

# Beyond The Green Book

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## ***Simulation Models of Vehicle Dynamics***

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### **Abstract**

Evaluations of geometric design features of highways and roadsides, with respect to the dynamic behavior of vehicles traversing them, have been supplemented since the late 60's by the use of computer simulation models of vehicle dynamics. This paper discusses the rationale for the use of computer simulation techniques and presents descriptions of two public-domain computer simulation models of vehicle dynamics (HVOSM and UMTRI-PHASE 4). Sample results of several applications of the two programs are included which demonstrate representative interactions between vehicle characteristics and roadway and roadside geometric design features.

### **Introduction**

Evaluation of the geometric design features of highways and roadsides, with respect to the dynamic behavior of vehicles traversing them, has been supplemented since the late 60's by the use of computer simulation models of vehicle dynamics. Rapid advances in the field of micro-electronics in the last decade have made the computerized manipulation of complex equations defining vehicle dynamics over a wide range of operating conditions very feasible, productive and cost effective.

The purpose of this presentation is to review the rationale for the use of computer simulation models of vehicle dynamics in the evaluation and refinement of geometric design features. Also, two public domain computer simulation models of vehicle dynamics will be described and sample applications discussed.

## Rationale

The selection of specific full scale experiments to evaluate highway geometric design features is made difficult by the wide ranges of variables that exist in the vehicle population and in operating conditions (e.g., vehicle sizes and characteristics, driver/environmental factors, speeds and maneuvers). Problems associated with the performance and repeatability of full-scale tests, including the selection and/or construction of specific geometric design features to test, instrumentation and the calibration of test instruments and the high unit cost per test run, all detract from a purely experimental approach involving a large number of full scale tests from which to make specific design decisions.

At the other extreme, the use of point-mass equations and/or simplified empirically derived equations to evaluate geometric design features is of questionable reliability. The present vehicle population includes passenger and commercial vehicles with wide ranges of size, weight, drive type, weight distribution, acceleration capabilities and handling characteristics. This diverse vehicle population includes an equally diverse array of drivers varying in experience, capabilities and characteristics. All of the cited variables in the vehicle and driver population need to be considered in an evaluation of geometric design features.

This large gap that exists between the cited extremes of techniques available to evaluate geometric design features, combined with the emerging capabilities and availability of computers in the sixties and seventies provided a logical alternative approach for supplementing our understanding and evaluation of geometric design features.

The basic approach in the utilization of a simulation model of vehicle dynamics is to create a computer code based on fundamental laws of physics, combined with empirical relationships for tires and structural properties, which can be applied so that the responses can be compared with instrumented full scale tests. Once the model is objectively "validated" the researcher can use the model to interpolate and extrapolate test data and test sensitivities to changes in the vehicle, driver and roadway design at a fraction of the cost of the full scale tests. Depending on the degree of sophistication of the simulation model and the simplifying assumptions used to create it, the variables which can be investigated are essentially unlimited. However, as a word of caution, when using simulation models to test the sensitivities of responses to changes in design elements, one must exercise appropriate care in the interpretation of results and in the formulation of conclusions. Limitations inherent in any computer simulation model due to simplifying assumptions and applications outside the

range of validation must be properly considered to insure that the results are representative of real world responses and not produced by some inherent artifact of the simulation model. Computer based simulation models should be viewed as one tool of many which can be used to supplement the other "tools" (e.g., full scale tests, sound engineering practices and principles and common sense) to ultimately evaluate a design problem.

Two public domain computer simulation models of vehicle dynamics which have been extensively validated and utilized in addressing geometric design problems are the *Highway Vehicle Object Simulation Model (HVOSM)* (Ref 1&2) and the Truck and Tractor-Trailer Dynamic Response Simulation-Phase4 computer model (Ref 3&4).

## Highway Vehicle Object Simulation Model (HVOSM)

In the mid-60's the Calspan Corporation (then Cornell Aeronautical Laboratory, Inc.) began development of a general mathematical model and computer simulation of the dynamic responses of automobiles under Contract CPR-11-3988 with the Bureau of Public Roads. The mathematical model, which was subsequently named the HVOSM, includes the 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 was performed to permit an objective assessment of the degree of validity of the computer model.

The HVOSM mathematical model consists of up to 15 degrees of 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 are defined in the form of a set of differential equations which constitute the mathematical model of the system

In 1976, after 10 years of development, refinement and applications of the HVOSM by Calspan as well as other research organizations, a Federal Highway Administration (FHWA) contract (DOT-FH-11-8265, Ref.2) was performed by Calspan to document all the various developments, refinements and validations of the HVOSM. Within that contract, two program versions were assembled, the HVOSM version (Roadside Design) and the HVOSM-VD2 version (Vehicle Dynamics).

