HVOSM STUDIES OF CROSS-SLOPE BREAKS ON HIGHWAY CURVES

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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. The reported research, which constitutes one part
of a Federal Highway Administration program entitled "Effective-
ness of Design Criteria for Geometric Elements," (Contract No.
DOT-FH-11-9575) was performed by McHenry Consultants, Inc. for
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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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Design Criteria Shoulders Driver Performance Simulations Driver Reaction Highway Curves Highway Design	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

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Introduction

One of the considerations in the design of 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 0.07 m/m. This requirement has existed since 1954 and is consistent with the combination of the AASHTO pavement cross slope of 0.01 m/m for high-type surfaces and the maximum AASHTO shoulder cross slope of 0.08 m/m 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 0.06 m/m superelevation, the cross-slope break requirement limits the maximum negative shoulder cross slope to 0.01 m/m, 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 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 the radius of the highway curve, would decrease in radius until the vehicle reached maximum lateral offset where the path radius would be less than the highway curve radius, and would then increase in radius 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. The "design" path (see Figure 1) selected for this study would be circular, of smaller radius than the highway curve, and tangent to a concentric arc that is 0.5 m inside of the outside edge of shoulder. The path radius as a function of the highway curve radius was represented by the 95th percentile transient path measured in highway operational studies conducted by Glennon and Weaver (3). This relationship which was originally expressed in degrees of curve (English) translates to the following radius relationship.

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

R_v = 95th percentile vehicle path radius (meters)

R = highway curve radius (meters)

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 0.1 g engine braking.

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
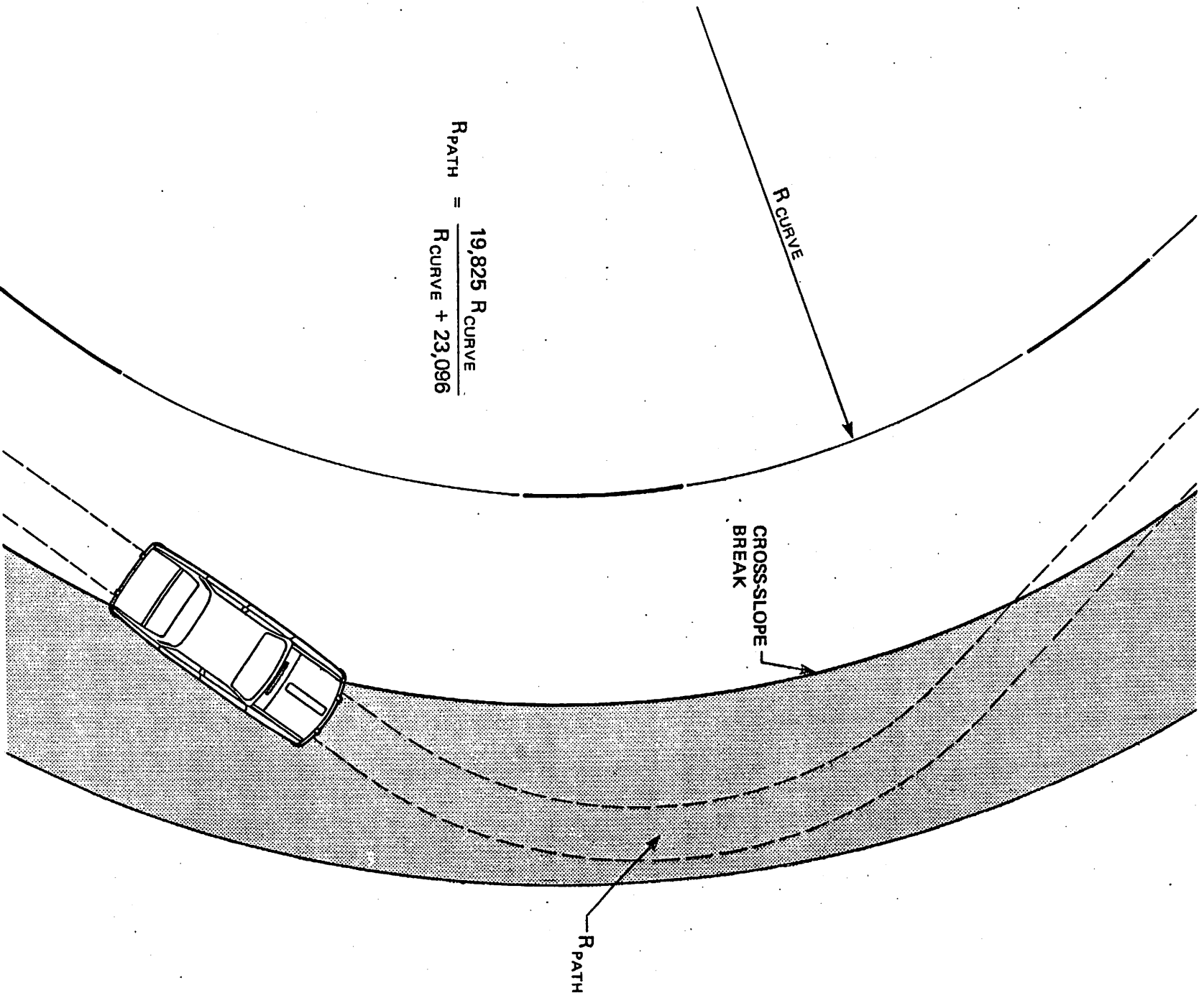
FIGURE 1 ASSUMED "DESIGN PATH" FOR ANALYSES OF TRAVERSALS ON CROSS-SLOPE BREAKS

$$R_{PATH} = \frac{19,825\ R_{CURVE}}{R_{CURVE} + 23,096}$$

R CURVE

CROSS-SLOPE BREAK

R PATH

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because intolerable centrifugal forces on the driver cause him to take actions (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 available skid resistance reasonably expected 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

friction demand and cornering friction demand may exceed available skid resistance. 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 accelerations of about 0.3 g in the speed range of 25-40 mph." (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 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 that 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 (100-120 km/h) highways would tend to reflect a lower overall threshold than measured on highways with moderate speeds, such as observed by Calspan.

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

VEHICLE ON SUPERELEVATED CURVE

$$f_D = a_l - g_l$$
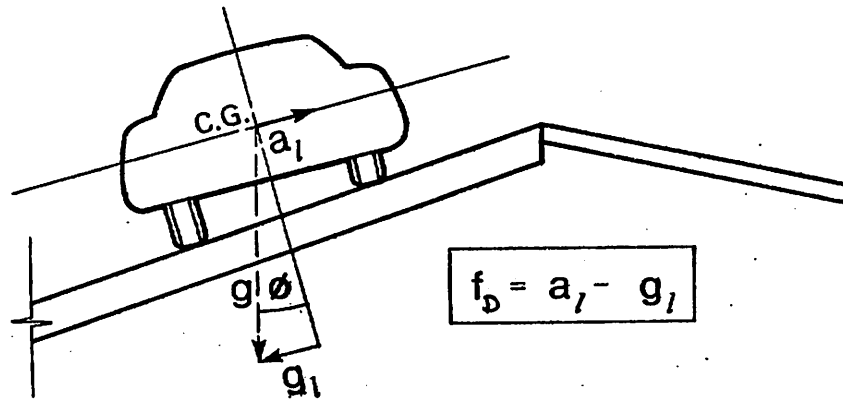
$\vec{f}_D$ = Discomfort Factor = $\vec{a}_l + \vec{g}_l$

Where:

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

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

ϕ = Roll Angle

a_l, g_l in Vehicle Fixed Coordinate System

VEHICLE ON SHOULDER WITH ADVERSE SLOPE

$$f_D = a_l + g_l$$
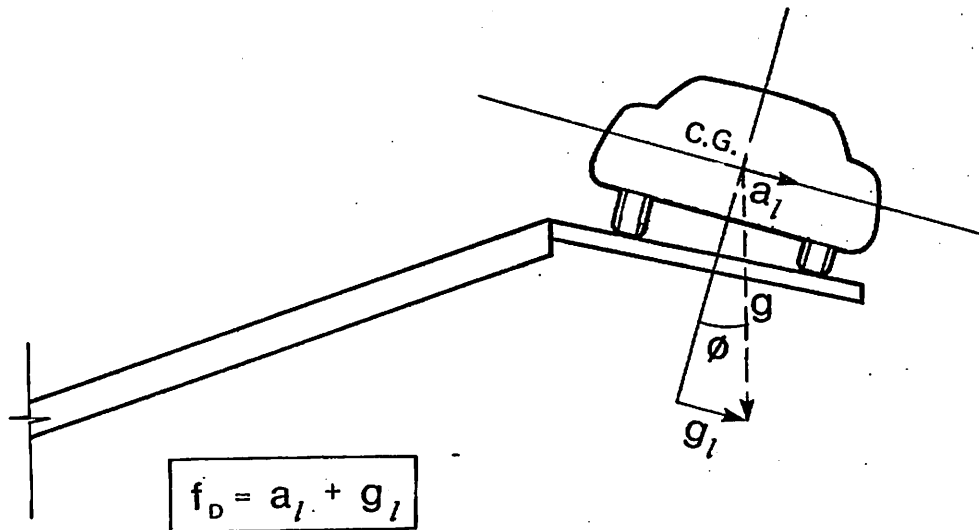
FIGURE 2   RELATIONSHIP BETWEEN DRIVER DISCOMFORT FACTOR AND
COMBINATION OF ROLL ANGLE AND LATERAL ACCELERATION

Of the five points discussed above, three support selection of a greater than 0.3 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 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 HVOSM (Highway-Vehicle-Object Simulation Model) is a computerized mathe-
matical 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

Because of FHWA contractual requirements, this study was conducted using
metric units. 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 metric 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

Table 1

HVOSM TEST CONDITIONS

Condition	Specification
Highway Curve Radius	Metricated AASHTO Controlling Curves (meters)
Superelevation	Metricated AASHTO Controlling Curves (.02 to .10 m/m)
Shoulder Width	2.7 meters
Shoulder Cross Slope	-.02 to -.06 m/m
Available Friction at Interface	0.8
Vehicle	1971 Dodge Coronet
Initial Vehicle Speed	Metricated Design Speed (kph)
Vehicle Deceleration	Engine Braking @ 0.1 g
Vehicle Path Radius	95th percentile measured by Glennon and Weaver
Vehicle Path Radius Tangent Point	2.2 meters from edge of traveled way

version for the upcoming edition of AASHTO Geometric Design Policy. These metricated controlling design curves are shown in Table 2.

