TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWATX77-225-1		

4. Title and Subtitle	5. Report Date March 1978 6. Performing Organization Code
"Safety Treatment of Roadside Culverts on Low Volume Roads"	
7. Author(s) T. L. Kohutek and H. E. Ross, Jr.	8. Performing Organization Report No. Research Report 225-1
9. Performing Organization Name and Address Texas Transportation Institute Texas A&M University College Station, Texas 77843	10. Work Unit No. 11. Contract or Grant No. Research Study 2-8-77-225
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation Transportation Planning Division P.O. Box 5051 Austin, Texas 78763	13. Type of Report and Period Covered Final Report January 1977 - March 1978 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with DOT, FHWA. Research Study Title: "Economics of Highway Design Alternatives". SDHPT Contact Man: Harold Cooner, FHWA Contact Man: C. P. Damon

16. Abstract

Current American Association of State Transportation and Highway Officials (AASHTO) criteria for safety-treating fixed roadside hazards suggest that all culverts within a certain clear distance of the edge of the traveled way be shielded by a roadside barrier. This is not necessarily a cost-effective solution for low volume highways.

Using a cost-effectiveness model currently recommended by AASHTO, guidelines for safety-treating culverts have been developed for 36 in. diameter pipe, 4 ft x 6 ft (4 ft height x 6 ft width) single box, and 4 ft x 6 ft multi-box (double box) culverts located on low volume, rural highways (average daily traffic less than 20,000). Each culvert design was evaluated on fill section embankments with $2\frac{1}{2}$:1 and 6:1 slopes and for end offsets of 12, 18, and 24 ft. The treatments considered for each culvert design and embankment slope were: 1) do nothing (i.e., leave the culvert unprotected); 2) extend the culvert end 30 ft from the edge of the traveled way; 3) provide guardrail protection; and 4) provide grate protection.

17. Key Words	18. Distribution Statement
Cost-Effectiveness, Culvert, Grates, Guardrail, Roadside Barriers, Safety Treatment, Severity Index	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	111	N/A

Form DOT F 1700.7 (8-69)

SAFETY TREATMENT

OF ROADSIDE CULVERTS

ON LOW VOLUME ROADS

by

T. L. Kohutek
Engineering Research Associate

and

H. E. Ross, Jr.
Research Engineer

Research Report 225-1
Economics of Highway Design Alternatives

Research Study 2-8-77-225

Sponsored by
The Texas State Department of Highways and Public Transportation
in cooperation with
The United States Department of Transportation
Federal Highway Administration

March 1978

Texas Transportation Institute
Texas A&M University
College Station, Texas

FOREWORD

The information contained herein was developed on Research Study 2-8-77-225 entitled "Economics of Highway Design Alternatives." It is a cooperative research study sponsored jointly by the Texas State Department of Highways and Public Transportation and the U. S. Department of Transportation, Federal Highway Administration.

The objective of the study is to develop guidelines for installing, upgrading, and safety-treating various types of culvert designs. Emphasis is placed primarily on culverts located on low volume roads (3,000 average daily traffic and less) although some work is done with intermediate volumes (20,000 average daily traffic).

A cost-effectiveness model was taken from the American Association of Highway and Transportation Officials (AASHTO) guide for the selecting, locating, and designing of highway traffic barriers (1). This model provides the present value of the total cost of each alternative as computed over a given period of time taking into consideration initial construction costs, maintenance costs, and accident costs. Accident costs incurred by the motorist, including vehicle damage and personal injury, are considered together with damage costs incurred by the highway department.

A ranking factor for each alternative is also calculated to aid the designer in establishing a priority system for reducing culvert hazards within a given roadway system. This factor is a ratio of the benefits (as measured in accident cost savings) received to direct costs incurred by the highway department when selecting an alternative.

The alternative with the highest ranking factor (or benefit to cost ratio) is generally the most desirable.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

SUMMARY

Key Words: Cost-Effectiveness, Culverts, Grates, Guardrail, Roadside Barriers, Safety Treatments, Severity Index.

Current American Association of State Transportation and Highway Officials (AASHTO) criteria for safety-treating fixed roadside hazards on high-speed facilities suggest that all culverts within a certain distance of the edge of the traveled way be shielded by a roadside barrier (1). In a restricted highway funding environment, this is not necessarily a cost-effective solution for low volume highways.

Using a cost-effectiveness model currently recommended by AASHTO (1), warrants for safety-treating culverts have been developed for 36 in. diameter pipe, 4 ft x 6 ft (4 ft height x 6 ft width) single box, and 4 ft x 6 ft multi-box (double box) culverts located on low volume, rural highways (average daily traffic less than 20,000). Each culvert design was evaluated on fill section embankments with 2½:1 and 6:1 slopes and for end offsets of 12, 18, and 24 ft. The treatments considered for each culvert design and embankment slope were: 1) do nothing (i.e., leave the culvert unprotected); 2) extend the culvert end 30 ft from the edge of the traveled way; 3) provide guardrail protection; and 4) provide grate protection.

Figures are given to identify cost-effective treatments for the range of variables (ADT, embankment slope, offset, culvert design and safety treatment, etc.) considered in this study. For traffic volumes less than 750 and offset distances greater than 12 ft, the most cost-effective alternative is to leave the culvert unprotected. At higher traffic volumes the most cost-effective safety treatments are extending

the culvert end to 30 ft or grating. Guardrail was found to be cost-effective only for larger culvert sizes and higher traffic volumes. However, guardrail protection was not the most cost-effective alternative for these situations.

All supporting data and a discussion of the cost-effectiveness model used in the study are included in this report. Examples are given to illustrate the use of the criteria developed and to show the techniques used to develop these criteria. Other examples are included to enable the user to develop warrants for situations other than those considered in this study.

IMPLEMENTATION

Generally, there are three alternatives to evaluate when considering the safety treatment of any roadside hazard: 1) do nothing, i.e., leave hazard unshielded; 2) remove or reduce hazard so that shielding is unnecessary; or 3) install a barrier. For culverts, the second alternative may be accomplished as follows: 1) extend the ends of the culvert a sufficient distance from the edge of the traveled way to allow an errant vehicle time and space to return to the road; and/or 2) "reduce" the hazard by providing grate treatment.

Extensive research has been performed to develop guidelines for safety-treating many types of roadside hazards, but little effort has been made to develop objective criteria for safety-treating culverts. This study provided objective criteria for the safety treatment of 36 in. diameter pipe, 4 ft x 6 ft single box, and 4 ft x 6 ft multi-box (double) culvert designs on both flat and steep roadside slopes and low volume highways. For each of these configurations, the alternatives discussed previously were considered as possible treatments. The criteria developed in this study will aid the highway designer in two ways. He will be able to (1) determine the most cost-effective safety treatment for existing culverts, or (2) design the most cost-effective culvert installation for new roadways. The same basic procedure used in this study may be used to develop objective criteria for other culvert designs on higher volume highways.

ACKNOWLEDGMENTS

This study was conducted under a cooperative program between the Texas Transportation Institute and the Texas State Department of Highways and Public Transportation (SDHPT). It was sponsored by SDHPT in cooperation with the U.S. Department of Transportation, Federal Highway Administration (FHWA).

The authors wish to thank Mr. Harold Cooner of SDHPT and Mr. C. P. Damon of FHWA for their opinions, guidance, and technical assistance throughout the study. Thanks should also be extended to Mr. Dan Williams of SDHPT for providing cost estimates for the various types of culvert designs and grate protection safety treatments. Special thanks go to Mrs. Sheila Darsie for her typing skills and overall assistance in preparing this report. Mrs. Sylvia Velasco also helped type the final manuscript.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF TABLES (continued)

I. INTRODUCTION

Vehicle collisions with roadside hazards are inherent to any existing highway facility. As highway improvement plans are prepared to minimize these hazards, it is essential in a restricted funding environment that final designs and alternatives be cost-effective to the highway department.

A common and dangerous roadside hazard is the open-ended culvert. There is little question that a collision with such a hazard can result in property damage and serious personal injury or possible fatalities. Culvert ends merit systematic and objective evaluation so that the most cost-effective safety treatment will be utilized.

Barrier warrants for fixed objects on high-speed facilities (1) suggest that all culverts within a predetermined "clear zone" be shielded by a roadside barrier. However, the guide (1) also encourages the application of a cost-effective procedure to provide an objective method of comparing alternate safety treatments for problem hazards such as the culvert. The options of "do nothing", i.e., leaving the hazard unshielded, and reduce or remove the hazard become possible safety treatments on low volume facilities where the probability of accidents is low.

There are many variables to consider in the safety treatment of any culvert design. Among these variables are the traffic volume, culvert size, culvert end offset distance, and the various available safety treatment designs. Chapter II discusses the range of those variables considered, along with the assumptions and limitations made in this study. Chapter III contains the safety treatment guidelines, and Chapter IV contains the conclusions. *Details of the cost-effective methodologies used in developing the guidelines are presented in the Appendix.*

II. CULVERT DESIGNS AND TREATMENTS

General

The culvert designs and treatments studied are those that would typically exist along low volume (average daily traffic less than 5000), high-speed, rural facilities. Figure 1 shows a typical rural roadway section considered in the study.

