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HVOSM-87

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ABSTRACT

A brief description and history of the Highway Vehicle Obstacle Simulation Model (HVOSM) computer program is presented. A number of references are cited that include applications of HVOSM and which present detailed descriptions of related extensions and refinements. This paper focuses attention on simulation developments of HVOSM and validation efforts specifically related to the simulation of collisions with concrete median barriers (CMB).

IN THE MID-60's the Calspan Corporation (then Cornell Aeronautical Laboratory, Inc.) began development of a general nonlinear mathematical model and computer simulation of the large-disturbance dynamic responses of automobiles under Contract CPR-11-3988 with the Bureau of Public Roads. The simulation program, which was subsequently named the Highway-Vehicle-Object-Simulation-Model (HVOSM) (e.g., Ref. 1-10), includes general three-dimensional motions resulting from vehicle control inputs, traversals of terrain irregularities and collisions with certain types of roadside obstacles. The development of the HVOSM included an extensive validation effort within which a series of repeated full-scale tests with instrumented vehicles were performed to permit an objective assessment of the degree of validity of the computer model.

The' HVOSM mathematical model (Fig. 1) consists of up to 15 degrees freedom; 6 for the sprung mass, and up to 9 for the unsprung masses. The mathematical model is based on fundamental laws of physics (i.e., Newtonian dynamics of rigid bodies) combined with empirical relationships derived from experimental test data (i.e., tire and suspension characteristics, load deflection properties of the vehicle structure). The balance of forces occurring within and applied to components of the system is defined in the form of a set of differential equations which constitute the mathematical model of the system.

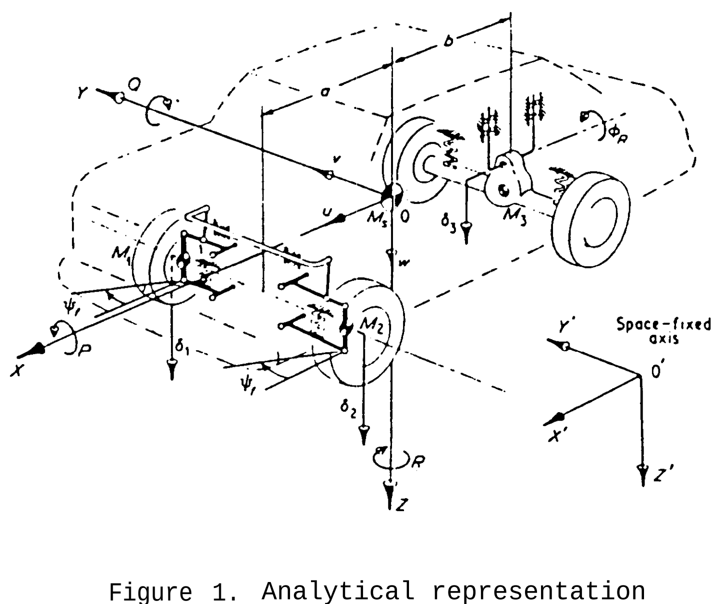

Figure 1. Analytical representation of the HVOSM vehicle.

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In 1976, after 10 years of development, refinement, validation and applications of the HVOSM by Calspan as well as other research organizations, a Federal Highway Administration (FHWA) contract (DOT-FH-11-8265, Ref.11) was performed by Calspan to document all of the various developments, refinements and validations of the HVOSM. Also, the input and output formats were revised for improved user convenience and an optional simulation of an independent rear- suspension was incorporated.

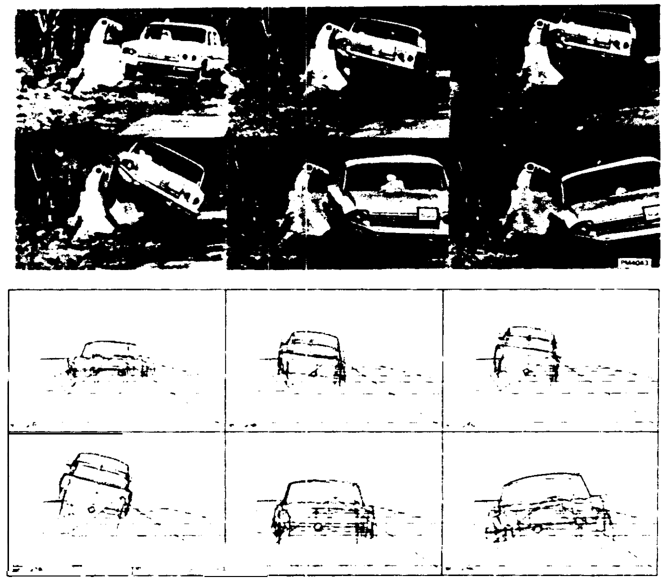
More recently, in 1987, further extensions and refinements were documented in relation to applications to off-road rollover accidents (Ref.12,13). In a recent TRB paper (Ref.14), brief descriptions are presented of a number of research applications of HVOSM which serve to further define its current general capabilities and limitations.