Table 2

METRIC AASHTO CONTROLLING HORIZONTAL CURVES

Design Speed (kph)	Design f	Horizontal Curve Radius (Meters) Superelevation Rate (m/m)				
		.02	.04	.06	.08	.10
120	.092	1020	870	750	670	600
100	.116	-	510	450	410	370
80	.140	-	280	260	230	210
60	.152	-	150	140	130	120
40	.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 (kph)	Path Radius (meters) Superelevation Rate (m/m)				
	.02	.04	.06	.08	.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 .02, .04 and .06 m/m 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

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A full-width shoulder of 2.7 m with negative cross slopes of .02, .04 and .06 m/m 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 m/m
Negative Shoulder Slope	.06 m/m
Cross-slope Break	.16 m/m
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 (-.02, -.04, and -.06) 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 .02 increments from .04 to .16 m/m.

Table 4 also shows the results from the basic HVOSM runs. A complete 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.

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Table 4

HVOSM DYNAMIC RESPONSE RESULTS

| | TEST CONDITIONS | | | | | | TEST RESULTS | | |
Speed (kph)	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. Friction Demand (g)	Max. Roll Angle (°)
120	1020	586	.02	-.02	.04		.24	.20	3.6
120	1020	586	.02	-.06	.08		.30	.25	6.6
120	870	525	.04	-.04	.08		.32	.27	5.8
120	670	435	.08	-.04	.12		.35	.29	6.0
120	600	400	.10	-.02	.12		.37	.30	5.0
120	600	400	.10	-.06	.16		.43	.36	7.8
100	510	351	.04	-.02	.06		.29	.25	4.2
100	510	351	.04	-.06	.10		.35	.34	7.2
100	450	318	.06	-.04	.10		.38	.31	6.3
100	370	270	.10	-.04	.14		.38	.31	6.3
80	280	212	.04	-.04	.08		.31	.26	5.5
80	260	198	.06	-.02	.08		.28	.24	4.0
80	260	198	.06	-.06	.12		.36	.30	7.1
80	210	164	.10	-.04	.14		.41	.38	6.6

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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. Friction Demand(g)	Max. Roll Angle(°)
120	870	525	.04	-.04	Full	.32	.27	5.8
120	870	525	.04	-.04	Partial	.25	.23	1.4
100	510	351	.04	-.06	Full	.35	.34	7.2
100	510	351	.04	-.06	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. Friction Demand(g)	Max. Roll Angle(°)
120	510	351	.04	-.06	.49	.42	8.5
100	510	351	.04	-.06	.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} .02				.04				.06				.08				.10			
		SHOULDER SLOPE FOR GIVEN SUPERELEVATION--e_{sh}																			
		-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08
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

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

Table 8

SMOOTHED RESULTS* FOR DRIVER DISCOMFORT FACTOR-- FULL TRAVERSAL ON WIDE SHOULDERS

Design Speed (km/h)	Design Radius (m)	SUPERELEVATION OF ADJOINING TRAVERED WAY -- e_{tw}																			
		.02				.04				.06				.08				.10			
		SHOULDER SLOPE FOR GIVEN SUPERELEVATION -- e_{sh}																			
		-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08
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}

SHOULDER SLOPE FOR GIVEN SUPERELEVATION--e_{sh}

Design Speed (km/h)	Design Radius (m)	.02				.04				.06				.08				.10			
		-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08
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 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}																		
		.02				.04				.06				.08				.10			
		SHOULDER SLOPE FOR GIVEN SUPERELEVATION--e_{sh}																		
		-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08
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

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

Table 8

SMOOTHED RESULTS* FOR DRIVER DISCOMFORT FACTOR-- FULL TRAVERSAL ON WIDE SHOULDERS

		SUPERELEVATION OF ADJOINING TRAVERED WAY--e_{tw}																		
		.02				.04				.06				.08				.10			
		SHOULDER SLOPE FOR GIVEN SUPERELEVATION--e_{sh}																		
Design Speed (km/h)	Design Radius (m)	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08
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

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Table 9

SMOOTHED RESULTS FOR DRIVER DISCOMFORT FACTOR--PARTIAL TRAVERSAL ON WIDE SHOULDERS AND TRAVERSAL ON NARROW SHOULDERS

Design Speed (km/h)	Design Radius (m)	SUPERELEVATION OF ADJOINING TRAVELED WAY--e_{tw} .02				.04				.06				.08				.10			
		SHOULDER SLOPE FOR GIVEN SUPERELEVATION--e_{sh} -.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08	-.02	-.04	-.06	-.08
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

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Table 10

MAXIMUM NEGATIVE SHOULDER CROSS SLOPES
USING 0.30 g DISCOMFORT CRITERION

	Superelevation of Highway Curve, m/m						
Design Speed (km/h)	.08	.07	.06	.05	.04	.03	.02
	Maximum Negative Shoulder Cross Slope, m/m						
120	-	.00	.01	.02	.03	.04	.06
100	-	.00	.01	.02	.03	.04	.06
80	-	.00	.02	.02	.03	.04	.06
60	.00	.01	.02	.02	.03	.04	.06
40	.00	.01	.02	.02	.03	.04	.06

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 a 0.08 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 (<1.6m) SHOULDERS

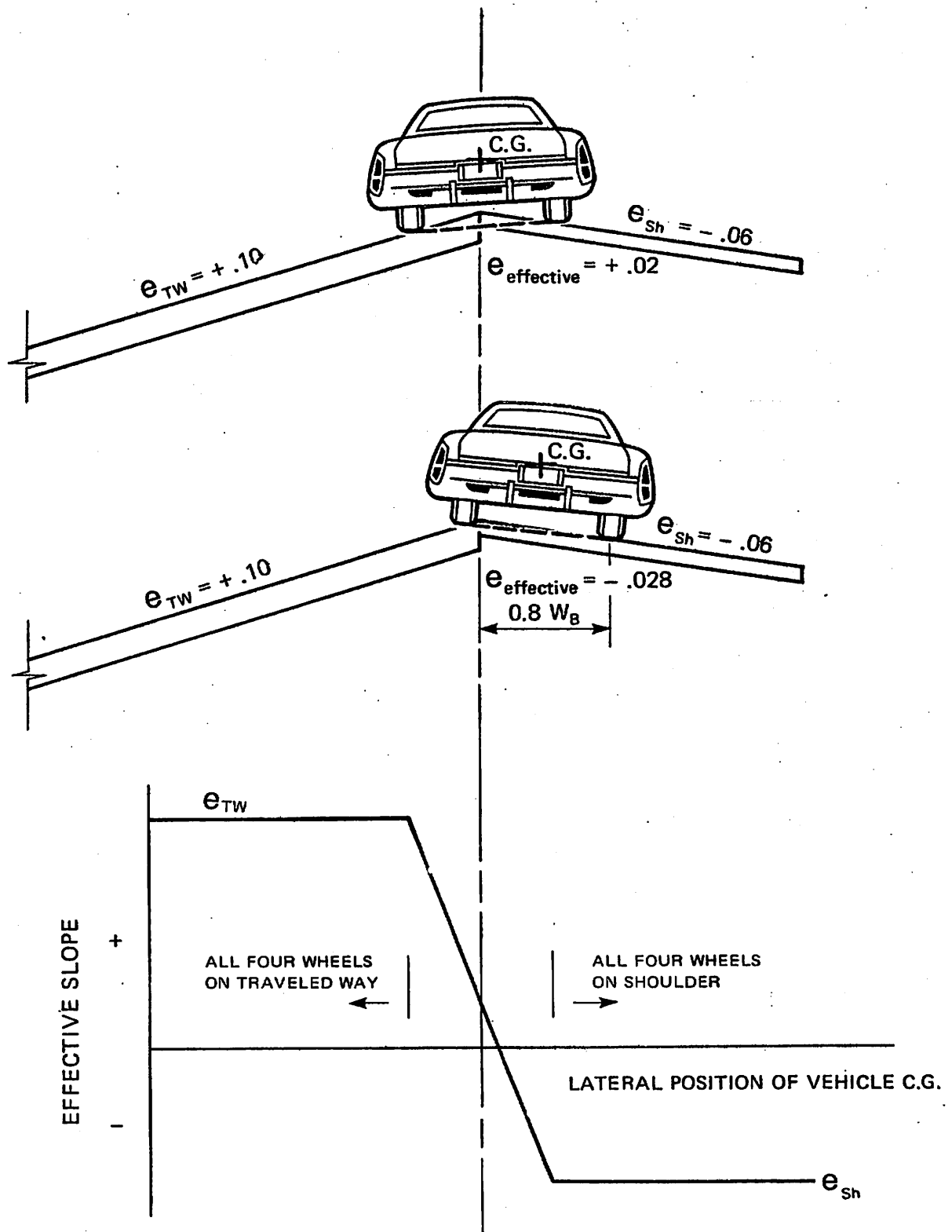| Shoulder Width(m)	Maximum Cross-Slope Break(m/m)
≤ 0.6	.18
0.8	.16
1.0	.14
1.2	.12
1.4	.10
1.6	.08

FIGURE 3   EFFECT OF VEHICLE LATERAL PLACEMENT
ON EFFECTIVE ADVERSE SHOULDER SLOPE

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Conclusions and Design Implications

1. <u>Shoulder Cross slope</u>.--The study results clearly show that the driver dis-
   comfort level (centrifugal acceleration) in negotiating shoulder traversals
   on curves is sensitive to speed, degree of curve, shoulder cross 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. Thus, for a given design speed, and superelevation of
   a horizontal curve, the maximum tolerable cross-slope break is a function
   of the shoulder cross slope; or in other words, the shoulder slope rather
   than the cross-slope break is the controlling feature.

   From the above discussion, as well as that dictated by logic and practical
   experience, the most important conclusion of this research is: where a
   negative shoulder cross slope is tolerable for a recovery maneuver, that
   shoulder cross slope should always be the minimum that is consistent with
   drainage requirements. This practice will minimize driver discomfort levels
   and maximize safety for drivers who need the shoulder as a secondary re-
   covery area.