Range of Variables

The range of variables considered are listed below.

1) Culvert Size. Three typical sizes of culverts shown in Figure 1, namely, the 36 in. diameter pipe, the 4 ft x 6 ft single box, and the 4 ft x 6 ft multi-box (or double box) were studied.

2) Culvert Safety Treatments. Four safety treatment alternatives were considered. These were: do nothing (i.e., provide no shielding for the culvert), extend the culvert end to 30 ft from the edge of the traveled way, install guardrail, and place a grate over the culvert end. These safety treatments are shown in Figure 2. Note that added fill material is required when the culvert end is extended as shown in Figure 2. Cost of the added fill was included in the analysis.

3) Traffic Volumes. Average daily traffic (ADT) ranged from 750 to 20,000 with emphasis placed on ADT's below 3000.

4) Original Culvert End Offset. Three offset distances -- 12, 18 and 24 ft -- were studied.

5) Embankment Slope. Culverts located on fill sections with slopes of 2½:1 and 6:1 were studied.

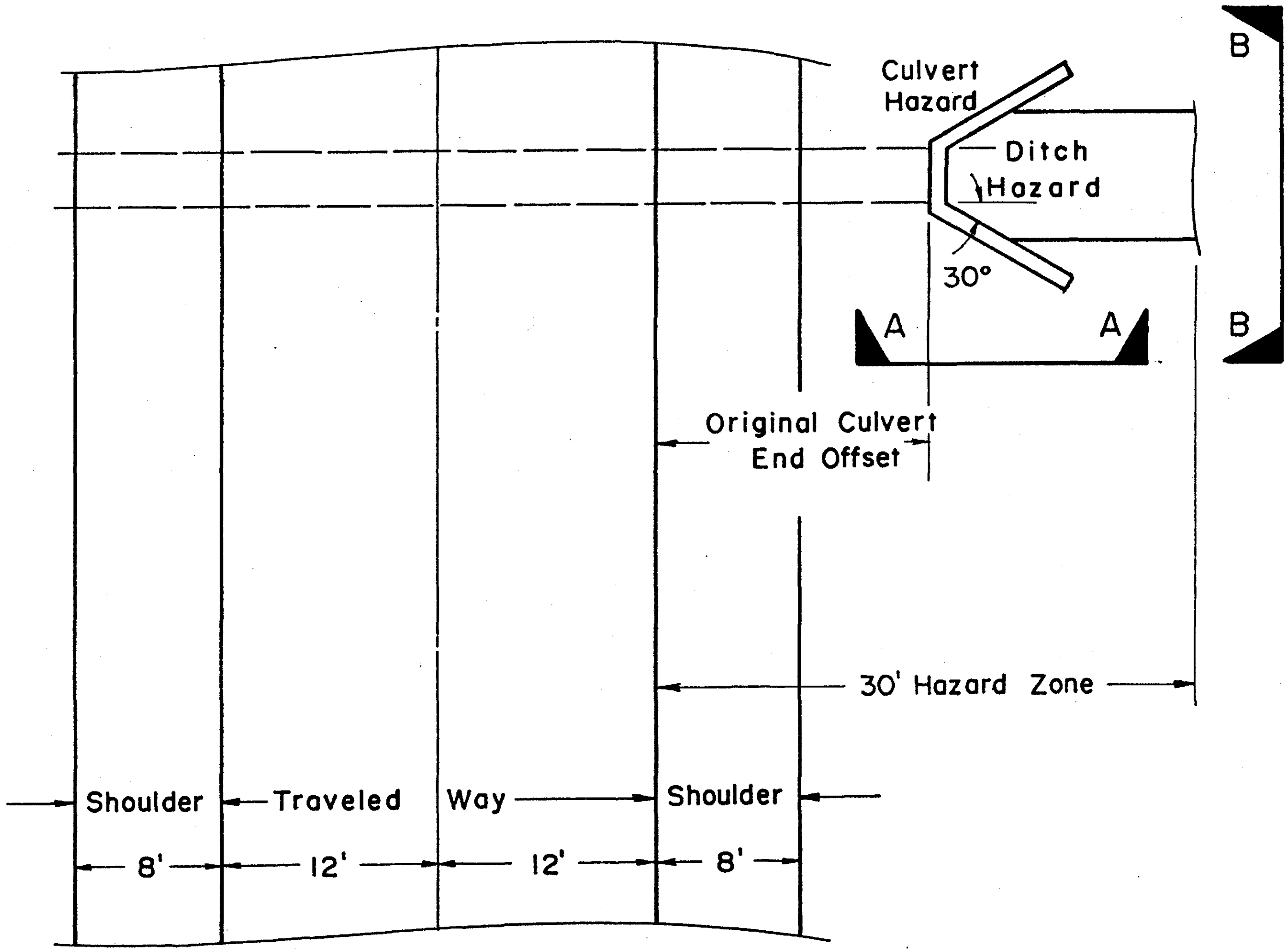


FIGURE 1. TYPICAL ROADWAY SECTION WITH THE VARIOUS CULVERT DESIGNS

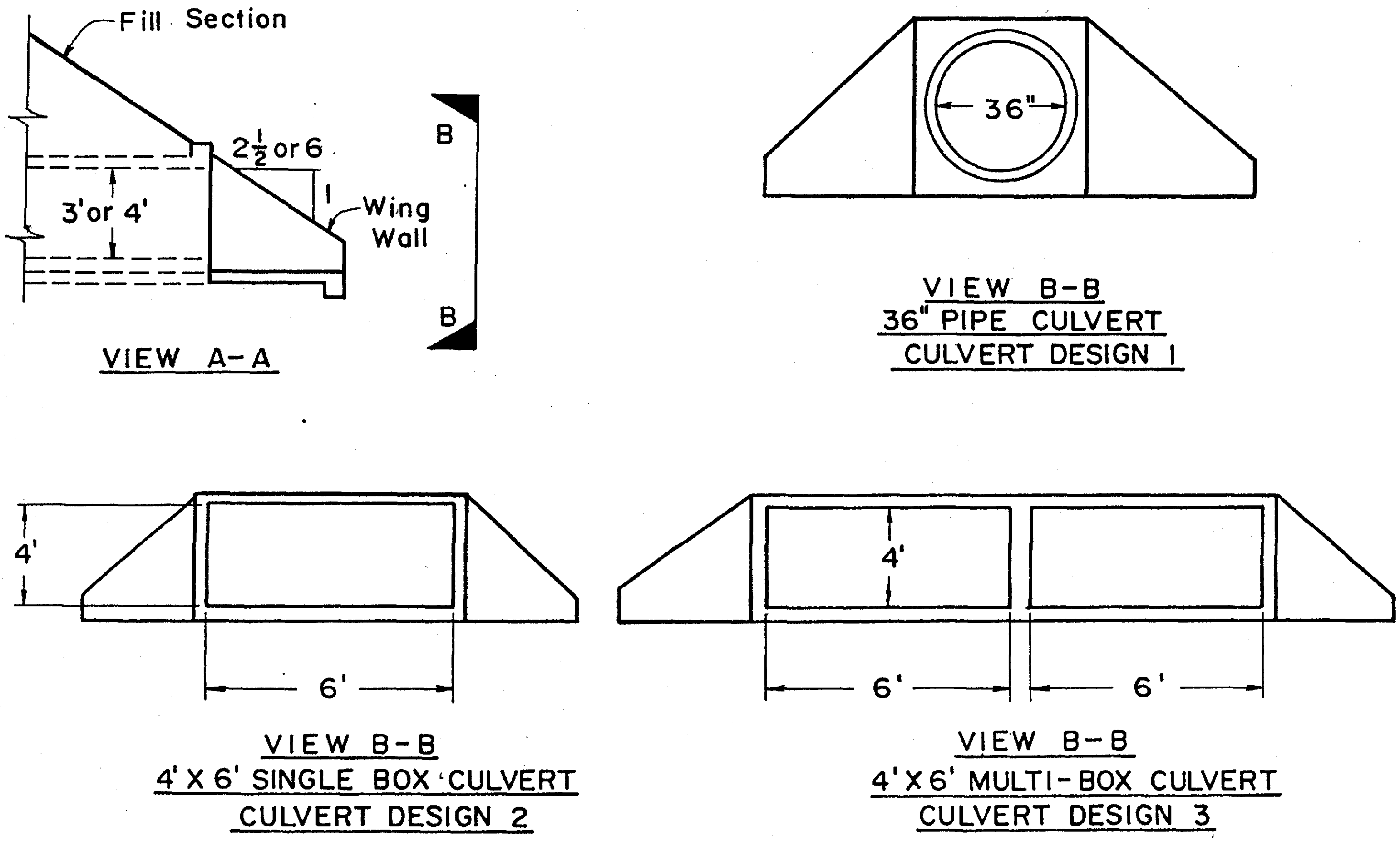
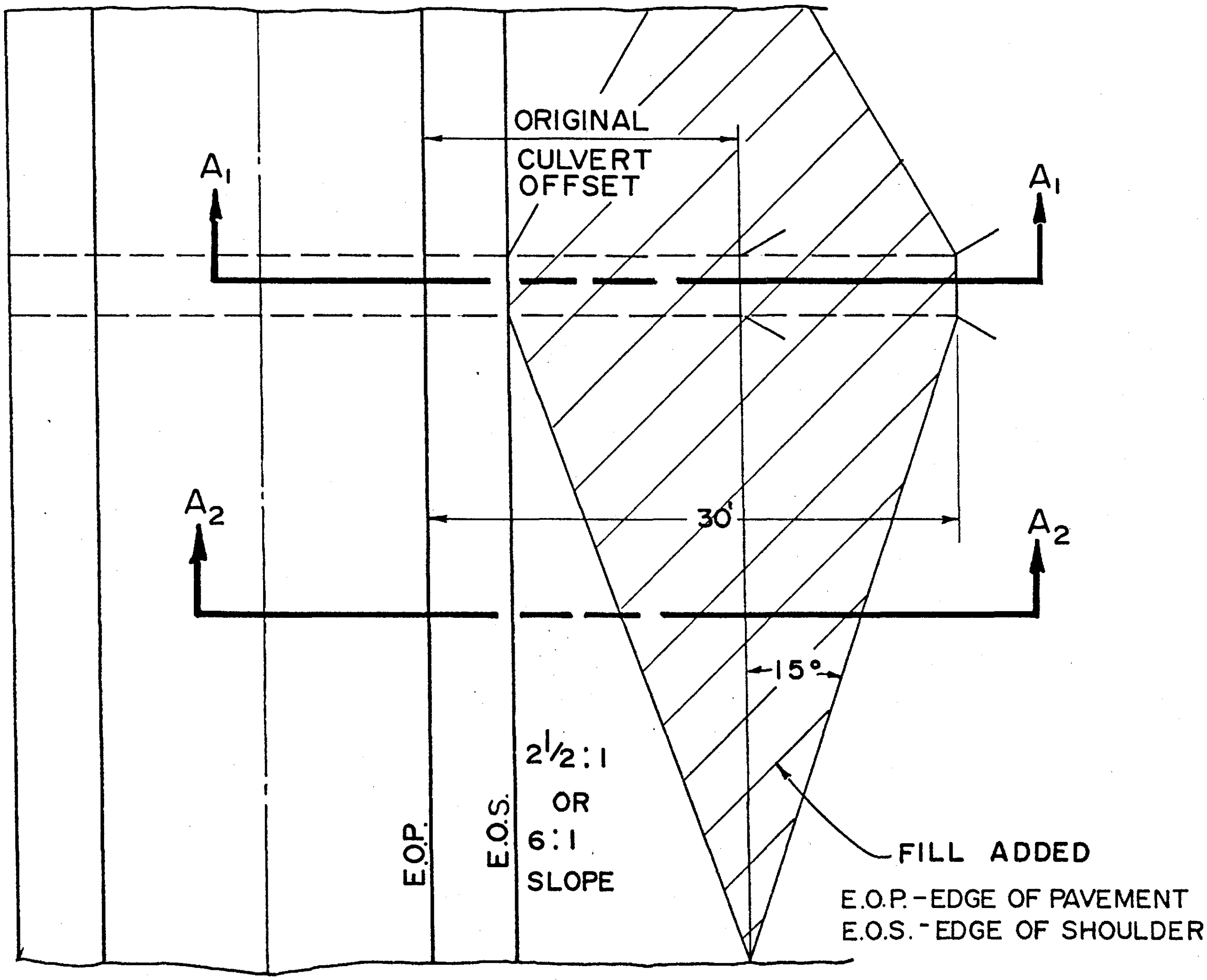
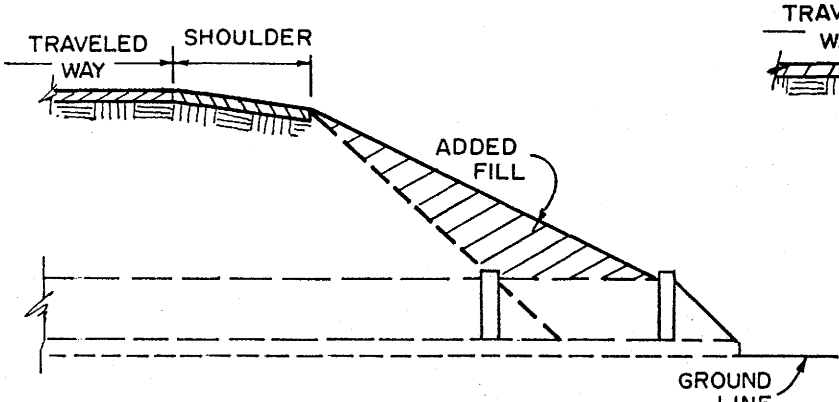


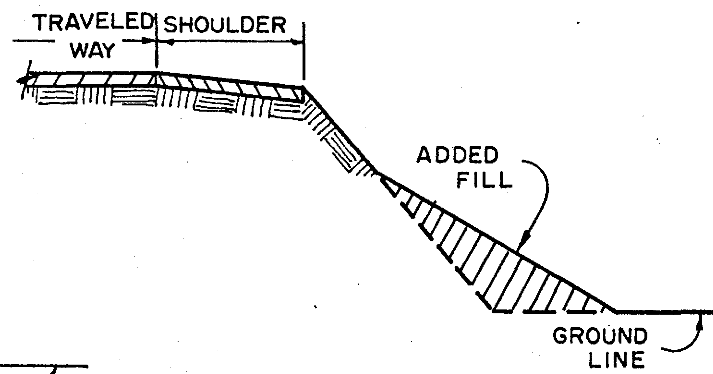
FIGURE 1 (CONTINUED). TYPICAL ROADWAY SECTION WITH THE VARIOUS CULVERT DESIGNS



SAFETY TREATMENT 1 - EXTEND TO 30ft.

