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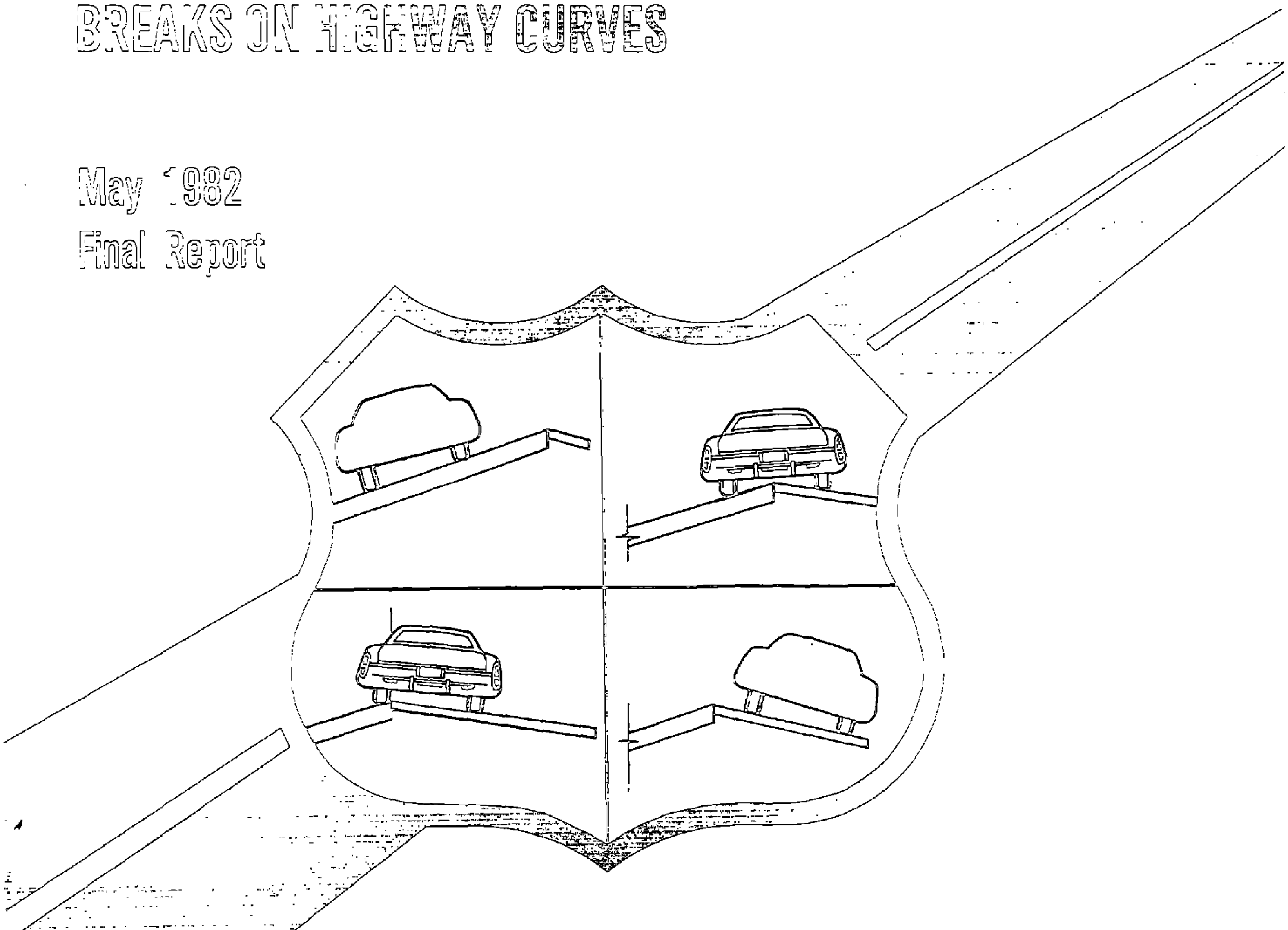
HIGHWAY-VEHICLE-OBJECT SIMULATION MODEL (HVOSM) STUDIES OF CROSS-SLOPE BREAKS ON HIGHWAY CURVES

May 1982

Final Report



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Washington, D.C. 20590

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FOREWORD

This report summarizes the results of a research task directed toward investigation of the effects on vehicle operations of encroachments on cross-slope breaks at the outside edge of highway curves. Highway-Vehicle-Object Simulation Model (HVOSM) computer predictions of vehicle behavior were used to determine these effects.

Sufficient copies of the report are being distributed to provide a minimum of one copy to each regional office, one to each division office, and one copy to each State highway agency. Direct distribution is being made to the division offices.

D Solomon
for Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract

This research was conducted to investigate the operational effects of cross-slope breaks on highway curves. These breaks are created by the superelevation of the traveled way and the adverse shoulder slope. HVOSM simulation studies were performed on a variety of break designs to test the effects of curvature, speed and vehicle path on vehicle operations.

The study findings revealed the importance of shoulder slope and width in designing the shoulder to accommodate vehicular recoveries on the outside of curves. Recommendations regarding design of cross-slope breaks, including treatments for special situations such as narrow shoulders, high superelevation and rehabilitation projects were derived from the research findings.

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Introduction

One of the considerations in the design of a highway cross section is the change in cross slope between the pavement and shoulder, referred to here as the cross-slope break.

AASHTO Policy (1,2) calls for a maximum cross-slope break of 7 percent. This requirement has existed since 1954 and is consistent with the combination of the AASHTO pavement cross slope of 1 percent for high-type surfaces and the maximum AASHTO shoulder cross slope of 8 percent specified for turf shoulders. AASHTO states that although this maximum break is not desirable (for safety), it is tolerable.

When designing superelevated horizontal curves according to AASHTO, the cross-slope break requirement can constrain the shoulder cross-slope design on the outside of the curve. For example, with 6 percent superelevation, the cross-slope break requirement limits the maximum negative shoulder cross slope to 1 percent, which does not meet the AASHTO drainage requirements for even paved shoulders. The alternatives are to either design a positive shoulder slope or a rounded shoulder. The positive shoulder slope drains more runoff water across the pavement and creates problems with the melting of stored snow on the outside shoulder; and, the rounded shoulder design is more difficult to construct and maintain.

The research reported here is a limited study of the safety aspects of cross-slope break to verify the adequacy of the AASHTO requirement. The primary research approach used the HVOSM computer simulation of vehicle traversals across various combinations of pavement and shoulder slope for a range of horizontal curvature.

Criteria Development

One major purpose of shoulders is to provide a secondary recovery area for drivers who inadvertently drive off the traveled lane and onto the shoulder. Given that the designer expects this kind of traversal, the cross-slope break should be designed so it does not "cause" loss of control. This loss of control potential, of course, is most pronounced on horizontal curves where both correction paths and cross-slope breaks tend to be more severe.

The major adverse dynamic effect of cross-slope break traversals is lateral acceleration, which increases with speed, path curvature, cross-slope break, and negative shoulder slope. Assuming that the "design" event begins as a controllable traversal, the objective should be to limit lateral acceleration to a level which is stable at the tire-pavement interface and tolerable to the driver.

Selection of Parameters for the Design Traversal

An inattentive driver can encroach on the shoulder at a horizontal curve in several ways:

1. *A very shallow departure,* in which the vehicle could be steered back to the pavement with minimal lateral displacement and a path curvature that is only slightly greater than the highway curve.
2. *A moderate departure,* in which the vehicle could be steered back to the pavement if the shoulder is wide enough and the cross-slope break and shoulder slope do not cause the vehicle to exceed available skid resistance, or result in intolerable centrifugal force on the driver.
3. *A severe departure and/or out-of-control traversal,* in which the vehicle cannot be steered back onto the pavement within the limits of the shoulder regardless of the amount of cross-slope break or shoulder slope.

A logical design is the cross-slope break which cannot effectively accommodate the most severe departures or out-of-control traversals but should accommodate the other two kinds of traversals. Therefore, the moderate departure has been selected as the controlling event for design.

Although the moderate traversal of a vehicle onto the outside shoulder of a horizontal curve has an infinite number of paths, the most common shape seems clear. This nominal path would have an initial radius greater than that of the highway curve, but would decrease in radius until the vehicle reached maximum lateral offset. At this point, the path radius would be *less* than the highway curve radius, and would then increase until the vehicle reached the highway curve radius within the normal travel lane. Because the variable dimensions and complexity of this path increase the difficulty of dynamic analysis, a simplified approach was used in this study to represent the criticality of the moderate traversal. Figure 1 depicts the "design" path selected for this study. This path is circular, with a radius smaller than that of the highway curve. To simulate a full recovery back to the traveled way, the path is made tangent to a concentric arc (A-A) that is 0.5 m inside the outside edge of shoulder. The basis for defining the path radius is a series of highway operational studies conducted by Glennon and Weaver (3). These studies identified the 95th percentile transient path of drivers negotiating highway curves. The relationship derived by Glennon and Weaver, originally expressed in degrees of curve (English system), translates to the following radius relationship.

$$R_v = \frac{19{,}825\ R}{R + 23{,}096}$$

R_v = 95th percentile vehicle path radius (metres)

R = highway curve radius (metres)

One other hypothesis in developing the design traversal for cross-slope breaks relates to speed. The driver was assumed to be driving at design speed just prior to the initial encounter with the cross-slope break. At the first point of encounter with the cross-slope break, the driver was assumed to remove his foot from the accelerator, initiating a deceleration of 1 m/s^2 (0.1 g) due to engine braking.

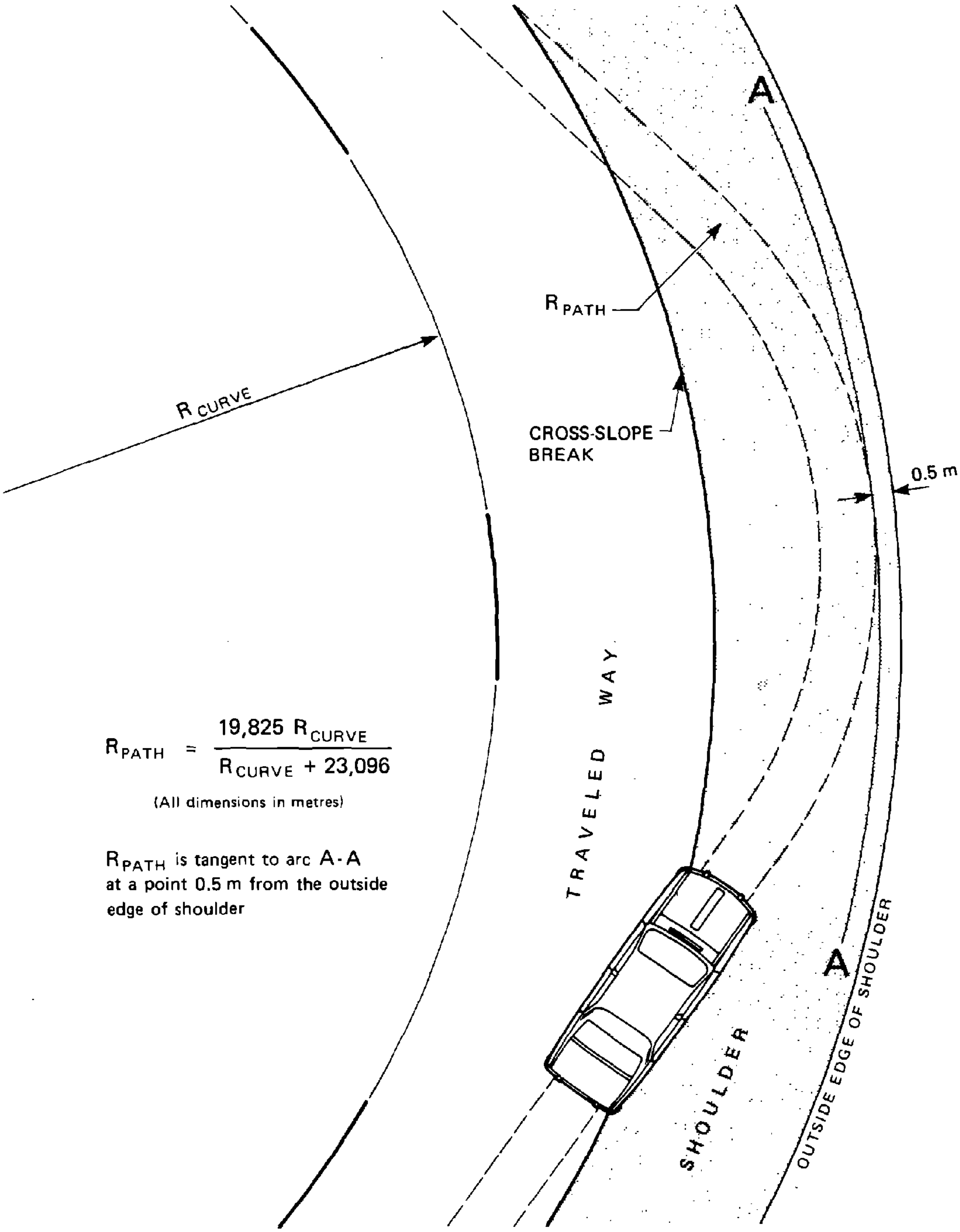


Figure 1. Assumed "Design Path" for Analyses of Traversals on Cross-slope Breaks

Performance Criteria for Lateral Friction Demand

As stated earlier, the major adverse effect of cross-slope break traversals is lateral acceleration. If lateral acceleration is great enough, vehicle loss of control can occur either directly because of vehicle skidding or indirectly because intolerable centrifugal forces on the driver could cause reactions (braking, increased steer angle, decreased steer angle) that lead to loss of control. Setting a "design" level for lateral acceleration at the tire pavement interface requires answers to the following.