Primary attention in the present paper will be focused on extensions, refinements and validation efforts specifically related to the simulation of collisions with concrete median barriers (CMB).

CONCRETE MEDIAN BARRIER SIMULATION

The HVOSM was first applied to CMB collisions in 1966 (Ref.1). A related topic of interest at that time was the extent of effects of a controlled low friction of the barrier surface. It was found that the computer simulation, as formulated at the time and with its validation limited by the fragmentary experimental measurements available for correlation evaluations, indicated that a reduced friction of the barrier surface had negligible effects on vehicle responses. This finding was supported by the results of experiments performed by the General Motors Proving Ground(Ref.15).

Computer graphics techniques were applied in 1969 to produce pictorial displays of predicted vehicle responses in a CMB collision (Fig.2, from Ref.10). The early "wire-form" graphics format (i.e., all hidden lines visible) was also used to produce motion picture films so that animations of predicted vehicle responses could be viewed, and compared with full scale test results. A lack at that time of detailed measurements of responses from experimental CMB collisions limited the extent of the early validation effort.



EXPERIMENTAL AND PREDICTED VEHICLE RESPONSES FOR A 50 MPH, 12° COLLISION WITH THE GENERAL MOTORS BRIDGE PARAPET

(REVISED 19 MARCH 1969)

Figure 2. Graphical Comparison of full scale test results with HVOSM predicted responses.

In 1976, the Southwest Research Institute (SWRI) performed a program of CMB research (Ref.16). That research included the performance of experimental CMB collisions and the application of an extended version of HVOSM to CMB collisions. The selected form of the extensions to HVOSM chosen by SWRI reflected their focus on vehicle response evaluations for impact angles less than approximately 16 degrees. Their limited use of HVOSM in the cited research program was for interpolations within the relatively small range of impact angles in which acceptable experimental responses were achieved. Since their measured test results were not acceptable at angles greater than approximately X6 degrees, the selected analytical approach for simulation of body-structure contacts with the CMB was extremely simplified. It consisted of the use of a Texas Transportation Institute (TTI) version of the HVOSM that modeled CMB barrier impacts by the use of three contact points on the vehicle body interacting with a single vertical plane representing the CMB. For impact angles less than approximately 7 degrees, SWRI omitted the simulation of body-structure contacts with the CMB. While the simulation approach selected by SWRI may have been appropriate for the limited scope of their research program, it clearly lacked the generality needed for simulating vehicle responses in many real-life contacts with CMBs. In particular, the limitation of their research to shallow angles of approach by tracking vehicles (i.e., no side-slip angle or yawing velocity) in both experiments and computer simulations, failed to deal with the nature and the hazards of vehicle responses to be expected in CMB collisions following a loss of control of a vehicle or subsequent to a prior collision with another vehicle.

The CMB has recently gained relatively widespread acceptance, apparently on the basis of two aspects of the design concept. First, the lack of a need for maintenance has made the economics attractive when compared with alternative designs. Second, its "positive barrier" performance acts to provide a high level of protection of oncoming traffic from the errant vehicle. An additional aspect of median barrier performance that received greater attention in the past was the provision of some minimum level of cushioning and, thereby, protection of the occupants of the errant vehicle (e.g., Ref.17, 18). This latter consideration has obviously been somewhat downgraded in recent years. Clearly, impact on the median barriers of multi-lane highways are not limited to 16 degrees (see Fig. 3). Yet the redirective performance of CMBs deteriorates rapidly for angles larger than 16 degrees, with the measured vehicle responses including severe deceleration levels and potential rollovers (Ref.16).

In the following, recent extensions and refinements of HVOSM are described which permit the simulation of more general CMB collision contacts. Vehicle responses predicted with the modified HVOSM are then compared with published experimental data.

