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FEASIBILITY STUDY OF COMBINING HVOSM AND BARRIER VII

FINAL REPORT

BY

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1750 NEW YORK AVENUE, N.W.
WASHINGTON, D.C.

MARCH 1987

ANALYSIS GROUP, INCORPORATED

1750 New York Avenue, N.W. Suite 200 • Washington, D.C. 20006

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/RD-87/084		

4. Title and Subtitle	5. Report Date
Feasibility of Combining HVOSM and Barrier VII	March 1987
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Sudhamay Basu and Arun Chatterjee	AGI-7900-01
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Analysis Group, Incorporated Engineering Science Division 6000 Executive Boulevard, Suite 308 Rockville, Maryland 20852	11. Contract or Grant No. DTFH61-86-Z-00034
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address Federal Highway Administration Turner-Fairbank Highway Research Center 6300 Georgetown Pike McLean, Virginia 22101	Final Report July 1986 - December 1986
	14. Sponsoring Agency Code

15. Supplementary Notes

Contracting Officer's Technical Representative: Mr. Leonard Meczkowski

16. Abstract

This report discusses the results of a feasibility study dealing with the development of a new simulation program by combining the two existing simulation programs HVOSM and BARRIER VII. The first of these programs has a sophisticated vehicle model including vehicle handling and maneuvering and one of its versions, HVOSM-RD2, even has the reported capability of crash simulation. Note that the barrier model in HVOSM-RD2 is very crude. The second program, BARRIER VII, has a good barrier model but its vehicle model is unrealistically simple. The idea, therefore, arose about the feasibility of combining the good features of both programs to make one improved crash simulation program.

This study concludes that it is theoretically feasible to combine HVOSM and BARRIER VII to obtain a new program with improved vehicle and barrier simulation features. However, many practical problems are associated with such a development, and the effort required to accomplish this task may far outweigh its benefits. The study further concludes that the new simulation program, if developed, will at best be able to simulate the gross barrier behavior. Two finite element simulation programs, CRUNCH and GUARD, already exist to study barrier and vehicle behavior in great detail. It is not, therefore, cost-effective to develop a new program.

The above conclusions are supported by thorough comparison of HVOSM and BARRIER VII with regard to program description, mathematical model, computer program structure, and input/output requirements. The results of the study are reported in detail in the text. Modifications were then analyzed from a cost-benefit standpoint.

17. Key Words	18. Distribution Statement
Simulation Programs, HVOSM, BARRIER VII, Mathematical Model, Analytical Representation, Program Structure, Input/Output, Vehicle Handling, Roadside Barrier, Vehicle Dynamics, Subroutines	Distribution unlimited. Available through NTIS.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	47	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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EXECUTIVE SUMMARY

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The above conclusions are supported by a thorough comparison of HVOSM and BARRIER VII programs with regard to program description, mathematical model, computer program structure, and input/output requirements. The results of the study are reported in detail in the text. Based on the comparison, a determination was made as to the likely analytical representation of the new program and the associated program structure. Possible modifications of HVOSM and BARRIER VII to arrive at the new program structure were then analyzed from the cost-benefit standpoint.

FEASIBILITY STUDY OF COMBINING HVOSM AND BARRIER VII

1. Program Description

The Highway Vehicle Object Simulation Model (HVOSM) provides the capability of simulating the rigid body dynamics of an automobile and its interaction with the roadside environment. Two primary versions of HVOSM currently exist in the Applied Physics Laboratory (APL) computing system. The HVOSM-RD2 version has the reported capability of simulating the collision of an automobile with both rigid and deformable roadside barriers, and of simulating the rigid body motion of an automobile in the presence of arbitrary terrain geometrics. The rigid body dynamics of an automobile undergoing extensive maneuvering due to driver inputs (steering, brake torque, etc.) is simulated by version HVOSM-VD2. The two versions provide the user with the overall capability of simulating the following:

- o Vehicle handling and vehicle ride with either independent suspension or solid axle suspension or a combination thereof.
- o Impact between the vehicle and the roadside structures. This reported capability has not been verified properly for barriers considered as roadside structures; however, terrain geometrics considered as roadside elements are properly simulated.
- o The effects of variable terrain, contact between tires and curbs, and dynamics of wheel spin on vehicle response.

BARRIER VII is a computer program which simulates the interaction of an automobile with a roadside barrier. In particular, the program has the capability of simulating the following features:

- o Pre-collision and post-collision dynamics of an automobile modeled as a rigid body of arbitrary shape surrounded by a set of discrete inelastic springs.
- o Complex nonlinear modes of behavior of barriers including hysteresis effects in yielding members and including nonlinear elastic-plastic deformation.

- o Structural members of seven different types in any combination. These types are: beams, cables, springs, ideal columns, viscous dampers, frictional dampers, and posts.

BARRIER VII has two versions - the original Berkeley version and the modified Southwest Research Institute (SWRI) version. The subtle difference between the two versions lies in the computation of interaction forces between the vehicle and the barrier.

Quite naturally, both HVOSM and BARRIER VII have certain limitations just as they have some novel simulation features. The most serious limitation of BARRIER VII is that it is a two-dimensional program. Likewise, the most serious limitation of HVOSM is that, although it has the reported capability of simulating the impact of an automobile with a roadside barrier, it can only do so in a very limited sense; that is, in the case of rigid barrier only and that only by considering the barrier as a mere extension of the road profile. Both TTI and SwRI reported on different occasions to the A2A04 Committee that they exercised the HVOSM-RD2 version to simulate flexible barriers, although we are not aware of any results or validation thereof.

2. Mathematical Model Description

The basic mathematical model describing vehicle dynamics in both HVOSM and BARRIER VII is the equation of dynamic equilibrium of a lumped mass system, i.e.:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \qquad (1)$$

in which
$[M]$ = mass matrix
$[C]$ = damping matrix
$[K]$ = stiffness matrix
$\{\ddot{x}\}$ = acceleration vector
$\{\dot{x}\}$ = velocity vector
$\{x\}$ = position vector
$\{F(t)\}$ = external force vector

In the case of HVOSM, the lumped mass system primarily consists of the following elements:

Sprung mass with six degrees of freedom
Unsprung masses with four degrees of freedom
Steering inertia with one rotational degree of freedom
Wheel spin inertia with four degrees of freedom (for HVOSM-VD2 version only)

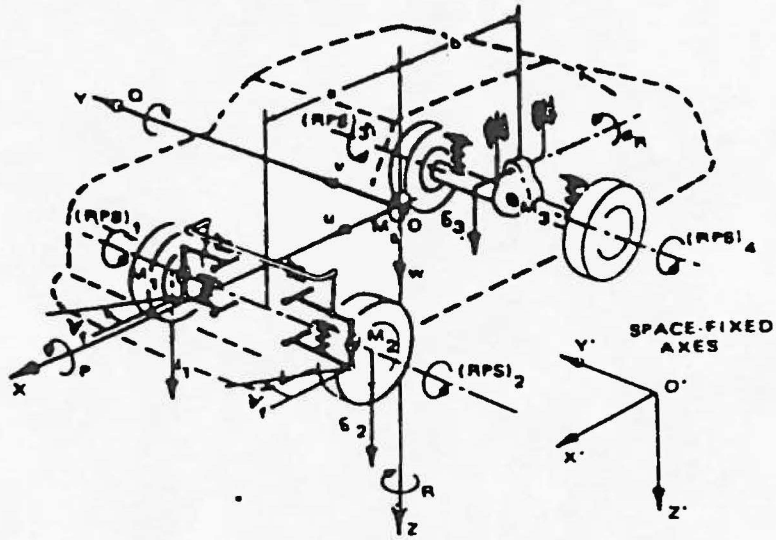
For sprung mass (chassis and body), the six degrees of freedom are three translational motion and three rotational motion. For unsprung masses (wheels and/or axles), the four degrees of freedom are vertical motion of two wheels (either front or rear), vertical motion of axle and relative rotation of axle. The steer angle of the front wheels is an optional degree of freedom which may be specified. Finally, the HVOSM-VD2 version includes the rotational degrees of freedom for the four wheels. This analytical representation of a vehicle in the HVOSM program is illustrated in figure 1. Note that the vectors in equation (1) above are 11-dimensional (i.e., 6+4+1) in the case of HVOSM-RD2 and 15-dimensional (i.e., 6+4+1+4) in the case of HVOSM-VD2.

The external force vector {F(t)} in equation (1) consists of tire forces and impact forces in the case of HVOSM-RD2, and tire forces, rolling resistance, and aerodynamic forces in the case of HVOSM-VD2. Tire forces include the radial forces in the plane of the wheel arising from in-plane tire deformations, the side force arising from slip and camber angles, and tractive (circumferential) force arising from applied torques. The resultant tire forces are calculated by adding vectorially the components as follows:

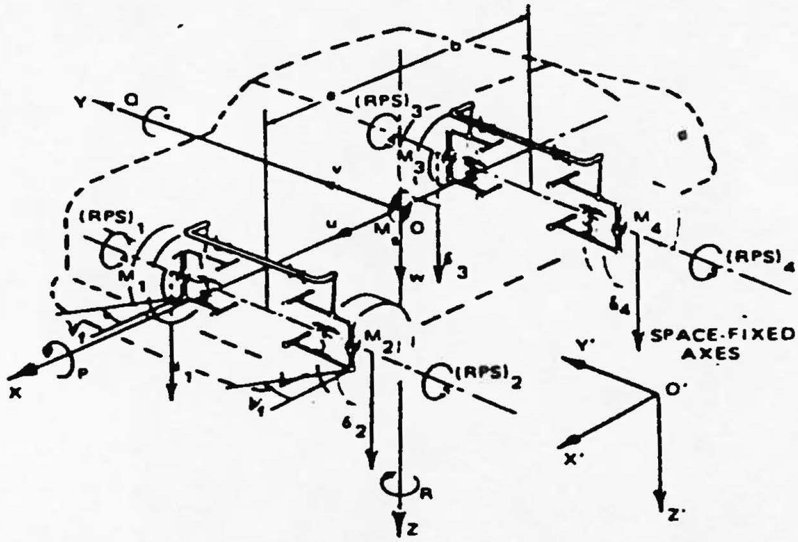
$$F_{ui} = F_{rui} + F_{cui} + F_{sui} \qquad (2)$$

where the subscripts u, i, r, c, and s stand for unsprung mass, ith tire, radial, circumferential, and side, respectively. Note that in the case of HVOSM-VD2, the circumferential tire force calculation accounts for wheel spin by incorporating four additional degrees of freedom and by using the "friction concept rather than the "friction circle" concept as in the case of HVOSM-RD2.

