EVALUATING THE BENEFITS OF SLOPE ROUNDING

by

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16. Abstract

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CHAPTER I
INTRODUCTION

I.1 Purpose and Objectives

Embankment side slopes are important element in roadside design. They should preferably be designed to ensure safety of run-off-the road vehicles. Research studies have reported that rounding the hinge line between the shoulder and the side slope can reduce risks to an errant motorist. Risks are reduced since a run-off-the-road vehicle is not as prone to becoming airborne on a rounded hinge as it would on a nonrounded hinge, thus affording the driver greater control to break and/or steer the vehicle.

While it is generally believed that slope rounding enhances roadside safety, no studies have been made to quantify or estimate its benefits. Providing and maintaining slope rounding is generally more costly than the unrounded conditions.

The objective of this study was to evaluate the benefits of slope rounding for freeways and rural arterials. It was concluded that the majority of slope rounding needs would occur on roadways of these types; furthermore, the scope of the study precluded analysis of other roadway types. If found to be cost beneficial, another objective of the study was to develop recommendations regarding rounding parameters for these two roadway types as a function of traffic volumes.

I.2 Literature Review

Weaver (*1*) and Deleys (*2*) obtained the response of vehicles during traversals of various roadside geometric configurations by using the Highway-Vehicle-Objective Simulation Model (HVOSM) computer program (*3-7*). Shoulder/side slope rounding was one of the important elements of the cross section considered in the study by Deleys (*2*). Results of the Deleys study showed how slope rounding could reduce the hazard to a vehicle accidentally leaving the roadway. It also illustrated the hazardous nature of various typical roadside terrain features and how their safety could be enhanced through the flattening of slopes and/or by providing adequate rounding of slope breaks. The hazard potential of a side slope increases as the steepness of the slope increases, but can be reduced if adequate rounding is provided at the juncture with the shoulder. Guidelines for selecting slope rounding parameters were given in the AASHTO "Guide for Selecting, Locating, and Designing Traffic Barriers" (*8*). These guidelines were developed from data in the cited literature and from additional HVOSM studies conducted in support of the development of the Guide.

Although slope rounding is recognized as providing a greater degree of safety than the unrounded condition, it is also more costly. To date, no studies have been conducted to analyze and estimate benefits of slope rounding, as measured by reduced societal or accident costs, in relation to additional direct costs to provide the slope rounding. In recent years, benefit-cost (B/C) analysis procedures have been widely accepted as a rational method for evaluating safety treatment alternatives. The AASHTO "Guide for Selecting, Locating, and Designing Traffic Barriers" (*8*) offered a "simplified" B/C analysis procedure. Subsequently, Sicking and Ross (*9*) developed an advanced B/C analysis algorithm, and the B/C procedures described in their study represent a significant improvement over existing procedures in terms of accuracy and versatility of analysis. Based on this algorithm, a B/C analysis microcomputer program was developed at the Texas Transportation Institute for use by highway engineers to evaluate various safety alternatives. With the problems of ever increasing highway construction costs and limited funding, B/C analyses cam be a valuable aid in the decision-making process. This is particularly true for rural, low volume highways.

CHAPTER II
RESEARCH APPROACH

In the initial part of the study an estimate was made of occupant risks associated with rounded versus unrounded slopes. The HVOSM computer program was used primarily for this purpose. Simulated encroachments of selected vehicles were made as they traversed rounded versus unrounded conditions, and occupant risks (and hence a severity index) were inferred from the vehicle's response. Societal costs were inferred from severity indices using Table A.2 of the AASHTO "Roadside Design Guide" (*10*). Benefits of slope rounding, measured in terms of reduced societal costs, were compared with added costs to provide the rounding to determine if the rounding was cost beneficial.

Guidelines were developed to identify recommended rounding parameters as related to roadway classification, cross-section geometries and traffic volumes. These guidelines were derived directly from results of the B/C study. The research approach consisted of the following:

(a) Identify Parameters to be Evaluated and Conduct Sensitivity Study

An initial study was conducted to identify key parameters and to evaluate the sensitivity of vehicular response to selected encroachment and roadside parameters. The more sensitive or important parameters were then selected for further study. A description of this phase of the study is given in chapter III.

(b) Conduct Occupant Risk Evaluation

The HVOSM computer program was used to estimate occupant risks for unrounded and rounded conditions. Severity indices were calculated by using the simulation results. A description of this phase of the study is given in chapter IV.

(c) Conduct Benefit/Cost (B/C) Analysis

All potential slope treatments, including unrounded, 2 ft (0.61 m) constant rounding, 4 ft (1.22 m) constant rounding, and optimum rounding for 3:1, 4:1, and 6:1 side slopes, were evaluated using a B/C analysis computer program developed by Sicking and Ross (*9*) at the Texas Transportation Institute. A description of this phase of the study is given in chapter V.

(d) Develop Slope Rounding Guidelines

Results of the B/C analysis were examined to determine guidelines for recommended slope rounding. These guidelines were developed to identify where slope rounding is cost beneficial for one of two functional classifications of roadways (freeways and rural arterials), as a function of cross-section geometry and traffic volume or average daily traffic (ADT). A description of this phase of the study is given in Section V.5.

CHAPTER III

PARAMETER IDENTIFICATION AND SENSITIVITY STUDY

The severity of a run-off-the-road accident on an embankment is dependent to a large extent on encroachment conditions (speed, angle, and attitude of vehicle), type of vehicle, roadway and roadside geometries, and driver response. The objective of this phase of the study was to determine the parameters that have the greatest influence on adverse vehicular behavior for roadside encroachment.

III.1 Determine Cross Section Parameters

Due to the unlimited combination of cross-section parameters it was necessary to constrain the parameters to a manageable and typical set. Roadway cross-section geometries for unrounded and rounded side slopes were selected in consultation with Minnesota DOT, and are illustrated in Figures 1 and 2, respectively. It was assumed that there was no rounding at the toe of the slope. Only straight roadway sections were considered; evaluation of curved roadway sections would be significantly more complex and costly, and were not within the scope of the study.

Two types of rounding were examined, optimum rounding and constant rounding. Optimum rounding is defined as the minimum rounding required to keep all tires of the design vehicle in contact with the ground for a specified encroachment speed and angle. In the present study, Minnesota DOT specified that optimum rounding be based on a speed of 70 mph (112.7 km/hr) and angle of 15 degrees. For optimum rounding the lateral extent of rounding needed, d_x, varies and is dependent on shoulder slope, side slope, and vehicular encroachment conditions, such as encroachment speed and angle. By definition, d_x is fixed for constant rounding. It is independent of the vehicle's encroachment conditions.

In general, optimum rounding provides a more smooth transition at the shoulder/side slope hinge than the constant rounding. The lateral extent d_x of optimum rounding and rounding curve equations are given in Equations 1 and 2, respectively, as taken from the AASHTO barrier guide (*8*).

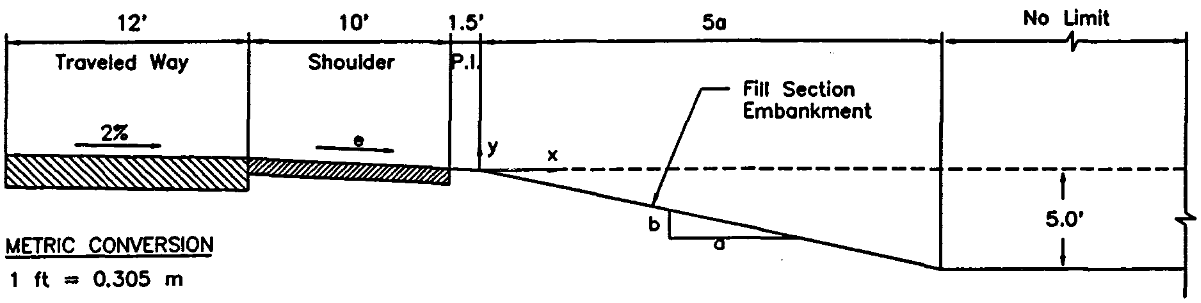

FIGURE 1. Roadway cross section with unrounded side slope.

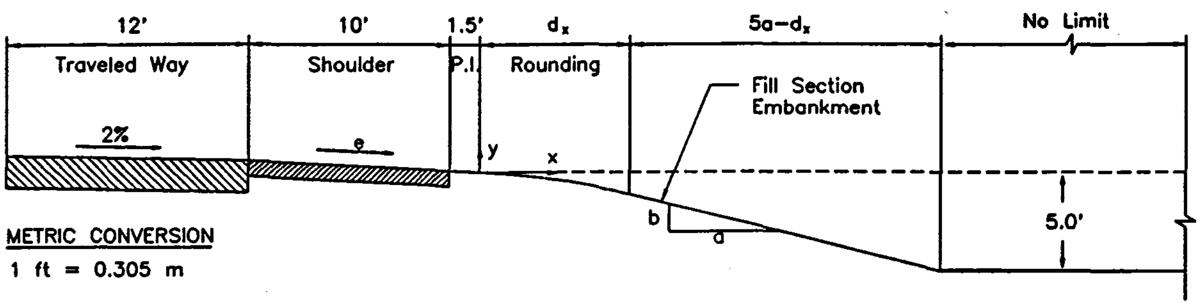

FIGURE 2. Roadway cross section with rounded side slope.

U.S. Units | S.I. Units

$$d_x = \frac{V^2 \sin^2\theta}{13.8} \left[e - \frac{b}{a} \right] \qquad d_x = \frac{v^2 \sin^2\theta}{4.2} \left[e - \frac{b}{a} \right] \tag{1}$$

$$y = x \left[e - \frac{6.9x}{V^2 \sin^2\theta} \right] \qquad y = x \left[e - \frac{2.1x}{v^2 \sin^2\theta} \right] \tag{2}$$

y, x, and d_x in ft. | y, x, and d_x in meters.

where e = shoulder slope (ft/ft) (m/m), positive if sloping upward;

b/a = reciprocal of embankment slope (ft/ft) (m/m), positive if sloping upward;

V = vehicular velocity (ft/sec) (m/sec);

θ = vehicular encroachment angle (deg);

d_x = lateral extent of slope rounding (ft) (m);

Note that θ was set equal to 15 degrees and V was set equal to 70 mph (112.7 km/hr) = 102.67 ft/sec (31.31 m/sec).

The 1977 AASHTO barrier guide (*8*) presents optimum rounding curve equations only. Constant rounding curve equations had to be determined. To match the curve type used for optimum rounding and provide a smooth transition from shoulder to side slope, an equal-tangent parabolic curve was used for constant rounding. Figure 3 illustrates its geometry and geometric relationships. The general curve equation is given in Equation 3, as taken from Brinker (*11*).

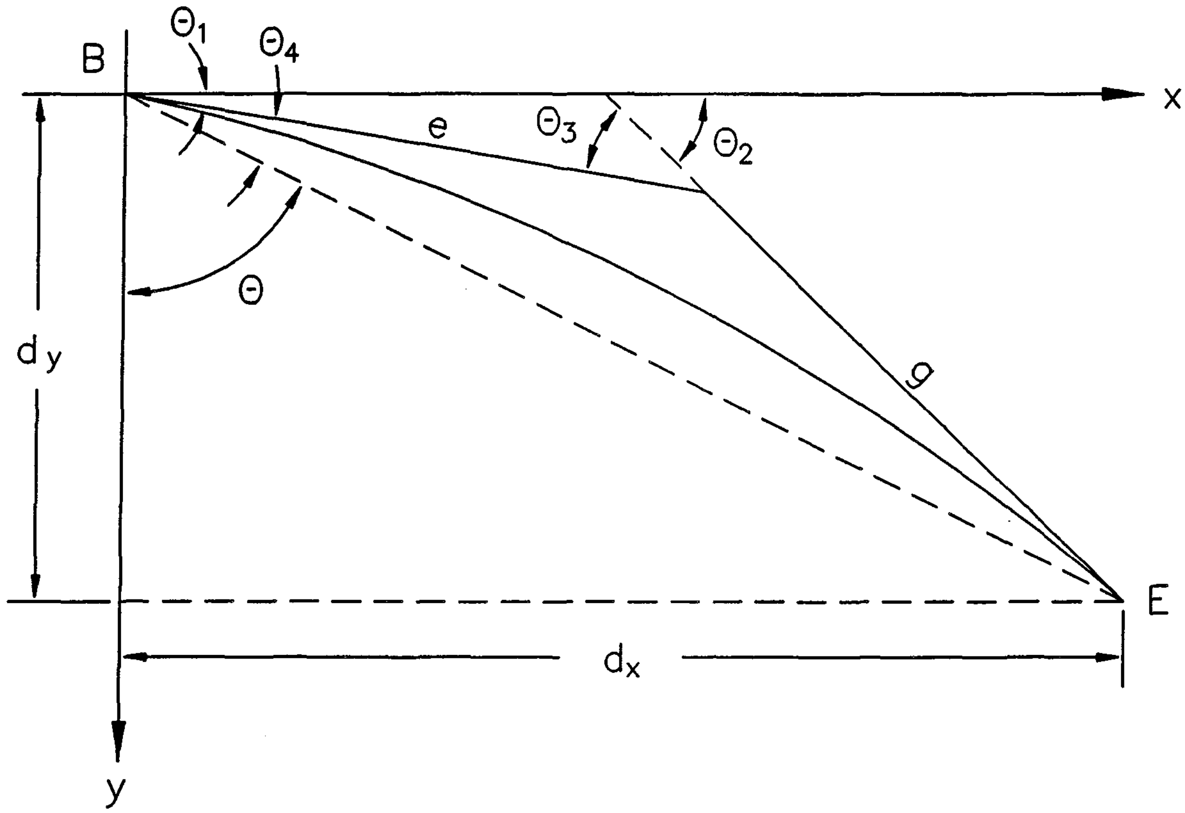

FIGURE 3. Equal-tangent parabolic curve.

$$y = x \left[e + \frac{e-g}{2L} x \right] = x \left[e + \frac{rx}{2} \right] \qquad (3)$$

where e = shoulder slope (ft/ft) (m/m), positive if sloping upward;

g = b/a = reciprocal of embankment slope (ft/ft) (m/m), positive if sloping upward;

r = a constant which is the rate of change of grade, (e-g)/L; for sag curve, it is positive; for crest curve, it is negative;

L = length of the curve (ft) (m);

y and x in ft (m).

The constant r can be calculated by substituting coordinates of one point on the curve into Equation 3. An expression for r, derived from Equation 3 is given in Equation 4.

$$r = \frac{2\,[\,y - ex]}{x^2} \tag{4}$$

Given e, g, and $x_{max} = d_x$, d_y can be calculated to obtain the constant r. From Figure 3, determination of d_y follows, using Equations 5 through 10.

$$\theta_1 = \arctan(e) \tag{5}$$

$$\theta_2 = \arctan(g) \tag{6}$$

$$\theta_3 = \theta_2 - \theta_1 = \arctan(g) - \arctan(e) \tag{7}$$

$$\theta_4 = \frac{\theta_3}{2} = \frac{\arctan(g) - \arctan(e)}{2} \tag{8}$$

$$\theta = \frac{\pi}{2} - (\theta_1 + \theta_4) = \frac{\pi - [\arctan(e) + \arctan(g)]}{2} \tag{9}$$

$$d_y = \frac{d_x}{\tan(\theta)} \tag{10}$$

Therefore, r can be calculated by substituting d_x and d_y, which are end point coordinates of the parabolic curve, into Equation 4. Then Equation 3 provides the constant rounding curve.

Summarizing, Equations 2 and 3 were used to determine the terrain profile for optimum and constant rounding.

III.2 Selection of Vehicular Simulation Model

The Highway Vehicle Object Simulation Model (HVOSM) computer program was developed to simulate three-dimensional behavior of a vehicle as it interacts with roadway and/or roadside features. The program employs a more sophisticated vehicle model than any other simulation program available today. There are several versions of HVOSM currently available. Two versions were considered for, HVOSM-RD2 (*3-6*) and HVOSM-TTI (*7*). The RD2 version is intended for safety appurtenance design and emphasizes barrier impacts. Its vehicular suspension model is capable of simulating all combinations of independent and solid axle suspension arrangements. However, it can not simulate contact between the vehicular's sprung mass (chassis) and the terrain. The TTI version was modified from the HVOSM V-3 version. Sprung mass contact with the terrain can be simulated in this version, but its suspension model is designed for independent front and solid rear suspension.

HVOSM-RD2 was initially selected because of it can simulate four-wheel independent suspension. However, after the initial sensitivity study in which both models were used (see next section), bumper contact with the terrain was found to be a very important factor. Note it was assumed that no rounding existed at the toe region of the embankment (juncture of side slope with ditch bottom). Vehicular overturn and/or high accelerations can be caused by bumper contact with the ground in this region. Since the importance of bumper-terrain contact outweighed the suspension limitation, the TTI version was selected for all subsequent simulations.

III.3 Identify Parameters and Conduct Sensitivity Study

Key parameters considered in the simulation of vehicular encroachment included slope of the traveled way, shoulder width and slope, roadside slope, slope rounding parameters, embankment depth, encroachment speed and angle, tire-terrain friction, vehicular type, and the driver's response. Values of the roadway and roadside parameters were selected to be consistent with the Minnesota DOT road design manual (*12*). Since the scope of the study precluded an extensive number of computer runs, a sensitivity study was conducted to examine the relative importance the selected parameters have on vehicular response, and hence on occupant risk.

In the sensitivity study three parameters were evaluated: (1) tire-terrain friction, (2) type of vehicle, and (3) type of driver response upon leaving the traveled way. Both rounded and unrounded slopes were considered in comparing the vehicular response. Two slope rounding options were evaluated in the sensitivity study, optimum rounding and constant rounding with d_x=2 ft (0.61 m).

All combinations of the following parameters were included in the sensitivity study.

(1) Two vehicular types - small car (Honda Civic) and full-size pickup (GMC);

(2) One encroachment speed -- 60 mph (96.5 km/hr);

(3) One encroachment angle -- 15 degrees;

(4) Two tire-terrain friction coefficients -- 0.5 and 1.0;

(5) Two types of driver response upon leaving the traveled way -- one panic "return-to-the-road" steer input and no steer input;

(6) Two side slopes -- 4:1 and 3:1;

(7) Two rounded conditions -- constant rounding with d_x=2 ft (0.61 m) and optimum rounding as given by Equation 2;

(8) One unrounded condition -- d_x=0 ft (0 m);

(9) Shoulder slope -- 25:1 (4%);

(10) Traveled way slope -- 50:1 (2%).

Combinations of computer runs are illustrated in Figure 4. A total of 48 runs were made. Results of the simulations are summarized in Tables 1 through 3.

An explanation of occupant risk as defined by occupant ridedown accelerations is given in Section IV.1. In general, occupant risk was assumed to be directly proportional to occupant ridedown acceleration.

From results given in Tables 1 through 3, the following was observed:

(1) In general, higher vehicular accelerations and roll angles occurred for a tire-terrain friction coefficient of 1.0 in comparison to those obtained for a coefficient of 0.5, all other conditions being equal.

(2) In general, higher vehicular accelerations and roll angles occurred for the Honda in comparison to those obtained for the pickup, all other conditions being equal.

(3) In general, higher vehicular accelerations and roll angles occurred for the emergency-steer driver input in comparison to the no steer, all other conditions being equal.

Based on simulation results and the above observations, the following conclusions were made:

(1) A tire-terrain friction coefficient of 1.0 is more critical than 0.5 and representative of the coefficient that would appropriate for "soft" soils.

(2) The small car is more critical than the full-size pickup.

(3) The panic "return-to-the-road" steer is more critical than the no steer input condition.

By the term "more critical" is meant that, as a general rule, the vehicle experiences higher accelerations and/or is more prone to overturn. These parameters were therefore selected for use in a more comprehensive study which defined the severity of vehicular encroachments on various slope rounding conditions, as described in the following chapter.

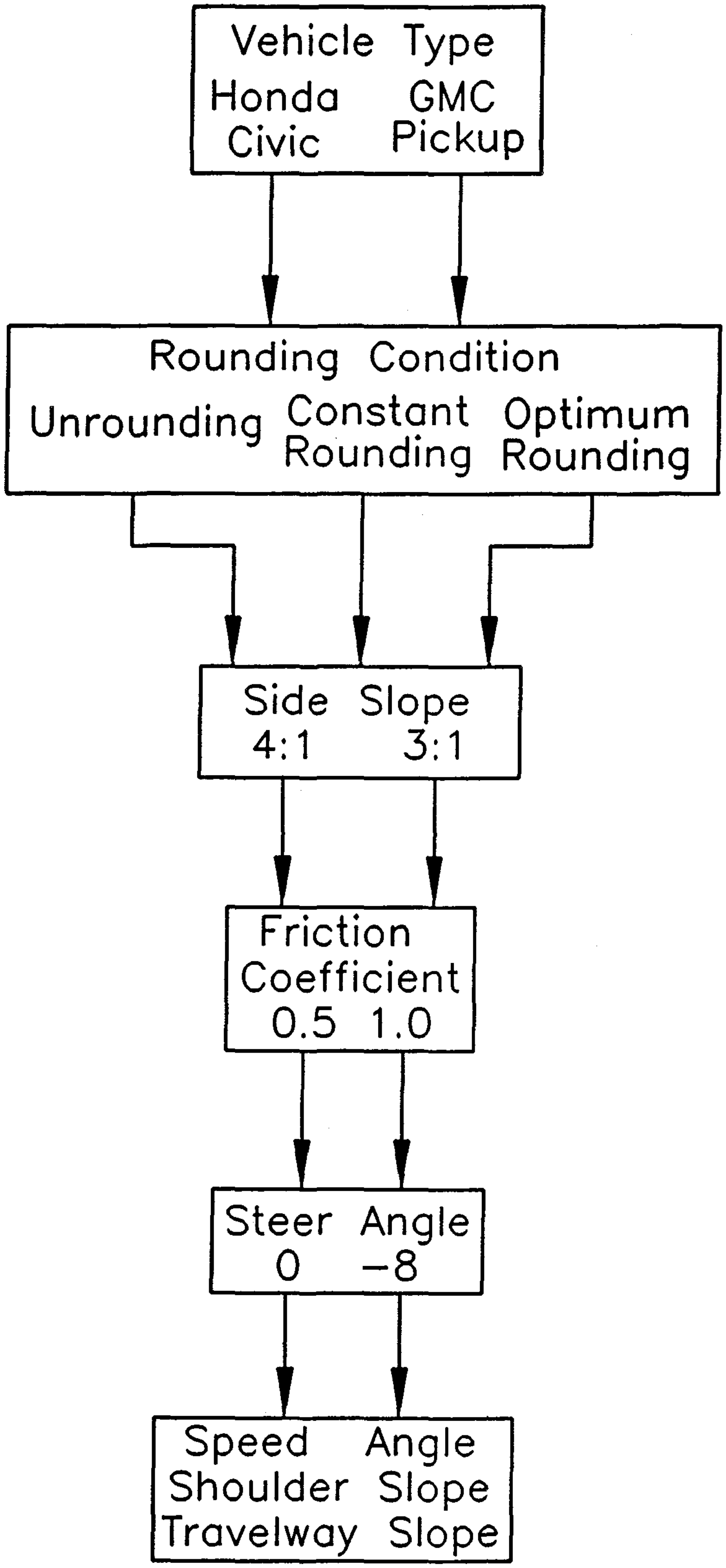

FIGURE 4. Combination of computer simulation runs.

TABLE 1. HVOSM Simulation of Unrounded Option, d_x = 0 ft (0 m)

Side Slope	Tire-Terrain Friction Coefficient	Steer Angle (deg)	Honda Civic		GMC Pickup	
			Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
4:1	0.5	0	0.770	16.27	0.792	16.80
		-8	0.670	15.80	0.748	16.59
	1.0	0	0.773	16.18	0.794	16.77
		-8	1.758	17.39	0.906	9.30
3:1	0.5	0	0.982	25.73	1.081	25.97
		-8	0.710	19.6	0.727	16.15
	1.0	0	0.984	25.44	1.078	25.96
		-8	1.190	Overturn	1.133	12.14

Note: 1 ft = 0.35 m.

TABLE 2. HVOSM Simulation of Constant Rounding, d_x = 2 ft (0.61 m)

Side Slope	Tire-Terrain Friction Coefficient	Steer Angle (deg)	Honda Civic		GMC Pickup	
			Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
4:1	0.5	0	0.671	15.49	0.649	15.52
		-8	0.670	16.70	0.727	14.25
	1.0	0	0.673	15.45	0.650	15.52
		-8	0.920	17.66	0.770	11.35
3:1	0.5	0	0.966	22.78	0.949	23.95
		-8	0.710	20.78	0.727	19.32
	1.0	0	0.974	22.63	0.949	23.94
		-8	1.384	23.16	0.734	13.68

Note: 1 ft = 0.305 m.

