

HVOSM (Highway-Vehicle-Object  
Simulation Model)  
Studies of Highway Cross Slope  
Design  
October, 1983  
Leisch and Associates

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PB86-114840

HVOSM (Highway Vehicle Object Simulation Model)  
Studies of Highway Cross Slope Design

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Prepared for

Federal Highway Administration, Washington, DC

Oct 83

U.S. Department of Commerce  
National Technical Information Service

**NTIS**

# Technical Report Documentation Page

1. Report No. FHWA/RD-84/006		2. Government Accession No. PB86-114840		3. Recipient's Catalog No.	
4. Title and Subtitle HVOSM Studies of Highway Cross Slope Design				5. Report Date October 1983	
				6. Performing Organization Code	
7. Author(s) Glennon, J.C., McHenry, B.G. and Neuman, T.R.				8. Performing Organization Report No.	
9. Performing Organization Name and Address Jack E. Leisch & Associates 1603 Orrington, Suite 1290 Evanston, Illinois 60201				10. Work Unit No. (TRIS) 3152-012	
				11. Contract or Grant No. DOT-FH-11-9575	
12. Sponsoring Agency Name and Address Office of Research and Development Federal Highway Administration U.S. Department of Transportation Washington, D.C. 20590				12. Type of Report and Period Covered Final Report August 1982 - October 1983	
				14. Sponsoring Agency Code T-0646	
13. Supplementary Notes FHWA Contract Manager: George B. Pilkington, II (HSR-20)					
16. Abstract <p>This research was performed to study the operational characteristics of variable pavement cross slopes. Computer simulation of vehicles conducting passing maneuvers on high-speed two-lane highways was the methodology employed. The objective was to determine the effects of cross slope and centerline crossover break on lateral tire acceleration, vehicle roll angle and driver comfort.</p> <p>The research utilized two simulation models of vehicle dynamics--the Highway Vehicle Object Simulation Model (HVOSM), and the Highway Safety Research Institute/Motor Vehicle Manufacturers Association Phase 4 Model (HSRI/MVMA). Vehicle simulations were performed for a range of vehicle types, and various combinations of design speed and cross slope design.</p> <p>The research demonstrates the potential severity of the passing maneuver on highways with even minimum cross slopes. On high-speed highways, cross slopes no greater than 2 percent are desirable. A practical maximum of 4 percent on lower speed highways was indicated by the dynamic responses of tractor-trailer combinations. In general, the research stresses the need to provide a cross slope design that is the minimum consistent with drainage requirements.</p>					
REPRODUCED BY NATIONAL TECHNICAL INFORMATION SERVICE U.S. DEPARTMENT OF COMMERCE SPRINGFIELD, VA. 22161					
17. Key Words Design Criteria Highway Design Simulation		Cross Section Vehicle Dynamics		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 66	
				22. Price 11.95	

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### Introduction

An important consideration in the design of a two-lane highway is the cross slope of each lane, and the manner in which these slopes join at the centerline of the highway. Frequently, the two plane cross slopes are joined to form a distinct break point or "crossover break." More often, the center portion of this crossover break is slightly rounded.

In the development of AASHTO Policy (1), pavement drainage, driver comfort, and general vehicle control were all considered in the process of selecting recommended values for pavement cross slope. The AASHTO discussion of pavement cross slope is as follows:

"...Since many highways are on tangent or flat curve alignment, the rate of cross slope for this condition is an important element in cross section design...A reasonably steep lateral slope is desirable to minimize water ponding of flat sections due to pavement imperfections and uneven settlement. On the other hand, pavements with steep cross slopes are objectionable in appearance and may be annoying and uncomfortable in operation. Hazard may attend driving on steep cross slopes on tangents due to the tendency of vehicles to veer toward the low edge of the pavement."

With these considerations in mind, AASHTO policy (1) recommends the following values for cross slope, which relate to the surface type.

<u>Surface Type</u>	<u>Cross Slope (Percent)</u>
High	1-2
Intermediate	1.5-3
Low	2-4

Recent research (2) recommends minimum cross slopes (1 percent for dense surfaces and 2 percent for open or permeable surfaces) on the basis of drainage requirements. The AASHTO values for maximum cross slope have never been scientifically substantiated. There remains the question, therefore, of just how high the cross slope can be designed for various vehicle speeds and still accommodate reasonable vehicle operations without producing undue hazard or discomfort to the motorist. The objective of this research, therefore, was to study the dynamic effects of pavement cross slope and crossover break on

expected vehicle maneuvers for the purpose of recommending maximum cross slope designs as a function of vehicle type and design speed. The basic form of research involved the use of computer simulation of nominally critical vehicle maneuvers that can be reasonably expected on high-speed, two-lane highways.

#### Investigation of Design Maneuvers

Highways should be designed so that each of the design elements does not "cause" or promote loss of control. This philosophy of course must be interpreted within the bounds of reasonable extremes of driver behavior. And, application of this philosophy requires an understanding of how each highway element relates to vehicle operations.

There are three basic vehicle operations that could be affected by the design of the pavement cross slope and centerline crossover break:

- (1) Tracking - In steering down the highway, the driver must compensate for the cross slope to keep his vehicle on the designed path. On tangent highway, the driver must, in effect, steer toward the centerline. For steeper cross slopes, this task requires more of the driver's attention and effort to keep from veering off the edge of the traveled way.
- (2) Braking - The cross slope also is an important feature with regard to sudden or emergency stops performed by the driver. Very flat cross slopes can add to pavement water depth, thereby reducing skid resistance during periods of wet weather. Steep cross slopes increase the probability that a vehicle would run off the road under severe braking conditions.
- (3) Passing - Under normal passing operations on two-lane highways, the higher speed passing vehicle usually performs a reverse curve across the centerline while accelerating. Under this kind of operation, the dynamic effects of path curvature and acceleration conceivably could be heightened by the amount of centerline crossover break encountered as the vehicle crosses the centerline, and by the "negative" or adverse slope in relation to the vehicle path in the opposing lane. Recent research (3) suggests that a fairly large crossover break does not

itself contribute to loss of control or vehicular instability. However, the research does indicate that negative cross slopes (in relation to vehicle path curvature) can produce an incremental increase in lateral acceleration on the vehicle.

#### Selection of the Basic Design Maneuver

A search of the literature did not reveal definitive research regarding the effect of maximum cross slope on the potential for loss of control under either normal tracking or severe braking operations. Research by Glennon (4), however, does provide insight on both the severity of vehicle operations and the effect of cross slope for automobile passing maneuvers.

Although pavement cross slope design should attempt to reasonably accommodate all expected operations, it is not totally clear which of these three operations would be most dominant in governing the maximum cross slope. However, within reasonable bounds, steeper cross slopes (say 6 to 10 percent) could be expected to seriously degrade all three operations. Therefore, it may be reasonable to infer a maximum cross slope for all operations based on the study of vehicle dynamics of one of the three.

The passing maneuver was selected as the controlling operation for studying the critical dynamic effects of maximum cross slope for the following reasons:

- (1) It is the only one of the three basic operations affected by cross slope that is dimensionally described in the literature.
- (2) Passing is a relatively frequent maneuver performed on two-lane highways.
- (3) Not only does passing occur more often than severe braking, but the severe braking maneuver tends to produce loss of control irrespective of the amount of cross slope.
- (4) Because the passing maneuver involves acceleration, high speeds, and a distinctly non-tangent path, it represents a reasonably critical maneuver.

- (5) The maximum cross slopes dictated by the passing maneuver could be expected to provide reasonable cross slopes for normal vehicle tracking.

#### Dimensions of the Passing Maneuver

The only research found that directly measured the passing path of vehicles under normal highway operation was the work of Glennon and Weaver (4,5). This research, conducted on two-lane Texas highways, had two specific objectives: (1) to study the critical nature of time-distance requirements for the purpose of verifying AASHTO passing sight distance requirements; and (2) to study the functional demands of passing vehicles as a potential basis for minimum skid resistance requirements and/or wet weather speed limits.

For the purpose of determining the dimensions of a critical passing maneuver, one phase of the Glennon and Weaver work used photographic techniques to measure the curvature of the initial passing path for about 160 maneuvers at two passing zones. These measurements were distributed among experiments where impeding vehicle speeds were 50, 56, 62 and 68 mph (80, 90, 100 and 110 km/h). For average speeds ranging from 50 to 81 mph (80 to 130 km/h), these studies determined the distribution of minimum vehicle path radius during the initial "pull-out" portion of the passing maneuver. Also, the analysis showed that the severity of this minimum radius was independent of speed. Higher speed passing vehicles were therefore just as likely to undergo critical path maneuvers as other passing vehicles.

Table 1 shows the critical end of the distribution of minimum path radius for the two different lengths of passing zone. Analysis of the data also indicated average automobile acceleration of about  $3.28 \text{ ft/s}^2$  ( $1.00 \text{ m/sec}^2$ ).

The Glennon and Weaver analysis (5) provides a basis for determining the time-distance aspects of the passing maneuver. The duration of the initial passing maneuver is about 4 seconds. This maneuver includes, in sequence, an initial tangent path ( $L_1$ ), a curve to the left ( $L_2$ ), a connecting tangent ( $L_3$ ), and a curve to the right ( $L_4$ ) bringing the vehicle back parallel to the roadway.

Table 1  
Distribution of Minimum Path Radii For Automobiles  
in the Passing Maneuver

Percent of Vehicles with Smaller Radius	Minimum Radius of Initial Path Maneuver--ft (m)	
	Site A 984 ft(300 m) Passing Zone	Site B 1684 ft(500 m) Passing Zone
5%	1614 (492)	1132 (345)
10%	1650 (503)	1289 (393)
15%	2011 (613)	1430 (436)

Source: Reference (4)

Based on these parameters of the passing maneuver it is possible to generate a nominally critical automobile passing traversal (see Figure 1) with the following additional set of assumptions:

- (1) The nominally critical minimum path radius is best represented by the path severity exceeded only by 5 percent of all drivers on the longer passing zone. This value is an 1132 ft (345 m) radius, as given in Table 1.
- (2) The left tires of the passing vehicle are initially 2.3 ft (0.7 m) right of the centerline.
- (3) The total lateral movement of the vehicle is 11.5 ft (3.5 m), which corresponds to a full lane width.
- (4) The duration of the initial tangent portion,  $L_1$ , of the maneuver is 1 second. The vehicle begins the designated acceleration rate at the beginning of this tangent portion.

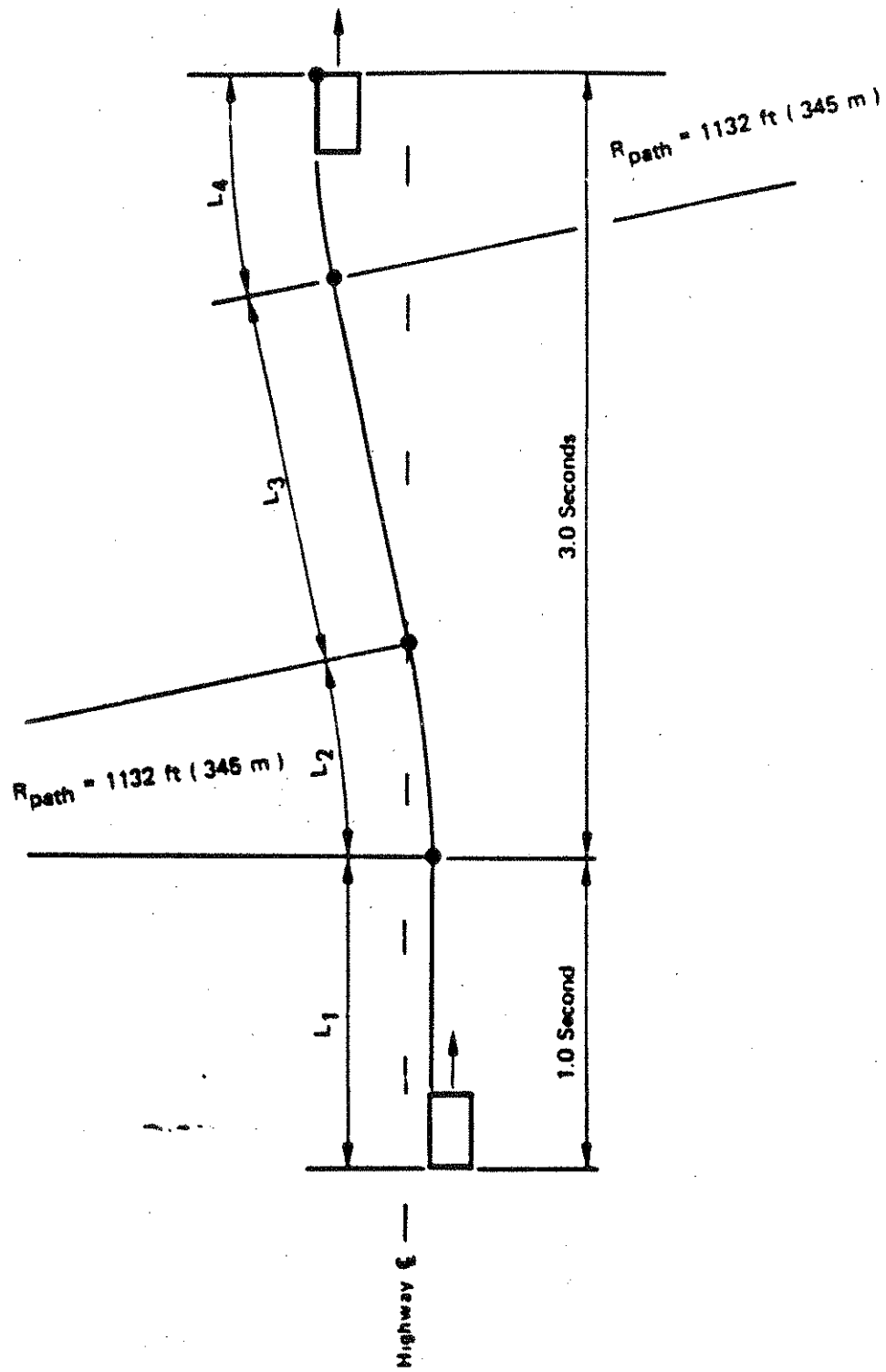


Figure 1. NOMINALLY CRITICAL INITIAL PASSING MANEUVER FOR AUTOMOBILES

- (5) A passing automobile accelerates from a starting speed that is 12 mph (20 km/h) slower than design speed.
- (6) The connecting tangent,  $L_3$ , between the reverse curves of the path is limited to not less than 66 ft (20 m). Under some lower design speed conditions, therefore, the duration of the initial maneuver is somewhat more than 4 seconds.

With these physical and operational parameters and constraints specified, it is possible to mathematically solve the complete geometric description of the initial automobile passing path for various design speeds. Table 2 shows these solutions.

Table 2  
Description of Derived Nominally Critical Initial  
Passing Maneuvers for Automobiles

Design Speed mph (km/h)	Length of Initial Path Segments* ft (m)			
	$L_1$	$L_2$	$L_3$	$L_4$
87 (140)	111 (33.8)	41 (12.6)	269 (82.1)	41 (12.6)
74 (120)	93 (28.3)	53 (16.2)	190 (58.0)	53 (16.2)
62 (100)	74 (22.7)	79 (24.1)	85 (25.9)	79 (24.1)
50 (80)	56 (17.2)	86 (26.2)	66 (20.0)	86 (26.2)

- \*  $L_1$  -- Initial tangent path in proper lane
- $L_2$  -- Initial "pull-out" maneuver to centerline
- $L_3$  -- Tangent path to opposite lane
- $L_4$  -- Curved, reversal path to correct vehicle path in opposite lane

Passing maneuvers undertaken by trucks are also of concern in design of the cross slope and crossover break. To generate the nominally critical initial paths for trucks the following additional assumptions were made:

- (1) Trucks initiating a passing maneuver would tend to utilize a rapid rate of acceleration (relative to vehicle type). For this study, loaded single-unit trucks and empty tractor-trailer combinations were assumed to accelerate at  $1.64 \text{ ft/s}^2$  ( $0.50 \text{ m/s}^2$ ). Fully loaded tractor-trailer combinations accelerate at  $0.66 \text{ ft/s}^2$  ( $0.20 \text{ m/s}^2$ ). These assumed rates compare with the assumed automobile acceleration rate of  $3.28 \text{ ft/s}^2$  ( $1.00 \text{ m/s}^2$ ).
- (2) In order to manage the passing maneuver with their lower acceleration capabilities, trucks start the initial passing maneuver at higher speeds than automobiles. For single-unit trucks and empty tractor-trailer combinations, the initial speed is 10 mph (16 km/h) below design speed. For loaded tractor-trailer combinations, the initial speed is 7.5 mph (12 km/h) below the design speed. These initial speed assumptions, in combination with the assumed truck acceleration rates, result in a final or critical truck passing speed identical to that of automobiles. This enables direct comparison of the effects of cross slope and crossover break on the full range of vehicle types studied.