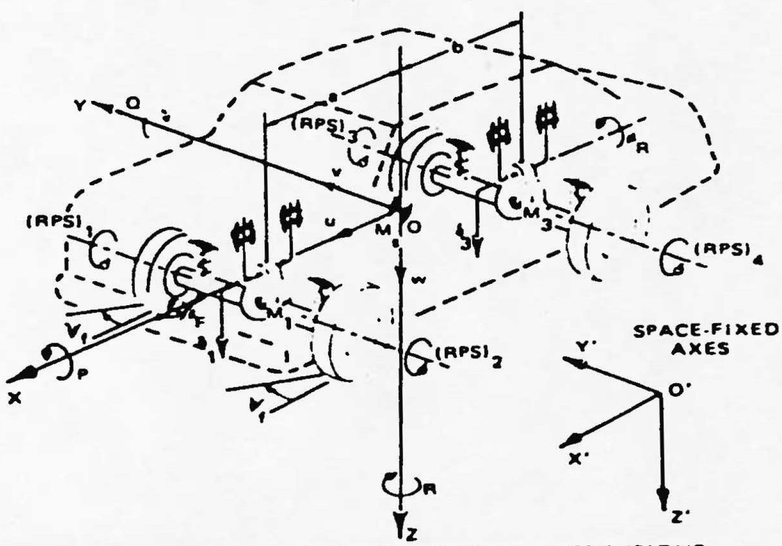
The effects of aerodynamic drag are approximated by a force $F_a(t)$ applied directly to the sprung mass. An empirical relationship is used to approximate



(a) INDEPENDENT FRONT - SOLID-AXLE REAR SUSPENSION



(b) INDEPENDENT FRONT AND REAR SUSPENSION



(c) SOLID AXLE FRONT AND REAR SUSPENSIONS

Figure 1. Analytical Representation of a Vehicle in HVOSM

the magnitude of the applied force as a function of the first and second powers of the longitudinal component of vehicle velocity. It is assumed, for simplicity, that the motion-resisting force acts through the center of gravity of the sprung mass, and along the longitudinal axis of the vehicle (i.e., the X-axis), in the direction opposite that of the longitudinal component of the vehicle velocity. Rolling resistance is approximated as a motion-resisting moment applied to each wheel. This moment varies with tire radial force $F_r(t)$.

Impact forces, considered in the HVOSM-RD2 version only, are calculated using the following relationship:

$$F_N = K_V \int A\,d\delta \qquad (3)$$

where K_V = stiffness of vehicle structure
A = contact area
δ = penetration depth

A number of assumptions are inherent in the above impact force calculation. These are:

1. The barrier must have flat, vertical faces typified by a vertical wall.

2. Tires cannot ride on barrier faces.

3. Inertial effects and curvature of the barrier are neglected.

4. The vehicle-barrier intersection (interference) points are treated as "hard points" which are defined relative to the vehicle C. G.

5. The vehicle sprung mass is treated as a rigid body surrounded by a layer of isotropic, homogeneous material which exhibits linear elastic-perfectly plastic behavior.

6. The barrier deflection is determined by equating the force required to produce the deflection to the vehicle crush force.

The hard points are a discrete set of points on the imaginary vehicle panel which define the vehicle-barrier interface. These points are rigid and, by definition, nondeformable. Therefore, in the interaction force calculation, pseudo-deflected positions of these hard points are assumed.

The total force, {F(t)}, is, in principle, the vector sum of the forces described above. In other words,

$$\{F(t)\} = F_{ui}(t) + F_a(t) + F_r(t) \tag{4}$$

for the case of HVOSM-VD2, and

$$\{F(t)\} = F_{ui}(t) + F_N(t) \tag{5}$$

for the case of HVOSM-RD2.

Note that the simulation program HVOSM solves equation (1) to determine the vectors $\{\ddot{x}(t)\}$, $\{\dot{x}(t)\}$, and $\{x(t)\}$ which then give the trajectory of a vehicle as a function of time. The solution procedure is as follows:

1. Determine the mass matrix [M], damping matrix [C], and the stiffness matrix [K] from given vehicle properties and input data

2. Evaluate the time dependent forcing function {F(t)}

3. Assume values of $\{\dot{x}(t)\}$ and $\{x(t)\}$ at a given time t, and evaluate $\{\ddot{x}(t)\}$ as follows:

$$\{\ddot{x}(t)\} = [M]^{-1}(\{F(t)\} - [C]\{\dot{x}(t)\} - [K]\{x(t)\}) \tag{6}$$

4. Integrate $\{\ddot{x}(t)\}$ to obtain $\{\dot{x}(t)\}$ and $\{x(t)\}$ at time $t+\Delta t$ and iterate the solution to obtain convergence.

Since the solution procedure is iterative, equation (6) is rewritten, in practice, in a compressed form as:

$$\{\ddot{x}(t)\} = [D]^{-1}\{E(\dot{x}, x, t)\} \tag{7}$$

where [D] is the "effective mass matrix" and $\{E(\dot{x}, x, t)\}$ is the "effective force vector" that includes both external and internal forces as well as forces resulting from specifying equations of motion in a non-Newtonian frame of reference. Equation (7) can be integrated iteratively using any standard numerical integration routine. The HVOSM program uses two such integration algorithms; namely, the classical Runge-Kutta method and the Adams-Moulton predictor-corrector method.

Although, as mentioned earlier, the basic mathematical model of BARRIER VII is the same as that of HVOSM, the similarity more or less ends here. First of all, BARRIER VII is a two-dimensional program in which barriers and automobiles are idealized as two-dimensional structural entities of arbitrary shape,s each possessing three degrees of freedom (two translations and one rotation) motion. Moreover, in BARRIER VII, the automobile is idealized as a rigid body surrounded by a cushion of discrete inelastic springs (see figure 2) and the barrier is idealized as a deformable body with complex nonlinear deformation behavior. This is in contrast to the descriptions in HVOSM where the automobile is considered to be crushable and the barrier (in RD2 version) is considered rigid.

The external force vector {F(t)} in BARRIER VII is basically composed of an interaction force between the automobile and the barrier. The formulation of this interaction force is based on two requirements; i.e., equilibrium of normal and tangential forces between the automobile and the barrier, and geometric compatibility. Tire forces, aerodynamic drag, and rolling resistance are not considered in the formulation of the external force vector as in the case of HVOSM. In the Berkeley version of BARRIER VII, it is assumed that the springs are always normal to the barrier wherever they are in contact. The SwRI version, however, considers that the springs are not always normal to the barrier. Consequently, in the interaction force calculation, the SwRI version takes only the component in the axial direction of the spring of the normal force coming from the barrier. It, therefore, appears that the estimate of interaction force in the Berkeley version is greater than that in the SwRI version.

In BARRIER VII, the dynamic equation of motion (equation (1)) is solved by a numerical integration procedure which basically transforms the second order differential equation into an algebraic equation in {x} involving an "effective" stiffness matrix and an "effective" force vector as follows:

$$[K_{eff}]\{x\} = \{P(\ddot{x}, \dot{x}, t, [M], [C])\} \qquad (8)$$

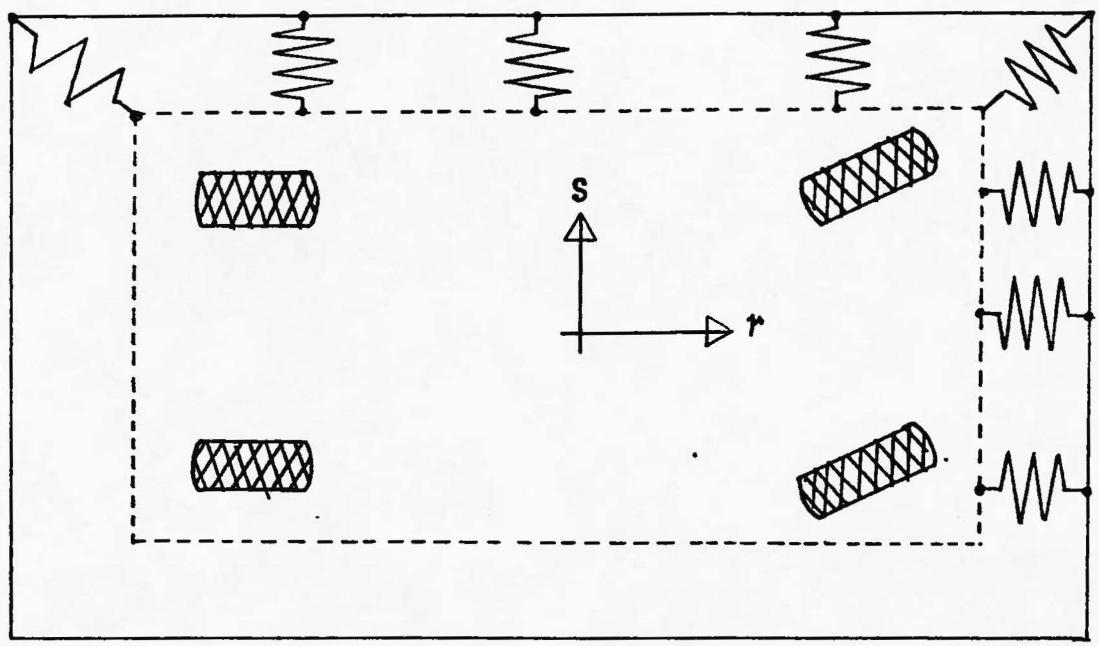


Figure 2. Analytical Representation of a Vehicle in BARRIER VII

The particular form of equation (8) when the Newmark-   method is used can be written as:

$$\left(\frac{1}{2\beta \Delta t^2}[M] + \frac{1}{\beta \Delta t}[C] + [K] \right) \{\Delta x\} =$$

$$\{\Delta F\} + [M]\left(\frac{1}{\beta}\ddot{x}_o + \dot{x}_o \frac{1}{2\beta \Delta t}\right) + [C]\left(\ddot{x}_o \frac{\Delta t}{2} + \frac{1}{\beta}\dot{x}_o\right) \qquad (9)$$

Note that when β = 1/6, the Newmark-β method reduces to the linear acceleration method and when β = 1/4, it reduces to the constant acceleration method. In general, β can vary from 0 to 1 depending on the stability and convergence requirements of the particular problem at hand. In our experience dealing with the execution of both the Berkeley and the Southwest versions of BARRIER VII, we noted that β = 1/4 gives the best stability and convergence of the solution.

A final but very important point to note here is that in HVOSM, the dynamic equation of motion is solved for the acceleration vector $\{\ddot{x}\}$. The velocity vector $\{\dot{x}\}$ and the position vector $\{x\}$ are then obtained by direct integration of the acceleration vector. In contrast, in BARRIER VII, the equation of motion is solved for the position vector $\{x\}$. The velocity vector $\{\dot{x}\}$ and the acceleration vector $\{\ddot{x}\}$ are then obtained by direct differentiation of the position vector. Therefore, one simulation program solves the inverse problem whereas the other simulation program solves the direct problem.