TABLE 3. HVOSM Simulation of Optimum Rounding

Side Slope	Tire-Terrain Friction Coefficient	Steer Angle (deg)	Honda Civic		GMC Pickup	
			Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
4:1	0.5	0	0.536	14.80	0.476	14.25
		-8	0.686	12.39	0.727	12.09
	1.0	0	0.536	14.86	0.476	14.28
		-8	0.907	11.65	0.844	8.53
3:1	0.5	0	0.619	19.24	0.534	18.54
		-8	0.740	14.28	0.727	12.71
	1.0	0	0.619	19.30	0.534	18.61
		-8	0.908	11.63	0.860	8.56

Note: 1 ft = 0.305 m.

CHAPTER IV
OCCUPANT RISK EVALUATION

IV.1 Severity Index

Benefit-Cost analysis of slope rounding requires that an estimate be made of a severity index (SI) of each accident predicted to occur with each alternative considered. As used herein, the SI is simply a scale from 0 to 10 that quantifies probability of injury of a given accident. In turn there is an assumed societal cost associated with a given SI or probability of injury.

HVOSM was used to estimate occupant risk as defined by occupant impact velocity, occupant ridedown acceleration and vehicular roll, associated with vehicular encroachments on the rounded and unrounded side slopes. NCHRP Report 230 (*13*) contains a description of occupant risks as defined by occupant impact velocity and occupant ridedown acceleration. Relationships between severity index, occupant impact velocity and ridedown acceleration were taken from a study by Ross, et al. (*14*). It is noted that for encroachments onto roadside slopes, occupant ridedown acceleration rather than occupant impact velocity typically control occupant risks. For this reason, occupant impact velocity was neglected in computing the severity index. A relationship between severity index and vehicular acceleration developed by Ross, et al. (*14*) is given in Equation 11.

$$SI_{(due\ to\ vehicle\ acceleration)} = \frac{a}{4} \qquad (11)$$

where SI = severity index; and

a = average resultant vehicular acceleration during any 50 millisecond period.

This equation is generally believed to be conservative in that it likely overstates the probability of injury.

The degree of vehicular roll during an encroachment can also affect occupant risk; an overturned vehicle is known to present high risks to occupants. A discontinuity on the roadway surface, such as a curb, or terrain irregularity, such as a mound of dirt, a large rock, or a washout, can induce vehicular instability, as measured by roll angle. These discontinuities could not be considered in the computer simulation program. Overturn will occur if the roll angle and/or roll velocity exceed certain limiting values. Therefore, it was concluded that in addition to vehicular accelerations, the SI is also dependent on vehicular roll. Equation 12 gives the estimated relationship between severity index and roll angle, as derived from engineering judgement.

$$SI_{(due\ to\ vehicle\ roll\ angle)} = \begin{cases} 7(\frac{\phi}{90})^2 & 0 < \phi < 90\ deg \\ 7 & \phi \geq 90\ deg \end{cases} \qquad (12)$$

where ϕ = vehicular roll angle (deg), and

"a" is as previously defined.

The total estimated severity index was obtained using Equation 13, which is the addition of Equations 11 and 12.

$$SI_{(Total)} = \begin{cases} \frac{a}{4}+7(\frac{\phi}{90})^2 \leq 10 & 0 < \phi < 90\ deg \\ 7 & \phi \geq 90\ deg \end{cases} \qquad (13)$$

As assumed, the limiting value of $SI_{(Total)}$ was ten (10) if overturn did not occur. If overturn occurred the limiting value of $SI_{(Total)}$ was assumed to be the maximum value before overturn, as computed by the upper expression in Equation 13, or seven (7), whichever was greater.

Note that, when $\phi \leq 90$ degrees, the maximum value of $SI_{(Total)}$ is determined by one of the following two situations, whichever produces the larger value:

(1) *a* is the maximum average acceleration during any 50 millisecond period and ϕ is the vehicular roll angle at the midpoint of the period, or

(2) ϕ is the maximum vehicular roll angle during the entire encroachment period, occurring at time T, and *a* is the 50 millisecond average resultant vehicular acceleration during the time period T - 0.025 to T + 0.025 seconds.

IV.2 Computer Simulations and Determination of Severity Index

The HVOSM computer program requires a large number of vehicular parameters, tire data, terrain data, and vehicular encroachment conditions. A sample set of input data is given in Appendix A. Figures 5 and 6 show the terrain configurations and the vehicle's initial position prior to encroachment for unrounded and rounded side slopes, respectively. It is noted that the tire-terrain friction coefficient of 1.0 applied to terrain beyond the shoulder hinge (at x = 11.5 ft) (3.5 m). The tire-terrain friction coefficient on the traveled way and shoulder was assumed to be 0.7.

The matrix of variables for the severity study was as follows:

(1) one vehicular type - small car (Honda Civic);

(2) two encroachment speeds - 45 and 60 mph (72.5 and 96.5 km/hr);

(3) five encroachment angles - 5, 15, 25, 35, and 45 degrees (severity indices at these particular angles are required input for the B/C analysis);

(4) one tire-terrain friction coefficient - 1.0;

(5) one driver's response upon leaving the traveled way - a panic "return-to-the-road" steer input of 8 degrees;

(6) three side slopes - 6:1, 4:1, and 3:1;

(7) three types of rounding - (1) constant rounding, d_x=2 ft (0.61 m), (2) constant rounding, d_x=4 ft (1.22 m), and (3) optimum rounding for each side slope at an encroachment speed of 70 mph (112.7 km/hr) and an encroachment angle of 15 degrees;

(8) one unrounded condition -- d_x=0 ft (0 m);

(9) shoulder slope -- 25:1 (4%); and

(10) traveled way slope -- 50:1 (2%).

A series of HVOSM runs were made to examine the small car's behavior when traversing unrounded and rounded side slopes, and to obtain severity index values. All runs were made with a panic "return-to-the-road" steer input of 8 degrees. Note that 8 degrees of steer input equals about 140 to 180 degrees of steering wheel turn, depending on the vehicle type.

A summary of the 50 millisecond average resultant accelerations and maximum roll angles are shown in Tables 4 through 7. Vehicular overturns were predicted for both unrounded and rounded side slopes for certain combinations of encroachment speed and angle. The severity index was relatively small when overturn did not occur.

Examination of the results showed that cornering from the assumed driver's panic steer input, in combination with bumper contact that occurred at the toe of the slope, had significant effects on vehicular stability. Most overturns were caused by a combination of high cornering,

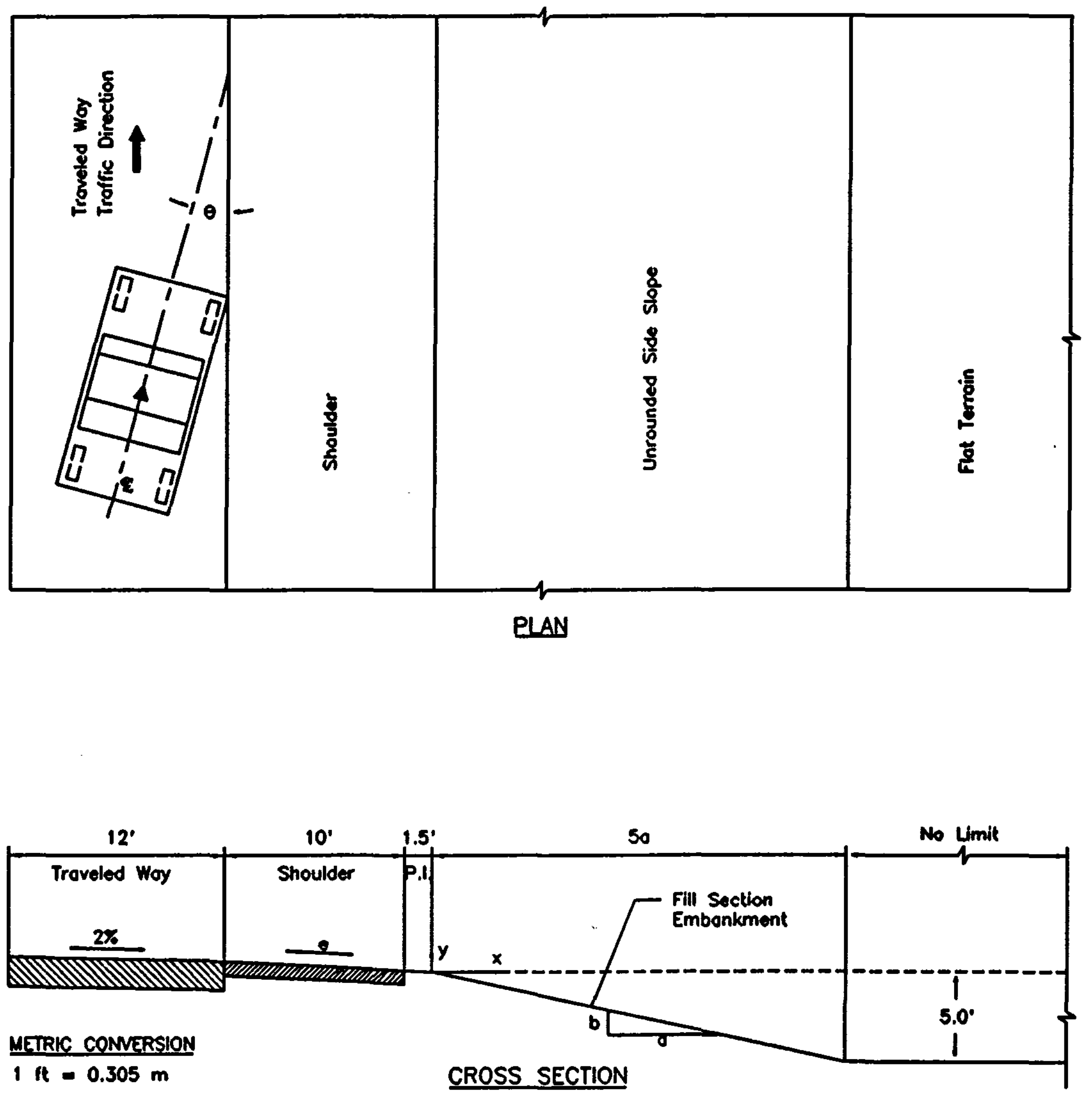

FIGURE 5. HVOSM computer simulation terrain configuration and vehicular encroachment initial position for unrounded side slope.

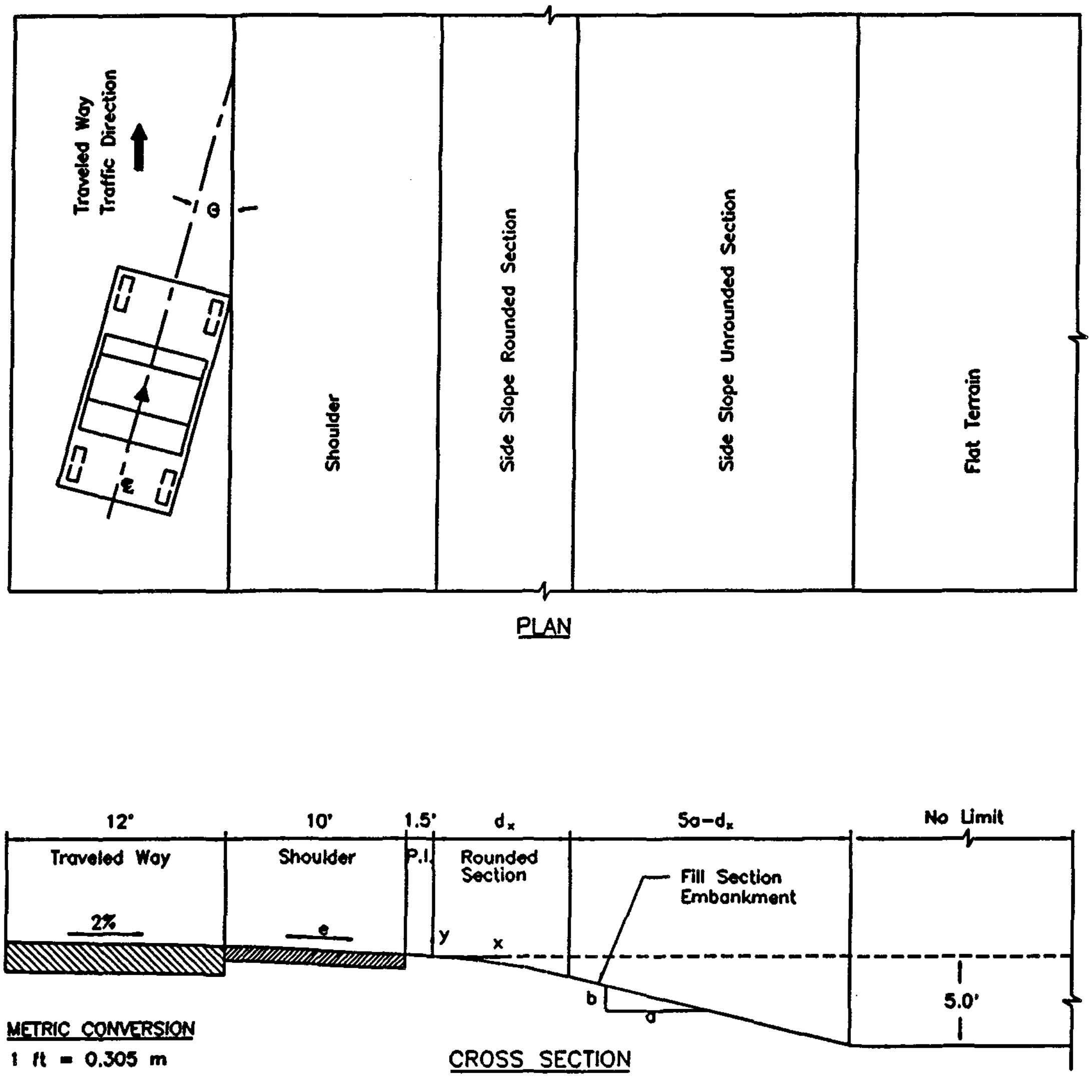

FIGURE 6. HVOSM computer simulation terrain configuration and vehicular encroachment initial position for rounded side slope.

TABLE 4. HVOSM Simulation of Unrounded Option, Honda Civic with a "Return-to-the-Road" Steer Angle of 8 Degrees

Encroachment Conditions		Side Slope					
		6:1		4:1		3:1	
Speed (mph)	Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.735	6.70	0.735	6.70	0.735	6.70
	15	0.730	7.83	0.730	7.83	0.730	7.83
	25	1.081	18.61	10.167	Overturn	9.828	Overturn
	35	1.223	19.24	3.316	27.44	11.508	Overturn
	45	1.728	18.35	7.897	Overturn	7.586	27.66
60	5	0.741	7.06	0.741	7.06	0.741	7.06
	15	1.027	13.83	1.644	19.73	11.086	Overturn
	25	1.784	20.41	3.312	31.71	8.797	41.04
	35	2.235	18.34	7.296	Overturn	7.915	Overturn
	45	11.826	Overturn	9.798	Overturn	9.107	Overturn

Note: 1 mi = 1.61 km.

TABLE 5. HVOSM Simulation of 2 ft (0.61 m) Constant Rounding, Honda Civic with a "Return-to-the-Road" Steer Angle of 8 Degrees

Encroachment Conditions		Side Slope					
		6:1		4:1		3:1	
Speed (mph)	Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.734	6.70	0.735	6.70	0.735	6.70
	15	0.730	7.83	0.729	7.83	0.730	7.83
	25	1.015	17.96	10.534	Overturn	9.021	Overturn
	35	13.070	Overturn	3.877	26.77	12.752	Overturn
	45	1.706	18.73	8.019	Overturn	7.162	27.35
60	5	0.741	7.06	0.741	7.06	0.741	7.06
	15	0.894	12.06	6.893	Overturn	11.093	Overturn
	25	1.223	19.24	3.131	30.67	7.124	39.97
	35	2.315	18.46	7.574	Overturn	8.177	Overturn
	45	5.945	Overturn	10.154	Overturn	9.862	Overturn

Note: 1 mi = 1.61 km.

TABLE 6. HVOSM Simulation of 4 ft (1.22 m) Constant Rounding, Honda Civic with a "Return-to-the-Road" Steer Angle of 8 Degrees

Encroachment Conditions		Side Slope					
		6:1		4:1		3:1	
Speed (mph)	Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.735	6.70	0.735	6.70	0.735	6.70
	15	0.730	7.83	0.730	7.83	0.730	7.83
	25	0.933	16.71	1.977	23.10	8.941	Overturn
	35	12.489	Overturn	3.613	23.78	10.592	Overturn
	45	1.664	19.22	7.080	Overturn	12.350	Overturn
60	5	0.741	7.06	0.741	7.06	0.741	7.06
	15	0.915	10.50	1.071	14.76	7.765	Overturn
	25	1.217	18.50	3.007	27.18	6.642	35.69
	35	2.471	18.11	7.667	Overturn	7.740	Overturn
	45	9.140	Overturn	9.734	Overturn	9.933	Overturn

Note: 1 mi = 1.61 km.

TABLE 7. HVOSM Simulation of Optimum Rounding, Honda Civic with a "Return-to-the-Road" Steer Angle of 8 Degrees

Encroachment Conditions		Side Slope					
Speed (mph)	Angle (deg)	6:1		4:1		3:1	
		Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.735	6.70	0.735	6.70	0.735	6.70
	15	0.729	7.83	0.730	7.83	0.730	7.83
	25	0.930	15.91	0.907	16.92	0.919	16.87
	35	12.581	Overturn	2.262	22.59	4.826	27.81
	45	1.606	19.77	9.824	Overturn	11.032	Overturn
60	5	0.741	7.06	0.741	7.06	0.740	7.06
	15	0.967	9.98	0.956	10.00	0.958	10.00
	25	9.704	Overturn	3.042	23.53	3.665	28.34
	35	2.428	18.58	7.094	22.24	12.471	Overturn
	45	8.5726	Overturn	11.662	Overturn	11.875	Overturn

Note: 1 mi = 1.61 km.

or side forces, on the tires and bumper contact with the terrain. Based on these observations, additional runs were made to examine other types of driver response on vehicular stability to ensure that the 8 degree steer input was the more critical case.

Two additional steer input conditions were examined: a locked steering angle option with a 0 degree steer angle, and a "steer degree of freedom option." The first of these simulates the response of a driver who panics and holds the steering wheel fixed with no steer input. The second option simulates the situation where a driver has lost contact with the steering wheel, in which case the steering angle of the tires is determined by the interactive forces between the tires and the terrain. The 50 millisecond average resultant acceleration and maximum roll angle predicted for these steer inputs was shown in Tables 8 through 15. It can be seen that vehicular rollover was not predicted in any of the 0 degree steer angle or the steer degree of freedom runs, and there was no large difference in the severity index value for both cases.

Based on the initial sensitivity study and the follow-up study it was concluded that the panic "return-to-the-road" steer of 8 degrees was the most severe condition. Simulation results with this condition were used in the benefit/cost (B/C) analysis in Chapter V.

The B/C analysis program (*9*) requires severity indices for various combination of encroachment speed and angle. Section V.3 gives details of input requirements and limitations. To obtain more accurate SI versus speed curves, additional HVOSM runs were necessary. Two speeds below 45 mph (72.5 km/hr) (66 ft/sec) (20.1 m/sec) were selected in approximately even speed intervals, 24 mph (38.6 km/hr) (35 ft/sec) (10.7 m/sec) and 34 mph (54.7 km/hr) (50 ft/sec) (15.3 m/sec), and one speed between 45 mph (72.5 km/hr) (66 ft/sec) (20.1 m/sec) and 60 mph (96.5 km/hr) (88 ft/sec) (26.8 m/sec) was selected, 53 mph (85.3 km/hr) (77 ft/sec) (23.5 m/sec). Severity index values were calculated and are shown in Tables 16 through 18.

TABLE 8. HVOSM Simulation of Unrounded Option, Honda Civic with a Steer Angle of 0 Degree

Encroachment Conditions		Side Slope					
Speed (mph)	Angle (deg)	6:1		4:1		3:1	
		Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.198	10.73	0.667	16.01	0.964	21.27
	15	0.668	10.34	1.058	15.26	1.327	20.40
	25	1.047	10.20	1.267	17.26	5.227	27.90
	35	1.657	9.76	5.427	18.33	7.347	20.84
	45	1.380	8.34	6.010	12.51	5.886	12.56
60	5	0.473	10.61	0.847	15.83	1.155	20.93
	15	0.910	10.62	1.499	16.75	3.892	26.28
	25	2.127	11.19	5.647	22.52	7.812	25.17
	35	1.849	11.98	8.388	31.33	8.362	31.24
	45	6.836	9.92	7.802	26.21	7.959	26.14

Note: 1 mi = 1.61 km.

TABLE 9. HVOSM Simulation of 2 ft (0.61 m) Constant Rounding, Honda Civic with a Steer Angle of 0 Degree

Encroachment Conditions		Side Slope					
Speed (mph)	Angle (deg)	6:1		4:1		3:1	
		Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.130	10.49	0.646	15.86	0.974	20.87
	15	0.647	10.35	1.058	15.21	1.640	20.07
	25	1.070	9.94	1.223	15.68	4.442	24.37
	35	1.596	9.46	4.979	16.62	7.903	21.04
	45	1.592	8.14	6.521	12.26	6.445	12.34
60	5	0.463	10.41	0.835	15.68	1.164	20.64
	15	0.913	10.32	1.442	15.98	3.240	23.41
	25	2.025	10.87	4.995	21.34	7.940	24.87
	35	2.036	11.14	8.705	31.23	9.117	31.27
	45	6.887	9.90	8.872	27.08	7.836	26.89

Note: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 10. HVOSM Simulation of 4 ft (1.22 m) Constant Rounding, Honda Civic with a Steer Angle of 0 Degree

Encroachment Conditions		Side Slope					
Speed (mph)	Angle (deg)	6:1		4:1		3:1	
		Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.129	10.34	0.678	15.61	0.972	20.67
	15	0.644	10.32	1.072	15.29	1.788	19.98
	25	1.026	9.81	1.167	14.97	4.892	21.51
	35	1.573	9.18	4.990	14.34	5.871	16.67
	45	1.884	8.03	6.562	11.59	6.501	12.05
60	5	0.446	10.28	0.838	15.50	1.179	20.42
	15	0.940	10.15	1.300	15.55	2.719	21.56
	25	2.010	10.43	4.972	19.01	7.019	23.06
	35	2.220	10.41	7.758	31.42	8.690	31.22
	45	6.965	9.70	7.814	27.31	8.046	27.37

Note: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 11. HVOSM Simulation of Optimum Rounding, Honda Civic with a Steer Angle of 0 Degree

Encroachment Conditions		Side Slope					
Speed (mph)	Angle (deg)	6:1		4:1		3:1	
		Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.128	10.25	0.826	15.15	0.967	20.04
	15	0.649	10.24	1.490	15.00	1.891	19.86
	25	1.026	9.72	4.035	15.46	3.408	18.51
	35	1.603	9.13	8.104	26.08	6.641	14.68
	45	1.937	8.09	9.303	22.56	5.461	10.89
60	5	0.453	10.16	0.671	15.18	1.199	19.88
	15	0.944	10.16	1.108	15.21	2.693	19.61
	25	1.986	10.14	1.904	14.30	5.632	18.94
	35	2.251	10.14	4.011	13.25	8.213	27.07
	45	6.591	8.72	5.725	10.91	8.588	22.90

Note: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 12. HVOSM Simulation of Unrounded Option, Honda Civic with the Steer Degree of Freedom

Encroachment Conditions		Side Slope					
Speed (mph)	Angle (deg)	6:1		4:1		3:1	
		Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.714	10.59	0.808	16.01	1.113	21.73
	15	0.827	10.21	1.179	35.00	1.568	20.29
	25	1.338	10.23	1.461	17.28	5.315	27.97
	35	1.641	9.82	5.298	18.39	7.407	21.00
	45	1.375	9.29	5.985	12.56	6.109	12.61
60	5	1.200	14.49	1.708	22.03	1.164	23.25
	15	1.161	10.63	1.518	16.74	3.877	26.29
	25	2.150	12.42	5.426	22.63	7.765	25.32
	35	1.872	12.02	8.080	31.32	8.923	31.24
	45	6.997	23.20	7.672	26.60	7.733	26.30

Note: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 13. HVOSM Simulation of 2 ft (0.61 m) Constant Rounding, Honda Civic with the Steer Degree of Freedom

Encroachment Conditions		Side Slope					
		6:1		4:1		3:1	
Speed (mph)	Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.703	10.57	0.835	15.62	1.071	20.86
	15	0.782	10.24	1.553	15.29	1.532	19.98
	25	1.332	9.96	1.301	15.68	4.394	24.38
	35	1.597	9.52	4.800	16.68	8.213	21.66
	45	1.559	11.92	6.623	12.31	6.363	12.39
60	5	1.045	13.78	1.457	17.72	1.405	23.03
	15	1.177	10.29	1.473	15.97	3.025	23.35
	25	2.127	11.55	5.025	21.41	8.239	25.02
	35	2.012	22.72	9.452	31.29	9.066	31.29
	45	7.059	68.50	8.906	27.30	7.789	27.19

Note: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 14. HVOSM Simulation of 4 ft (1.22 m) Constant Rounding, Honda Civic with the Steer Degree of Freedom