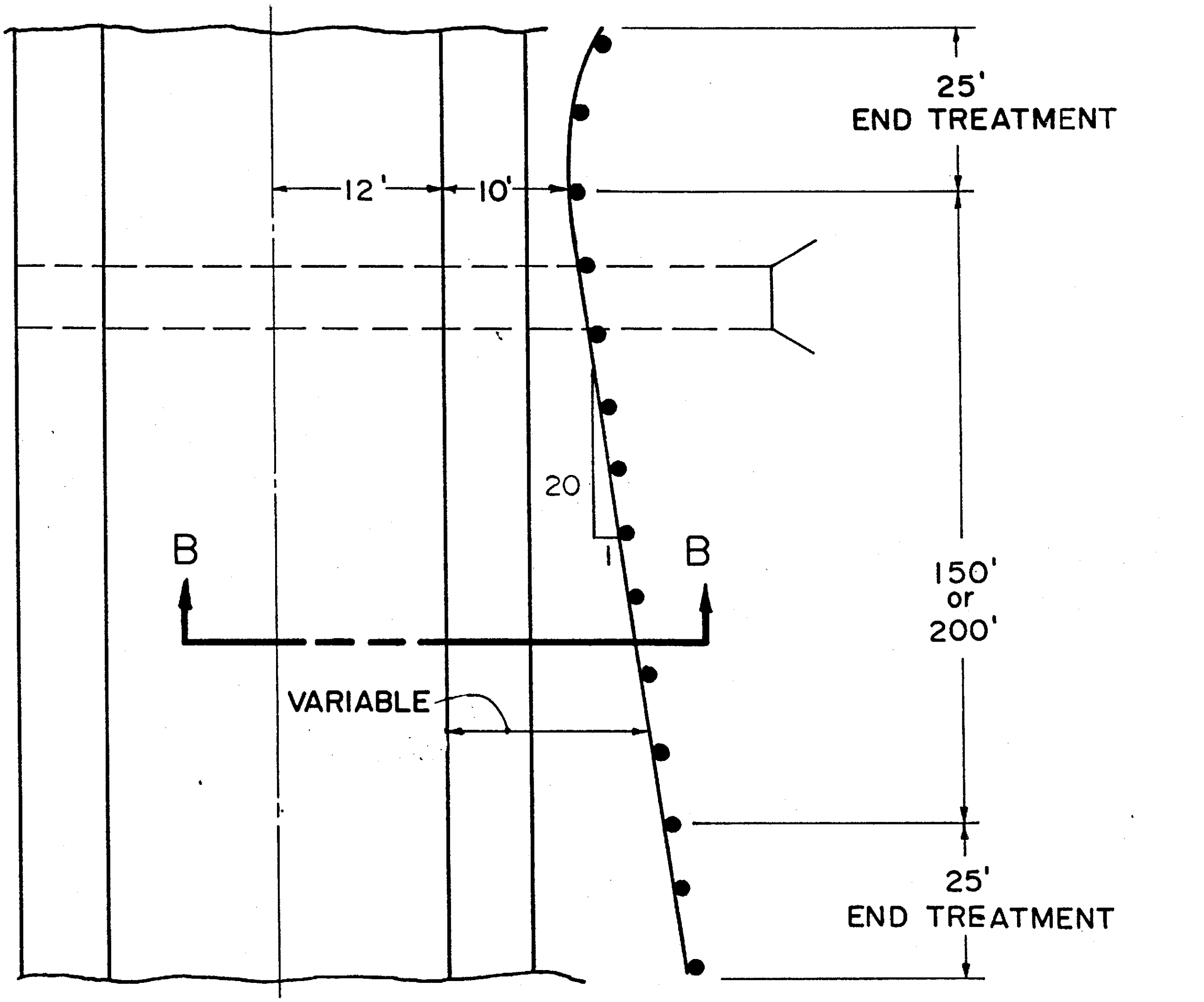


—SECTION A_1—A_1—

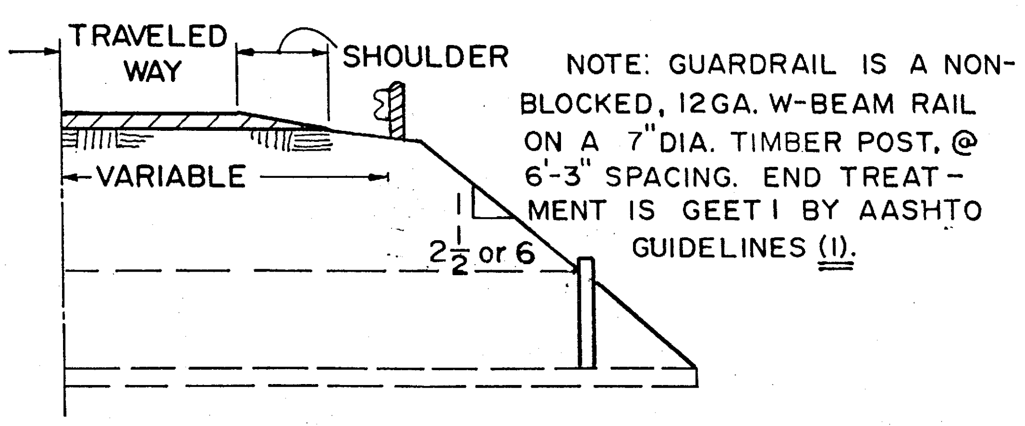


—SECTION A_2—A_2—

FIGURE 2. CULVERT SAFETY TREATMENTS.

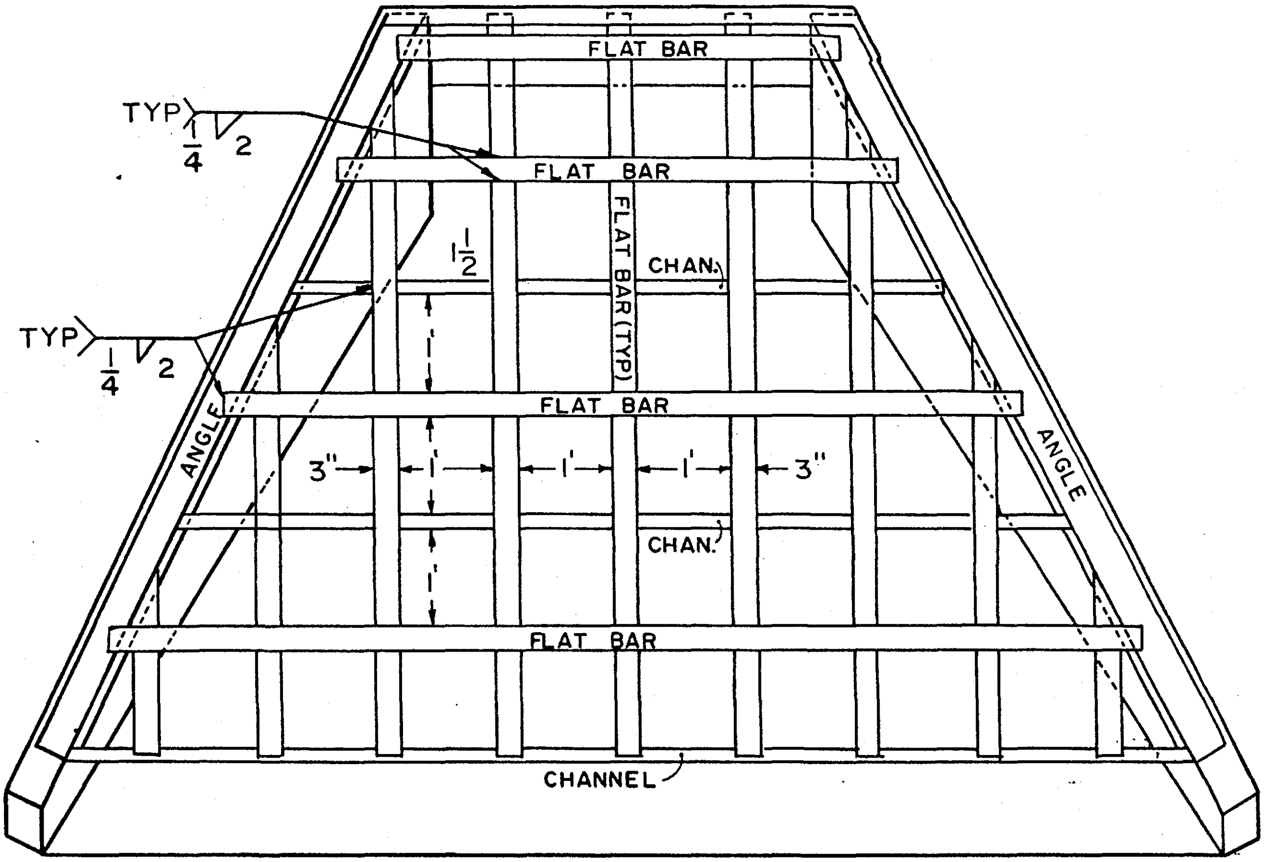


SAFETY TREATMENT 2 - GUARDRAIL PROTECTION



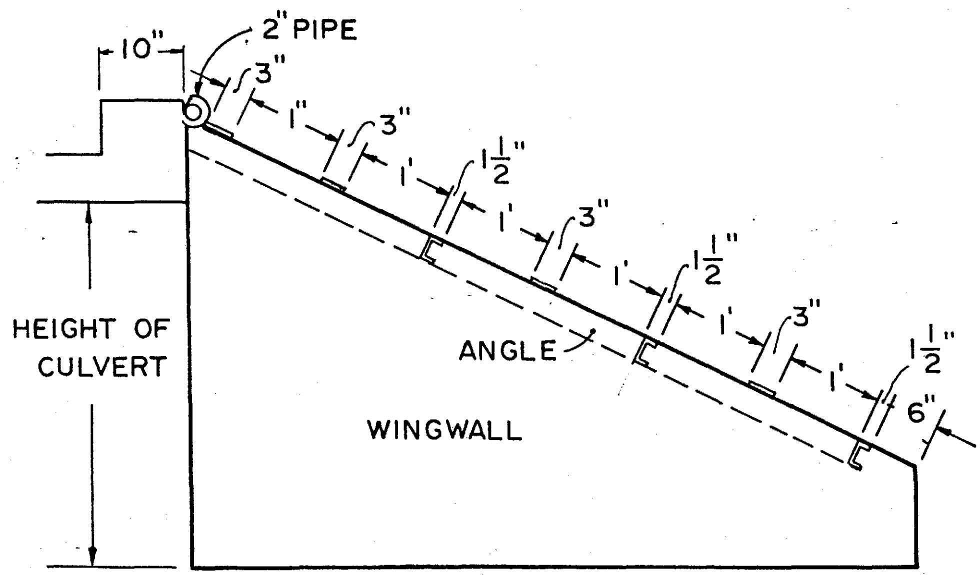
SECTION B—B

FIGURE 2 (CONTINUED). CULVERT SAFETY TREATMENTS



SAFETY TREATMENT 3-GRATE PROTECTION

TOP VIEW



SIDE VIEW

FIGURE 2 (CONTINUED). CULVERT SAFETY TREATMENTS

Assumptions and Limitations

A certain number of assumptions and limitations were essential in the development of the cost-effectiveness model used in this study. Discussion of the basic assumptions, including encroachment rates and severity indices with their related accident costs, can be found in the AASHTO guide (1). Listed below are assumptions that were made in addition to those necessary to develop the model:

1) ADT would remain relatively constant for the highway design life (20 years).
2) The ditch at the culvert end will have 2:1 sloping walls and the depth of the ditch will be half the height of the culvert.
3) The wing walls of the culvert will be the same slope as the fill section (2½:1 or 6:1).
4) Grates placed on any culvert end will be designed such that it is traversable and can support a 4500 lb vehicle under anticipated dynamic loads.
5) A vehicle leaving the traveled way would have redirection capabilities on a 6:1 fill section but not on a 2½:1 fill section.
6) For all culvert sizes with offsets of 12 ft, 200 ft of guardrail plus two 25-ft end treatments would be necessary to protect the culvert. Culverts with offsets of 18, 24, or 30 ft require 150 ft of guardrail plus two 25 ft end treatments.
7) The severity indices and resulting accident costs were determined based on a survey sent to 15 personnel from the Texas Transportation Institute, Texas State Department of Highways and Public Transportation and the United States Department of Transportation, Federal Highway Administration (5).