2. <u>Cross-slope Break Requirements for Full Shoulders</u>.--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 0.08 m/m. For
   superelevation rates between 0.02 and 0.06 m/m, this criterion allows
   maximum (negative) shoulder cross slopes ranging from 0.06 to 0.02 m/m,
   respectively. For superelevation rates exceeding 0.06 m/m, a different
   kind of shoulder cross-slope design is required. The alternatives are to
   either carry the superelevation rate across the shoulder, or to continue
   this upward cross 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.

Top diagram labels:
$S_1 = +.02$ $S = -.04$
$S_{effective} = -.01$
$\Theta_{TW} = +.08$ to $+.10$
$1/2\ W_{Sh}$ $1/2\ W_{Sh}$

Middle diagram labels:
$S_1 = +.03$ $S_2 = -.03$
$S_{effective} = 0$
$e_{TW} = +.08$ to $+.10$
$1/2\ W_{Sh}$ $1/2\ W_{Sh}$

Bottom diagram labels:
$S_1 = +.03$ $S_2 = -.05$
$e_{TW} = +.08$ to $+.10$
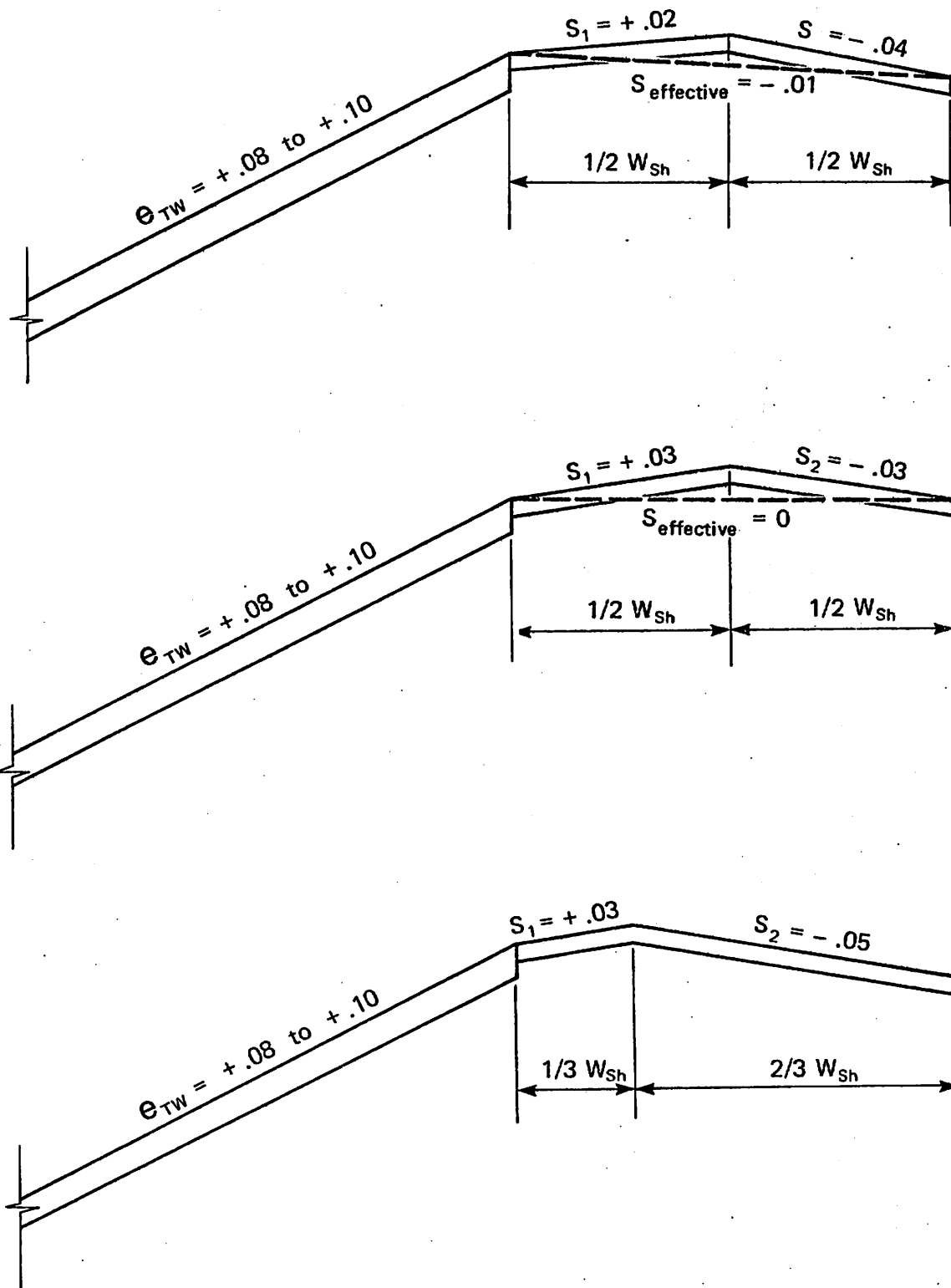$1/3\ W_{Sh}$ $2/3\ W_{Sh}$

FIGURE 4   BROKEN SHOULDER DESIGNS FOR FULL ($\geq$1.6 m) SHOULDERS

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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(m/m)
$\leq$ 0.6	0.18
0.8	0.16
1.0	0.14
1.2	0.12
1.4	0.10
1.6	0.08

Although these greater cross-slope breaks do not further compromise safety
beyond the implicit decision of choosing the narrower shoulder, Conclusion 1
regarding minimizing (negative) shoulder cross slope consistent with drainage
requirements should be strictly observed. Actually, if a smaller than maximum
cross-slope break is feasible, it will tend to compensate for the reduced
safety of the less than full shoulder width.

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 extreme or isolated 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 encroachments within the
shoulder) shoulder encroachments. In this case, the caveat expressed by
Conclusion 1 regarding minimum possible shoulder cross 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. <u>Special Considerations for Turf Shoulders</u>.--Because of greater cross slopes
   and lower wet surface skid resistance, turf shoulders present a dilemma in
   satisfying the proposed cross-slope break requirements. Not only can the
   AASHTO shoulder cross slope of -0.08 m/m not be met using the 0.08 m/m
   cross-slope break recommendation for superelevated curves, but also for the
   path criterion used in this research, even a 0.02 m/m cross slope on a turf
   shoulder with a 0.25 wet coefficient of friction will produce skidding.

   What this discussion suggests is that turf shoulders on the outside of
   highway curves must either have a positive cross slope or have paved or
   gravel surfaces with allowable negative cross slopes.

   Another implication of this discussion is the unsuitability of turf shoulders
   on tangent sections of higher speed roadways. For example, on a 100 km/h
   roadway, a wet turf shoulder with a cross slope of -0.08 m/m and a co-
   efficient 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, high-speed
   tangent sections should 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.

5. <u>Implications for Roadside Slopes on Highway Curves</u>.--The dynamic responses
   observed with HVOSM for negative shoulder cross slopes up to -0.06 m/m
   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 road-
   side 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. <u>Considerations for Underdesigned Existing Highway Curves</u>.--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 cross slope to carry the superelevation across the shoulder may be a worthwhile accident countermeasure at such locations.

7. <u>Consideration of Trucks in Design</u>.--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 tractor-semi-trailer 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 must 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.

References

1. American Association of State Highway Officials, "A Policy on Geometric Design of Rural Highways," 1954.

2. American Association of State Highway Officials, "A Policy on Geometric Design of Rural Highways," 1965.

3. Glennon, J.C. and Weaver, G.D., "Highway Curve Design for Safe Vehicle Operations," Highway Research Record No. 390, 1972.

4. Rice, R.S. and Dell, Amico F., "An Experimental Study of Automobile Driver Characteristics and Capabilities," Calspan Report No. ZS-5208-k-1, March 1974.

5. Wright, Paul H., and Zador, Paul, "A Study of Fatal Rollover Crashes in Georgia," for presentation at the Annual Transportation Research Board Meeting, January 1981.

6. Hall, Jerome W, and Zador, Paul, "A Survey of Fatal Overturning Crash Sites," for presentation at the Annual Transportation Research Board Meeting, January 1981.

7. McHenry, R.R., Deleys, N.J., "Vehicle Dynamics in Single Vehicle Accidents--Validation and Extensions of a Computer Simulation," CAL Report No. VJ-2251-3, Contract No. CPR-11-3988, December 1968.

8. McHenry, R.R., "The Astro Spiral Jump--An Automobile Stunt Designed via Simulation," SAE Paper No. 7600339, Automotive Engineering Congress and Manufacturing Meeting, October 18-33, 1976.

9. McHenry, R.R., Deleys, N.J., "Automobile Dynamics--A Computer Simulation of Three-Dimensional Motions for Use in Studies of Braking Systems and of the Driving Task," CAL Report No. VJ-2251-V7, Contract No. CPR-11-3988, August 1970.

10. Segal, D.J., Ranney, T.A., "Evaluation of Horizontal Curve Requirements," Final Report No. FHWA-RD-79-48, October 1978.

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 (equation (44), page 192 of Reference 7; equation (61), page 104 of Reference 9).