With these additional assumptions, the dimensions for the critical initial path maneuvers for trucks are solved as shown in Table 3.

#### Description of Simulation Models

The dynamic effects of various cross slopes for the initial passing maneuver at various design speeds were studied using two different previously developed computer simulation models. The HVOSM and the HSRI/MVMA PHASE4 model were used to cover the full range of vehicle types on the highway. These two models and their modification for this research are described below.

##### HVOSM

The HVOSM (Highway-Vehicle-Object Simulation Model) is a computerized mathematical model originally developed at Cornell Aeronautical Laboratories (6) and



Table 3  
Description of Derived Nominally Critical  
Initial Passing Maneuver For Trucks

Loaded Single-Units and Empty Tractor-Trailers

Design Speed mph (km/h)	Length of Initial Path Segments ft (m)*			
	<u>L<sub>1</sub></u>	<u>L<sub>2</sub></u>	<u>L<sub>3</sub></u>	<u>L<sub>4</sub></u>
87 (140)	114 (34.7)	42 (12.8)	267 (81.5)	42 (12.8)
74 (120)	95 (29.1)	53 (16.2)	190 (58.0)	53 (16.2)
62 (100)	77 (23.6)	77 (23.5)	93 (28.5)	77 (23.5)
50 (80)	59 (18.0)	86 (26.2)	66 (20.0)	86 (26.2)

Loaded Tractor-Trailers

Design Speed mph (km/h)	Length of Initial Path Segments ft (m)*			
	<u>L<sub>1</sub></u>	<u>L<sub>2</sub></u>	<u>L<sub>3</sub></u>	<u>L<sub>4</sub></u>
87 (140)	117 (35.7)	41 (12.6)	269 (82.1)	41 (12.6)
74 (120)	99 (30.1)	53 (16.2)	192 (58.8)	53 (16.2)
62 (100)	80 (24.5)	79 (24.1)	87 (26.5)	79 (24.1)
50 (80)	62 (19.0)	86 (26.2)	66 (20.0)	86 (26.2)

- \* L<sub>1</sub> -- Initial tangent path in proper lane
- L<sub>2</sub> -- Initial "pull-out" maneuver to centerline
- L<sub>3</sub> -- Tangent path to opposite lane
- L<sub>4</sub> -- Curved, reversal path to correct vehicle path in opposite lane

subsequently refined by Calspan Corporation (7). The HVOSM is capable of simulating the dynamic response of a two-axle vehicle traversing a three-dimensional terrain configuration. The vehicle is composed of four rigid masses; viz., a sprung mass, unsprung masses of the left and right independent suspensions of the front wheels, and an unsprung mass representing a solid rear-axle assembly.

This study used the Roadside Design version of HVOSM that is currently available from FHWA. Certain modifications were necessary to perform the range of studies undertaken in this research. These modifications, described in Appendix A, included the following:

- (1) Driver discomfort factor output;
- (2) Friction demand output;
- (3) Driver model modifications;
- (4) Wagon-tongue path-following algorithm; and
- (5) Dual rear tire option.

For the centerline crossover break traversal studies, the important parameters of the driver simulation are the probe length, steer velocity and damping. The probe length represents the driver preview of the highway measured from the center of gravity of the vehicle. The steer velocity (PGAIN) is a steering correction factor that is multiplied by the lateral path error of the probe. The damping (QGAIN) is a term that smooths out the steer response.

A longer probe, slower steer response, and larger damping term simulate an attentive and non-aggressive driver by smoothing the path into a combination of sweeping spirals. A shorter probe length, quicker steer response, and smaller damping term simulate a very aggressive driver who turns sharply with a tendency to overshoot the intended path.

It is extremely important to carefully define the driver behavior being modeled. Highly variable dynamic results can be obtained using different driver simulation parameters on the same specified path at the speed. Guidance on appropriate driver behavior parameters was provided by previous simulation research (3).

#### HSRI/MVMA PHASE4 Model

The PHASE4 simulation program is a general purpose mathematical model for simulating the three-dimensional dynamic responses of trucks, tractor/trailers and triples combinations. The PHASE4 program was developed in 1980 by the Highway Safety Research Institute of the University of Michigan under the sponsorship of the Motor Vehicle Manufacturers Association and the Federal Highway Administration (8,9).

Modifications similar to those made for the HVOSM were made for the PHASE4 model. These modifications, described in Appendix B, included the following:

- (1) Driver discomfort factor output;
- (2) Friction demand output;
- (3) Driver model modifications;
- (4) Wagon-tongue path-following algorithm; and
- (5) Terrain option.

#### Comparison of Models

For the purpose of comparing the dynamic effects of cross slope design for various vehicles, it was necessary to obtain some degree of correlation between the HVOSM (2-axle) and the HSRI/MVMA PHASE4 models. Since both models can accommodate single-unit trucks with a single rear axle, a 1974 White Road Boss (4x2) was used for comparison simulations. Measured properties of this vehicle were reported in a study of truck tire properties performed by the Highway Safety Research Institute (10).

The documentation for the comparison of the two models is quite extensive and is reported in a separate project document (11). The conclusions from this effort were: (1) the two models give comparable dynamic responses for the types of maneuvers investigated in this research; and (2) the effects of the small-angle assumption of the PHASE4 model are negligible for the types of maneuvers investigated in this research.

### Simulation Experiments

Fourteen basic simulation runs were performed to test the dynamic effects of the centerline crossover break design for various vehicles and design speed. The range of test parameters is shown in Table 4.

Previous project research (3) on pavement/shoulder cross-slope break designs for highway curves had indicated that the centripetal force equation gave a reasonable estimate of tire friction demand. Table 5 shows the computation of the calculated range of lateral tire accelerations for various speeds and cross slopes using the 95th percentile passing automobile path radius described in Table 1. With regard to cross slope, the tentative conclusions that could be made from this analytical result are (1) the effect of cross slope appears reasonably minor; and (2) despite this apparently minor effect, minimal cross slopes are desirable for higher speeds because of the already marginal dynamics of the passing vehicle.

### Determination of Driver Simulation Parameters

The results of Table 5 provide a basis for determining the driver simulation parameters to be used in the path-following algorithm. By using various combinations of parameters, preliminary simulations were run until dynamic results similar to Table 5 were produced. This kind of exercise was done using a standard passenger car, with the following parameters determined for testing the effects of pavement cross slope and crossover break:

$$\begin{aligned}L &= 0.25 V \\PGAIN &= 1/L \\QGAIN &= 1/(10L)\end{aligned}$$

Where

$$\begin{aligned}L &= \text{Probe Length ft (m)} \\V &= \text{Vehicle Speed ft/s (m/s)} \\PGAIN &= \text{Steer Velocity rad/ft (rad/m)} \\QGAIN &= \text{Steer Damping rad-s/ft (rad-s/m)}\end{aligned}$$

In attempting to use these same parameters for simulation of truck passing maneuvers, very severe and highly unstable dynamics were produced. These results indicated a threshold of dynamic instability related to very aggressive

Table 4  
Test Parameters For Simulation Experiments

Vehicles

Mid-Size Automobile (1971 Dodge Coronet)  
Compact Automobile (1971 Vega Sports Coupe)  
Loaded Single-Unit Truck (White Road Boss)  
Loaded Tractor Trailer (PHASE4 spec, 68,855 lbs. (31,298 kg))  
Empty Tractor Trailer (PHASE4 spec, 28,855 lbs. (13,116 kg))

Centerline Crossover Break Designs

2 percent each side (no rounding)  
4 percent each side (no rounding)

Test Speeds--mph (km/h)

87 (140)  
74 (120)  
62 (100)  
50 ( 80)

Test Paths

Radius = 1132 ft (345 m) (path segments L<sub>2</sub> and L<sub>4</sub>)  
Segment Lengths as per Tables 2 and 3

Table 5  
Nominal Tire Friction Values Using 1132 Foot (345 Metre) Radius  
(From Table 1) in Centripetal Force Equation

<u>Cross Slope (Percent)</u>	<u>Speed mph (km/h)</u>	<u>f Calculated at End of Initial Passing Maneuver*</u>
2	87 (140)	0.47
	74 ( 20)	0.35
	62 (100)	0.25
	50 ( 80)	0.17
4	87 (140)	0.49
	74 (120)	0.37
	62 (100)	0.27
	50 ( 80)	0.19
6	87 (140)	0.51
	74 (120)	0.39
	62 (100)	0.29
	50 ( 80)	0.21

\* See Figure 1 for description of Initial Passing Maneuver

sinusoidal steering (and not related to the cross slope or other highway geometrics). It was evident that the parameters selected for simulating nominally critical passenger car drivers were inappropriate for simulating truck driver behavior. It was therefore necessary to test various driver simulation parameters to determine a nominally critical level of operation appropriate for trucks. As always, the objective was to discover a reasonably critical threshold for which dynamic sensitivities associated with the vehicle, its speed and the cross slope could be observed. This exercise produced the following driver simulation parameters for trucks to test the effect of centerline crossover break:

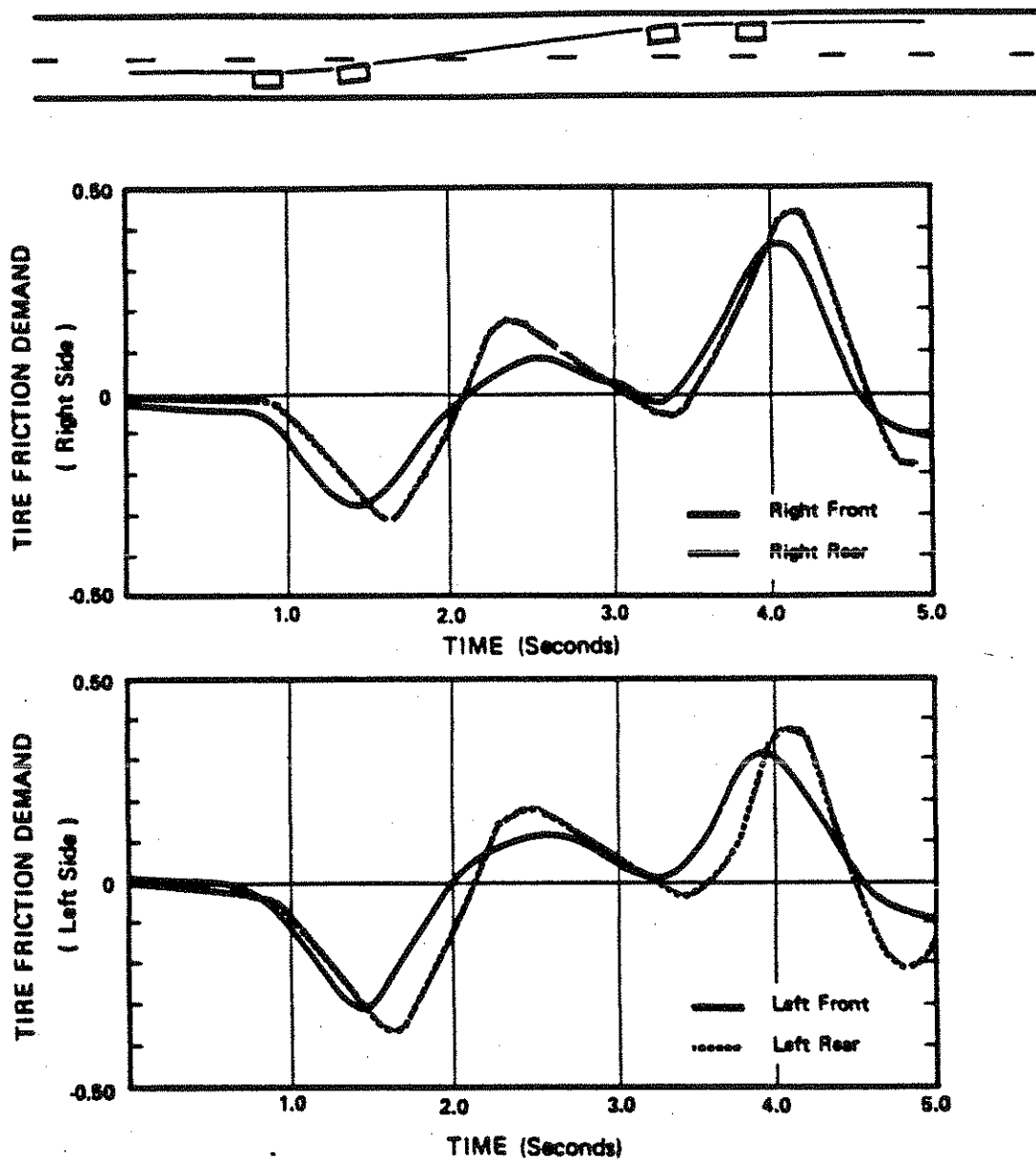
#### TRUCK DRIVER PARAMETERS

$$\begin{aligned}L &= 0.25 V \\PGAIN &= 1/(2L) \\QGAIN &= 1/(5L)\end{aligned}$$

Where L, V, PGAIN and QGAIN are as before

#### Results of Experiments

Figures 2 through 5 show sample results of the 14 simulation experiments. Summaries of the dynamic response for all experiments are shown in three comparison tables which report some of the experiments more than once. Table 6 provides a direct comparison of the dynamic responses of various vehicles for the same test speed and cross slope. Table 7 directly compares the dynamic effect of speed for the same vehicle and cross slope. Table 8 is a direct comparison of the dynamic effects of cross slope for a given vehicle and speed.



#### TEST CONDITIONS

Vehicle Type: Mid - size Auto

Cross Slope: 2 percent

Initial Speed: 100 km / h

Design Speed: 120 km / h

Note: 1 km / h = 0.62 mph, 1 m = 3.28 ft.