8) Severity indices for the three open-ended culvert sizes studied on $2\frac{1}{2}$:1 and 6:1 slopes were for perpendicular ditch crossings.

9) The encroachment data used in the study (2) limit the results obtained to two-lane highways (using the total ADT) and to the right side of divided highways using one-way ADT (half the total ADT).

III. GUIDELINES FOR EXTENDING OR UPGRADING EXISTING UNPROTECTED CULVERTS

Historically, roadside barriers have been the primary safety treatment for culverts. Only recently has there been the development of other alternatives such as the grate safety treatment. Determination of the type of treatment used (if any) has been based primarily on engineering judgment and available highway funds. This is especially true of low volume highways. Development of selection and priority procedures based on cost-effectiveness has enabled highway officials to make more objective decisions. It was through such procedures, described in the Appendices, that the guidelines presented in this chapter were developed.

Figures 3 through 8 contain guidelines for determining the most cost-effective means of treating 36 in. diameter pipe, 4 ft x 6 ft single box, and 4 ft x 6 ft double box culverts for various offset, traffic volume, and side slope conditions. These figures indicate the circumstances where ranking factors exceed unity (i.e., where benefits exceed costs), and which alternative has the highest ranking factor for a given culvert size, ADT, side slope, and original culvert offset. Where ranking factors for two alternatives were approximately the same for given conditions, both treatments are shown as acceptable. The alternate chosen would rest with the designer. Tables C1 through C6, Appendix C, show the ranking factors calculated through application of the cost-effectiveness model.