Encroachment Conditions		Side Slope					
		6:1		4:1		3:1	
Speed (mph)	Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.681	10.26	0.837	15.13	1.131	20.34
	15	0.756	10.27	1.104	15.42	1.808	20.02
	25	1.337	9.81	1.162	14.96	4.983	21.51
	35	1.595	9.24	4.972	14.42	5.872	16.75
	45	1.337	9.81	6.596	11.64	6.324	12.10
60	5	0.918	12.91	1.140	16.93	1.319	22.28
	15	1.180	10.16	1.317	15.56	2.932	21.52
	25	2.152	11.02	4.887	19.10	7.756	23.18
	35	2.095	10.45	8.163	31.45	8.511	31.45
	45	6.792	9.73	7.817	27.75	8.085	27.50

Note: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 15. HVOSM Simulation of Optimum Rounding, Honda Civic with the Steer Degree of Freedom

Encroachment Conditions		Side Slope					
Speed (mph)	Angle (deg)	6:1		4:1		3:1	
		Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)	Maximum 50 ms Resultant Acceleration (g's)	Maximum Roll Angle (deg)
45	5	0.721	9.90	0.775	14.86	1.057	18.99
	15	0.728	10.32	1.099	49.25	2.134	20.66
	25	1.340	9.64	1.911	14.36	3.353	18.61
	35	1.542	9.19	3.806	13.37	6.373	14.77
	45	1.828	8.17	5.322	10.98	5.688	10.96
60	5	0.939	12.97	1.077	13.90	1.385	16.31
	15	1.135	10.08	1.467	15.36	2.583	19.93
	25	1.988	10.61	4.263	15.53	6.071	19.06
	35	2.319	10.21	8.080	27.40	8.198	27.51
	45	6.469	8.76	8.802	22.81	9.345	23.13

Note: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 16. Severity Indices of Vehicular Encroachment on a Side Slope of 6:1

Roadside terrain	Encroachment Speeds (mph)	Encroachment Angle (degrees)				
		5	15	25	35	45
Unrounded Slope	24	0.162	0.169	0.176	0.293	0.368
	34	0.212	0.217	0.340	0.439	0.562
	45	0.214	0.225	0.522	0.585	0.508
	53	0.216	0.277	0.513	0.509	0.835
	60	0.216	0.422	0.539	0.625	7.000
2 ft constant Rounding	24	0.162	0.169	0.176	0.248	0.367
	34	0.212	0.217	0.282	0.446	0.507
	45	0.214	0.225	0.498	7.000	0.506
	53	0.216	0.256	0.504	0.515	0.820
	60	0.216	0.345	0.595	0.648	7.000
4 ft constant Rounding	24	0.162	0.169	0.176	0.215	0.366
	34	0.212	0.217	0.275	0.444	0.476
	45	0.214	0.225	0.437	7.000	0.529
	53	0.216	0.262	0.490	0.667	0.827
	60	0.216	0.324	0.548	0.690	7.000
Optimum Rounding	24	0.162	0.169	0.176	0.204	0.364
	34	0.212	0.217	0.272	0.433	0.469
	45	0.214	0.225	0.443	7.000	0.566
	53	0.216	0.265	0.504	0.715	0.780
	60	0.216	0.319	7.000	0.683	7.000

Notes: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 17. Severity Indices of Vehicular Encroachment on a Side Slope of 4:1

Roadside terrain	Encroachment Speeds (mph)	Encroachment Angle (degrees)				
		5	15	25	35	45
Unrounded Slope	24	0.162	0.169	0.176	0.396	0.552
	34	0.212	0.217	0.411	0.760	0.933
	45	0.214	0.225	7.000	1.001	7.000
	53	0.216	0.260	7.000	2.029	7.000
	60	0.216	0.601	1.022	7.000	7.000
2 ft constant Rounding	24	0.162	0.169	0.176	0.308	0.541
	34	0.212	0.217	0.289	0.739	0.838
	45	0.214	0.225	7.000	1.172	7.000
	53	0.216	0.251	7.000	1.494	7.000
	60	0.216	7.000	1.386	7.000	7.000
4 ft constant Rounding	24	0.162	0.169	0.176	0.239	0.527
	34	0.212	0.217	0.278	0.668	0.770
	45	0.214	0.225	0.661	1.237	7.000
	53	0.216	0.256	0.949	7.000	7.000
	60	0.216	0.363	1.017	7.000	7.000
Optimum Rounding	24	0.162	0.169	0.176	0.203	0.456
	34	0.212	0.217	0.272	0.543	0.734
	45	0.214	0.225	0.457	1.006	7.000
	53	0.216	0.265	0.650	7.000	7.000
	60	0.216	0.319	0.836	1.798	7.000

Notes: 1 mi = 1.61 km, 1 ft = 0.305 m.

TABLE 18. Severity Indices of Vehicular Encroachment on a Side Slope of 3:1

Roadside terrain	Encroachment Speeds (mph)	Encroachment Angle (degrees)				
		5	15	25	35	45
Unrounded Slope	24	0.162	0.169	0.176	0.625	0.880
	34	0.212	0.217	0.531	1.388	7.000
	45	0.214	0.225	7.000	7.000	1.941
	53	0.216	0.307	1.590	7.000	7.000
	60	0.216	7.000	3.655	7.000	7.000
2 ft constant Rounding	24	0.162	0.169	0.176	0.396	1.032
	34	0.212	0.217	0.314	1.369	7.000
	45	0.214	0.225	7.000	7.000	2.286
	53	0.216	0.247	2.040	7.000	7.000
	60	0.216	7.000	3.160	7.000	7.000
4 ft constant Rounding	24	0.162	0.169	0.176	0.270	0.830
	34	0.212	0.217	0.283	1.282	1.771
	45	0.214	0.225	7.000	7.000	7.000
	53	0.216	0.254	1.344	7.000	7.000
	60	0.216	7.000	2.758	7.000	7.000
Optimum Rounding	24	0.162	0.169	0.176	0.204	0.461
	34	0.212	0.217	0.270	0.555	0.787
	45	0.214	0.224	0.448	1.857	7.000
	53	0.216	0.265	7.000	1.711	7.000
	60	0.216	0.322	1.542	7.000	7.000

Notes: 1 mi = 1.61 km, 1 ft = 0.305 m.

CHAPTER V
BENEFIT/COST ANALYSIS

A Benefit/Cost program developed at TTI (*9*) was used to evaluate various slope rounding options, and ultimately to develop recommendations for rounding as a function of roadway type and traffic volume. The program employs an encroachment probability model to predict accident frequency and severity. Based on this model, a certain percentage of vehicles will inadvertently leave the travel way. The program provides an estimate of the number and severity of all run-off-the-road encroachments predicted to occur over a given length of roadway for a given period of time on each type of roadway. The B/C methodology compares the benefits with direct costs associated with each roadside safety treatment.

Benefits are measured in terms of reductions in accident costs. Direct costs are those associated with the initial cost, maintenance, and accident repair costs of a safety treatment. Equation 14 is used to determine if a safety improvement is cost beneficial.

$$BC_{2-1} = (SC_1 - SC_2)/(DC_2 - DC_1) \tag{14}$$

where BC_{2-1} = Benefit-Cost ratio of alternative 1 compared with alternative 2;
SC_1 = Annualized societal cost of alternative 1;
DC_1 = Annualized direct cost of alternative 1;
SC_2 = Annualized societal cost of alternative 2;
DC_2 = Annualized direct cost of alternative 2;

Note that alternative 2 is normally considered to be an improvement relative to alternative 1.

The following assumptions were made in the B/C analysis related to the program input data:

(1) average Daily Traffic (ADT) increases at an annual rate of 3%;
(2) speed limits are 55 mph (88.6 km/hr) for rural arterials and 65 mph (104.7 km/hr) for freeways;
(3) service life for all alternatives is 20 years;
(4) the discount rate is 4%;
(4) roadway is straight with no horizontal or vertical curves;
(5) traffic delay cost associated with predicted accidents is negligible;

(6) maintenance costs for all alternatives is the same and therefore can be neglected;
(7) salvage value for all alternatives is negligible;
(8) accident repair cost for all alternatives is negligible; and
(9) effects of traffic mix is negligible.

V.1 Candidate Treatments

A total of 4 alternatives were considered: the do-nothing or unrounded option, constant rounding with d_x = 2 ft (0.61 m), constant rounding with d_x = 4 ft (1.22 m), and optimum rounding. Three side slopes were considered: 6:1, 4:1, and 3:1. In order of increasing improvement and increasing cost, the options were:

(1) unrounded (do nothing);
(2) constant rounding with d_x = 2 ft (0.61 m);
(3) constant rounding with d_x = 4 ft (1.22 m); and
(4) optimum rounding.

V.2 Costs

Costs consist of societal and direct costs. The severity index was used to quantify societal costs associated with each predicted accident. Table 19, taken from 1989 AASHTO "Roadside Design Guideline" (*10*), shows the relationship between severity index and accident costs.

Direct costs are those associated with initial cost, maintenance, and accident repair cost. Increased costs for designs that include slope rounding as compared with those that do not were provided by Minnesota Department of Transportation. Estimated unit costs used in determining initial cost of all options were as follows:

Average borrow costs:	\$3.39/yd^3 (\$4.43/m^3)
Average right-of-way costs:	\$2,000/ac (\$4,938/ha) for agricultural property
	\$5,000/ac (\$12,346/ha) for residential property
	\$10,000/ac (\$24,691/ha) for commercial property

The scope of the study was limited to an analysis of freeways and rural arterials. Further, most slope rounding needs for freeways will occur in rural areas. It is believed the need for slope rounding is more prevalent on these roadway types than on urban roadways or lower service level roadways. Since rural conditions were assumed, right of way costs for agricultural property were used in the B/C analysis.

TABLE 19. Severity Index and Cost by Accident Type Distribution (*9*)

Severity Index	Property Damage (1)	Property Damage (2)	Slight Injury	Moderate Injury	Severe Injury	Fatal Injury	Accident Cost ($)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	000
0.5	100.0	0.0	0.0	0.0	0.0	0.0	500
1.0	66.0	23.7	7.3	2.3	0.0	0.0	1,375
2.0	0.0	71.0	22.0	7.0	0.0	0.0	3,135
3.0	0.0	43.0	34.0	21.0	1.0	1.0	10,295
4.0	0.0	30.0	30.0	32.0	5.0	3.0	25,350
5.0	0.0	15.0	22.0	45.0	10.0	8.0	56,535
6.0	0.0	7.0	16.0	39.0	20.0	18.0	116,555
7.0	0.0	2.0	10.0	28.0	30.0	30.0	186,150
8.0	0.0	0.0	4.0	19.0	27.0	50.0	281,720
9.0	0.0	0.0	0.0	7.0	18.0	75.0	395,500
10.0	0.0	0.0	0.0	0.0	0.0	100.0	500,000

Based on the aforementioned data and cross sections as shown in Figures 5 and 6, incremental cost per mile per side of the highway were estimated for rounded slopes compared to unrounded slopes. Note that initial cost of the unrounded option was assumed to be zero. To illustrate computation of the incremental cost consider the following example for constant rounding with d_x = 2 ft (0.61 m), on a 6:1 side slope:

<u>Borrow cost:</u>

Additional fill or borrow required for the slope is shown in Figure 7. A computer program was written to compute the additional fill, given the cross-section parameters. The volume per mile for the given example is determined as follows:

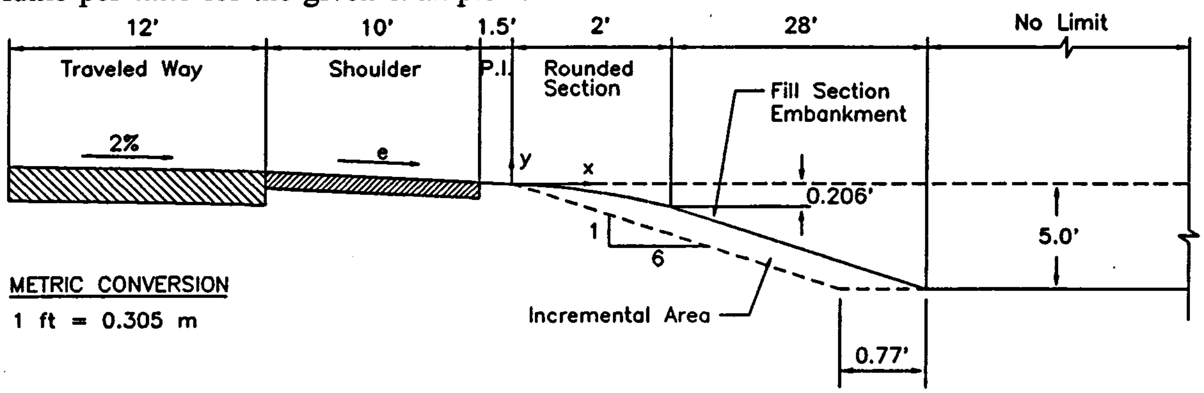

FIGURE 7 Example of additional fill or borrow area required for 2 ft (0.61 m) constant rounding.

3.79 ft^2 (0.352 m^2) x 5,280 ft/mi (1,000 m/km) = 20,011 ft^3/mi (352 m^3/km) = 741.2 yd^3/mi (352 m^3/km).

Then, borrow cost is determined as follows:

741.2 yd^3/mi (352 m^3/km) x \$3.39/yd^3 (\$4.43/m^3) = \$2,513/mi (\$1,560/km).

<u>Right-of-way cost:</u>

Additional right of way required is determined as follows:

0.77 ft (0.235 m) x 5,280 ft/mi (1,000 m/km) = 4,065.6 ft^2/mi (235 m^2/km) = 0.0933 ac/mi (0.0235 ha/km).

Then, right-of-way cost is determined as follows:

0.0933 ac/mi (0.0235 ha/km) x \$2,000/ac (\$4,938/ha) = \$187/mi (\$116/km).

<u>Total incremental cost:</u>

The total incremental cost for this example is as follows:

\$2,513/mi (\$1,560/km) + \$187/mi (\$116/km) = \$2,700/mi (\$1,676/km).

Table 20 summarizes borrow costs, right-of-way costs, and total incremental costs of the safety alternatives for each of the three side slopes and each of the three rounded options.

V.3 Construction of Severity Index Curves

Severity index data obtained from simulation runs, and presented in Section IV.2, could not be used directly in the B/C program because of input restrictions. SI data is input according to the form shown in Figure 8. Note that five input parameters are necessary to describe the SI versus encroachment speed curve for a given encroachment angle, Θ. As shown, the SI is assumed to vary in a piecewise linear manner over three speed ranges.

For a given encroachment angle, vehicular behavior (and hence SI values) varied in a somewhat erratic fashion with speed for some encroachments onto the rounded and unrounded options. For certain side slope options, overturn was predicted at an intermediate speed, say 45 mph (72.5 km/hr), but the vehicle was predicted to be stable at higher and lower speeds. SI values at speeds below and above the overturn speed were relatively small compared to the 7 assumed for an overturn. This erratic response pattern was attributed primarily to the effect the toe of the side slope (juncture of side slope with the flat bottom ditch) had on vehicular response. As a general rule, overturn was caused by a combination of the roll and roll rate of the vehicle due to cornering forces on the tires in combination with tripping forces due to bumper contact with the terrain in the region of the toe of the side slope.

When such behavior was predicted, it was necessary to make assumptions and approximations to meet SI input requirements of the B/C program. First, it was assumed that the SI remained at 7 for all speeds at or greater than the initial overturn speed. The rationale for this assumption is as follows: (a) the propensity for vehicular overturn on an embankment is believed to be speed dependent, i.e., the greater the speed the greater the potential for overturn, (b) hypothetical conditions were assumed for the side slope and ditch (smooth surface with no obstacles) and for the driver's reaction (variations in these conditions obviously occur in practice which could adversely affect vehicular behavior and stability), and (c) the assumption is believed to be conservative in the sense that it probably overpredicts overturns. Secondly, it was necessary to approximate the initial portion of the SI versus speed curve. The manner in which this was done is illustrated by the following example.

Shown in Figure 9 are data points determined from the simulation program for the indicated slope option and encroachment angle, with straight lines connecting the points. Shown

TABLE 20. Incremental Costs for Safety Alternatives

Side Slope	Safety Alternative	Borrow Cost ($/mi)	Right-of-Way Cost ($/mi)	Total Incremental Cost ($/mi)
6:1	Constant Rounding, d_x = 2 ft	2,513	187	2,700
	Constant Rounding, d_x = 4 ft	4,979	371	5,350
	Optimum Rounding, d_x = 6.5 ft	7,913	597	8,510
4:1	Constant Rounding, d_x = 2 ft	2,793	207	3,000
	Constant Rounding, d_x = 4 ft	5,507	413	5,920
	Optimum Rounding, d_x = 10.8 ft	13,966	1,094	15,060
3:1	Constant Rounding, d_x = 2 ft	2,951	219	3,170
	Constant Rounding, d_x = 4 ft	5,801	439	6,240
	Optimum Rounding, d_x = 15.0 ft	19,412	2,038	21,450

Notes: 1 ft = 0.305 m, 1 mi = 1.61 km.

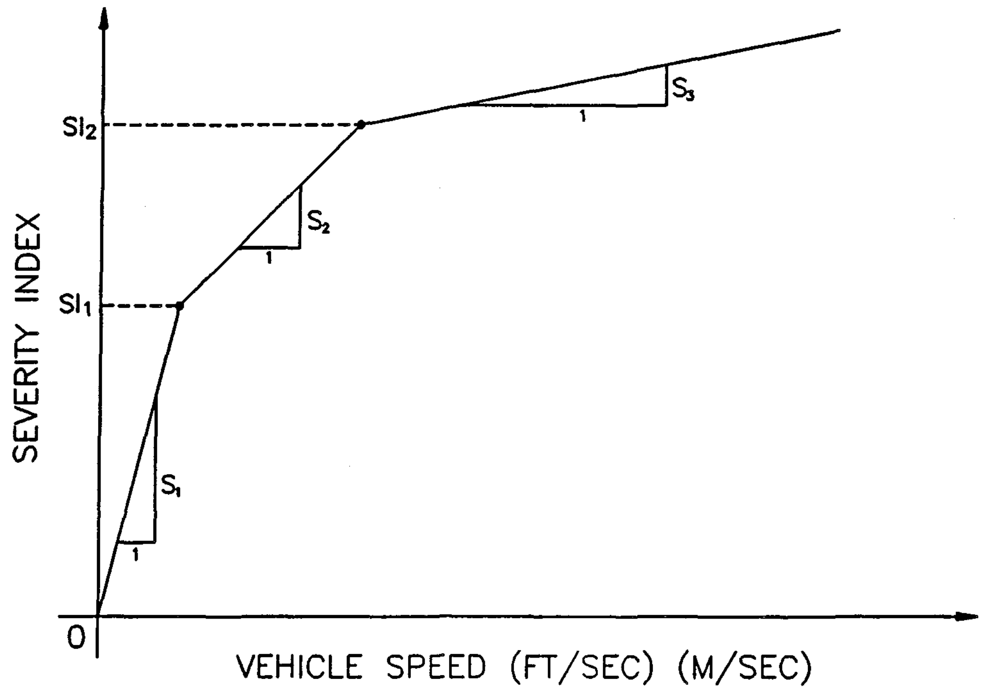

FIGURE 8. SI versus speed curve parameters required by B/C program.

in Figure 10 are the approximations made to fit the input requirements of the B/C program. Note that a straight line is fitted, using a linear regression procedure, to data points between 0 and 66 ft/sec (20.1 m/sec) (45 mph) (72.5 km/hr); from that point a straight line connects the end point of the initial line to the point having SI of 7 at a speed of 77 ft/sec (23.5 m/sec) (53 mph) (85.3 km/hr); and from that point it is assumed the SI remains constant for all higher speeds.

For those encroachment angles for which overturn did not occur at any speed, judgement was used in fitting three straight lines to the data points. As an example, Figure 11 shows data points determined from the simulation program for the indicated slope option and encroachment angle, with straight lines connecting the data points. Shown in Figure 12 are the approximations made to fit the input requirements of the B/C program. A complete set of SI versus speed relationships so determined is given in Appendix B.

V.4 Results of B/C Analysis

Analysis of the options and selection of recommended treatments were based on an incremental B/C analysis. In this procedure B/C ratios were determined by comparing each rounded option with the unrounded option, and then with each other. Steps in the procedure are as follows:

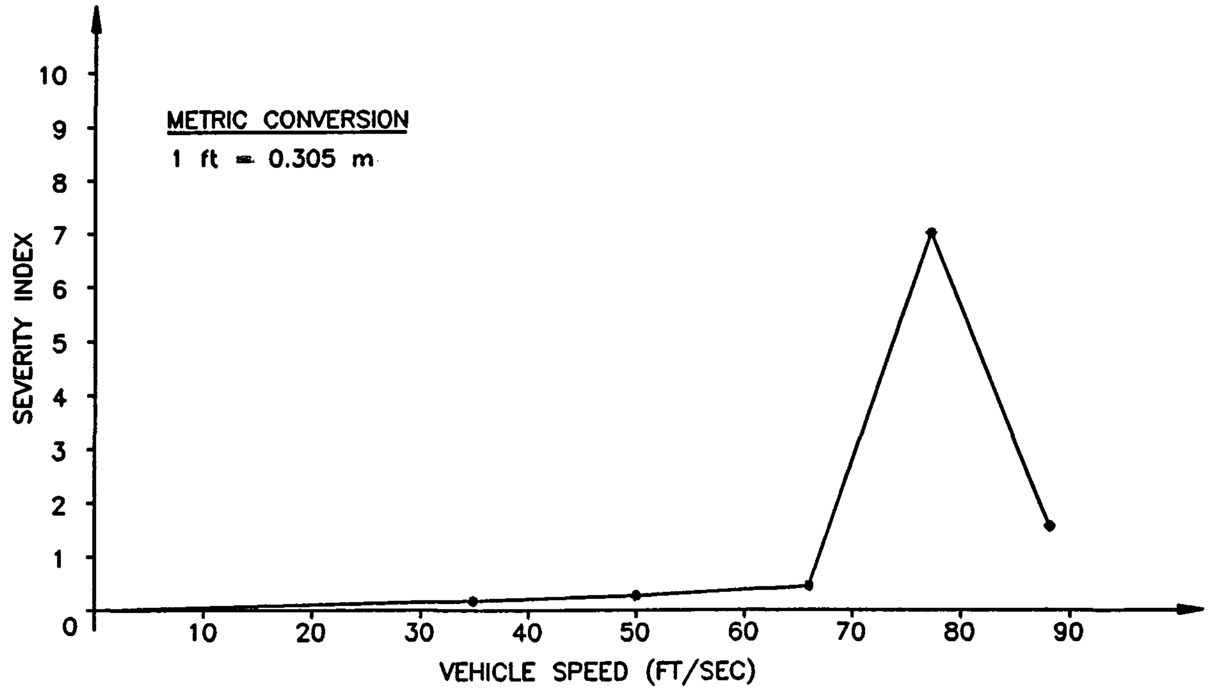

FIGURE 9. Severity indices determined from the HVOSM program for optimum rounding, side slope = 3:1, and encroachment angle = 25 degrees.

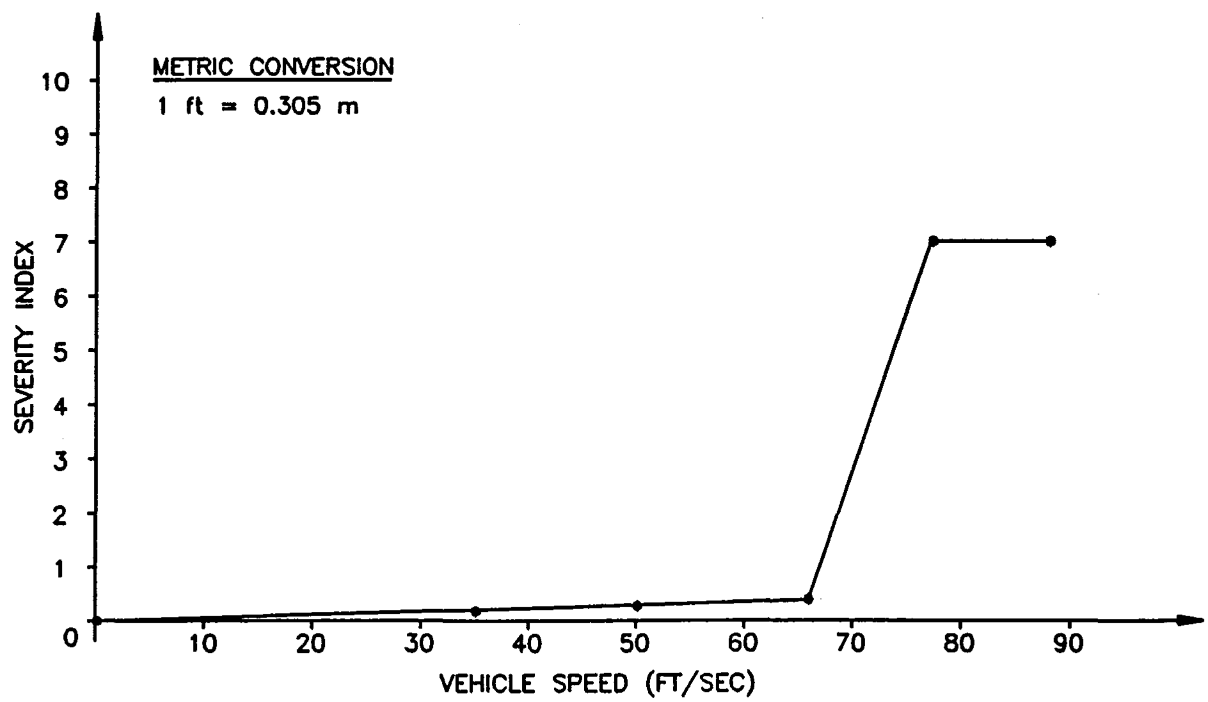

FIGURE 10. Approximations of severity indices from the HVOSM program for optimum rounding, side slope = 3:1,and encroachment angle = 25 degrees.