3. Computer Program Structure

3.1 Program Structure of HVOSM

The program structures of the HVOSM-RD2 and HVOSM-VD2 versions are shown in figures 3 and 4, respectively. The program structure of the RD2 version is organized on two functional levels. The MAIN routine controls the upper level which performs functions associated with overall program control, including initialization, input, output, integration control, invariant constants determination, and checks for normal as well as abnormal program stops. The

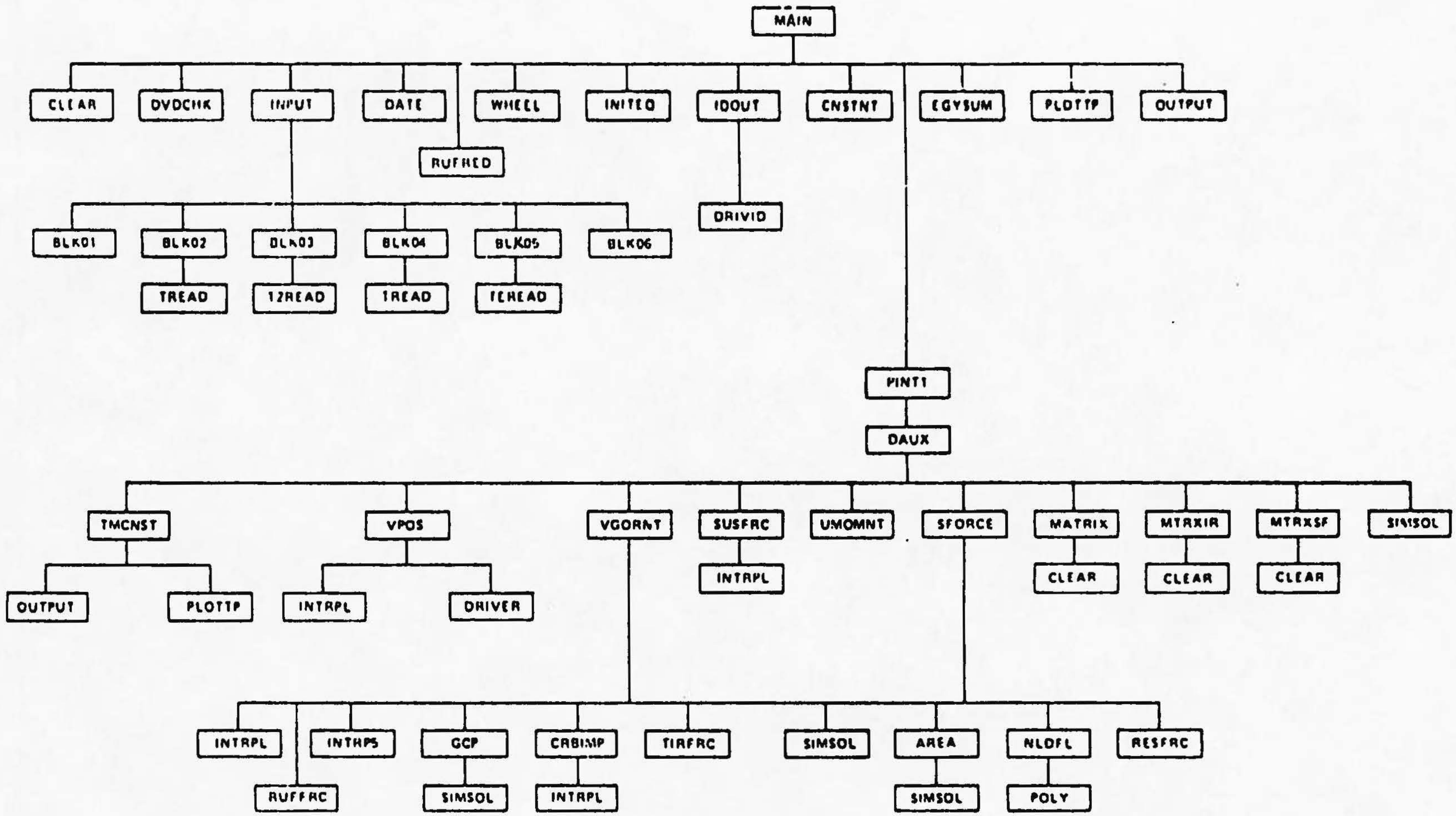


Figure 3. Program Structure of HVOSM-VD2

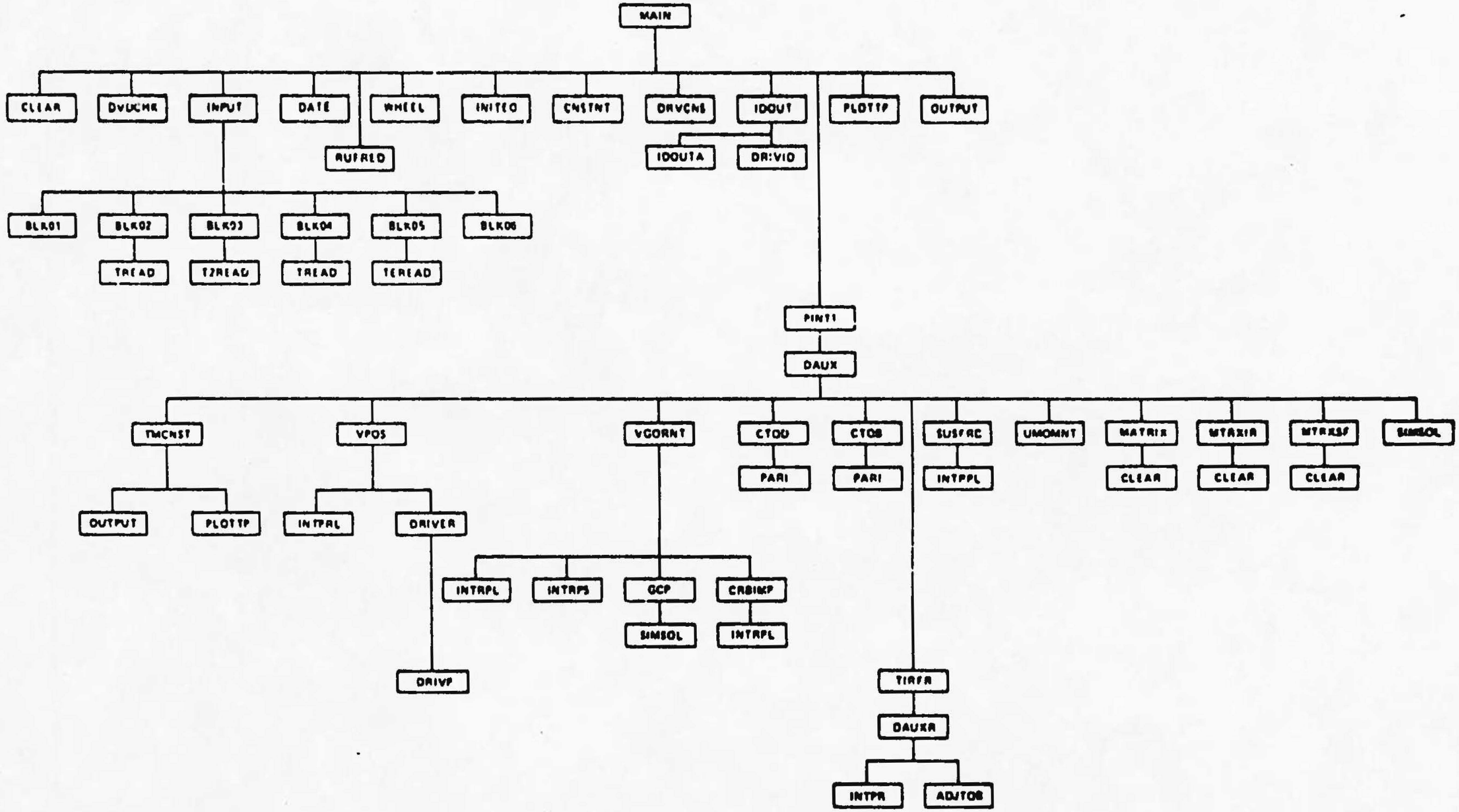


Figure 4. Program Structure of HVOSM-RD2

lower level is controlled by the subroutine DAUX, and the functions at this level are directly associated with evaluation of the time derivatives of the dependent variables for numerical integration. The lower level functions require the performance of three tasks: (1) the evaluation of forces acting on the vehicle; (2) the evaluation of the elements of the inertial matrix and the forcing functions; and (3) the evaluation of the derivatives of the dependent variables.

The first task is performed by calls from subroutine DAUX to next level subroutines TMCNST, VPOS, VGORNT, SUSFRC, UMOMNT and SFORCE. These subroutines, along with subsequent calls to other subroutines, evaluate forces acting at the interface between the vehicle tires and ground, forces acting between the vehicle sprung and unsprung masses, and impact forces acting between the vehicle and the barrier.

The second task is performed by calls from subroutine DAUX again to next level subroutines MATRIX, MTRXIR or MTRXSF, which evaluate the elements of the "effective" mass matrix [D] and the "effective" force vector {E}. The third task is accomplished by subroutines SIMSOL and DAUX. SIMSOL performs a simultaneous solution for the second order time derivatives of the dependent variables in equation (7) above. DAUX then evaluates the first order time derivatives of the dependent variables, which are numerically integrated by subroutine PINT1 to arrive at the solution.

The program structure of VD2 is organized on three levels. The upper level is controlled by the MAIN routine and performs functions that are similar to that in the RD2 version. The middle level is controlled by the subroutine DAUX which again performs functions that are substantially similar to that on the RD2 version. The lower level is controlled by the subroutine TIRFR which performs the integration of more rapidly changing variables, such as the spin derivatives and velocities, independent of the integration of other variables by PINT1. This independent integration algorithm is necessary to maximize computational efficiency and to ensure stability for the more rapidly changing variables that require integration interval orders of magnitude smaller than otherwise necessary.

The major difference between the RD2 and the VD2 versions of the HVOSM program is the detail in which the interface between the tire and the ground is modeled. Another difference is the addition of a preview-predictor driver model in the VD2 version. This model employs computational subroutines DRIVER and DRIVP which determine the front wheel steer angle for path following or skid recovery and control vehicle speed or speed changes, respectively. A description of the functions performed by various subroutines of HVOSM-RD2 and HVOSM-VD2 is summarized in table 1. Also, a summary of HVOSM dependent variables and their derivatives is given in table 2.

One subroutine in HVOSM-RD2 which is of particular interest to the present feasibility study is SFORCE. Given the position and the orientation of the vehicle and the barrier, this subroutine calculates the geometrical interface between the two through an iterative process of changing the barrier displacement until a force balance between the barrier and the vehicle is achieved if the deformable barrier option is employed, or by returning the barrier to its undeformed position if the rigid barrier option is employed. The above computation is done by SFORCE in conjunction with two other subroutines AREA and RESFRC in the case of rigid barrier option and an additional subroutine NLDFL in the case of deformable barrier option.

3.2 Program Structure of BARRIER VII

The program structure of BARRIER VII is shown in figure 5. Like HVOSM, the structure of BARRIER VII is organized on two functional levels. The upper level is controlled by the MAIN program which calls two main subroutines INPTT and CYCLE and, as such, performs as a controller of its overlays. The second level is controlled by the subroutine CYCLE which performs all computational functions.

Table 1. Summary of HVOSM Subroutine Descriptions

Subroutine Name	Description of Subroutine Functions	Variables Evaluated	Lower Level Subroutines Called
DAUX	Controls the lower level program functions by calling other subroutines	All forces and derivatives of dependent variables	TMCNST, VPOS, VGORNT, SUSFRC, UMOMNT, SFORCE, MATRIX, MTRXIR, MTRXSF, SIMSOL
TMCNST	Calculates time variables for general use	Time	None
VPOS	Calculates the position, orientation, and velocity of the wheels, torque acting on the wheels, and direction cosines of vehicle	$\{x\}$, $\{\dot{x}\}$, transformation matrix [A], (T_i), (T_j), and cos α's	INTRPL, DRIVER,DRIVP
VGORNT	Calculates orientation of vehicle with respect to the local ground and circumferential tire	$\{x\}$, $\{\dot{x}\}$, cos α's, (T), and (Φ_i)	INTRP5, INTRPL, GCP, CRBIMP, TIRFRC
SFORCE	Calculates the geometrical interface between the vehicle and the barrier	Location and direction cosines of vehicle corner points and "hard points"	AREA, NLDFL, RESFRC
MATRIX	Calculates the elements of the inertial matrix and forcing matrix for independent front and rigid rear suspension option	[D] and [E]	None
MTRXIR	Calculates the elements of the inertial matrix and forcing matrix for independent front and rear suspension option	[D] and [E]	None
MTRXSF	Calculates the elements of the inertial matrix and forcing matrix for solid axle front and rear suspension option	[D] and [E]	None
SUSFRC	Computes the suspension forces acting between the sprung mass and the unsprung mass	(F_{1Fi}, F_{1Ri}), etc.	INTRPL
UMOMNT	Calculates the moments acting on the sprung mass	N_ϕ, N_θ, N_ψ etc.	None
SIMSOL	This subroutine solves a set of real simultaneous linear algebraic equation	$[A]\{x\} = \{B\}$	None
PINT1	Integrates numerically the differential equation using Runge-Kutta or Adams-Moulton methods	Differential equation	Overlay on DAUX
CTQD	Computes driveline torque at the driving end of the vehicle based on the engine speed, throttle setting, etc.	Hydraulic pressure Pc and driving torque TQ_D	PARI
CTQB	Calculates the braking torque at each wheel as a function of brake system characteristics	Brake wheel cylinder pressure P and brake torque TQ_B	PARI
TIRFC	Provides control of the integration of the wheel spin velocities at the reduced integration step size	Φ_{ci}, U_{GWi}, etc.	DAUXR, INTPR, ADJTQB

Note: Second and subsequent level subroutines are not incorporated in this tabular summary.