1. Level of friction available on highway shoulders;
2. Consideration of dry or wet shoulder surface;
3. Margin of safety required between the "design" lateral acceleration and the expected level of available friction.

The answer to the third point is the easiest to rationalize. Given that the moderate shoulder traversal is a recovery from an infrequent event, a much lesser safety factor is needed than used for, say, highway curve design or stopping sight distance design which both involve maneuvering on the traveled way. When examining the (critical) design event, the required skid resistance need only be as high as the lateral acceleration demands.

Whether the design case should consider a wet shoulder surface is not clear. Paved shoulders, because they usually are not worn by traffic, should exhibit reasonably high wet pavement skid resistance. Gravel shoulders have nearly equal skid resistance for dry and wet surfaces. Turf shoulders, on the other hand, exhibit adequate skid resistance when dry but very low skid resistance when wet. It is probably reasonable to expect a skid resistance (coefficient of friction at the tire-pavement interface) of about 0.40 for paved and gravel shoulders with wet surfaces and for dry turf shoulders. A more appropriate expectation of skid resistance for wet turf shoulders would be about 0.25.

Performance Criteria for Driver Discomfort

Although the study by Weaver and Glennon (3) showed that the selected shoulder traversal is entirely manageable without adverse cross slope, it would put the driver on the threshold of control loss if, with adverse cross slope, the level of discomfort (centrifugal force) causes him to brake or change his steering. If he flattens his path, he will run off the shoulder and encounter the usually more severe cross-slope break at the outside edge of the shoulder. If he sharpens his path, the higher lateral friction demand may exceed available skid resistance. And, if he brakes, the resultant of both braking and cornering friction demand may exceed available friction. Therefore, the appropriate criterion is that level of discomfort below which most drivers could handle the selected shoulder traversal without performing one or more of the loss-of-control maneuvers described above. Figure 2 illustrates how cross slope affects driver discomfort.

A 1974 Calspan study of driver performance on a test-track course gives some guidance on an appropriate driver discomfort threshold. The pertinent conclusion from that study is: (4)

> "Under unfamiliar route conditions, the average driver utilizes lateral acceleration of about 0.3 g (3 m/s^2) in the speed range of 25-40 mph (40-65 km/h)." (Note: lateral acceleration was measured at the center of gravity of the vehicle.)

This result would be directly appropriate to the cross-slope break problem with five exceptions which probably tend to neutralize each other.

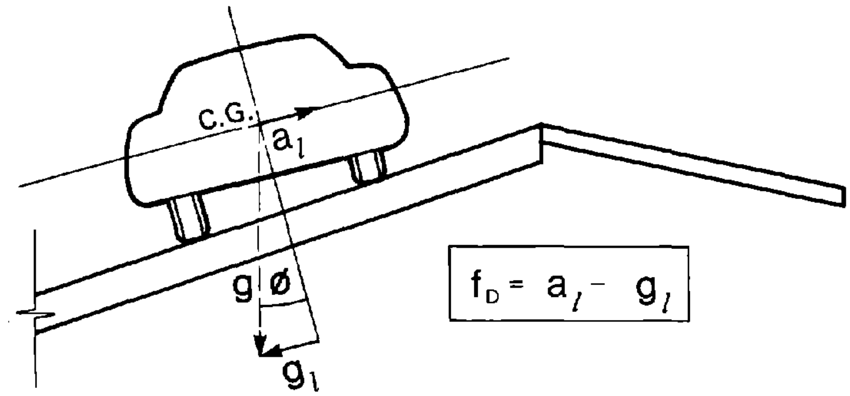
1. The Calspan tests cited above were performed on airport runways, which resulted in the drivers maneuvering around unsuperelevated curves. In such cases discomfort levels experienced by the drivers would be somewhat higher than the 0.3 g (3 m/s^2) lateral acceleration measured at the c.g. of the vehicle. Thus, a slightly higher discomfort level for design could be inferred from these tests.

2. To be consistent with the safety-conservative design philosophy generally employed by AASHTO, a discomfort threshold lower than the average (say, 15th percentile) may be appropriate.

3. An even more appropriate design threshold would consider the relationship between driver discomfort and speed. Drivers such as those observed by Calspan who tolerated lower discomfort levels probably represent those drivers who would generate the lower end of the speed distribution under actual highway conditions. A design threshold selected for consistency with the concept of design speed would reflect the higher discomfort levels experienced by drivers who travel at or near design speed.

4. The distribution of discomfort levels on high-speed (over 100 km/h) highways would tend to reflect a lower overall threshold than

VEHICLE ON SUPERELEVATED CURVE



$\vec{f}_D$ = Discomfort Factor = $\vec{a}_l + \vec{g}_l$

Where:

$\vec{a}_l$ = Lateral Acceleration of Occupants

$\vec{g}_l$ = Lateral Component of Gravity

ϕ = Roll Angle

a_l, g_l in Vehicle Fixed Coordinate System

VEHICLE ON SHOULDER WITH ADVERSE SLOPE

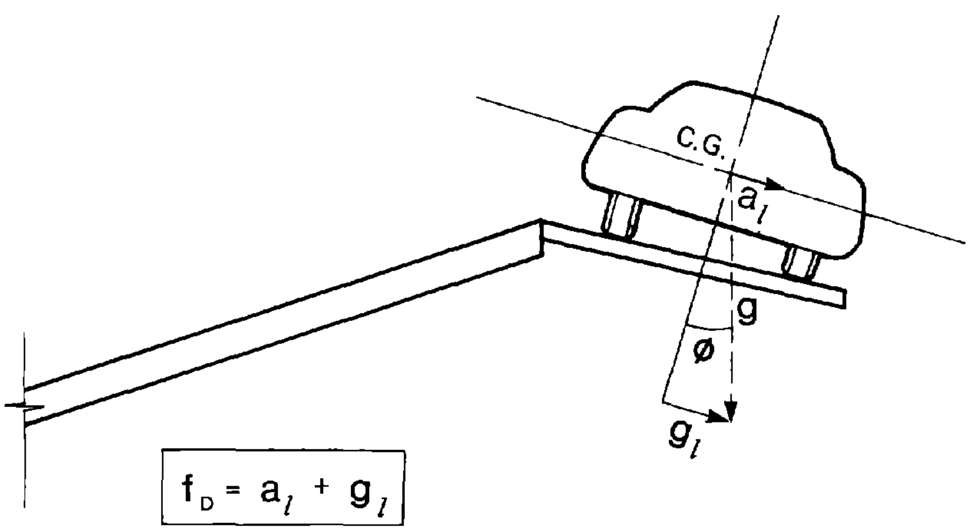


Figure 2. Relationship Between Driver Discomfort Factor and Combination of Roll Angle and Lateral Acceleration

measured on highways with moderate speeds, such as observed by Calspan.

5. The relative infrequency and involuntary nature of the design event justifies consideration of higher discomfort levels than those experienced in normal steering associated with operations on a highway.

Of the five points discussed above, three support selection of a greater than 3 m/s^2 (0.3 g) discomfort level, and two support a lower threshold. Although there appears to be no strong justification for any specific discomfort level, a value of about 3 m/s^2 (0.3 g) would thus appear reasonable. It should be noted that this measure would only apply to that portion of drivers who would need most of the shoulder width for their corrective maneuver.

HVOSM Experiments

The Highway-Vehicle-Object Simulation Model (HVOSM) is a computerized mathematical model originally developed at Cornell Aeronautical Laboratories and subsequently refined by Calspan Corporation (7). The HVOSM is capable of simulating the dynamic response of a vehicle traversing a three-dimensional terrain configuration. The vehicle is composed of four rigid masses; viz., 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 cross-slope break traversals and to interpret the appropriate dynamic response. These modifications, which included the following, are described in more detail in Appendix A.

1. Ground Contact Point Interpolation
2. Effective Range Angled Boundary Option (ERABO)
3. Driver discomfort factor output
4. Friction demand output
5. Terrain Table Generator
6. Driver Model inputs (damping, steer velocity, steer initialization)

The objective of the HVOSM experiments was to evaluate the dynamic effects of the cross-slope breaks associated with outside shoulder traversals on highway curves. Table 1 lists the general conditions and specifications for the HVOSM runs, which are described more fully below.

Basic Test Conditions

Since the most critical highway curve conditions are the AASHTO controlling curves for design, the AASHTO criteria relating design speed and design "f" were used to develop the geometrics (rounded) of controlling highway curves for 20 km/h design-speed increments. The criterion curve used was the one developed for inclusion in the current draft version for the upcoming edition of AASHTO Geometric Design Policy; shown in Table 2.

Table 1. HVOSM Test Conditions

Condition	Specification
Highway Curve Radius	Metricated AASHTO Controlling Curves (metres)
Superelevation	Metricated AASHTO Controlling Curves (2 to 10 percent)
Shoulder Width	2.7 metres
Shoulder Cross Slope	-2 to -6 percent
Available Friction at Interface	f = 0.8
Vehicle	1971 Dodge Coronet
Initial Vehicle Speed	AASHTO Design Speed (km/h)
Vehicle Deceleration	Engine Braking @ 1 m/s^2 (0.1 g)
Vehicle Path Radius	95th percentile as measured by Glennon and Weaver (3)
Vehicle Path Radius Tangent Point	2.2 metres from edge of traveled way

Table 2. Metric AASHTO Controlling Horizontal Curves

Design Speed (km/h)	Design f	Horizontal Curve Radius (Metres) Superelevation Rate (Percent)				
		2	4	6	8	10
120	0.092	1020	870	750	670	600
100	0.116	-	510	450	410	370
80	0.140	-	280	260	230	210
60	0.152	-	150	140	130	120
40	0.164	-	65	60	55	50

As previously described, the design shoulder traversal would have a circular radius that represents the 95th percentile path relative to each highway curve radius. Using the equation shown earlier, Table 3 gives the radius of vehicular traversals for each metricated AASHTO highway curve.

Table 3. Assumed Maximum Path Curvature for Controlling Curves

Design Speed (km/h)	Path Radius (Metres) Superelevation Rate (Percent)				
	2	4	6	8	10
120	586	525	472	435	400
100	-	351	318	294	270
80	-	212	198	178	164
60	-	120	113	105	97
40	-	54	50	46	42

A full-width shoulder of 2.7 m with negative cross slopes of 2, 4, and 6 percent was used in the basic HVOSM runs. The circular traversal path for these runs was, as previously described, tangent to a concentric arc at 2.2 m from the edge of pavement. A small number of similar runs were made to evaluate the dynamics of both traversals on narrower shoulders and partial traversals on full-width shoulders.

Since the objective of the HVOSM test was to study the demands for various lateral acceleration components irrespective of available skid resistance, a high (0.8) available friction factor was used. A 1971 Dodge Coronet was used as the design vehicle, since it seemed to best represent the current population of passenger cars among the vehicles that have been modeled for HVOSM application. Although there are some strong concerns about the dynamic effects of cross-slope breaks on articulated trucks, this HVOSM option was not available and would have been beyond the study scope to develop.

Preliminary HVOSM Runs

A series of initial HVOSM runs was made to study the dynamic differences between (1) 4-wheel and 2-wheel traversals onto the shoulder, and (2) entry to and exit from the shoulder. These runs were made at the most extreme test conditions as follows:

Condition	Specification
Speed	120 km/h
Highway Radius	600 m
Path Radius	400 m
Superelevation	10 %
Negative Shoulder Slope	6 %
Cross-slope Break	16 %
Deceleration	None

The results of these runs indicated that the 4-wheel traversal and the entry to the cross-slope break produced the most extreme dynamic responses. For reasons of economy, therefore, the basic HVOSM experiment concentrated on full 4-wheel traversals over four seconds of real time (sufficient to measure dynamic responses).

Basic HVOSM Experiments

The 21 controlling highway curve geometries with three shoulder cross-slope dimensions (-2, -4, and -6 percent) combine to make 63 potential test conditions. However, the budget for this study would not allow testing all of these conditions. Table 4 shows the 14 test conditions that were selected for inclusion in the basic experiment. These include the three highest design speeds and cross-slope breaks ranging in 2 percent increments from 4 to 16 percent.

Table 4 also shows the results from the basic HVOSM runs. An example time trace of these dynamics is shown for one experiment in Appendix B. In general, results indicate that the dynamic effects are most sensitive to shoulder cross slope and exceed reasonable driver discomfort levels for the design conditions that produce the higher cross-slope breaks. The dynamic effects, however, seem fairly insensitive to cross-slope break within the range studied. The obvious relation between dynamic effects and cross-slope break is basically an indirect one that is a function of (1) the relation between negative shoulder slope and cross-slope break, and (2) the relation between highway curve (and path) radius and superelevation.

HVOSM Experiments to Test Sensitivities

Because the 14 basic HVOSM runs did not produce a universal relationship among all of the parameters of interest, three additional HVOSM runs were made. Two of these were identical to two of the basic runs with the exception that they involved only 2-wheel traversals with a lateral displacement of 0.8 m. A comparison of these runs with the 4-wheel traversals, as shown in Table 5, indicates that 2-wheel traversals (because of a less severe "effective" cross slope) have significantly less severe dynamic responses.