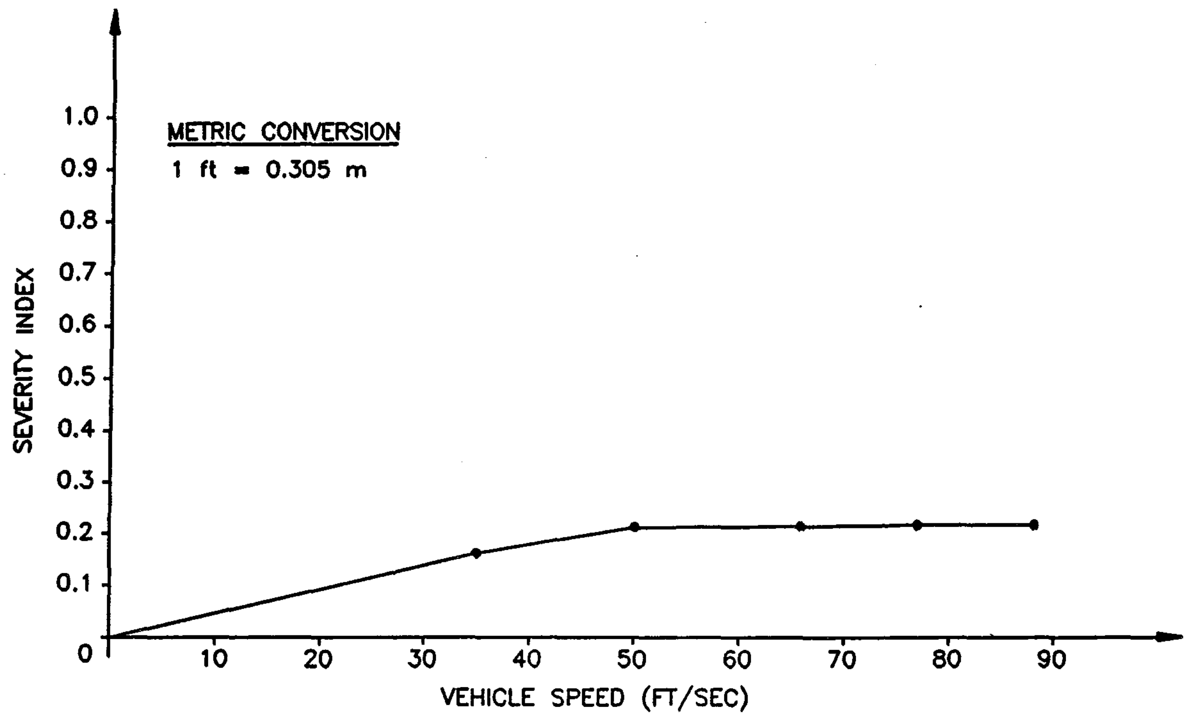

FIGURE 11. Severity indices determined from the HVOSM program for unrounded option, side slope = 3:1, and encroachment angle = 5 degrees.

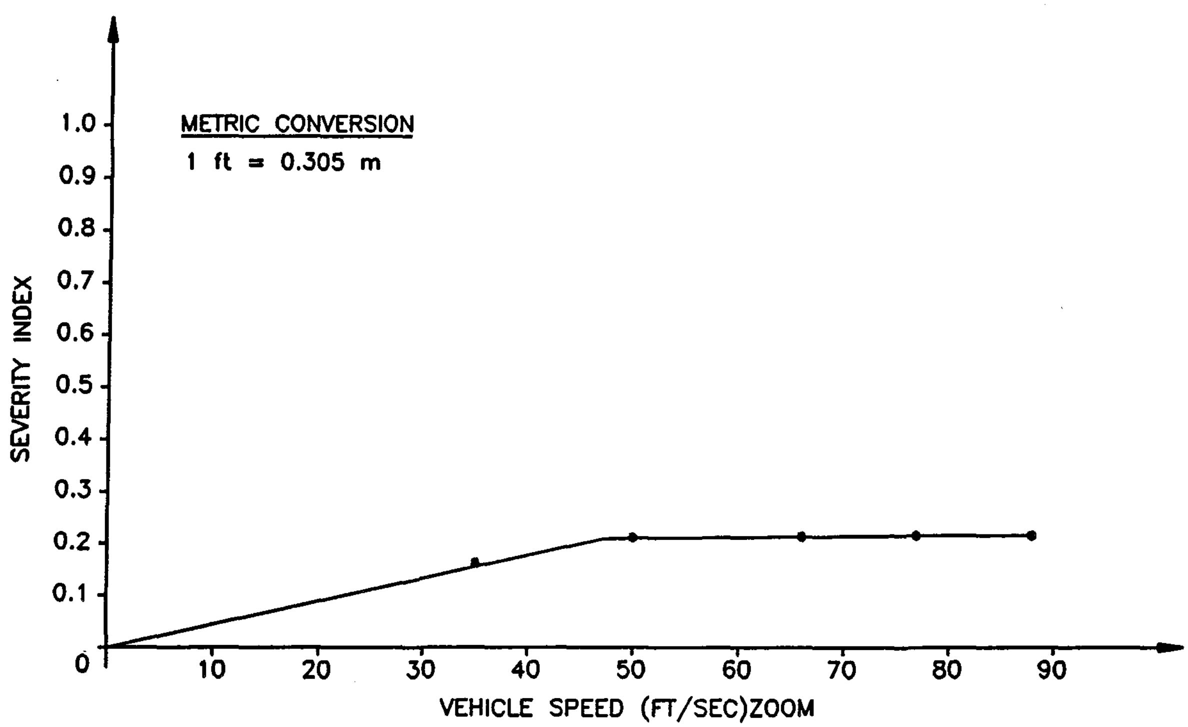

FIGURE 12. Approximations of severity indices from the HVOSM program for unrounded option, side slope = 3:1, and encroachment angle = 5 degrees.

(1) For a given ADT, the B/C ratio of each rounding alternative with respect to the unrounded or do-nothing option is determined. If the B/C ratio for any given alternative is less than 1.0, the option is not cost beneficial for the ADT being investigated. Table 21 summarizes traffic volume ranges at which each alternative is cost beneficial for different roadway type and side slope combinations, using the unrounded option as the base option. Note that constant rounding with d_x = 2 ft (0.61 m) is not cost effective for rural arterials and thus is eliminated from further consideration for this roadway class. The B/C ratios for constant rounding with d_x = 4 ft (1.22 m) and optimal rounding exceed unity (i.e. become cost beneficial with respect to the unrounded option) at ADT's of 140 and 360, respectively. The curves used in generating Table 21 are presented in Appendix D.

TABLE 21. Range of Traffic Volume (ADT) at Which Given Option Is Cost Beneficial, Based on B/C Ratios of Rounded to Unrounded Alternatives

Option	2-Lane Rural Arterial			4-Lane Freeway		
	6:1[a]	4:1[a]	3:1[a]	6:1[a]	4:1[a]	3:1[a]
Unrounded Option	>0	<140	<310	>0	<120	<300
2 ft Rounding	N/A	N/A	N/A	N/A	≥21,200	≥27,100
4 ft Rounding	N/A	≥140	≥490	N/A	≥120	≥470
Optimum Rounding	N/A	≥360	≥310	N/A	≥310	≥300

[a] Side slope.
Notes: N/A - Not Applicable.
1 ft = 0.305 m.

(2) The alternatives which were determined to be cost effective with respect to the do-nothing option are then compared to each other using an incremental B/C analysis. The incremental benefit/cost ratio is defined as the ratio of the additional benefit to the additional cost between two alternatives. This ratio is computed for each combination of more expensive alternatives to less expensive alternatives. Tables 22 and 23 summarize the traffic volumes at which one rounding alternative becomes cost beneficial with respect to another more expensive rounding alternative. The

B/C ratio versus ADT curves used in the development of these tables are shown in Appendix D.

TABLE 22. Range of Traffic Volume (ADT) at Which Given Option Is Cost Beneficial, Based on Incremental B/C Ratios of More Expensive Rounding Option to 2 ft (0.61 m) Rounding

Option	4-Lane Freeway		
	6:1[a]	4:1[a]	3:1[a]
2 ft Rounding	N/A	<60	<230
4 ft Rounding	N/A	≥60	≥230
Optimum Rounding	N/A	≥250	≥260

[a] Side slope.
Notes: N/A - Not Applicable.
1 ft = 0.305 m.

TABLE 23. Range of Traffic Volume (ADT) at Which Given Option Is Cost Beneficial, Based on Incremental B/C Ratios of Optimum Rounding to 4 ft (1.22 m) Rounding

Option	2-Lane Rural Arterial			4-Lane Freeway		
	6:1[a]	4:1[a]	3:1[a]	6:1[a]	4:1[a]	3:1[a]
4 Feet Rounding	N/A	>0	<270	N/A	>0	<270
Optimum Rounding	N/A	N/A	≥270	N/A	N/A	≥270

[a] Side slope.
Notes: N/A - Not Applicable.
1 ft = 0.305 m.

(3) Results of the incremental B/C analysis are then used to select the most cost beneficial alternative for a given set of roadway and roadside conditions. If the incremental B/C ratio between two rounding alternatives is less than 1.0, the higher cost alternative is not cost beneficial for the given ADT and the next alternative is considered. For example, given that alternatives 2, 3, and 4 are all cost beneficial with respect to alternative 1 (the do-nothing option) for a given ADT, the incremental B/C ratio between alternatives 3 and 2 (3:2) would be checked. If this B/C ratio is less than 1.0, alternative 3 is dropped and the incremental B/C ratio

between alternatives 4 and 2 (4:2) is checked. If alternative 4 is found to be cost beneficial with respect to alternative 2 (i.e. 4:2 $\geq$ 1.0), alternative 4 is selected. If the ratio of 4:3 is less than 1.0, alternative 4 is not cost beneficial and alternative 2 is selected. Following this procedure, the most cost beneficial alternative for a given ADT is selected. This type of analysis is then performed for multiple ADT values within the range of interest to generate recommended guidelines for a given set of roadway and roadside conditions.

To illustrate the selection of the most cost-beneficial alternative using the incremental B/C procedure, consider the following two examples with the alternatives defined as follows:

Alternative 1 = unrounded or do-nothing option

Alternative 2 = constant rounding with d_x = 2 ft (0.61 m)

Alternative 3 = constant rounding with d_x = 4 ft (1.22 m)

Alternative 4 = optimal rounding

Example 1: Given a 4-lane rural freeway with an ADT of 2000 and a 4:1 side slope, the following incremental B/C ratios are obtained:

2/1 $\Rightarrow$ 0.24
3/1 $\Rightarrow$ 12.86
4/1 $\Rightarrow$ 5.06 4/3 $\Rightarrow$ 0.01

Since the B/C ratio of 2/1 is less than 1.0, alternative 2 is not cost beneficial for the given ADT and it is eliminated from further consideration. Since alternatives 3 and 4 are both cost beneficial with respect to the unrounded option (alternative 1), they are compared to each other to determine the most cost effective option. Since the incremental B/C ratio of 4/3 is less than 1.0, alternative 3, constant rounding with d_x = 4 ft (1.22 m), is recommended.

Example 2: Given a 2-lane rural arterial with an ADT of 500 and a 3:1 side slope, the following incremental B/C ratios are obtained:

2/1 $\Rightarrow$ 0.12
3/1 $\Rightarrow$ 1.95
4/1 $\Rightarrow$ 2.98 4/3 $\Rightarrow$ 3.40

As in the above example, alternative 2 is not cost effective. Since the incremental B/C ratio of 4:3 is greater than 1.0, alternative 4, optimal rounding, is recommended.

Recommendations regarding the use of slope rounding based on the above procedure are summarized in the following section.

V.5 Recommended Slope Rounding Guidelines

Results of the B/C analysis were used to develop recommended guidelines for slope rounding. These guidelines, summarized in Table 24 and Figure 13, identify the most cost-beneficial rounding alternative for given combinations of roadway type, side slope, and ADT.

TABLE 24. ADT Range for Recommended Slope Rounding

Option	2-Lane Rural Arterial			4-Lane Freeway		
	6:1[a]	4:1[a]	3:1[a]	6:1[a]	4:1[a]	3:1[a]
Unrounded Option	>0	<140	<310	>0	<120	<300
2 ft Rounding	N/A	N/A	N/A	N/A	N/A	N/A
4 ft Rounding	N/A	≥140	N/A	N/A	≥120	N/A
Optimum Rounding	N/A	N/A	≥310	N/A	N/A	≥300

[a] Side slope.
Notes: N/A - Not Applicable.
1 ft = 0.305 m.

In examining these guidelines within the assumed conditions, certain general observations can be made.

(a) Constant rounding with d_x = 2 ft (0.61 m) is not a cost beneficial option. Incremental benefits achieved over the unrounded option are too small to justify the additional expense.

(b) It is not cost beneficial to round a 6:1 side slope, regardless of roadway type and traffic volume.

(c) As the steepness of the side slope increases beyond a 6:1 slope, constant rounding with d_x = 4 ft (1.22 m) and optimal rounding become cost beneficial.

(d) The constant rounding option with d_x = 4 ft (1.22 m) is cost beneficial for all ADT's in excess of 120-140 for 4:1 side slopes for both rural arterials and freeways. Since it is expected that practically all freeways have ADT's in excess of this range, the 4 ft (1.22 m) constant rounding appears to be cost beneficial on all freeways having 4:1 side slopes.

(e) The optimum rounding option is cost beneficial for all ADT's in excess of 300-310 for 3:1 side slopes for both rural arterials and freeways. Since it is expected that practically all freeways have ADT's in excess of this range, optimum rounding appears to be cost beneficial on all freeways having 3:1 side slopes.

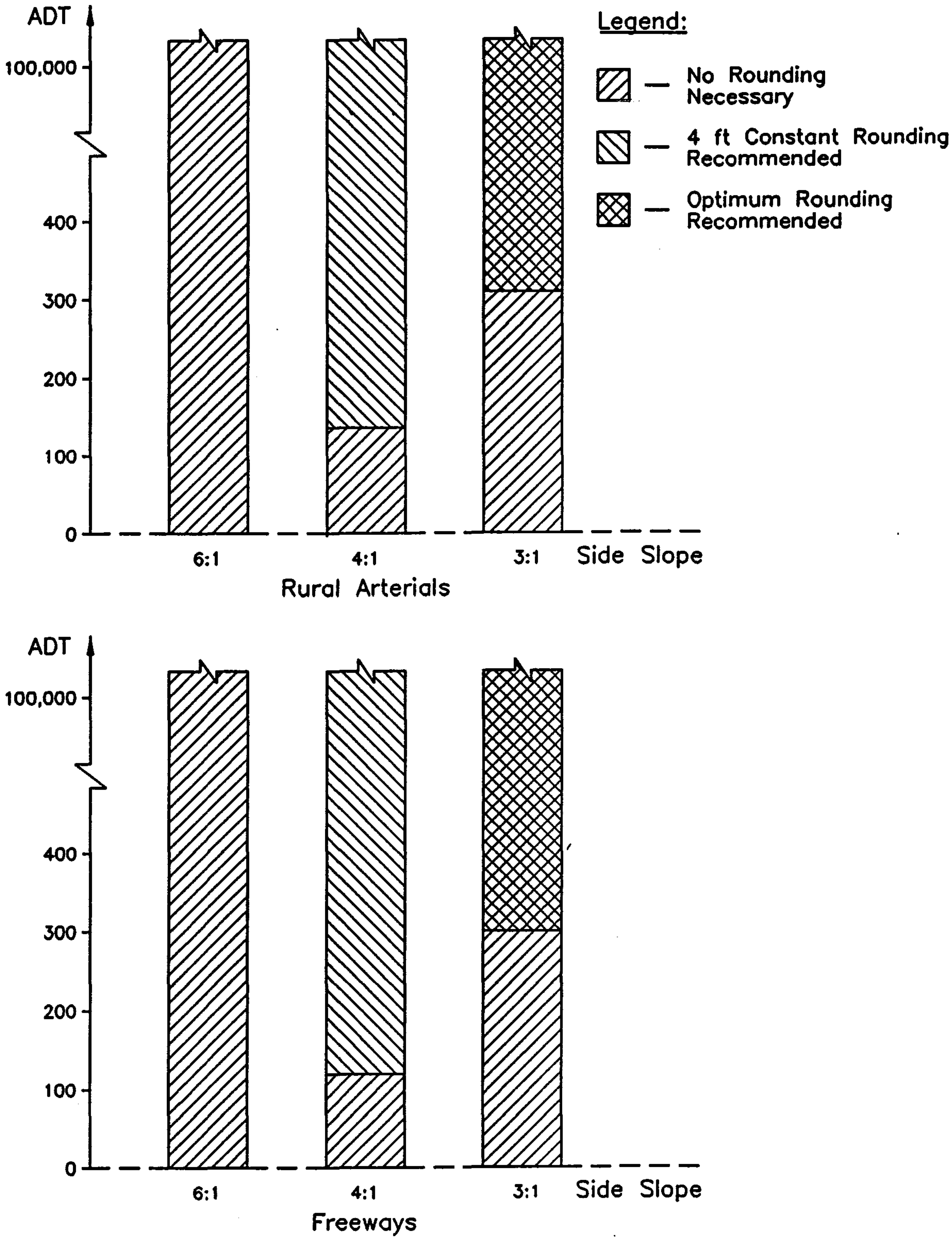

FIGURE 13. Slope rounding recommendations.

The use of Table 24 in determining a recommended slope-rounding option requires only basic information such as roadway classification, ADT, and roadside slope. For example, consider a 2-lane rural arterial with a roadside slope of 3:1. Referring to Table 24, if the ADT on the roadway segment of interest is less than 310, an unrounded hinge is acceptable. For ADT's above 310, the optimum rounding option is indicated.

It should be noted, however, that due to the probabilistic nature of the B/C analysis and the assumptions inherent therein, a certain degree of judgment should be exercised in the application of these guidelines. The information summarized in Table 24 is intended to provide guidance to highway engineers in the selection of a roadside slope treatment and some flexibility in the application of these guidelines is considered acceptable.

CHAPTER VI
CONCLUSIONS AND RECOMMENDATIONS

VI.1 Conclusions

This study was undertaken to evaluate benefits of rounding the hinge at the intersection of a shoulder and a side slope, for freeways and rural arterials. The study approach consisted of (a) identification of parameters to be evaluated, (b) HVOSM computer simulations of vehicular encroachments to estimate occupant risk on the rounded and unrounded side slopes, (c) an incremental benefit/cost (B/C) analysis of rounded versus unrounded side slopes, and (d) development of slope rounding guidelines for freeway and rural arterial roadways. The budget and scope of the study limited the evaluation to selected cross-sectional parameters, design vehicles, vehicular encroachment conditions, and driver response to roadside encroachments. Key assumptions made in the analysis were: (a) the travelway was straight and level, (b) the ditch was flat bottomed with a depth of 5 ft (1.53 m), (c) there was no rounding at the toe of the side slope, (d) costs for added fill and right of way to accommodate rounding were based on rural or agricultural conditions, (e) the design vehicle was a small car, and (f) upon leaving the travelway a driver will initiate a panic steer-back- to-the-road maneuver without braking. Variables examined included side slope, degree of hinge rounding, traffic volume, and roadway type.

Guidelines were developed to identify ADT ranges for which rounding becomes cost beneficial for a roadway type. Based on results of the study, and recognizing the limitations inherent therein, the following conclusions were made:

(a) Constant rounding with d_x = 2 ft (0.61 m) is not a cost beneficial option for any of the conditions considered. Incremental benefits achieved over the unrounded option are too small to justify the additional expense.

(b) It is not cost beneficial to round a 6:1 side slope, regardless of roadway type and traffic volume.

(c) As the steepness of the side slope increases beyond a 6:1 slope, constant rounding with d_x = 4 ft (1.22 m) and optimal rounding become cost beneficial.

(d) The constant rounding option with d_x = 4 ft (1.22 m) is cost beneficial for all ADT's in excess of 120-140 for 4:1 side slopes for both rural arterials and freeways. Since it is expected that practically all freeways have ADT's in excess of this range, the 4 ft (1.22 m) constant rounding appears to be cost beneficial on all freeways having 4:1 side slopes.

(e) The optimum rounding option is cost beneficial for all ADT's in excess of 300-310 for 3:1 side slopes for both rural arterials and freeways. Since it is expected that practically all freeways have ADT's in excess of this range, optimum rounding appears to be cost beneficial on all freeways having 3:1 side slopes.

Due to the limited scope of the study, the probabilistic nature of the B/C analysis, and the necessary assumptions, judgment should be exercised in the application of the study findings. Further study may reveal other alternatives are more cost beneficial and preferred. For example, in lieu of slope rounding other options not studied that may be cost beneficial include widening the travelway and/or shoulder, or flattening the side slope (e.g., flattening a 4:1 slope to a 6:1 slope). The stated limitations notwithstanding, the guidelines provide valuable insight on effects important parameters have on benefits of slope rounding, and as such will offer guidance to those responsible for roadside design policies and procedures.

VI.2 Recommendations for Further Study

The following items should be considered in further studies of slope rounding:

(a) Other options should be evaluated as alternatives to or used in conjunction with slope rounding, including widening the travelway and/or shoulder, or flattening the side slope.

(b) Effects of rounding the toe of the slope should be studied. Results of the present study indicate that the toe of the slope is critical with regard to vehicular stability; most of the predicted overturns occurred due to vehicular interaction with the toe. However, from a practical viewpoint, maintaining a well rounded toe may be difficult due to ditch erosion. It is believed that the non-rounded toe assumed in the present study tends to replicate an eroded ditch bottom.

(c) Effects of different ditch sections, and ditch depths should be studied.

(d) Effects of borrow and right-of-way costs should be examined. In the present study, costs for rural or agricultural conditions were assumed. As these costs escalate benefits of rounding decrease.

(e) Effects of slope rounding on horizontal curves should be studied. A disproportionate number of ran-off-the-road accidents occur in curves, and rounding may provide added benefits compared to straight sections of roadway.

(f) Certain assumptions made in the present analysis are believed to be conservative in that they probably result in an overstatement of encroachment severity. For example, the small car design vehicle tends to be more unstable than larger passenger vehicles, and the panic return-to-the-road steer input is probably more critical than other types of driver response (such as full braking, with or without steer input). Future studies should examine the effects of a more realistic, statistical distribution of vehicle types and driver response.

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APPENDIX A
SAMPLE HVOSM COMPUTER SIMULATION INPUT

Sample Hvosm Computer Simulation Input

```
Honda Civic Run-off-the-Road, 60 mph (96.5 km/hr),15 degree
Optimum Rounding, 3:1 Side Slope, 5 ft (1.53 m) Embankment Depth
0.00    5.00    0.001   1.0     0.005   70.0    0.0     0.0     0.0           1
11.0                                                                          2
4.280   .462    .356    386.4   1777.0  7292.0  6007.0  1500.0  108.0         3
37.68   48.92   51.0    51.0    13.26   12.78   0.00    10.875  1421.44       4
133.0   .75             3.47    31.0    0.001   11700.0                       5
115.4   .71             2.68    32.5    0.001   30900.0 36.0    0.000         6
800.0   4.625   15.0    5.67    2409.7  1.197   .7      1.00    -7459.03      7
1.13    -0.060  15.0    0.0     0.00    0.00    0.0     0.00                  8
100.0   109.62  -21.16  1056.   0.000   0.000                                 9
0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0                   10
0.0     0.0     0.0     0.0     0.0     0.0                                   11
-3.0    3.0     0.5                                                           12
-1.5  -1.375-1.25 -1.125-1.0  -0.625-0.3750.0   0.625 1.00  1.45  1.75  2.125
0.0     6.0     0.5     0.0     1.0     1.0                                   13
-8.0  -8.0  -8.0  -8.0  -8.0  -8.0  -8.0  -8.0  -8.0  -8.0  -8.0  -8.0  -8.0
2.0     21.0    18.0                                                          14
  1 0.000  0.000  0.000 12.000  0.240 23.500  0.700 24.438  0.746 25.376  0.809
26.314  0.890 27.252  0.988 28.190  1.103 29.128  1.235 30.066  1.384
31.004  1.550 31.942  1.734 32.880  1.935 33.818  2.153 34.756  2.388
35.694  2.641 36.632  2.911 37.571  3.198 38.509  3.502 45.104  5.700
1045.10 5.700
  2 1000.0 0.000  0.000 12.000  0.240 23.500  0.700 24.438  0.746 25.376  0.809
26.314  0.890 27.252  0.988 28.190  1.103 29.128  1.235 30.066  1.384
31.004  1.550 31.942  1.734 32.880  1.935 33.818  2.153 34.756  2.388
35.694  2.641 36.632  2.911 37.571  3.198 38.509  3.502 45.104  5.700
1045.10 5.700
0103  1.00
0104  1.00
0105  1.00
0106  1.00
0107  1.00
0108  1.00
0109  1.00
0110  1.00
0111  1.00
0112  1.00
0113  1.00
0114  1.00
0115  1.00
0116  1.00
0117  1.00
0118  1.00
0119  1.00
0120  1.00
8.      4000.   0.001   0.25                                                  23
```

```
66.93 30.0  5.68  66.93 -30.0 5.68  59.80 29.65 15.57 59.80 -29.6515.57
59.18 18.50 15.78 59.18 -18.5015.78 -72.2229.65 15.57 -72.22-29.6515.57
278.9    238.08  -2.05   278.9    10.0     2.85                                   26
70.0     203.57  -2.25   70.0     10.0     2.55                                   27
                                                                                9999
NONE
FINI
```

APPENDIX B
SEVERITY INDEX CURVES

Severity Index Curves

A family of severity index versus encroachment speed curves for encroachment angles of 5, 15, 25, 35, and 45 degrees were constructed for each of the four options considered in the B/C analysis. A discussion of the methodology used in determining these curves is given in chapter V. The curves are given in Figures B-1 through B-12.