Table 2. Summary of HVOSM Dependent Variables and Derivatives

Variable Name	Mathematical Symbol	Derivative
Linear velocity of sprung mass in the x-direction	u	$\dot{u}$
Linear velocity of sprung mass in the y-direction	v	$\dot{v}$
Linear velocity of sprung mass in the z-direction	w	$\dot{w}$
Angular velocity of sprung mass in the x-direction	P	$\dot{P}$
Angular velocity of sprung mass in the y-direction	Q	$\dot{Q}$
Angular velocity of sprung mass in the z-direction	R	$\dot{R}$
Right front suspension deflection for independent front suspension	δ_1	$\dot{\delta}_1, \ddot{\delta}_1$
Left front suspension deflection relative to the vehicle	δ_2 or Φ_F	$\dot{\delta}_2, \dot{\Phi}_F$
Right rear suspension deflection for independent rear suspension	δ_3	$\dot{\delta}_3, \ddot{\delta}_3$
Left rear suspension deflection relative to the vehicle	δ_4 or Φ_R	$\dot{\delta}_4, \dot{\Phi}_R$
Euler angle of sprung mass x-axis relative to inertial axis system	θ'_t	$\dot{\theta}'_t$
Euler angle of sprung mass y-axis relative to inertial axis system	ϕ'_t	$\dot{\phi}'_t$
Euler angle of sprung mass z-axis relative to inertial axis system	ψ'_t	$\dot{\psi}'_t$
X-coordinate of sprung mass C.G. with respect to the fixed axis system	X'_C	U'
Y-coordinate of sprung mass C.G. with respect to the fixed axis system	Y'_C	V'
Z-coordinate of sprung mass C.G. with respect to the fixed axis system	Z'_C	W'
Front wheel steer angle	ψ_f	$\dot{\psi}_f, \ddot{\psi}_f$

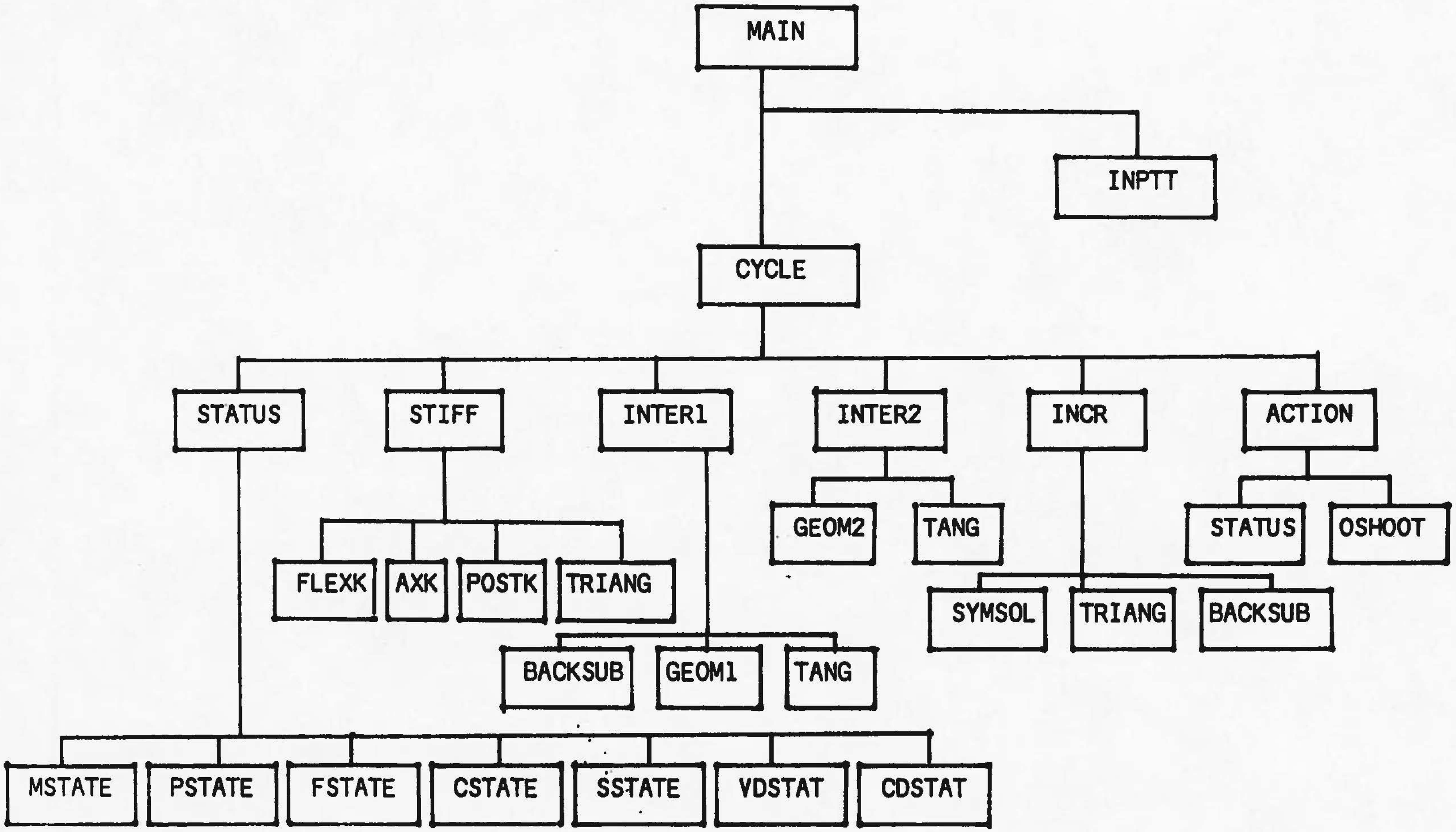


Figure 5. Program Structure of BARRIER VII

Following initialization of variables in the MAIN routine, INPTT is called to read the following data and perform necessary operations:

1. Control information
2. Nodal coordinates, list of interface joints, and coefficient of friction
3. Member property information; also elements of common block TPROP
4. Member location information; also some elements of mass matrix and elements of common block EPROP
5. Barrier weight data; also remaining elements of mass matrix
6. Mass, moment of inertia, spring properties, and wheel positions; also coordinates at which trajectories are to be completed
7. Initial position and orientation of vehicle
8. Initial prestress in the members, if any; also modification of EPROP.

The subroutine CYCLE performs five tasks through different second and subsequent level subroutines. The first task is concerned with the determination of the status (elastic, yielding, etc.) of each member of the structure. This step is controlled by the subroutine STATUS which identifies each member according to member type and calls the appropriate subroutine.

The second task is concerned with the generation of the structural stiffness matrix, and this is accomplished by the subroutine STIFF. Appropriate stiffness properties are assigned to the members, depending on the current values of the status indicators, and the member stiffnesses are formed by calling FLEXK for flexural stiffness, AXK for extensional stiffness, and POSTK for post stiffness. After the stiffness matrix is formed, it is reduced by the Gauss elimination procedure in subroutine TRIANG.

As its third task, CYCLE solves the interaction problem in five steps. In Step 1, the automobile and barrier motions under constant load are computed using subroutine INTER1. In Step 2, new points of contact and normal directions are found for each of the automobile points using subroutines GEOM1 and TANG. Step 3 of the interaction solution, in which the automobile and barrier motions are computed allowing for the effect of change in position and direction of the interaction forces, is carried out in subroutine INTER2. New barrier contact points and normal directions including gap and overlap are determined in Step 4 using subroutines GEOM2 and TANG. Finally, the displacement compatibility between the automobile and the barrier is re-established and the increments in the interaction forces are computed in Step 5 using subroutines INCR and SYMSOL.

The fourth task of CYCLE deals with the calculation of member force increments using the subroutine ACTION. This subroutine also initiates another subroutine OSHOOT to determine whether the member forces exceed the upper limits of the specified yield ranges. At the end of subroutine ACTION, control is returned to subroutine CYCLE.

The fifth and final task of CYCLE is concerned with results printout. The print and punch indicators are checked to determine whether output of the automobile trajectory, barrier joint deflections, or barrier member forces has been requested. If so, the subroutine PRIN is called to output the required information. Immediately following this, a check on the elapsed simulated time is made to determine whether execution should continue for further time steps or be terminated. Table 3 gives a summary of subroutines and their functions while table 4 lists the dependent variables and their derivatives.

4. Input/Output Requirements

4.1 HVOSM Input/Output

Input to the HVOSM-RD2 is supplied in 80-column card format. All data cards or lines must contain a three-digit number in columns 78-80. The first of these represents the data block number and the remaining two numbers represent the card number within the data block. Data blocks are categorized and numbered as follows:

Block Number	Data Content
1	Simulation Control data
2	Vehicle data
3	Tire data
4	Vehicle Control data
5	Terrain/Environmental data
6	Initial Conditions data

Table 3. Summary of BARRIER VII Subroutine Descriptions

Subroutine Name	Description of Subroutine Functions	Variables Evaluated	Lower Level Subroutines Called
INPTT	Reads and organizes data following preliminary initialization in the MAIN routine	Common blocks EPROP and TPROP	None
CYCLE	As the main program of its overlays, it performs all necessary computations through next level subroutines	All vehicle and barrier output of interest	STATUS, STIFF, INTER1, INTER2, INCR, SYMSOL, ACTION, and PRIN
STATUS	Identifies member status and calls appropriate subroutines for state indicators	State of flexure, axial tension, cables and columns, etc.	MSTATE, FSTATE, CSTATE, PSTATE, SSTATE, VDSTAT, and CDSTAT
STIFF	Generates structural stiffness matrix by a direct assembly procedure	Elements of [K]	FLEXK, AXK, POSTK, and TRIANG
INTER1	Computes vehicle and barrier motion under constant load	Vehicle and barrier positions, geometry, etc.	BAKSUB, GEOM1, and TANG
INTER2	Computes vehicle and barrier motion allowing for changes in interaction forces	Vehicle and barrier positions, geometry, etc.	GEOM2 and TANG
INCR	Establishes displacement compatibility between the vehicle and barrier	Displacements and elements of flexibility matrix	SYMSOL, TRIANG, and BAKSUB
ACTION	Computes member forces and force increments, and detects overshoot	Member forces	STATUS and OSHOOT

Table 4. Summary of BARRIER VII Dependent Variables

Variable Name	Mathematical Symbol	Derivative
Longitudinal coordinate of vehicle C.G.	X_G	$\dot{X}_G$, $\ddot{X}_G$
Lateral coordinate of vehicle C.G.	Y_G	$\dot{Y}_G$, $\ddot{Y}_G$
Longitudinal velocity of vehicle	$\dot{X}_G$	$\ddot{X}_G$
Lateral velocity of vehicle	$\dot{Y}_G$	$\ddot{Y}_G$
Resultant velocity of vehicle		
Longitudinal acceleration of vehicle	$\ddot{X}_G$	
Lateral acceleration of vehicle	$\ddot{Y}_G$	
Resultant acceleration		
Barrier deflection	X_B	$\dot{X}_B$, $\ddot{X}_B$
Barrier axial force	F	
Barrier bending moment	M_i, M_j	

Data are entered on individual data cards and on table cards in 9 fields of 8 columns each (9F8.0 format). Any data not supplied default to 0.0. An example of a data card is shown in figure 6 and an example of a table card is shown in figure 7. The last card in the input data deck must be numbered 9999 in columns 77-80. Input decks may be stacked so that multiple runs can be made in a single job. Only cards which are changed from the previous deck must be supplied. However, each data deck must contain card number 9999 as the last card in the deck. In addition to card input, Fortran unit 4 is used to supply road roughness data if this option is being used. These data are read from subroutine RUFRED and are assumed to be unformatted in sequential form.