Since 1976 a number of further refinements and enhancements of the HVOSM-RD2 version have been developed and incorporated by McHenry Consultants, Incorporated, (MCI) under subcontracts with Jack Leisch and Associates (DOT-FH-11-9575, Ref.5), Midwest Research Institute (DTFH-61-80-C-00146, Ref.6) Calspan (DTFH61-83-C-00060, Ref.7) and the Highway Safety Research Center of the University of North Carolina (DTFH61-84-C-00067, Ref.8) under FHWA sponsorship as well as through internal research.

#### **Truck and Tractor-Trailer Dynamic Response Simulation-Phase4**

Since 1971, the Transportation Research Institute (formerly the Highway Safety Research Institute) of the University of Michigan (UMTRI) has been conducting research under the sponsorship of the MVMA and the FHWA to develop a means of predicting and evaluating the directional response characteristics of trucks, tractor-semi trailers, tractor-trailers and triples. In 1980, UMTRI released the PHASE4 program which constitutes a compilation and consolidation of nearly a decade of development of the existing models into a single program (Ref.3). The PHASE4 program is a time-domain mathematical simulation in which the vehicles are represented by differential equations derived from Newtonian mechanics combined with empirical and/or tabular relationships for some components (e.g., tires) that are solved for successive time increments by digital integration. The mathematical model incorporates up to 71 degrees of freedom with the number of degrees of freedom being dependent on the vehicle configuration and options chosen. The PHASE4 program includes small angle assumptions in its basic mathematical equations which means that in many of the equations, an angle in radians is used in place of the sine or tangent of the angle. As a result, the program is limited to ranges wherein the accuracy of the approximations is acceptable (i.e., angles < 15 degrees).

#### **Sample Applications**

In the late 70's and early 80's an FHWA study was conducted by Jack Leisch and Associates (JEL) on Safety and Operational Considerations for the design of Rural Highway Curves (Ref.5) which included the use of the HVOSM and the PHASE4 program to supplement operational field studies of curve sites.

The HVOSM was used to simulate the driver/vehicle operations on a wide range of highway curves. The basic input requirements for the performance of an HVOSM or any simulation run include definition of the vehicle, the roadway and of the driver control inputs.

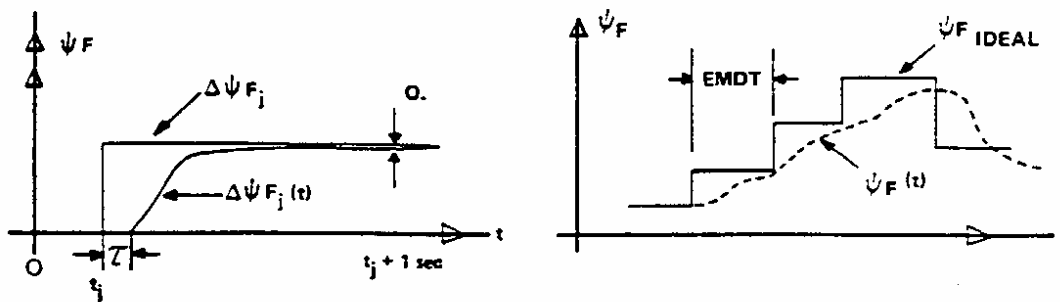
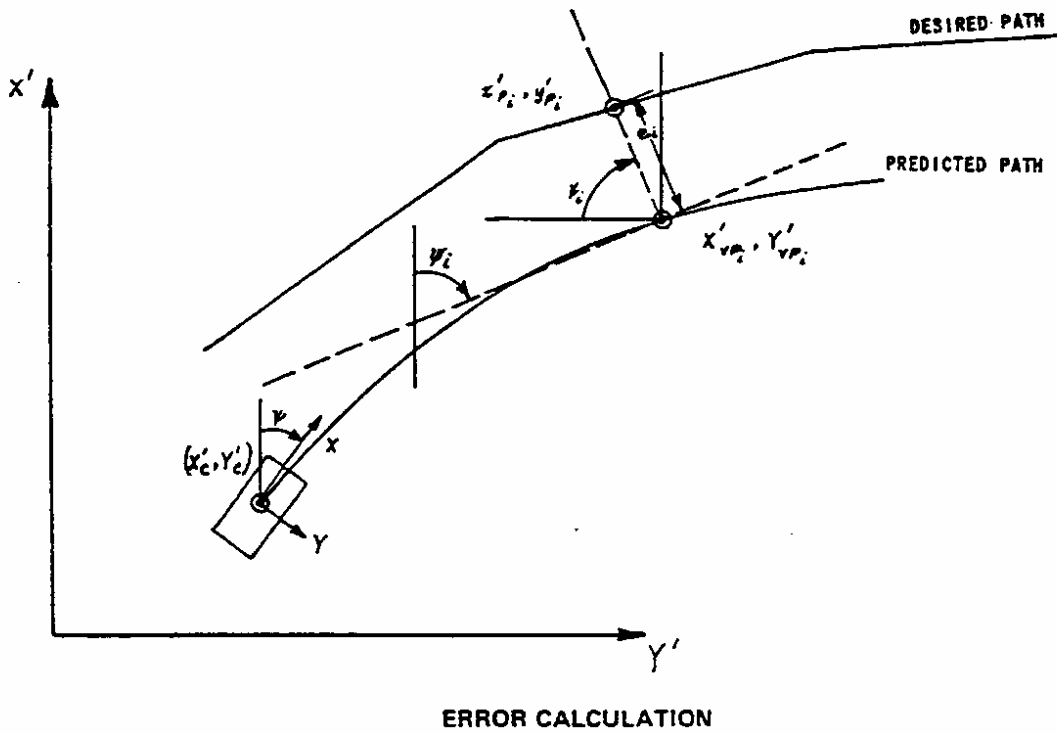
The specification of the vehicle inputs for the HVOSM requires selection of a vehicle type and the creation of corresponding inputs to define the vehicle properties. A growing number of measured vehicle data sets exists which can be supplemented by approximation techniques (Ref. 2).