Probe Length: 8.94 m

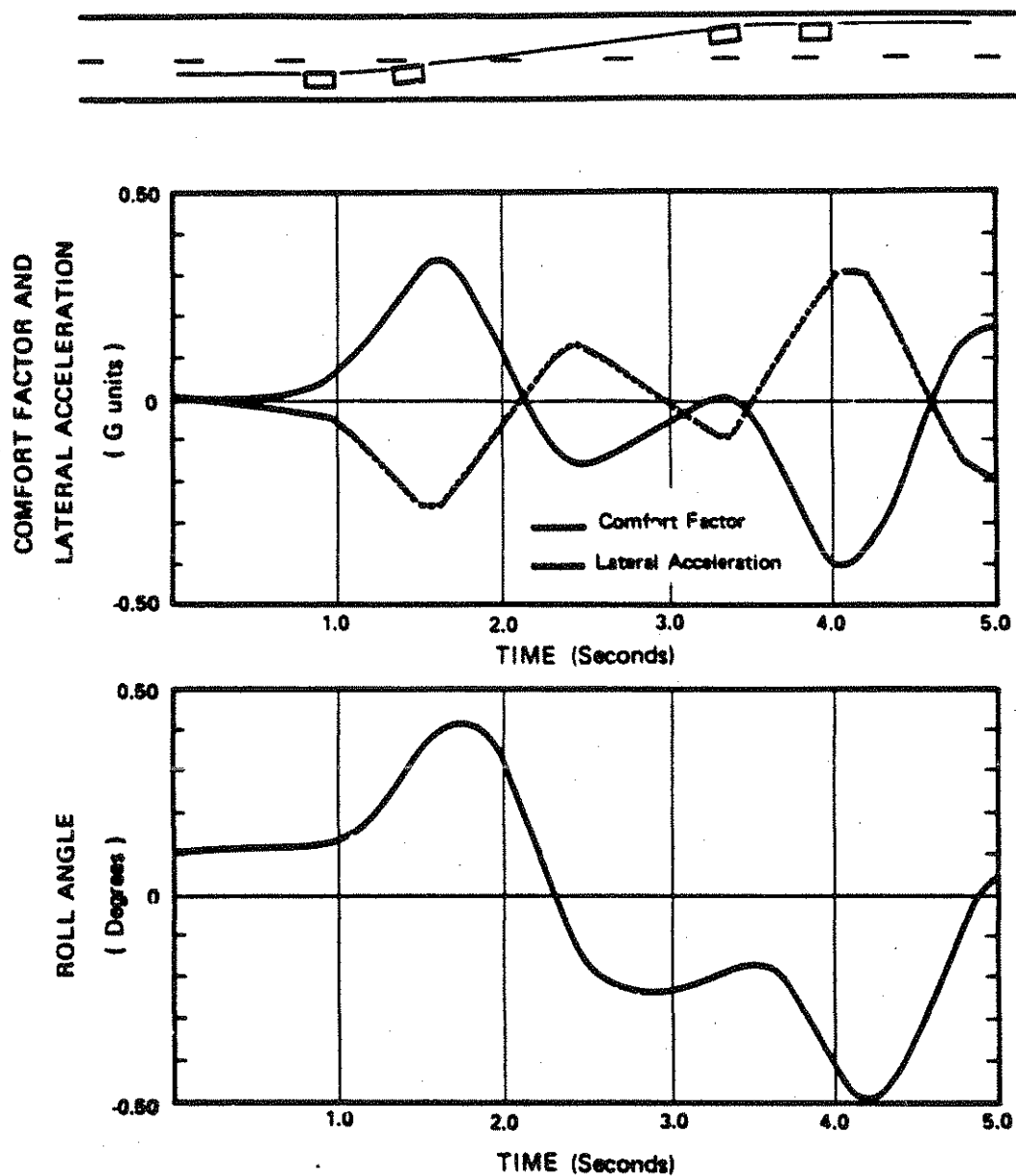
P Gain:  $1.44 \times 10^{-1}$  rad / m

Q Gain:  $1.44 \times 10^{-2}$  rad · s / m

Acceleration:  $1.00 \text{ m} / \text{s}^2$

Figure 2. SIMULATION RESULTS FOR MID - SIZE AUTOMOBILE USING HVOSM





#### TEST CONDITIONS

Vehicle Type: Mid-size Auto

Cross Slope: 2 percent

Initial Speed: 100 km / h

Design Speed: 120 km / h

Note: 1 km / h = 0.62 mph, 1 m = 3.28 ft.

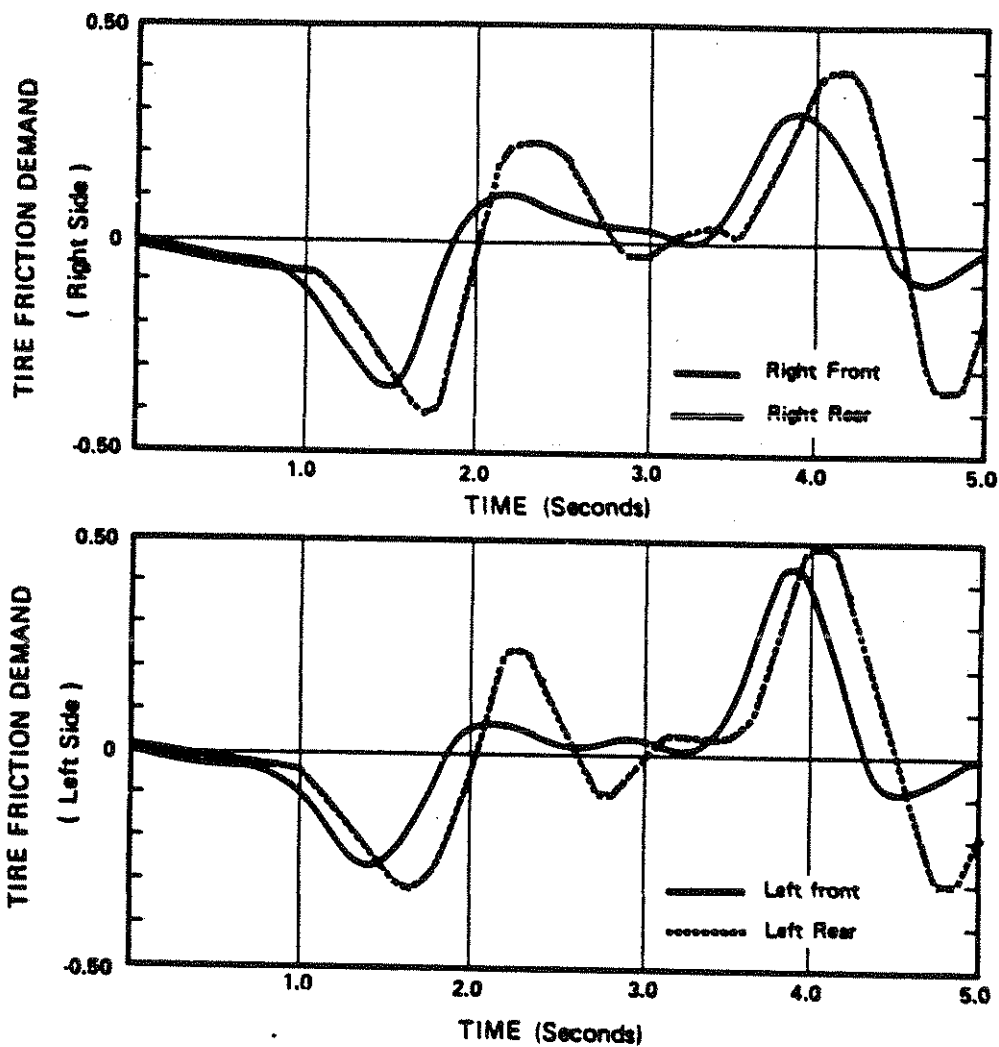
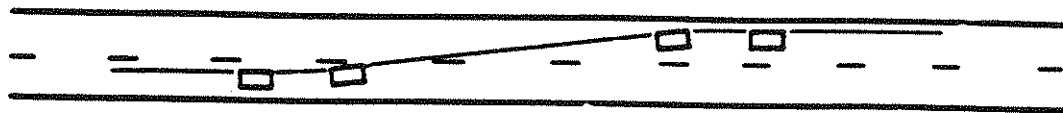
Probe Length: 6.94 m

P Gain:  $1.44 \times 10^{-1}$  rad / m

Q Gain:  $1.44 \times 10^{-2}$  rad - s / m

Acceleration:  $1.00 \text{ m} / \text{s}^2$

Figure 2. SIMULATION RESULTS FOR MID-SIZE AUTOMOBILE USING HVOSM ( continued )



#### TEST CONDITIONS

Vehicle Type: Compact Car

Cross Slope: 2 percent

Initial Speed: 100 km / h

Design Speed: 120 km / h

Note: 1 km / h = 0.62 mph, 1 m = 3.28 ft.

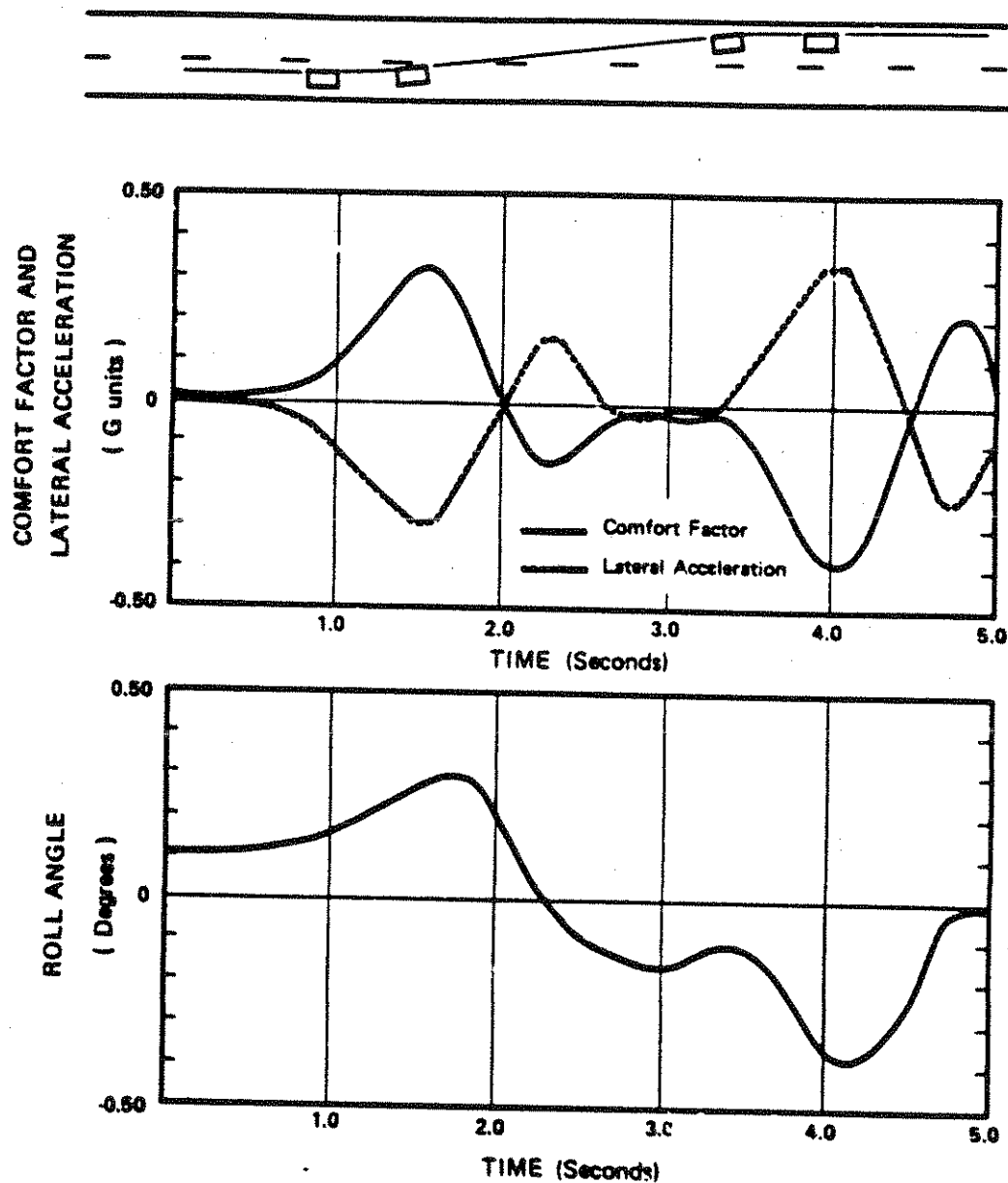
Probe Length: 6.93 m

P Gain:  $1.46 \times 10^{-1}$  rad / m

Q Gain:  $1.46 \times 10^{-2}$  rad - s / m

Acceleration:  $1.00 \text{ m} / \text{s}^2$

Figure 3. SIMULATION RESULTS FOR COMPACT AUTOMOBILE USING HVOSM



#### TEST CONDITIONS

Vehicle Type: Compact Car  
 Cross Slope: 2 percent  
 Initial Speed: 100 km / h  
 Design Speed: 120 km / h

Probe Length: 6.93 m  
 P Gain:  $1.48 \times 10^{-1}$  rad / m  
 Q Gain:  $1.48 \times 10^{-2}$  rad · s / m  
 Acceleration:  $1.08 \text{ m / s}^2$

Note: 1 km / h = 0.62 mph, 1 m = 3.28 ft.

Figure 3. SIMULATION RESULTS FOR COMPACT AUTOMOBILE USING HVOSM ( continued )

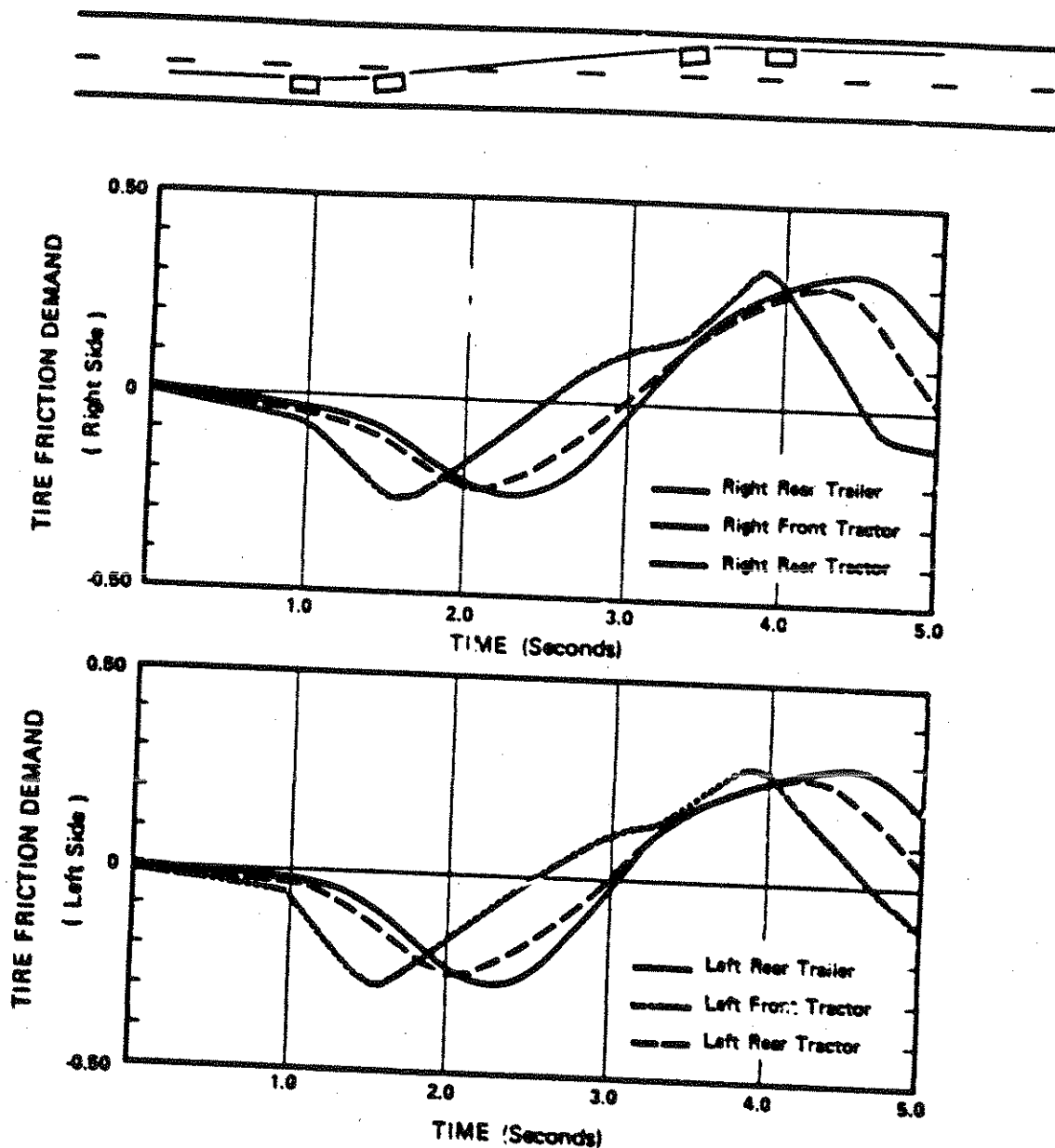
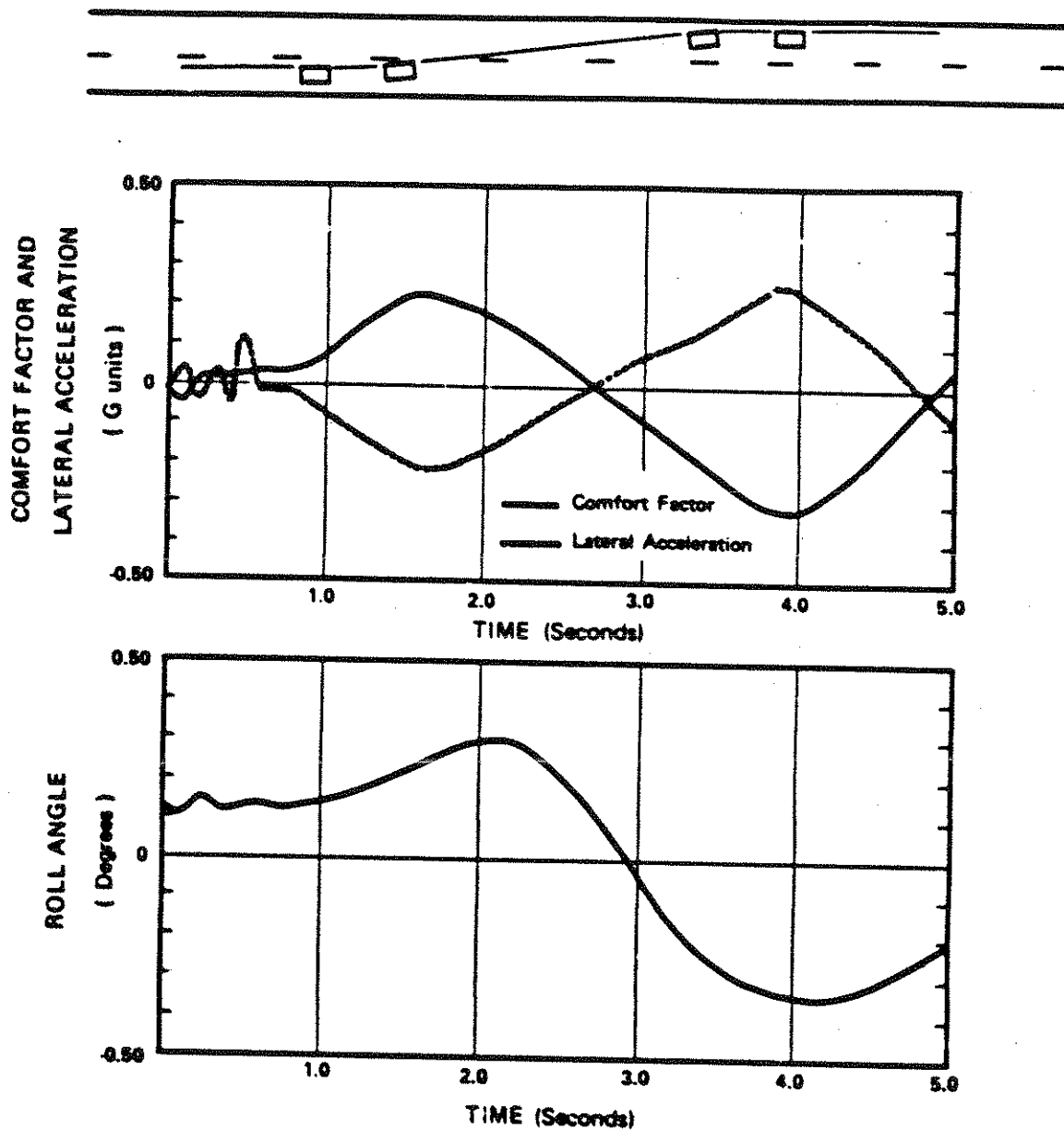