The objective of the increased simulation generality is to permit realistic evaluations of the overall performance of CMBs by means of (1) analytical studies of vehicle responses in non-tracking and/or large angle collision conditions and (2) reconstructions of the detailed impact conditions in actual injury producing CMB contacts.

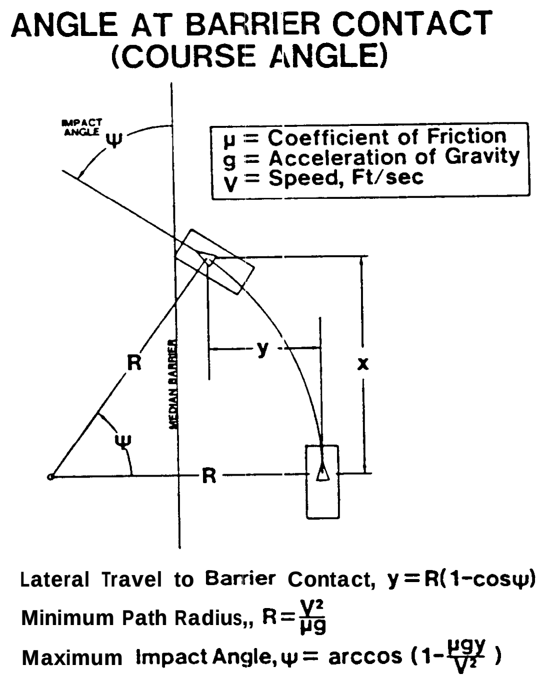


Figure 3. Analytical equations for the calculation of maximum vehicle course angle at barrier impact.

HVOSM EXTENSIONS & REFINEMENTS

Several extensions and refinements to HVOSM have been implemented in recent years which permit the simulation of more general CMB collision contacts. Three areas of refinement specifically related to the simulation of CMB collisions are:

(1) Structural Hardpoints
(2) Tire-Model Refinements
(3) Wheel/Suspension Displacements by Damage

STRUCTURAL HARDPOINTS-The HVOSM-76 RD2 model (Ref.11) included a simplified vehicle/barrier impact model (originally developed in Ref. 7) in which the vehicle periphery was modeled by three omni-directional structural hardpoints with inelastic structural properties which interacted with a single vertical barrier plane. Refinements were implemented into the HVOSM-84 version (Ref.12,13) which included both an increase in the number of hardpoints to 40 as well as the option to permit interaction between the hardpoints and. rigid terrain (e.g., rollover responses). In HVOSM, the terrain is modeled by up to 5 terrain tables with up to 21x21 grid elements each, which define elevation changes. The space-fixed location of a given vehicle hard-point is determined and the terrain table interpolation routine is utilized to determine the elevation and slope of the terrain at that point. The extent of interference with the rigid terrain by the vehicle hard-point is then determined, the hard-point is displaced to the terrain surface, and the resulting forces and moments acting on the vehicle are calculated.

Initial exploratory attempts to simulate a CMB collision using a terrain table form of definition of the CMB were unsuccessful. A modified approach was required to deal with the specialized interaction between the vehicle structure and a CMB type barrier. The specific selected approach was designed to make direct use of the multi-face curb definition of the tire force routine. In that routine, the program logic determines when a tire is sufficiently close to contact the curb and it switches from the terrain table interpolation routine to a "curb-impact" mode. The curb-impact mode utilizes curb slope/elevation change inputs to determine the elevation and slope of the local terrain and it then calculates the tire forces (e.g., Ref.10,11). The same type of logic was incorporated into the hardpoint option to permit vehicle hardpoint interaction with the identical multi-faced curb definition as the tire force routine (Fig.4). Additional logic was incorporated for the specialized hard-point CMB type collision to establish and store the slope of the contacted curb face for use in determining the proper directions of the resulting forces and magnitudes of the corresponding moments.

TIRE-MODEL REFINEMENTS- Several refinements to the HVOSM which have been implemented as a part of recent government and internal research (Ref 12-14,19,20) are utilized for the simulation of CMB impacts:

(a) Refinements of the Logic for Overloaded Tires
(b) Inelastic Deflection of the Wheel Rims
(c) Extensions of the Display Graphics
(d) Revision of the "equivalent" single-plane terrain.