The specification of the roadway for the HVOSM consists of creating terrain tables to define the elevation of the terrain for each grid segment of the table. HVOSM has the capability of accommodating 5 terrain tables with up to 441 terrain elevation points in each table. An auxiliary Terrain Table Generating program was created as part of the JEL Study to permit the automatic generation of tables for any type of roadway based on standard roadway and shoulder geometric descriptions.

A driver model was also incorporated into the revised HVOSM-RD2 program as a part of the JEL study. It was based on the form of driver model contained in the HVOSM-VD2 model. The revised driver model consists of a polynomial definition of the desired path and a wagon-tongue steer control with a "neuro-muscular" filter to permit variations in the driver observation and response characteristics (Fig.1). The "wagon tongue" form of steer control consists of the use of a line which extends forward of the vehicle centerline at a user specified distance at which an error from the "desired" path is calculated and used as input to the "neuro-muscular" filter. The filter serves to delay the response for a specified perception reaction time after which it applies a correction to the steer angle based on an input gain factor.

Problems which can arise from using a simulated driver control occur when either (1) only optimum driver control is achieved (no dynamic overshoot) and the corresponding justification for the simulation is questionable, or (2) excessively oscillatory steering responses occur which reflect artifacts of the driver model rather than the real world roadway characteristics. Care must be taken to insure that neither of these situations occur and form the basis for an incorrect conclusion.

The basic methodology utilized for the JEL study was to initially compare simulations of optimum driver/vehicle performance on a number of sample curves with calculated lateral acceleration and tire friction factors (i.e., simulating a path-following with a



**FIGURE 1 HVOSM driver model (from Ref. 2).**

minimum of dynamic overshoot of the desired path). Next the driver model of the HVOSM was calibrated to be more representative of the "typical" driver observed in field studies (i.e., a somewhat less than optimum driver who overshoots the desired path radius). Then this "driver" was used to guide the simulated vehicle through a wide range of curve entry runs to test several design variables (i.e., superelevation runoff and runout, spirals, etc.).

The resulting driver model inputs that were selected for the study produced response characteristics representative of the field observations, however, there were some discrepancies later found in the manner in which the critical radius was generated. The drivers observed in the field tended to approach from the outer edge of the curve and follow a spiral path which began approximately 50-100' before the PC and which headed the vehicle to the inside of the curve (Fig.2&3). The