Figure 4. SIMULATION RESULTS FOR LOADED SEMI-TRAILER TRUCK USING HSRI / MVM PHASE 4 MODEL



#### TEST CONDITIONS

Vehicle Type: Loaded Semi-trailer

Cross Slope: 2 percent

Initial Speed: 108 km/h

Design Speed: 120 km/h

Note: 1 km/h = 0.62 mph, 1 m = 3.28 ft.

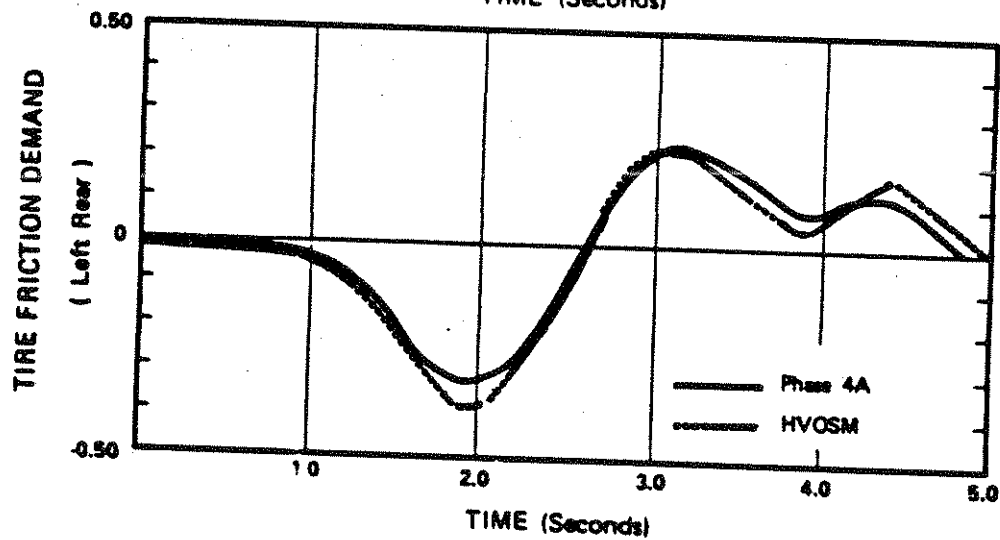
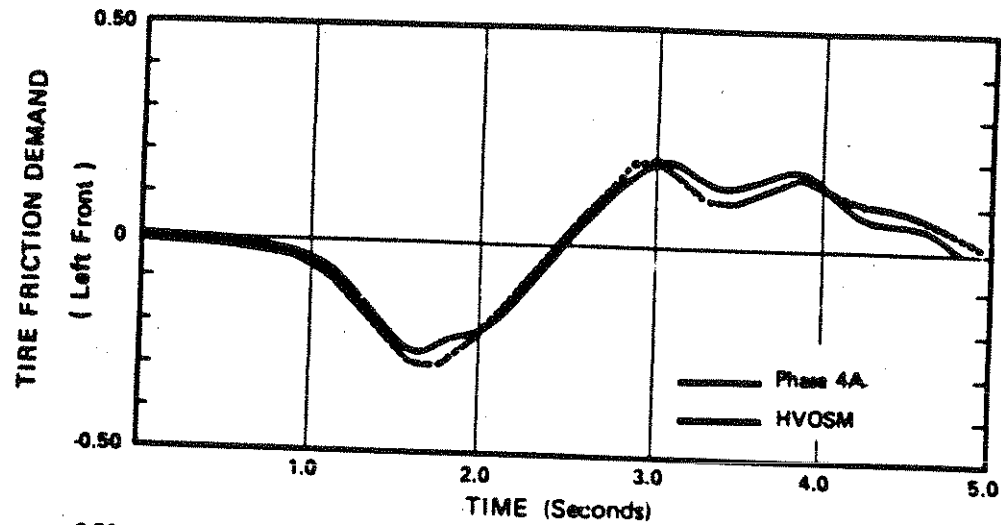
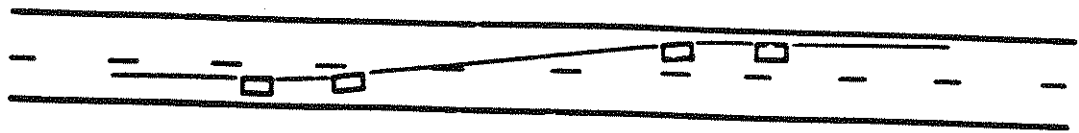
Probe Length: 7.21 m

P Gain:  $8.9 \times 10^{-2}$  rad/m

Q Gain:  $2.8 \times 10^{-2}$  rad-s/m

Acceleration:  $0.2 \text{ m/s}^2$

Figure 4. SIMULATION RESULTS FOR LOADED SEMI-TRAILER TRUCK  
USING HSRI / M/M PHASE 4 MODEL ( continued )



#### TEST CONDITIONS

Vehicle Type: Single-unit Truck

Cross Slope: 2 percent

Initial Speed: 104 km / h

Design Speed: 120 km / h

Note: 1 km / h = 0.62 mph, 1 m = 3.28 ft.

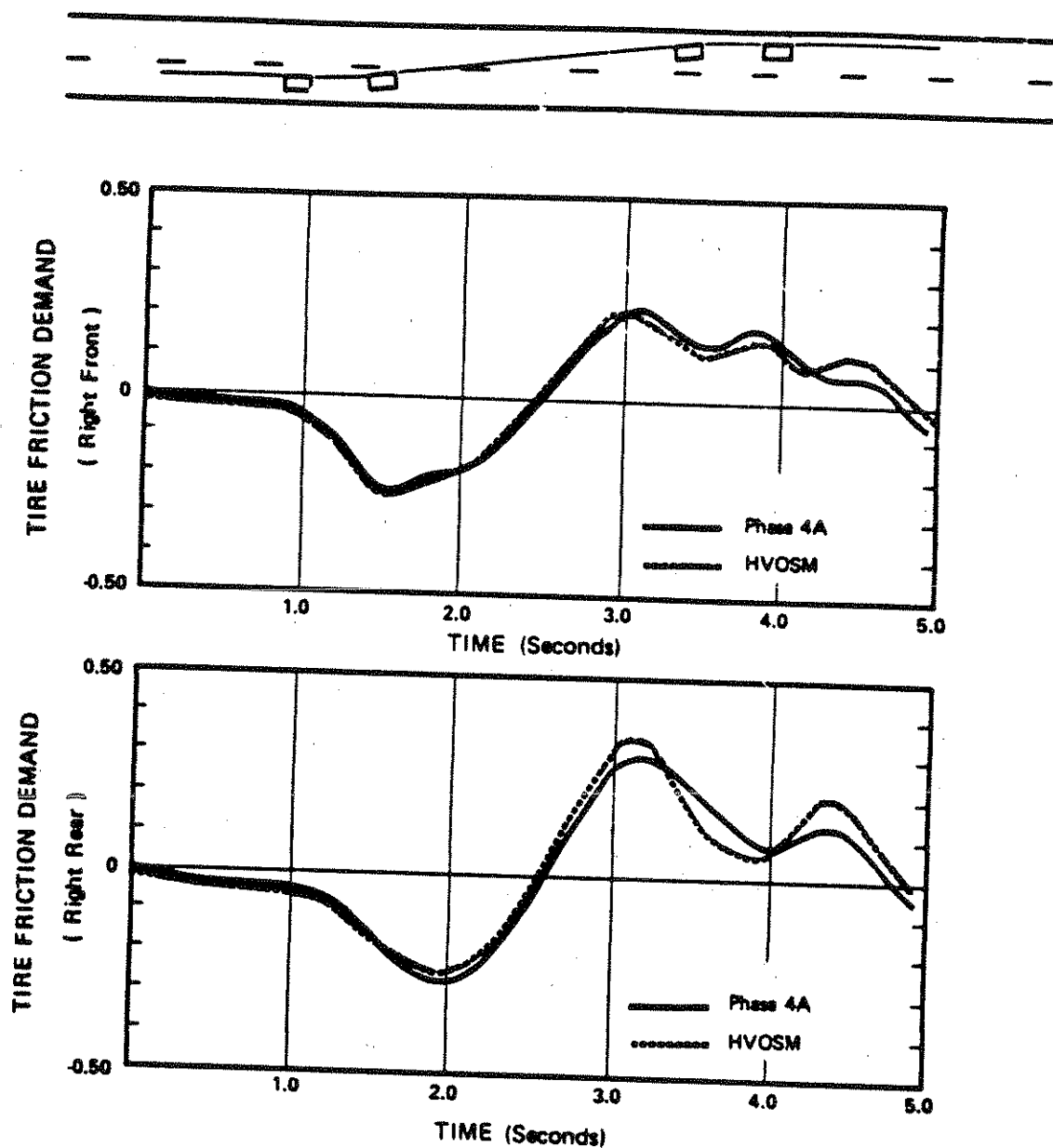
Probe Length: 7.21 m

P Gain:  $6.9 \times 10^{-2}$  rad / m

Q Gain:  $2.8 \times 10^{-2}$  rad - s / m

Acceleration:  $0.5 \text{ m / s}^2$

Figure 5. SIMULATION RESULTS FOR SINGLE-UNIT TRUCK -- COMPARISON BETWEEN HVOSM AND HSRI / MVM PHASE 4 MODEL



#### TEST CONDITIONS

Vehicle Type: Single-unit Truck

Cross Slope: 2 percent

Initial Speed: 104 km/h

Design Speed: 120 km/h

Note: 1 km/h = 0.62 mph, 1 m = 3.28 ft.

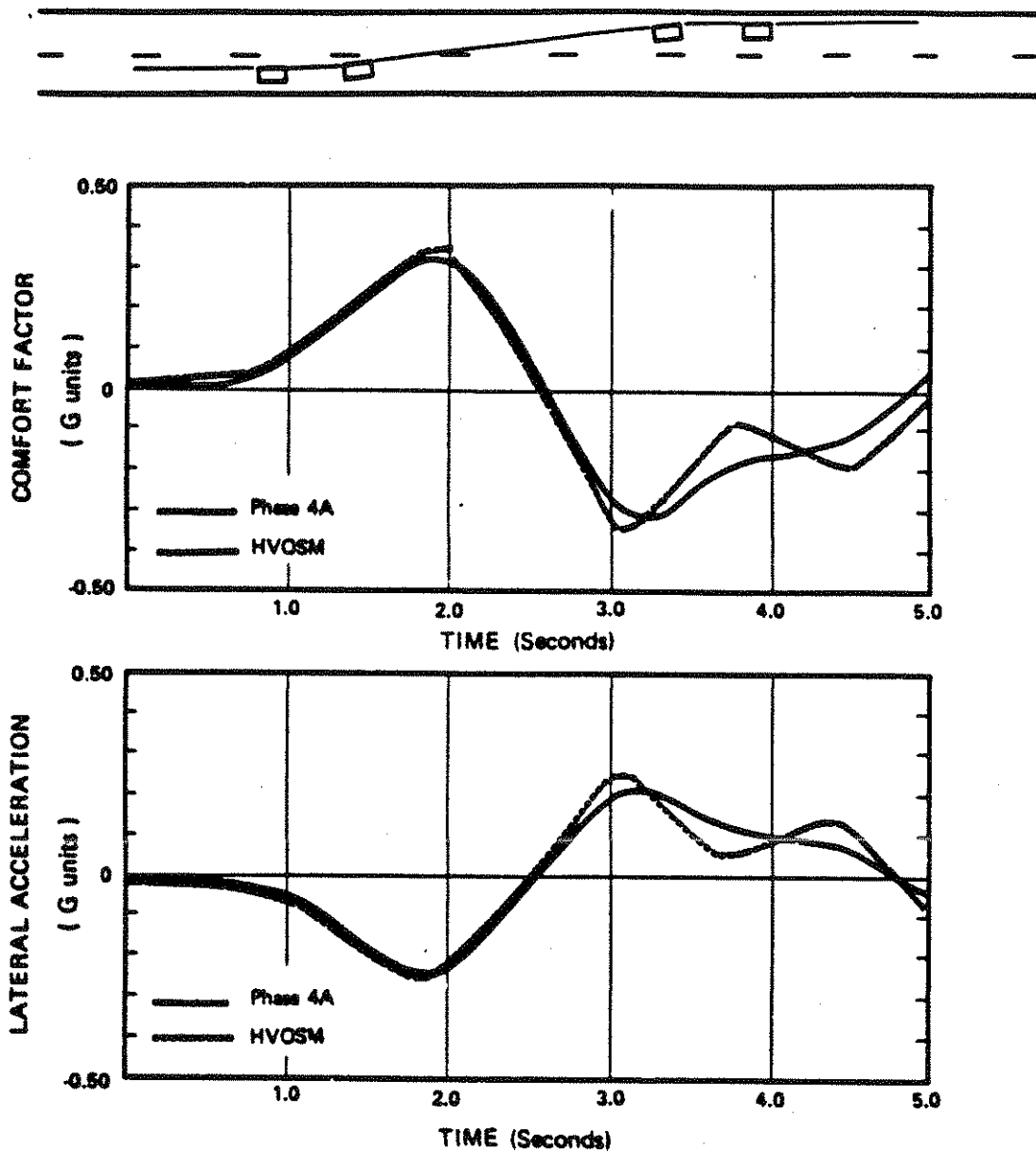
Probe Length: 7.21 m

P Gain:  $6.9 \times 10^{-2}$  rad/m

Q Gain:  $2.8 \times 10^{-2}$  rad-s/m

Acceleration:  $0.50 \text{ m/s}^2$

Figure 5. SIMULATION RESULTS FOR SINGLE-UNIT TRUCK -- COMPARISON BETWEEN HVOSM AND HSRI / MVM PHASE 4 MODEL ( continued )