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 A-1). 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 A-2) 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:
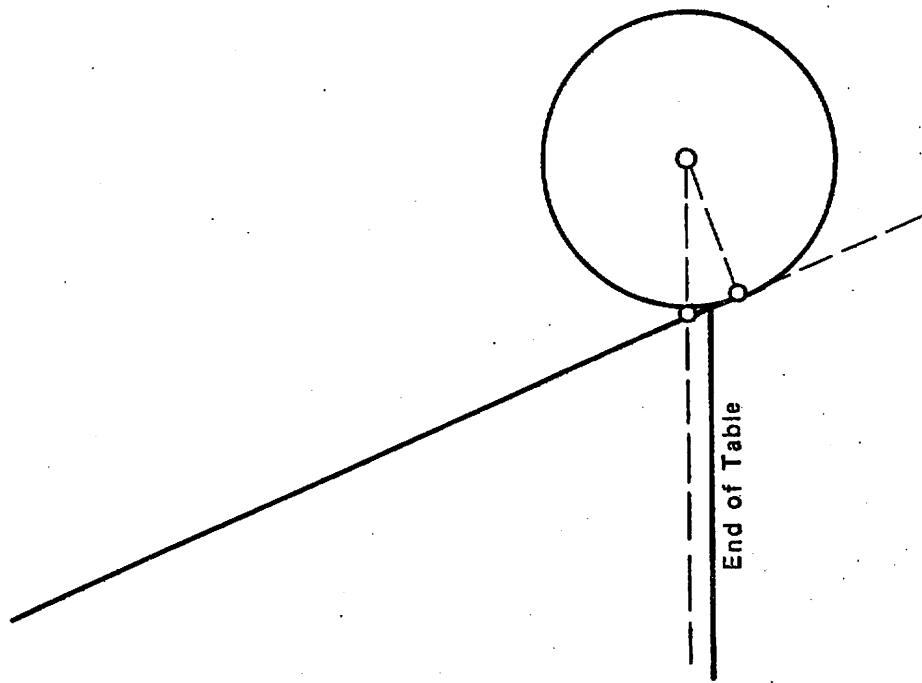
End of Table

FIGURE A1 ILLUSTRATION OF ERRONEOUS EXTENSIONS OF ENDS OF RAMPS
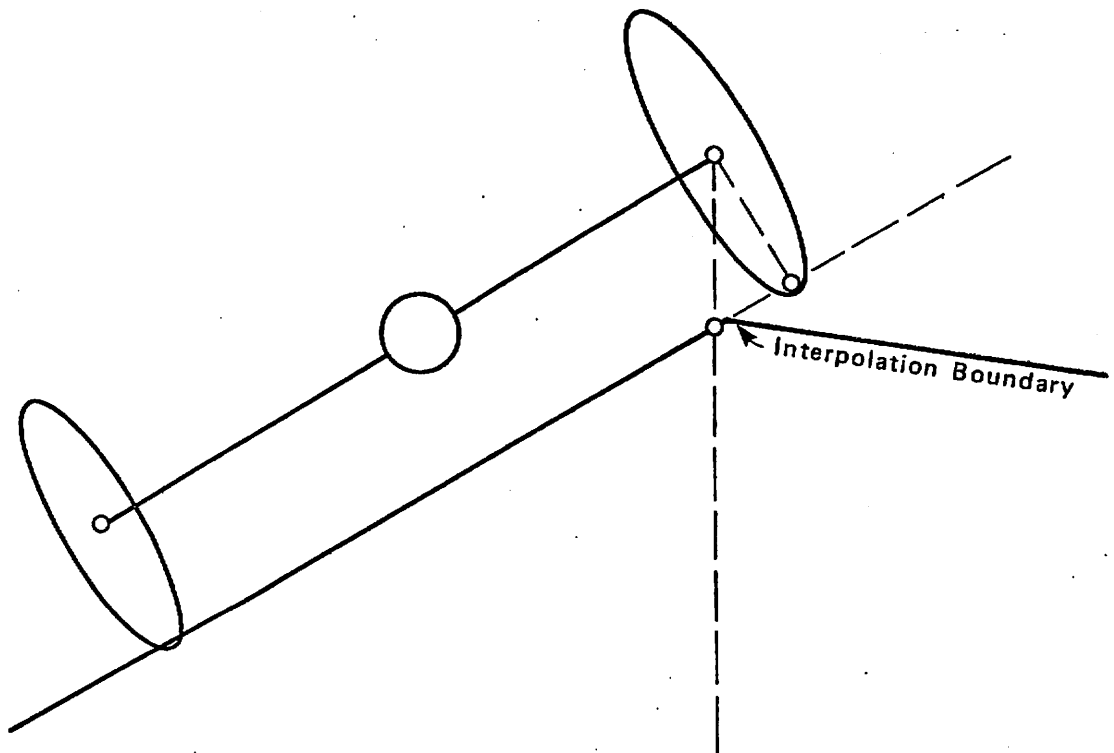

Interpolation Boundary

FIGURE A2 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 sub-
sequent 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         = PX(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

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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:

$$\text{DISCOMFORT FACTOR} = -\text{YLAT} + 1.0 * \text{SIN } \emptyset$$

where: DISCOMFORT FACTOR = G-units

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

$\emptyset$ = Vehicle roll angle, radians.

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

2. <u>Friction Demand</u>.--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.

<u>Terrain Table Generator</u>

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-bene-
ficial 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 Refer-
ence 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. Damping

   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. 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 A-10.

Table A-1 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 A-1

CROSS-SLOPE BREAK STUDY DRIVER INPUTS

Run No.	Speed Ft/Sec	Vehicle Path Ft	Path V^2/R G-Units	Break %	PGAIN Deg/Ft	QGAIN Deg-Sec/Ft	Probe Length Ft
CSB1	109.0	1312.3	.28	12	.516	.034	103.
CSB2	109.0	1312.3	.28	16	.516	.034	103.
CSB3A	109.0	1427.2	.26	12	.254	.027	54.2
CSB6A	109.0	1722.4	.21	8	.165	.017	102.7
CSB7	109.0	1922.6	.19	4	.516	.034	103.0
CSB8	109.0	1922.6	.19	8	.516	.034	103.0
CSB9B	91.0	885.8	.29	14	.413	.027	60.0
CSB12A	91.0	1043.3	.25	10	.523	.055	43.3
CSB13A	91.0	1151.6	.22	6	.447	.034	60.0
CSB14C	91.0	1151.6	.22	10	.447	.034	60.0
CSB14PA	109.0	1151.6	.32	10	.344	.034	78.3
CSB14PP	91.0	1151.6	.22	10	.447	.034	60.0
CSB16A	73.0	538.6	.31	14	.825	.069	41.7
CSB18D3	73.0	649.6	.25	8	1.06	.138	40.0
CSB19D2	73.0	649.6	.25	12	1.06	.000	40.0
CSB20A	73.0	695.5	.24	8	.894	.089	41.7

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    -1.50      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
   -7.03   -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 A3   EXAMPLE CARD IMAGE

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```
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   51.53   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 8949.12 11949.12 300.00 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
```

```
 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

```
05710 C SUBROUTINE DRIVER FOR HVOSM RD-2
05720 C
05730       SUBROUTINE DRIVER(PSI,DPSI,JJ,IFLAG,A,B,AMTX,OMGPS)
05740       DIMENSION AMTX(3,3),PPD(50),TPD(50)
05750       COMMON/PATHD/IPATH,KLI,DI(10),RLI(10),NPTS,XINIT,YINIT,
05760      1       PSA,DELL,X(100),Y(100),DX(100),DY(100),D(100)
05770       COMMON/WAGON/IWAGN,TPRB,DPRB,PLGTH,PMIN,PMAX,PGAIN,QGAIN,PSIFD
05780       COMMON/FILT/ IFILT,TIL ,TI ,TMT ,TAUF
05790       COMMON/INTG/ NEQ ,T ,DT ,VAR(50),DER(50)
05800       COMMON/ACC/CMFCG,CMFA1,CMFA2
05810       DATA NPDMAX/50/,NPD/0/,DPSL/0.0/,N/0/
05820       JJ  = 0
05830       IF(IWAGN.EQ.0)GO TO 90
05840       JJ  = 1
05850       PSIA = PSI
05860       DTP  = 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) + AMTX(1,1)*PLGTH
05940       YP = VAR(19) + AMTX(2,1)*PLGTH
05950       CALL PROBE(XP,YP,NPTS,X,Y,DX,DY,D,IPRB,DIST,XX,YY)
05960 C  SELECTED POINT INDEX IPRB AND LOCATION OF CLOSEST POINT ON PATH XX,YY
05970 C  ARE NOT CURRENTLY USED
05980       IF(DIST.EQ.0.0)GO TO 8
05990       SGND=DIST/ABS(DIST)
06000       IF(T.NE.TPRB) DDIST = (DIST-DISTA)/DPRB
06010  9    IF(ABS(DIST).GT.PMIN)DPS = -PGAIN*(ABS(DIST)-PMIN)*SGND
06020      1                       -QGAIN*DDIST
06030  8    IF(ABS(DIST).LE.PMIN) DPS= -QGAIN*DDIST
06040       IF(IFILT.EQ.0)GO TO 55
06050       IF(NPD.EQ.NPDMAX)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.NPDMAX) GO TO 10
06140       TPDTMP = 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(TPDTMP.LT.TPD(N)) DPSL = 0.0
06200       DPSI = PPD(N)*TMT*EXP(-(T - TPD(N))/TIL)/TIL
06210       DPSN = PPD(N) - TIL*DPSI
06220       DTP  = 0.0
06230       DPS  = DPSN - DPSL
06240       DPSL = DPSN
06250       IF(NPD.EQ.1)GO TO 50
06260 C
06270 C
```

FIGURE A4   SUBROUTINE DRIVER
42

```
06280  35  L    = 1
06290          DO 40 NN = N,NPD
06300          PPD(L) = PPD(NN)
06310          TPD(L) = TPD(NN)
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(CMFA1).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((OMGPS.GT.0.0).AND.(ABS(PSI) .GT.  OMGPS))
06460      1   PSI = SIGN(OMGPS,PSI)
06470          IF(DTP.NE.0.0)DPSI = (PSI-PSIA)/DTP
06480 C***    1/16/81   MCI   ****************************************
06490          DPSO = DPS*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          XXFT = XX/12.0
06560          YYFT = YY/12.0
06570 C     IF(FKD.EQ.1.0) GO TO 90
06580          IF(KPAGE.LE.50.AND.T.NE.0.0000) GO TO 110
06590          WRITE(50,100)
06600     100 FORMAT(
06610      A1H1,33X,37HPROBE COORDINATES    PATH COORDINATES,5X,3HPSI,6X,
06620      B3HDPS,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(50,120) T,DELPSI,DIST,XPFT,YPFT,XXFT,YYFT,PSIO,DPSO,
06680      A                PSIAO,DPSI,DPSN,IFLAG,IPRB
06690     120 FORMAT(1H ,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,I3,2X,I2)
06710          KPAGE = KPAGE + 1
06720      90 RETURN
06730 C*****************************************************************
06740          END
06750 C*****************************************************************
```

