APPLICATION OF THE ACCIDENT SIMULATION PROGRAMS CRASH AND SMAC

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1. INTRODUCTION

Accident analysis is an important tool for automobile engineers to evalute the behaviour of vehicle components which are built for minimizing accident consequences. The knowledge about the accidents sequence, the physics of impact, ΔV and acceleration levels are important parameters for analysing an accident. The computer programs Crash and Smac were tested taking into consideration their value and applicability for the development engineer in the following fields:

- Differences between simulation, real accidents and tests
- Differences between results of a simulation and physical calculations and sensetivity of the Smac-Calculation procedure.

This analysis is performed with the most frequent and common accident types.
The achieved data are based on numerus test results and Smac-runs.

2. DESCRIPTION OF ACCIDENT RECONSTRUCTION PROGRAMS

2.1 Accident Reconstruction Program Crash

We assume that the crash program is well known to this auditorium. The crash program is fed with accident input data, such as assumed impact coordinates, rest coordinates and damage data, which generate the output datalist, shown on table 1.

Table No. 1

	Vehicle 1	Vehicle 2
Speed Change (Traj only)	21.2 mph	10,5 mph
Collision Force Angle	- 9.0 Deg	81.0 Deg
Speed Change (Damage only)	28.0 mph	13,7 mph
Collision Force Angle	- 12 Deg	70 Deg
Impact Speed	54,5 mph	- 2,3 mph
Energy Dissipated by Damage	84094,3 FT-LB	38 334.3 FT-LB
Speed Along Line Throu CGS	54,3 mph	- 1.3 mph
Speed orthog. to C.G. line	34,8 mph	2.0 mph
Closing Velocity	53,0 mph	

Those output data are parts of the input-data for the subsequent Smac-runs. The exacter the input-information is, the preciser are the generated output-data.

2.2 Description of Smac

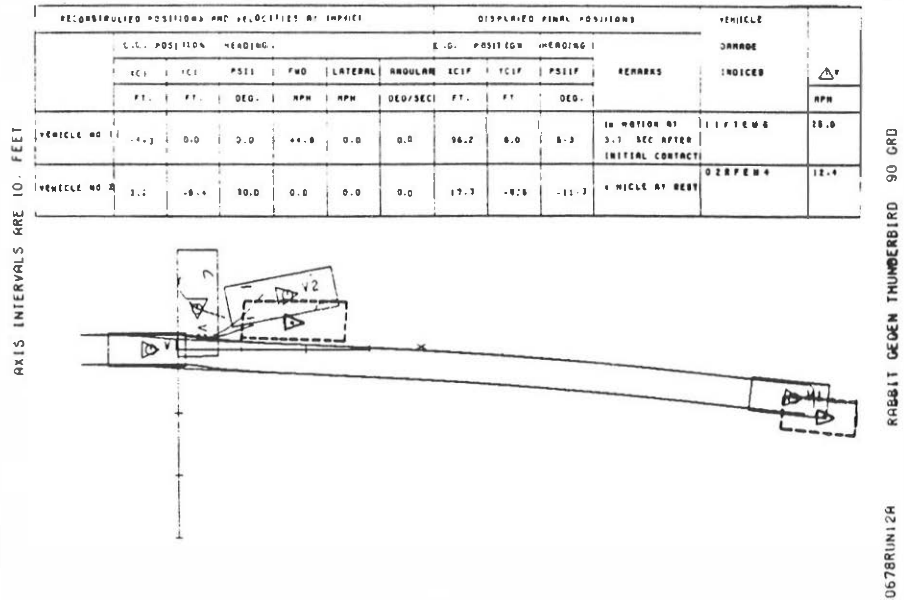
Smac is a "simulation" type of computer program which generates a time-history form of response prediction and a corresponding body of "evidence" (i.e., rest positions, damage and tire marks and tracks) in the same manner as an exploratory physical experiment. Applications follow an iterative procedure in which successive runs are performed, with adjustments of speeds and driver control inputs, until an acceptable overall match of the available real evidence in a given case is obtained.