Input to HVOSM-VD2 is identical to that of RD2 in format, data blocks, and categories. Evidently, some data types in the VD2 version are different from those in the RD2 version and some data types are not common between the two versions. For example, the input deck of the VD2 version contains several cards on wheel spin inertia and brake system which are not required in the RD2 version. On the other hand, the input deck of the RD2 version contains a card in block 5 describing barrier characteristics and this card shown in figure 8 is not required in the VD2 version.

The card in figure 8 is of particular interest to note here since this is the only card in the HVOSM input deck which describes the barrier properties in some fashion. Note from the card that the barrier in HVOSM has no inertial properties, and the only properties describing the behavior of the barrier are ratio of permanent deflection to maximum deflection and the ratio of conserved energy to maximum energy absorbed by the barrier. For the purpose of comparison later on, table 5 lists a few typical vehicle and barrier input for HVOSM.

VHED(1), I=1,18									200

Program Variable	Analytical Variable	Description	Input Units
VHED	-	VEHICLE DESCRIPTION TITLE THIS CARD MAY CONTAIN UP TO 72 CHARACTERS OF ALPHANUMERIC INFORMATION DESCRIBING THE SIMULATED VEHICLE. NOTE THAT ONLY THE FIRST 40 CHARACTERS ARE PRINTED ON EACH OUTPUT PAGE.	

XMS	XMUF	XMUR	XIX	XIY	XIZ	XIXZ	XIR	XIF	201

Program Variable	Analytical Variable	Description	Input Units
XMS	M_S	SPRUNG MASS	$lb-sec^2/in$
XMUF	M_{uF}	TOTAL FRONT UNSPRUNG MASS	$lb-sec^2/in$
XMUR	M_{uR}	TOTAL REAR UNSPRUNG MASS	$lb-sec^2/in$
XIX	I_X	MASS MOMENT OF INERTIA OF THE SPRUNG MASS ABOUT THE VEHICLE X AXIS	$lb-sec^2-in$
XIY	I_Y	MASS MOMENT OF INERTIA OF THE SPRUNG MASS ABOUT THE VEHICLE Y AXIS	$lb-sec^2-in$
XIZ	I_Z	MASS MOMENT OF INERTIA OF THE SPRUNG MASS ABOUT THE VEHICLE Z AXIS	$lb-sec^2-in$
XIXZ	I_{XZ}	MASS PRODUCT OF INERTIA OF THE SPRUNG MASS IN THE VEHICLE X-Z PLANE	$lb-sec^2-in$
XIR	I_R	MASS MOMENT OF INERTIA OF THE SOLID AXLE REAR UNSPRUNG MASS ABOUT A LINE PARALLEL TO THE VEHICLE X-AXIS AND THROUGH THE REAR UNSPRUNG MASS CENTER OF GRAVITY. REQUIRED ONLY IF ISUS = 0 OR 2	$lb-sec^2-in$
XIF	I_F	MASS MOMENT OF INERTIA OF THE SOLID AXLE FRONT UNSPRUNG MASS ABOUT A LINE PARALLEL TO THE VEHICLE X-AXIS AND THROUGH THE FRONT UNSPURNG MASS CENTER OF GRAVITY. REQUIRED ONLY IF ISUS = 2.	$lb-sec^2-in$

Figure 6. An Example of HVOSM Data Card

DELB	DELE	DDEL	NDTHF	NDTHR					209

Program Variable	Analytical Variable	Description	Input Units
		NOTE: THE PARAMETERS ON CARD 209 APPLY TO FOUR TABLES DEFINING CAMBER AND HALF-TRACK CHANGES AS A FUNCTION OF WHEEL DISPLACEMENT. CARD 209 AND SUBSEQUENT TABLE CARDS ARE NOT REQUIRED IF ISUS = 2	
DELB		BEGINNING VALUE OF WHEEL DISPLACEMENT FOR TABLES	in
DELE		END VALUE OF WHEEL DISPLACEMENT FOR TABLES	in
DDEL		INCREMENT VALUE OF WHEEL DISPLACEMENT FOR TABLES	in
NDTHF		INDICATOR FOR FRONT HALF-TRACK CHANGE TABLE. TABLE IS SUPPLIED IF NDTHF ≠ 0	
NDTHR		INDICATOR FOR REAR HALF-TRACK CHANGE TABLE. TABLE IS SUPPLIED IF NDTHR ≠ 0	
		FOLLOWING CARD 209 ARE UP TO 4 TABLES CONTAINING [(DELE-DELB)/DDEL]+1 ENTRIES IN THE ORDER:	
		PHIC(I) FRONT WHEEL CAMBER TABLE	deg
		PHIRC(I) REAR WHEEL CAMBER TABLE (REQUIRED IF ISUS=1)	deg
		DTHF(I) FRONT HALF-TRACK CHANGE (REQUIRED IF NDTHF≠0)	in
		DTHR(I) REAR HALF-TRACK CHANGE (REQUIRED IF ISUS=1 AND NDTHR≠0)	in
		TABLE ENTRIES ARE READ IN FIELDS OF 8 AND MUST CONTAIN 209 IN COLUMNS 78-80. A TABLE SEQUENCE NUMBER MUST ALSO BE SUPPLIED IN COLUMN 76 AND SEQUENCE NUMBER MUST INCREASE WITH EACH CARD. EACH NEW TABLE MUST START ON A NEW CARD. A MAXIMUM OF 50 ENTRIES IS ALLOWED FOR EACH TABLE.	

-5.0	-5.0	1.0	1.0	1.0					209
PHIC(1)	PHIC(2)	...				...		PHIC(9)	1 209
PHIC(10)	PHIC(11)								2 209
PHIRC(1)	PHIRC(2)	...				...		PHIRC(9)	3 209
PHIRC(10)	PHIRC(11)								4 209
DTHF(1)	DTHF(2)	...				...		DTHF(9)	5 209
DTHF(10)	DTHF(11)								6 209
DTHR(1)	DTHR(2)	...				...		DTHR(9)	7 209
DTHR(10)	DTHR(12)								8 209

Figure 7. An Example of HVOSM Table Card

YBPO	ZBTP	ZBBP	DELYBP	AMUB	EPSV	EPSB	SET	CONS	S10

Program Variable	Analytical Variable	Description	Input Units
YBPO	$(y'_B)_O$	INITIAL LATERAL POSITION OF THE BARRIER FACE PLANE	in
ZBTP	z'_{BT}	ELEVATION OF TOP OF FINITE VERTICAL BARRIER	in
ZBBP	z'_{BB}	ELEVATION OF BOTTOM OF FINITE VERTICAL BARRIER	in
DELYBP	$\Delta y'_B$	INCREMENTAL DISPLACEMENT OF DEFORMABLE BARRIER	in
AMUB	μ_B	COEFFICIENT OF FRICTION ACTING BETWEEN VEHICLE SPRUNG MASS AND BARRIER	-
EPSV	ϵ_V	FRICTION LAG FOR VEHICLE-BARRIER FRICTION FORCE	in/sec
EPSB	ϵ_B	ERROR LIMIT IN FORCE BALANCE BETWEEN VEHICLE AND BARRIER	lbs
SET	$\overline{SET}$	RATIO OF PERMANENT DEFLECTION TO MAXIMUM DEFLECTION OF BARRIER	-
CONS	$\overline{CONS}$	RATIO OF CONSERVED ENERGY TO MAXIMUM ENERGY ABSORGED BY BARRIER	-