Table 4. HVOSM Dynamic Response Results

TEST CONDITIONS						TEST RESULTS		
Speed (km/h)	Highway Design Curve R(m)	Path R_v(m)	Super-elevation e_{tw}%	Shoulder Slope e_{sh}%	Cross-Slope Break %	Max. Dis-Comfort Factor(g)*	Max. Fric-tion Demand (f)	Max. Roll Angle(°)
120	1020	586	2	-2	4	.24	.20	3.6
120	1020	586	2	-6	8	.30	.25	6.6
120	870	525	4	-4	8	.32	.27	5.8
120	670	435	8	-4	12	.35	.29	6.0
120	600	400	10	-2	12	.37	.30	5.0
120	600	400	10	-6	16	.43	.36	7.8
100	510	351	4	-2	6	.29	.25	4.2
100	510	351	4	-6	10	.35	.34	7.2
100	450	318	6	-4	10	.38	.31	6.3
100	370	270	10	-4	14	.38	.31	6.3
80	280	212	4	-4	8	.31	.26	5.5
80	260	198	6	-2	8	.28	.24	4.0
80	260	198	6	-6	12	.36	.30	7.1
80	210	164	10	-4	14	.41	.38	6.6

*1 g = 9.8 m/s^2

Table 5. Comparison of Full and Partial Traversals

TEST CONDITIONS						TEST RESULTS		
Speed (km/h)	Highway Design Curve R(m)	Path R_V(m)	e_{tw} %	e_{sh} %	Traversal Type	Max. Dis-Comfort Factor(g)	Max. Fric-tion Demand(f)	Max. Roll Angle(°)
120	870	525	4	-4	Full	.32	.27	5.8
120	870	525	4	-4	Partial	.25	.23	1.4
100	510	351	4	-6	Full	.35	.34	7.2
100	510	351	4	-6	Partial	.27	.23	4.8

Table 6 shows another sensitivity comparison wherein one of the basic test conditions was modified to run the vehicle at a speed 20 km/h higher than design speed. The extreme responses associated with overdriving a design condition are apparent.

Table 6. Speed Sensitivity for Full Traversals

TEST CONDITIONS					TEST RESULTS		
Speed (km/h)	Highway Design Curve R(m)	Path R_V(m)	e_{tw} %	e_{sh} %	Max. Dis-Comfort Factor(g)	Max. Fric-tion Demand(f)	Max. Roll Angle(°)
120	510	351	4	-6	.49	.42	8.5
100	510	351	4	-6	.35	.34	7.2

Analysis of HVOSM Results

The basic HVOSM results presented in the prior section of this report indicate that the driver discomfort factor generally exceeds the lateral acceleration on the tires (the difference being a function of the roll angle experienced on the negative shoulder slope). Therefore, the tentative performance criterion established for driver discomfort was the controlling threshold.

For comparison with the basic HVOSM test runs, Table 7 shows the nominal lateral acceleration for shoulder traversals computed with the standard centripetal force equation using the design speed, the shoulder cross slope, and the traversal path from Table 3. In comparing Tables 4 and 7, certain fairly distinct trends are apparent:

1. For a given curve design, the incremental dynamic effect varies directly at 1.5 times the increase in shoulder slope.
2. The incremental dynamic effect increases with decreasing horizontal curve radius for a given design speed.
3. The incremental dynamic effect increases slightly with design speed for any given combination of superelevation and shoulder slope.

Although there are some minor inconsistencies in the test results (due to minor flexibilities in the HVOSM path control algorithm), the noted trends allow a reasonable interpolation and extrapolation of the results as shown in Table 8.

It must be noted that Table 8 is for a full traversal onto a wider shoulder. For traversal onto narrower shoulders (less than 1.6 m) and for partial traversals on wider shoulders, the discomfort levels would be less because the effective (negative) cross slope is less. Because the net effect of shoulder slope is apparent from the HVOSM tests, it is possible to estimate the driver discomfort levels for partial traversals. Table 9 shows the driver discomfort levels when the vehicle is half on the superelevation and half on the negative shoulder slope (approximately 0.8 m beyond the cross-slope break).

Intrepretation of HVOSM Results

Based on the tentative criterion of a maximum 0.3 g for driver discomfort, Table 10 shows the tolerable shoulder cross-slope designs for full shoulders (1.6 m or more). This result is very similar to the 1965 AASHTO single recommendation of 0.07 maximum cross-slope break.

Table 7. Nominal Centripetal Lateral Acceleration*-- Full Traversal on Wide Shoulders

V Highway Design Speed (km/h)	R Highway Design Radius (m)	SUPERELEVATION OF ADJOINING TRAVELED WAY--e_{tw} (percent)																			
		2				4				6				8				10			
		SHOULDER SLOPE FOR GIVEN SUPERELEVATION--e_{sh} (percent)																			
		-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8
120	1020	.21	.23	.25	.27																
	870					.24	.26	.28	.30												
	750									.26	.28	.30	.32								
	670													.28	.30	.32	.34				
	600																	.30	.32	.34	.36
100	510					.24	.26	.28	.30												
	450									.27	.29	.31	.33								
	410													.29	.31	.33	.35				
	370																	.31	.33	.35	.37
80	280					.26	.28	.30	.32												
	260									.27	.29	.31	.33								
	230													.30	.32	.34	.36				
	210																	.33	.35	.37	.39
60	150					.26	.28	.30	.32												
	140									.27	.29	.31	.33								
	130													.29	.31	.33	.35				
	120																	.31	.33	.35	.37
40	65					.25	.27	.29	.31												
	60									.27	.29	.31	.33								
	55													.29	.31	.33	.35				
	50																	.32	.34	.36	.38

* $f = \frac{V^2}{127 R_v} - e_{sh}$; $R_v = \frac{19,825 R}{R + 23,096}$ where: R_v = Radius of "design" path

Table 8. Smoothed Results* for Driver Discomfort Factor--
Full Traversal on Wide Shoulders

		SUPERELEVATION OF ADJOINING TRAVELED WAY--e_{tw} (percent)																			
		2				4				6				8				10			
		SHOULDER SLOPE FOR GIVEN SUPERELEVATION--e_{sh} (percent)																			
Design Speed (km/h)	Design Radius (m)	-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8
120	1020	.24	.27	.30	.33																
	870					.28	.31	.34	.37												
	750									.31	.34	.37	.40								
	670													.34	.37	.40	.43				
	600																	.37	.40	.43	.46
100	510					.28	.31	.34	.37												
	450									.31	.34	.37	.40								
	410													.34	.37	.40	.43				
	370																	.37	.40	.43	.46
80	280					.28	.31	.34	.37												
	260									.30	.33	.36	.39								
	230													.34	.37	.40	.43				
	210																	.37	.40	.43	.46
60	150					.28	.31	.34	.37												
	140									.30	.33	.36	.39								
	130													.33	.36	.39	.42				
	120																	.36	.39	.42	.45
40	65					.28	.31	.34	.37												
	60									.30	.33	.36	.39								
	55													.33	.36	.39	.42				
	50																	.36	.39	.42	.45

* Based on values from Tables 4 and 7

Table 9. Smoothed Results for Driver Discomfort Factor--Partial Traversal on Wide Shoulders and Traversal on Narrow Shoulders

		SUPERELEVATION OF ADJOINING TRAVELED WAY--e_{tw} (percent) 2				4				6				8				10			
		SHOULDER SLOPE FOR GIVEN SUPERELEVATION--e_{sh} (percent)																			
Design Speed (km/h)	Design Radius (m)	-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8	-2	-4	-6	-8
120	1020	.22	.23	.24	.25																
	870					.24	.25	.26	.27												
	750									.26	.27	.28	.29								
	670													.27	.28	.29	.30				
	600																	.29	.30	.31	.32
100	510					.24	.25	.26	.27												
	450									.26	.27	.28	.29								
	410													.27	.28	.29	.30				
	370																	.29	.30	.31	.32
80	280					.24	.25	.26	.27												
	260									.26	.27	.28	.29								
	230													.27	.28	.29	.30				
	210																	.29	.30	.31	.32
60	150					.24	.25	.26	.27												
	140									.26	.27	.28	.29								
	130													.26	.27	.28	.29				
	120																	.28	.29	.30	.31
40	65					.24	.25	.26	.27												
	60									.26	.27	.28	.29								
	55													.26	.27	.28	.29				
	50																	.28	.29	.30	.31

Table 10. Maximum Negative Shoulder Cross Slopes Using 3 m/s² Discomfort Criterion

Design Speed (km/h)	Superelevation of Highway Curve, % 8	7	6	5	4	3	2
	Maximum Negative Shoulder Cross Slope, %						
120	-	0	1	2	3	4	6
100	-	0	1	2	3	4	6
80	-	0	2	2	3	4	6
60	0	1	2	2	3	4	6
40	0	1	2	2	3	4	6

Inspection of the sensitivity of these design recommendations to the criterion for driver discomfort reveals considerable variance in the recommendations over a range of ± .03 g in the discomfort threshold. Given this sensitivity; the uncertainty of the optimum level; the uncertainty of the distribution of lateral offset, speed and radius of actual shoulder traversals on highway curves; and the practicality of applying various results; consideration should be given to an 0.31 g threshold. With this threshold, an appropriate single recommendation for wider shoulders would be an 8 percent maximum cross-slope break. In other words, for those drivers who recovered from a full traversal onto the shoulder, only a few would have maximum discomfort levels above 0.31 g. On the other hand, for a partial traversal, which is probably the more frequent event, most drivers would not exceed a maximum discomfort level of about 0.26 g assuming the same traversal path with the less lateral offset.

Narrow Shoulder Design Considerations

Adoption of driver discomfort level as a basis for cross-slope break design has important implications in the treatment of narrow shoulders. When less than full-width shoulders are selected for design, an implicit decision has been made to not accommodate 4-wheel traversals with the designed shoulder. Traversals which are possible on narrow shoulders, and for which the cross-slope break should therefore be designed, include a range of 2-wheel traversals.

As has been demonstrated previously, the driver discomfort level is largely a function of negative shoulder slope. Figure 3 illustrates the sensitivity of lateral placement of the vehicle during a 2-wheel traversal on effective negative shoulder slope. For increasingly wider shoulders, the maximum effective negative shoulder slope increases. It can be shown, therefore, that relatively large negative slopes are tolerable on very narrow shoulders. Conversely, as shoulder width increases, permissible shoulder slopes must decrease in order to maintain the established driver discomfort level.

Table 11 gives tolerable maximum cross-slope breaks for shoulders less than 1.6 m in width. It should be emphasized that cross-slope breaks employing values under those shown in Table 11 will produce an operationally superior (in terms of lower driver discomfort levels) design.

Table 11. Maximum Cross-Slope Breaks for Narrow Shoulders

Shoulder Width (m)	Maximum Cross-Slope Break %
≤ 0.6	18
0.8	16
1.0	14
1.2	12
1.4	10
1.6	8

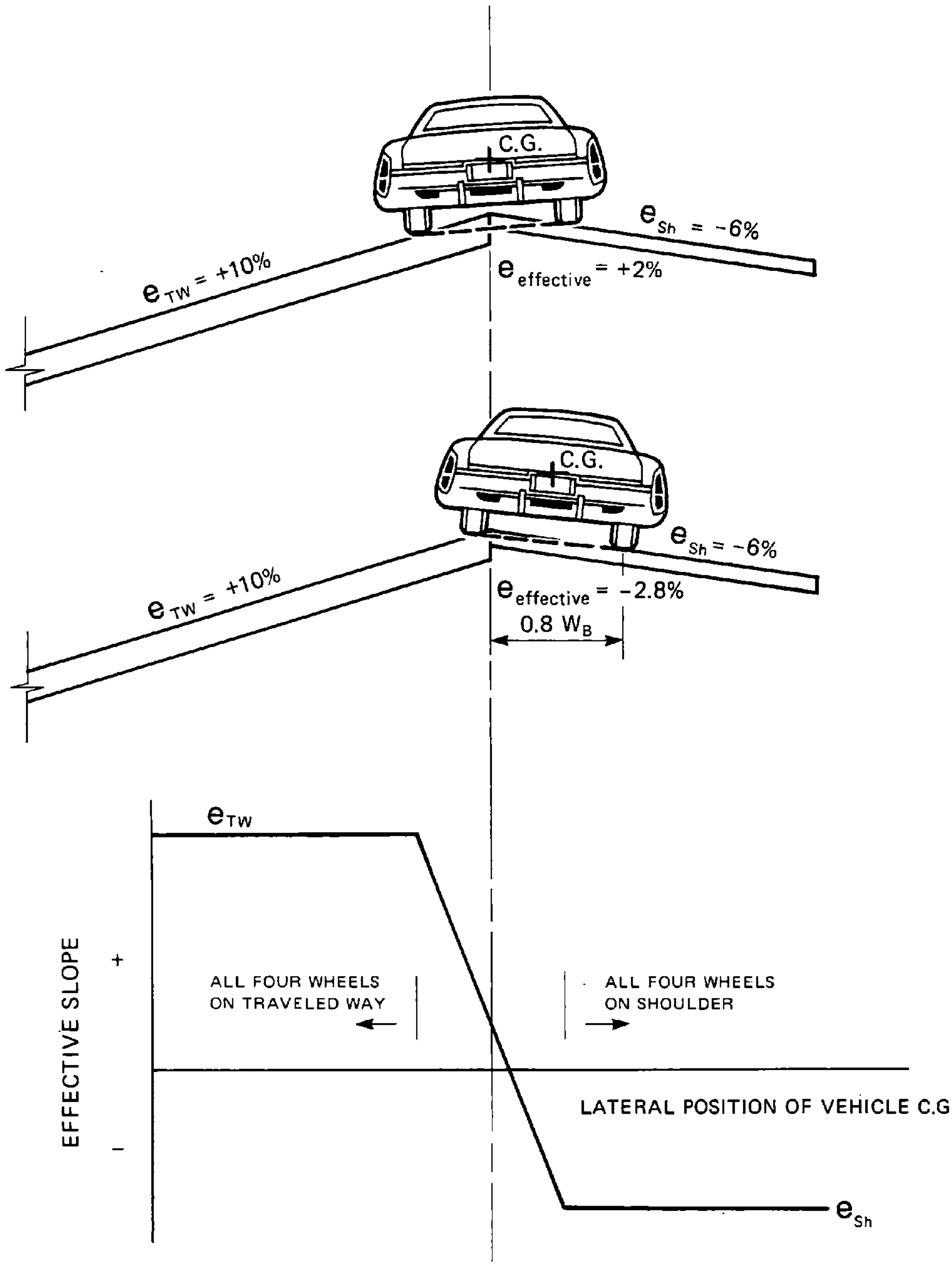


Figure 3. Effect of Vehicle Lateral Placement on Effective Adverse Shoulder Slope