The Smac computer program consists of a set of equations and associated solution logic defining the behaviour of a two-body physical system, which are programmed for simultaneous step-by-step solutions on a digital computer throughout a selected interval of time. The equations define the balance of applied and inertial forces and moments acting on each of the two vehicles during both collision contacts between the vehicles and the separate trajectories that precede and follow a collision. They are based on fundamental physical laws (i.e., Newtonian dynamics of rigid bodies) and on empirical relationships fitted to measured experimental data, such as the load-deflection characteristics of automobile structures and the force-generating properties of tires.

An optional computer graphics display of predicted results serves to ease the task of making comparisons of predicted and measured evidence.

2.3 Example for Application of the Smac-Program

For better understanding an accident reconstruction with "Smac" is shown in figure No. 1.



	RECONSTRUCTED POSITIONS AND VELOCITIES AT IMPACT						DISPLACED FINAL POSITIONS				VEHICLE DAMAGE INDICES	
	C.G. POSITION		HEADING				C.G. POSITION		HEADING			
	XC1	YC1	PSI1	FWD	LATERAL	ANGULAR	XC1F	YC1F	PSI1F	REMARKS		ΔV
	FT.	FT.	DEG.	MPH	MPH	DEG/SEC	FT.	FT	DEG.			MPH
VEHICLE NO 1	-4.3	0.0	0.0	44.8	0.0	0.0	96.2	0.0	8.3	IN MOTION AT 3.1 SEC AFTER INITIAL CONTACT	11FYEW8	25.0
VEHICLE NO 2	3.2	-8.4	10.0	0.0	0.0	0.0	17.1	-0.6	-11.3	VEHICLE AT REST	02RFEW4	12.4

Figure No. 1

In order to be able to compare the results of a simulation with a real-world-test, a lateral collision of a Rabbit (the US-version of the Golf) and a thunder-bird was performed. The basic problem of each accident reconstruction is the poor knowledge of the impact vector and the impact coordinates. In order to find out the ability of such a simulation program with known-pre-crash data, we simulated the above mentioned lateral collision. It took us some ten runs until we achieved a certain simularity between the results of the real test and the computer simulation. Those results are shown in picture No. 1. The ΔV of the striking Rabbit is calculated approximately 10 % higher than the measured ΔV in the real test.

If the starting parameters are unknown, several iteration steps have to be performed until a simularity of calculated and real world test results is achieved. When the iteration steps led to the same results already found on the accident-site, it can be concluded that this accident happend as assumed. We are now going to hear more about the application of the computer programs comparing the results with those of crash tests conducted in our Wolfsburg proving ground. A better knowledge of the impact configuration than achieved in those tests cannot be expected in real world accidents. Although all input parameters were known from the previous tests, we still got simulation results, differing slightly from the test-results. This clearly indicates the limitations of "Smac" and "Crash".

3. Frontal Collision Vehicle-Vehicle

3.1 Conducted Test

According to Table 2, two vehicles were crashed. The table shows the most important test parameters.

Table No. 2 Collision Test Vehicle-Vehicle

		Test	Simulation		
			1	2	3
Masses (kg)	V1	1172	1172	1656	2012,5
	V2	1150	1150	1150	1150
impact (mph) speed	V1	32,1	32,1	32	32
	V2	31,4	31,5	32	32
structural stiffness $(\frac{KN}{m})$	V1	882,9	877,5	444,3	444,3
	V2	882,9	877,5	444,3	444,3
ΔV (mph)	V1	34,5	37,2	43,3	46,3
	V2	33,6	37,9	30,1	26,7
crush (mm)	V1	500	518,2	522	522
	V2	500	518,2	522	522
ΔV ratio		1,026	0,89	1,43	1,735
mass ratio		1,019	1,019	1,44	1,75