#### TEST CONDITIONS

Vehicle Type: Single-unit Truck

Probe Length: 7.21 m

Cross Slope: 2 percent

P Gain:  $6.9 \times 10^{-2}$  rad / m

Initial Speed: 104 km / h

Q Gain:  $2.8 \times 10^{-2}$  rad - s / m

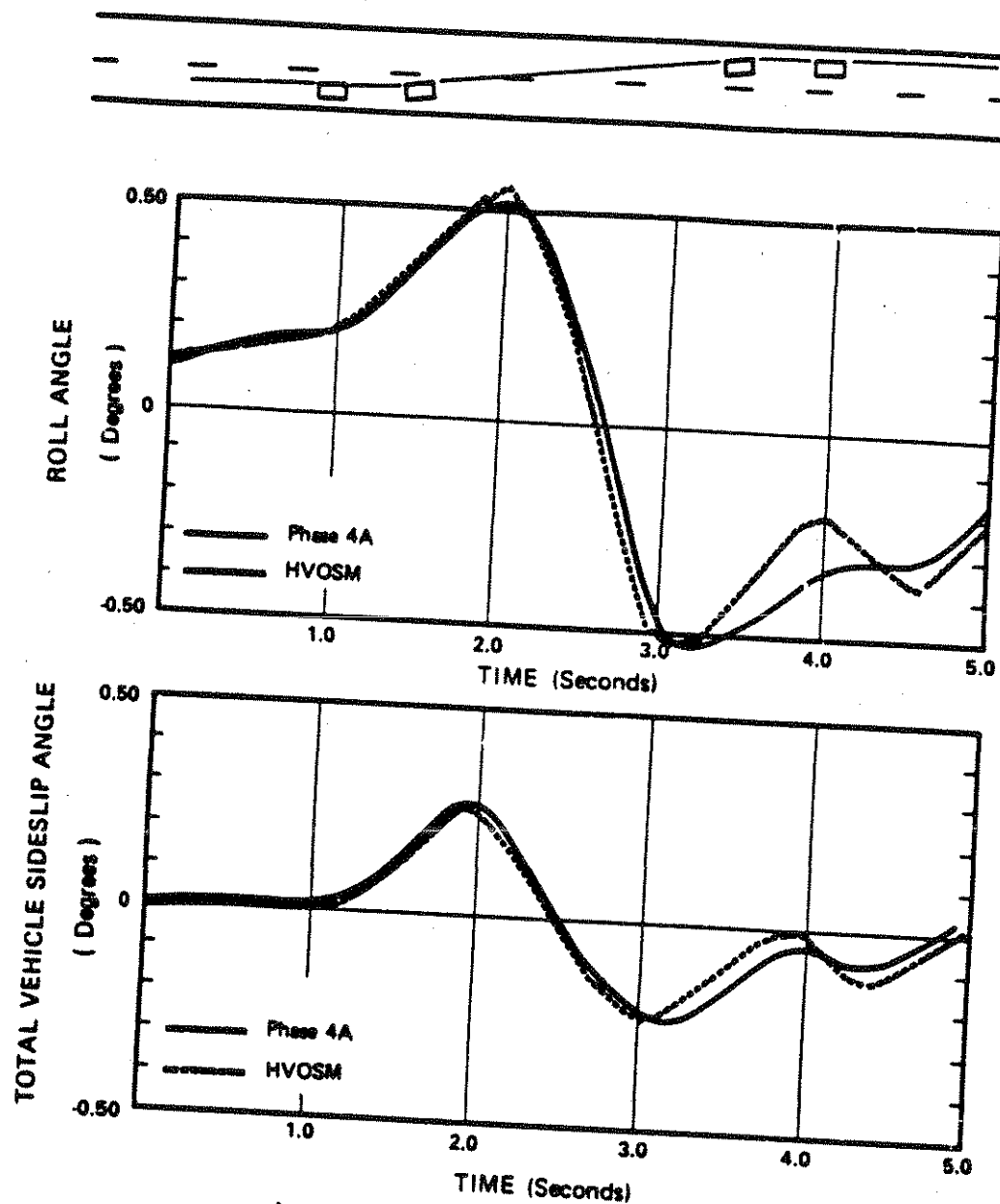
Design Speed: 120 km / h

Acceleration:  $0.50 \text{ m} / \text{s}^2$

Note: 1 km / h = 0.62 mph, 1 m = 3.28 ft.

Figure 5. SIMULATION RESULTS FOR SINGLE-UNIT TRUCK -- COMPARISON BETWEEN HVOSM AND HSRI / MVM PHASE 4 MODEL ( continued )





#### TEST CONDITIONS

Vehicle Type: Single-unit Truck

Cross Slope: 2 percent

Initial Speed: 104 km / h

Design Speed: 120 km / h

Note: 1 km / h = 0.62 mph, 1 m = 3.28 ft.

Probe Length: 7.21 m

P Gain:  $6.9 \times 10^{-3}$  rad / m

Q Gain:  $2.8 \times 10^{-3}$  rad · s / m

Acceleration:  $0.50 \text{ m / s}^2$

Figure 5. SIMULATION RESULTS FOR SINGLE-UNIT TRUCK -- COMPARISON BETWEEN HVOSM AND HSRI / MVM PHASE 4 MODEL ( continued )

Table 6  
Comparison of vehicle Effects  
on Dynamics of Passing Maneuvers

VEHICLE TYPE	TIRE FRICTION DEMAND (g's)	DRIVER DISCOMFORT (g's)	VEHICLE ROLL ANGLE (degrees)
Test Conditions: 74 mph (120 km/h) Design Speed, 2 percent Cross Slope			
Compact Auto	0.36	0.38	3.7
Mid-Size Auto	0.34	0.38	4.9
Tractor-Trailer (empty)	0.30	0.22	1.8
Tractor-Trailer (loaded)	0.29	0.30	3.3
Single-Unit Truck (HVOSM)	0.23	0.32	6.3
Single-Unit Truck (PHASE 4)	0.22	0.31	6.3
Test Conditions: 62 mph (100 km/h) Design Speed, 4 percent Cross Slope			
Tractor-Trailer (loaded)	0.38	0.42	5.3
Compact Auto	0.32	0.36	4.2
Mid-Size Auto	0.29	0.34	5.2

Summary of Vehicle Comparison

The following conclusions describe the effects of cross slope on the full range of vehicle types tested.

- (1) The compact automobile generates higher tire friction demands than the mid-size automobile.
- (2) The compact automobile generates the highest tire friction demand on a 2 percent cross slope.
- (3) The loaded tractor-trailer generates the highest tire friction demand on a 4 percent cross slope.
- (4) The empty tractor-trailer produces similar tire friction demands as a loaded tractor-trailer, but with significantly lower driver discomfort and roll angle.

Table 7  
Comparison of Speed Effects  
on Dynamics of Passing Maneuvers

Vehicle Type	Speed mph (km/h)	Cross-Slope (percent)	Tire Friction Demand (g's)	Driver Discomfort (g's)	Vehicle Roll Angle (degrees)
Mid-Size Auto	87 (140)	2	0.33	0.36	4.6
	74 (120)	2	0.34	0.38	4.9
	62 (100)	2	0.28	0.32	4.0
Mid-Size Auto	74 (120)	4	0.36	0.40	6.2
	62 (100)	4	0.29	0.34	5.2
	50 (80)	4	0.22	0.26	4.4
Compact Auto	74 (120)	2	0.36	0.38	3.7
	62 (100)	2	0.31	0.34	3.0
Tractor-Trailer (Loaded)	74 (120)	2	0.29	0.30	3.3
	62 (100)	2	0.34	0.37	3.8

Summary of Speed Comparison

The results of comparisons across speeds are mixed. While the comparisons generally show an increase in tire friction demand with an increase in speed, two comparisons show the opposite. Although these discontinuities cannot be directly explained, it is believed they are partially an artifact of the total simulation process, which included varying the driver parameter values and passing path segment lengths with speed.

Table 8  
Comparison of Cross Slope Effects  
on Dynamics of Passing Maneuvers

Vehicle Type	Speed mph (km/h)	Cross-Slope (percent)	Tire Friction Demand (g's)	Driver Discomfort (g's)	Vehicle Roll Angle (degrees)
Mid-Size Auto	74 (120)	2	0.34	0.38	4.9
	74 (120)	4	0.36	0.40	6.2
Mid-Size Auto	62 (100)	2	0.28	0.32	4.0
	62 (100)	4	0.29	0.34	5.2
Compact Auto	62 (100)	2	0.31	0.34	3.0
	62 (100)	4	0.32	0.36	4.2
Tractor-Trailer (Loaded)	62 (100)	2	0.34	0.37	3.8
	62 (100)	4	0.38	0.42	5.3

#### Summary of Cross Slope Comparison

The dynamic effect of increasing cross slope from 2 to 4 percent is an increase in the tire friction ranging from 0.01 to 0.04 g's.

#### Conclusions

Although the simulation experiments only represent a small segment of real highway operations and did produce a few conflicting results with regard to speed effects, the implications with regard to pavement cross slope and centerline crossover break design are reasonably clear. These implications which are generally consistent with AASHTO requirements are as follows:

- (1) The passing maneuver on two-lane, high-speed (greater than 60 mph (100 km/h)) highways is potentially severe regardless of the cross slope. Simulation of nominally critical passing behavior produced vehicle dynamic responses on the order of 0.28 to 0.34 g's for cross slopes of 2 percent and a full range of vehicle types.

- (2) The dynamic effect of increased cross slopes (say, from 2 percent to 4 percent) is a marginal increase in driver discomfort and tire friction demand. Because of conclusion (1), any such increase is undesirable as it worsens an already critical situation. It is therefore clear that, to minimize the dynamic contribution of cross slope, cross-slope design should be kept to a minimum on high-speed highways.
- (3) Higher cross slopes may be permissible on highways with lower design speeds (say, 50 mph (80 km/h) or less). A practical maximum of 4 percent is indicated by the dynamic responses for tractor-trailer passing maneuvers on such highways.
- (4) In general, for all design speeds, the cross slope should be kept to the minimum consistent with drainage requirements for the type of surface and highway. It should be recognized that the establishment of a design cross slope affects other design elements. Greater cross slopes generally result in less design flexibility and a reduction in the safety effectiveness of the highway. They require longer super-elevation runout lengths, and affect the design of the shoulder slope. As shoulder slopes tend to be designed with greater slope than the cross slope to facilitate drainage of the traveled way, cross slopes of 4 to 6 percent would tend to be accompanied by shoulder slopes of 6 or 8 percent. Recent research on the dynamics of roadside traversals (3) points out the disadvantages of such steep shoulder slopes.

From the above four conclusions, it appears that current AASHTO criteria for maximum centerline cross slope, as shown on page 1, are appropriate. AASHTO policy should explicitly note the operational effects of pavement cross slope on the passing maneuver, and should encourage the use of minimal cross slopes on high speed highways.

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  - Vol. II - Report No. PB-263-879
  - Vol. III - Report No. PB-263-880
  - Vol. IV - Report No. PB-263-881
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## Appendix A - HVOSM Modifications

A number of refinements and revisions to the HVOSM program were required, including additional outputs of vehicle responses, revision of the path-following driver model, and input of dual rear tire specifications. These revisions are described below.

### Additional Outputs

Additional calculations and outputs of the existing HVOSM RD2 program were found to be required to enable the evaluation of the centerline crown. The revisions were as follows:

"Discomfort Factor".--The lateral acceleration output of HVOSM corresponds to measurements made with a "hard-mounted," or body-fixed accelerometer oriented laterally on the vehicle. During cornering, the lateral acceleration of the vehicle is directed toward the center of the turn. On a superelevated turn, the component of gravity that acts laterally on the vehicle is also directed toward the turn center. Thus, the lateral acceleration output is increased by superelevation.

Since the vehicle occupants respond to centrifugal force, their inertial reaction is toward the outside of the turn and therefore the component of gravity that acts laterally on them in a superelevated turn reduces the magnitude of the disturbance produced by cornering. A corresponding program output has been defined to evaluate occupant discomfort in turns.

The effects of a vehicle's roll angle and lateral acceleration on occupants are combined in a "discomfort factor" relationship which represents the net lateral disturbance felt by the occupants (i.e., the occupants' reaction to the combined effects of the lateral acceleration and roll angle).

The "discomfort factor" is coded in the following form:

$$\text{DISCOMFORT FACTOR} = - \text{YLAT} + 1.0 * \sin \theta$$

Where: DISCOMFORT FACTOR = G units

YLAT = Vehicle Lateral Acceleration in vehicle-fixed coordinate system, G units

$\theta$  = Vehicle roll angle, radians.

Calculations related to the discomfort factor and corresponding outputs were incorporated into the HVOSM.

Friction Demand.--The friction demand is defined to be the ratio of the side force to the normal load of an individual tire. It is indicative of the friction being utilized by each individual tire. The standard outputs of HVOSM include the side force and normal force for each tire. Coding changes were incorporated to calculate and print out the friction demand for each tire at each interval of time.

#### Driver Model

A recognized problem in the use of either simulation models or full-scale testing in relation to investigations of automobile dynamics is the manner of guiding and controlling the vehicle. Repeatability is essential, and the control inputs must be either representative of an average driver or optimized to achieve a selected maneuver without "hunting" or oscillation. In this investigation of geometric features of highways, the transient portions of the vehicle responses constituted justification for applying a complex computer simulation. The steady-state portions of the vehicle responses can be predicted by means of straightforward hand calculations. Thus, it is essential that the transient responses should not be contaminated by oscillatory steering control inputs.

The Driver model contained in the distributed version of the HVOSM Vehicle Dynamics program was intended to be incorporated into the HVOSM Roadside Design version, but it proved to be inadequate for the present research effort. Therefore, new routines were written for the HVOSM Roadside Design program as described below.



"Wagon-Tongue" Algorithm.--The "wagon-tongue" type of steering control incorporated into the HVOSM Roadside Design Version is one in which the front wheel steer angle is directly proportional to the error of a point on a forward extension of the vehicle X-axis relative to the desired path.

The basic inputs to the "wagon-tongue" algorithm are described in Table 9.