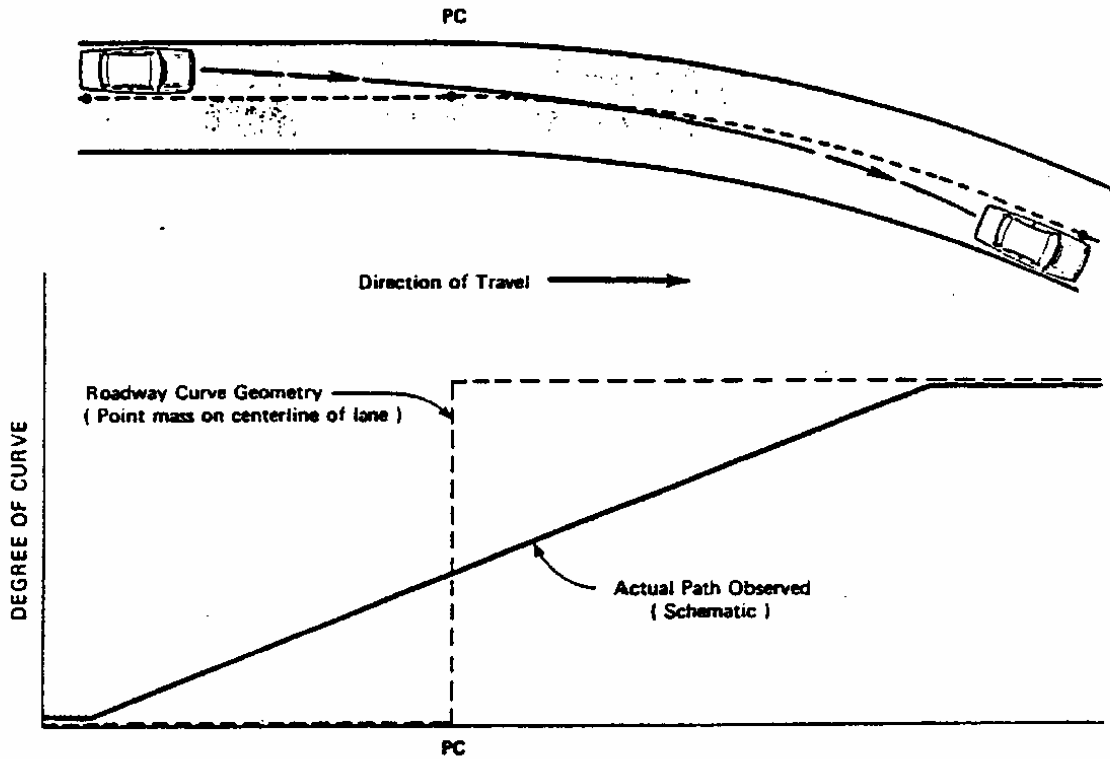


FIGURE 2 Comparison of observed, schematic path with centerline geometry (from Ref. 5).