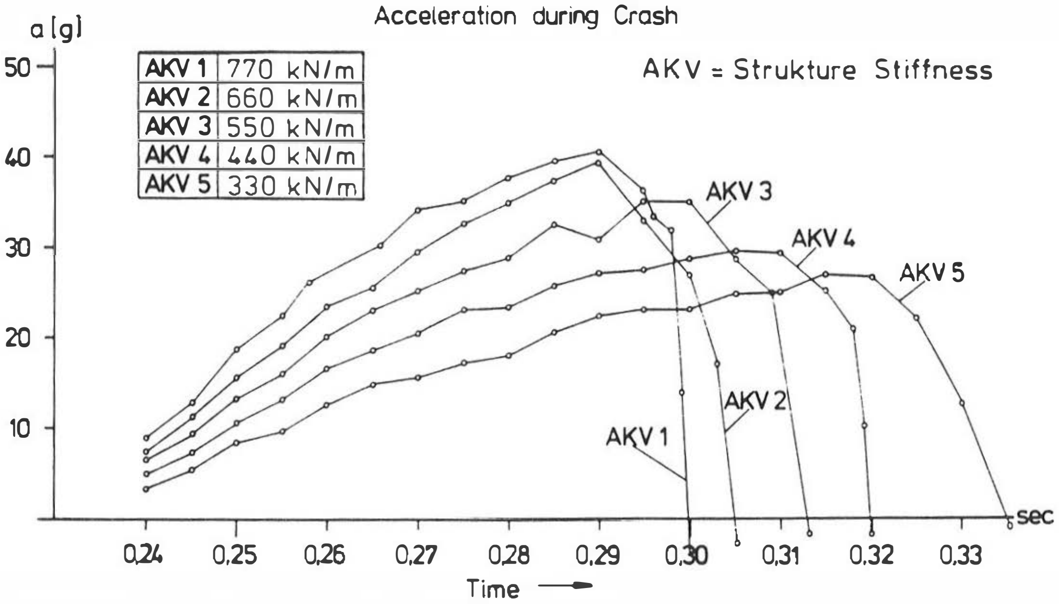
3.2 Smac-simulation-results

Smac-results of a frontal crash simulation are shown in column "Simulation 1" on table 2. The Δ Vs differs only by some 10 %. As follows the influence of variations of stiffness and masses is demonstrated.

Figure No. 2

Frontal Collision - Vehicle - Vehicle

Acceleration during Crash



3.2.1 Influence of Vehicle structural stiffness

The influence of an assumed linear structural stiffness upon the level of acceleration and the Δ Vs was simulated. The structural stiffnesses were varied between 330 KN/m and 770 KN/m. Depending upon this, the Δ Vs increased from 30,5 mph to 36,4 mph, because Smac generated coefficient of Restitution is a function of structure stiffness. The closing velocity was 32 mph. It is obvious that the rest positions of the cars described by the distance of the Centers of Graphity after the crash will increase. At a structural stiffness of 330 KN/m the distance of 9,4 ft after crash increases to 13,6 ft at a stiffness of 770 KN/m.

The variation of stiffnesses have the most obvious effect on the acceleration curve during the impact-phase. This influence is clearly demonstrated on picture No. 2 showing the variations of the acceleration levels between 25 and 40 g.

3.2.2 Influence of the Mass Ratio

If all other parameters but the mass-ratio are kept constant, we obtain the results of column "Simulation 2, 3" in table No. 2. In this simulation the structural stiffness was assumed with 440,0 KN/m and the closing velocity was chosen with 32 mph. The variations of mass-ratios result in different ΔV-distributions on both vehicles, just as the result was expected from the real Physics of Impact.

3.3.1 Special Case of Frontal Collisions

Vehicle Crash against rigid Barrier

Test Conduction

A frontal collision test against a rigid barrier (according to SAE J 850) was conducted. All important parameters are shown in left column of table No. 3.

Table No. 3 Rigid barrier crash test

	Test	Simulation
Masses (kg)	1164	1164
Impact speed (mph)	29,98	30,0
Structural stiffness $(\frac{KN}{m})$	884,9	884,9
C.O.R. (%)	15	14,5
ΔV (mph)	34,68	37,2
Crush (mm)	480	455

3.3.2 Frontal Collision-Simulation with Smac

Before the computer simulation could be performed, the following physical basic data had to be calculated from test results.

a) Coefficient of restitution (C.O.R.) by the ratio

$$\varepsilon = \frac{V\ \text{Rebound}}{V\ \text{Impact}} \qquad \varepsilon(\%) = \frac{V\ \text{Rebound}\ .\ 100}{V\ \text{Impact}} = \frac{2{,}1\ \frac{m}{s}\ .\ 100}{13{,}4\ \frac{m}{s}} = 15{,}6\ \%$$

b) Structural stiffness by difference of the kinetic energy, pre- and post-crash.

$$E_{kin_1} - E_{kin_2} = E_{def} = 101\ 936{,}12\ \text{Nm}$$

$$E_{def} = \int K ds$$

Assumption: $K = D\ .\ S$ $\qquad D = \frac{K}{S} = \text{const.}$

$$E_{def} = \int D\ .\ sds = D \int sds = D\ \frac{s^2}{2}$$

S = Crush

$$D = \frac{2\ E_{def}}{S^2} = \frac{2\ .\ 101\ 936{,}12\ Nm}{0{,}48^2\ m^2} = 884\ 862\ \frac{N}{m}$$

Calculated from these test conditions the program variables for the Smac Input File can be generated.