Table 9  
Inputs For "Wagon-tongue" Driver Model

<u>Input</u>	<u>Description</u>	<u>Units</u>
TPRB	Time at which driver model is to begin	sec
DPRB	Time between driver model samples	sec
PLGTH	Probe length measured from the center of gravity of the vehicle along the vehicle-fixed X axis	in
PMIN	Null band, minimum acceptable error	in
PMAX	Maximum allowable discomfort factor above which driver model will only reduce steer angle	g-units
PGAIN	Steer correction multiplier--error of probe from desired path multiplied by PGAIN to determine steer correction	rad/in

1 in = 25.4 mm

Desired Path Definition.--The revision to the HVOSM driver model included the incorporation of a "path generating" routine to create a desired path of X,Y data pairs from standard roadway geometric descriptors. Figure 6 lists the path generating routine.

```

C PATHT.FOR P12          30 DECEMBER 1968      J T FLECK
C PATH GENERATOR
C ROUTINE TO TEST PATH GENERATION SUBROUTINES SETD AND PATNG
C MAY BE USED TO GENERATE DATA SETS FOR TERRAIN GENERATOR
C OR NYOSH
C
C INPUTS:
C   NPTS      NUMBER OF POINTS DESIRED
C   XINIT     X COORDINATE OF FIRST POINT
C   YINIT     Y COORDINATE OF FIRST POINT
C   DELL      SPACING BETWEEN POINTS (ALONG STRAIGHT LINE)
C   PSA       INITIAL HEADING (TANGENT TO PATH)
C   ELI       NUMBER OF SECTIONS (CURVATURES)
C             IF = 0 PROGRAM DEFAULTS TO POINTS IN DATA STATEMENT
C             IF > 0 REQUIRES THE FOLLOWING INPUT
C                   L = 1, ELI
C                   DI(L) CURVATURE > 0 RIGHT TURN
C                           = 0 STRAIGHT
C                           < 0 LEFT TURN
C                   ELI(L) DISTANCE FROM INITIAL POINT WHERE DI(L)
C                           IS EFFECTIVE.
C                           DISTANCE IS MEASURED IN STRAIGHT LINE
C                           SEGMENTS BETWEEN POINTS. IF DISTANCE
C                           ALONG ARC IS REQUIRED SUBROUTINE SETD
C                           MUST BE MODIFIED.
C
C NOTE: ELI MAY BE 1 OR GREATER
C       E.G. TO GENERATE A STRAIGHT PATH N*DELL UNITS
C       LONG AND THEN A RIGHT TURN WITH A CURVATURE OF 20
C       INPUT ELI = 1, DI(1) = 20., ELI(1) = N*DELL
C       THE ANGLE OF TURN IS GIVEN BY
C       ANGLE = 2*ARCSIN((DELL/2)*(PI/180)*(DI(1)/100))
C
C OUTPUT
C   X(I), Y(I) COORDINATES OF POINT I I = 1 TO NPTS
C   BE(I), BT(I) TANGENT AT POINT I (DIRECTION OF PATH)
C   DI(I)        CURVATURE DEFINING PATH FROM POINT I TO POINT I+1
C
C THESE ARE WRITTEN ON A DATA SET (ST1:PTH.DAT) FOR USE BY OTHER
C ROUTINES
C
C INTEGER PLOT
C DIMENSION X(100), Y(100), BE(100), BT(100), DI(100), ELI(100)
C DIMENSION PLOT(70,70)
C DATA RAD/0.01745329/, D /10*0.0, 9*20.0, 9*20.0, 9*20.0, 63*0.0/
C DATA ELI/0/, DI/100*0.0/, ELI/100*0.0/
C
C CALL OPEN(6, 'ST1:PTH.DAT ')
C ENTER INITIAL DATA
C   1 WRITE(1,5)
C   2 FORMAT(1X, ' ENTER NPTS,XINIT,YINIT,DELL,PSA '/')
C   3 READ(1,6)NPTS,XINIT,YINIT,DELL,PSA
C   4 FORMAT(10,4F9.0)
C   5 IF(NPTS.LT.2)ENDFILE 6
C   6 IF(NPTS.LT.2)STOP NPTS
C
C ENTER # OF CURVATURES (IF 0 ROUTINE USES 0 SET BY DATA STATEMENT)
C AND OUTPUT UNIT TOUT =0 DEFAULTS TO SCREEN, TOUT =2 FOR PRINTER
C   7 WRITE(1,7)
C   8 FORMAT(' ENTER ELI,TOUT/')
C   9 READ(1,11)ELI,TOUT

```

Figure 8. PATH GENERATING ROUTINE

```

11  FORMAT(2I4)
C
      IF(IOUT.EQ.0)IOUT = 1
CHECK IF DI'S AND RLI' ARE TO BE INPUTTED
      IF(KLI.EQ.0)GO TO 17
      DO 15 I =1,KLI
      WRITE(1,14)
14  FORMAT(' ENTER DI, RLI'//)
15  READ(1,16)DI(I),RLI(I)
16  FORMAT(2F9.0)
C
CALL ROUTINE TO COMPUTE D'S FROM DI'S
      CALL SETD(KLI,DI,RLI,NPTS,DELL,D)
C
C INITIALIZE POINTS
17  X(1) = XINIT
      Y(1) = YINIT
C
C INITIALIZE TANGENT
      DX(1) = COS(PSA *RAD)
      DY(1) = SIN(PSA *RAD)
C
CALL ROUTINE TO SET PATH
      CALL PATNG(NPTS,DELL,X,Y,D,DX,DY)
C
      WRITE(6)NPTS,DELL,PSA ,X,Y,DX,DY,D
      WRITE(IOUT,23)NPTS,KLI,DELL,PSA
23  FORMAT(1X,'NPTS=',I4,', KLI=',I4,', DELL=',F10.4,', PSA =',F10.4/)
      IF(KLI.GT.0)WRITE(IOUT,24)(L,DI(L),RLI(L),L=1,KLI)
24  FORMAT(1X,I4,2F10.4)
      WRITE(IOUT,25)
25  FORMAT('/' POINT #      POSITION',19X,'TANGENT',10X,'CURVATURE')
      WRITE(IOUT,26)(I,X(I),Y(I),DX(I),DY(I),D(I),I=1,NPTS)
26  FORMAT(1X,I4,2F10.2,10X,2F10.5,F10.2)

```

Figure 8. PATH GENERATING ROUTINE ( continued )

C  
C PRINTER PLOT: SPECIAL ROUTINE TO TEST ABOVE DATA

```

      M = NPTS
      XX = X(1)
      XM = X(1)
      YX = Y(1)
      YM = Y(1)
      DO 35 I = 1, M
      IF(X(I).GT.XX)XX = X(I)
      IF(X(I).LT.XM)XM = X(I)
      IF(Y(I).GT.YX)YX = Y(I)
35   IF(Y(I).LT.YM)YM = Y(I)
      SC = XX-XM
      IF(YX-YM.GT.SC)SC = YX-YM
      SX = 60./SC
      SY = 0.6*SX
      DO 38 I = 1, 70
      DO 38 J = 1, 70
38   PLOT(I, J) = ' '
      IMAX = 1
      DO 40 K = 1, M
      J = (X(K)-XM)*SX + 1.
      I = (Y(K)-YM)*SY + 1.
      IF(I.GT.IMAX)IMAX = I
40   PLOT(I, J) = '0'
      IF(IOUT.EQ.2)WRITE(2, 41)

```

41 FORMAT(1H1)

C

```

      DO 50 I = 1, IMAX
      LM = 61
      DO 44 J = 1, 60
      IF(PLOT(I, LM).NE.' ')GO TO 45
44   LM = LM-1
45   WRITE(IOUT, 47)(PLOT(I, L), L = 1, LM)
47   FORMAT(5X, 71A1)
50   CONTINUE
      GO TO 1
      END

```

Figure 6. PATH GENERATING ROUTINE ( continued )

```

C SUBROUTINE PATH: PATH.FOR F12 30 DECEMBER 1980 J T FLECK
C PATH GENERATOR HVOSM RD-2
C ROUTINE USED IN HVOSM RD-2 TO GENERATE PATH DATA
C
C INPUTS:
C NPTS NUMBER OF POINTS DESIRED
C XINIT X COORDINATE OF FIRST POINT
C YINIT Y COORDINATE OF FIRST POINT
C DELL SPACING BETWEEN POINTS (ALONG STRAIGHT LINE)
C PSA INITIAL HEADING (TANGENT TO PATH)
C KLI NUMBER OF SECTIONS (CURVATURES)
C IF = 0 PROGRAM DEFAULTS TO POINTS IN DATA STATEMENT
C IF > 0 REQUIRES THE FOLLOWING INPUT L = 1, KLI
C DI(L) CURVATURE > 0 RIGHT TURN
C > 0 STRAIGHT
C < 0 LEFT TURN
C RLI(L) DISTANCE FROM INITIAL POINT WHERE DI(L)
C IS EFFECTIVE.
C DISTANCE IS MEASURED IN STRAIGHT LINE
C SEGMENTS BETWEEN POINTS. IF DISTANCE
C ALONG ARC IS REQUIRED SUBROUTINE SETD
C MUST BE MODIFIED.
C
C NOTE: KLI MAY BE 1 OR GREATER
C E.G. TO GENERATE A STRAIGHT PATH N*DELL UNITS
C LONG AND THEN A RIGHT TURN WITH A CURVATURE OF 20
C INPUT KLI = 1, DI(1) = 20., RLI(1) = N*DELL
C THE ANGLE OF TURN IS GIVEN BY
C  $ANGLE = 2 * \arcsin((DELL/2) * (PI/180) * (DI(L)/100))$ 
C
C OUTPUT
C X(I), Y(I) COORDINATES OF POINT I I = 1 TO NPTS
C DX(I),DY(I) TANGENT AT POINT I (DIRECTION OF PATH)
C D(I) CURVATURE DEFINING PATH FROM POINT I TO POINT I+1
C
C
C SUBROUTINE PATH
C COMMON/PATHD/IPATH ,KLI ,DI(10),RLI(10),
C 1 NPTS,XINIT,YINIT,PSA,DELL,
C 2 X(100),Y(100),DX(100),DY(100),D(100)
C LIMIT ARRAY SIZES
C IF(KLI.GT.10)KLI = 10
C IF(NPTS.GT.100)NPTS = 100
C CALL SETD(KLI,DI,RLI,NPTS,DELL,D)
C SETD WAS MODIFIED ON 30 DEC 1980 TO PRODUCE SPIRAL
C INITIALIZE FIRST POINT AND TANGENT
C X(1) = XINIT
C Y(1) = YINIT
C DX(1) = COS(PSA)
C DY(1) = SIN(PSA)
C
C CALL PATHG(NPTS,DELL,X,Y,D,DX,DY)
C
C RETURN
C END

```

Figure 6. PATH GENERATING ROUTINE ( continued )

```

C PROBE.FOR F12
C SUBROUTINE PROBE: CALCULATES DISTANCE OF A POINT FROM CENTERLINE
C USED IN HVCSM RD-2 MOD'S
C
C INPUTS
C     XP,YP          GIVEN POINT
C     M              NUMBER OF REFERENCE POINTS (= NPTS)
C     X(I), Y(I)     REFERENCE POINTS OF PATH, I = 1,NPTS
C     DX(I),DY(I)    TANGENT VECTOR AT REFERENCE POINT
C     D(I)           DEGREE OF CURVATURE AT BETWEEN POINT I AND I+1
C                   D > 0 RIGHT TURN
C                   D = 0 STRAIGHT LINE
C                   D < 0 LEFT TURN
C
C OUTPUTS
C     I              POINT IDENTIFYING SECTOR OF CLOSEST APPROACH
C     DIST           DISTANCE OF POINT FROM ARC
C                   POSITIVE IF POINT IS TO RIGHT OF ARC
C                   NEGATIVE IF POINT IS TO LEFT OF ARC
C     XX ,YY         POINT ON ARC NEAREST GIVEN POINT
C
C NOTE: ON FIRST ENTRY ROUTINE STARTS WITH I = 1, ON SUBSEQUENT
C       ENTRIES THE PREVIOUS VALUE OF I IS USED. THIS LOGIC SHOULD BE
C       ADEQUATE FOR THE PROPOSED USE OF THE ROUTINE.
C
C       CALCULATION OF XX AND YY MAY BE DELETED IF THIS POINT IS NOT NEEDED
C
C       SUBROUTINE PROBE(XP,YP,M,X,Y,DX,DY,D,I,DIST,XX,YY) :
C       DIMENSION X(1),Y(1),DX(1),DY(1),D(1)
C       DATA RAD/0.017453292519943296/,ILAST/1/
C INITIALIZE
C     I = ILAST
C     TEST = DX(I)*(XP-X(I))-DY(I)*(YP-Y(I))
C     TSAV = SIGN(1.0,TEST)
C     GO TO 15
C
C START SEARCH
C
C   7   I = I + 1
C       IF(I.LE.M)GO TO 10
C       IF(TSAV.LT.0.0)GO TO 20
C       I = M
C       GO TO 25
C  10   TEST = DX(I)*(XP-X(I))-DY(I)*(YP-Y(I))
C       IF(TEST*TSAV.LE.0.0)GO TO 25
C  15   IF(TEST)20,25,7
C  20   I = I - 1
C       IF(I.GE.1)GO TO 10
C       IF(TSAV.GT.0.0)GO TO 7
C       I = 1
C
C FINISH SEARCH
C  25   IF((TEST.LT.0.0).AND.(I.GT.1))I=I-1
C       ILAST = I
C FINISH OF DETERMINATION OF I

```

Figure 8. PATH GENERATING ROUTINE ( continued )

```

C
CALCULATE DISTANCE
  ZDN = -DY(I)*(XP-X(I))+DX(I)*(YP-Y(I))
  CONS = D(I)*RAD*0.005
  ZDZ = ((XP-X(I))**2+(YP-Y(I))**2)*CONS
  DIST = (ZDN-ZDZ)/(0.5*SQRT(0.25-CONS*(ZDN-ZDZ)))
C
CALCULATE POSITION OF CLOSEST APPROACH POINT ON ARC
C THE FOLLOWING CODE MAY BE DELETED AND THE REFERENCES TO XX AND YY TAKEN
C OUT OF THE CALL IF THE POINT OF CLOSEST APPROACH ON THE ARC IS NOT NEEDED
C
  DEN = 1.0-2.0*DIST*CONS
C
  IF(DEN.GT.0.0)GO TO 30
  WRITE(1,26)I,XP,YP,DIST,DEN
26  FORMAT(' SUBROUTINE PROBE HAS NEGATIVE OR ZERO DENOMINATOR'/
1    ' IN POSITION FORMULA; IMPLIES POINT NOT IN SECTOR'/I6,4F10.4)
  STOP PROBE
C THIS STOP SHOULD NEVER OCCUR IN NORMAL USAGE
C
30  XX = (XP-X(I)+DIST*DY(I))/DEN + X(I)
  YY = (YP-Y(I)-DIST*DX(I))/DEN + Y(I)
35  RETURN
  END
C
C
C*****
C  IF TANGENT VECTOR IS NOT AVAILABLE IT MAY BE REPLACED BY
C    DX = X(I+1)-X(I) , DY = Y(I+1)-Y(I) , I < M
C    DX = X(M) -X(M-1), DY = Y(M) -Y(M-1), I = M
C
C    USE DX FOR DX(I) AND DY FOR DY(I) IN CALCULATION OF TEST
C
C  RETURN CAN BE PUT AT END OF DETERMINATION OF I AND THE
C  DISTANCE AND CALCULATION OF XX,YY DONE BY ANOTHER ROUTINE.
C  (FORMULAS FOR DIST, XX AND YY ARE ONLY VALID FOR CIRCULAR ARCS
C  OR STRAIGHT LINES)

```

Figure 8. PATH GENERATING ROUTINE ( continued )

```

C PATHG.FOR F12          30 DECEMBER 1980      J T FLECK
C PATH GENERATOR, SUBROUTINE PATHG      HVOSH RD-2
C INPUTS
C      NPTS          NUMBER OF DESIRED POINTS ( > 1)
C      DELL          SPACING BETWEEN POINTS
C      X(1), Y(1)    INITIAL POSITION SET BY CALLING ROUTINE
C      DX(1), DY(1)  INITIAL TANGENT SET BY CALLING ROUTINE
C      D(1)          DEGREE OF CURVATURE, I = 1 TO NPTS
C                   D(I) > 0 TURN TO RIGHT
C                   D(I) = 0 STRAIGHT
C                   D(I) < 0 TURN TO LEFT
C      NOTE: RADIUS OF CURVATURE IS DEFINED AS
C             EQUAL TO (180/PI)*(100/D) = (5729.6/D)
C             (D HAS DIMENSION OF DEGREES PER 100 UNITS OF DELL)
C
C OUTPUTS          I = 1 TO NPTS
C      X(I), Y(I)   COORDINATES OF POINTS
C      DX(I), DY(I) TANGENT VECTOR (DIRECTION OF PATH AT X,Y)
C      NOTE: ROUTINE PRODUCES SMOOTH CURVE SUCH THAT TANGENTS ARE CONTINUOUS
C
C      SUBROUTINE PATHG(NPTS,DELL,X,Y,D,DX,DY)
C      DIMENSION X(1),Y(1),DX(1),DY(1),D(1)
C      DATA RAD/0.017453292519943296/
C INITIALIZE
C      CONS = DELL*RAD/200.0
C
C      DX1 = DELL*DX(1)
C      DTY = DELL*DY(1)
C
C      DS1 = 0.0
C      DC1 = 1.0
C START LOOP
C      DO 20 I = 2, NPTS
C      COMPUTE SINE AND COSINE OF HALF SECTOR ANGLE
C      DS2 = CONS*D(I-1)
C      DC2 = SQRT((1.0-DS2)*(1.0+DS2))
C
C      COMPUTE SINE AND COSINE OF SECTOR ANGLE
C      SP = 2.0*DS2*DC2
C      CP = 1.0 - 2.0*DS2**2
C      C UPDATE TANGENT VECTOR
C      DX(I) = CP*DX(I-1) - SP*DY(I-1)
C      DY(I) = SP*DX(I-1) + CP*DY(I-1)
C
C      COMPUTE SINE AND COSINE OF AVERAGE SECTOR ANGLE
C      SP = DS1*DC2 + DC1*DS2
C      CP = DC1*DC2 - DS1*DS2
C      COMPUTE NEW INCREMENTS
C      DXS = DX1
C      DEX = DXS*CP - DTY*SP
C      DTY = DEX*SP + DTY*CP
C      C UPDATE POSITION
C      X(I) = X(I-1) + DXS
C      Y(I) = Y(I-1) + DTY
C      C SAVE SINE AND COSINE OF HALF SECTOR ANGLE FOR NEXT I
C      DS1 = DS2
C      DC1 = DC2
C 20 RETURN
C      END

```

Figure 6. PATH GENERATING ROUTINE ( continued )



Neuro-Muscular Filter.--The "neuro-muscular" filter from the HVOSM-Vehicle Dynamics Version (7) was incorporated into the HVOSM Roadside Design version. The filter structure corresponds to the first-order effects of the neurological and muscular systems of a human driver.