FIGURE A4 (Continued)

```
133100 C  SUBROUTINE PATH:  PATHM.FOR
133200 C    PATH GENERATOR  HVOSM RD-2
133300      SUBROUTINE PATH
133400      COMMON/PATHD/IPATH ,KLI ,DI(10),RLI(10),
133500     1            NPTS,XINIT,YINIT,PSA,DELL,
133600     2            X(100),Y(100),DX(100),DY(100),D(100)
133700 C LIMIT ARRAY SIZES
133800      IF(KLI.GT.10)KLI = 10
133900      IF(NPTS.GT.100)NPTS = 100
134000      CALL SETD(KLI,DI,RLI,NPTS,DELL,D)
134100 C SETD WAS MODIFIED ON 30 DEC 1980 TO PRODUCE SPIRAL
134200 C INITIALIZE FIRST POINT AND TANGENT
134300      X(1) = XINIT
134400      Y(1) = YINIT
134500      DX(1) = COS(PSA)
134600      DY(1) = SIN(PSA)
134700 C
134800      CALL PATHG(NPTS,DELL,X,Y,D,DX,DY)
134900 C
135000      RETURN
135100 C******************************************************************
135200      END
```

FIGURE A5   SUBROUTINE PATH

```
135400 C PATHG
135500 C    PATH GENERATOR, SUBROUTINE PATHG
135600 C
135700        SUBROUTINE PATHG(NPTS,DELL,X,Y,D,DX,DY)
135800        DIMENSION X(1),Y(1),DX(1),DY(1),D(1)
135900        DATA RAD/0.017453292519943296/
136000 C INITIALIZE
136100        CONS = DELL*RAD/200.0
136200 C*
136300        DXX  = DELL*DX(1)
136400        DYY  = DELL*DY(1)
136500 C*
136600        DS1  = 0.0
136700        DC1  = 1.0
136800 C START LOOP
136900        DO 20 I = 2, NPTS
137000 COMPUTE SINE AND COSINE OF HALF SECTOR ANGLE
137100        DS2  = CONS*D(I-1)
137200        DC2  = SQRT((1.0-DS2)*(1.0+DS2))
137300 C**
137400 COMPUTE SINE AND COSINE OF SECTOR ANGLE
137500        SP   = 2.0*DS2*DC2
137600        CP   = 1.0 - 2.0*DS2**2
137700 C UPDATE TANGENT VECTOR
137800        DX(I) =  CP*DX(I-1) - SP*DY(I-1)
137900        DY(I) =  SP*DX(I-1) + CP*DY(I-1)
138000 C**
138100 COMPUTE SINE AND COSINE OF AVERAGE SECTOR ANGLE
138200        SP   =    DS1*DC2 + DC1*DS2
138300        CP   =    DC1*DC2 - DS1*DS2
138400 COMPUTE NEW INCREMENTS
138500        DXS  = DXX
138600        DXX  = DXS*CP  - DYY*SP
138700        DYY  = DXS*SP  + DYY*CP
138800 C UPDATE POSITION
138900        X(I)  =  X(I-1)  + DXX
139000        Y(I)  =  Y(I-1)  + DYY
139100 C SAVE SINE AND COSINE OF HALF SECTOR ANGLE FOR NEXT I
139200        DS1  =  DS2
139300     20 DC1  =  DC2
139400        RETURN
139500 C
139600 C
139700 C
139710        END
```

FIGURE A6   SUBROUTINE PATHG

```
140800 C PROBE
140900 C SUBROUTINE PROBE:  CALCULATES DISTANCE OF A POINT FROM CENTERLINE
141000 C
141100       SUBROUTINE PROBE(XP,YP,M,X,Y,DX,DY,D,I,DIST,XX,YY)
141200       DIMENSION X(1),Y(1),DX(1),DY(1),D(1)
141300       DATA RAD/0.0174532925199432296/,ILAST/1/
141400 C INITIALIZE
141500       I    = ILAST
141600       TEST = DX(I)*(XP-X(I))+DY(I)*(YP-Y(I))
141700       TSAV = SIGN(1.0,TEST)
141800       GO TO 15
141900 C
142000 C START SEARCH
142100 C
142200     7 I = I + 1
142300       IF(I.LE.M)GO TO 10
142400       IF(TSAV.LT.0.0)GO TO 20
142500       I = M
142600       GO TO 25
142700    10 TEST = DX(I)*(XP-X(I))+DY(I)*(YP-Y(I))
142800       IF(TEST*TSAV.LE.0.0)GO TO 25
142900    15 IF(TEST)20,25,7
143000    20 I = I - 1
143100       IF(I.GE.1)GO TO 10
143200       IF(TSAV.GT.0.0)GO TO 7
143300       I = 1
143400 C
143500 C FINISH SEARCH
143600    25 IF((TEST.LT.0.0).AND.(I.GT.1))I=I-1
143700       ILAST = I
143800 C FINISH OF DETERMINATION OF I
143900 C
144000 C
144100 C
144200 C
144300 CALCULATE DISTANCE
144400       ZDN  = -DY(I)*(XP-X(I))+DX(I)*(YP-Y(I))
144500       CONS = D(I)*RAD*0.005
144600       ZDZ  = ((XP-X(I))**2+(YP-Y(I))**2)*CONS
144700       DIST = (ZDN-ZDZ)/(0.5+SQRT(0.25-CONS*(ZDN-ZDZ)))
144800 C
144900 CALCULATE POSITION OF CLOSEST APPROACH POINT ON ARC
145000 C THE FOLLOWING CODE MAY BE DELETED AND THE REFERENCES TO XX AND YY TAKE
145100 C OUT OF THE CALL IF THE POINT OF CLOSEST APPROACH ON THE ARC IS NOT NEE
145200 C
145300       DEN = 1.0-2.0*DIST*CONS
145400 C
145500       IF(DEN.GT.0.0)GO TO 30
145600       WRITE(6,26)I,XP,YP,DIST,DEN
145700    26 FORMAT(' SUBROUTINE PROBE HAS NEGATIVE OR ZERO DENOMINATOR'/
145800       X' IN POSITION FORMULA: IMPLIES POINT NOT IN SECTOR'/I6,4F10.4)
145900       STOP
146000 C THIS STOP SHOULD NEVER OCCUR IN NORMAL USAGE
146100 C
146200    30 XX = (XP-X(I)+DIST*DY(I))/DEN + X(I)
146300       YY = (YP-Y(I)-DIST*DX(I))/DEN + Y(I)
146400    35 RETURN
146500 C********************************************************************
146600       END
```

FIGURE A7   SUBROUTINE PROBE

```
146800 C SUBROUTINE SETD FOR HVOSM RD-2
146900 C   ROUTINE TO SET DEGREE OF CURVATURE FROM DI'S
147000 C
147100       SUBROUTINE SETD(KLI,DI,RLI,NPTS,DELL,D)
147200       DIMENSION DI(1),RLI(1),D(1)
147300 C INITIALIZE
147400       L    = 1
147500       Z    = 0.0
147600       DELL2 = DELL*0.5
147700 C START LOOP
147800       DO 10 N = 1,NPTS
147900       D(N) = DI(L)
148000       IF(L.EQ.KLI)GO TO 10
148100       IF(Z+DELL2.LT.RLI(L))GO TO 10
148200       D(N) = D(N) + (DI(L+1) - DI(L))*(Z - RLI(L) + DELL)
148300     1                          /(RLI(L+1) - RLI(L) + DELL)
148400       IF(Z+DELL2.GT.RLI(L+1))L = L + 1
148500    10 Z = DELL*FLOAT(N)
148600       RETURN
148700       END
```

FIGURE A8 SUBROUTINE SETD

The following pages document representative output from the 13 HVOSM cross-slope break simulations. The following parameters apply:
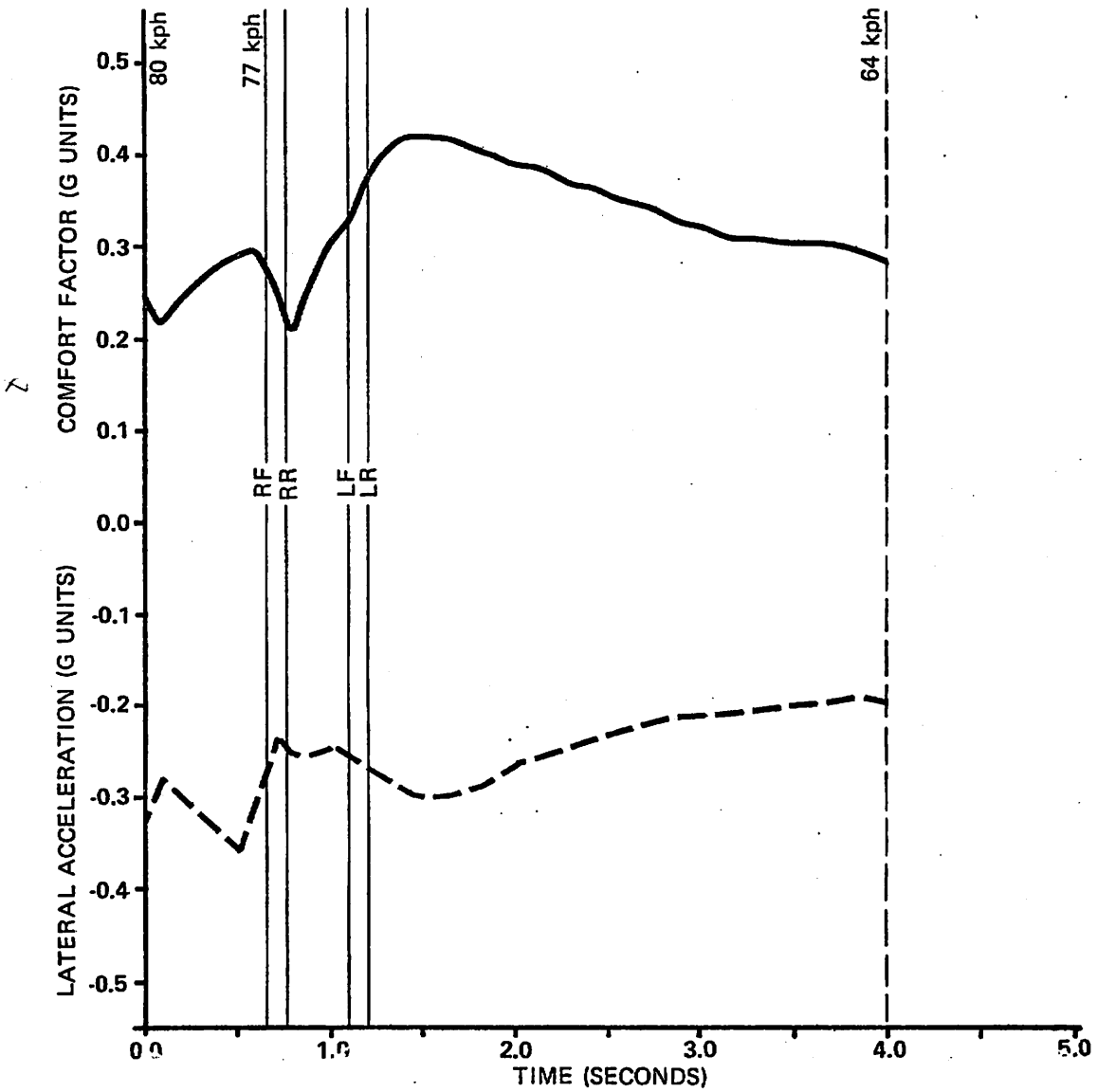
Run CSB-16A