To a) Program Variable for Smac C.O.R. Input:

$$C = Co - C_1 \delta + C_2 \delta^2 \qquad \delta = \text{crush}$$

The coefficients Co, C_1, C_2 generate the C.O.R. (ε) as a function of vehicle crush as demonstrated in Figure No. 4.

For the above Simulation, the input parameters Co, C_1, C_2 were chosen in such a way, that you get a structure behavior, described by ε 5 in Figure No. 4.

Accordingly you will get with a crush of 455 mm (17,9 in) a Coefficient of Restitution of 14,5 %.

Assigned C.O.R., $\varepsilon_{Smac} = 14{,}5\ \%$

To b) Program Variable for Smac Stiffness Input is AKV which is defined as

$$\left(\frac{lbs}{inch_{\ crush} \cdot inch_{\ vehicle\ width}} \right)$$

That means $AKV = \frac{D\ .\ 2{,}2046}{veh.\ width\ .\ 39{,}37} = 79{,}66\ \frac{(lbs)}{(in^2)}$

The above discussed input parameters for Smac Simulation of a rigid barrier test led to the results shown in the right column of table No. 3.

Plotted results of the Smac run are demonstrated in Figure No. 3. The rigid barrier is marked as V2. There is a relativ high difference in ΔV between simulation and test. The in picture No. 4 mentioned function of coefficient of restitution and crush seems to limit the fidelity of the program as only linear characteristics can be computed. Nonlinear characteristics cannot be computed with the present available program. The base for all calculations is the following assumption: Linear characteristics between force and crush of the structure and the returned energy without hysteresis. Picture No. 5 shows this relations, which is taken from the manual of our available Smac-program.

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Figure No. 3

170478RUN V4

	RECONSTRUCTED POSITIONS AND VELOCITIES AT IMPACT						DISPLATED FINAL POSITIONS				VEHICLE DAMAGE INDICES	
	C.G. POSITION		HEADING				C.G. POSITION		HEADING	REMARKS		
	XC1	YC1	PSI1	FWD	LATERAL	ANGULAR	XC1F	YC1F	PSI1F			ΔV
	FT.	FT.	DEG.	MPH	MPH	DEG/SEC	FT.	FT.	DEG.			MPH
VEHICLE NO 1	13.0	6.7	0.0	30.0	0.0	0.0	10.8	6.7	-0.1	IN MOTION AT 4.8 SEC AFTER INITIAL CONTACT	11FDEW3	37.2
VEHICLE NO 2	25.0	6.7	180.0	0.0	0.0	0.0	25.1	6.7	179.3	IN MOTION AT 4.8 SEC AFTER INITIAL CONTACT	[illegible]	0.0