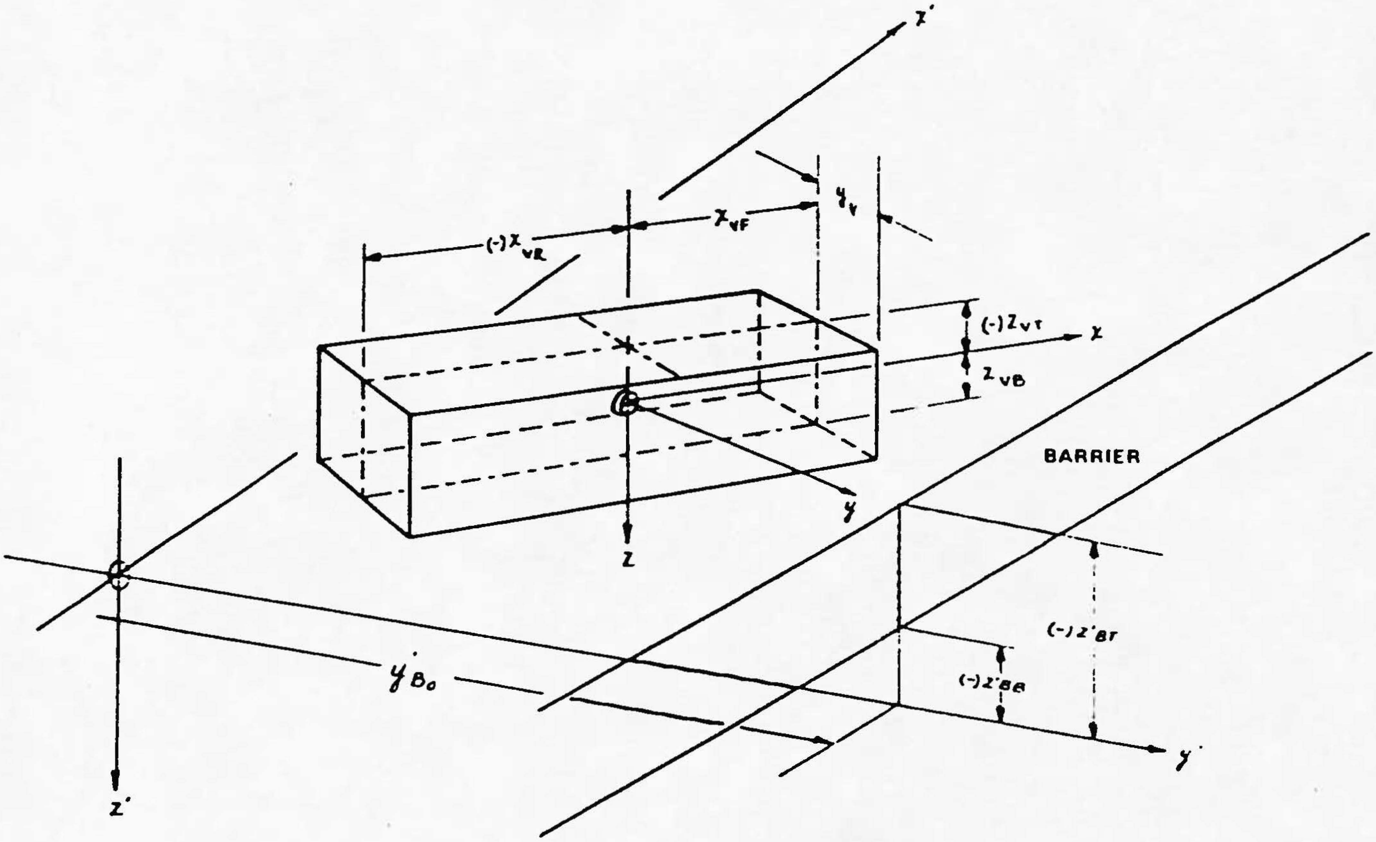


Figure 8. HVOSM Data Card Describing Barrier Characteristics

Table 5. List of Typical Vehicle and Barrier Input for HVOSM

1971 VEGA W/2 PASSENGERS IMPACTS G.M. BARRIER									0 100
0.0	1.5	.005	.01	70.	0.0	0.0			0 101
0.0	1.0	4.0	.005	1.0	.005				0 102
1.									0 103
1.0	1.0	1.0	1.0	1.0	1.0	1.0			0 104
1971 VEGA 2300 SPORT COUPE 2-PASSENGER LOAD									0 200
5.831	0.424	0.575	2640.	14400.	14400.	-100.	250.		0 201
43.87	53.13	55.1	54.1	1.31	38.0				0 202
						8.58	7.21		0 203
96.0	300.	600.	300.	600.	.05	-2.2	3.84		0 204
121.0	300.	600.	300.	600.	.05	-2.2	4.85		0 205
2.0	37.0	0.01	2.0	58.0	0.01				0 206
0.0	11690.	-0.01							0 207
.492	600.	.4	5000.	.075	1.5				0 208
-4.0	4.0	1.0							0 209
-4.75	-3.08	-1.75	-0.73	0.0	0.48	0.65	0.78	0.83	1 209
-5.0	5.0	.5							0 210
.1079	.1053	.103	.1011	.0994	.0981	.0971	.0964	.0959	1 210
.0958	.0960	.0965	.0973	.0984	.0998	.1015	.1035	.1058	2 210
.1085	.1114	.1147							3 210
-5.0	5.0	5.0							0 211
0.092	0.092	0.092							1 211
72.882	-90.019	31.05	-12.00	12.00	666.67				0 212
47.4	-47.5	65.2	28.0	28.0	21.2				0 213
14.45	17.0	0.0	2500.	2500.0	2500.				0 214
STANDARD TIRES									0 300
1.0	1.0	1.0	1.0	6.	.25				0 301
1098.	3.	10.	4400.	8.276	2900.	1.78	3900.	1.0	1 301
.75				13.					0 302
0.0	1.5	.1	1.0	0.0	0.0				0 401
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1 401
0.0	0.0	0.0	0.0	0.0	0.0	0.0			2 401
60.4	60.4	69.58	72.40			.5			0 507
-2.	-15.	-32.							0 508
-89.	-55.	-80.30	0.						0 509
72.4	-32.	0.0	1.0	.5	1.	1000.	0.0	1.0	0 510
0.0	90000.								0 511
0.	0.	15.5	0.	0.	0.	0.	0.		0 601
0.	0.	-20.00	1036.64	0.	0.				0 602
									09999

The HVOSM-RD2 output is organized into 19 output groupings. Each output group is written to a separate Fortran unit number commencing with 11. The groups are as follows:

Group Number	Description
1	Sprung mass C.G., linear velocity and acceleration components
2	Sprung mass angular velocity and orientation components; also slip, heading, and steer angles
3	Wheel ride deflection and velocity
4	Sprung mass angular acceleration components, wheel ride acceleration; roll center deflection, velocity, and acceleration; and roll angle, angular velocity, acceleration
5	Steering torque, steer angular velocity and acceleration
6	Steer angle, camber angle
7	Wheel longitudinal and lateral velocities
8	Elevation of rear and front contact points
9	Suspension force, anti-pitch force
10	Suspension damping force and spring force
11	Tire radial force and rolling radius
12	Tire normal force, side force, and slip angle
13	Tire circumferential force, wheel torque
14	Tire vertical force and forces in the X' and Y' directions
15	Terrain elevation and slopes(camber and pitch)
16	Acceleration components of vehicle at point 1 and point 2
17	Vehicle and barrier deformation; also force
18	Barrier velocity, conserved energy, dissipated energy; also sprung mass dissipated energy
19	"Hard point" deflection and crush force

The HVOSM-VD2 output is organized into 20 output groupings. Of these, the first 16 groupings are almost identical to those in the RD2 version. The remaining four groups replace the last three groups in the RD2 version as follows:

Group Number	Description
17	Wheel circumferential slip, friction ratio, and rotational velocity
18	Brake hydraulic pressure, brake torque, and assembly temperature
19	Brake dissipated energy, tire dissipated energy
20	Command steer angle, desired acceleration, and brake force

Two typical HVOSM output tables of interest for later comparison are given in tables 6 and 7, respectively. The first of these tables gives some idea of typical vehicle output while the second gives the barrier output.

4.2 BARRIER VII Input/Output

Like HVOSM, input to BARRIER VII is supplied in 80-column card format and in the following categories:

Category	Description
1	Simulation control data
2	Barrier geometry data
3	Barrier properties data
4	Vehicle position and trajectory data
5	Vehicle properties data

However, the fields are not formatted uniformly like those in HVOSM. In BARRIER VII, some fields by definition have integer (I) format while other fields have variable size real (F) formats. An example of barrier input data for BARRIER VII is shown in figure 9, and an example of vehicle input data is shown in figure 10.

In general, input data requirements for BARRIER VII are considerably simpler than those for HVOSM. Also, BARRIER VII input contains very little vehicle data but reasonably complete barrier data.

The output of BARRIER VII is printed in four groups which are:

Group Number	Data Content
1	Echo of input data
2	Automobile trajectory
3	Barrier deflections
4	Barrier forces

An output table of automobile output from BARRIER VII is shown in table 8. A similar one for barrier output is shown in table 9.

5. Comparison of HVOSM and BARRIER VII

5.1 Mathematical Model

From the foregoing discussion of mathematical models of HVOSM and BARRIER

Table 6. An Example of HVOSM Output Table for Vehicle Output

HVOSM-RD2 OUTPUT FORMAT | OUTPUT GROUP NUMBER 1

PRINT COLUMN	PROGRAM VARIABLE	ANALYTICAL VARIABLE	DESCRIPTION	UNITS
1	T	t	Simulated time	sec.
2	XCP	x'_c	Location of vehicle sprung mass c.g. with respect to the space fixed coordinate system	ft.
3	YCP	y'_c		
4	ZCP	z'_c		
5	ULON	u	Vehicle forward velocity	ft/sec.
6	VLAT	v	Vehicle lateral velocity	ft/sec.
7	WVER	w	Vehicle vertical velocity	ft/sec.
8	ACLON	$\dot{u}-vR+wQ$	Vehicle longitudinal acceleration	g's
9	ACLAT	$\dot{v}+uR-wP$	Vehicle lateral acceleration	g's
10	ACVER	$\dot{w}+vP-uQ$	Vehicle vertical acceleration	g's
11	ACRES		Resultant vehicle acceleration	g's

This group is always printed.

Table 7. An Example of HVOSM Output Table for Barrier Output

HVOSM-RD2 OUTPUT FORMAT

OUTPUT GROUP NUMBER 18

PRINT COLUMN	PROGRAM VARIABLE	ANALYTICAL VARIABLE	DESCRIPTION	UNITS
1	T	t	Simulated time	sec.
2	VMAX(1)	$1/\Delta t_B[(y'_B)_t-(y'_B)_{t-1}]$	Velocity of barrier deflection	in/sec.
3	URP	U'_R	Velocity components of the point of application of the vehicle-barrier interference force with respect to the space fixed axes	in/sec.
4	VRP	V'_R		
5	WRP	W'_R		
6	EEE	$(E_1)_t$	Barrier conserved energy	lb/ft.
7	DISS	$1/12 \sum_{o}^{t} E-(E_1)_t$	Barrier dissipated energy	lb/ft.
8	SPENGY	$1/24\sum_{o}^{t}(F_{Nt}-F_{Nt-1})(\Delta y'_B(n'_t-n'_{t-1}))$	Sprung mass dissipated energy	lb/ft.
9	SWORK	$1/12\sum_{o}^{t}(FRICT)(VTAN)\Delta t$	Friction force energy dissipation	lb/ft.

This group is output when INDB $\neq$ 0.

Program Variable	Analytical Variable	Description	Input Units
		HEADING CARD IN COLUMNS 1 THROUGH 72	
		CONTROL CARDS (5I5,3F10.0,2I5,F5.0/5I5) :	
		NUMBER OF BARRIER JOINTS (120 MAXIMUM)	
		NUMBER OF BARRIER ELEMENTS	
		NUMBER OF DIFFERENT MEMBER SERIES (100,200,..,700)	
		NUMBER OF ADDITIONAL WEIGHTS PLACED AT NODES	
		BASIC TIME STEP FOR SOLUTION	sec
		LARGEST PERMISSIBLE TIME STEP	sec
		MAXIMUM INTERACTION TIME	sec
		MAXIMUM NUMBER OF TIME STEPS WITH NO CONTACT	
		INDEX TO SUPRESS OVERSHOOT CORRECTION	
		DAMPING MULTIPLIER FOR RIGID BODY ROTATION	
		BARRIER OUTPUT PRINT CONTROL CARD :	
		BARRIER NODE COORDINATES (I5,2F10.0) :	
		LIST OF INTERFACE JOINTS (14I5) :	
		COEFFICIENTS OF FRICTION (14F5.0) FOR INTERFACE NODES:	
		MEMBER TYPE DATA :	
		MEMBER SERIES NUMBER (100,200,,, ETC.)	
		NUMBER OF TYPES WITHIN THE SERIES (I5)	
		GEOMETRIC AND OTHER DATA FOR EACH TYPE IN SERIES	
		MEMBER LOCATIONS, TYPES AND PRESTRESS (4I5,3F10.0) :	
		(ONE CARD FOR EACH MEMBER IN BARRIER)	
		ADDITIONAL NODE WEIGHTS (I5,F10.0) :	
		(ONE CARD FOR EACH ADDITIONAL WEIGHT)	

Figure 9. An Example of BARRIER VII Barrier Data Card

Program Variable	Analytical Variable	Description	Input Units
		<u>AUTOMOBILE CONTROL DATA</u> (2F10.0,4I5) :	
		WEIGHT	lb
		MOMENT OF INERTIA ABOUT AN AXIS THROUGH CENTROID	$lb.in.sec^2$
		NUMBER OF POSSIBLE CONTACT POINTS WITH BARRIER	
		NUMBER OF WHEELS (MAXIMUM 6)	
		BRAKE CODE (1 = ON , 0 = OFF)	
		NUMBER OF POINTS ON THE VEHICLE FOR TRAJECTORY INFO.	
		<u>AUTOMOBILE CONTACT POINT DATA</u> (I5,6F10.0)	
		FOR EACH CONTACT POINT :	
		CONTACT POINT NUMBER	
		r COORDINATE	in
		s COORDINATE	in
		SHEET METAL SPRING STIFFNESS	k/in
		BOTTOMING STIFFNESS	k/in
		STIFFNESS ON UNLOADING	k/in
		BOTTOMING DISTANCE	in
		<u>WHEEL DATA</u> (I5,4F10.0)	
		FOR EACH WHEEL :	
		WHEEL NUMBER IN SEQUENCE	
		r COORDINATE	in
		s COORDINATE	in
		STEER ANGLE FROM r AXIS	deg
		MAXIMUM DRAG FORCE BETWEEN WHEEL AND GROUND	ib
		<u>OUTPUT POINT DATA</u> (I5,2F10.0) :	
		INITIAL AUTOMOBILE POSITION AND TRAJECTORY (I5,6F10.0)	
		(SPECIFY THE POSITION AND VELOCITY OF ONE POTENTIAL CONTACT POINT OR THE CENTROID)	