<u>Refinements of the Logic for Tire Overload</u>--The original form of the HVOSM tire model (Ref.1) was found in recent research (Ref.12,13, 19,20) to fail to produce full saturation of the tire side forces under conditions of a broadside slide at extreme tire overload. While definitive data for tire properties under conditions of extreme overload and large slip angles have not been found to date, an examination of available measures of the side force properties of underinflated tires (e.g., Fig.5 from Ref.21) indicates that at large tire loads, relative to the inflation pressure, the side force increases at an increasing rate, as a function of slip angle. For the tire overload situation, logic was added to the HVOSM tire routine, TIRFRC, (Ref.19) to make adjustments that insure full saturation of the tire side forces at slip angles of 40 degrees or more.

<u>Inelastic Deflection of Wheel Rims</u>-The original HVOSM simulates the radial load-deflection characteristics of a tire as a "hardening" spring. The hardening spring is used to simulate radial forces generated during excessive radial deflections of the tire and rim. The "elastic" representation of the radial force properties was found to produce excessive rebound of the tire in some cases. Such rebound does not occur in the real world, where energy is dissipated in deforming the rim. Therefore as a part of extensions included in Ref. 12, logic was included to apply the hardening spring only during the loading phase,, thereby reducing the rebound and producing "plastic" load-deflection properties for the hardening phase of the deflection.

In CMB simulations, the revised logic was found to sometimes produce large step discontinuities in the resulting radial force responses. This occurred as the wheel contacting the curb was redirected in a direction parallel to the barrier. As the suspension deflection due to the initial impact (i.e.,compression) was reversed (to extension) and the wheel was moved downward in a direction towards the barrier, a small linear displacement would produce a large step increase in the radial tire force. A series of rapid changes, from the loading to unloading properties would act to produce discontinuous behavior.

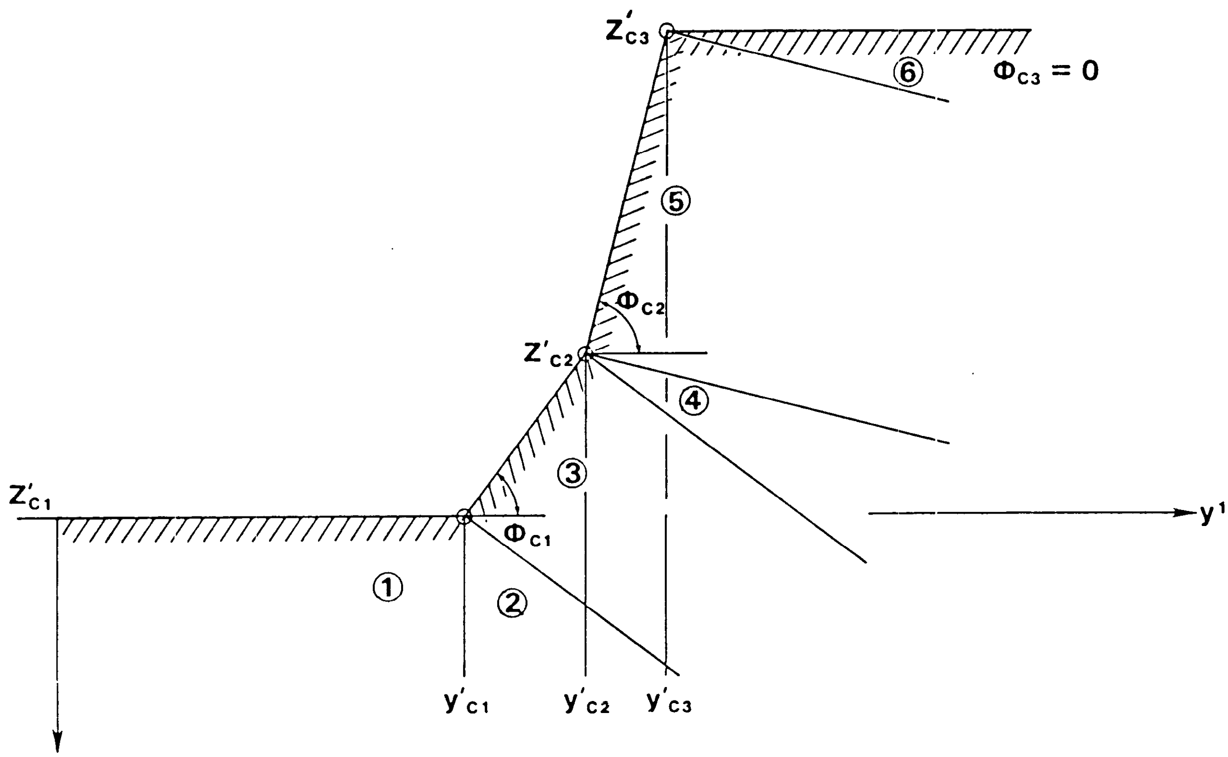


Figure 4A. HVOSM multi-plane curb definition indicating zones of possible hardpoint interaction.