AXIS INTERVALS ARE 10. FEET

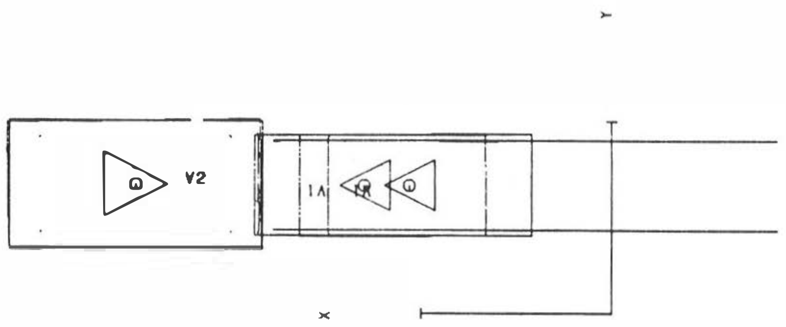


Figure No. 4
Coeffitient of restitution as funktion of residual Crush

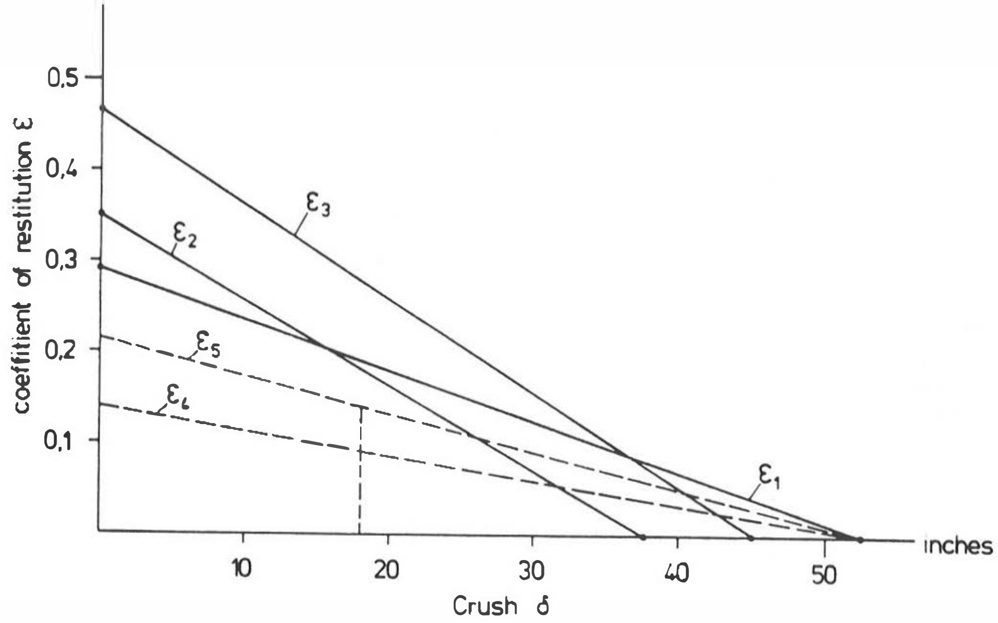
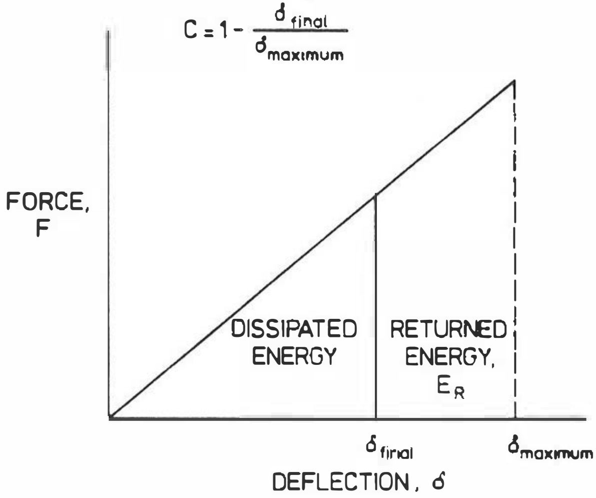


Figure No. 5

Assumed Form of Load-Deflection Characteristic for Loading and Unloading



The coefficient of restitution obviousely influences the rest positions of the computer simulations, because it is a parameter for the rebound energy. Assuming the tires are blocked during the rebound phase (snagging with the body) the rest positions shown on picture No. 6 will be generated. It is obvious, that with an increase of elasticity up to 26 % the rebound distance and △V will increase accordingly (look at rest position No. 7 in picture No. 6).