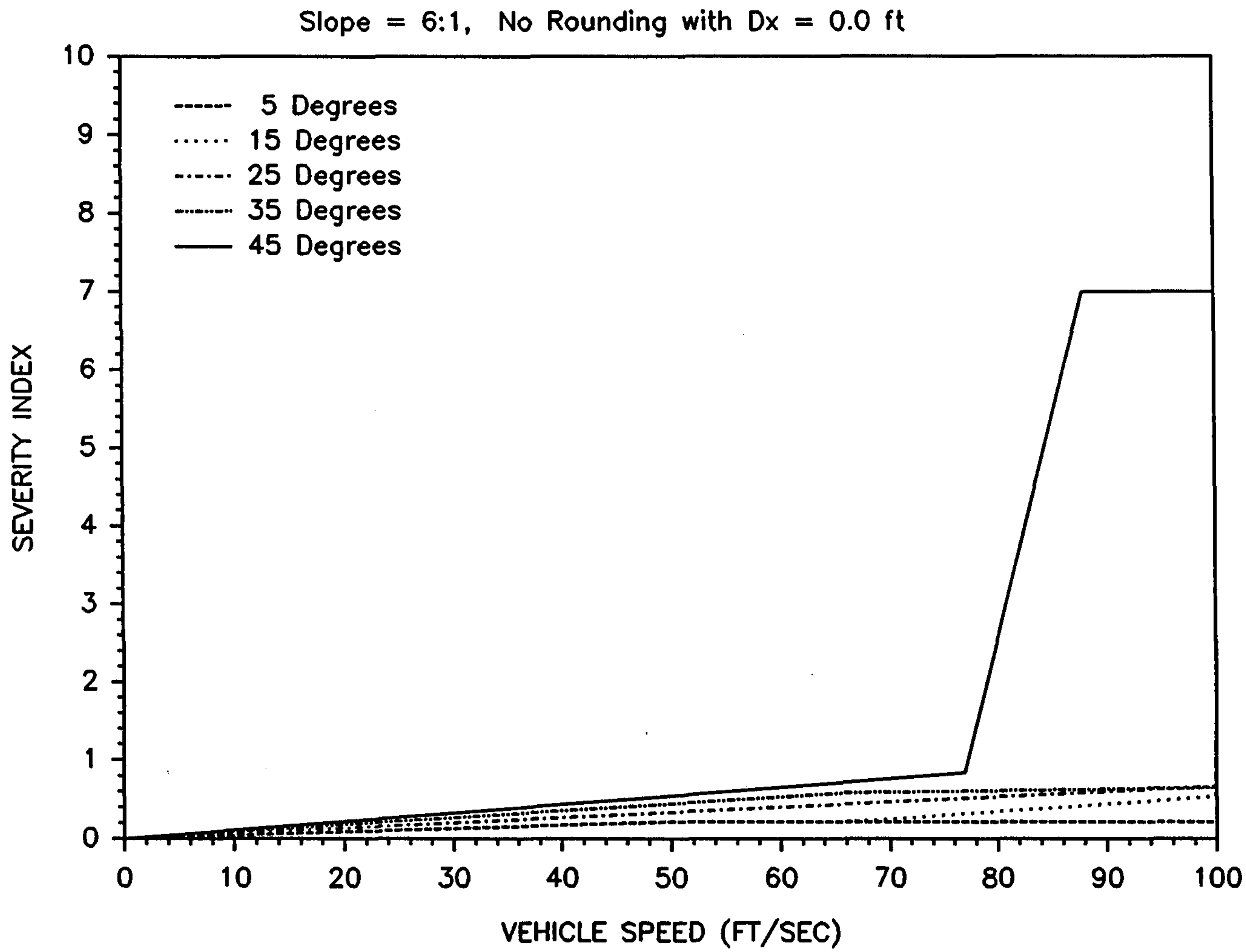

FIGURE B-1. Severity curves for unrounded option with 6:1 side slope.

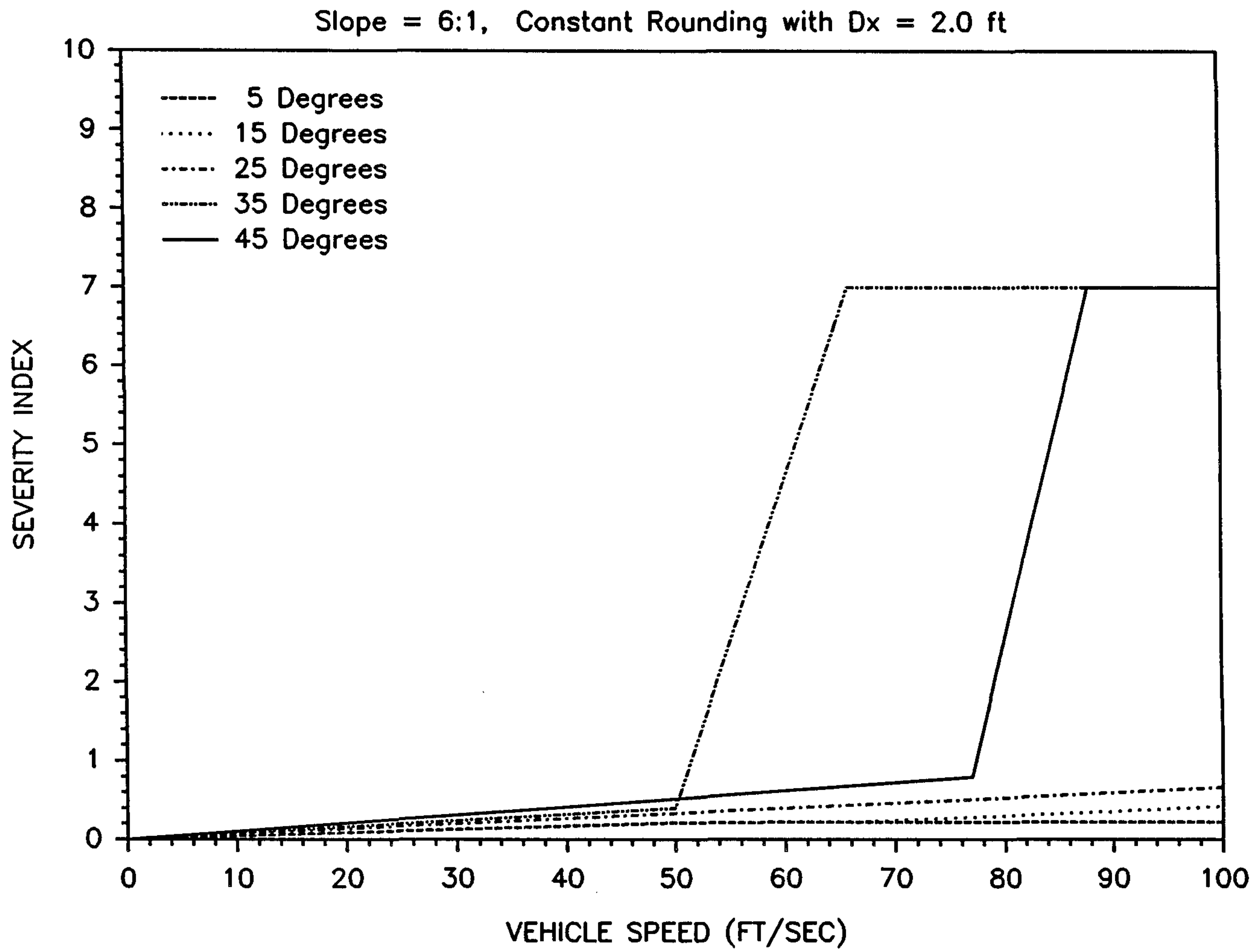

FIGURE B-2. Severity curves for 2 ft (0.61 m) constant rounding option with 6:1 side slope.

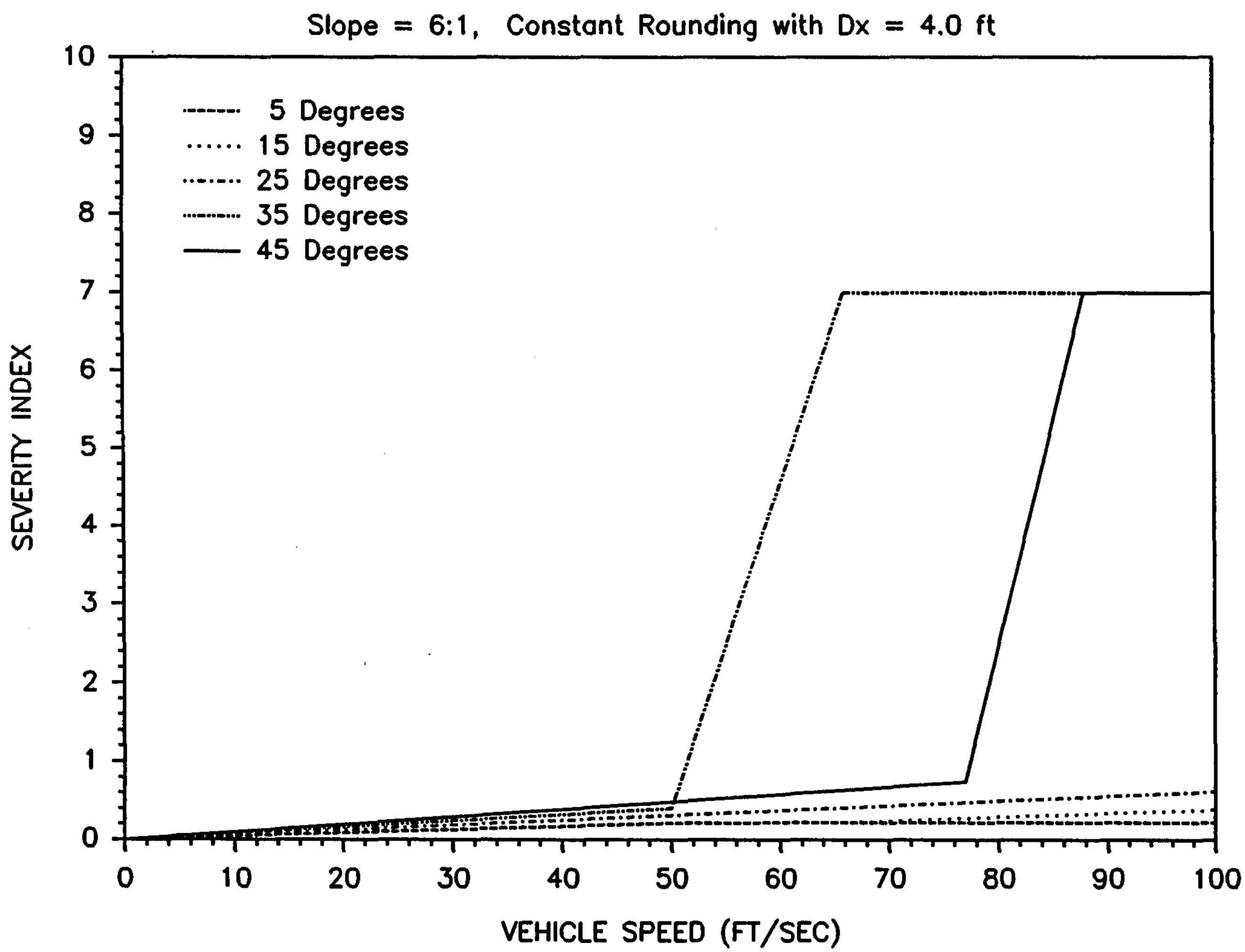

FIGURE B-3. Severity curves for 4 ft (1.22 m) constant rounding option with 6:1 side slope.

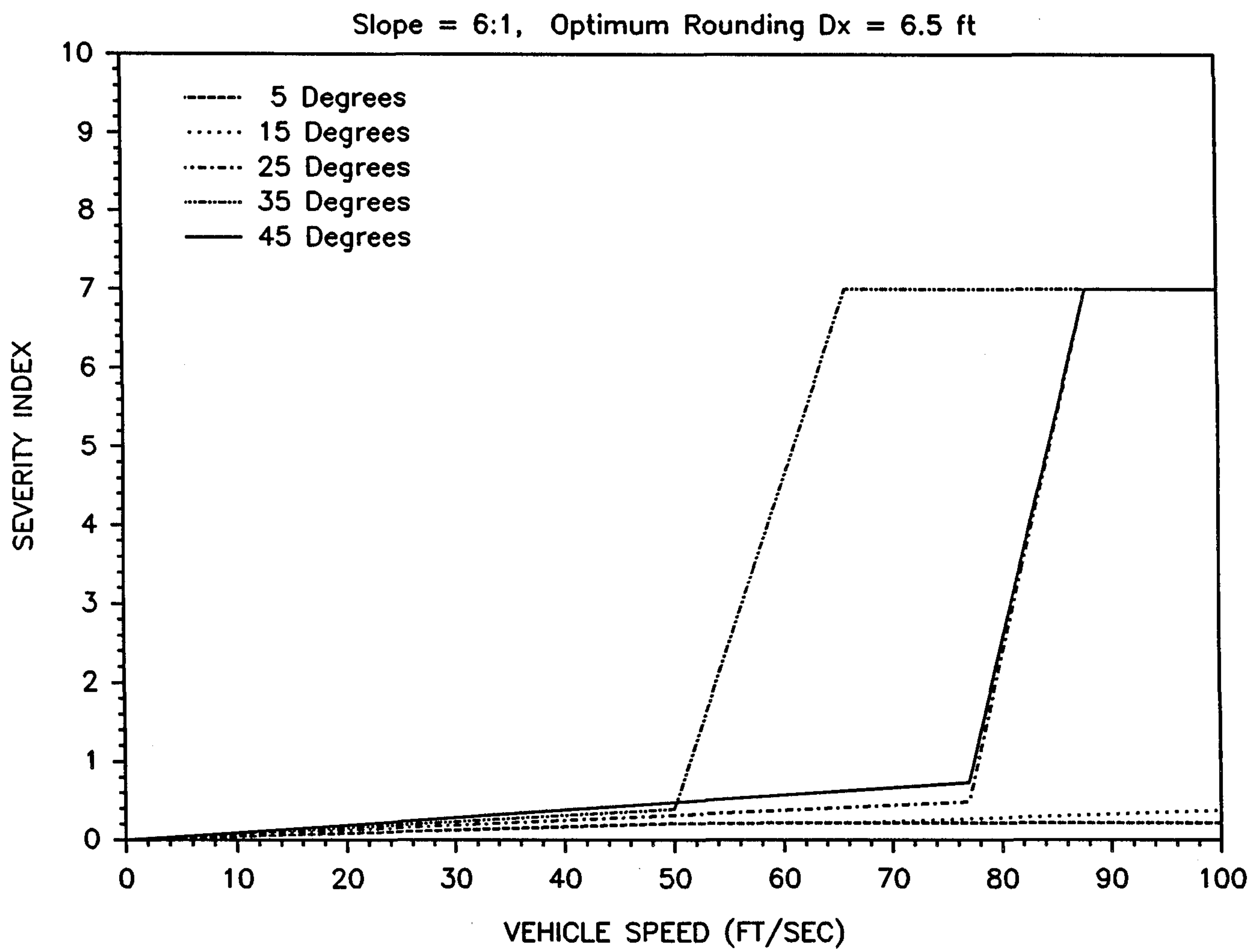

FIGURE B-4. Severity curves for optimum rounding option with 6:1 side slope.

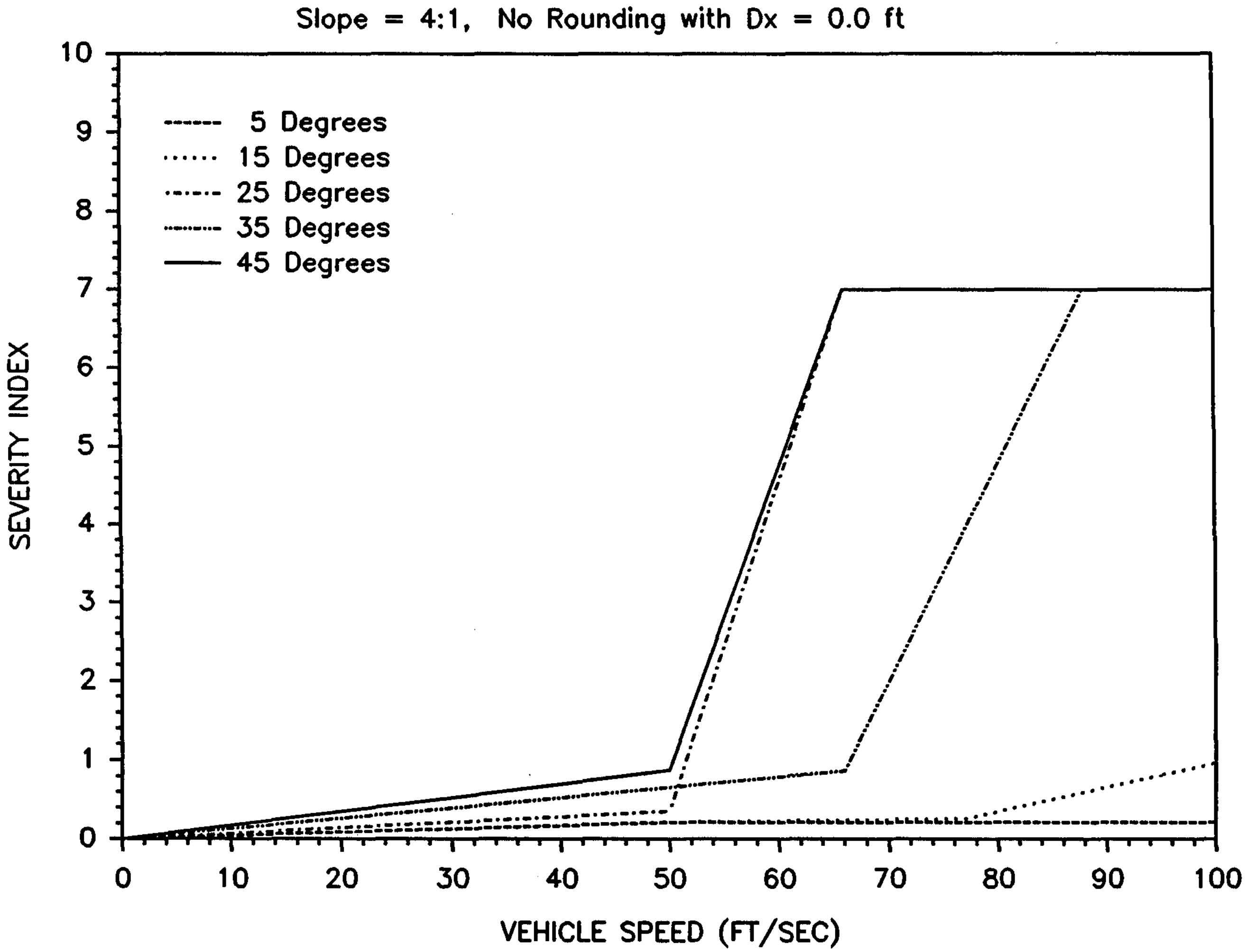

FIGURE B-5. Severity curves for unrounded option with 4:1 side slope.

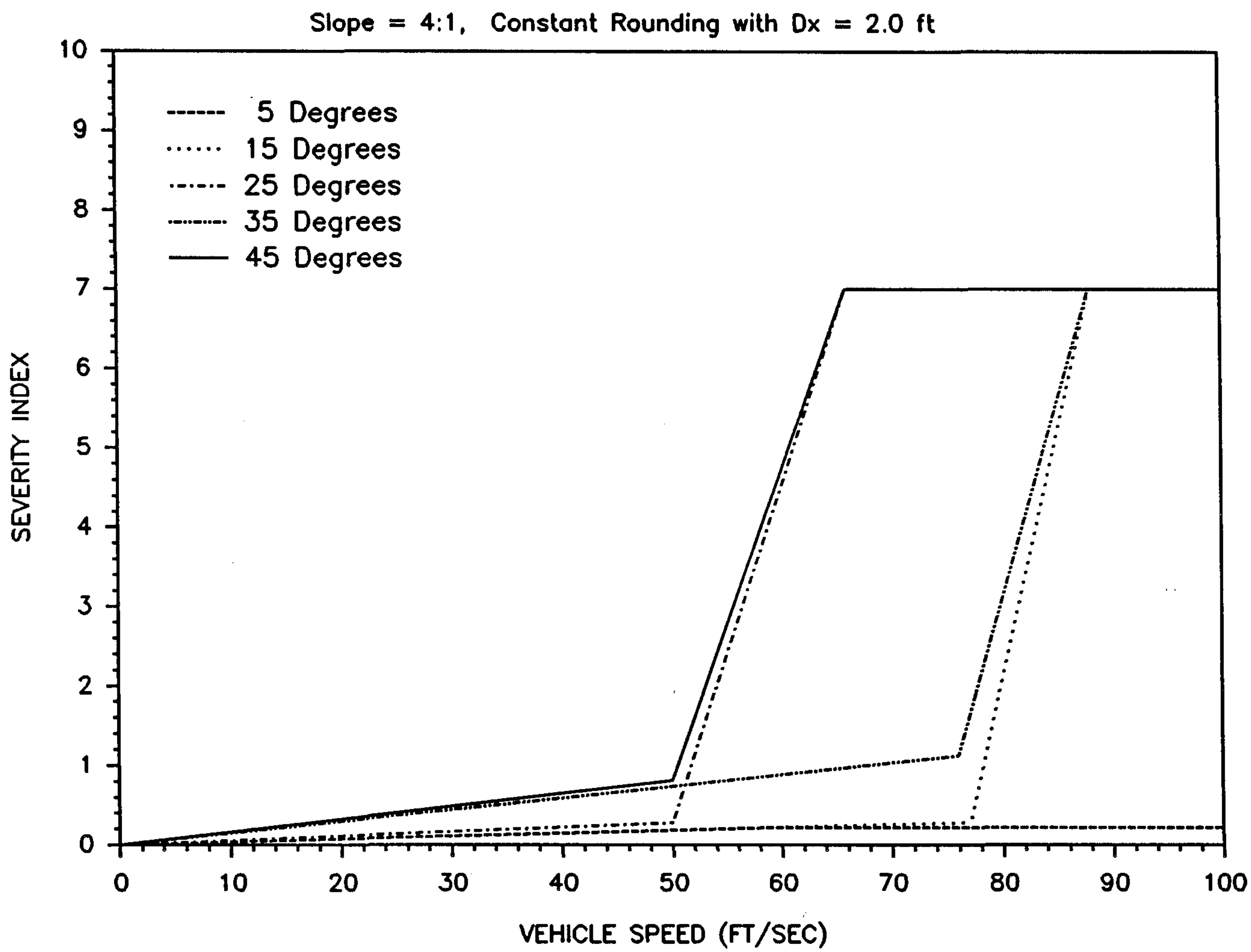

FIGURE B-6. Severity curves for 2 ft (0.61 m) constant rounding option with 4:1 side slope.