Initial Speed: 80 km/h

Roadway Radius: 210 m

Roadway Superelevation: .10

Shoulder Slope: -.04

Vehicle Path Radius: 164 m -- four-wheel excursion

FIGURE B1   EXAMPLE HVOSM OUTPUT FOR STUDIES OF CROSS-SLOPE BREAKS ---
DISCOMFORT FACTOR AND LATERAL ACCELERATION VS. TIME

49

**FIGURE B2   EXAMPLE HVOSM QUTPUT FOR STUDIES OF CROSS-SLOPE BREAKS ---
TIRE FRICTION DEMAND VS. TIME**

50
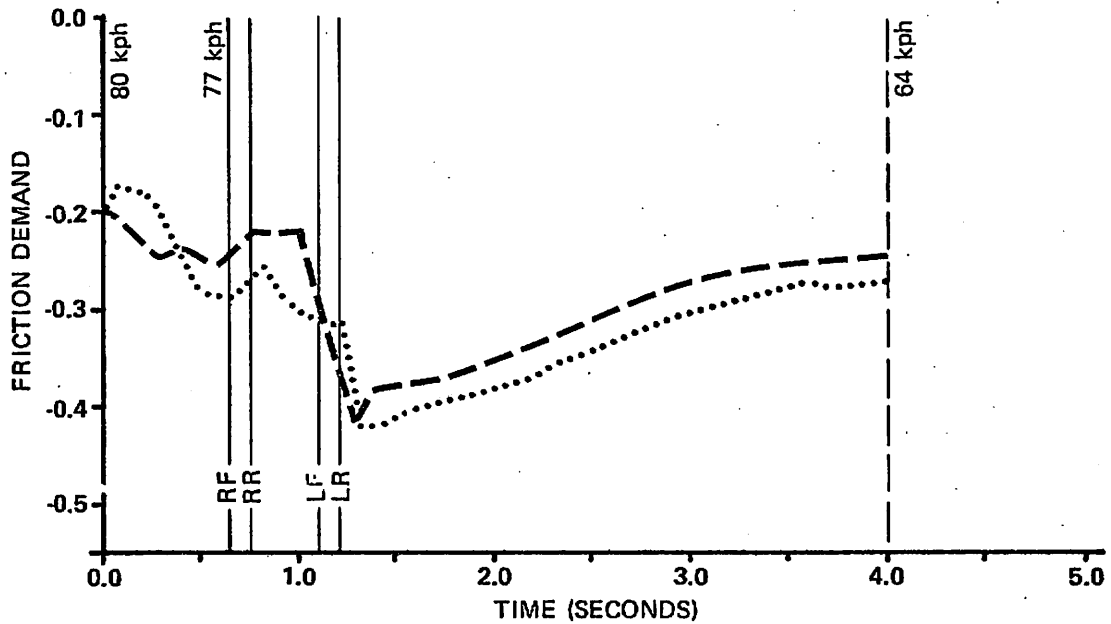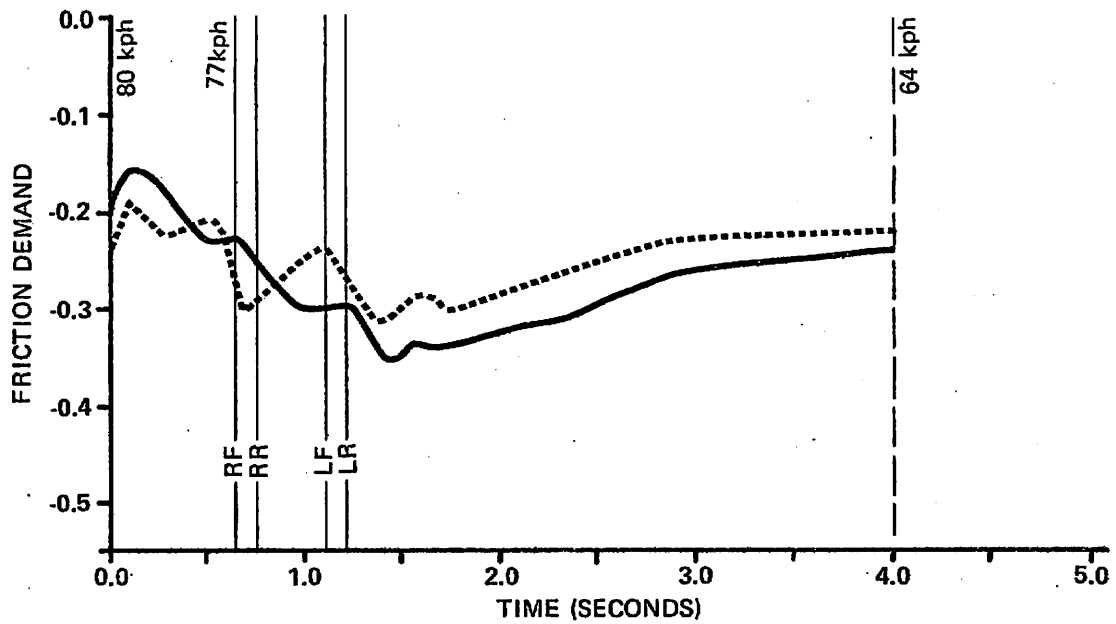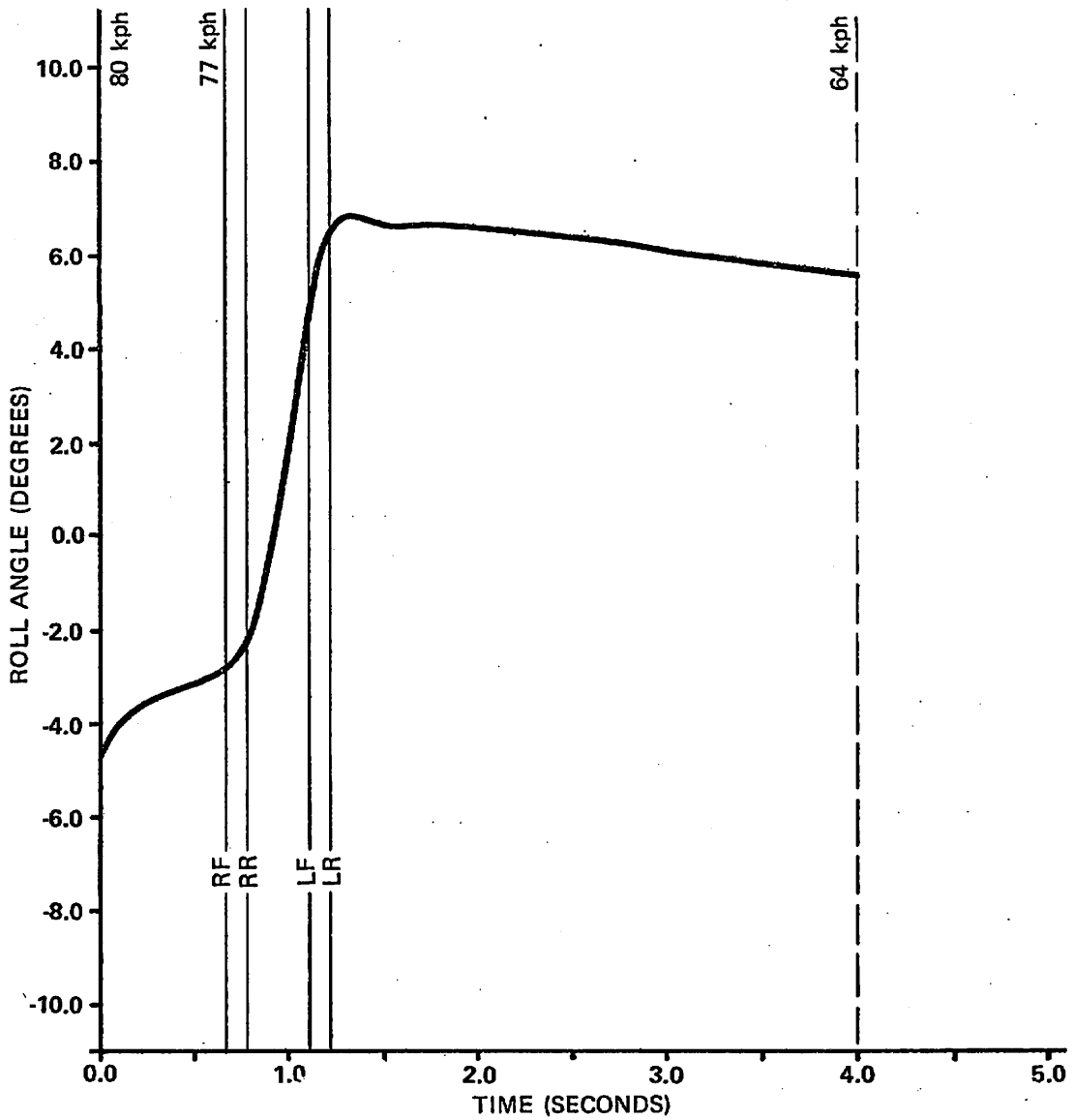
TEST CONDITIONS

Initial Speed -- 80 kph

ROADWAY GEOMETRY

Centerline Radius	210 m
Superelevation	0.10 m/m
Shoulder Slope	-0.04 m/m

VEHICLE

Path Radius	164 m
Probe Length	1270 cm
P Gain	0.00047 Rad/cm
Q Gain	0.00004 Rad-sec/cm
Driveline Braking	0.1 G

KEY

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

FIGURE B3   EXAMPLE HVOSM OUTPUT FOR STUDIES OF CROSS-SLOPE BREAKS ---
ROLL ANGLE VS. TIME

NO. 341-20 DIETZGEN GRAPH PAPER
20 X 20 PER INCH

DIETZGEN CORPORATION
MADE IN U.S.A.