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Figure No.6

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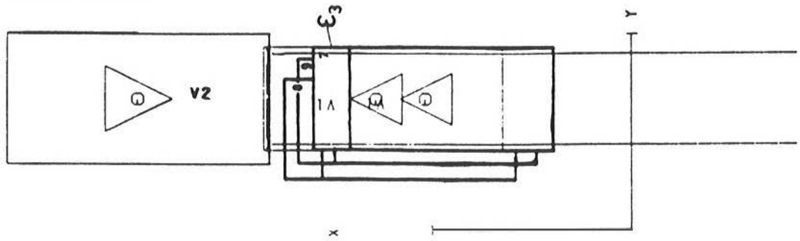
	RECONSTRUCTED POSITIONS AND VELOCITIES AT IMPACT						DISPLAYED FINAL POSITIONS				VEHICLE	
	C.G. POSITION		HEADING				C.G. POSITION		HEADING		DAMAGE	
	XC1	YC1	PSI1	FWD	LATERAL	ANGULAR	XC1F	YC1F	PSI1F	REMARKS	INDICES	△V
	FT.	FT.	DEG.	MPH	MPH	DEG/SEC	FT.	FT.	DEG.			MPH
VEHICLE NO 1	12.9	8.7	0.0	28.8	0.0	0.0	10.4	8.7	-0.0	IN MOTION AT 0.0 SEC AFTER INITIAL CONTACT	12FDEW3	36.2
VEHICLE NO 2	25.0	8.7	180.0	0.0	0.0	0.0	25.0	8.7	180.1	IN MOTION AT 0.0 SEC AFTER INITIAL CONTACT	0000 00	0.0

Rest Position	ε
7	0,26
8	0,16
9	0,19



4. Lateral Collision

4.1

A lateral collision was performed with a heading angle of 90 degree into the side of a stationary vehicle. The accident parameters of the test are given in table No. 4 (left column).

Table No. 4 Lateral Collision

		Test	Simulation
masses (kg)	V1	870	870,39
	V2	1020	1020,42
impact speed (mph)	V1	26,4	25,5
	V2	0,0	0,0
ΔV (mph)	V1	15,4	17,5
	V2	14,7	13,4
Crush (mm)	V1	80	145
	V2	260	337
C.O.R. (%)		4,24	11

4.2 Results of Accident Reconstruction

Picture No. 7 shows the results of the simulation comparing the results from test with the computer simulation results. The rest positions in the simulation were in a relative good fidelity with the test. Picture No. 7 also shows the Δ Vs of both vehicles. Also there is a good fidelity as far as geometrical rest positions are concerned the differences of the ΔV however are rather high up to 13 %. Specially in the case of a lateral crash the friction coefficient between tires and road has a great influence upon the angular velocities after crash. This influence is demonstrated in picture No. 8. The picture shows the rest positions of 6 computer runs (positions a - f) which are generated by varying the coefficient of friction from 0.4 to 0.8 on the left side of the boundry (front wheels of struck car). On the right side of the boundry there is an assumed constant coefficient of 0.8. The results in picture No. 8 are self explanatory.

Figure No. 7
Lateral Impact

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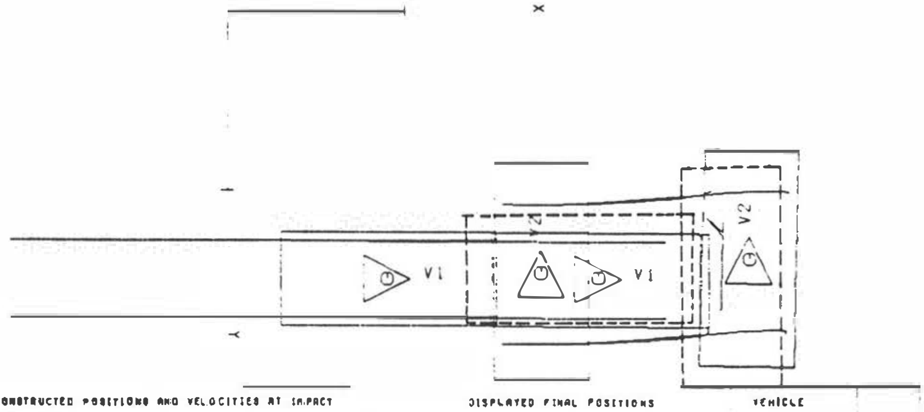
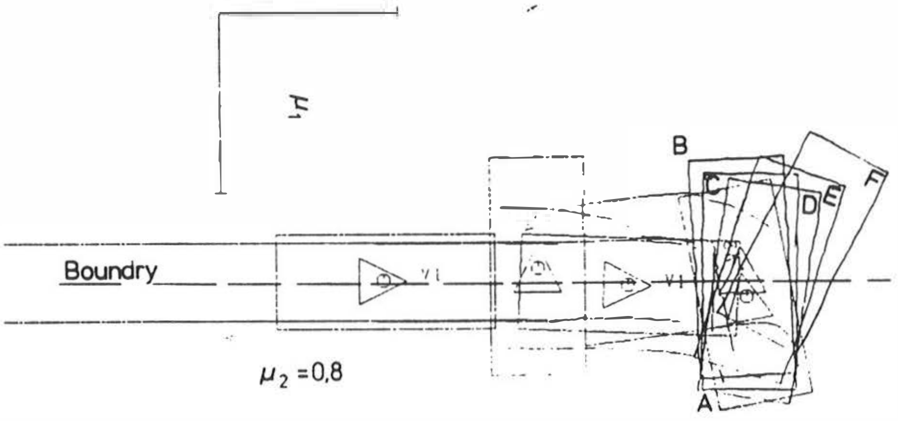