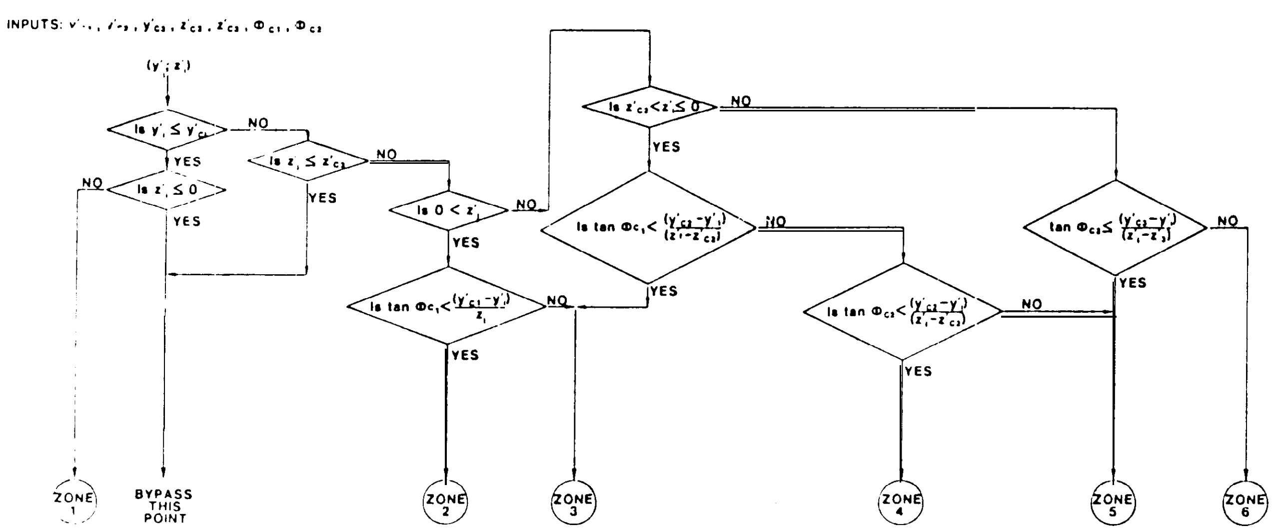
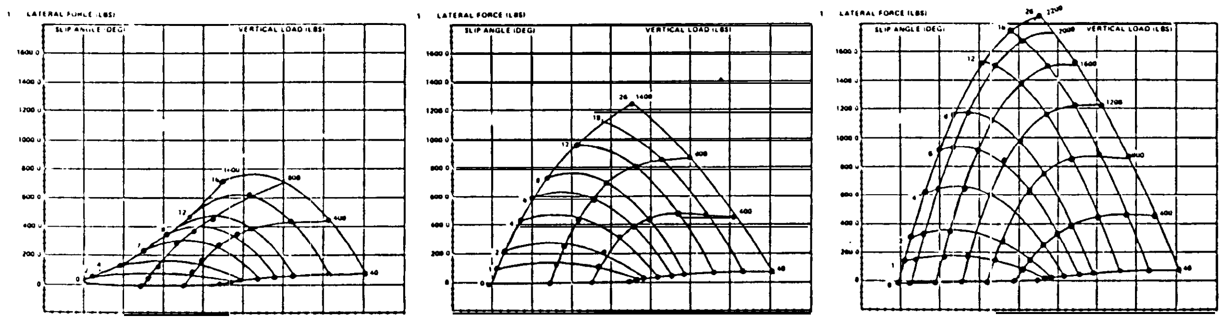


Figure 413. Flowchart of logic to establish hardpoint zones.



8 psi 16 psi 32 psi

Figure 5. Side Force tire properties for a tire inflated from 8-32 psi (from Ref.12).

Therefore a further refinement was implemented to produce the same type of "plastic" rim response without the step discontinuities. The hardening spring was modified in HVOSM87 to be combined with a viscous damper (Fig.6) which in the general case produces the same results as the earlier HVOSM84 modifications. However, in curb impacts, the viscous damper prevents step discontinuities from occurring in the radial spring forces.