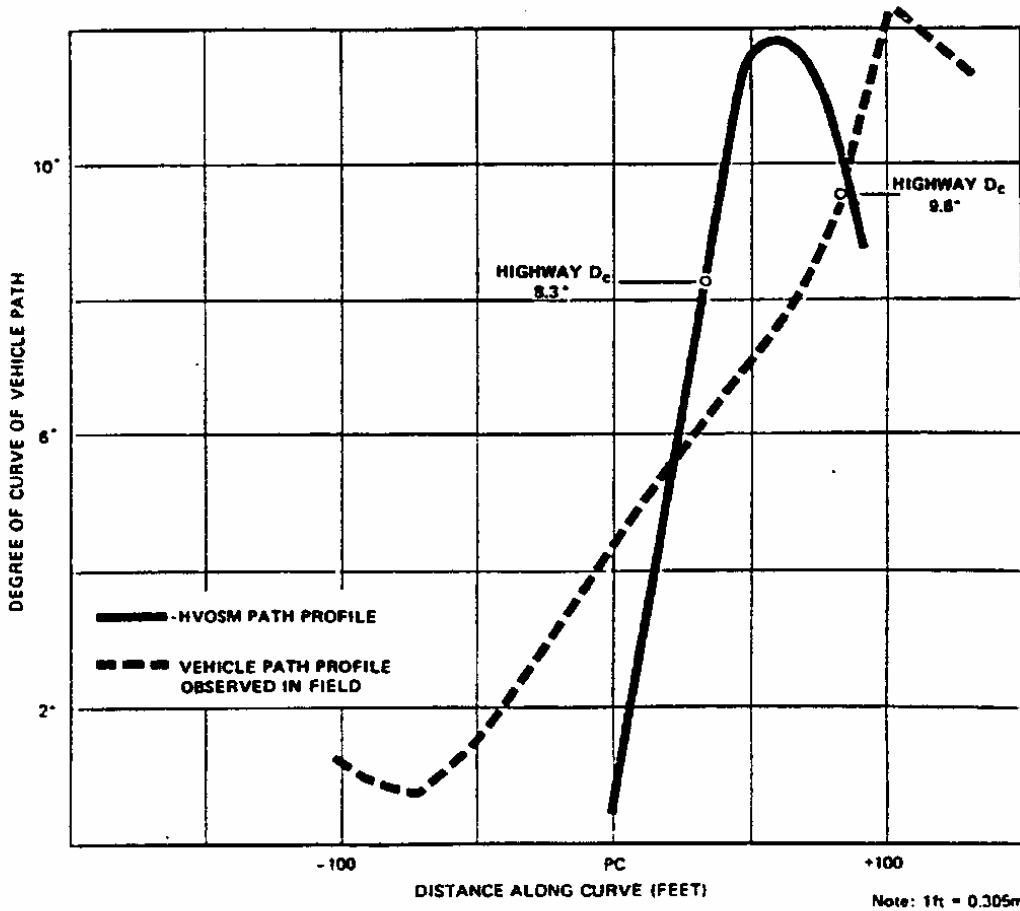


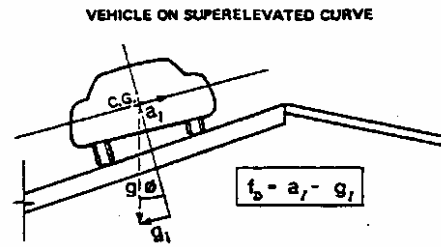
FIGURE 3 Comparison of vehicle path transitioning behavior from HVOSM and vehicle traversal studies (from Ref. 5).

HVOSM driver model was attempting to follow the specified centerline of the roadway and developed a more rapid rate of spiral, which developed after the PC. This discrepancy can be overcome in future studies by an alternative specification of the desired path to be more representative of the observed path and/or variation of the neuro-muscular filter of the wagon tongue to be more representative of the observed vehicle and driver characteristics.

The standard outputs from a typical HVOSM simulation run include the vehicle position, orientation, acceleration, tire forces, suspension forces and steer and camber angles. Additional output calculations added to the HVOSM during the JEL project were the driver "discomfort factor" and the friction demands of the individual tires.

The "discomfort factor" is representative of the resultant acceleration that an occupant experiences during a recovery maneuver (Fig.4). The use in the evaluation of cornering maneuvers of a hard mounted accelerometer measurement of lateral acceleration of the vehicle does not include the effects that the vehicle roll angle has on the occupant. For example, a vehicle in a normal cornering maneuver rolls in a direction opposite to the turn (i.e., rolls positive, or right for a left hand turn & visa versa) and therefore the "discomfort" which would be experienced is greater than the calculated lateral acceleration (i.e.,  $V^2/R$ ). Curves are superelevated to reduce or reverse the magnitude of the vehicle roll angle to reduce the "discomfort factor" felt by the driver and occupants. Many of the earlier geometric design criteria standards were based on experimental measures of a ball bank indicator during cornering maneuvers which essentially measured the same resultant acceleration as the HVOSM calculated "discomfort factor." The "discomfort factor" output of the HVOSM illustrated the problems associated with cross-slope breaks on highway curves in "HVOSM Studies of Highway Cross Slope Breaks on Highway Curves", (Ref.9) which was also prepared as a part of the JEL study. In that study the problems associated with cornering on an adversely super-elevated curve (i.e., cross slope break) were demonstrated by examination of the "discomfort factor." Subsequent recommendations were made to reduce excursions onto the shoulder break which can result in unacceptable levels of driver "discomfort."

The friction demand is another calculated variable that has been added to the HVOSM output (Fig.5). As a vehicle is steered into a turn, side forces develop at the tires which permit the vehicle to make the cornering maneuver. The amount of surface friction required to support a given cornering maneuver is defined as the



$f_d$  = Discomfort Factor =  $\vec{a}_l + \vec{g}_l$   
 Where:  
 $\vec{a}_l$  = Lateral Acceleration of Occupants  
 $\vec{g}_l$  = Lateral Component of Gravity  
 $\phi$  = Roll Angle  
 $a_l, g_l$  in Vehicle Fixed Coordinate System

