3.7	43.1	0.3	0.1
12	Measured	22.3	-5.5	118.0	6.8	2.6	-12.0								
	EDVAP	23.7	-8.3	140.7	7.1	1.6	-1.9	3.1	45.0	22.7	6.3	1.0	14.3	10.1	2.8
	HVE	23.5	-8.2	141.2	7.1	1.6	-1.9	3.0	42.4	23.2	6.4	1.0	14.3	10.1	2.8
13	CALC	10.0	105.9	90.0	-10.0	-99.5	-90.0								
	HVE	10.0	105.9	90.0	-10.0	-99.5	-90.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	HVE*	73.3	10.7	0.8	-73.3	-9.3	179.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
							HVE Average Error	15.99	29.22	4.80	1.33	9.69	25.84	-0.43	-0.12
							Standard Deviation	13.88	18.04	16.77	4.66	6.68	16.10	16.81	4.67

CONCLUSIONS

1. This research provides an initial validation of the current EDVAP programs (EDSVS, EDVTS, EDCRASH and EDSMAC) in the three-dimensional HVE environment.

2. By using the existing validation test suites and the RICSAC staged collisions, the HVE results compared very closely with the earlier EDVAP validations. Minor differences were found and attributed to rounding of the inputs.

3. Significant ifferences were observed between the simulated and measured values for several tests. These differences occurred because the length of the simulation (t_{max}) was too short and the vehicles had not reached the end of the run when the simulation terminated. An earlier study [3] addressed this issue and produced a set of optimized input files. No optimization was performed in this study.

4. This validation was limited to vehicle trajectories. Additional validation work is required for damage profiles and the *trajectory simulation* option in EDCRASH.

5. Validations of EDSVS, EDVTS and EDSMAC on sloped surfaces confirmed results consistent with the magnitude and direction of the gravity vector. Additional validation is under way for combined braking and steering on sloped surfaces.

6. The classic definition of error was shown to lead to erroneous conclusions regarding program accuracy in certain cases (e.g., for the case of a struck vehicle with zero initial velocity). For this reason, the combined impact speed was chosen as the error criterion.

7. The term *accuracy* had little meaning when applied to simulation programs because, given enough time, nearly any level of desired accuracy could be achieved.

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