<u>Extensions of Display Graphics for Radial Spring Mode</u>-While the existing radial spring form of the simulation of the tire forces in curb contacts has been retained, the graphic displays of tire tracks have been extended to include the entire contact ranges of the radial spring scans. In this manner, reconstructed CMB contacts can be correlated with actual tire marks (e.g., Fig.7, 8). It should be noted that the "equivalent ground contact" values printed out in such simulation runs correspond to the efeective "point of application" of the resultant radial tire force, rather than the maximum elevation of tire marking.

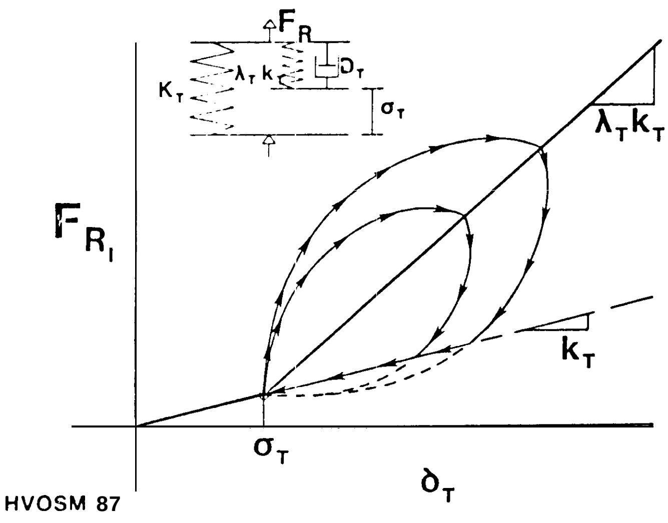
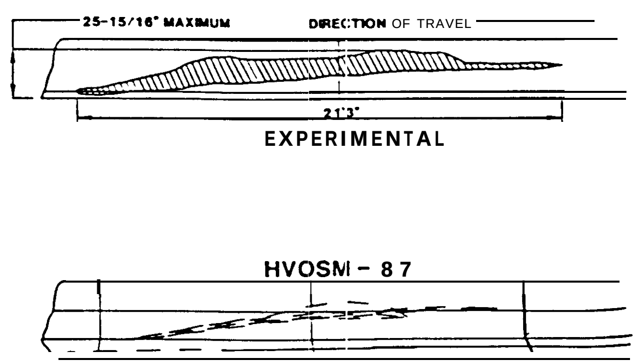
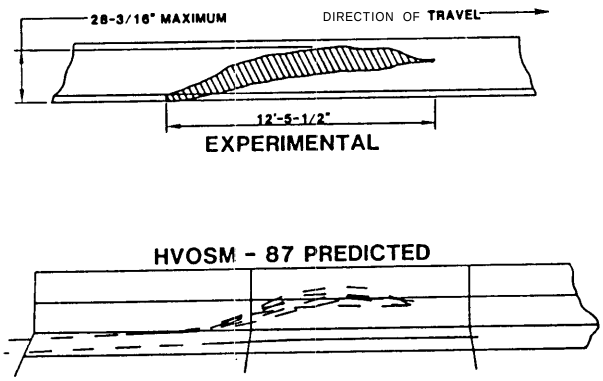


Figure 6. HVOSM-87 tire/rim properties including viscous damping.