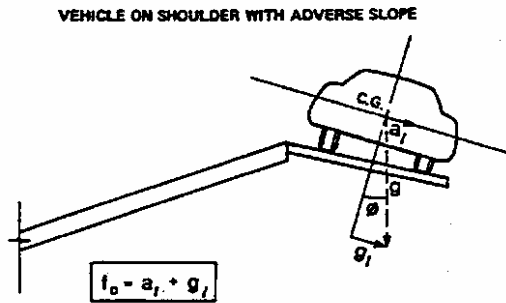
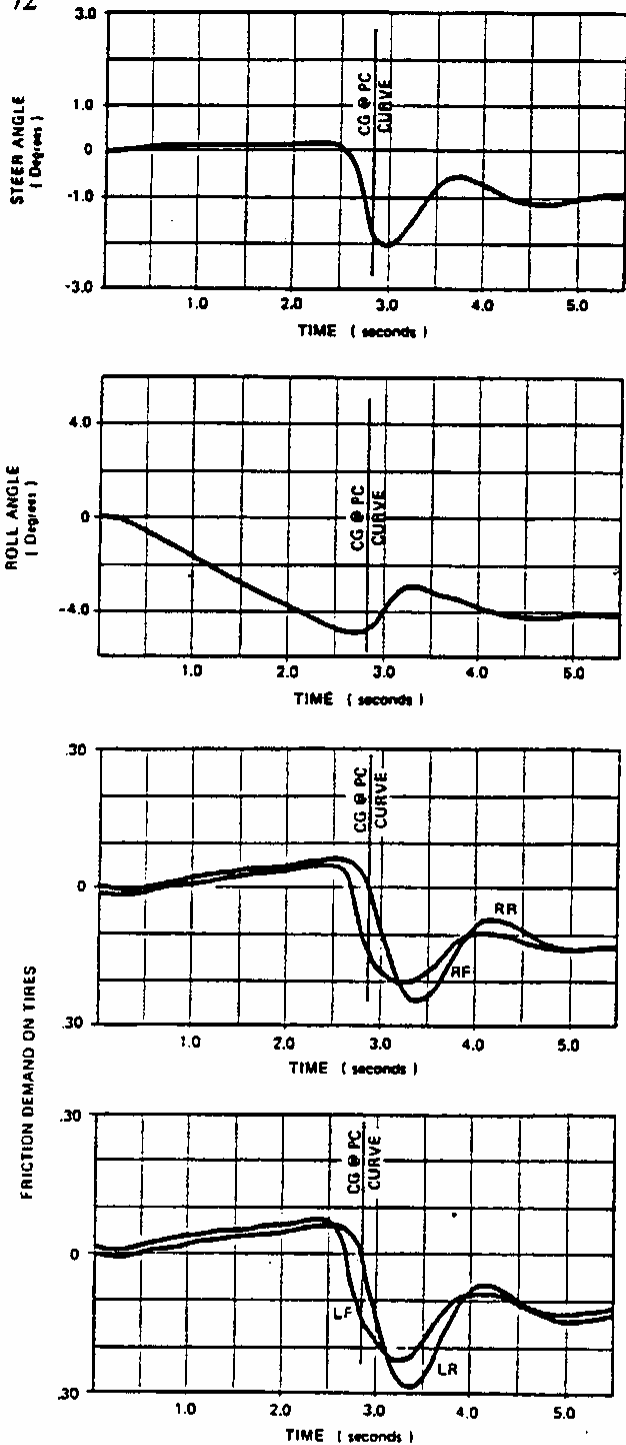


FIGURE 4 Relationship between driver discomfort factor and combination of roll angle and lateral acceleration (from Ref. 9).

"friction demand" which is equal to the ratio of the side force to the normal load for an individual tire. The standard output of HVOSM already included the individual tire side forces and normal loads so the output modifications entailed a simple calculation of the time-history of the cited ratio at each tire.

Another subtask of the JEL study included the use of both the HVOSM and the PHASE4 programs to evaluate passing maneuvers over centerline crowns (Ref 10)(Fig.6). The research included a direct comparison of the HVOSM and the PHASE4 programs to obtain a measure of the degree of correlation between the simulation models. The Phase4 program was modified to utilize the same driver model and terrain definition and interpolation routine as the HVOSM to implement the comparison. Since both programs can handle single unit trucks, inputs for a 1974 White Road Boss (4x2) were used for the comparison simulations (Ref 11). The results of the comparison of the programs demonstrated a generally good agreement of the predicted response characteristics of the two simulation programs for maneuvers such as a passing-type maneuver.



**TEST CONDITIONS**  
Speed -- 50mph (80km/h)

**Roadway Geometry**

Centerline Radius 689ft (210m)  
Superelevation 10 percent  
Super. Runoff 236ft (72m)  
Super. Dist. 70% on tangent  
Grade 0 percent

**Vehicle and Driver Characteristics**

Probe Length 17.7ft (5.4m)  
P GAIN  $5.8 \times 10^{-6}$  rad / ft  
( $1.9 \times 10^{-5}$  rad / m)  
Q GAIN  $5.8 \times 10^{-7}$  rad - s / ft  
( $1.9 \times 10^{-6}$  rad - s / m)  
No Deceleration