Figure 10. An Example of BARRIER VII Vehicle Data Card

Table 8. An Example of BARRIER VII Output Table for Vehicle Output

SEQUENCE	VARIABLE DESCRIPTION	UNITS
1	INPUT DATA (PRINTED FOR CHECKING PURPOSES)	
2	AUTOMOBILE TRAJECTORY	
	FOR EACH SPECIFIED OUTPUT POINT :	
	A. x COORDINATE	in
	B. y COORDINATE	in
	C. VEHICLE HEADING ANGLE	deg
	D. x VELOCITY	mph
	E. y VELOCITY	mph
	F. r VELOCITY	mph
	G. s VELOCITY	mph
	H. RESULTANT VELOCITY	mph
	I. ANGLE OF RESULTANT VELOCITY VECTOR	deg
	J. x ACCELERATION	g
	K. y ACCELERATION	g
	L. r ACCELERATION	g
	M. s ACCELERATION	g
	N. RESULTANT ACCELERATION	g
	O. ANGLE OF RESULTANT ACCELERATION VECTOR	deg

Table 9. An Example of BARRIER VII Output Table for Barrier Output

SEQUENCE	VARIABLE DESCRIPTION	UNITS
1	BARRIER DEFLECTIONS (Barrier deflection at each node and the new position of the node are printed)	in
2	BARRIER FORCES (The forces on each member of the barrier are printed at the specified intervals, with indicators showing the status e.g. elastic, failed etc.) : A. BEAMS (100 SERIES) AXIAL FORCE BENDING MOMENT AT i BENDING MOMENT AT j EXTENSIONAL STATE INDICATOR FLEXURAL STATE INDICATOR B. CABLES (200 SERIES) AXIAL FORCE EXTENSIONAL STATE INDICATOR C. POSTS (300 SERIES) FORCE ALONG A AXIS FORCE ALONG B AXIS STATE INDICATOR D. SPRINGS (400 SERIES) AXIAL FORCE STATE INDICATOR E. VISCOUS DAMPER (500 SERIES) AXIAL FORCE STATE INDICATOR F. FRICTION DAMPERS (600 SERIES) AXIAL FORCE STATE INDICATOR G. PINNED LINKS (700 SERIES) AXIAL FORCE STATE INDICATOR	

VII (Section 2), it is apparent that both simulation programs have a common mathematical structure that is expressed basically in terms of the equation of dynamic equilibrium (equation (1)). Also, in both simulation programs, this single equation of motion is solved to obtain vehicle trajectory (both pre-collision and post-collision) and deformational behavior of barrier. However, the detail methods of solving the equation are substantially different.

To start with, the vehicle motion in HVOSM is described in terms of vectors $\{\ddot{x}\}$, $\{\dot{x}\}$, and $\{x\}$ which are 11-dimensional in the case of the RD2 version and 15-dimensional in the case of the VD2 version. The corresponding vectors are 3-dimensional in the case of BARRIER VII. Next, consider the inertia or the mass matrix [M]. In HVOSM, barriers are considered massless; therefore, the mass matrix essentially has elements that are functions of vehicle sprung and unsprung masses. In BARRIER VII, barriers are considered to have inertia properties; therefore, the mass matrix contains contributions from barrier masses. Also, consider the stiffness matrix [K]. In HVOSM, this matrix is made up of elements that refer to both sprung and unsprung masses of a vehicle. However, there is no contribution from the stiffness of a barrier. The latter is somewhat accounted for in the formulation through the incorporation of a quantity which is the ratio between the permanent deflection and the maximum deflection. In BARRIER VII, [K] is made up of stiffness properties of the barrier as well as stiffness properties of the vehicle. The vehicle in BARRIER VII, however, is a rigid body surrounded by a series of nonlinear springs which have extensional or compressive property in one direction only. Finally, consider the external force vector {F(t)}. In HVOSM, this vector consists of tire forces, rolling resistance, aerodynamic drag, and impact forces between the vehicle and the barrier. In BARRIER VII, the same vector consists essentially of impact forces, although the effects of tire forces are indirectly considered through the incorporation of friction drag between the tire and the ground. A comparative summary of the analytical representations of HVOSM and BARRIER VII is given in table 10.

With regard to the application of numerical integration techniques to solve the equation of motion (a second order differential equation), we noted elsewhere that one simulation program solves the direct problem whereas the other solves the inverse problem. In particular, the equation of motion (equation (1)) is rewritten in HVOSM in terms of an "effective mass matrix" [D] and an effective force vector {E(t)} as shown in equation (7). The latter is then solved for the acceleration vector $\{\ddot{x}\}$ which, upon successive integration, gives a velocity vector $\{\dot{x}\}$ and a position vector {x}. In contrast, the equation of motion in BARRIER VII is rewritten in terms of an "effective stiffness matrix" [K] and another effective force vector {P(t)} as shown in equation (8). This equation is solved for the position vector {x} which upon successive differentiation, gives the velocity vector $\{\dot{x}\}$ and the acceleration vector $\{\ddot{x}\}$.

5.2 Program Structure

From the discussion of program structure in Section 3, it is evident that the structure of the BARRIER VII program is considerably simpler than that of the HVOSM program. Both programs are organized primarily at two functional levels. In the case of HVOSM, the first level is controlled by the MAIN routine which, in addition, controls the overall program, calls necessary subroutines for the initialization of variables, specifies simulation control parameters through other subroutines, and calls the controller of the second level for program execution. The second level is controlled by the subroutine DAUX, which calls many other subroutines to perform actual computation of vehicle motion before and after collision. The vehicle-barrier interaction calculation is only a small portion of the overall computation algorithm controlled by DAUX, and this interaction calculation is carried out by a simple subroutine SFORCE.

Table 10. Comparative Summary of Analytical Representation of HVOSM and BARRIER VII

Analytical Feature	HVOSM	BARRIER VII
Equation of Motion	$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\}$	$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\}$
Degrees of Freedom	11 for RD2, 15 for VD2	3
Mass or Inertia Matrix	Vehicle only	Both vehicle and barrier
Damping Matrix	Vehicle only	Both vehicle and barrier
Stiffness Matrix	Vehicle only	Both vehicle and barrier
Force Vector {F}	Tire forces, rolling resistance, aerodynamic drag, and impact forces	Impact forces only
Solution Technique	$[D]\{\ddot{x}\}=\{E(x, \dot{x}, t)\}$	$[K]\{x\}=\{P(\dot{x}, \ddot{x}, t)\}$
Integration Method	Runge-Kutta or Adams-Moulton	Newmark-β

Like HVOSM, the first level structure of the BARRIER VII program is controlled by the MAIN routine which, however, does not perform any other function. Control of simulation parameters, specification of input, and initialization of variables are performed by the subroutine INPTT at the second level. The actual computation of barrier deformation and vehicle motion is performed by another subroutine ACTION at the second level. A large portion of ACTION and associated subroutines at the next level below are concerned with the computation of barrier deformation. The calculation of vehicle trajectory in BARRIER VII is somewhat simpler than that in HVOSM.

The overall program structure of BARRIER VII is simple due mainly to the two-dimensional nature of the problem. In contrast, the overall program structure of HVOSM is considerably more involved due in part to the three-dimensional nature of the problem and in part to the amount of sophistication rendered in modeling the vehicle structure.

5.3 Input/Output

The differences between HVOSM and BARRIER VII become more apparent when one compares their input and output. For example, consider the comparison of vehicle related data in these two programs. An example of vehicle input for HVOSM is given earlier in figure 6 and a similar example for BARRIER VII is given in figure 10. A side by side comparison reveals that the inertia property of the vehicle is expressed in terms of one mass variable and one moment of inertia variable in BARRIER VII. In contrast, the same property is expressed in terms of three mass variables and six moments of inertia variables in HVOSM. As noted elsewhere, the vehicle in BARRIER VII is modeled as a simple rigid body surrounded by a set of discrete nonlinear springs whereas in HVOSM, the vehicle has both sprung and unsprung masses.

Consider again another example of input which describes the barrier. For HVOSM, this example is given in figure 8 and, for BARRIER VII, it is given in figure 9. Note that in HVOSM, the entire barrier characteristics are described in terms of nine field variables of which only two are related to barrier properties and four related to barrier geometry. In contrast, in BARRIER VII, the barrier characteristics are described by a large number of field variables that are related to barrier geometry and properties, as may be evident from figure 9. Here again, the barrier is simplified as a massless object in HVOSM whereas in BARRIER VII, all inertial properties are considered.

Like input, the output of HVOSM and BARRIER VII differs considerably in content and in format. The differences are due mainly to distinctions in the analytical representation of vehicle and barrier in these two programs - an issue that has already been discussed several times in the text above. The readers are directed to tables 6 and 8 for a comparison of HVOSM and BARRIER VII in terms of vehicle output, and to tables 7 and 9 for a similar comparison in terms of barrier output.

5.4 Program Statistics

To make the present comparison of HVOSM and BARRIER VII complete, a comparison of program statistics is shown in table 11. This table gives an indication of memory requirements, run time, compiler requirements, and other pertinent data related to the execution of the programs.

6. Feasibility of HVOSM/BARRIER VII Combination

6.1 Analytical Representation

In order to make the development of a combined HVOSM/BARRIER VII program feasible, the analytical representation of the new program must be consistent throughout. This means, first of all, that a three-dimensional representation of the barrier is necessary. Secondly, barrier properties as well as vehicle

Table 11. Comparision of Program Statistics of HVOSM and BARRIER VII

Program Statistics	HVOSM-VD2		HVOSM-RD2		BARRIER VII	
	Base Run	APL Run	Base Run	APL Run	Base Run	APL Run
System	IBM 360 (TCC)	IBM 3033 (APL)	IBM 360 (TCC)	IBM 3033 (APL)	None Provided	IBM 3033 (APL)
Space Requirement (Load Module)(bytes)	320K	444K	228K	524K		392 K
Run Time (sec)	43.83	25.01	124.74	38.75		17.56
Extent of Execution (msec)	4260	4260	1505	500		496
Cost (if available) in dollars	-	14.95	-	27.15		11.31

properties must properly be accounted for in the formulation of the interaction problem. This is to say that, if the deformable behavior of a barrier is to be properly modeled in three dimensions, an Eulerian description of the barrier will be necessary whereby a moving axis system must be embedded in every node and/or element of the barrier. At each simulation time step, it will be advantageous to describe the barrier deformation with respect to the local axis system (moving system). Eventually, however, it will be necessary to translate the deformation parameters to the global (fixed) axis system. This will require the introduction of a transformation matrix which will be carried throughout the entire formulation. This points to basically developing a new interaction module without which BARRIER VII cannot be combined with HVOSM.

Once a proper analytical basis of the interaction module is developed, it will be necessary to ensure that such analytical representation is compatible with the structure of HVOSM. Note here that, in the impact force computation in HVOSM, an empirical formalism is currently used. Even if this formalism is retained, one has to make sure that the same can be extended to the case of a new barrier description. Preferably, the impact forces should be calculated using the current BARRIER VII formulation but extended to a three-dimensional case. This will require a totally new analytical formulation the development of which will entail a substantial amount of effort.

Finally, if the sophistication of the vehicle model in HVOSM is to be retained in conjunction with the improved barrier model, the analytical basis for the computation of vehicle trajectory and vehicle motion in general must be revised to include the out-of-plane contribution of barrier deformation.

6.2 Program Structure Modification

As may be evident from the foregoing discussion of the feasibility of combining HVOSM and BARRIER VII, a considerable amount of program structure modification will be necessary to make the combined program perform its expected task, that is, provide an improved vehicle and barrier simulation model. If, for example, the basic program structure of HVOSM is to be retained for the benefit of improved vehicle modeling, the subroutine SFORCE must be replaced by a set of subroutines that relate to an improved barrier model. In fact, it will likely require a three-level functional program structure shown conceptually in figure 11. In this program structure, the first and second levels will be controlled by the MAIN routine and the subroutine DAUX, respectively, as in HVOSM and the third level will be controlled by the example subroutine INTER.