For the curve study, the following inputs were used for the filter for all runs:

TIL	Time lag of filter	0.05	seconds
TI	Time lead of filter	0.00905	seconds
TAUF	Time delay of filter	0.0	seconds

The related revisions to the Driver model were incorporated into the FHWA distributed Roadside Design version of the HVOSM. However, the revised path-following algorithm was found to produce sustained oscillations about a specified path under some operating conditions. Since the extent of oscillation is dependent on the guidance system parameters as well as the vehicle speed and path curvature, it is possible to obtain peak values of transient response predictions that reflect an artifact of the guidance system rather than a real effect of the highway geometrics under investigation. For example, in Reference (12), comparisons are made between peak transient and steady-state response values which are believed to be more reflective of effects of the guidance system than of the simulated roadway geometrics. Therefore, the following additional modifications were added to the Driver model:

(1) Damping

A damping term (QGAIN) was added to limit the extent of steering activity. Initial runs utilizing the damping term exhibited a reduction in the steering activity as expected. The value used in the curve study was  $QGAIN \text{ (rad-sec/m)} = PGAIN/10$ , where PGAIN is the steering velocity term described below.

(2) Steer Velocity

In addition to the damping term, an adjustable limit on the steering angle velocity was incorporated in the path-follower algorithm, enabling the user to limit the maximum instantaneous front wheel steer velocity to a selected value.

(3) Steer Initialization

For runs such as those being performed in relation to the cross-slope break study, the starting point must be relatively close to the cross-slope break to achieve an economical use of computer time. Thus, the input of an initial steer angle to approximate steady-state steer was

required. Previously, the path-follower algorithm was initialized to a steer angle of 0.0 degrees, regardless of the input value for the initial steer angle. Corresponding revisions were made to Subroutine DRIVER to enable input of an initial steer angle.

A revised listing of Subroutine DRIVER, including the cited modifications, is presented in Figure 7.

#### Dual Tires

To permit the comparison simulation runs to be performed, the HVOSM program had to be modified to enable the simulation of dual rear tires such as are found in many single-unit trucks. The modification required to simulate dual rear tires consisted of a modification to subroutine TIRFRC to double the tire forces at the rear when the option is chosen. While a more elaborate definition of dual rear tires could be pursued, the selected approach was most efficient and equivalent to that used in the PHASE4 program.

```

05710 C SUBROUTINE DRIVER FOR HVOSH RD-2
05720 C
05730 SUBROUTINE DRIVER(PSI,DPSI,JJ,IFLAG,A,B,ANTI,CHOPS)
05740 DIMENSION ANTI(3,3),PPD(50),TPD(50)
05750 COMMON/PATH/IPATH,X(1),D(10),RL(10),NPTS,ZINIT,YINIT,
05760 I PSA,DELL,X(100),Y(100),DX(100),DY(100),D(100)
05770 COMMON/WAGON/IWGN,TPRB,DPRB,PLGTH,PRIN,PRAI,PGAIN,QGAIN,PSIFD
05780 COMMON/FILT/IFILT,TIL,TI,TNT,TAUF
05790 COMMON/INTG/NEQ,T,DT,WR(50),DER(50)
05800 COMMON/ACC/CHFG,CHFA1,CHFA2
05810 DATA NPDRAI/50/,NPD/0/,DPSL/0.0/,N/0/
05820 JJ = 0
05830 IF(IWGN.EQ.0)GO TO 90
05840 JJ = 1
05850 PSIA = PSI
05860 JTP = DPRB
05870 DPS = 0.0
05880 DPSI = 0.0
05890 IF(IFLAG.EQ.0)GO TO 90
05900 IF(TPRB.GT.T + 0.1*DT)GO TO 10
05910 C COMPUTE NEW CHANGE IN STEER ANGLE
05920 TPRB = TPRB + DPRB
05930 XP = VAR(18) + ANTI(1,1)*PLGTH
05940 YP = VAR(19) + ANTI(2,1)*PLGTH
05950 CALL PROBE(XP,YP,NPTS,X,Y,DX,DY,D,IPRB,DIST,II,YY)
05960 C SELECTED POINT INDEX IPRB AND LOCATION OF CLOSEST POINT ON PATH II,YY
05970 C ARE NOT CURRENTLY USED
05980 IF(DIST.EQ.0.0)GO TO 8
05990 SQND=DIST/ABS(DIST)
06000 IF(T.NE.TPRB) DDIST = (DIST-DISTA)/DPRB
06010 9 IF(ABS(DIST).GT.PRIN)DPS = -PGAIN*(ABS(DIST)-PRIN)+SQND
06020 1 -QGAIN*DDIST
06030 8 IF(ABS(DIST).LE.PRIN) DPS= -QGAIN*DDIST
06040 IF(IFILT.EQ.0)GO TO 55
06050 IF(NPD.EQ.NPDRAI)GO TO 10
06060 NPD = NPD + 1
06070 PPD(NPD) = DPS - PSIA
06080 TPD(NPD) = T + TAUF
06090 10 IF(IFILT.EQ.0)GO TO 55
06100 C
06110 C FILTER
06120 C
06130 IF(NPD.EQ.NPDRAI) GO TO 10
06140 TPDTRP = TPD(N)
06150 DO 20 NN = 1,NPD
06160 N = NPD + 1 - NN
06170 20 IF(T.GE.TPD(N))GO TO 30
06180 GO-TO 90
06190 30 IF(TPDTRP.LT.TPD(N)) DPSL = 0.0
06200 DPSI = PPD(N)+TNT*EXP(-(T - TPD(N))/TIL)/TIL
06210 DPSN = PPD(N) - TIL*DPSI
06220 BTP = 0.0
06230 DPS = DPSN - DPSL
06240 DPSL = DPSN
06250 IF(NPD.EQ.1)GO TO 50
06260 C
06270 C

```

Figure 7. SUBROUTINE DRIVER

```

06280 35 L = 1
06290 DO 40 NM = N,NPD
06300 PPD(L) = PPD(NM)
06310 TPD(L) = TPD(NM)
06320 40 L = L + 1
06330 NPD = L - 1
06340 C
06350 50 PSI = PSIA + DPS
06360 GO TO 58
06370 55 PSI = DPS
06380 58 CONTINUE
06390 C CHECK PREVIOUS TIME INTERVAL COMFORT FACTOR (SEE SUBROUTINE OUTPUT)
06400 C IF GREATER THAN PMAX ALLOW ONLY REDUCTION IN STEER ANGLE
06410 IF((PMAX.GT.0.0).AND.(ABS(CFAT).LT.PMAX))GO TO 60
06420 IF(ABS(PSI).GT.ABS(PSIA)) PSI=PSIA
06430 60 CONTINUE
06440 C CHECK MAX STEER ANGLE
06450 IF((CHOPS.GT.0.0).AND.(ABS(PSI).GT. CHOPS))
06460 1 PSI = SIGN(CHOPS,PSI)
06470 IF(DTP.NE.0.0)DPSI = (PSI-PSIA)/DTP
06480 C*** 1/16.781 MCI *****
06490 DPSI = DPSI*57.2958
06500 PSIAO = PSIA*57.2958
06510 PSIO = PSI*57.2958
06520 DELPSI = PSIO- PSIAO
06530 XPFT = XP/12.0
06540 YPFT = YP/12.0
06550 IXFT = XI/12.0
06560 YYFT = YY/12.0
06570 C IF(IPRO.ER.1.0) GO TO 90
06580 IF(IPAGE.LE.50.AND.T.NE.0.0000) GO TO 110
06590 WRITE(30,100)
06600 100 FORMAT(
06610 A1H1,33X,37HPROBE COORDINATES PATH COORDINATES,5X,3HPST,6X,
06620 B3HOPS,6X,4HPSIA,2X,7HDPSI ,2X,7HDPSN ,5HIFLAG,2X,4HIPRB/
06630 C31H TIME DELTA PSIF ERROR ,6X,1HX,9X,1HY,10X,1HX,8X,1HY/
06640 D31H (SEC) (DEG) (IN) ,4X,4H(FT),6X,4H(FT),7X,
06650 E4H(FT),5X,4H(FT)/)
06660 KPAGE = 0
06670 110 WRITE(30,120) T,DELPSI,DIST,XPFT,YPFT,IXFT,YYFT,PSIO,DPSO,
06680 A PSIAO,DPSI,DPSN,IFLAG,IPRB
06690 120 FORMAT(11H ,F7.3,2(4X,F7.3),2(3X,F7.1),2X,2(2X,F7.1),3(2X,F7.4),
06700 - - A- 2X,F7.5,2X,F7.5,2X,13,2X,12)
06710 KPAGE = KPAGE + 1
06720 90 RETURN
06730 C*****
06740 END
06750 C*****

```

Figure 7. SUBROUTINE DRIVER ( continued )

## Appendix B - HSRI/MVMA PHASE4 Modifications

### New Routines Added to PHASE4 Program

Several new routines were added to the PHASE4 simulation program to permit the use of identical terrain definitions and/or driver model path-following in the PHASE4 and HVOSM simulation programs. The routines added to the PHASE4 program are essentially routines from either the HVOSM-76 (7) or the HVOSM-81 (routines previously added or modified within this contract).

The routines added to the PHASE4 program are as follows:

**INPUT2** Purpose:

- (1) Obtains card inputs from Fortran Unit 7 for terrain table and/or driver model option(s)
- (2) Prints card inputs.

Subroutine called from: INPUT

Subroutines called: BLK04, BLK05, PATH, IDOUT

Origin: Modified version\* of subroutine INPUT from HVOSM-76

**BLK04** Purpose: Assigns input values of simulation driver model data

Subroutine called from: INPUT2

Subroutine called: none

Origin: Modified version of subroutine BLK04 from HVOSM-76

**BLK05** Purpose: Assigns input values of simulation terrain table data

Subroutine called from: INPUT2

Subroutine called: TEREAD

Origin: Modified version of subroutine BLK05 from HVOSM-76

**TEREAD** Purpose: Reads terrain table input cards

Subroutine called from: BLK04

Subroutines called: none

Origin: Subroutine TEREAD from HVOSM-76

---

\* The modifications mentioned herein to the HVOSM routines consisted of the elimination of unnecessary codes and storage prior to their installation into the PHASE4 program.

**PATH**      **PURPOSE:** Initializes the first point and computes the initial tangent from a specified heading angle  
                  Subroutine called from: IDOUT  
                  Subroutine(s) called: SETD, PATH6  
                  Origin: Subroutine PATH from HVOSM-81

**SETD**      **Purpose:** Produces a set of degree of curves from a gross description of the path such that a set of equally spaced points describing the path may be computed  
                  Subroutine called from: PATH  
                  Subroutines called: none  
                  Origin: Subroutine SETD from HVOSM-81

**PATH6**      **Purpose:** Computes the path coordinates from the degree of curve  
                  Subroutine called from: PATH  
                  Subroutines called: none  
                  Origin: Subroutine PATH6 from HVOSM-81

**IDOUT**      **Purpose:** Prints terrain table inputs with units and headings  
                  Subroutine called from: INPUT2  
                  Subroutines called: PTHOUT, ROAD0Z  
                  Origin: Modified version of subroutine IDOUT from HVOSM-76

**PTHOUT**      **Purpose:** Prints driver model inputs with units and headings  
                  Subroutine called from: IDOUT  
                  Subroutines called: none  
                  Origin: Subroutine PTHOUT from HVOSM-81

**ROAD**      **PURPOSE:** Calculates the elevation and slopes of the x,y coordinates passed to the routine  
                  Subroutines called from: IDOUT, FCT1, OUTPUT  
                  Subroutine called: none  
                  Entry points: ROAD0Z, ROAD  
                  Origin: Modified version of subroutine INTRPS from HVOSM-76

DRIVE1 Purpose: Computes the front wheel steer angle from the driver model and path descriptor inputs

Subroutine called from: FCT1

Subroutines called: PROBE, CGERR

Entry points: DRIVER, DRIVE2

Origin: Modified version of subroutine DRIVER from HVOSM-81

PROBE PURPOSE: Calculates the error of an arbitrary point on the vehicle from the desired path

Subroutines called from: DRIVE1

Subroutines called: none

Origin: Subroutine PROBE from HVOSM-81

CGERR Purpose: Calculates the error of the vehicle center of gravity from the desired path

Subroutine called from: DRIVE1

Subroutine called: none

Origin: Subroutine CGERR from HVOSM-81

#### Modified Routines for the PHASE4

Two routines for the PHASE4 program required modification to enable their use with the program. The modified routines are as follows:

INPUT Purpose: Reads card inputs and echo's input parameters with units and headings and initializes variables

Modifications:

(1) Print card inputs prior to echo

(2) Call to INPUT2 to input and process terrain table and or driver model inputs

MAIN Purpose: Assign I/O devices, initialize variables, and act as program supervisor

Modifications:

(1) Input and initialize initial heading angle

(2) Permit the setting of initial conditions caused by road when terrain table option used

The program listings for the added and modified routines are shown in Figure 8.