**FIGURE 5 Sample HVOSM outputs (from Ref. 5).**

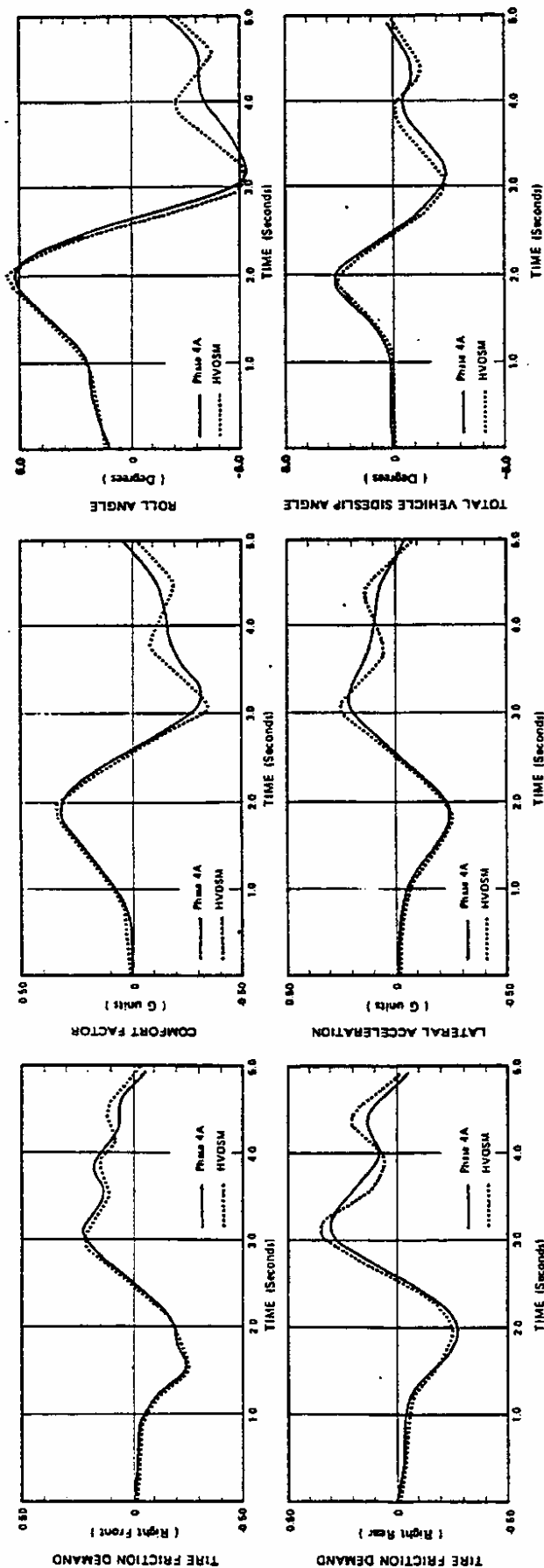
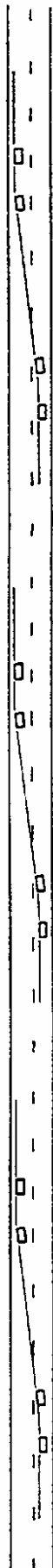
In other research in the 1980's, Midwest Research Inc., included an application of HVOSM in their FHWA sponsored research on Work Zone Design Considerations for Truck Operations and Pavement/Shoulder Drop-Offs (Ref.6). In that study, the HVOSM was modified to include an enhanced tire model which simulated the tire sidewall interaction (i.e. scrubbing) that can occur in pavement/shoulder drop-off maneuvers. Early curb-impact research by Texas A&M (Ref.12) had revealed a degraded correlation of HVOSM with full scale curb impact tests for shallow encroachment angles which was later confirmed by follow up studies by McHenry, et al (Ref. 13) and Segal, et al

(Ref.14). The modification for the MRI project improved the modeling technique utilized for shallow angle encroachments and allowed the scrubbing interaction to be simulated for curbs as well as shoulder drop-offs. However, the generally fragmentary documentation of full scale test runs of pavement/shoulder drop-offs and shallow angle encroachments of curbs precluded a rigorous validation from being achieved. Of particular importance in this type of maneuver is the front wheel steering response immediately subsequent to the curb or pavement/shoulder mount.

A study performed for FHWA by Calspan in 1986 entitled "Rollover Potential of Vehicles on Embankments, Sideslopes and other Roadside Features" (Ref.7) included the application of HVOSM to predict the dynamic responses of vehicles encountering a variety of roadside-feature configurations. Enhancements to the HVOSM that were provided to Calspan by McHenry Consultants, Incorporated were the aforementioned refinements from the other projects as well as options to allow the modeling of deformable soil plowing, an enhanced tire model to improve modeling of the rollover phenomenon and a sprung-mass ground contact model to permit multiple rollovers to occur by simulating interactions between the vehicle structure and the terrain.