Conclusions and Design Implications

1. Shoulder Slope.--The study results clearly show that the driver discomfort level (centrifugal acceleration) in negotiating shoulder traversals on curves is sensitive to speed, degree of curve, shoulder slope, and the lateral extent of movement onto the shoulder. For a given path and speed of shoulder traversal, therefore, the driver's discomfort mainly increases with shoulder slope and very little, if any, with the amount of cross-slope break. This is illustrated by Figure 12 in the Appendix, which shows that maximum driver discomfort occurs when all four tires are on the shoulder, not when the vehicle crosses the break. Thus, for a given design speed and superelevation of a horizontal curve, the maximum tolerable cross-slope break is a function of the shoulder slope; or in other words, the shoulder slope rather than the cross-slope break itself is the controlling feature.

   From the above discussion, the most important conclusion of this research is: where a negative shoulder slope is tolerable for a recovery maneuver, that shoulder slope should be the minimum that is consistent with other needs for the slope. From a practical design point of view, such other needs primarily involve providing sufficient slope to drain the shoulder. The practice of minimizing the negative shoulder slope will maximize safety for drivers who need the shoulder as a secondary recovery area.

2. Cross-slope Break Requirements for Full Shoulders.--For paved or gravel shoulders with widths of 1.6 m or greater, where the shoulder cross slope is intended to accommodate up to a 4-wheel traversal onto the shoulder, research indicates a maximum tolerable cross-slope break of 8 percent. For superelevation rates between 2 and 6 percent this criterion allows maximum (negative) shoulder slopes ranging from 6 to 2 percent respectively. For superelevation rates exceeding 6 percent, a different kind of shoulder slope design is required. The alternatives are to either carry the superelevation rate across the shoulder, or to continue this upward slope about half way across the shoulder and then break the remainder (or outer half) of the shoulder with a negative slope. Figure 4 illustrates this practice.

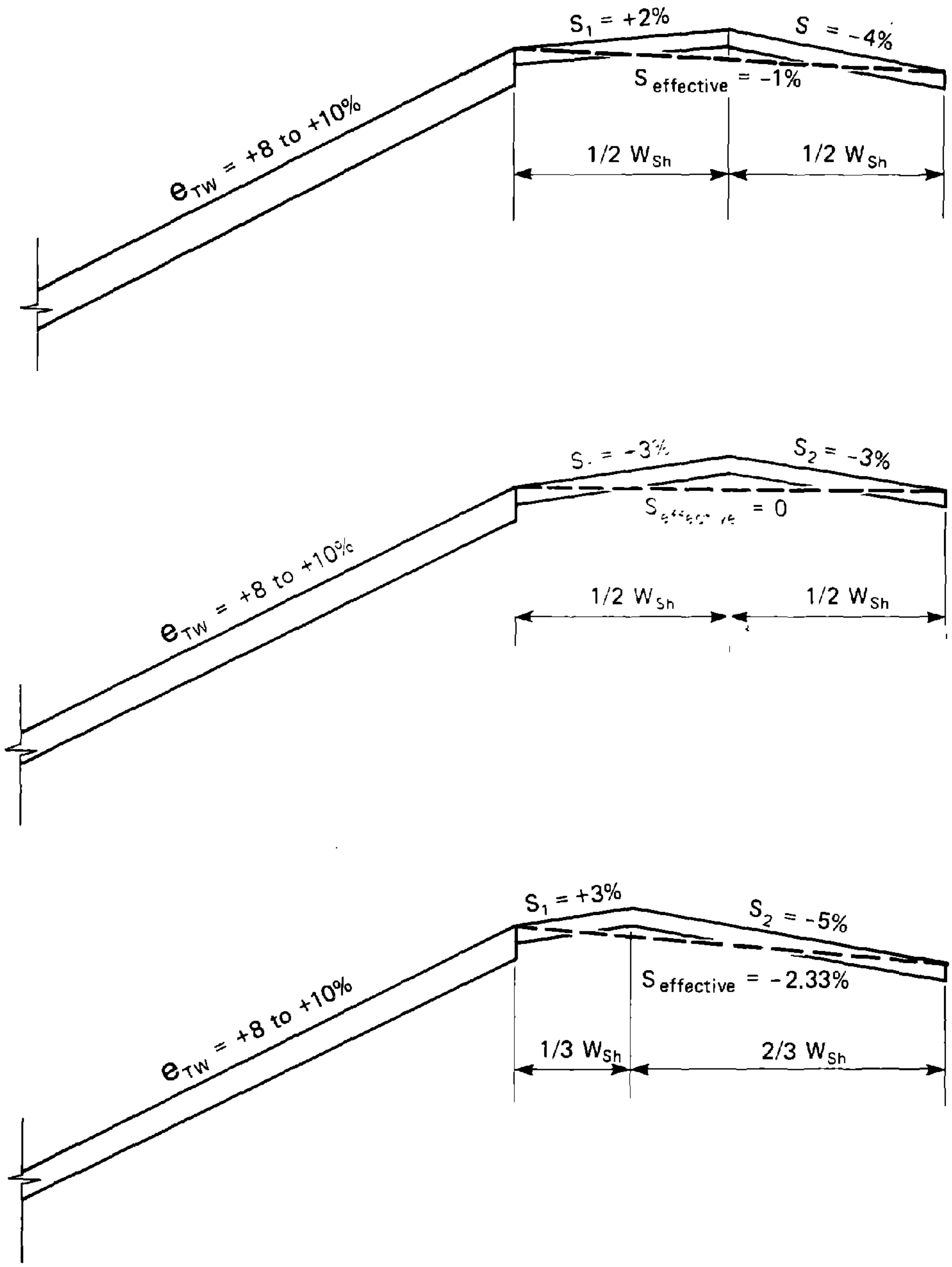


Figure 4. Broken Shoulder Designs for Full (≥1.6 m) Shoulders

3. <u>Cross-slope Break Requirements for Narrow Shoulders</u>.--For paved or gravel shoulders with widths less than 1.6 m, which are designed to only accommodate 2-wheel traversals within the bounds of the shoulder, this research has demonstrated that the maximum tolerable cross-slope break varies as follows:

Shoulder Width(m)	Maximum Cross-slope Break %
≤ 0.6	18
0.8	16
1.0	14
1.2	12
1.4	10
1.6	8

These greater cross-slope breaks do not further compromise safety beyond the implicit decision of choosing the narrower shoulder. Again, as is the case with full shoulders, minimizing the negative shoulder slope consistent with other design requirements (primarily drainage) will maximize the safety of the narrow shoulder design.

The conclusion of greater tolerable cross-slope breaks for narrower shoulders has important implications for rehabilitation projects where (1) narrow shoulders cannot be widened, (2) pavements are widened at the expense of shoulder width; and/or (3) superelevation rates are increased on roadways with narrow shoulders. In these cases where the prior decision has been made to use a narrower shoulder, the greater tolerable cross-slope break designs can accommodate "safe" (i.e., 2-wheel) shoulder encroachments as long as the encroachment path remains on the shoulder. In this case, the caveat expressed by Conclusion 1 regarding minimum possible shoulder slopes remains as the primary principle of shoulder design. Also, in establishing design criteria the narrower shoulders with greater tolerable cross-slope breaks should be weighed against the sensitivity of traffic operations, the probability of incidents, the distribution of lateral displacements for encroaching vehicles, and other conditions.

4. Special Considerations for Turf Shoulders.--Because of greater required slopes for drainage and lower available friction, full width turf shoulders present a dilemma in satisfying the proposed cross-slope break requirements. Not only can the AASHTO shoulder cross slope of -8 percent not be met using the 8 percent cross-slope break recommendation for superelevated curves, but also for the path criterion used in this research, even a 2 percent cross slope on a turf shoulder with a 0.25 wet coefficient of friction will produce skidding.

   The research therefore suggests that turf shoulders on the outside of controlling curves with negative slopes may not provide for recovery of moderate traversals. Possible design solutions which need further study include provision for positive slopes throughout the curve; and consideration of paved or gravel shoulder surfaces along the outside of such curves.

   Another implication of this discussion concerns the use of turf shoulders on tangent sections of higher speed roadways. On a 100 km/h roadway, a wet turf shoulder with a slope of -8 percent and a coefficient of friction of 0.25 could only accommodate a 4-wheel traversal with a 600 m path radius without skidding. Since this kind of shoulder design may not satisfy the objective for secondary recovery, it may be necessary for high-speed tangent sections to either have flatter turf shoulders (if possible), or have paved or gravel surfaces. The third option, for existing high-speed tangent sections, is to insure a safe traversable roadside with flat roadside slopes clear of fixed objects. Further research on turf shoulders is suggested.

5. Implications for Roadside Slopes on Highway Curves.--The dynamic responses observed with HVOSM for negative shoulder slopes up to -6 percent indicate the severity of vehicular traversals onto the roadsides of highway curves. For example, for a 100 km/h speed and 370 m radius of traversal path, the driver discomfort level would reach about 0.63 g on a 4:1 roadside slope. More important, the lateral friction demand would be close to 0.55 g and

the roll angle might be severe enough to create overturning. This kind of relationship between highway curves and overturning accidents, particularly fatal accidents, seems to be partially substantiated by two recent research efforts (5,6). The implications for design might be to (1) design flatter than normal roadside slopes on highway curves (2) justify a greater need for guardrail related to embankment configurations on highway curves than on tangent sections, and (3) provide wider than normal clear zones on highway curves.

6. Consideration for Underdesigned Existing Highway Curves.--The one HVOSM comparison to test speed sensitivity indicates that the higher cross-slope breaks on existing highway curves where the design speed is at least 10 km/h less than the speed limit (expected operating speed) may cause loss-of-control for otherwise controllable shoulder traversals. Therefore, modifying the shoulder slope to carry the superelevation across the shoulder may be a worthwhile accident countermeasure at such locations, providing drainage of the shoulder across the pavement does not present a problem.

7. Consideration of Trucks in Design.--This study was constrained to the consideration of the dynamic responses of passenger vehicles in traversing shoulders on highway curves. Because of the higher centers of gravity and the fifth-wheel characteristics of truck combinations, the dynamic responses of these vehicles to similar traversals would probably be more severe than those observed for passenger vehicles. How much more severe these responses would be, however, cannot be estimated from the results of this research.

   If trucks were found to be much more sensitive to cross-slope break traversals than passenger vehicles, two additional questions much be addressed for design recommendation. First, do professional truck drivers exhibit higher tolerable levels of driver discomfort? And, second, do shoulder traversals by trucks occur often enough to justify the truck as the "design" vehicle for cross-slope break recommendations? Although truck shoulder traversals may represent only a small portion of all such events and, therefore, trucks may not be the appropriate "design" vehicle, the application of Conclusion 1 will help to ameliorate any increased sensitivities exhibited by trucks. For special cases in which the truck is identified as the design vehicle, the use of a positive (upward) shoulder slope sooner than called for in Conclusion 2 may be appropriate.

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APPENDIX A

HVOSM Modifications

To perform this research, a number of refinements and revisions to the Highway-Vehicle-Object Simulation Model (HVOSM) program were required. These refinements and revisions included changes in the definition of the terrain, additional outputs of vehicle responses and revision of the Path-Following Driver Model. Additionally, two preprocessing programs were developed to simplify the interface between highway definition and HVOSM inputs.

Ground Contact Point Interpolation

Prior to the present research effort, the FHWA-distributed version of the HVOSM computer program contained the assumption that the terrain slopes under each wheel of the simulated vehicle remain constant within the terrain region that is covered by the combination of camber, pitch and steer angles. The elevations and slopes of the terrain under the individual wheel centers of the vehicle were obtained by interpolation of the terrain tables. A "ground plane" through the terrain point directly under the wheel center was used in the determination of the ground contact point.

Earlier simulation studies of ramp traversals (e.g., Ref. 7, 8) revealed a minor problem with erroneous extensions of the ends of ramps (see Figure 5). In the present application to cross-slope breaks, the wheel centers and corresponding ground contact points can be on opposite sides of an interpolation boundary (see Figure 6) and the erroneous terrain elevations can be sustained for a significant period of time. An alternate version of the HVOSM RD2 which was obtained from Calspan Corporation was found to contain changes dated 9/16/76 in Subroutine INTRP5(INDX) which corrected the interpolation problem related to a simulated transition across a pavement edge that includes a significant slope change.