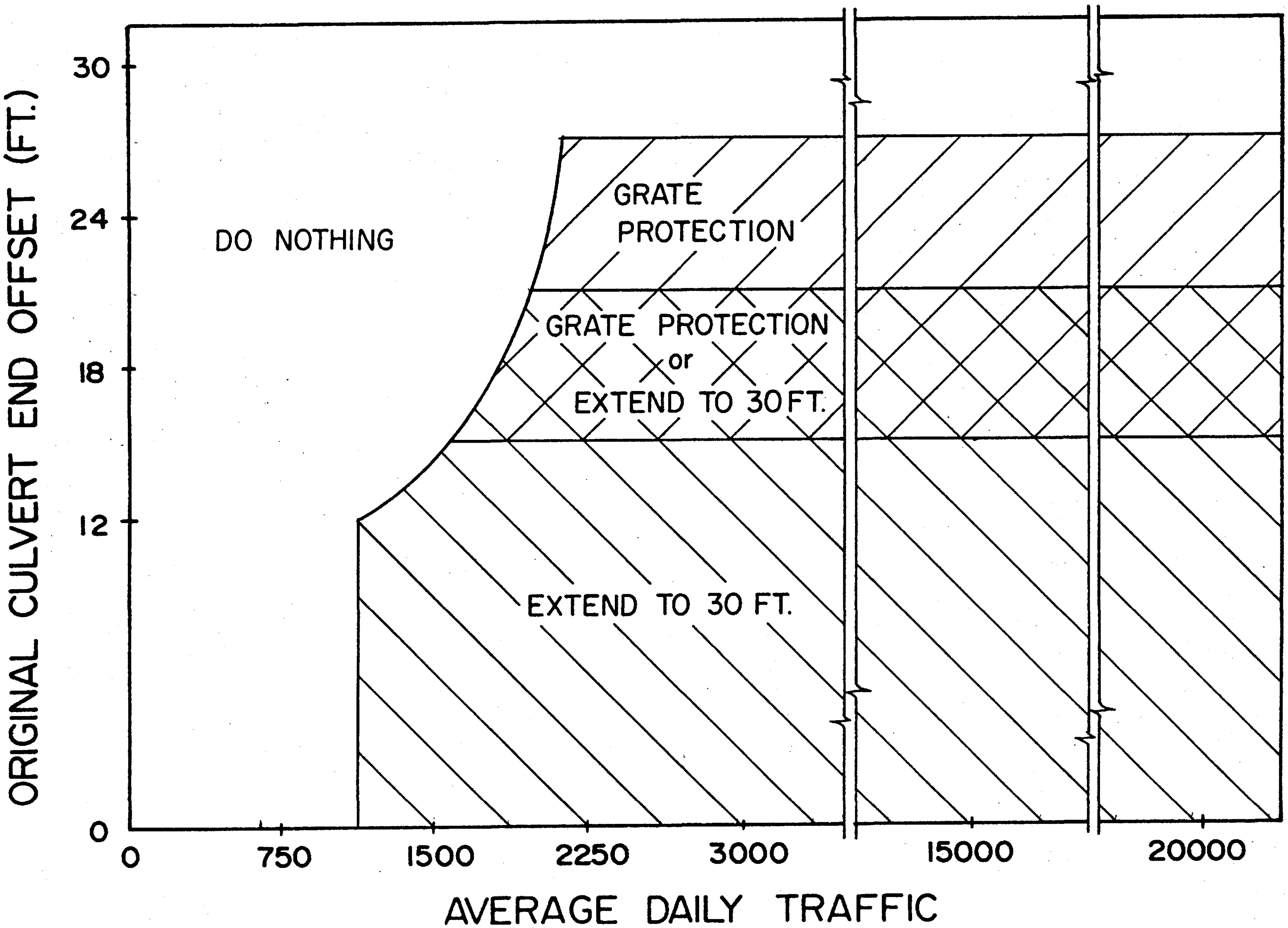


FIGURE 3. WARRANTS FOR EXTENDING OR UPGRADING A 36-INCH PIPE CULVERT ON A 2½:1 SLOPE

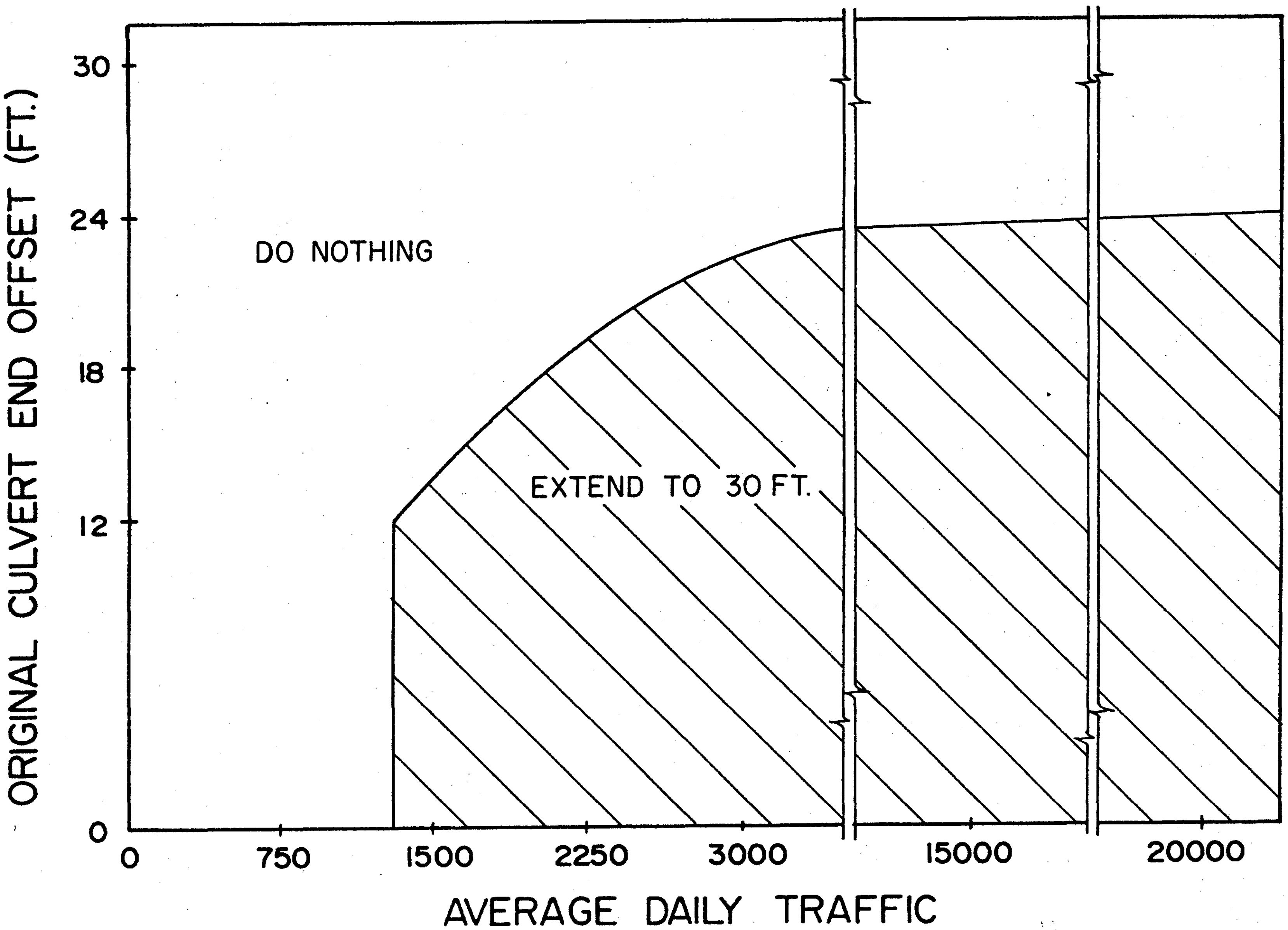


FIGURE 4. WARRANTS FOR EXTENDING OR UPGRADING A 36-INCH PIPE CULVERT ON A 6:1 SLOPE

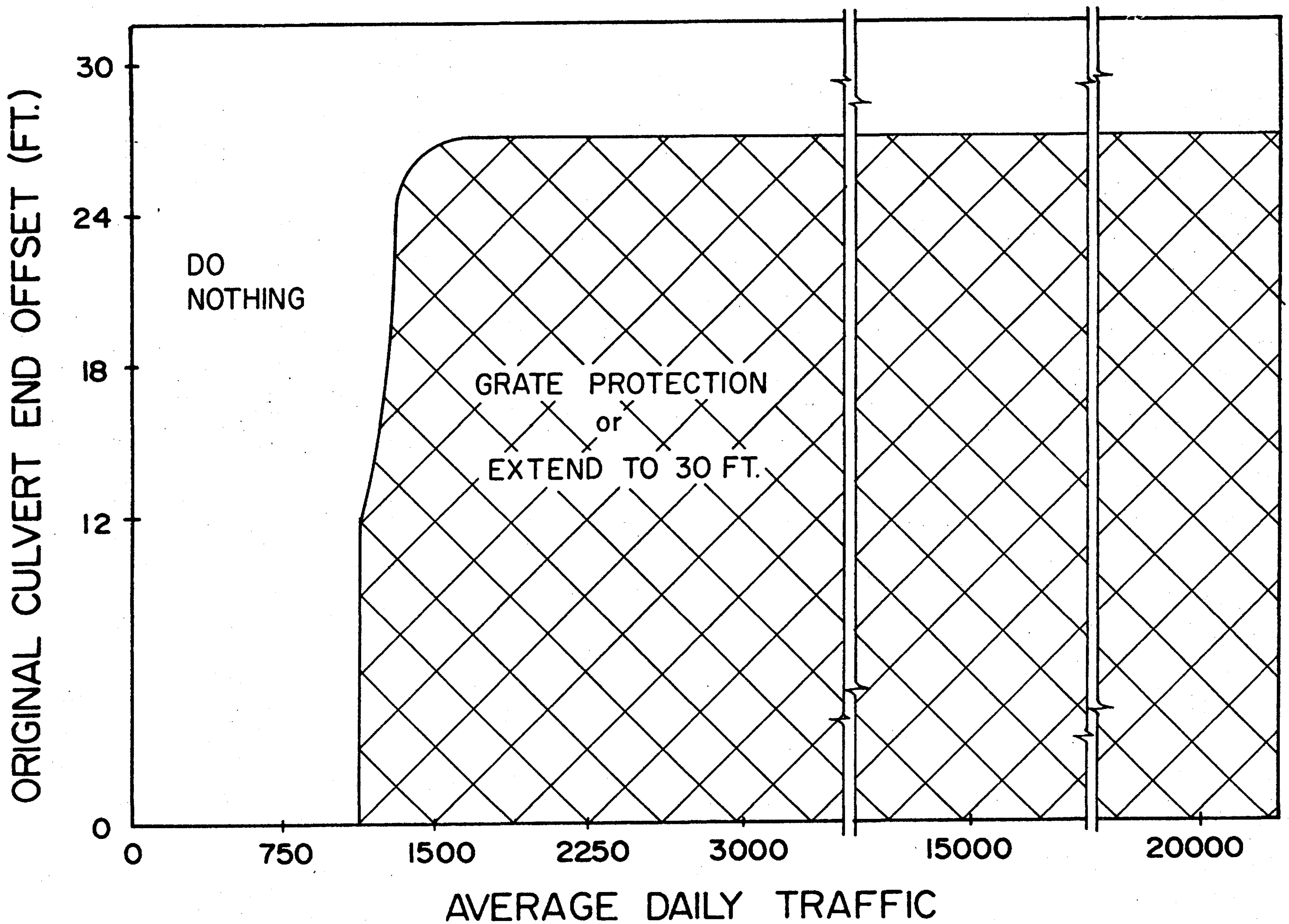


FIGURE 5. WARRANTS FOR EXTENDING OR UPGRADING A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

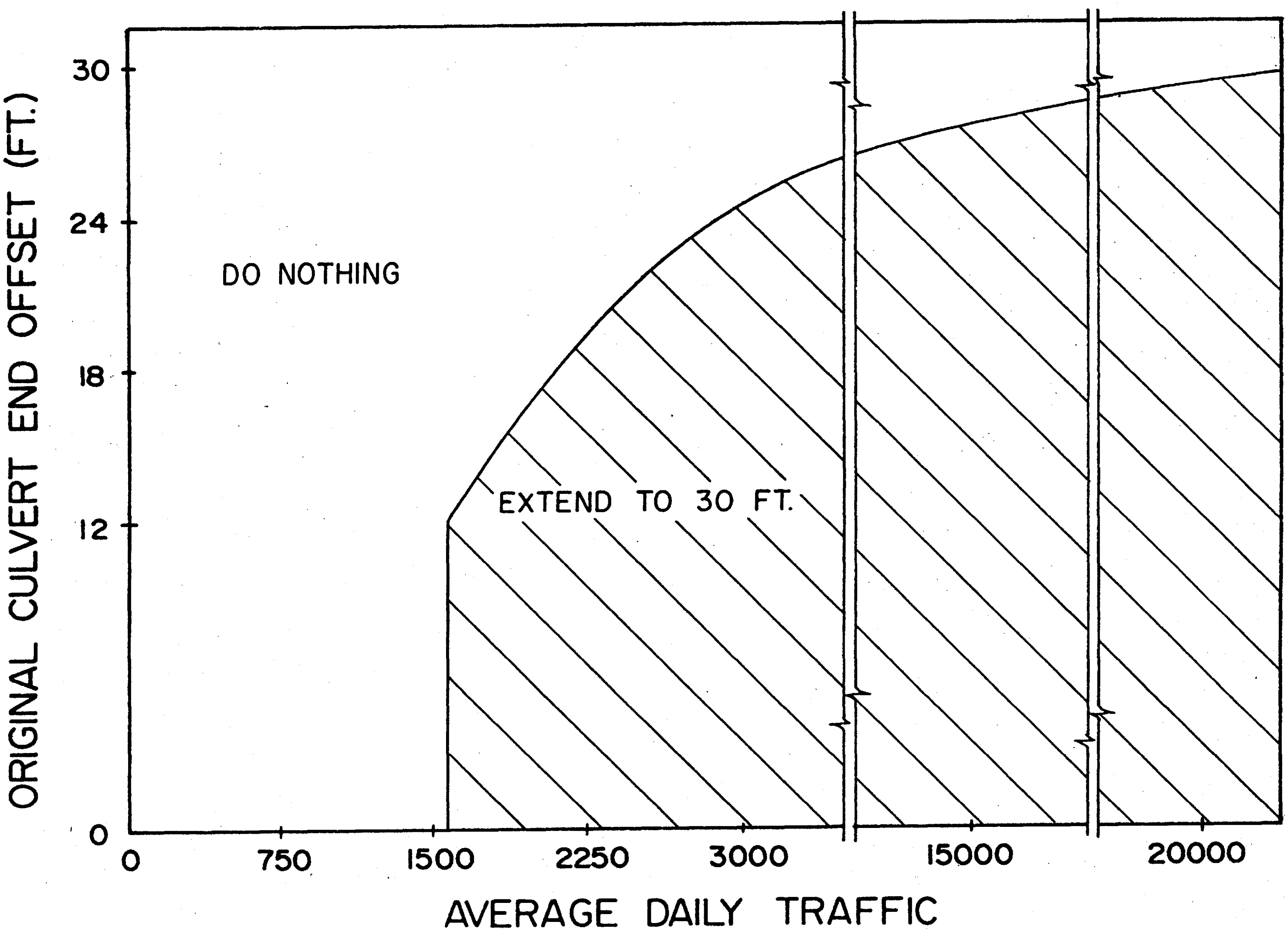