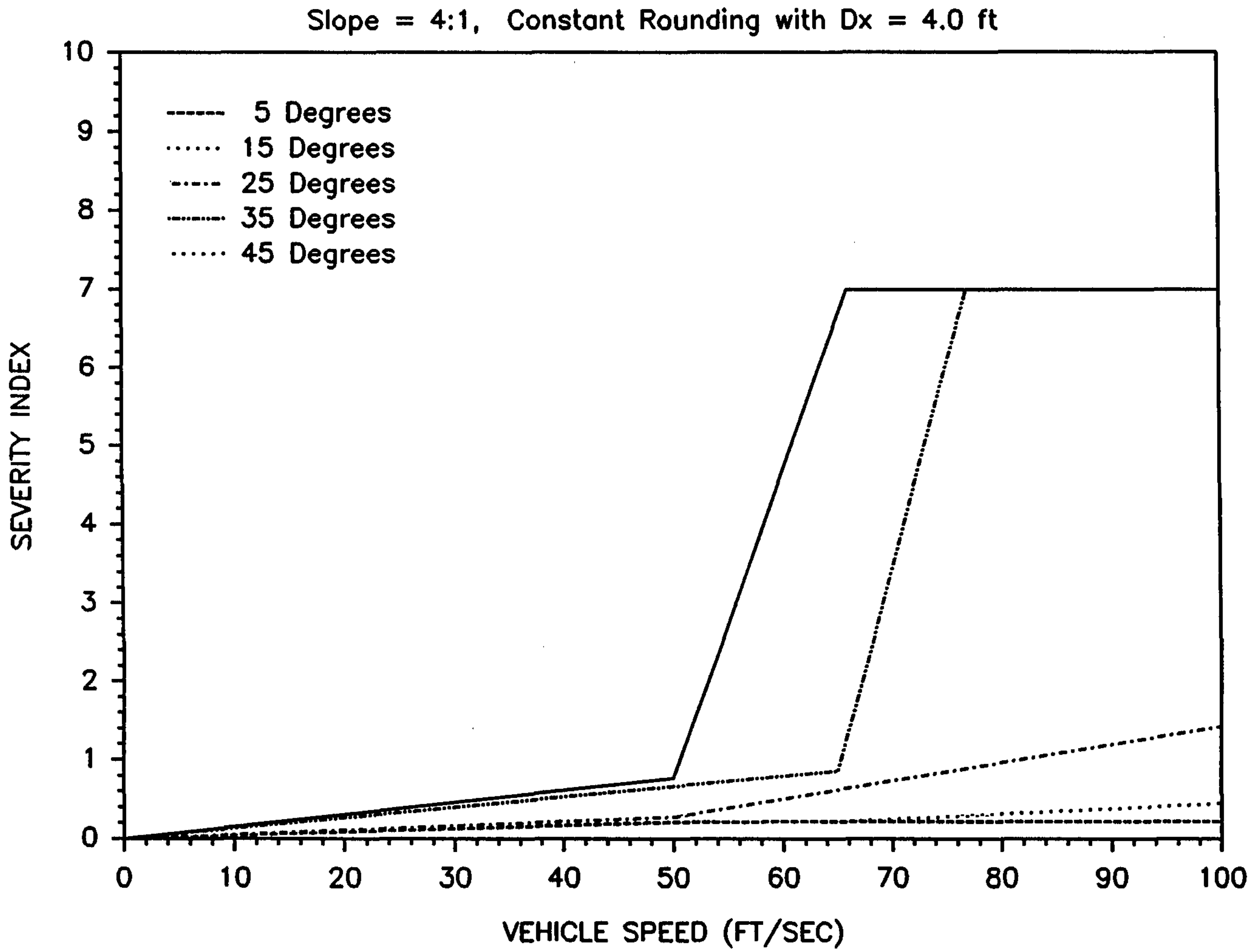

FIGURE B-7. Severity curves for 4 ft (1.22 m) constant rounding option with 4:1 side slope.

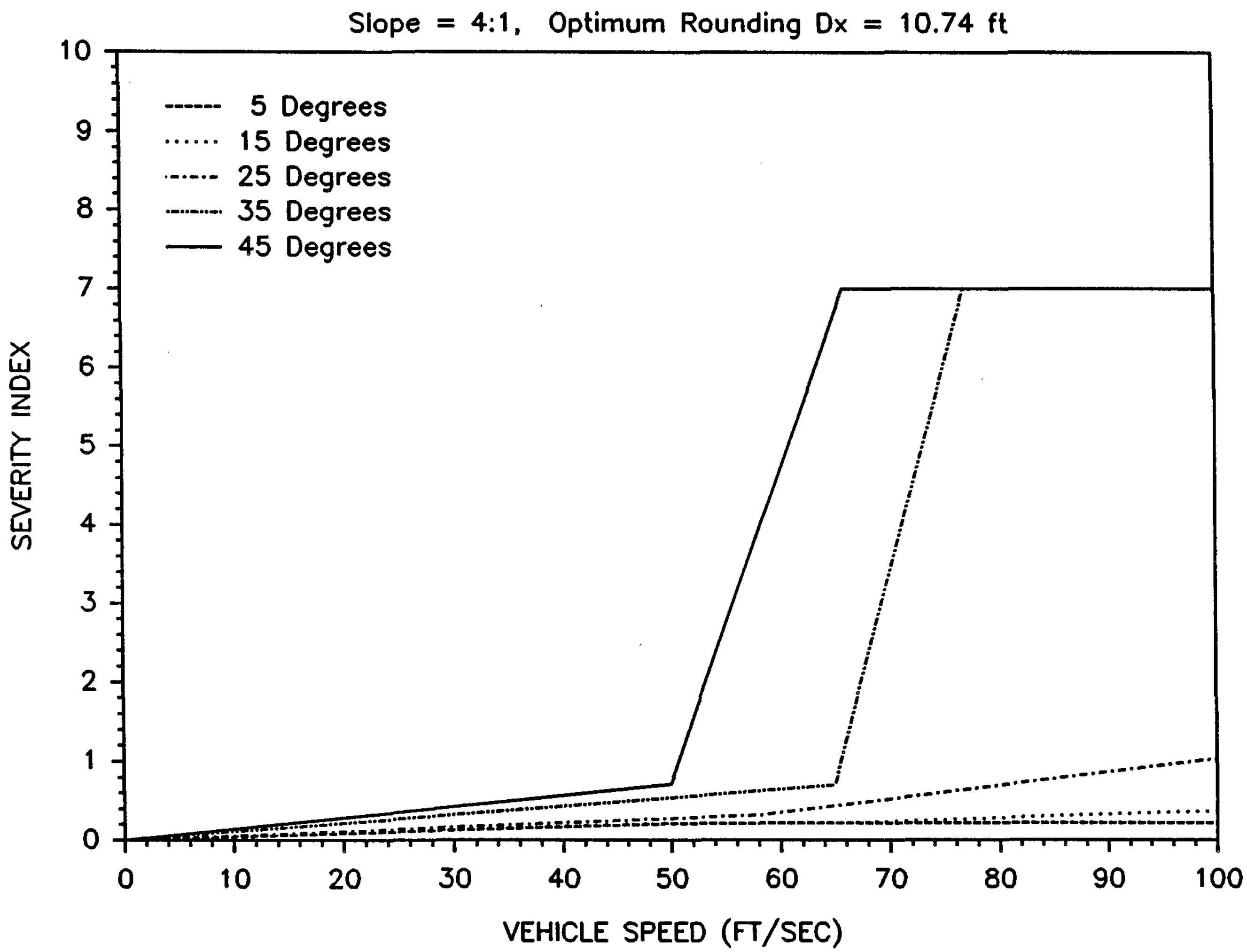

FIGURE B-8. Severity curves for optimum rounding option with 4:1 side slope.

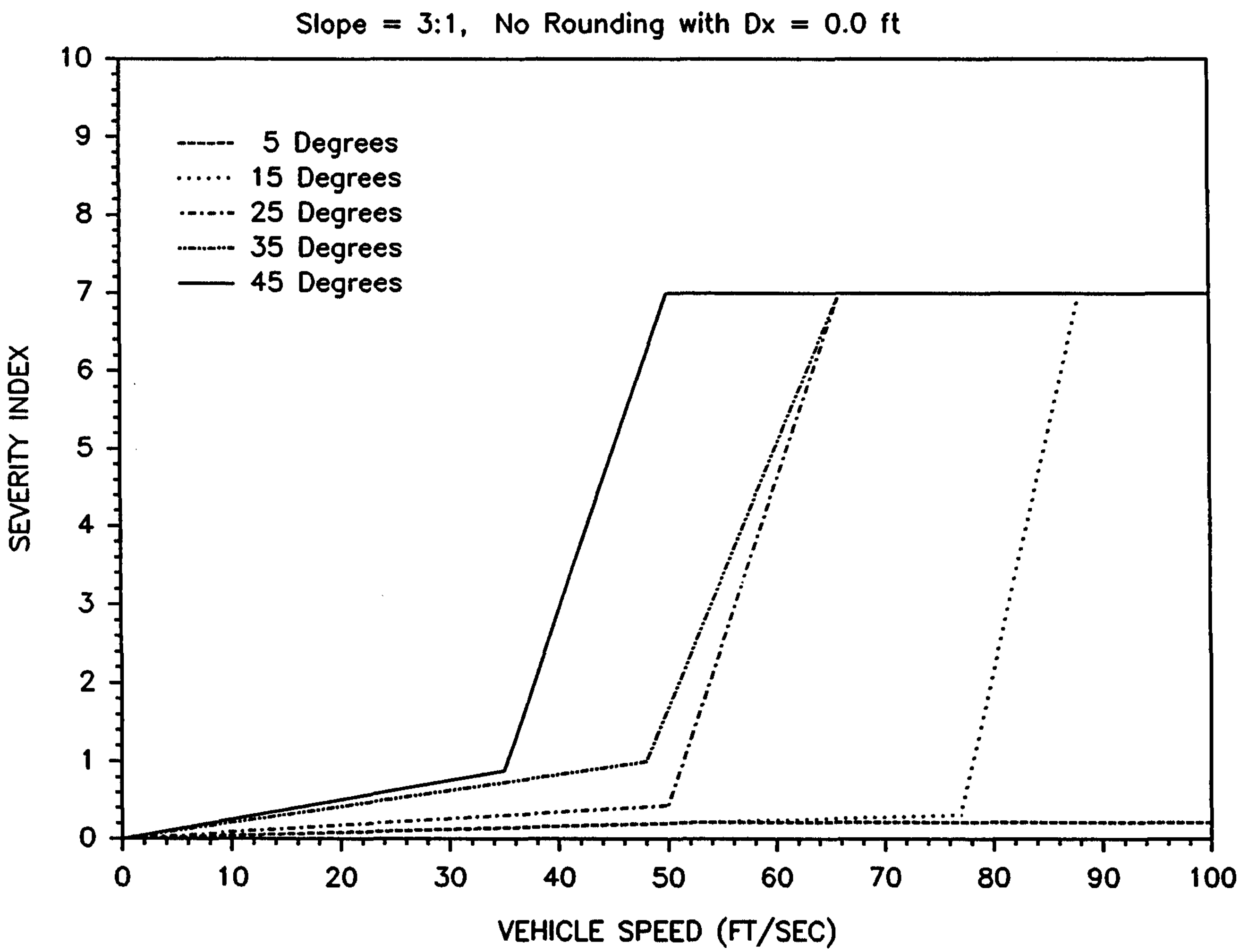

FIGURE B-9. Severity curves for unrounded option with 3:1 side slope.

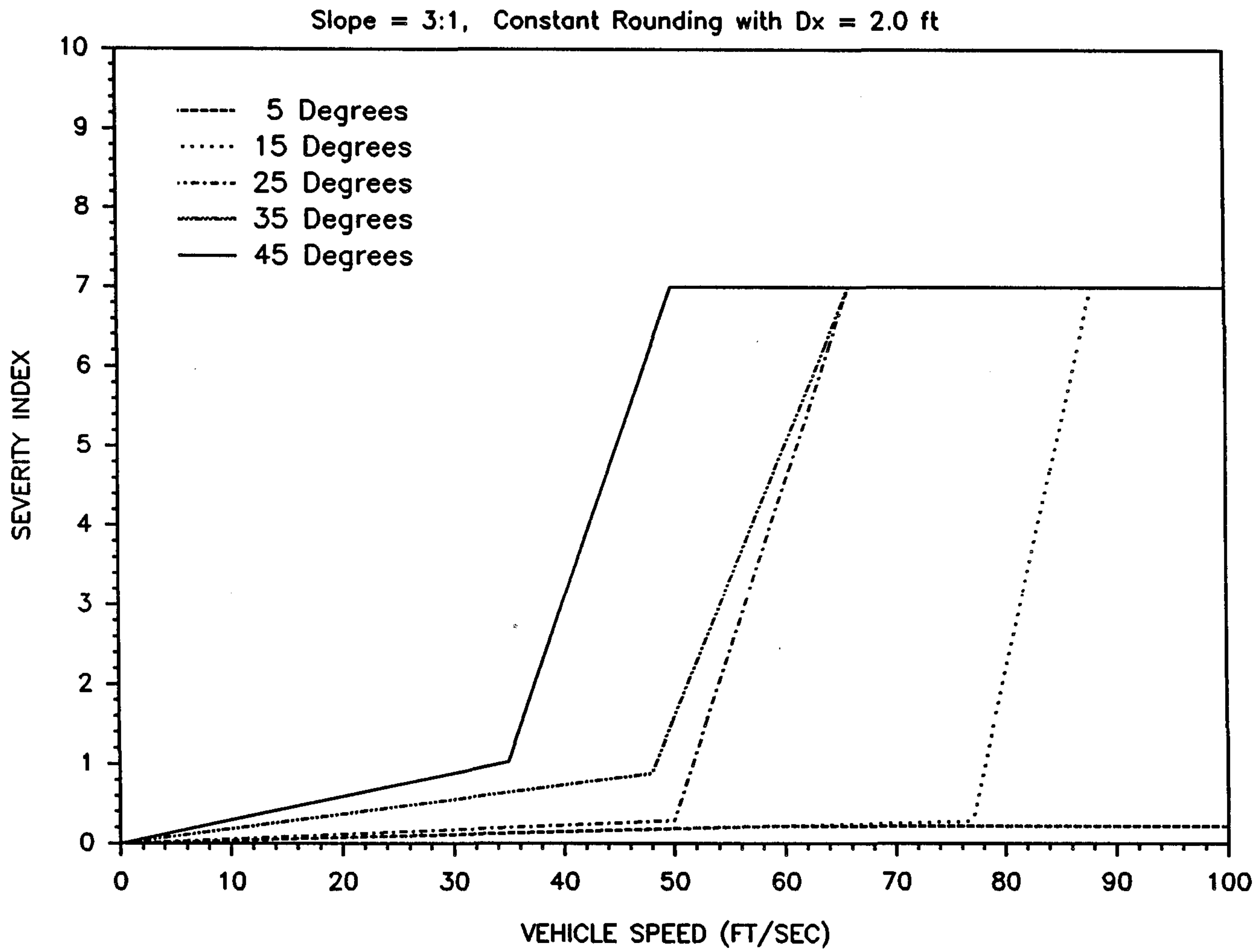

FIGURE B-10. Severity curves for 2 ft (0.61 m) constant rounding option with 3:1 side slope.

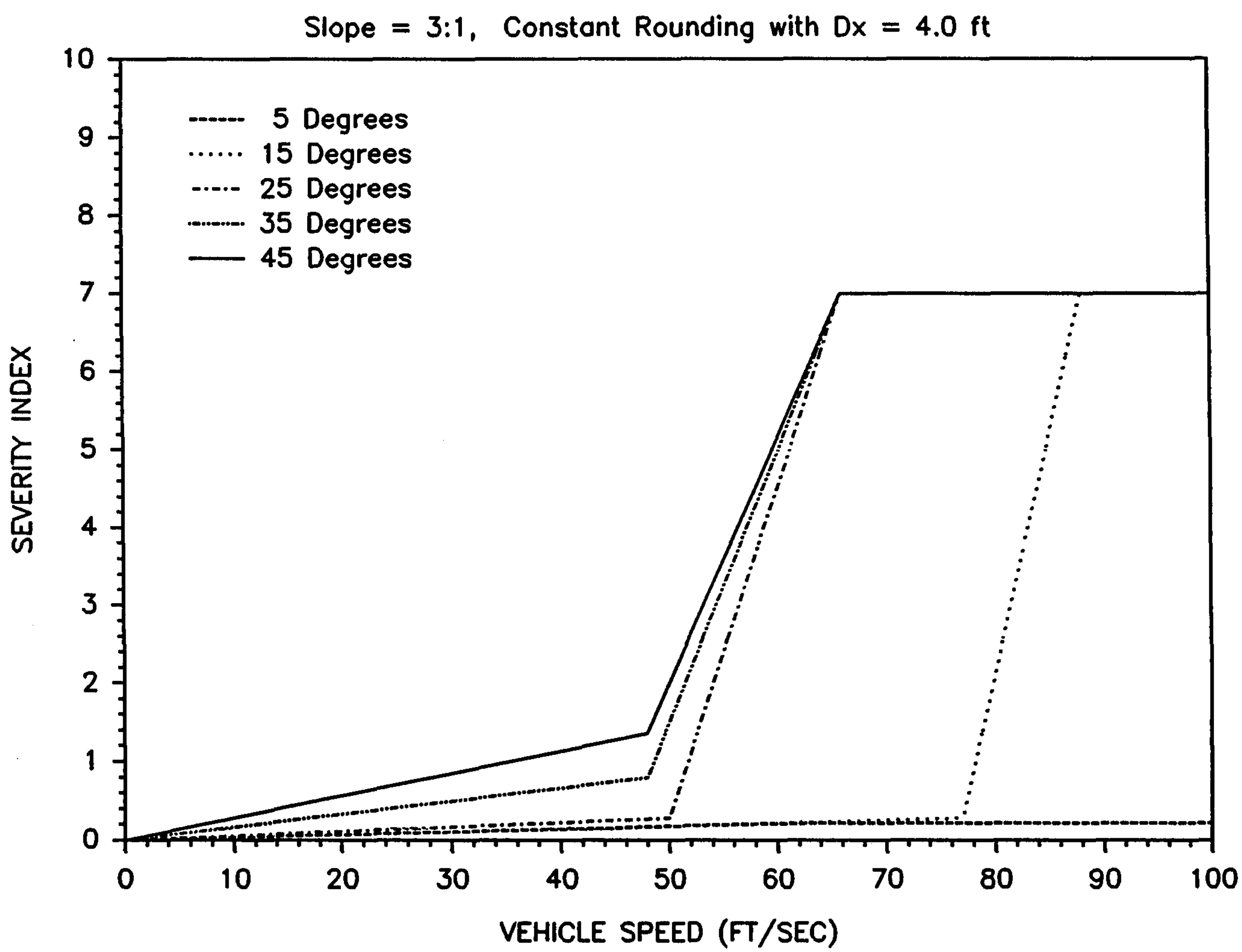

FIGURE B-11. Severity curves for 4 ft (1.22 m) constant rounding option with 3:1 side slope.

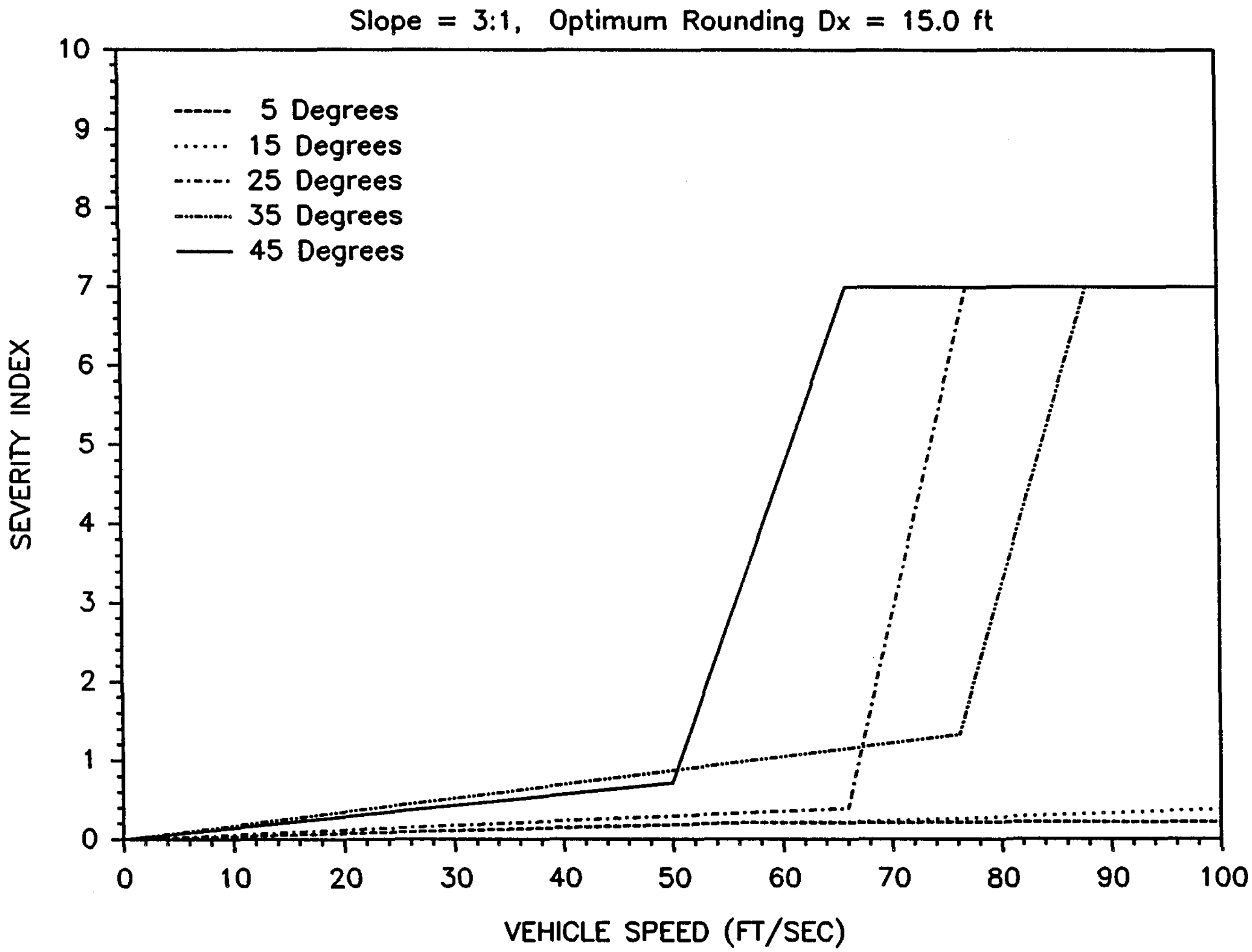

FIGURE B-12. Severity curves for optimum rounding option with 3:1 side slope.