COMFORT FACTOR, LATERAL ACCELERATION VS TIME

RUN: CSB16A		
DATE: 4/27/81		
SPEED: 80 KPH		KPH
M×: 0.78		
ROAD:		
RADIUS: 210.0	METERS	
	8.32	DEGREES
SE: 10.0		%
SHOULDER: -4.0		%
VEHICLE PATH:		
RADIUS: 164.0	METERS	
	10.65	DEGREES
PROBE: 1270.0	CM	
P GAIN: 0.00047	RAD/CM	
O GAIN: 0.00004	RAD-SEC/CM	
DRIVELINE		
BRAKING: -0.16 G'S		

McHENRY
CONSULTANTS, INC.
FH-11-9575

LATERAL ACCEL
COMFORT FACTOR

TIME (SECONDS)

COMFORT FACTOR (UNITS)   LATERAL ACCELERATION (G's)

RF, RR Friction Demand vs Time

RUN: CSB-16A
DATE: 4/27/81
SPEED: 80.0 KPH
μ: 0.78
ROAD:
RADIUS: 210.0 METERS
8.32 DEGREES
SE: 10.0 %
SHOULDER: -4.0 %
VEHICLE PATH:
RADIUS: 164.0 METERS
10.65 DEGREES
PROBE: 1270.0 CM
P.GAIN: 0.00047 RAD/CM
Q.GAIN: 0.0004 RAD.SEC/CM
DRIVELINE
BRAKING: -0.1 G's

McHENRY CONSULTANTS, INC.
FH-11-9575

RF
RR

80 KPH   77 KPH   64 KPH

TIME (SECONDS)

DIETZGEN CORPORATION
MADE IN U.S.A.

NO. 341-20 DIETZGEN GRAPH PAPER
20 X 20 PER INCH

FLLR Friction Demand vs Time

FRICTION DEMAND

TIME (SECONDS)

80 km/h   77 kph   64 kph

RF RR LF LR

Run:	CSB-16A
Date	4/27/81
Speed:	80.0 KPH
μ	0.78

Road:
Radius:	210.0 METERS
SE	8.32 DEGREES
Shoulder	10.0 %
	-4.0 %

Vehicle Path:
Radius:	164.0 METERS
	10.65 DEGREES
Probe	1270.0 CM
P Gain	0.00047 RAD/CM
Q Gain	0.0004 RAD-SEC/CM
Driveline	
Braking:	=0.1 G's

McHENRY CONSULTANTS, INC.

FH-11-9575

ROLL ANGLE VS TIME

ROLL ANGLE (DEGREES)

80KPH
77 KPH
64 KPH

TIME (SECONDS)

RUN CSB-16A
DATE: 4/27/81
SPEED: 80.0 KPH
M 0.78

ROAD:

RADIUS: 210.0 METERS
8.32 DEGREES
SE: 10.0 %
SHOULDER: -4.0 %

VEHICLE PATH:
RADIUS: 164.0 METERS
10.65 DEGREES
PROBE: 1270.0 CM
P GAIN: 0.00047 RAD/CM
Q GAIN: 0.00004 RAD-SEC/CM
DRIVELINE
BRAKING: -0.1 G's

MCHENRY
CONSULTANTS, INC.

FH-11-9575

STEER ANGLE VS TIME

RUN: OSB-16A
DATE: 4/27/21
SPEED: 80.0 KPH
μ: 0.78

ROAD:

RADIUS: 210.0 METERS
θ: 8.32 DEGREES
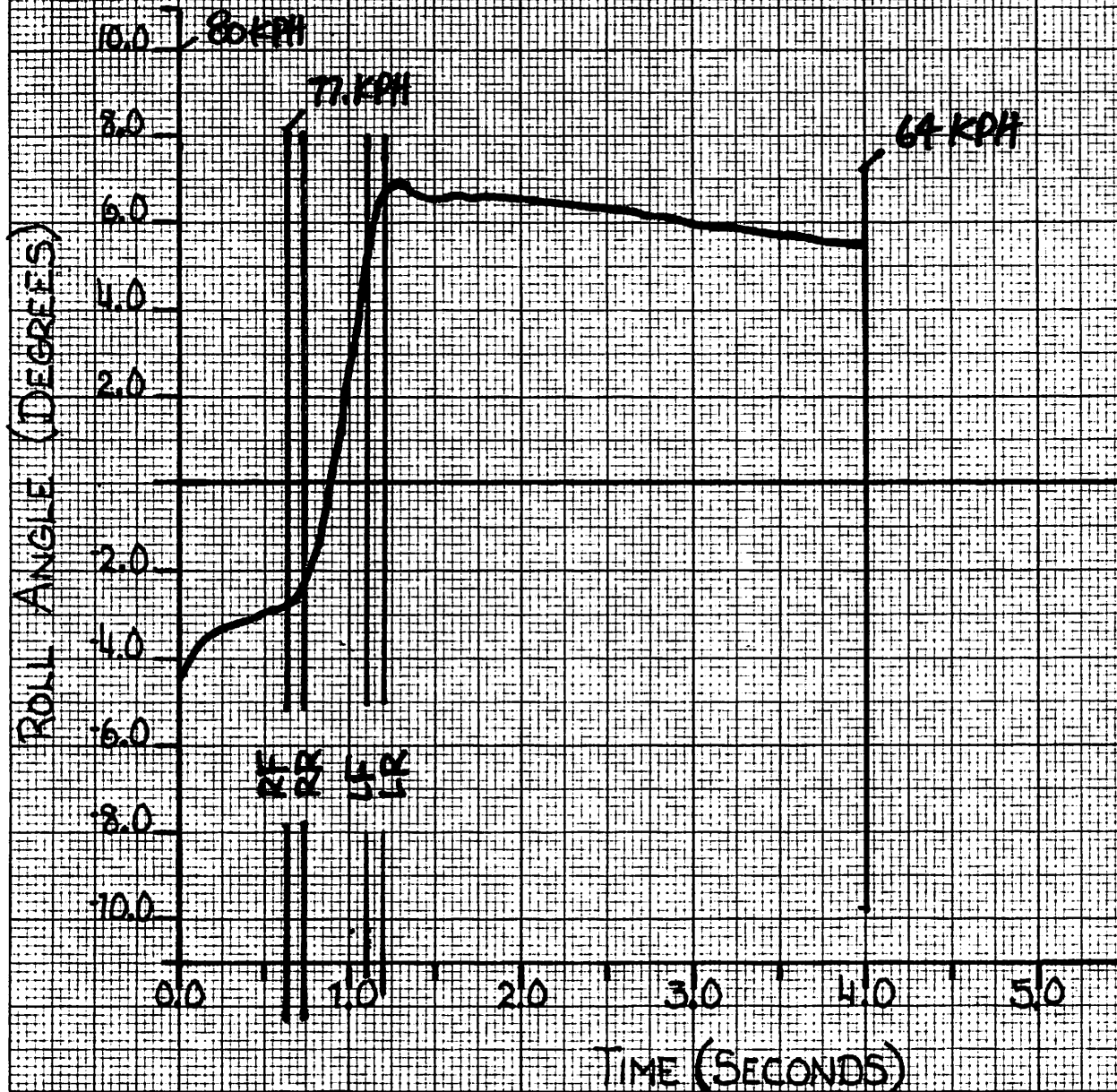SE: 10.0 %
SHOULDER: -4.0 %