The related changes were incorporated into the FHWA-distributed version of the HVOSM RD2 which is being utilized for the present research effort as follows:

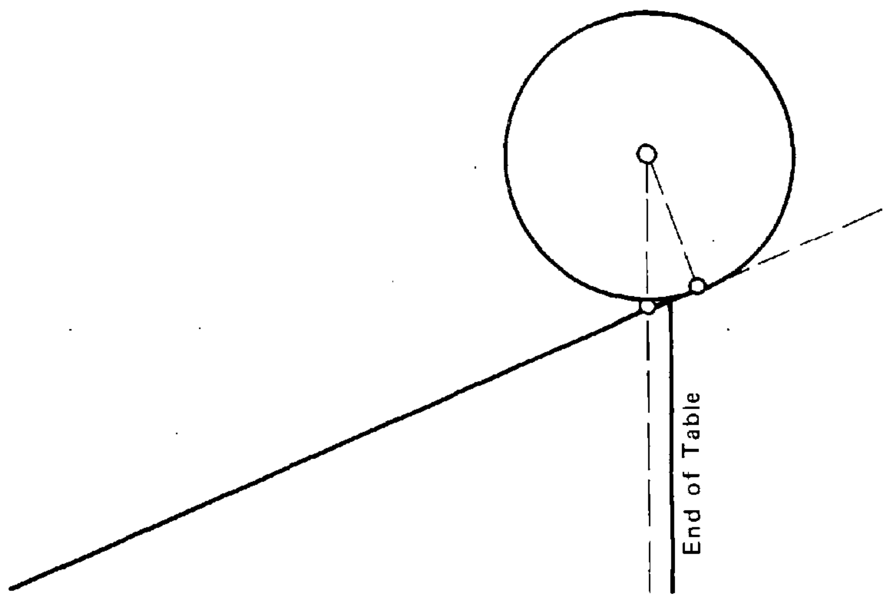


Figure 5. Illustration of Erroneous Extensions of Ends of Ramps

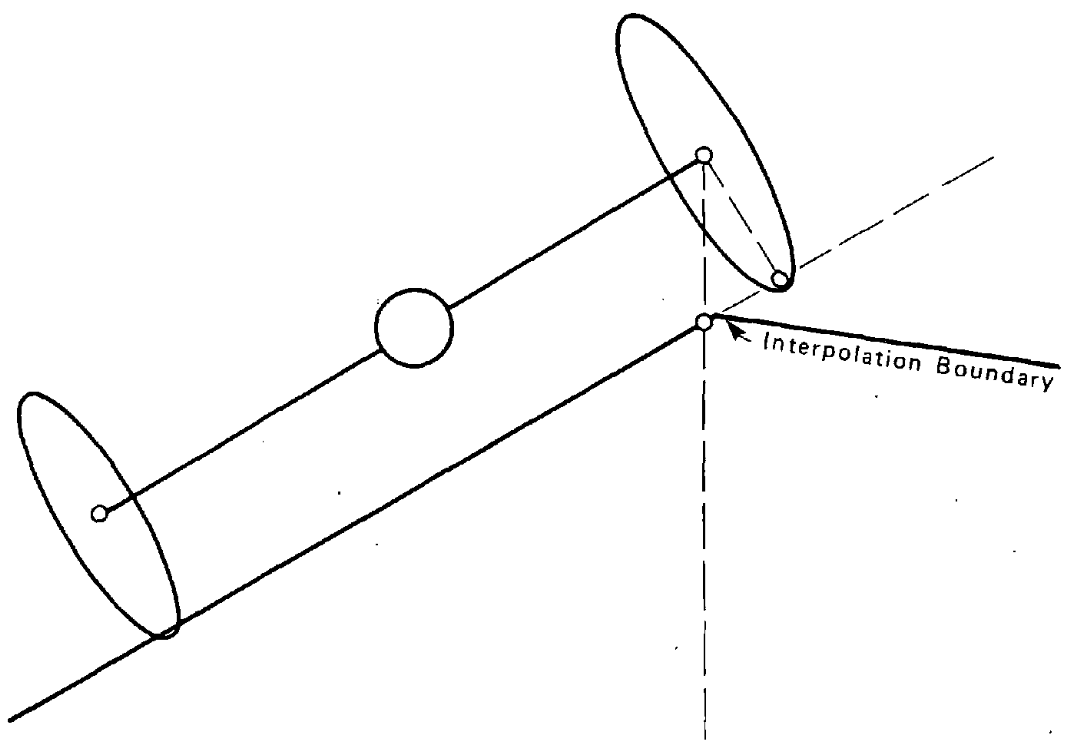


Figure 6. Problems With Ground Contact Point Determination Near Cross-slope Breaks

1. Prior to calculation in Subroutine INTPR5(INDX) of the pitch and slope of the terrain under each individual wheel, the tire contact point as determined from the previous rolling radius and current orientation is calculated. This contact point is then used for calculation of the pitch and camber of the terrain under the wheel. The code associated with this modification is as follows:

```
10 TCPH   = COS (PHII(INDX))
   TSPH   = SIN (PHII(INDX))
   BMTX13 = - AMTX(1,2) * TSPH + AMTX(1,3) * TCPH
   BMTX23 = - AMTX(2,2) * TSPH + AMTX(2,3) * TCPH
   XXX    = XP(INDX) + BMTX13 * HI(INDX)
   YYY    = YP(INDX) + BMTX23 * HI(INDX)
```

where: PHII(INDX) = Camber Angle of wheel INDX relative to vehicle

XXX = X Coordinate of Ground Contact Point of wheel INDX

YYY = Y Coordinate of Ground Contact Point of wheel INDX

HI(INDX) = Previous time interval rolling radius for wheel INDX

2. Subroutine INTRP5 then calculates the pitch and camber of the terrain under wheel INDX as previously documented in Reference 7 and Reference 9.

3. Prior to the return from Subroutine INTRP5(INDX), the pitch, camber and elevation of the terrain under the ground contact point is used to calculate the corresponding elevation of the terrain under the wheel center for subsequent use in Subroutine GCP(I). The code associated with this is as follows:

```
TCPG       = TCPG * SIN (THGI(INDX))
TCB        = - SIN (PHGI(INDX))
TCG        = COS (THGI(INDX)) * TCPG
XDF        = XP(INDX) - XXX
YDF        = YP(INDX) - YYY
ZPGI(INDX) = ZPGI(INDX) - (TCA * XDF + TCB * YDF)/TCG
```

where: THGI(INDX) = Pitch angle of terrain under wheel INDX with respect to the space-fixed axes

PHGI(INDX) = Camber angle of terrain under wheel INDX with respect to the space-fixed axes

XP(INDX) = X coordinate of the wheel center INDX with respect to the space-fixed axes

YP(INDX) = Y coordinate of the wheel center INDX with respect to the space-fixed axes

ZPGI(INDX) = Z coordinate of the wheel center INDX with respect to the space-fixed axes

Effective Range Angled Boundary Option (ERABO)

The original purpose of the angled boundaries as documented in Reference 9 was to permit the simulation of abrupt slope changes and/or linear terrain irregularities such as ridges that intersect the roadway at angles substantially different from 90 degrees (e.g., edges or cracks in pavement, railroad tracks, etc.). The angled boundaries served to preclude the "rounding," by interpolation, of these profile changes. Up to four angled boundaries were available to the user, but the user was restricted by the requirement that there be a minimum of two tabular values between like boundaries (i.e., two angled boundaries or two Y' boundaries) or between a boundary and the beginning or end of a terrain table.

Within the present research effort, the angled boundaries have been used to approximate chords of a circular arc representing the edge of the pavement and separating a roadway curve from the shoulder. This utilization requires placement of the angled boundaries at close intervals not in keeping with the stated limitations of the original version.

The code in subroutine INTRP5(IND) of the HVOSM RD2 version uses the following interpolation procedure for choosing the appropriate angled boundary:

1. The highest number terrain table applicable to the wheel is determined.
2. The particular grid segment within which the wheel is located is determined.
3. The angled boundaries are scanned and the first angled boundary to pass through the grid segment in which the wheel is located is chosen.

Modification of the procedure to limit the ranges of the angled boundaries and, thereby, to permit their use to approximate a circular arc is the objective of the ERABO option. It gives the HVOSM user control over the X and/or Y range in which a specific angled boundary is used.

When used, the ERABO option performs additional tests to determine if the ground contact coordinates are within the effective range of a given angled boundary. If they are, the modified program will proceed with the interpolation procedure. If not, the modified program ignores the particular angled boundary and continues the scan of other angled boundaries. Source modification of HVOSM included the following:

1. Modification of Subroutine BLKØ5 to include the inputs defining the ranges of boundaries.
2. Modification of Subroutine INTRP5(IND) to include additional tests of the ranges of the angled boundaries.

Other related modifications were made in subroutine BLKØ5 and COMMON/INPT/ to permit the input of up to eight angled boundaries per table.

It was also found to be necessary to automate the generation of multiple angled boundaries and their corresponding effective ranges for the approximation of the successive chords of a circular arc representing the edge of the pavement and separating the roadway curve from its shoulder.

Additional Outputs

Additional calculations and outputs of the existing HVOSM RD2 program were found to be required to enable the evaluation of the cross slope break study. The revisions were as follows:

1. "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, of course, 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 a 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:

DISCOMFORT FACTOR = - YLAT + 1.0 * SIN Ø

where: DISCOMFORT FACTOR = G units

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

Ø = Vehicle roll angle, radians.

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

2. Friction Demand.--The friction demand is defined to be the ratio of the side force to the normal load at an individual tire. The friction demand 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.

Terrain Table Generator

The primary research mode of Federal Highway Administration Research Contract DOT-FH-11-9575, "Effectiveness of Design Criteria for Geometric Elements," uses the HVOSM technology for analytical study of the dynamics of vehicle traversals of highway curves with widely varying combinations of geometrics.

The version of the HVOSM maintained by FHWA has the capability of accepting a 3-dimensional definition of the highway surface. The manual generation of these inputs to the HVOSM, however, is time consuming, and the nature and number of geometric configurations to be studied in the contract required automation of the procedure.

The Terrain Table Generator (TTG) was developed as an effective, cost-beneficial interface between standard roadway geometric descriptors and inputs to the HVOSM.

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 the present investigation of geometric features of highways, the transient portions of the vehicle responses constitute the justification for application of 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 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 to accomplish the following:

1. A "wagon-tongue" type of guidance algorithm to calculate path errors.
2. Interface within HVOSM to convert inputs of path descriptors to second-order polynomial definitions of the desired path.
3. Inclusion of a "neuro-muscular" filter within HVOSM to enable smooth driver steering activity.

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 10, 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. <u>Damping</u>

   A damping term was added to limit the extent of steering activity. Initial runs utilizing the damping term exhibited a reduction in the steering activity as expected. However, they were also found to contain an unexpected initial disturbance. This fact led to the discovery of an initialization problem in the path-following algorithm (see (3) below).

2. <u>Steer Velocity</u>

   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. <u>Steer Initialization</u>

   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 8.

Table 12 documents the values for probe length, PGAIN and QGAIN utilized to date for the reported research effort. The tables are presented as a guide for future utilization of the revised Driver model.