FIGURE 6. WARRANTS FOR EXTENDING OR UPGRADING A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

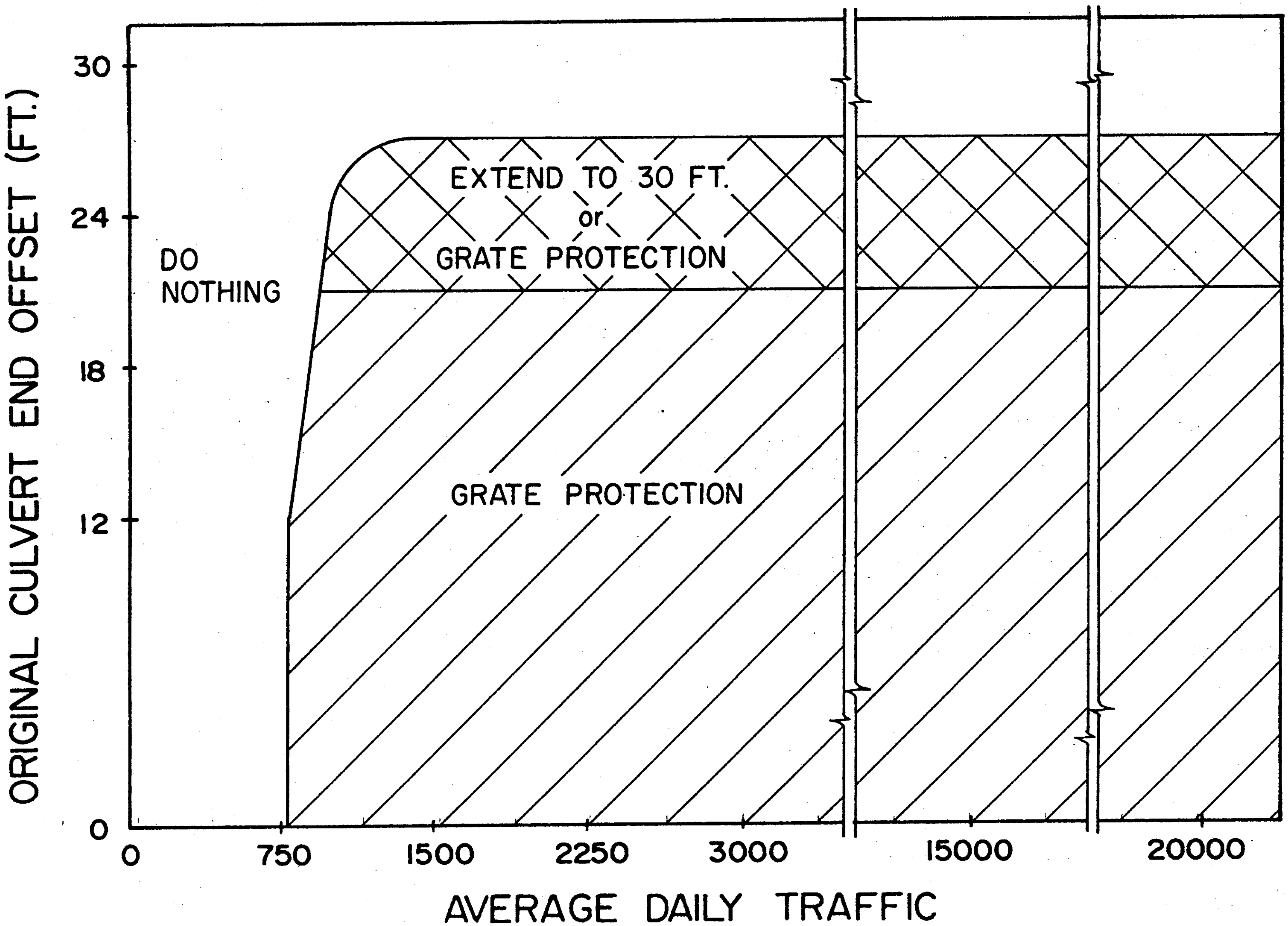


FIGURE 7. WARRANTS FOR EXTENDING OR UPGRADING A 4' X 6' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

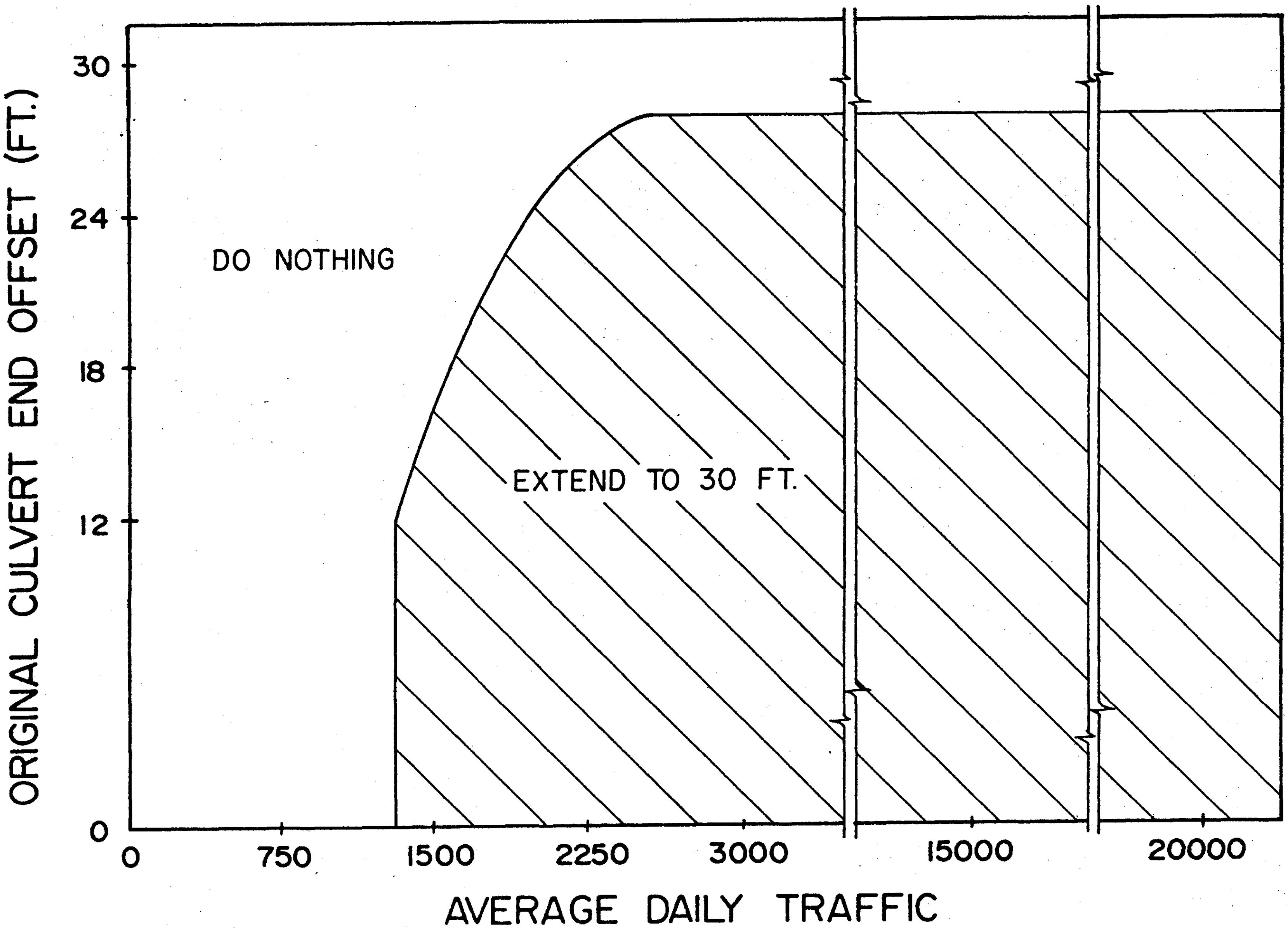


FIGURE 8. WARRANTS FOR EXTENDING OR UPGRADING A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

To use the figures:

1) Select the figure with the appropriate culvert size and slope.

2) Enter that figure with the proper ADT and culvert end offset.

3) Determine the appropriate treatment.

Note that these figures consider only the hazards of the slope, culvert and ditch. Other hazards near or around the culvert may warrant other types of safety treatment based on current AASHTO guidelines (1). The information presented in these figures should be used in conjunction with sound evaluation of the facts and engineering judgment.