	RECONSTRUCTED POSITIONS AND VELOCITIES AT IMPACT						DISPLAYED FINAL POSITIONS				VEHICLE DAMAGE INDICES	
	C.G. POSITION		HEADING				C.G. POSITION		HEADING			
	XC1	YC1	PSI1	FWD	LATERAL	ANGULAR	XC1F	YC1F	PSI1F	REMARKS		ΔV
	FT.	FT.	DEG.	MPH	MPH	DEG/SEC	FT.	FT.	DEG.			MPH
VEHICLE NO 1	9.0	16.0	0.0	25.6	0.0	0.0	20.8	15.1	0.3	VEHICLE AT REST	12FDEW2 test	17.6 15.4
VEHICLE NO 2	17.6	14.7	-90.0	0.0	0.0	0.0	29.3	14.0	-88.6	VEHICLE AT REST	09LPEW3 test	13.4 14.7

Figure No. 8
Lateral Impact

	Coef. of friction	Rest Position
μ_1	0,8	A
μ_1	0,75	B
μ_1	0,7	C
μ_1	0,65	D
μ_1	0,55	E
μ_1	0,4	F



5. Rear End Collision

5.1 Conducted Test of a Rear End Collision

A rear end-collision of a movable rigid barrier with a mass of 4000 lbs, according to SAE J 850 and a vehicle with a mass of 2475,8 lbs was performed.

The results of test and simulation are demonstrated in Table No. 5.

Table No. 5 Rear end collision

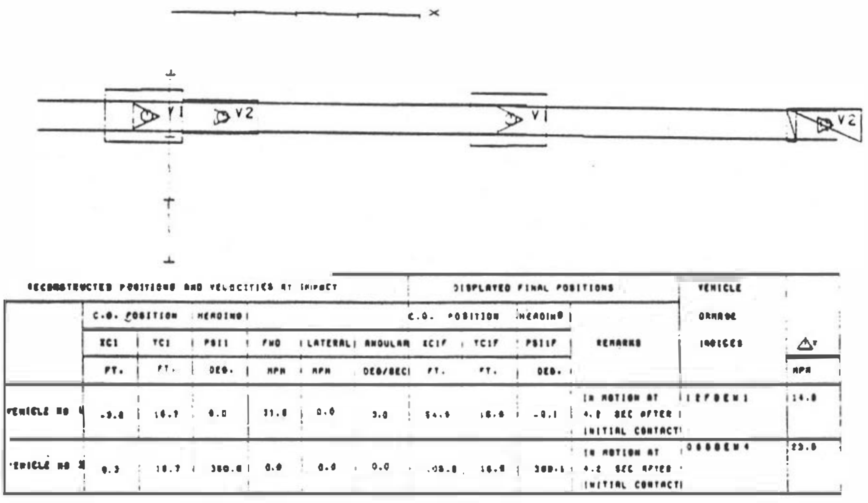
		Test	Simulation
masses (kg)	V1 V2	1814,4 1123	1814,4 1123
impact speed (mph)	V1 V2	31,32 0,0	31,2 0,0
ΔV (mph)	V1 V2	13,4 21,0	14,9 23,0
Crush (mm)	V2	510	500
C.O.R. (%)	V2	10	12.6

5.2 Results of Simulation

Picture No. 9 shows the results of simulation with Smac. With an assumed structure stiffness of 40 lbs/in² (444,3 KN/m) for the struck vehicle a relatively good fidelity will be generated, as far as the residual crush and the ΔVs are concerned.