The subroutine INTER and all associated lower level subroutines will perform the computation of interaction forces between the vehicle and the barrier and will return the results of computation to DAUX so that the latter can perform calculations related to vehicle trajectory, vehicle motion, and barrier deformation. This means the third level program structure and all associated subroutines must be carefully developed, and this will require a considerable amount of effort.

The other major modification of the program will involve the incorporation of a coordinate transformation algorithm for each physical quantity computed in one or the other coordinate systems. A new subroutine has to be written for coordinate transformation, and this subroutine has to be appended to many subroutines in the second and third levels as part of the modified program structure. Moreover, consistency checks must be provided whenever coordinate transformations are involved.

Other than the above major modifications of program structure, minor modifications must be carried out in almost every subroutine that involves either computation of physical quantities or mathematical operations.

Considering the large number of subroutines that are currently residing in HVOSM and the additional subroutines that must be appended for the barrier part, the total effort for these minor modifications could be significant.

6.3 Input/Output Description

With major modifications of analytical representation and program structure as anticipated above, it is inevitable that there will be some changes in the input/output data structure and data description. Simple input modifications will involve a pure extension of HVOSM input to include detail barrier data as given in the BARRIER VII input. However, in this case, the uniform formatting procedure in HVOSM has to be revised to accommodate integer formatting and variable size real number formatting of BARRIER VII. Similarly, simple output modifications will involve a pure extension of HVOSM output to include detail barrier output data as obtained from BARRIER VII.

Note that in HVOSM, both input and output are specified through respective subroutines INPUT and OUTPUT, which are controlled by the MAIN routine in the first functional level. Moreover, the subroutine INPUT has various lower level subroutines as well as common blocks and block data. These common blocks and block data must be modified as necessary.

One final item of importance with regard to input/output requirements is the future improvement of the combined HVOSM/BARRIER VII program, if such a program can be developed, to provide pre-processing and post-processing capability. Note that both HVOSM and BARRIER VII have graphics post-processing capability. The present graphics processors are program-specific and do not utilize any commercial software. This means with the required changes in the input and output data structure, the graphics processors have to be modified accordingly. Considering the fact that the graphics processors incorporate in principle several files such as static file, object file, and dynamic file, all of which change with the modification of input/output data structure, any modification of graphics post-processing will require a significant amount of effort.

6.4 Cost-Benefit Analysis

A detailed cost-benefit analysis is not within the scope of the research reported herein. However, a qualitative discussion of relative costs associated with the development of a combined program and relative benefits expected to be derived from such a program is presented here.

To start with, one can safely assume that many subroutines of HVOSM can be retained in the combined program with minor modifications as necessary. The interaction module (that is, the third level program structure in figure 11) has to be totally developed. Also, all subroutines related to barrier have to be developed. The second level program structure in figure 3 has to be modified somewhat to account for changes of physical parameters due to coordinate transformation. Finally, the MAIN routine has to be modified, perhaps substantially, to provide control functions for all new features and/or improvements of old features. In total, therefore, this amounts to the development of a completely new program using a few commercially available subroutines. The total effort needed for such a development could very well be in excess of 10,000 hours of professional time. This estimate excludes any effort that may be necessary for the validation of the new program. Experience indicates that the validation effort could be fairly significant, especially if the original version of the new program happens to be far from being realistic in terms of its simulation capability.

Let us now suppose that it is feasible to develop a combined HVOSM/BARRIER VII program at the expense of a fair amount of effort. It is timely to ask what benefits can be derived from such a program. It is clear that the new program will have the capability to simulate the collision of a vehicle with a barrier.

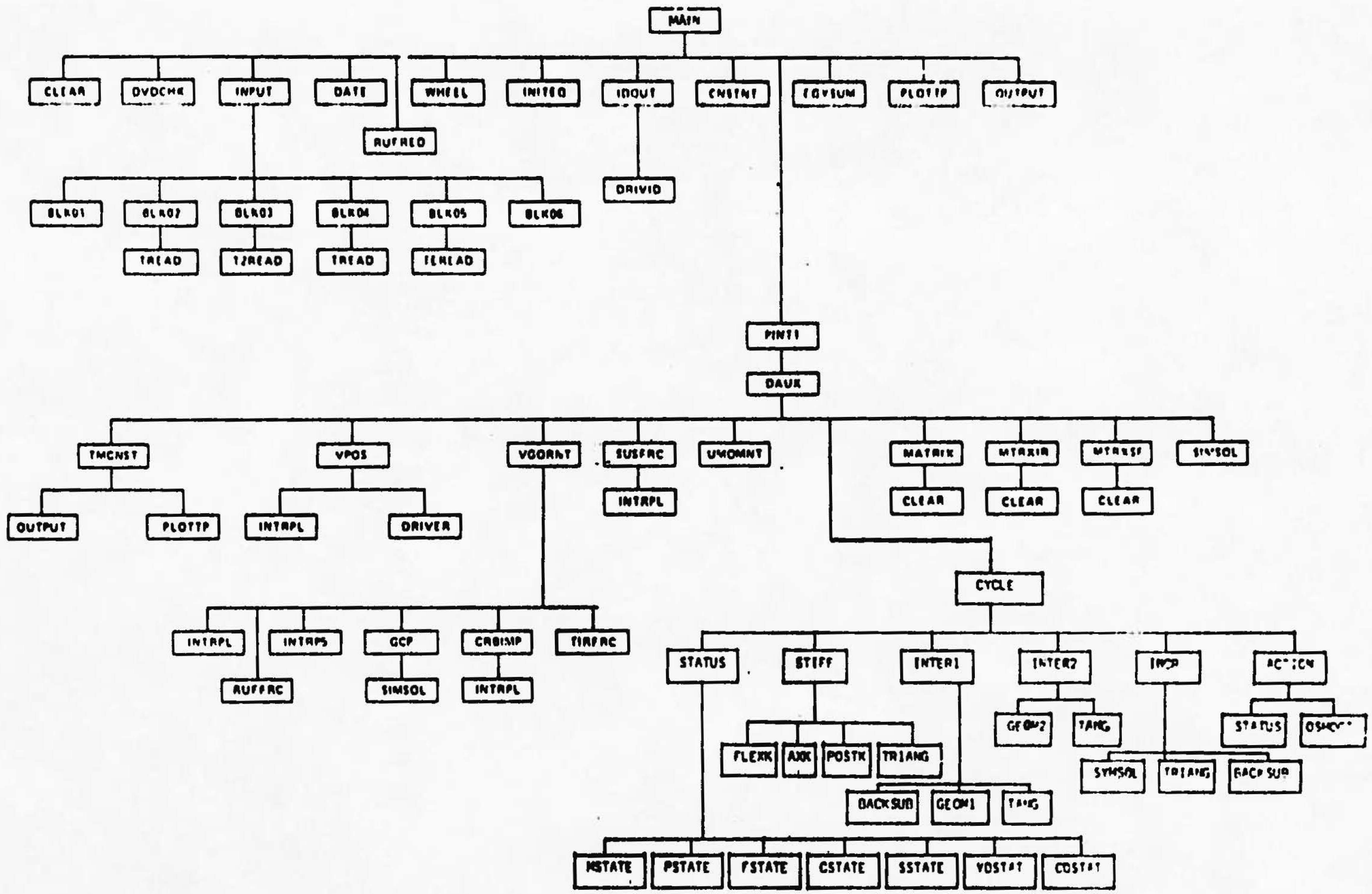


Figure 11. Conceptual Program Structure of a Combined HVOSM/BARRIER VII Program

Since HVOSM can only simulate a non-articulated vehicle (a passenger car, for example), the capability of the new program will be limited to the crash simulation of a non-articulated vehicle. Currently, a program called GUARD exists which has similar capability. Moreover, GUARD is a finite element program and, as such, can simulate the barrier behavior in finer detail. In contrast, the new program can at best simulate the gross vehicle behavior.

Admittedly, several arguments can be put forward aginst GUARD. For one, GUARD has not been validated either and, therefore, it is not known if GUARD can simulate a vehicle crash realistically. Also, input/output data structure and requirements in GUARD are believed to be unnecessarily complex and far from being user-friendly. If we follow the same argument, we are even more unsure as to whether the new program will be able to simulate a vehicle crash realistically. Finally, cannot also ascertain that the input/output data structure of the new program will be any simpler. With these uncertainties, one can reasonably assume that no additional benefit may be derived from the new program that may not otherwise be available in the existing programs.

7. Feasible Alternatives to HVOSM/BARRIER VII

From the foregoing discussion, it has become evident that the sole purpose of combining HVOSM/BARRIER VII is to derive benefits from the good features of both programs so long as the cost justifies the benefits. To the extent that is not the case, it is proper to ask if there are feasible alternatives to HVOSM/BARRIER VII. Indeed, the programs CRUNCH and GUARD are two such alternatives which are worth mentioning.

The program CRUNCH simulates the collision of both articulated and non-articulated vehicles with rigid and deformable barriers taking into consideration the three-dimensional nature of both the vehicles and the barriers. Various barrier systems such as concrete median barrier, guardrail, bridge railing, a certain class of crash cushions, and signs and luminaires with breakaway or base-bending support devices can be simulated by CRUNCH.

The program GUARD may be considered as a simpler version of CRUNCH whose primary purpose is to simulate the collision of a non-articulated vehicle with a standard barrier system. Historically, GUARD was developed first and the formulation was then extended to incorporate the collision of articulated vehicles resulting in the program CRUNCH. Other than the articulated versus non-articulated simulation capability, CRUNCH differs from GUARD only in terms of modeling the bumper characteristics.

Both CRUNCH and GUARD are three-dimensional finite element programs with modular architecture. Each program consists of an executive or main program and three computational modules: vehicle, barrier, and interaction. The vehicle module computes the motion of the vehicle based on a three-dimensional model consisting of spring mass, suspension system, unsprung mass/axle system, tires, and exterior impact panels. The barrier module computes the deformation and stresses in the barrier as well as their derivatives based on a three-dimensional finite element model. The interaction module computes the vehicle/barrier interaction forces.

Until recently, CRUNCH and GUARD suffered from several deficiencies, the major of which is the large rotation instability. The large rotation was caused by an incorrect computational algorithm arising from inappropriate coordinate transformation. The program would stop prematurely whenever this large rotation instability occurred. Under an ongoing Federal Highway Administration contract, the instability problem has been corrected.

Admittedly, neither CRUNCH nor GUARD has a vehicle model as sophisticated as that in HVOSM. More critical, however, is the fact that both CRUNCH and GUARD suffer from unnecessarily complicated imput data requirements and data structure and equally complicated output format. It is in this regard that

CRUNCH and GUARD have not gained as much user-acceptance as HVOSM and BARRIER VII. With a few modifications, none of which is too involved, it is possible to make CRUNCH and GUARD more user-friendly and at the same time serve the purpose that can be achieved in a limited sense by the combined HVOSM/BARRIER VII program.

8. Concluding Remarks

In conclusion, would we like to emphasize that it is theoretically feasible to combine HVOSM with BARRIER VII to obtain a new program with improved vehicle and barrier simulation features. However, many practical problems are associated with such a development, and the effort required to accomplish this task may far outweigh the benefits. We also conclude that the new simulation program, if developed, can at best simulate gross barrier behavior. When two finite element simulation programs, CRUNCH and GUARD, with improved barrier simulation capability already exist, it is not cost-effective to develop a new program.