CMB-8 TIRE BARRIER INTERFACE PROFILE FOR A 55.9 MPH, 8 DEGREE COLLISION WITH A NJ MEDIAN BARRIER

Figure 7. Tire/barrier interface profile for test CMB-8 (Ref.16),

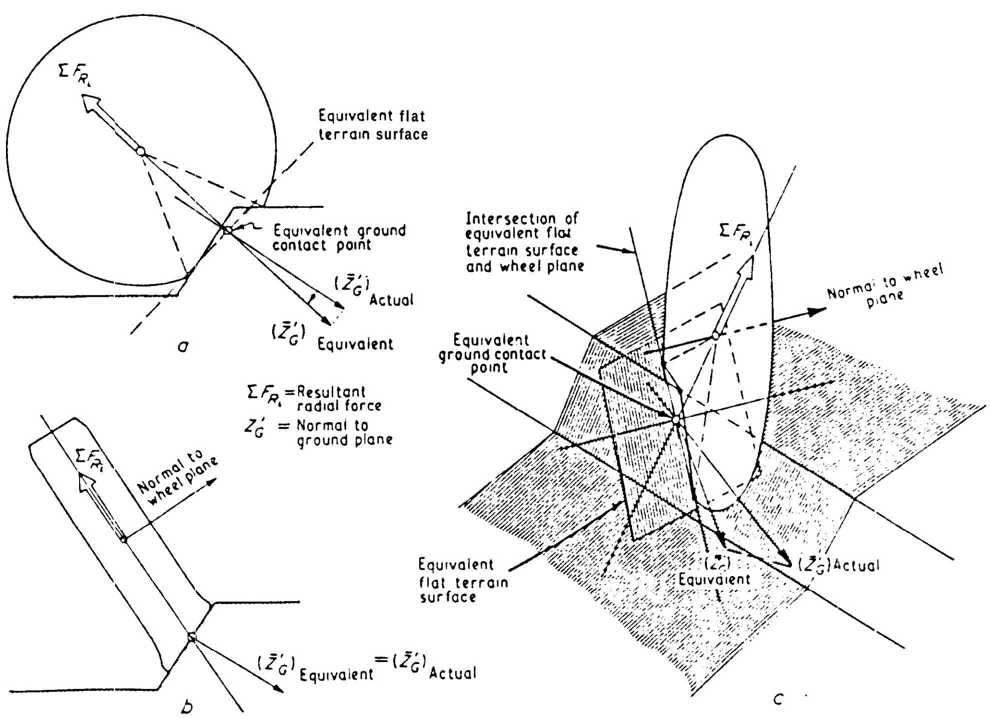


CMB-9 TIRE/BARRIER INTERFACE PROFILE FOR A 58.9 MPH, 15.5 DEGREE COLLISION WITH A NJ MEDIAN BARRIER

Figure 8. Tire/barrier interface profile for test CMB-9 (Ref.16),

Revision of the "Equivalent" Single Plane Terrain-A time varying "equivalent" single-plane terrain surface is defined for a tire in contact with a curb or CMB, in order that calculations of side, tractive and braking forces can be continued during the contact. In the previous analytical approach,(e.g.,Ref.10,11) the normal to the single-plane "equivalent" surface was forced to lie in the plane determined by the resultant radial force vector and a normal to the wheel plane (See Fig. 9). More recent, detailed investigations of the correlation of analytical predictions with experimental CMB and curb responses and related examinations of the time-histories of "equivalent" plane transitions have led to the conclusion that the previous analytical approach produced frequently discontinuous transitions which acted to limit the degree of correlation with experiments. Therefore, the definition of an "equivalent" single-plane terrain surface was modified in the following manner:

The "equivalent" plane concept may be viewed as simply a means of replacing an irregular, distributed, multi-plane tire contact with a single plane that will match the direction and magnitude of the resultant radial tire force. It need not be analytically related to the actual shape of the curb or CMB, since by definition it reflects the "effective" shape in terms of the



a Case 1. Wheel plane perpendicular to obstacle profile.
b Case 2. Wheel plane parallel to obstacle profile.
c Case 3. Oblique contact with terrain irregularity.

Figure 9. "Equivalent" flat terrain surface for non-planar tire-terrain contact.

generated radial tire force. Thus. a substantially simpler analytical approach has been adopted in which adjustments of the equivalent single-plane terrain slope are limited to rotations in the ϕ direction. Any indeterminate solutions (e.g., wheel plane parallel to **x'** axis) are replaced by the actual curb slope at the effective ground contact point.

The direction cosines of a line perpendicular to an individual CMB or curb surface are given by

$$A' = \cos\alpha_z' = 0$$
$$B' = \cos\beta_z' = -\sin\phi_G'$$
$$C' = \cos\gamma_z' = \cos\phi_G'$$

(actual slope at equivalent ground contact point.)

If a single-plane equivalent surface is defined to replace the actual multi-plane contact, with $\theta_G = 0$, it will have the following direction cosines:

$$A = \cos\alpha_z' = 0$$
$$B = \cos\beta_z' = -\sin\phi_G$$
$$C = \cos\gamma_z' = \cos\phi_G$$

(Single plane equivalent of CMB contacts.)