In 1985, the Highway Safety Research Center of the University of North Carolina (HSRC) conducted a study of Safe Geometric Design for Mini-Cars for FHWA (Ref. 8), which included among many other things the use of HVOSM to supplement an investigation of sideslopes and related issues, traffic islands and relationships between vehicle parameters and rollover propensity.

The findings related to sideslopes confirmed earlier work by Calspan (Ref.7). The finding with respect to traffic islands took the form of a "rollover envelope" defining a range of speeds in which a vehicle may roll over when impacting a traffic island.



**TEST CONDITIONS**

Vehicle Type: Single-unit Truck  
 Crest Slope: 2 percent  
 Initial Speed: 104 km/h  
 Design Speed: 120 km/h  
 Nose: 1 km/h = 0.62 mph, 1 m = 3.28 ft

Probe Length: 7.20 m  
 P Gain:  $0.9 \times 10^{-2}$  rad/m  
 Q Gain:  $2.8 \times 10^{-3}$  rad-s/m  
 Acceleration: 0.50 g

**SIMULATION RESULTS FOR SINGLE-UNIT TRUCK**

FIGURE 6 Comparison of phase4 and HVOSM simulation programs (from Ref. 5).

With respect to rollover propensity, many researchers have referred to the "static stability factor" (i.e.,  $T/2H$ ,  $T$ =track width,  $H$ =CG height) which is used as a measure of a vehicle's propensity to roll over. HVOSM was used to test the merits of the equation. The HVOSM demonstrated the fact that the responses of a vehicle differ from these of a concrete block, and, therefore, the "static stability" factor is an oversimplification (Fig.7). A vehicle constitutes a dynamic system which combines inertial, tire and suspension properties as well as dimensional characteristics to define handling properties which can, under some circumstances, produce a rollover. There also appears to be a relationship between the inertial ellipsoid of a vehicle and the vehicle's rollover propensity

when the tires suspension and dimensional properties are also considered. The exact relationship or a calculatable "factor" defining a vehicle's rollover has yet to be determined.

In summary, two very powerful and well documented vehicle simulation programs, HVOSM and the PHASE4, can be utilized to supplement investigations of the changing vehicular population and its effect on roadway and roadside geometric design requirements. Several applications of these programs performed in recent years have been briefly presented and discussed. The applications demonstrate the range of interactions between vehicle characteristics and roadway and roadside geometric design features which can be investigated by simulation techniques.

Relationship between Flat Surface  $\mu_{CRITICAL}$  and Static Stability Factor ( $T/2H$ )

Vehicle	Total Weight (lb)	Mass (kg)	Flat Surface $\mu_{CRITICAL}$	$T/2H$	$\mu_{CRIT}/T/2H$ %
<u>Ordered with respect to <math>T/2H</math>:</u>					
Civic	1699	770	1.00	1.23	81%
Rabbit1	2410	1093	0.85	1.27	67%
Omni	2138	969	0.95	1.35	70%
Rabbit2	1800	816	0.95	1.37	69%
Malibu	3580	1624	1.15	1.40	82%
Celebrity	2974	1349	1.15	1.42	81%
Vega	2639	1197	1.25	1.46	86%
LTD	4450	2018	1.40	1.55	90%
<u>Ordered with respect to <math>\mu_{CRITICAL}</math>:</u>					
Rabbit1	2410	1093	0.85	1.27	67%
Omni	2138	969	0.95	1.35	70%
Rabbit2	1800	816	0.95	1.37	69%
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LTD	4450	2018	1.40	1.55	90%

Comparison of Critical Friction Coefficients for Rollovers for Various Vehicles Modified to Have Identical Static Stability Factors

Vehicle	Modified Sprung Mass CG Height		Static Stability Factor ( $T/2H$ )	Critical Rollover $\mu$	% of $\mu_{CRITICAL}/T/2H$	
	(in)	(mm)			For $T/2H = 1.30$	For Original $T/2H$
Honda	-21.97	-558	1.30	1.10	85%	81%
Celebrity	-24.12	-613	1.30	1.00	77%	81%
LTD	-24.70	-627	1.30	1.17	90%	90%
Vega	-22.52	-572	1.30	1.05	81%	86%

FIGURE 7 Comparison of "static stability factor" with HVOSM simulated rollovers (from Ref. 8).

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