APPENDIX C

SAMPLE BENEFIT/COST PROGRAM INPUT

Sample Input Data for B/C Analysis, 3:1 Side Slope, 4-Lane Freeway

```
4.0     3.
0.      1.      4.0     50000.0 0.03    65.
20.0    20.0    20.0    20.0    0.04
0.0     1375.   3135.   10295.  25350.  56535.  116555. 186150. 281720. 395500.
500000. 0.      0.      0.      0.      0.      00.
5.      14.     2250.   1.0     0.0     6.      18.     4000.   0.0     0.0
8.5     40.     12812.  0.0     0.0     8.5     55.     55121.  0.0     0.0
1.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
OPTION 1 - NO ROUNDING, DX = 0.0 ft (0.0 m)
3:1 SIDE SLOPE, 5 FT (1.53 m) EMBANKMENT DEPTH
1.0     0.0     0.0     0.0
1.0     0.0     1.0                     LINE HAZARD ALONG THE ROADWAY
0.0     0.0     5280.   5280.   0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0
0.0     0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0040  0.307   0.6085  7.00    0.0
0.0     0.0088  0.440   0.4100  7.00    0.0
0.0     0.0208  1.000   0.3333  7.00    0.0
0.0     0.0251  0.880   0.4080  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0040  0.307   0.6085  7.00    0.0
0.0     0.0088  0.440   0.4100  7.00    0.0
0.0     0.0208  1.000   0.3333  7.00    0.0
0.0     0.0251  0.880   0.4080  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0040  0.307   0.6085  7.00    0.0
0.0     0.0088  0.440   0.4100  7.00    0.0
0.0     0.0208  1.000   0.3333  7.00    0.0
0.0     0.0251  0.880   0.4080  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0040  0.307   0.6085  7.00    0.0
0.0     0.0088  0.440   0.4100  7.00    0.0
0.0     0.0208  1.000   0.3333  7.00    0.0
```

```
0.0     0.0251  0.880   0.4080  7.00    0.0
0.0     0.0     0.0
OPTION 2 - CONSTANT ROUNDING, DX = 2.0 FT (0.61 m)
3:1 SIDE SLOPE, 5 FT (1.53 m) EMBANKMENT DEPTH
1.0     3170.0  0.0     0.0
1.0     0.0     1.0                         LINE HAZARD ALONG THE ROADWAY
0.0     0.0     5280.   5280.   0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0
0.0     0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0036  0.279   0.6110  7.00    0.0
0.0     0.0058  0.288   0.4195  7.00    0.0
0.0     0.0183  0.880   0.3400  7.00    0.0
0.0     0.0295  1.032   0.3979  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0036  0.279   0.6110  7.00    0.0
0.0     0.0058  0.288   0.4195  7.00    0.0
0.0     0.0183  0.880   0.3400  7.00    0.0
0.0     0.0295  1.032   0.3979  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0036  0.279   0.6110  7.00    0.0
0.0     0.0058  0.288   0.4195  7.00    0.0
0.0     0.0183  0.880   0.3400  7.00    0.0
0.0     0.0295  1.032   0.3979  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0036  0.279   0.6110  7.00    0.0
0.0     0.0058  0.288   0.4195  7.00    0.0
0.0     0.0183  0.880   0.3400  7.00    0.0
0.0     0.0295  1.032   0.3979  7.00    0.0
0.0     0.0     0.0
OPTION 3 - CONSTANT ROUNDING, DX = 4.0 FT (1.22 m)
3:1 SIDE SLOPE, 5 FT (1.53 m) EMBANKMENT DEPTH
1.0     6240.0  0.0     0.0
1.0     0.0     1.0                         LINE HAZARD ALONG THE ROADWAY
0.0     0.0     5280.   30.00   0.0     0.0     0.0     0.0     0.0     0.0
```

```
0.0     0.0     0.0
0.0     0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0036  0.280   0.6109  7.00    0.0
0.0     0.0056  0.278   0.4201  7.00    0.0
0.0     0.0167  0.800   0.3444  7.00    0.0
0.0     0.0283  1.360   0.3133  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0036  0.280   0.6109  7.00    0.0
0.0     0.0056  0.278   0.4201  7.00    0.0
0.0     0.0167  0.800   0.3444  7.00    0.0
0.0     0.0283  1.360   0.3133  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0036  0.280   0.6109  7.00    0.0
0.0     0.0056  0.278   0.4201  7.00    0.0
0.0     0.0167  0.800   0.3444  7.00    0.0
0.0     0.0283  1.360   0.3133  7.00    0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0036  0.280   0.6109  7.00    0.0
0.0     0.0056  0.278   0.4201  7.00    0.0
0.0     0.0167  0.800   0.3444  7.00    0.0
0.0     0.0283  1.360   0.3133  7.00    0.0
0.0     0.0     0.0
OPTION 4 - OPTIMUM ROUNDING, DX = 15.00 FT (4.6 m)
3:1 SIDE SLOPE , 5 FT (1.53 m) EMBANKMENT DEPTH
1.0     21450.0 0.0     0.0
1.0     0.0     1.0                     LINE HAZARD ALONG THE ROADWAY
0.0     0.0     5280.   30.00   0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0
0.0     0.0
0.0     0.0047  0.210   0.00005 7.00    0.0
0.0     0.0048  0.220   0.0015  7.00    0.0
0.0     0.0059  0.390   0.6009  7.00    0.0
0.0     0.0206  1.590   0.4918  7.00    0.0
0.0     0.0144  0.720   0.3925  7.00    0.0
```

0.0	0.0047	0.210	0.00005	7.00	0.0
0.0	0.0048	0.220	0.0015	7.00	0.0
0.0	0.0059	0.390	0.6009	7.00	0.0
0.0	0.0206	1.590	0.4918	7.00	0.0
0.0	0.0144	0.720	0.3925	7.00	0.0
0.0	0.0047	0.210	0.00005	7.00	0.0
0.0	0.0048	0.220	0.0015	7.00	0.0
0.0	0.0059	0.390	0.6009	7.00	0.0
0.0	0.0206	1.590	0.4918	7.00	0.0
0.0	0.0144	0.720	0.3925	7.00	0.0
0.0	0.0047	0.210	0.00005	7.00	0.0
0.0	0.0048	0.220	0.0015	7.00	0.0
0.0	0.0059	0.390	0.6009	7.00	0.0
0.0	0.0206	1.590	0.4918	7.00	0.0
0.0	0.0144	0.720	0.3925	7.00	0.0
0.0	0.0	0.0			

APPENDIX D

B/C RATIO VERSUS ADT CURVES

B/C Ratio Versus ADT Curves

B/C ratios were obtained for each of the three rounding options with respect to the unrounded option by using the B/C analysis program (*9*). For those safety treatments whose B/C ratio with respect to the unrounded option was greater than one, an incremental B/C analysis, as described in section V.4 was conducted. Using these results, a family of B/C ratio versus ADT curves were constructed for freeways and rural arterials for roadside slopes of 6:1, 4:1, and 3:1. These curves are presented in Figures D-1 through D-12.

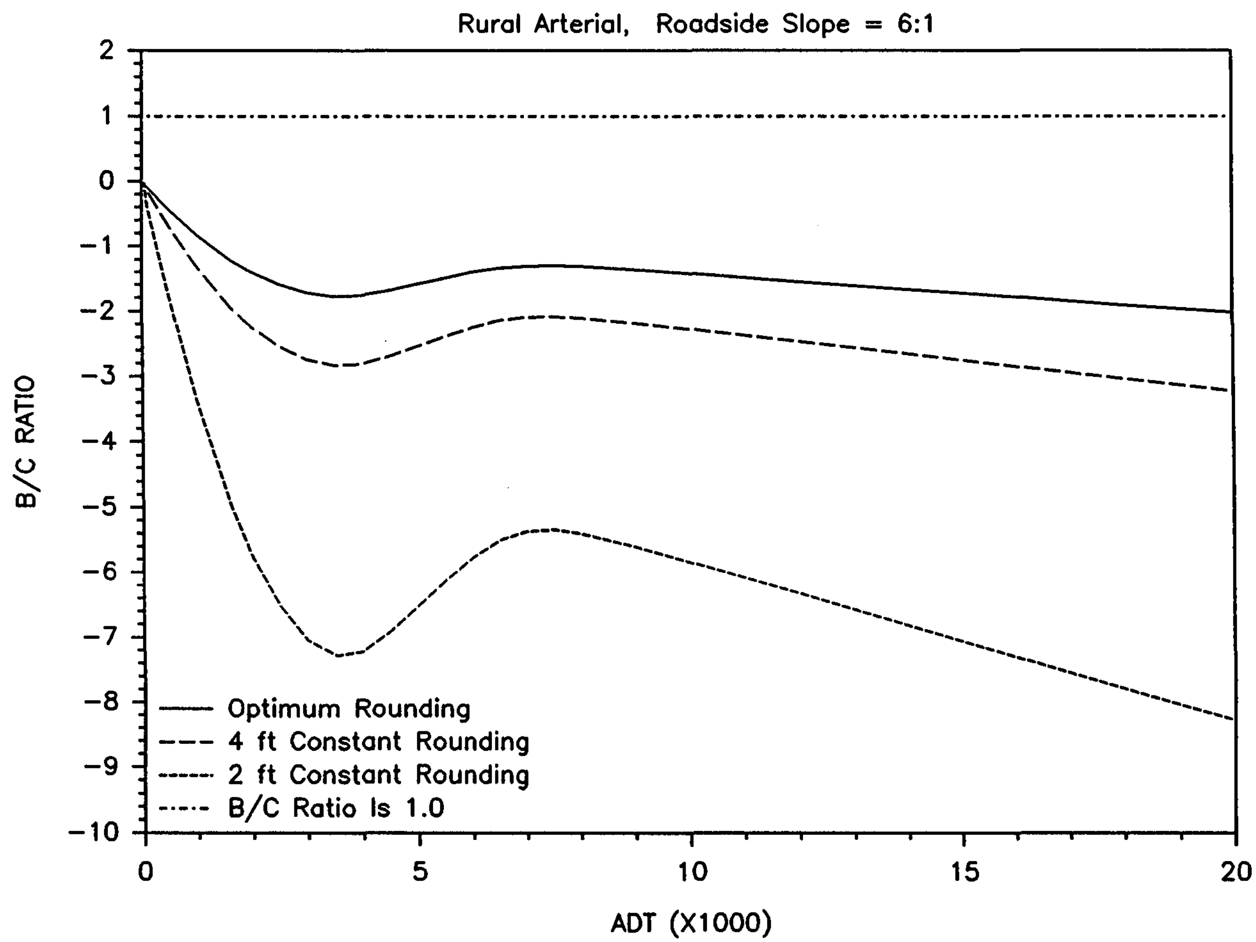

FIGURE D-1. B/C ratio versus ADT for 2-lane rural arterial, 6:1 side slope, compared to unrounded option.

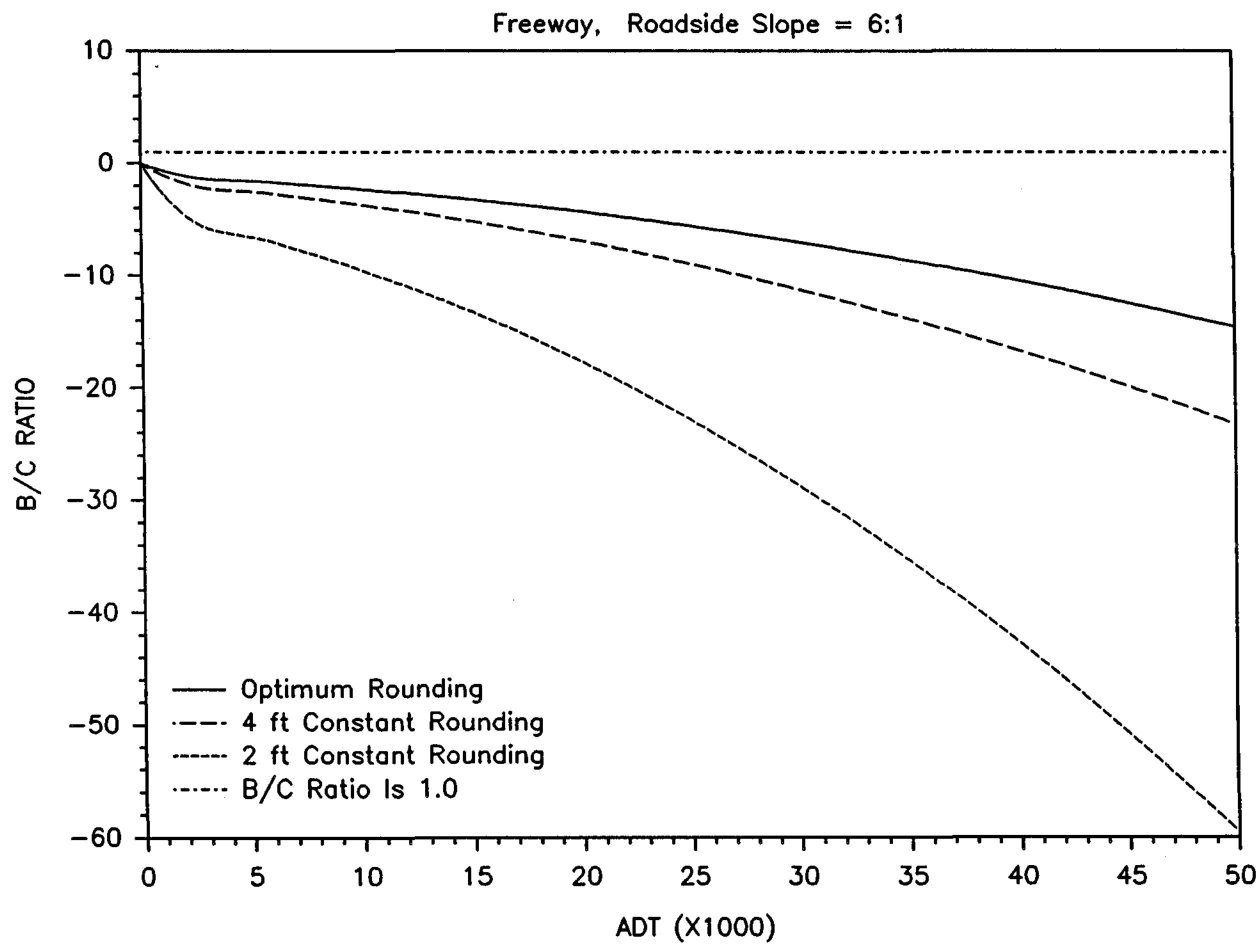

FIGURE D-2. B/C ratio versus ADT for 4-lane freeway, 6:1 side slope, compared to unrounded option.

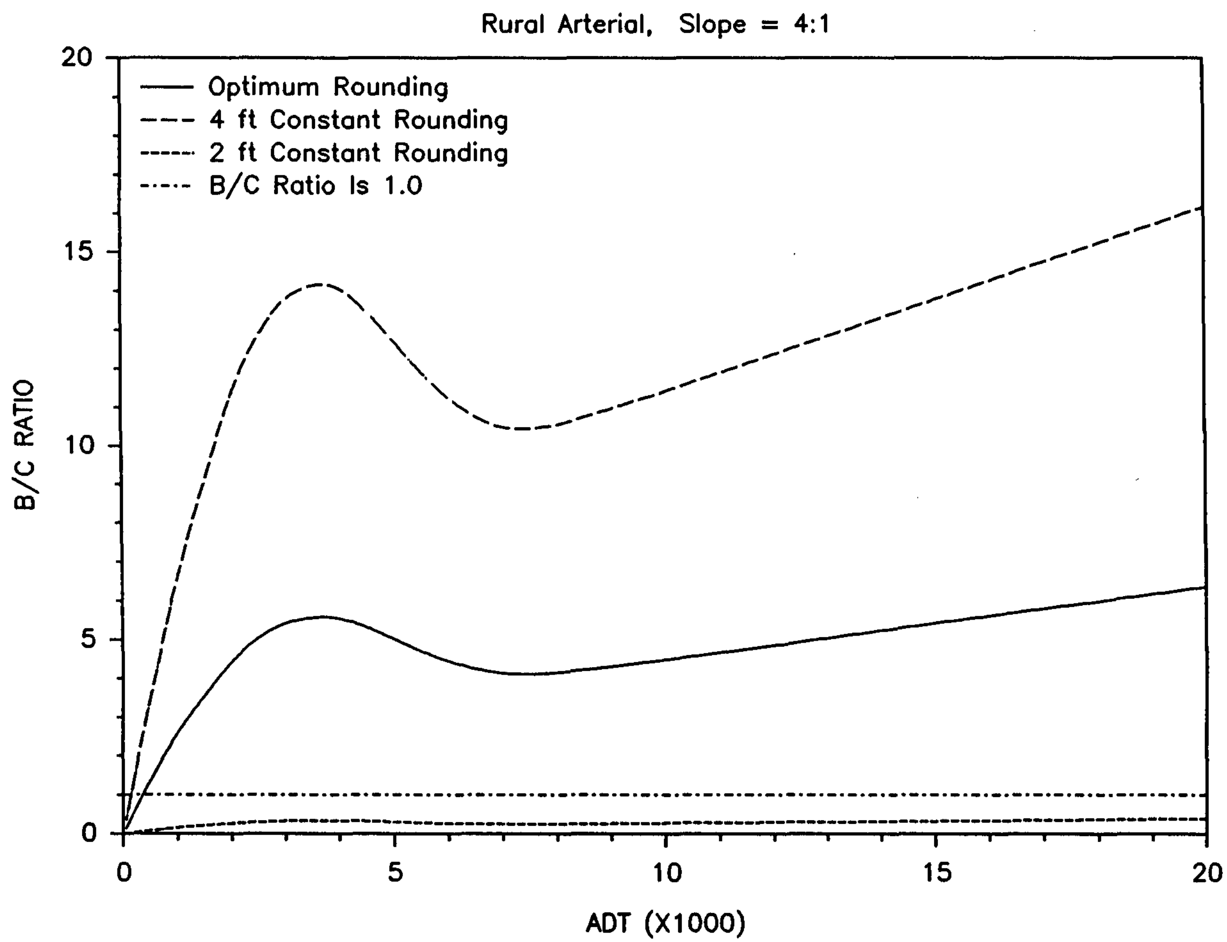

FIGURE D-3. B/C ratio versus ADT for 2-lane rural arterial, 4:1 side slope, compared to unrounded option.

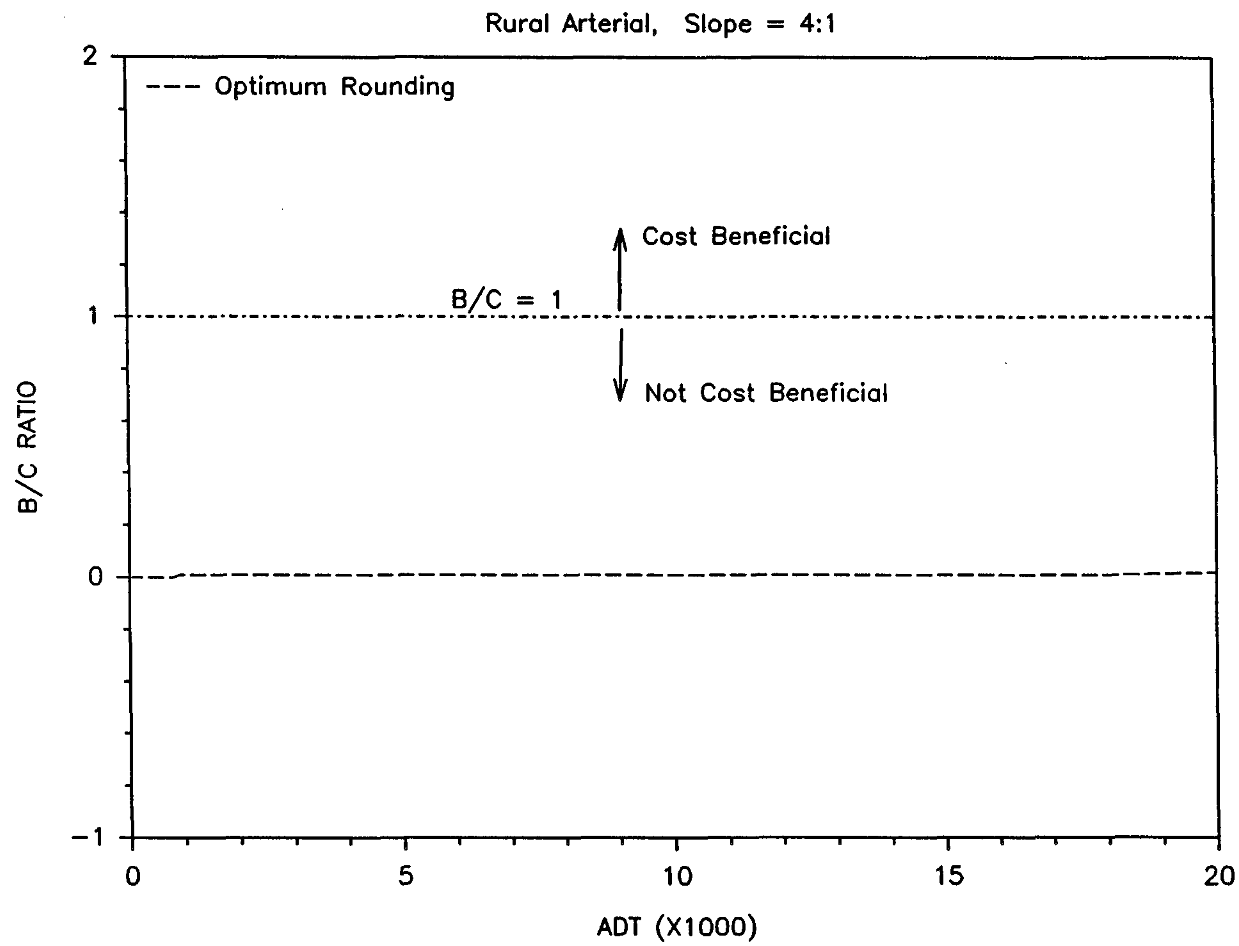

FIGURE D-4. B/C ratio versus ADT for 2-lane rural arterial, 4:1 side slope, compared to 4 ft (1.22 m) constant rounding option.

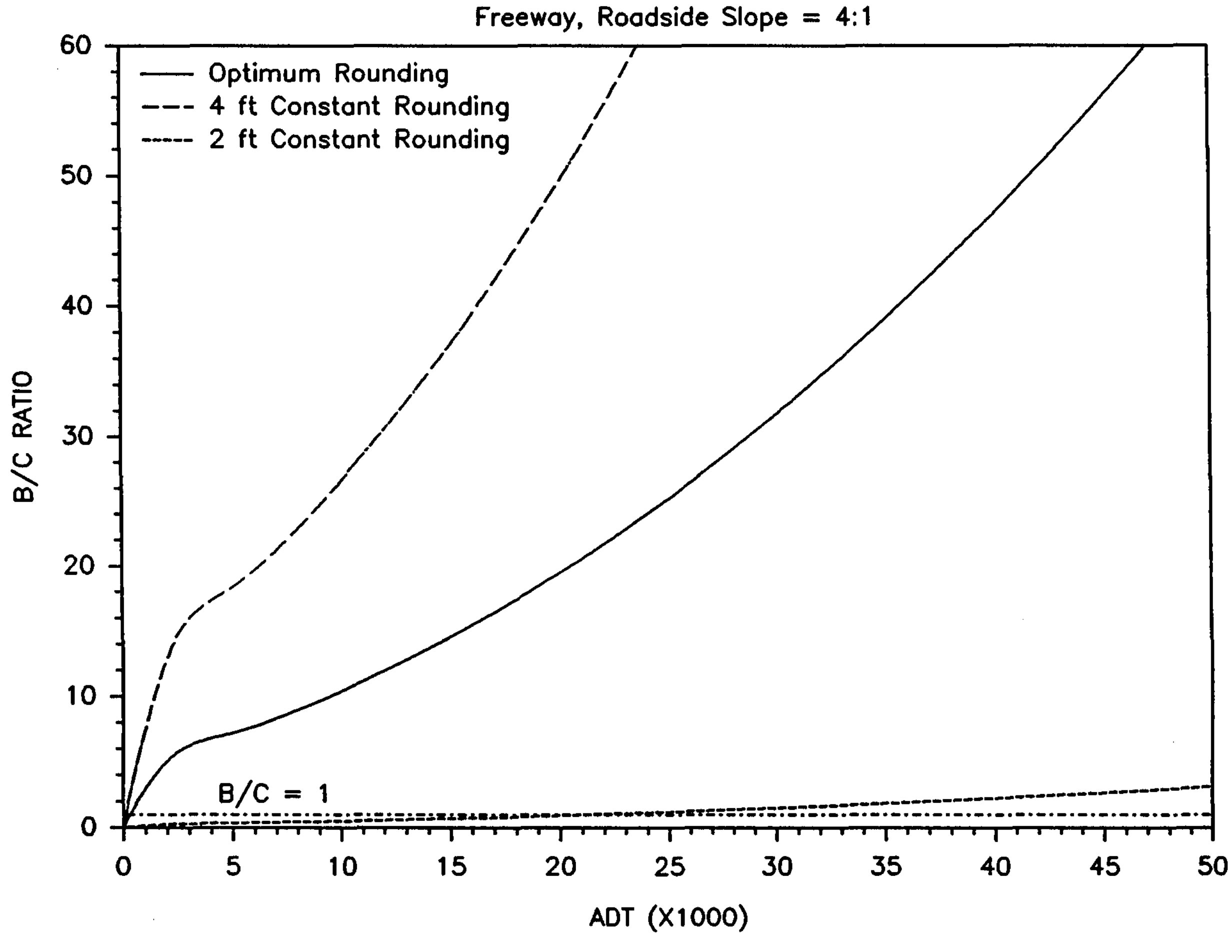

FIGURE D-5. B/C ratio versus ADT for 4-lane freeway, 4:1 side slope, compared to unrounded option.