The line with direction components a_i', b_i', c_i' which is perpendicular to both the normal to the wheel plane and F_{Ri}' must be parallel to the single equivalent plane or lie in it. Therefore, the sum of the products of the direction components of the line and plane must be equal to zero:

$$aA + bB + cC = 0$$

$$a\,(0) + b(-\sin\phi_G) + c\,(\cos\phi_G) = 0$$

$$b \sin\phi_G = c \cos\phi_G$$

$$\tan\phi_G = \frac{c}{b}$$

WHEEL/SUSPENSION DISPLACEMENT BY DAMAGE-The original form of the HVOSM-RD2 version did not include any provisions for damage induced movement of wheels in the vehicle-fixed x-y plane and/or side to side differences in the rolling resistances and steer responses of the individual wheels. Therefore, the program was modified to permit the specification for each wheel of steer angle and/or rolling resistance and an option was added to permit the deflection of a wheel in the X-Y vehicle plane when forces on an individual wheel exceed a user specified threshold. Above the force threshold, the wheel may be displaced at a specified load deflection rate.

COMPARISON OF THE HVOSM WITH CMB CRASH TESTS

Preliminary simulations of the baseline tests for the NJ and GM barrier shapes for both the subcompact and full size vehicles contained in SWRI CMB research report (Ref.16) indicate good correlation between the HVOSM87 and the full scale tests. Two samples of the tire/barrier interface profile comparison (Fig.7,8) for tests CMB-8 and CMB-9 indicate that the HVOSM87 length and height are in good agreement with the full scale tests. Also, comparisons with the reported roll and yaw response time histories (Fig.10,11) demonstrate good correlation (note that discrepencies exist in the SWRI report between the data plots and the reported <u>maximum</u> values). Areas to be investigated in the future to further improve the correlation between the HVOSM and the full scale tests will be a sensitivity analysis of effects of the available and/or a modified version of the HVOSM steer-degree-of-freedom. Examination of test film for the SWRI CMB impacts with the GM and NJ barrier shapes indicates that the force of the impact produces a large steer angle toward the barrier which produces a longer duration of interaction between the vehicle and barrier and, in some instances, a recontact. The HVOSM87 responses included a steering response toward the wall with magnitude and duration somewhat less than those in the reported full scale test results. Therefore, a further sensitivity analysis of variation of the inputs and/or logic associated with the steer-degree of freedom will be pursued.

In summary, a brief description and history of the HVOSM computer program has been presented. Also, recent extensions and refinements of the HVOSM related to the simulation of collisions with concrete median barriers have been described and sample results of validation efforts have been presented.

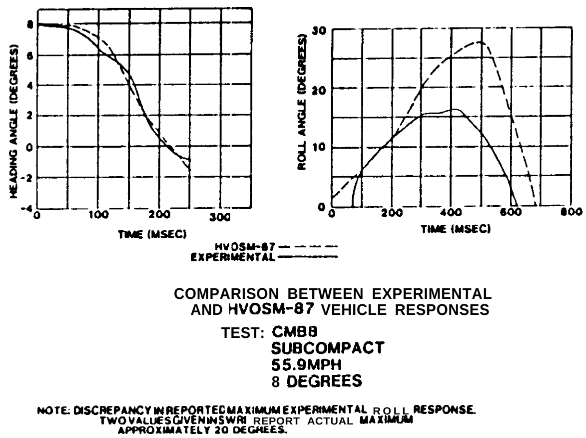


Figure 10. Comparison tire history of heading angle and roll angle for HVOSM 87 and full scale test results.

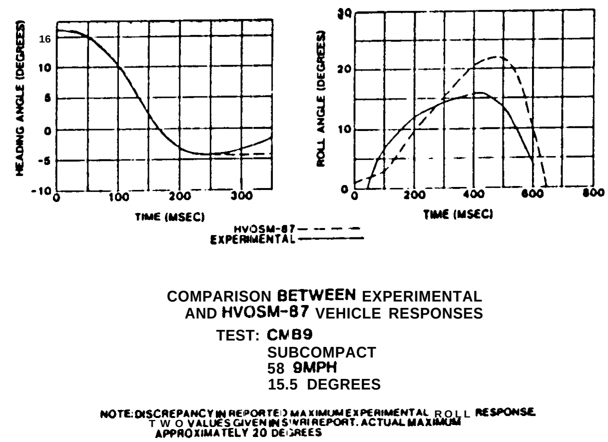


Figure 11. Comparison of time history heading and roll responses for HVOSM 87 and full scale test results.

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