Table 12. Cross-Slope Break Study Driver Inputs

Run No.	Speed m/s	Vehicle Path m	Path V^2/R	Break %	PGAIN Deg/m	QGAIN Deg-Sec/m	Probe Length m
CSB1	33.2	400	2.7	12	0.16	0.010	31.4
CSB2	33.2	400	2.7	16	0.16	0.010	31.4
CSB3A	33.2	435	2.5	12	0.08	0.008	16.5
CSB6A	33.2	525	2.1	8	0.05	0.005	31.3
CSB7	33.2	586	1.9	4	0.16	0.010	31.4
CSB8	33.2	586	1.9	8	0.16	0.030	31.4
CSB9B	27.7	270	2.8	14	0.13	0.008	18.3
CSB12A	27.7	318	2.5	10	0.16	0.017	13.2
CSB13A	27.7	351	2.2	6	0.14	0.010	18.3
CSB14C	27.7	351	2.2	10	0.14	0.010	18.3
CSB14PA	33.2	351.6	3.1	10	0.10	0.010	23.4
CSB14PP	27.7	351.6	2.2	10	0.14	0.010	18.3
CSB16A	22.3	164	3.0	14	0.25	0.021	12.7
CSB18D3	22.3	198	2.5	8	0.32	0.042	12.2
CSB19D2	22.3	198	2.5	12	0.32	.000	12.2
CSB20A	22.3	212	2.4	8	0.27	0.027	12.7

HVOSM Run Setup Procedure

Procedure for setup of a Cross-Slope Break (CSB) study run used in the present research effort:

1. Analytically determine the extent of roadway required to meet the requirements of the particular run (i.e., roadway radius, vehicle path radius, etc.).
2. Perform an ERABO run to define the edge of roadway. Put the ERABO outputs in HVOSM form to define the angled boundaries and their effective ranges.
3. Perform two TTG runs, one with the shoulder slope, one with the roadway superelevation.
4. Determine, from TTG outputs, the shoulder and roadway points for each table.
5. Insert the corresponding points for the shoulder into the roadway tables.
6. Insert the roadway/shoulder tables into the HVOSM input deck.
7. Add the angled boundaries and their effective ranges to the HVOSM input deck.
8. Determine analytically the vehicle's heading, location and desired path inputs required to cross onto the shoulder from the roadway at approximately 0.7 sec after initial simulation time.
9. Insure the vehicle is dynamically in equilibrium and perform the simulation run.

```
L
CROSS-SLOPE BREAK STUDY: FH-11-9575                                              0 100
0.0      4.50     0.010    0.010    70.0     0.0      0.0                         0 101
0        0                                                                        0 102
      1                                                                           0 103
      1        1        1        1        1        1        1                     0 104
1971 DODGE CORONET 4-DOOR SEDAN                                                   0 200
8.43     0.51     0.82     3760.0   23000.0  23300.0  530.0    550.0              0 201
49.3     68.7     59.8     61.8     0.0      47.0                                 0 202
0.0      -14.0    0.0      0.0      14.0     0.0      10.82    10.68              0 203
105.0    189.0    600.0    588.0    600.0    0.50     -2.40    2.1                0 204
120.0    324.0    600.0    864.0    600.0    0.50     -4.40    3.6                0 205
6.85     40.0     0.10     7.48     38.0     0.10                                 0 206
40400.0  -5100.   0.02                                                            0 207
                  0.559                                                           0 208
-3.0     3.0      1.0                                                             0 209
-0.43    -0.95    -1.22    -1.26    -0.98    -0.41    0.0                         1 209
FIRESTONE RADIAL VI                                                               0 300
1.0      1.0      1.0      1.0      6.0      0.25                                 0 301
1450.0   3.0      10.0     -37.0    13.2     3043.    .58      91435.   1.0       1 301
.78                                 13.2                                          0 302
400 METER RADIUS,LH TURN,W/FILTER&DAMPING                                         0 400
0.0      5.0      1.0      0.0      0.0      1.0                                  0 401
-199.0   -199.0   -199.0   -199.0   -199.0   -199.0                               1 401
1.0      1.0      1.0      0.05     .00905   0.819    0.0                         0 402
4.0      100.0    960.0    0.0      1.92000  120.0                                0 403
-.36384  0.0      -.36384  6000.    -.36384  9000.    -.36384  12000.0.           0 404
0.0      0.10     1236.0   0.0      1.0      500.0    0.0007500.00005             0 405
CSB#1,600 METER RADIUS,10%SE,-2%SHOULDER                                          0 500
 -600.00  600.00  120.00     0.0  6000.00  300.00  8.0                            0 501
-158.705-207.847-264.281-328.052-399.220-477.856-564.039-657.868                  1 501
89.5     88.5     87.5     86.5     85.5     84.5     83.5     82.5               2 501
0.0      -0.49    -1.07    -1.65    -2.22    -2.80    -3.38    -3.95    -4.53     3 501
-4.50    -4.38    -4.20    -3.94    -3.60    -3.19    -2.71    -2.16    -1.53     4 501
-0.83    -0.05    0.79        0.0      0.0      0.0      0.0      0.0      0.0    5 501
0.0      -0.79    -1.67    -2.55    -3.42    -4.30    -5.18    -6.05    -6.93     6 501
-6.90    -6.78    -6.60    -6.33    -6.00    -5.59    -5.11    -4.55    -3.91     7 501
-3.21    -2.43    -1.58       0.0      0.0      0.0      0.0      0.0      0.0    8 501
0.0      -1.09    -2.27    -3.45    -4.62    -5.80    -6.98    -8.15    -9.33     9 501
-9.30    -9.18    -8.99    -8.73    -8.39    -7.98    -7.50    -6.94    -6.30    10 501
-5.59    -4.81    -3.96       0.0      0.0      0.0      0.0      0.0      0.0   11 501
0.0      -1.39    -2.87    -4.35    -5.82    -7.30    -8.78    -10.25   -11.73   12 501
-11.69   -11.58   -11.39   -11.13   -10.79   -10.37   -9.89    -9.32    -8.68    13 501
-7.97    -7.19    -6.33       0.0      0.0      0.0      0.0      0.0      0.0   14 501
    0.0    -1.50    -3.00    -4.50    -6.00    -7.50    -9.00   -10.50   -12.00 15 501
  -12.18   -12.76   -13.70-13.52   -13.18   -12.77   -12.28   -11.71   -11.07   16 501
-10.35   -9.57    -8.70       0.0      0.0      0.0      0.0      0.0      0.0   17 501
    0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0    -0.00 18 501
   -0.18    -0.76    -1.71    -3.05    -4.76    -6.85    -9.32   -12.16-13.45   19 501
-12.74   -11.94   -11.07      0.0      0.0      0.0      0.0      0.0      0.0   20 501
    0.0     1.50     3.00     4.50     6.00     7.50     9.00    10.50    12.00 21 501
   11.81    11.23    10.28     8.94     7.22     5.12     2.64    -0.22    -3.47 22 501
   -7.08   -11.06-13.44       0.0      0.0      0.0      0.0      0.0      0.0   23 501
    0.0     3.00     6.00     9.00    12.00    15.00    18.00    21.00    24.00 24 501
   23.80    23.23    22.27    20.92    19.19    17.08    14.59    11.71     8.45 25 501
    4.83     0.83    -3.59     0.0      0.0      0.0      0.0      0.0      0.0  26 501
    0.0     4.50     9.00    13.50    18.00    22.50    27.00    31.50    36.00 27 501
```

Figure 7. Example Card Image

```
  35.80   35.23   34.26   32.91   31.17   29.04   26.54   23.65   20.38  28 501
  16.73   12.71    8.27    0.0     0.0     0.0     0.0     0.0     0.0   29 501
   0.0     6.00   12.00   18.00   24.00   30.00   36.00   42.00   48.00  30 501
  47.80   47.22   46.25   44.89   43.14   41.01   38.49   35.59   32.29  31 501
  28.63   24.59   20.13    0.0     0.0     0.0     0.0     0.0     0.0   32 501
   0.0     7.50   15.00   22.50   30.00   37.50   45.00   52.50   60.00  33 501
  59.80   59.22   58.24   56.88   55.12   52.97   50.44   47.52   44.21  34 501
  40.53   36.47   32.00    0.0     0.0     0.0     0.0     0.0     0.0   35 501
 -600.00 1200.00  120.00 5706.72 9306.72  300.00  8.0                     0 502
93.47   86.128  71.384  49.156  19.355  -18.118 -63.384 -116.571          1 502
81.5    80.5    79.5    78.5    77.5    76.5    75.5    74.5              2 502
-0.04   0.81    1.73    2.72    3.79    4.91    6.11    7.39    7.47      3 502
7.47    7.47    7.47    7.47      0.0     0.0     0.0     0.0     0.0     4 502
-2.41   -1.56   -0.63   0.36    1.43    2.56    3.76    5.05    6.38      5 502
7.47    7.47    7.47    7.47      0.0     0.0     0.0     0.0     0.0     6 502
-4.79   -3.94   -3.00   -2.00   -0.94   0.21    1.42    2.70    4.05      7 502
5.49    6.98    7.47    7.47      0.0     0.0     0.0     0.0     0.0     8 502
-7.17   -6.3    -5.37   -4.37   -3.29   -2.15   -0.92   0.36    1.71      9 502
3.16    4.66    6.23    7.47      0.0     0.0     0.0     0.0     0.0    10 502
-9.55   -8.68   -7.74   -6.73   -5.65   -4.50   -3.27   -1.98   -0.62    11 502
0.83    2.34    3.91    5.53      0.0     0.0     0.0     0.0     0.0    12 502
-11.92  -11.05  -10.11  -9.09   -8.01   -6.85   -5.62   -4.32   -2.93    13 502
-1.50   0.02    1.57    3.23      0.0     0.0     0.0     0.0     0.0    14 502
  -11.15-13.42  -12.48  -11.45  -10.37  -9.20   -7.96   -6.65   -5.27    15 502
-3.82   -2.34   -0.74   0.92      0.0     0.0     0.0     0.0     0.0    16 502
   0.73   -3.69   -8.44  -13.57-12.72  -11.55  -10.31   -8.99   -7.60    17 502
-6.15   -4.66   -3.05   -1.41     0.0     0.0     0.0     0.0     0.0    18 502
  12.62    8.17    3.40   -1.76   -7.24  -13.13-12.65  -11.33   -9.93    19 502
-8.48   -6.98   -5.36   -3.71     0.0     0.0     0.0     0.0     0.0    20 502
  24.50   20.03   15.23   10.04    4.54   -1.38   -7.68-13.66  -12.27    21 502
-10.80  -9.29   -7.67   -6.01     0.0     0.0     0.0     0.0     0.0    22 502
  36.37   31.90   27.06   21.86   16.32   10.39    4.04   -2.65   -9.68   23 502
-13.12  -11.56  -9.98   -8.31     0.0     0.0     0.0     0.0     0.0    24 502
  48.25   43.75   38.89   33.67   28.10   22.13   15.75    9.11    1.97   25 502
  -5.43  -13.27-12.29  -10.59     0.0     0.0     0.0     0.0     0.0    26 502
  60.13   55.61   50.72   45.47   39.87   33.88   27.46   20.79   13.61   27 502
   6.11   -1.70   -9.75-12.89     0.0     0.0     0.0     0.0     0.0    28 502
  72.01   67.46   62.55   57.27   51.63   45.62   39.19   32.47   25.25   29 502
  17.71    9.86    1.77   -6.73    0.0     0.0     0.0     0.0     0.0    30 502
  83.88   79.31   74.38   69.06   63.40   57.35   50.89   44.14   36.89   31 502
  29.31   21.58   13.29    4.57    0.0     0.0     0.0     0.0     0.0    32 502
  95.75   91.16   86.20   80.88   75.16   69.05   62.59   55.71   48.52   33 502
  41.14   33.14   24.81   16.05    0.0     0.0     0.0     0.0     0.0    34 502
 -120.00 1680.00  120.00 8949.1211949.12  300.00  8.0                     0 503
782.668 775.073 759.762 736.594 705.409 666.037 618.285 561.942           1 503
73.5    72.5    71.5    70.5    69.5    68.5    67.5    66.5              2 503
3.61    5.20    6.89    7.47    7.47    7.47    7.47    7.47    7.47      3 503
 7.47  0 7.47  0    0.0     0.0     0.0     0.0     0.0     0.0     0.0   4 503
1.29    2.90    4.60    6.38    7.47    7.47    7.47    7.47    7.47      5 503
7.47    7.47      0.0     0.0     0.0     0.0     0.0     0.0     0.0     6 503
-1.02   0.60    2.30    4.09    5.94    7.47    7.47    7.47    7.47      7 503
7.47    7.47      0.0     0.0     0.0     0.0     0.0     0.0     0.0     8 503
-3.36   -1.70   0.0     1.84    3.66    5.68    7.47    7.47    7.47      9 503
7.47    7.47      0.0     0.0     0.0     0.0     0.0     0.0     0.0    10 503
-5.67   -4.01   -2.26   -0.45   1.38    3.28    5.34    7.41    7.47     11 503
7.47    7.47      0.0     0.0     0.0     0.0     0.0     0.0     0.0    12 503
-7.98   -6.34   -4.55   -2.74   -0.83   1.01    3.08    5.16    7.30     13 503
```

Figure 7. (Continued)

```
7.47    7.47       0.0     0.0     0.0     0.0     0.0     0.0     0.0    14 503
-10.30  -8.64   -6.84   -5.01   -3.11   -1.26   0.82    2.97    5.06      15 503
7.24    7.47       0.0     0.0     0.0     0.0     0.0     0.0     0.0    16 503
-12.61  -10.94  -9.16   -7.29   -5.38   -3.44   -1.41   0.72    2.82      17 503
5.01    7.16       0.0     0.0     0.0     0.0     0.0     0.0     0.0    18 503
  -8.08-13.24   -11.45  -9.57   -7.62   -5.71   -3.66   -1.52   0.53      19 503
2.78    4.95       0.0     0.0     0.0     0.0     0.0     0.0     0.0    20 503
    3.45  -5.06-13.74  -11.89  -9.89   -7.97   -5.92   -3.87   -1.70     21 503
0.56    2.65       0.0     0.0     0.0     0.0     0.0     0.0     0.0    22 503
  14.90    6.43   -2.51   -11.79-12.16  -10.24  -8.18   -6.12   -3.93     23 503
-1.90   0.44       0.0     0.0     0.0     0.0     0.0     0.0     0.0    24 503
  26.43   17.91   8.74    -0.39   -9.86-12.50  -10.43  -8.36   -6.13     25 503
-4.13   -1.77      0.0     0.0     0.0     0.0     0.0     0.0     0.0    26 503
  37.95   29.21   20.17   11.00   1.49    -8.86-12.62  -10.54  -8.36     27 503
-6.35   -3.91      0.0     0.0     0.0     0.0     0.0     0.0     0.0    28 503
  49.59   40.68   31.60   22.05   12.82   2.31    -8.30-12.77  -10.58    29 503
-8.44   -6.12      0.0     0.0     0.0     0.0     0.0     0.0     0.0    30 503
  61.10   52.14   42.95   33.42   24.15   13.58   2.92    -7.33-12.81    31 503
-10.65  -8.32      0.0     0.0     0.0     0.0     0.0     0.0     0.0    32 503
  72.60   63.72   54.37   44.79   35.07   24.85   14.68   3.84    -7.47  33 503
-12.95  -10.48     0.0     0.0     0.0     0.0     0.0     0.0     0.0    34 503
1.0     1.0     1.0                                                        0 506
0.0     2814.6652814.6653229.2013229.2013643.4883643.4884057.3951.0        0 515
4057.3954470.7974470.7974883.5664883.5665295.5785295.5785708.00 1.0        1 515
5706.7116116.8366116.8366525.8286525.8286933.5626933.5627339.9222.0        2 515
7339.9227744.7707744.7708147.9928147.9928549.4658549.4658950.0  2.0        3 515
8949.00 9346.6649346.6649742.1489742.14810135.4110135.4110526.303.0        4 515
10526.3010914.7210914.7211300.5411300.5411683.6611683.6612080.943.0        5 515
,120 KPH                                                                   0 600
-4.29   0.73    93.82   0.26    0.0     -4.37   -0.71   0.0     0.0        0 601
75.36   4194.84 -22.68  1308.0  15.0    1.68                               0 602
-0.77   0.53    -0.03   -1.25   0.0     0.0                                0 603
                                                                             9999
END OF DATA
```