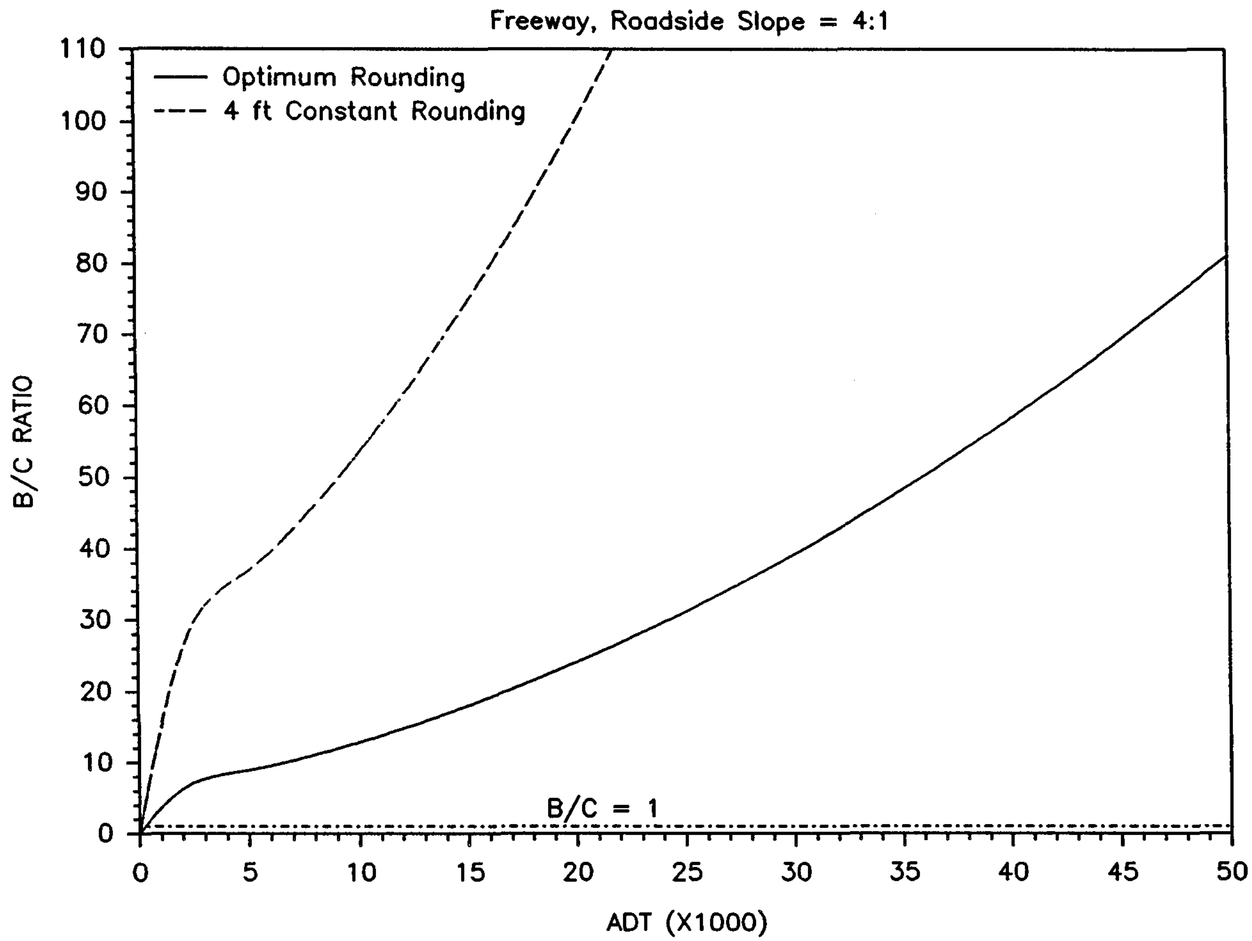

FIGURE D-6. B/C ratio versus ADT for 4-lane freeway, 4:1 side slope, compared to 2 ft (0.61 m) constant rounding option.

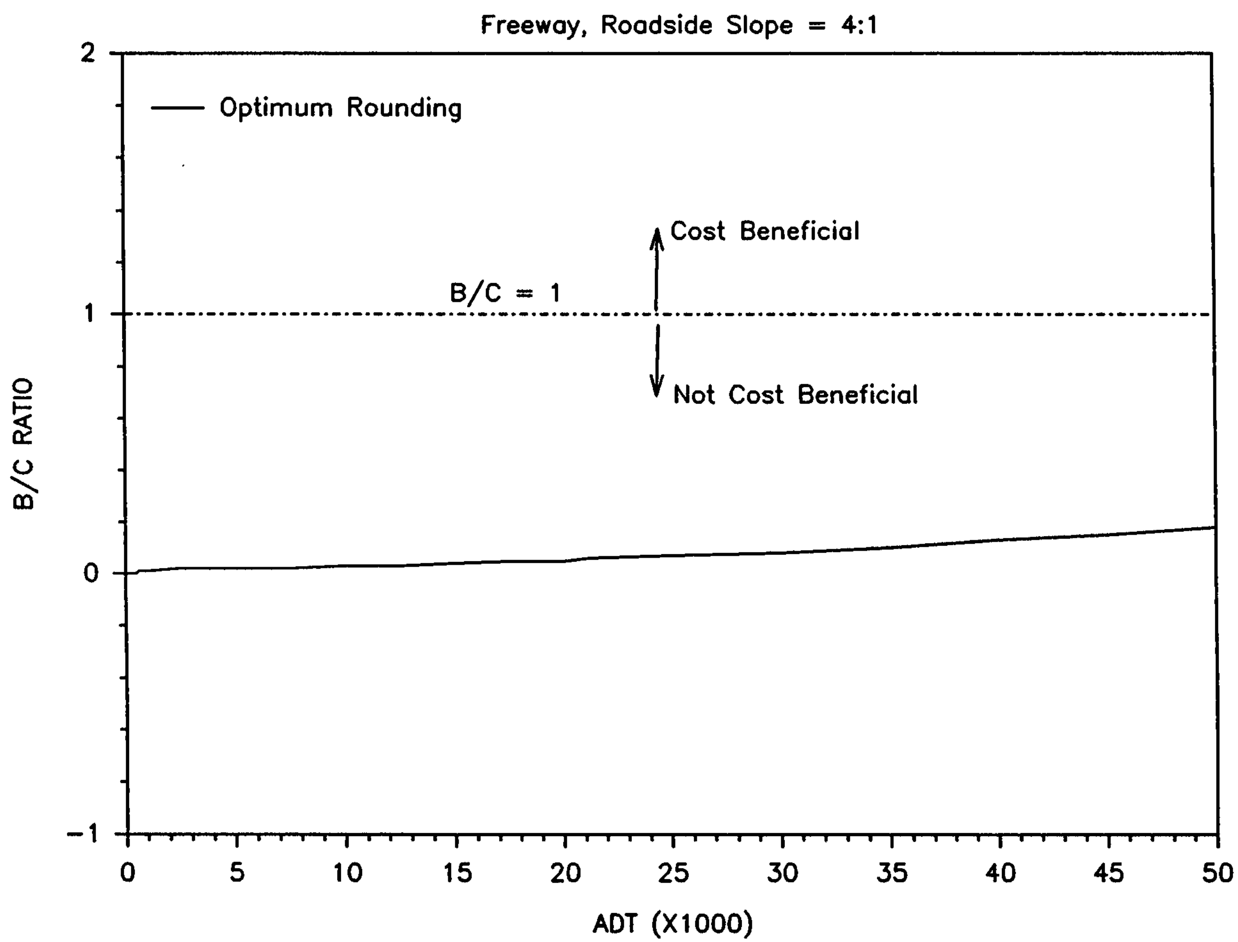

FIGURE D-7. B/C ratio versus ADT for 4-lane freeway, 4:1 side slope, compared to 4 ft (1.22 m) constant rounding option.

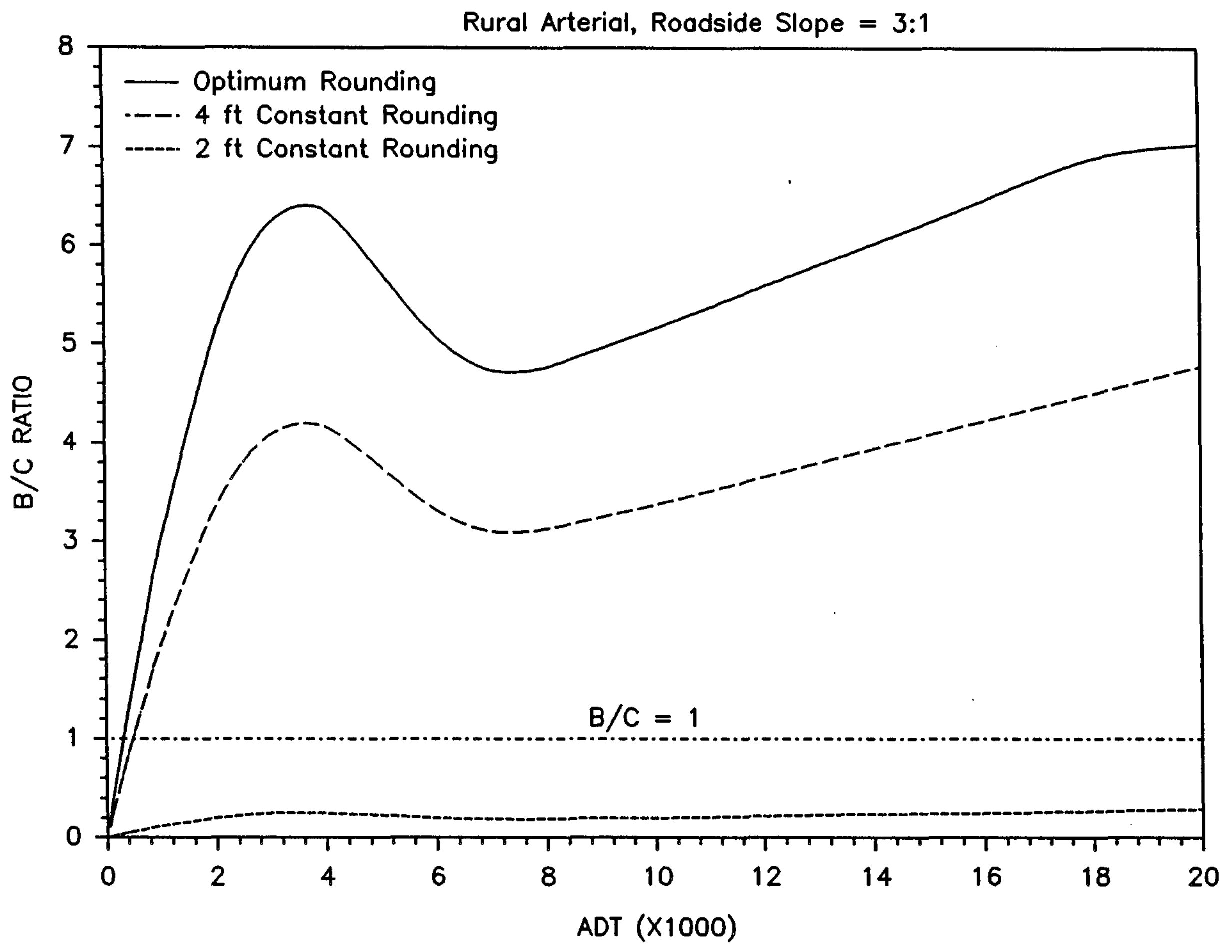

FIGURE D-8. B/C ratio versus ADT for 2-lane rural arterial, 3:1 side slope, compared to unrounded option.

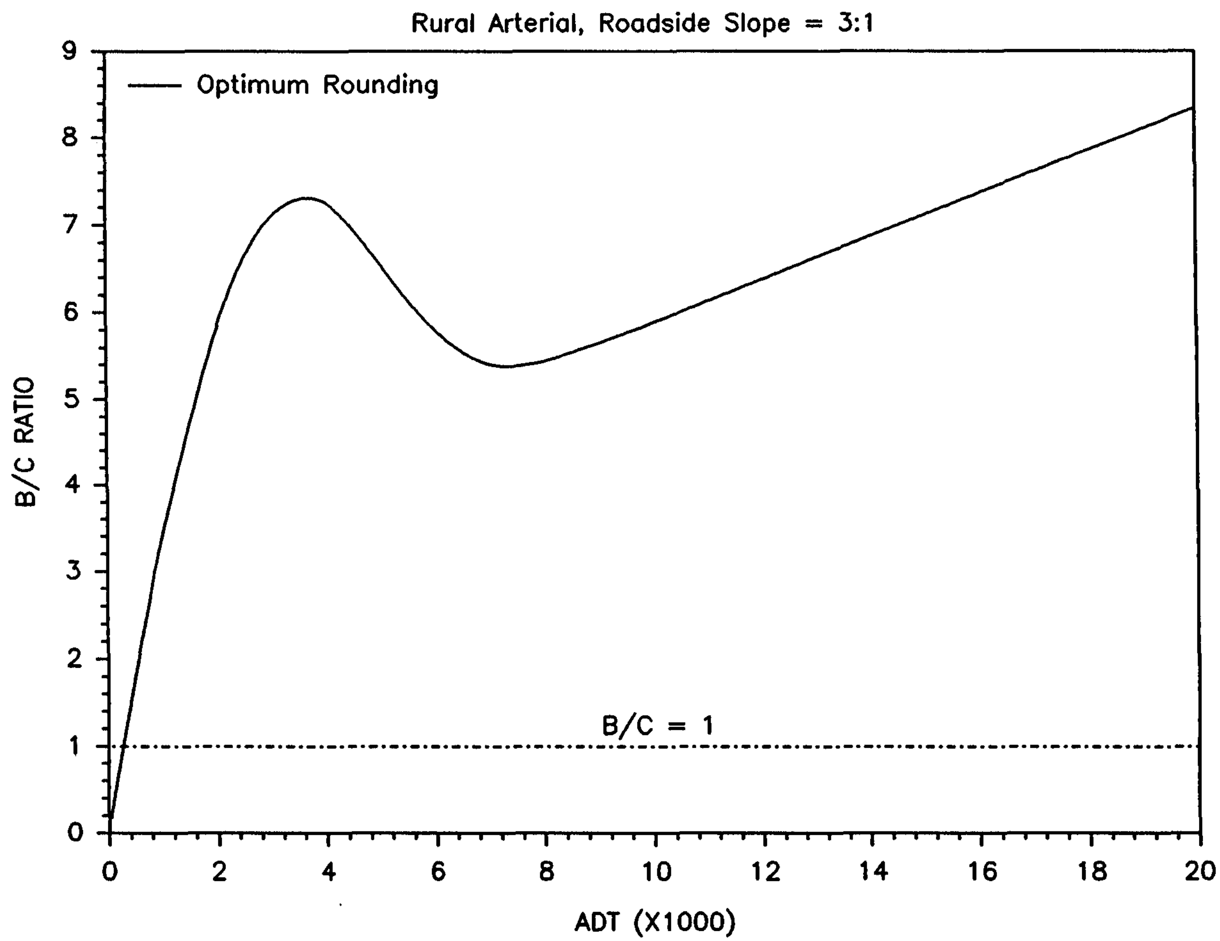

FIGURE D-9. B/C ratio versus ADT for 2-lane rural arterial, 3:1 side slope, compared to 4 ft (1.22 m) constant rounding option.

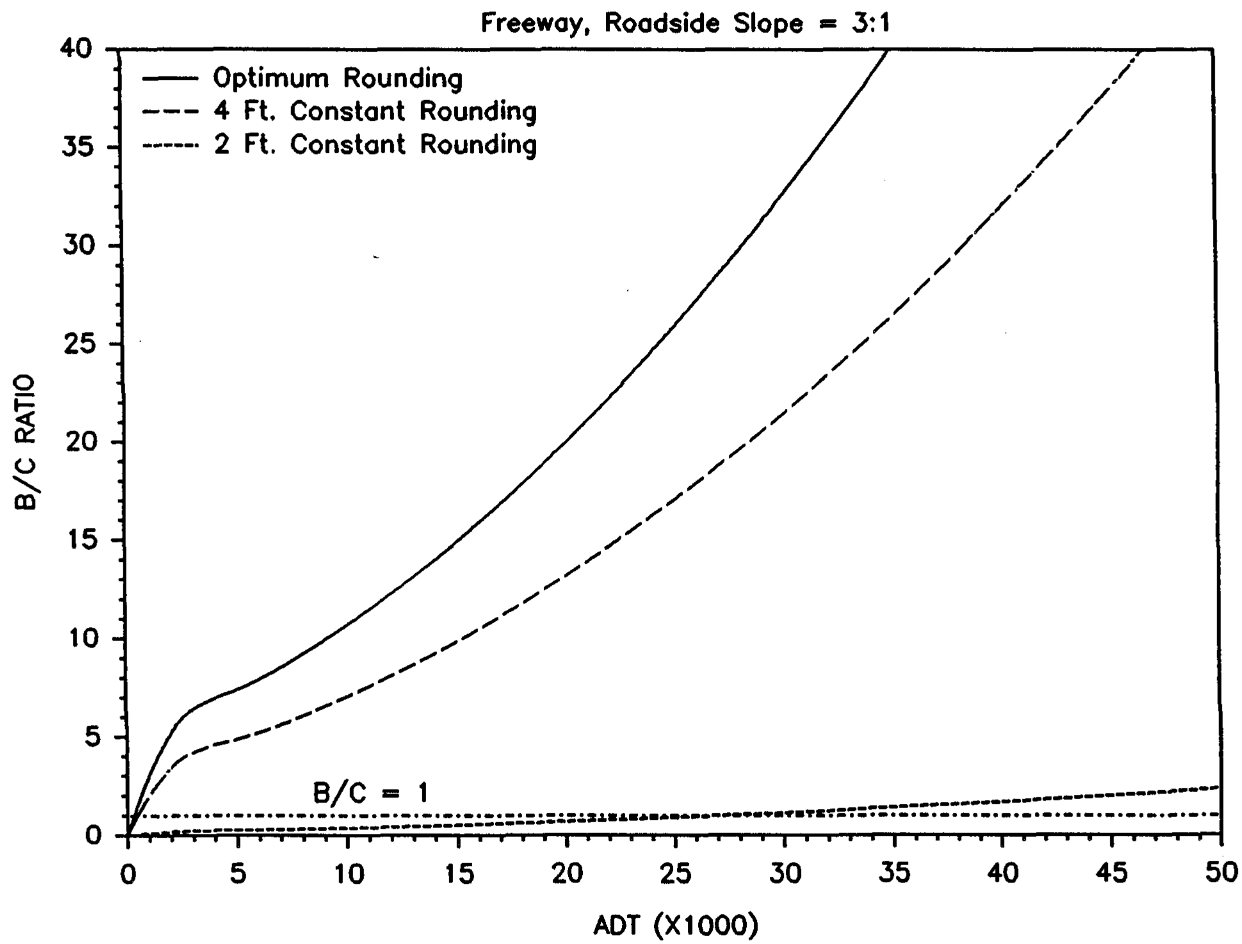

FIGURE D-10. B/C ratio versus ADT for 4-lane freeway, 3:1 side slope, compared to unrounded option.

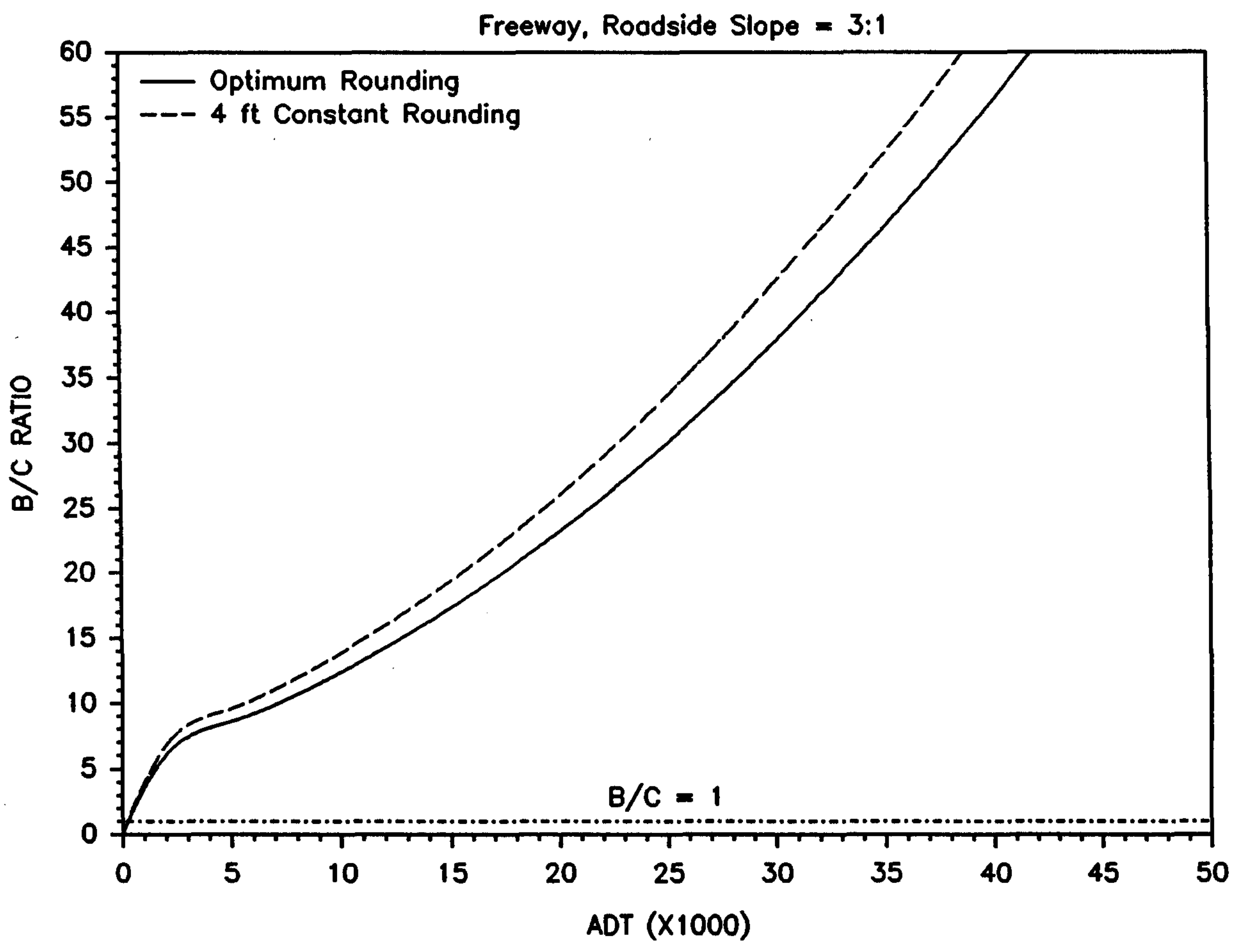

FIGURE D-11. B/C ratio versus ADT for 4-lane freeway, 3:1 side slope, compared to 2 ft (0.61 m) constant rounding option.

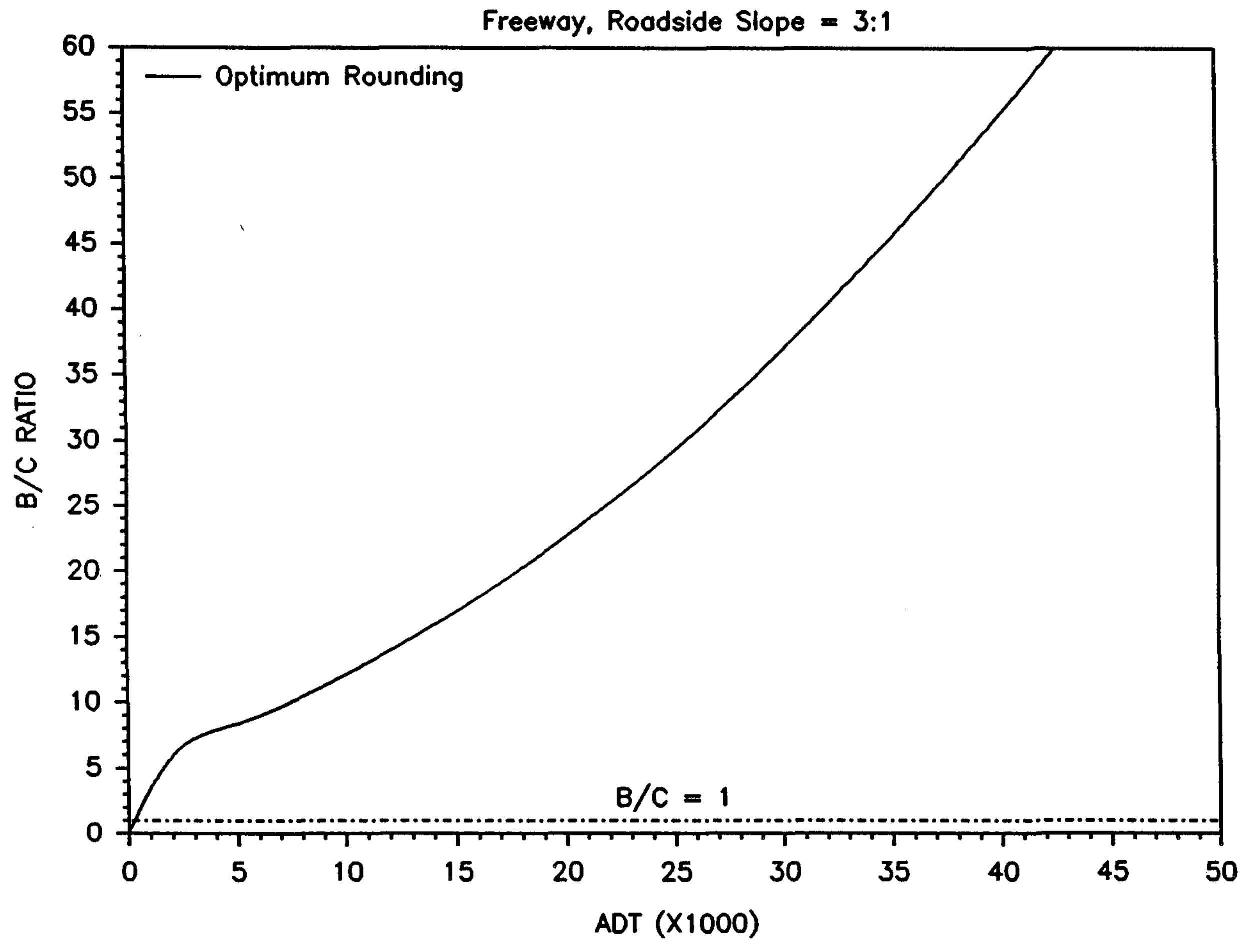

FIGURE D-12. B/C ratio versus ADT for 4-lane freeway, 3:1 side slope, compared to 4 ft (1.22 m) constant rounding option.