VEHICLE PATH:
RADIUS: 164.0 METERS
10.65 DEGREES

PROBE: 1270.0 CM
P GAIN: 0.00047 RAD/CM
Q GAIN: 0.0004 RAD·SEC/CM
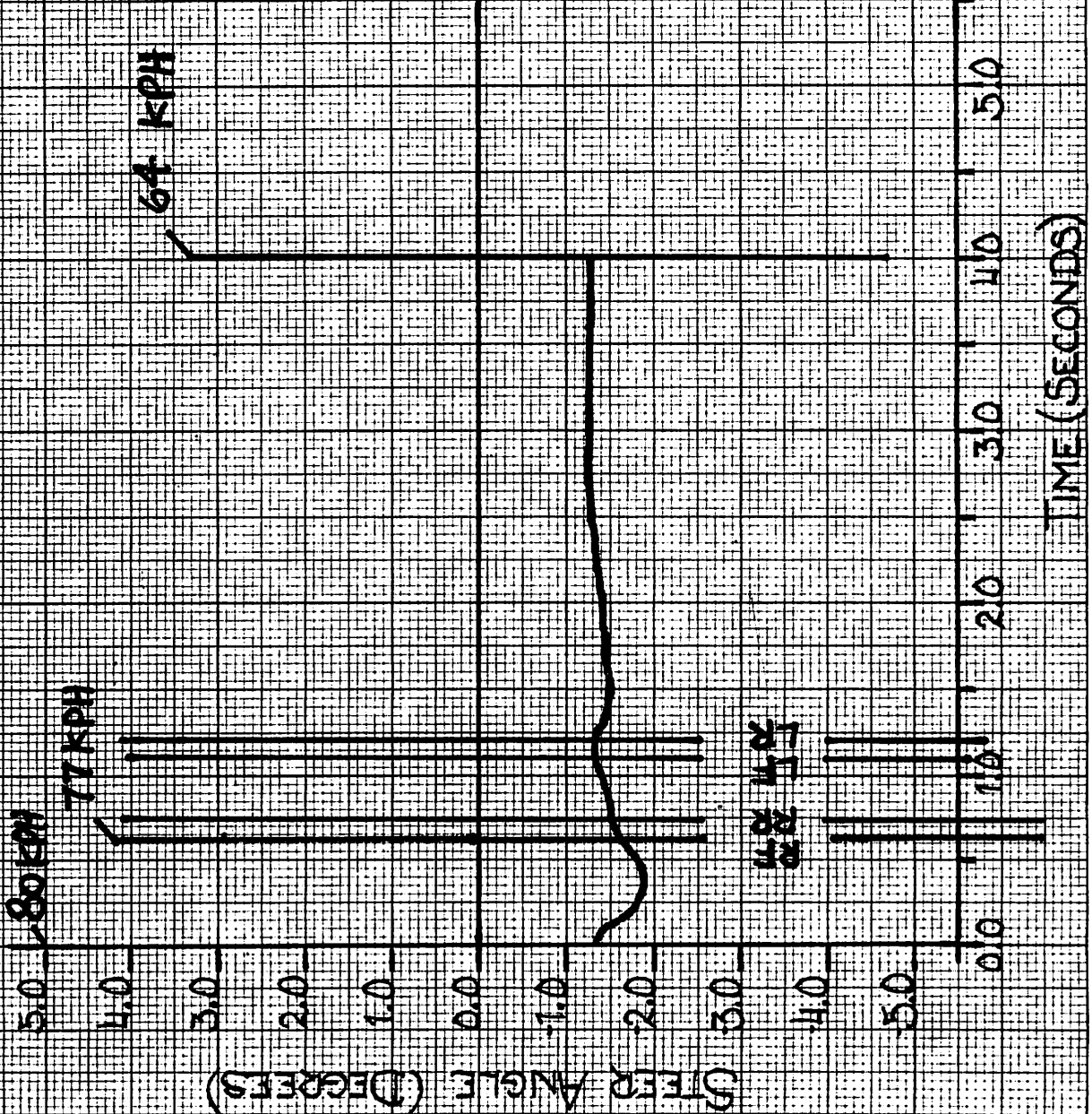DRIVELINE
BRAKING: =0.1 G's

McHENRY
CONSULTANTS, INC.

FH-11-9575

80 KPH
77 KPH
64 KPH

5.0 4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0 -5.0

(DEGREES) ANGLE (S) (H) (M)

.10 .20 .30 .40 .50

TIME (SECONDS)

```
list csb#16 nonum
DSNAME='MCIJEL.CSB#16'
CROSS SLOPE BREAK STUDY: DOT-FH-11-9575                              0 100
0.0     4.00    0.010   0.010   70.0    30.0    30.0    0.08    1.0     0 101
        0.0     0.0     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
300.0   1000.0  0.523   100000. 0.010   1.50                           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  5.0     10.0    -37.0   13.2    3043.   .58     91435.  1.0     1 301
.78                             13.2                                    0 302
164 M PATH: LH TURN W/FILTER & DAMPING                                 0 400
0.10    0.40    0.050   0.0     0.0     1.0                             0 401
-199.0  -199.0  -199.0  -199.0  -199.0  -199.0  -199.0                  1 401
1.0     1.0     1.0     0.05    0.00905 0.0     0.0                     0 402
4.0     75.0    0.0     1320.   1.7366  120.                            0 403
-.8875  0.0     -.8875  3000.0  -.8875  6000.0  -.8875  9000.0          0 404
0.0     0.10    500.0   0.0     1.0     500.0   0.0012  .0001           0 405
CSB#16: 210 M RADIUS, 10%SE,-4% SHOULDER                               0 500
 -600.00 360.00 120.00 1200.00 2400.00 240.00 8.0                      0 501
-137.76 -140.32 -145.45 -153.15 -163.43 -176.32 -191.82 -209.97        1 501
89.5    88.5    87.5    86.5    85.5    84.5    83.5    82.5            2 501
4.70    4.85    5.24    5.88    6.79    7.95    0.0     0.0     0.0     3 501
-0.09   0.05    0.44    1.10    2.02    3.19    0.0     0.0     0.0     4 501
-4.88   -4.75   -4.35   -3.68   -2.75   -1.56   0.0     0.0     0.0     5 501
-9.67   -9.55   -9.14   -8.47   -7.52   -6.31   0.0     0.0     0.0     6 501
   -11.99 -12.34-13.37  -13.25  -12.29  -11.07  0.0     0.0     0.0     7 501
    -0.00   -0.35   -1.39   -3.13   -5.56   -8.670.0    0.0     0.0     8 501
    12.00   11.65   10.59   8.82    6.36    3.21    24.00   23.64   22.57  9 501
    24.00   23.64   22.57   20.78   18.28   15.08   36.00   35.64   34.55  10 501
    36.00   35.64   34.55   32.73   30.19   26.94   0.0     0.0     0.0    11 501
 -480.00 480.00 120.00 2369.88 3569.88 240.00 8.0                      0 502
-55.95  -58.55  -63.76  -71.62  -82.17  -95.42  -111.43 -130.25        1 502
81.5    80.5    79.5    78.5    77.5    76.5    75.5    74.5            2 502
3.03    4.43    6.09    7.99    10.14   12.53   0.0     0.0     0.0     3 502
-1.73   -0.31   1.37    3.30    5.48    7.90    0.0     0.0     0.0     4 502
-6.48   -5.04   -3.34   -1.39   0.82    3.28    0.0     0.0     0.0     5 502
-11.24  -9.78   -8.06   -6.07   -3.83   -1.35   0.0     0.0     0.0     6 502
    -8.24 -11.94-12.76  -10.75  -8.49   -5.96   0.0     0.0     0.0     7 502
    3.64    -0.11   -4.55   -9.65-13.13  -10.57  0.0     0.0     0.0     8 502
    15.52   11.71   7.21    2.04    -3.79   -10.28  27.39   23.53   18.96  9 502
    27.39   23.53   18.96   13.72   7.80    1.23    39.26   35.34   30.71  10 502
    39.26   35.34   30.71   25.38   19.38   12.71   0.0     0.0     0.0    11 502
 -240.00 840.00 120.00 3516.84 4716.84 240.00 8.0                      0 503
187.85  185.16  179.74  171.55  160.51  146.51  129.69  109.76        1 503
73.5    72.5    71.5    70.5    69.5    68.5    67.5    66.5            2 503
2.71    5.36    8.24    11.35   14.69   18.25   0.0     0.0     0.0     3 503
```

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 -1.92    0.77    3.68    6.84    10.22   13.82   0.0     0.0     0.0        4 503
 -6.54   -3.82   -0.87    2.33    5.75    9.40    0.0     0.0     0.0        5 503
-11.16   -8.40   -5.41   -2.18    1.29    4.99    0.0     0.0     0.0        6 503
         -8.78-12.98   -9.95   -6.67   -3.15    0.59   0.0     0.0     0.0    7 503
          2.73   -4.33  -12.02-11.15   -7.59   -3.81   0.0     0.0     0.0    8 503
         14.24    7.08   -0.73   -9.14-12.02   -8.19   0.0     0.0     0.0    9 503
         25.74   18.48   10.56    2.02   -7.11-12.55   0.0     0.0     0.0   10 503
         37.21   29.85   21.82   13.17    3.91   -5.940.0      0.0     0.0   11 503
         48.68   41.21   33.07   24.29   14.91    4.92   0.0      0.0      0.0  12 503
        120.00 1320.00  120.00 4618.80 5818.80  240.00  8.0                   0 504
588.92  586.08  580.33  571.60  559.78  544.81  526.56  504.92               1 504
65.5    64.5    63.5    62.5    61.5    60.5    59.5    58.5                   2 504
3.45    7.27    11.32   15.56   20.0    24.66   0.0     0.0     0.0            3 504
-0.97   2.90    7.00    11.28   15.78   20.49   0.0     0.0     0.0            4 504
-5.38   -1.46   2.68    7.02    11.59   16.34   0.0     0.0     0.0            5 504
-9.78   -5.81   -1.62   2.78    7.39    12.17   0.0     0.0     0.0           '6 504
        -12.79-10.14   -5.90   -1.46    3.22    8.05    0.0     0.0     0.0    7 504
         -1.84  -12.05-10.18   -5.66   -0.94    3.97    0.0     0.0     0.0    8 504
          9.07   -1.26  -12.11-9.86    -5.11   -0.11    0.0     0.0     0.0    9 504
         19.95    9.49   -1.51  -13.12-9.23    -4.15    0.0     0.0     0.0   10 504
         30.79   20.20    9.06   -2.69-13.32   -8.20    0.0     0.0     0.0   11 504
         41.61   30.91   19.56    7.69   -4.69-12.19   0.0     0.0     0.0   12 504
         52.41   41.54   30.05   18.08    5.42   -7.73   0.0      0.0      0.0  13 504
1.0     1.0     1.0     1.0                                                   0 506
1200.   1346.70 1346.70 1493.35 1493.35 1639.91 1639.91 1786.34 1.0          0 515
1786.34 1932.59 1932.59 2078.62 2078.62 2224.37 2224.37 2400.00 1.0          1 515
2369.00 2514.91 2514.91 2659.60 2659.60 2803.85 2803.85 2947.60 2.0          2 515
2947.60 3090.83 3090.83 3233.47 3233.47 3375.50 3375.50 3600.00 2.0          3 515
3516.00 3657.53 3657.53 3797.44 3797.44 3936.56 3936.56 4074.85 3.0          4 515
4074.85 4212.26 4212.26 4348.75 4348.75 4484.29 4484.29 4700.00 3.0          5 515
4618.00 4752.32 4752.32 4884.73 4884.73 5016.02 5016.02 5146.14 4.0          6 515
5146.14 5275.07 5275.07 5402.75 5402.75 5529.15 5529.15 5900.00 4.0          7 515
80 KPH                                                                       0 600
-4.29   0.73    99.5    0.70    0.30    -4.37   -1.33                         0 601
0.0     1320.   -23.3   874.92  13.0    -7.20   0.0     0.0     0.0           0 602
-1.2    0.4     -.03    -1.25                                                 0 603
                                                                             9999
```

END OF DATA
READY