Figure 7. (Continued)

```
C SUBROUTINE DRIVER FOR HVOSM RD-2
C
      SUBROUTINE DRIVER(PSI,DPSI,JJ,IFLAG,A,B,AMTX,OMGPS)
      DIMENSION AMTX(3,3),PPD(50),TPD(50)
      COMMON/PATHD/IPATH,KLI,DI(10),RLI(10),NPTS,XINIT,YINIT,
     1       PSA,DELL,X(100),Y(100),DX(100),DY(100),D(100)
      COMMON/WAGON/IWAGN,TPRB,DPRB,PLGTH,PMIN,PMAX,PGAIN,QGAIN,PSIFD
      COMMON/FILT/ IFILT,TIL ,TI  ,TMT  ,TAUF
      COMMON/INTG/ NEQ  ,T   ,DT  ,VAR(50),DER(50)
      COMMON/ACC/CMFCG,CMFA1,CMFA2
      DATA NPDMAX/50/,NPD/0/,DPSL/0.0/,N/0/
      JJ   = 0
      IF(IWAGN.EQ.0)GO TO 90
      JJ   = 1
      PSIA = PSI
      DTP  = DPRB
      DPS  = 0.0
      DPSI = 0.0
      IF(IFLAG.EQ.0)GO TO 90
      IF(TPRB.GT.T + 0.1*DT)GO TO 10
C  COMPUTE NEW CHANGE IN STEER ANGLE
      TPRB  = TPRB + DPRB
      XP = VAR(18) + AMTX(1,1)*PLGTH
      YP = VAR(19) + AMTX(2,1)*PLGTH
      CALL PROBE(XP,YP,NPTS,X,Y,DX,DY,D,IPRB,DIST,XX,YY)
C  SELECTED POINT INDEX IPRB AND LOCATION OF CLOSEST POINT ON PATH XX,YY
C  ARE NOT CURRENTLY USED
      IF(DIST.EQ.0.0)GO TO 8
      SGND=DIST/ABS(DIST)
      IF(T.NE.TPRB) DDIST = (DIST-DISTA)/DPRB
 9    IF(ABS(DIST).GT.PMIN)DPS = -PGAIN*(ABS(DIST)-PMIN)*SGND
     1                          -QGAIN*DDIST
 8    IF(ABS(DIST).LE.PMIN) DPS= -QGAIN*DDIST
      IF(IFILT.EQ.0)GO TO 55
      IF(NPD.EQ.NPDMAX)GO TO 10
      NPD = NPD + 1
      PPD(NPD) = DPS - PSIA
      TPD(NPD) = T + TAUF
   10 IF(IFILT.EQ.0)GO TO 55
C
C  FILTER
C
      IF(NPD.EQ.NPDMAX) GO TO 10
      TPDTMP = TPD(N)
      DO 20 NN = 1,NPD
      N = NPD + 1 - NN
   20 IF(T.GE.TPD(N))GO TO 30
      GO TO 90
  30  IF(TPDTMP.LT.TPD(N)) DPSL = 0.0
      DPSI = PPD(N)*TMT*EXP(-(T - TPD(N))/TIL)/TIL
      DPSN = PPD(N) - TIL*DPSI
      DTP  = 0.0
      DPS  = DPSN - DPSL
      DPSL = DPSN
      IF(NPD.EQ.1)GO TO 50
C
C
```

Figure 8. Subroutine DRIVER

```
 35   L    = 1
      DO 40 NN = N,NPD
      PPD(L) = PPD(NN)
      TPD(L) = TPD(NN)
   40 L = L + 1
      NPD = L - 1
C
   50 PSI = PSIA + DPS
      GO TO 58
   55 PSI = DPS
   58 CONTINUE
C CHECK PREVIOUS TIME INTERVAL COMFORT FACTOR (SEE SUBROUTINE OUTPUT)
C     IF GREATER THAN PMAX ALLOW ONLY REDUCTION IN STEER ANGLE
      IF((PMAX.GT.0.0).AND.(ABS(CMFA1).LT.PMAX))GO TO 60
      IF(ABS(PSI).GT.ABS(PSIA)) PSI=PSIA
  60  CONTINUE
C CHECK MAX STEER ANGLE
      IF((OMGPS.GT.0.0).AND.(ABS(PSI) .GT.  OMGPS))
     1    PSI = SIGN(OMGPS,PSI)
      IF(DTP.NE.0.0)DPSI = (PSI-PSIA)/DTP
C***  1/16/81   MCI  ***********************************************
      DPSO = DPS*57.2958
      PSIAO = PSIA*57.2958
      PSIO = PSI*57.2958
      DELPSI = PSIO- PSIAO
      XPFT = XP/12.0
      YPFT = YP/12.0
      XXFT = XX/12.0
      YYFT = YY/12.0
C     IF(FKD.EQ.1.0) GO TO 90
      IF(KPAGE.LE.50.AND.T.NE.0.0000) GO TO 110
      WRITE(50,100)
  100 FORMAT(
     A1H1,33X,37HPROBE COORDINATES    PATH COORDINATES,5X,3HPSI,6X,
     B3HDPS,6X,4HPSIA,2X,7HDPSI    ,2X,7HDPSN    ,5HIFLAG,2X,4HIPRB/
     C31H  TIME      DELTA PSIF     ERROR ,6X,1HX,9X,1HY,10X,1HX,8X,1HY/
     D31H  (SEC)       (DEG)         (IN)  ,4X,4H(FT),6X,4H(FT),7X,
     E4H(FT),5X,4H(FT)/)
      KPAGE = 0
  110 WRITE(50,120) T,DELPSI,DIST,XPFT,YPFT,XXFT,YYFT,PSIO,DPSO,
     A               PSIAO,DPSI,DPSN,IFLAG,IPRB
  120 FORMAT(1H ,F7.3,2(4X,F7.3),2(3X,F7.1),2X,2(2X,F7.1),3(2X,F7.4),
     A         2X,F7.5,2X,F7.5,2X,I3,2X,I2)
      KPAGE = KPAGE + 1
   90 RETURN
C*******************************************************************
      END
C*******************************************************************
```

Figure 8. (Continued)

```
C  SUBROUTINE PATH:  PATHM.FOR
C   PATH GENERATOR  HVOSM RD-2
      SUBROUTINE PATH
      COMMON/PATHD/IPATH ,KLI ,DI(10),RLI(10),
     1           NPTS,XINIT,YINIT,PSA,DELL,
     2           X(100),Y(100),DX(100),DY(100),D(100)
C LIMIT ARRAY SIZES
      IF(KLI.GT.10)KLI = 10
      IF(NPTS.GT.100)NPTS = 100
      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
      X(1)  =  XINIT
      Y(1)  =  YINIT
      DX(1) =  COS(PSA)
      DY(1) =  SIN(PSA)
C
      CALL PATHG(NPTS,DELL,X,Y,D,DX,DY)
C
      RETURN
C*********************************************************************
      END
```

Figure 9. Subroutine PATH

```
C PATHG
C   PATH GENERATOR, SUBROUTINE PATHG
C
      SUBROUTINE PATHG(NPTS,DELL,X,Y,D,DX,DY)
      DIMENSION X(1),Y(1),DX(1),DY(1),D(1)
      DATA RAD/0.017453292519943296/
C INITIALIZE
      CONS  = DELL*RAD/200.0
C*
      DXX   = DELL*DX(1)
      DYY   = DELL*DY(1)
C*
      DS1   = 0.0
      DC1   = 1.0
C START LOOP
      DO 20 I = 2, NPTS
COMPUTE SINE AND COSINE OF HALF SECTOR ANGLE
      DS2   = CONS*D(I-1)
      DC2   = SQRT((1.0-DS2)*(1.0+DS2))
C**
COMPUTE SINE AND COSINE OF SECTOR ANGLE
      SP    = 2.0*DS2*DC2
      CP    = 1.0 - 2.0*DS2**2
C UPDATE TANGENT VECTOR
      DX(I) =  CP*DX(I-1) - SP*DY(I-1)
      DY(I) =  SP*DX(I-1) + CP*DY(I-1)
C**
COMPUTE SINE AND COSINE OF AVERAGE SECTOR ANGLE
      SP    =     DS1*DC2 + DC1*DS2
      CP    =     DC1*DC2 - DS1*DS2
COMPUTE NEW INCREMENTS
      DXS   =  DXX
      DXX   =  DXS*CP  - DYY*SP
      DYY   =  DXS*SP  + DYY*CP
C UPDATE POSITION
      X(I)  =  X(I-1)  + DXX
      Y(I)  =  Y(I-1)  + DYY
C SAVE SINE AND COSINE OF HALF SECTOR ANGLE FOR NEXT I
      DS1   =  DS2
   20 DC1   =  DC2
      RETURN
C
C
C
      END
```

Figure 10. Subroutine PATHG

```
C PROBE
C SUBROUTINE PROBE:  CALCULATES DISTANCE OF A POINT FROM CENTERLINE
C
      SUBROUTINE PROBE(XP,YP,M,X,Y,DX,DY,D,I,DIST,XX,YY)
      DIMENSION X(1),Y(1),DX(1),DY(1),D(1)
      DATA RAD/0.01745329251994329 6/,ILAST/1/
C INITIALIZE
      I    = ILAST
      TEST = DX(I)*(XP-X(I))+DY(I)*(YP-Y(I))
      TSAV = SIGN(1.0,TEST)
      GO TO 15
C
C START SEARCH
C
    7 I = I + 1
      IF(I.LE.M)GO TO 10
      IF(TSAV.LT.0.0)GO TO 20
      I = M
      GO TO 25
   10 TEST = DX(I)*(XP-X(I))+DY(I)*(YP-Y(I))
      IF(TEST*TSAV.LE.0.0)GO TO 25
   15 IF(TEST)20,25,7
   20 I = I - 1
      IF(I.GE.1)GO TO 10
      IF(TSAV.GT.0.0)GO TO 7
      I = 1
C
C FINISH SEARCH
   25 IF((TEST.LT.0.0).AND.(I.GT.1))I=I-1
      ILAST = I
C FINISH OF DETERMINATION OF I
C
C
C
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 TAKE
C OUT OF THE CALL IF THE POINT OF CLOSEST APPROACH ON THE ARC IS NOT NEE
C
      DEN = 1.0-2.0*DIST*CONS
C
      IF(DEN.GT.0.0)GO TO 30
      WRITE(6,26)I,XP,YP,DIST,DEN
   26 FORMAT(' SUBROUTINE PROBE HAS NEGATIVE OR ZERO DENOMINATOR'/
     X' IN POSITION FORMULA: IMPLIES POINT NOT IN SECTOR'/I6,4F10.4)
      STOP
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
C*********************************************************************
      END
```