00001910  
00001920  
00001930  
00001940  
00001950  
400001960  
00001970  
00001980  
00001990  
00002000  
00002010  
00002020  
00002030  
00002040  
00002050  
00002060  
00002070  
00002080  
00002090  
00002100  
00002110  
00002120  
00002130  
00002140  
00002150  
00002160  
00002170  
00002180  
00002190  
00002200  
00002210  
00002220  
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00002980  
00002990

150

0080	S143 CONTINUE	00002870
0081	IF (N2745, LE, 1) GO TO S145	00002880
0082	READ (7, S142) (DUM(N), N=1, 9), NSEQ, NCARD	00002890
0083	GO TO S14	00002900
0084	S145 IERASK = 1	00002910
0085	GO TO 99	00002920
0086	S15 IF (NCARD, GE, S15) GO TO 98	00002930
0087	IF (FIX(DUM(9)))	00002940
0088	DO S151 J = 1, 4	00002950
0089	J1 = (J-1)*2 + 1	00002960
0090	J2 = J*2	00002970
0091	YZERO(J, 1) = DUM(J1)	00002980
0092	YZERO(J, 2) = DUM(J2)	00002990
0093	S151 CONTINUE	00003000
0094	IF (N2745, LE, 4) GO TO S154	00003010
0095	READ (7, S142) (DUM(N), N=1, 9), NSEQ, NCARD	00003020
0096	IF (FIX(DUM(9)))	00003030
0097	IF (N2745, LE, 1) GO TO 98	00003040
0098	DO S153 J = 1, 4	00003050
0099	J1 = (J-1)*2 + 1	00003060
0100	J2 = J*2	00003070
0101	J3 = J*4	00003080
0102	YZERO(J, 1) = DUM(J1)	00003090
0103	YZERO(J, 2) = DUM(J2)	00003100
0104	S152 CONTINUE	00003110
0105	S154 IF (N2745, LE, 1) GO TO S155	00003120
0106	READ (7, S142) (DUM(N), N=1, 9), NSEQ, NCARD	00003130
0107	GO TO S14	00003140
0108	S155 IERASK = 1	00003150
0109	GO TO 99	00003160
0110	98 NERR = 1	00003170
0111	99 RETURN	00003180
0112	END	00003190

Figure 8. NEW AND MODIFIED ROUTINES FOR HSRI / MVM PHASE 4 MODEL ( continued )

```

0001 SUBROUTINE TERRAD1 (NRX,NRY,NRZ,NRST,NERR)
0002     MODIFICATIONS PER FM-11-4572, STUDY OF CENTERLINE CROWN
0003     INSTALLED IN HSRI/MVMA PHASE 4 SIMULATION MODEL
0004     NOVEMBER 1982 BY MCHEERY CONSULTANTS, INC.
0005     UNDER SUBCONTRACT TO JACK E. LEISCH & ASSOC.
0006
0007     INSTALLED ROUTINE TO ENABLE USE OF MVSEN TERRAIN TABLES IN PHASE 4
0008     ALL ROUTINES FROM MVSEN-76
0009
0010 COMMON/MVROAD/CHD(20), NZTAB, IS(5), ZE(5), XINC(5),
0011     YB(5), YZ(5), YVNC(5), NZS, NR(5), NY(5),
0012     XZERO(8,5), XZERO(8,5), YZERO(8,5), YZERO(8,5), IERABX, IERABY,
0013     NZ(5), NY(5), XZCP(8,5), YZCP(8,5), YBORY(2,5),
0014     YZCP(2,5), YVZCP(2,5), XZCP(5,2),
0015     YZCP(5,2)
0016 DIMENSION DUM(18)
0017     LSEQ = 0
0018     IF (NRX .LE. 0) GO TO 10
0019     READ(7,2000) (DUM(K),K=1,9), NSEQ, NCARD
0020     IF (NSEQ .EQ. 0) LSEQ = 1
0021     IF (NSEQ .LE. 1) LSEQ = 0
0022     IF (NSEQ .EQ. 1) GO TO 98
0023     LSEQ = NSEQ
0024     IF (NRX .GT. 8) GO TO 98
0025     DO 11 K=1, NRX
0026     11 XZCP(K,1) = DUM(K)
0027     READ(7,2000) (DUM(K),K=1,9), NSEQ, NCARD
0028     IF (NSEQ .LE. 1) LSEQ = 0
0029     IF (NSEQ .EQ. 1) GO TO 98
0030     LSEQ = NSEQ
0031     DO 12 K=1, NRX
0032     12 XZCP(K,1) = DUM(K)
0033     IF (NRX .LE. 0) GO TO 20
0034     IF (NRX .GT. 2) GO TO 98
0035     READ(7,2000) (DUM(K),K=1,9), NSEQ, NCARD
0036     IF (NSEQ .LE. 1) LSEQ = 0
0037     IF (NSEQ .EQ. 1) GO TO 98
0038     LSEQ = NSEQ
0039     DO 13 K=1, NRY
0040     13 YZCP(K,1) = DUM(K)
0041     NYCD = (NRY-1)/9 + 1
0042     DO 20 J=1, NYCD
0043     N = 0
0044     DO 40 K=1, NYCD
0045     READ(7,2000) (DUM(H),H=1,9), NSEQ, NCARD
0046     IF (NSEQ .LE. 1) LSEQ = 0
0047     IF (NSEQ .EQ. 1) GO TO 98
0048     LSEQ = NSEQ
0049     DO 50 H=1, 9
0050     N = H-1
0051     YZCP(J,N,1) = DUM(H)
0052     IF (N .GT. NRY) GO TO 30
0053     30 CONTINUE

```

```

0054 40 CONTINUE
0055 20 IF (N .GT. 0) GO TO 99
0056 N = 0
0057 DO 60 K=1, NYCD
0058 READ(7,2000) (DUM(H),H=1,9), NSEQ, NCARD
0059 IF (NSEQ .LE. 1) LSEQ = 0
0060 IF (NSEQ .EQ. 1) GO TO 98
0061 LSEQ = NSEQ
0062 DO 61 H=1, 9
0063 YZCP(K,H,1) = DUM(H)
0064 IF (N .GT. NRY) GO TO 70
0065 61 CONTINUE
0066 60 CONTINUE
0067 70 NYCD = (NRY-1)/9 + 1
0068 N = 0
0069 DO 71 K=1, NYCD
0070 READ(7,2000) (DUM(H),H=1,9), NSEQ, NCARD
0071 IF (NSEQ .LE. 1) LSEQ = 0
0072 IF (NSEQ .EQ. 1) GO TO 98
0073 LSEQ = NSEQ
0074 DO 72 H=1, 9
0075 N = H-1
0076 YZCP(K,H,1) = DUM(H)
0077 IF (N .GT. NRY) GO TO 99
0078 72 CONTINUE
0079 71 CONTINUE
0080 98 NERR = 1
0081 RETURN
0082 END

```

Figure 8. NEW AND MODIFIED ROUTINES FOR HSRI / MVMA PHASE 4 MODEL ( continued )

```

0001      SUBROUTINE PATH
0002      COMMON/PATND/PATH, KLI, OI(10), RI(10),
0003      NPTS, XINI, YINI, PSA, DELL,
0004      X(100), Y(100), DX(100), DY(100), D(100), CMED(20)
0005      C LIMIT ARRAY SIZES
0006      IF (G1) KLI = 10
0007      IF (G1) NPTS = 100
0008      CALL SETO(KLI, OI, RI, NPTS, DELL, D)
0009      C SET MAX MODIFIED ON 30 DEC 1980 TO PRODUCE SPIRAL
0010      C INITIALIZE FIRST POINT AND TANGENT
0011      X(1) = XINI
0012      Y(1) = YINI
0013      DX(1) = COS(PSA)
0014      DY(1) = SIN(PSA)
0015      C CALL PATHS(NPTS, DELL, X, Y, D, DX, DY)
0016      C RETURN
0017      RETURN
0018      END

```

```

0001      SUBROUTINE PATHS(NPTS, DELL, X, Y, D, DX, DY)
0002      COMMON PATHS, NCT
0003      C PATH GENERATOR ROUTINE
0004      DIMENSION X(1), Y(1), DX(1), DY(1), D(1)
0005      DATA RAD/0.017453292519943296/
0006      C INITIALIZE
0007      CMED = DELL/RAD/200.0
0008      DX = DELL*DX(1)
0009      DY = DELL*DY(1)
0010      D(1) = 0.0
0011      C START LOOP
0012      DO 10 I = 2, NPTS
0013      COMPUTE SINE AND COSINE OF HALF SECTOR ANGLE
0014      DS = COS(0.5*I-1)
0015      DS2 = SORT((1.0-DS2)/(1.0+DS2))
0016      COMPUTE SINE AND COSINE OF SECTOR ANGLE
0017      DS = 2.0*DS2-DS
0018      C UPDATE TANGENT VECTOR
0019      DX(1) = DS*DX(1) - DS2*DY(1)
0020      DY(1) = DS*DY(1) + DS2*DX(1)
0021      COMPUTE SINE AND COSINE OF AVERAGE SECTOR ANGLE
0022      DS = DS2-DS
0023      DS2 = DS2-DS
0024      COMPUTE NEW INCREMENTS
0025      DX = DX*DS
0026      DY = DY*DS
0027      C UPDATE POSITION
0028      X(1) = X(1) + DX
0029      Y(1) = Y(1) + DY
0030      C SAVE SINE AND COSINE OF HALF SECTOR ANGLE FOR NEXT I
0031      D(1) = DS
0032      RETURN
0033      END

```

CODE BETWEEN C's MAY BE DELETED IF TANGENT VECTORS  
 ARE NOT REQUIRED; HOWEVER IN THE CODE BETWEEN THE C's  
 DX(1) IS COS(PST) AND DY(1) IS SIN(PST), THESE WERE SET  
 BY CALLING PROGRAM  
 POLYNOMIAL OR OTHER TYPE OF FITS TO THE X(I) AND Y(I) MAY  
 BE DONE BY OTHER ROUTINES

Figure 8. NEW AND MODIFIED ROUTINES FOR HSRI / MVM PHASE 4 MODEL ( continued )









```

0001      C      SUBROUTINE DRIVE1
0002      ENTRY DRIVER(T,VAR,PSI)
      SUBROUTINE DRIVER INSTALLED IN NSRI/MVMA PHASE4 PROGRAM
      BY HOWENRY CONSULTANTS, INC
      UNDER SUBCONTRACT WITH JACK E. LEISCH & ASSOC.
      PER CONTRACT NO. D01-PH-11-9979
      WHEN CALLING ARGUMENTS:
      T = CURRENT TIME
      VAR = 5 MEMBER ARRAY:
      VAR(1) = Y
      VAR(2) = YDOT
      VAR(3) = PSIDOT
      VAR(4) = VEHICLE HEADING ANGLE
      VAR(5) = X
      PSI = FRONT WHEEL STEER ANGLE RETURNED BY DRIVER
      DIMENSION PPD(50),TPD(50),VAR(5)
      COMMON/PATHD/PATH,RL(10),RLI(10),NPYS,XINIT,YINIT,
      1 PS2,DELL,X(100),Y(100),DX(100),DY(100),CHED(20)
      COMMON/INACH/INACH,TPRS,DPRS,PLGTH,PWIN,PHAX,PGAIN,OGAIN,PSIFD,
      1 TDOPT,TPD(50),TMAX
      COMMON/FILT/IFILT,TILT,TMT,TAMP
      COMMON/ACC/ACLONG(4),ACLAT(4),CHFA(4)
      DATA NPOMAX/50.,NPD/0./,DPSL/0./,N/0./
      DATA DISTA/0.0.,RAD/0.017453293/.,FT/12.0/
      DATA DMCP5/-.4343/.,DT/0.005/.,TPRNT/0.0/.,IFLAG/0/
      IF(INACH.EQ.0)GO TO 90
      IFLAG = 0
      PSIA = PSI
      DTA = DPRS
      DPS = 0.0
      DPSI = 0.0
      DOST = 0.0
      CHECK IF T > TLAST
      IF(T.LT.TLAST) RETURN
      CALCULATE CURRENT TIME INCREMENT
      TLT=TLAST,GT.0) JT = T-TLAST
      TLAST = T
      CHECK FOR PRINT INTERVAL HERE
      IF(T.LT.TPRNT) GO TO 1
      IFLAG = 1
      TPRNT = TPRNT + 0.010
      CHECK IF THIS IS A SAMPLE TIME OF FILTER APPLICATION
      1 IF(TPRS.GT.T + 0.0005)GO TO 10

```

```

      COMPUTE NEW CHANGE IN STEER ANGLE
      TPRS = TPRS + DPRS
      XP = VAR(1) - COS(VAR(4))*PLGTH
      YP = VAR(2) - SIN(VAR(4))*PLGTH
      CALL PRON(XP,YP,NPYS,X,Y,DX,DY,0,IPRS,DIST,XX,YY)
      SELECTED POINT INDEX: IPRS
      LOCATION OF CLOSEST POINT ON PATH: XX,YY
      NOT CURRENTLY USED
      IF(DIST.EQ.0.0)GO TO 8
      SONG=DIST/ABS(DIST)
      DOST = (DOST-DISTA)/DPRS
      IF(ABS(DIST).GT.PWIN)DPS = -PSAIN*(ABS(DIST)-PWIN)/SONG
      1 IF(ABS(DIST).LE.PWIN) DPS = -OGAIN*DOST
      DISTA = DIST
      IF(FILT.EQ.0)GO TO 25
      IF(NPD.EQ.NPOMAX)GO TO 10
      NPD = NPD + 1
      PROLMPD = DPS - PSIA
      TPD(NPD) = T + TAMP
      10 IF(FILT.EQ.0)GO TO 25
      HUBS=HUBCLAR FILTER
      IF(NPD.EQ.NPOMAX) GO TO 10
      TPD(N) = TPD(N)
      GO 20 NN = 1, NPD
      N = NPD + 1 - NN
      IF(T.GE.TPD(N))GO TO 20
      CONTINUE
      GO TO 30
      IF(TPD(N).LT.TPD(N)) DPSL = 0.0
      DPSI = TPD(N)*TMT*EXP(-T - TPD(N))/TILT/TILT
      DTA = 0.0
      DPS = DPSL - DPSL
      DPSI = DPSI
      IF(NPD.EQ.1)GO TO 20
      20 GO 40 NN = N,NPD
      TPD(N) = TPD(N)

```

Figure 8. NEW AND MODIFIED ROUTINES FOR NSRI / MVM PHASE 4 MODEL (continued)



```

0001 SUBROUTINE PROBE(XP,YP,N,X,Y,DR,DY,D,I,DIST,XX,VY)
0002
0003 PATW MC *****
0004 PROBE CALLED FROM DRIVER TO FIND ERROR OF PROBE FROM PATH
0005
0006 DIMENSION X(1),Y(1),DR(1),DY(1),D(1)
0007 DATA RAD/0.017453292519943296/.ILAST/1/
0008 C INIT
0009 I = 1
0010 TEST = DR(1)*(XP-X(1))-DY(1)*(YP-Y(1))
0011 ISAV = SIGN(1.0,TEST)
0012 GO TO 15
0013
0014 START SEARCH
0015
0016 7 I = I + 1
0017 IF (I.LE.N) GO TO 10
0018 IF (ISAV.LT.0.0) GO TO 20
0019 I = N
0020 GO TO 25
0021 10 TEST = DR(I)*(XP-X(I))-DY(I)*(YP-Y(I))
0022 IF (TEST.LT.ISAV) ISAV = TEST
0023 IF (TEST.GT.0.0) GO TO 25
0024 20 I = I - 1
0025 IF (I.GE.1) GO TO 10
0026 IF (ISAV.GT.0.0) GO TO 7
0027
0028 FINISH SEARCH
0029 IF (TEST.LT.0.0) AND (I.GT.1) I = I - 1
0030 LAST = I
0031 FINISH OF DETERMINATION OF I
0032
0033 CALCULATE DISTANCE
0034 ZDN = -DY(LAST)*(XP-X(LAST))-DR(LAST)*(YP-Y(LAST))
0035 CONE = D(LAST)*RAD*0.005
0036 ZDZ = ((XP-X(LAST))**2+(YP-Y(LAST))**2)**0.5*CONE
0037 DIST = (ZDN-ZDZ)/(0.9-SORT(0.25-CONE*(ZDN-ZDZ)))
0038
0039 CALCULATE POSITION OF CLOSEST APPROACH POINT ON ARC
0040 THE FOLLOWING CODE MAY BE DELETED AND THE REFERENCES TO XX AND VY TAKEN
0041 OUT OF THE CALL IF THE POINT OF CLOSEST APPROACH ON THE ARC IS NOT REQUIRED
0042
0043 XX = (XP-X(LAST))-DIST*DY(LAST)/DEN
0044 VY = (YP-Y(LAST))-DIST*DR(LAST)/DEN
0045
0046 RETURN
0047
0048 END

```

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```

0026 DEN = 1.0-2.0*DIST*CONE
0027
0028 C
0029 IF (DEN.GT.0.0) GO TO 30
0030 WRITE(6,26) XP,YP,DIST,DEN
0031 26 FORMAT('SUBROUTINE PROBE HAS NEGATIVE OR ZERO DENOMINATOR',
0032 X IN FOLLOWING FORMULA: IMPLIES POINT NOT IN SECTOR'/16.4F10.4)
0033 STOP
0034 THIS STOP SHOULD NEVER OCCUR IN NORMAL USAGE
0035
0036 30 XX = (XP-X(LAST))-DIST*DY(LAST)/DEN
0037 VY = (YP-Y(LAST))-DIST*DR(LAST)/DEN
0038
0039 RETURN
0040
0041 END

```

Figure 8. NEW AND MODIFIED ROUTINES FOR HSRI / MVM PHASE 4 MODEL ( continued )