Figure No. 9

Rear End Collision



	RECONSTRUCTED POSITIONS AND VELOCITIES AT IMPACT						DISPLAYED FINAL POSITIONS				VEHICLE DAMAGE INDICES	
	C.G. POSITION		HEADING				C.G. POSITION		HEADING	REMARKS		ΔV
	XC1	YC1	PSI1	FWD	LATERAL	ANGULAR	XC1F	YC1F	PSI1F			
	FT.	FT.	DEG.	MPH	MPH	DEG/SEC	FT.	FT.	DEG.			MPH
VEHICLE NO 1	-3.0	16.7	0.0	31.0	0.0	0.0	54.0	16.0	-0.1	IN MOTION AT 4.2 SEC AFTER INITIAL CONTACT	12FDEW1	14.0
VEHICLE NO 2	0.3	16.7	360.0	0.0	0.0	0.0	103.0	16.0	360.1	IN MOTION AT 4.2 SEC AFTER INITIAL CONTACT	06BDEW4	23.0

6. Application of **Subroutine Snag**

The Snag-function serves the purpose to simulate inhomogenious structure charcteristics. This subroutine is used to simulate stiff structure points, which cause snagging between two colliding vehicles or impacts between vehicles and narrow rigid obstacles.

During side-impacts, for example, at angles different from 90 degree friction forces are continously varying because of different stiffnesses of the engaging components. Those friction-changes are simulated by the Snag-subroutine by permitting to input arbitrary forces at an arbitrary time for an arbitrary duration at an arbitrary structure-point. The force is defined as a deflection-dependent linear spring with a constant increase. This force is limited by a chosen deflection. This so defined force acts until abitrary time-duration is exceeded, then it drops to zero. Picture No. 10 shows an application of the Snag function. The three rest-positions 4, 8 and 16 are the plotted results of three Smac-runs with different Snag-input-parameters. The results clearly indicate that an increasing Snag-force causes larger rotation of the vehicles. This effect can clearly be observed in picture No. 10 by comparing the rest positions of vehicle No. 2.

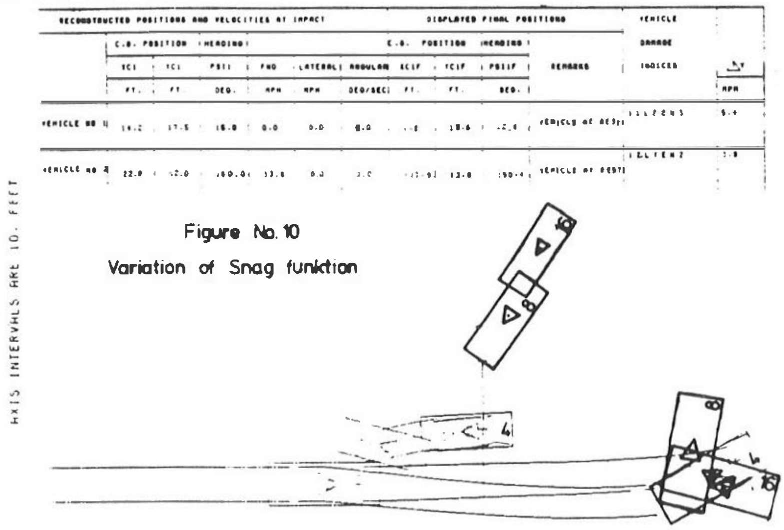


Figure No. 10
Variation of Snag funktion

Conclusions:

In order to get a precise simulation it is extremely important to have besides the pre-crash-configuration, a next to complete knowledge about the colliding vehicles, such as overall structure-stiffness **characteristics** and residual crushlayers of both impact partners. In multible accidents (primary and secondary vehicle collisions), such as run-off-road accidents with subsequent impact against another obstacle, the difficulties for reconstructing increase remarkably. In "normal, simple" accidents, such as front-end, rear-end, or side-impacts, the Smac-Crash-simulations allow the operator to predict ΔVs with a fidelity of some ± 15 %. For all accidents, more complicated than the standard like SAE-configurations, the reconstruction with Smac will become less exact, to a certain degree. This same limitation is valid too, if a reconstruction is done by using conventional physical methods (momentum). Therefor, the application of Smac and Crash computer-programs, will always lead to a more reliable result than a pure subjective statement with the limitations mentioned above, obtained in a vehicle-inspection and testimonius of occupant of witnesses.