Figure 11. Subroutine PROBE

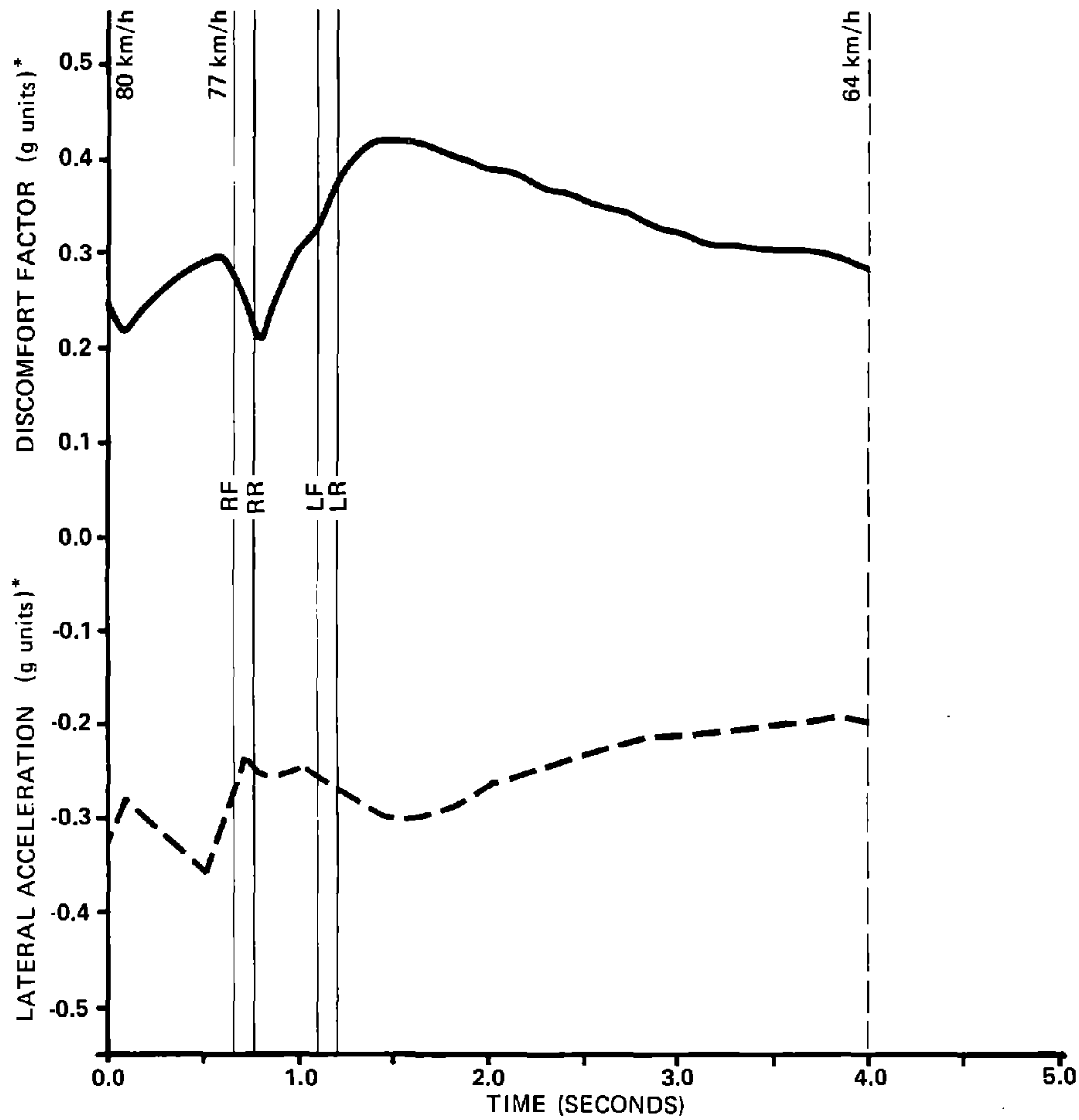
```
C SUBROUTINE SETD FOR HVOSM RD-2
C   ROUTINE TO SET DEGREE OF CURVATURE FROM DI'S
C
      SUBROUTINE SETD(KLI,DI,RLI,NPTS,DELL,D)
      DIMENSION DI(1),RLI(1),D(1)
C INITIALIZE
      L    = 1
      Z    = 0.0
      DELL2 = DELL*0.5
C START LOOP
      DO 10 N = 1,NPTS
      D(N) = DI(L)
      IF(L.EQ.KLI)GO TO 10
      IF(Z+DELL2.LT.RLI(L))GO TO 10
      D(N) = D(N) + (DI(L+1) - DI(L))*(Z - RLI(L) + DELL)
     1                         /(RLI(L+1) - RLI(L) + DELL)
      IF(Z+DELL2.GT.RLI(L+1))L = L + 1
   10 Z = DELL*FLOAT(N)
      RETURN
      END
```

Figure 12. Subroutine SETD

APPENDIX B

The following pages document representative output from the 13 HVOSM cross-slope break simulations. The following parameters apply:

Run CSB-16A
Initial Speed: 80 km/h
Roadway Radius: 210 m
Roadway Superelevation: 10 percent
Shoulder Slope: -4 percent
Vehicle Path Radius: 164 m -- four-wheel excursion



TEST CONDITIONS

Initial Speed -- 80 km/h

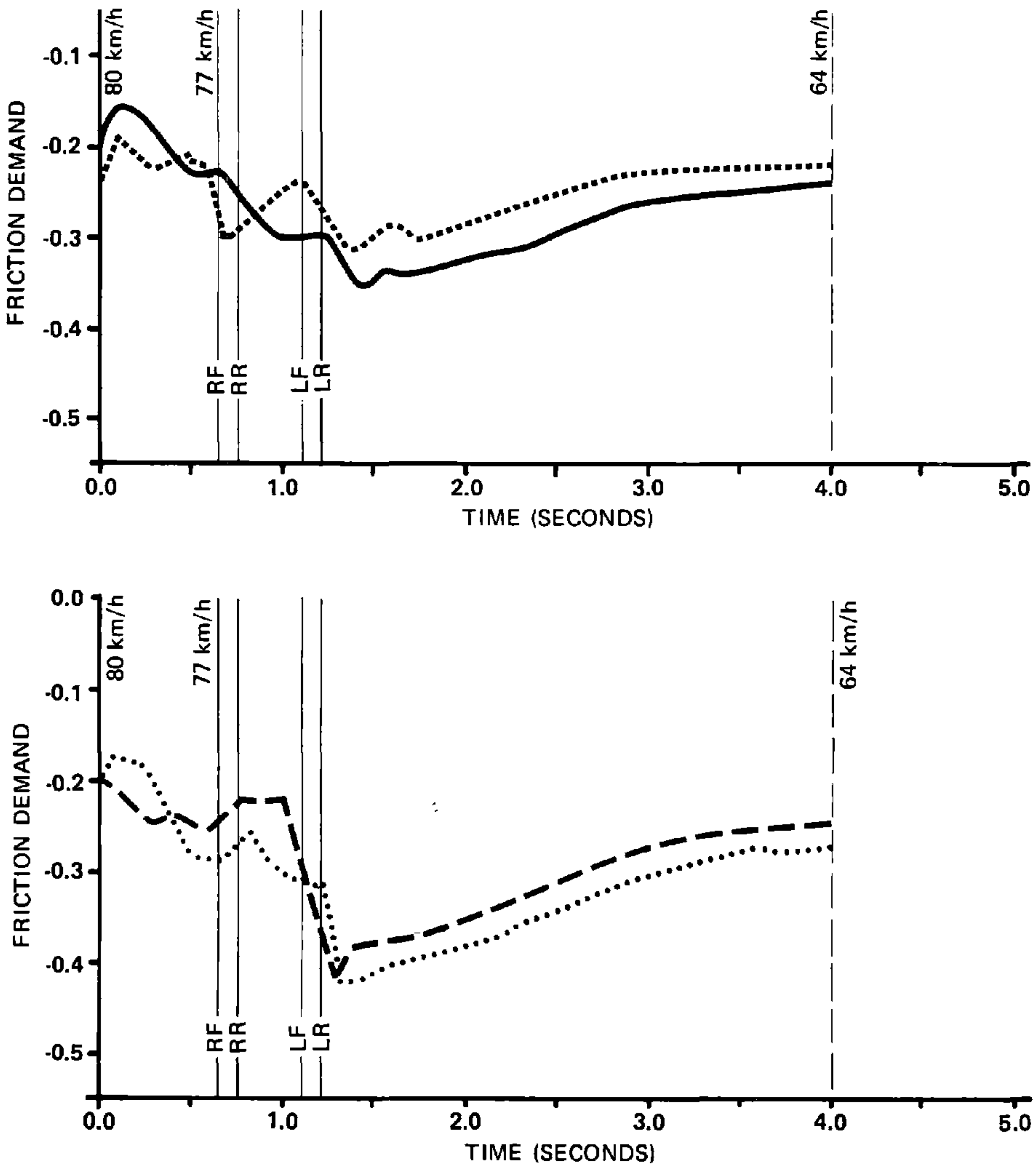
ROADWAY GEOMETRY		VEHICLE	
Centerline Radius	210 m	Path Radius	164 m
Superelevation	+10%	Probe Length	12.7 m
Shoulder Slope	--4%	P Gain	0.047 Rad/m
		Q Gain	0.004 Rad-sec/m
		Driveline Braking	1 m/s²

KEY

————	Lateral Acceleration
— — — —	Discomfort Factor
RF, RR, LF, LR	Denotes Time at Which Respective Tires Contact Cross-Slope Break

*Note: 1 g = 9.8 m/s²

Figure 13. Example HVOSM Output for Studies of Cross-slope Breaks---
Discomfort Factor and Lateral Acceleration vs. Time



TEST CONDITIONS

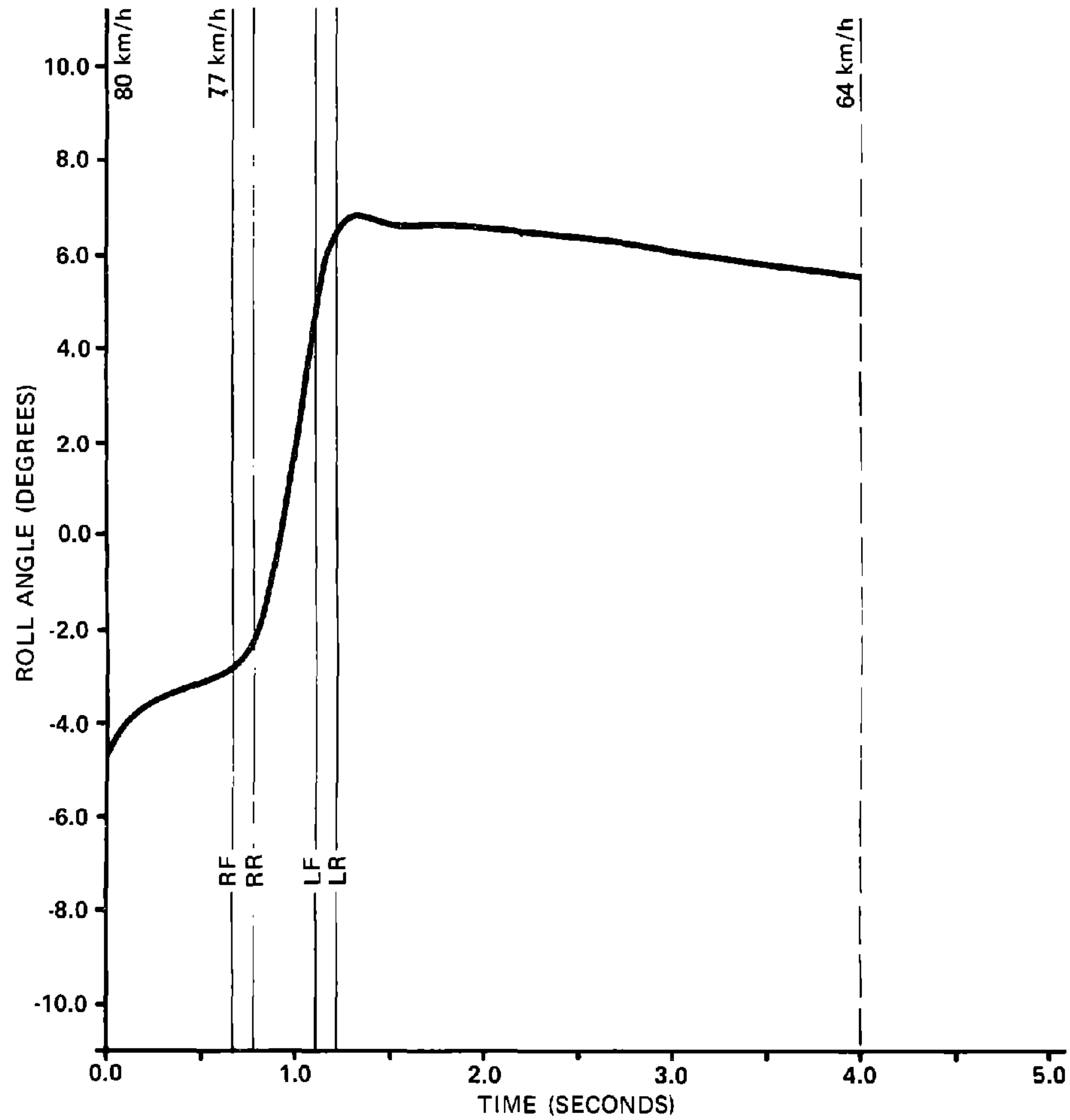
Initial Speed -- 80 km/h

ROADWAY GEOMETRY		VEHICLE	
Centerline Radius	210 m	Path Radius	164 m
Superelevation	+10%	Probe Length	12.7 m
Shoulder Slope	−4%	P Gain	0.047 Rad/m
		Q Gain	0.004 Rad-sec/m
		Driveline Braking	1 m/s²

KEY

■■■■■■■■■■■■■■■■	Right Front Tire
————————	Right Rear Tire
— — — — —	Left Front Tire
....	Left Rear Tire
RF, RR, LF, LR	Denotes Time at Which Respective Tires Contact Cross-Slope Break

Figure 14. Example HVOSM Output for Studies of Cross-slope Breaks—Tire Friction Demand vs. Time



TEST CONDITIONS

Initial Speed -- 80 km/h

ROADWAY GEOMETRY		VEHICLE	
Centerline Radius	210 m	Path Radius	164 m
Superelevation	+10%	Probe Length	12.7 m
Shoulder Slope	−4%	P Gain	0.047 Rad/m
		Q Gain	0.004 Rad-sec/m
		Driveline Braking	1 m/s²

KEY

RF, RR, LF, LR — Denotes Time at Which Respective Tires Contact Cross-Slope Break

Figure 15. Example HVOSM Output for Studies of Cross-slope Breaks---
Roll Angle vs. Time

*U.S. GOVERNMENT PRINTING OFFICE: 1982 522-046/8530 1-3

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

   Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

   Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

   Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

   Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

   Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

   This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

   This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

   This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.