To more precisely define the conditions where treatment is cost-effective, the ranking factor data were processed one further step. Table 1 shows interpolated values of ADT for ranking factors of 1.0. Figure 9 shows sample calculations for the ADT interpolation.

The interpolated ADT values shown in Table 1 were plotted versus offset distance as shown in Figures 10 and 11 for steep and flat slopes, respectively. The curves represent a ranking factor (i.e., benefit/cost ratio) of 1.0; thus the curves define the boundary conditions where treatment becomes cost-effective.

These curves may be used directly to develop design guidelines for upgrading existing facilities. Although new location projects would involve the added cost of about 48 ft of culvert (under travel lane and shoulder to provide 12-ft offset) construction, it may be rationalized that larger projects usually result in lower unit prices and thus the curves are a good starting point for developing design guidelines for routes on new locations.

Figures 12 through 18 illustrate the potential for developing design guidelines for these curves. Once a set of guidelines has been formulated,

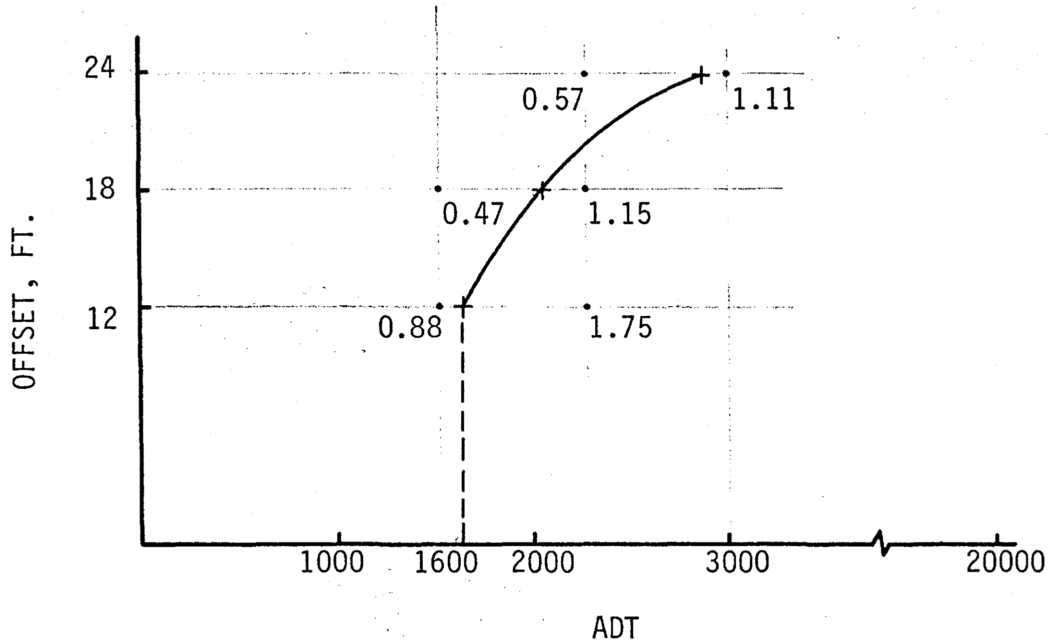
Table 1. Interpolated ADT Volumes for Ranking Factor = 1.0

Culvert Size	Side Slope	ADT		
		A = 12'	A = 18'	A = 24'
36" dia.	$2\frac{1}{2}$:1	1110 (E)*	2020 (E)	1900 (G)
36" dia.	6:1	1310 (E)	1980 (E)	** (DN)
1-4'x6'	$2\frac{1}{2}$:1	1130 (G)	1270 (G)	1300 (G)
1-4'x6'	6:1	1600 (E)	2090 (E)	2850*** (E)
2-4'x6'	$2\frac{1}{2}$:1	800 (G)	880 (G)	990 (E)
2-4'x6'	6:1	1350 (E)	1600 (E)	2000 (E)

*Parenthesis include treatment, i.e., (E) = extend, (G) = grate, that becomes cost effective at lowest volume.

**RF = 1.0 for ADT = 15,000 or less; assume RF = 1.0 for A = 23' for 3000<ADT<15,000.

***RF = 1.0 appears to level off at a slightly larger offset than 24 ft for ADT's up to 15,000.



Example: Single 4' x 6' box culvert, 6:1 slope; extension is the most cost effective solution for each set of traffic volumes and offsets.

Sample calculation:

$$\text{Interpolated } ADT_{RF} = 1.0 = ADT_2 - (ADT_2 - ADT_1) \left(\frac{RF_2 - 1.0}{RF_2 - RF_1} \right)$$

At offset = 12'

$$\text{Interpolated } ADT_{RF} = 1.0 = 2250 - (2250 - 1500)((1.75 - 1.0)/1.75 - 0.88))$$

$$= 2250 - 750\ (0.75/0.87)$$

$$= 2250 - 650$$

$$\text{Interpolated } ADT_{RF} = 1.0 = 1600$$

FIGURE 9. SAMPLE ADT INTERPOLATION FOR UNITY RANKING FACTOR

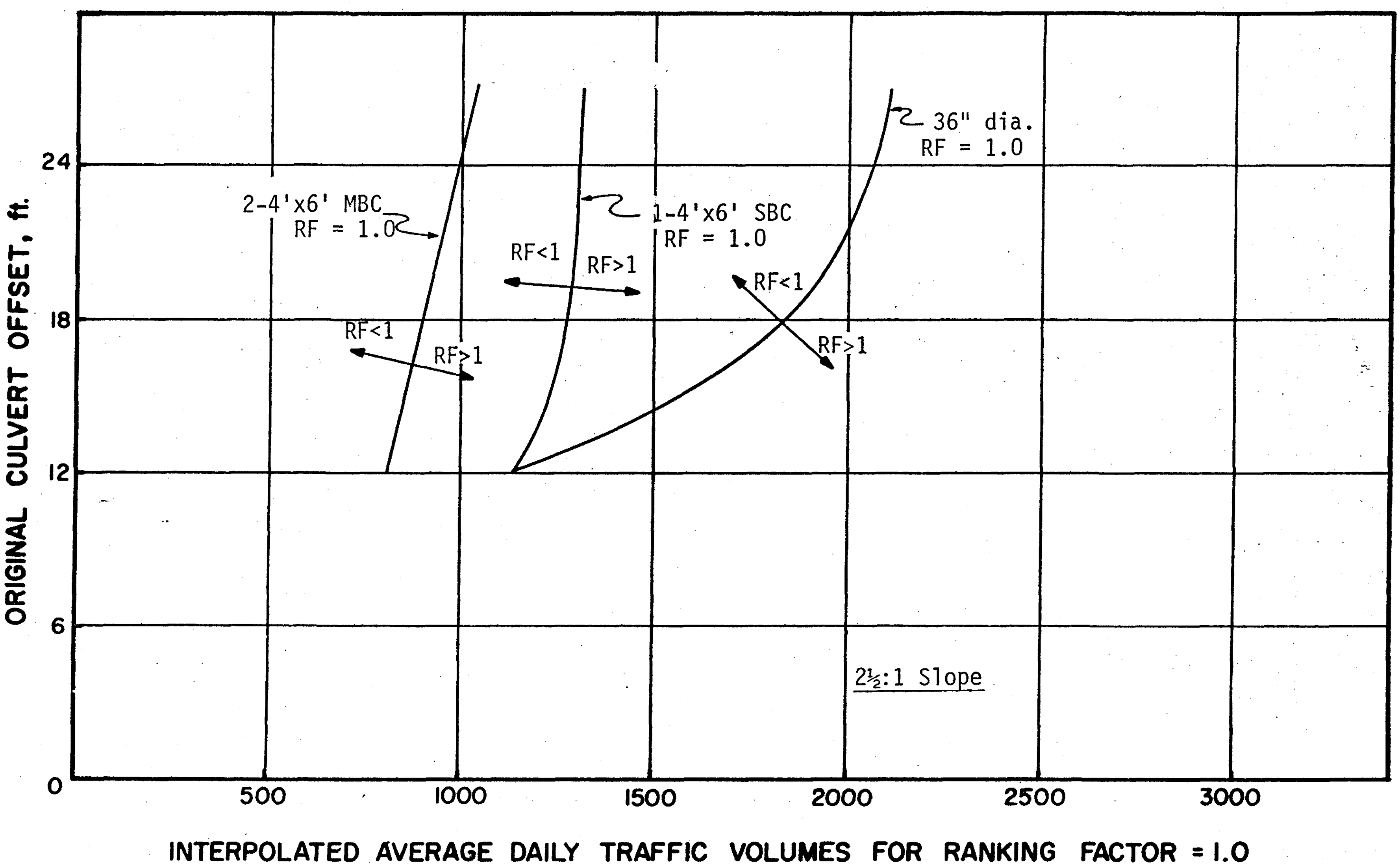


FIGURE 10. COST-EFFECTIVENESS CURVES FOR TYPICAL CULVERT ENDS ON 2½:1 SLOPES

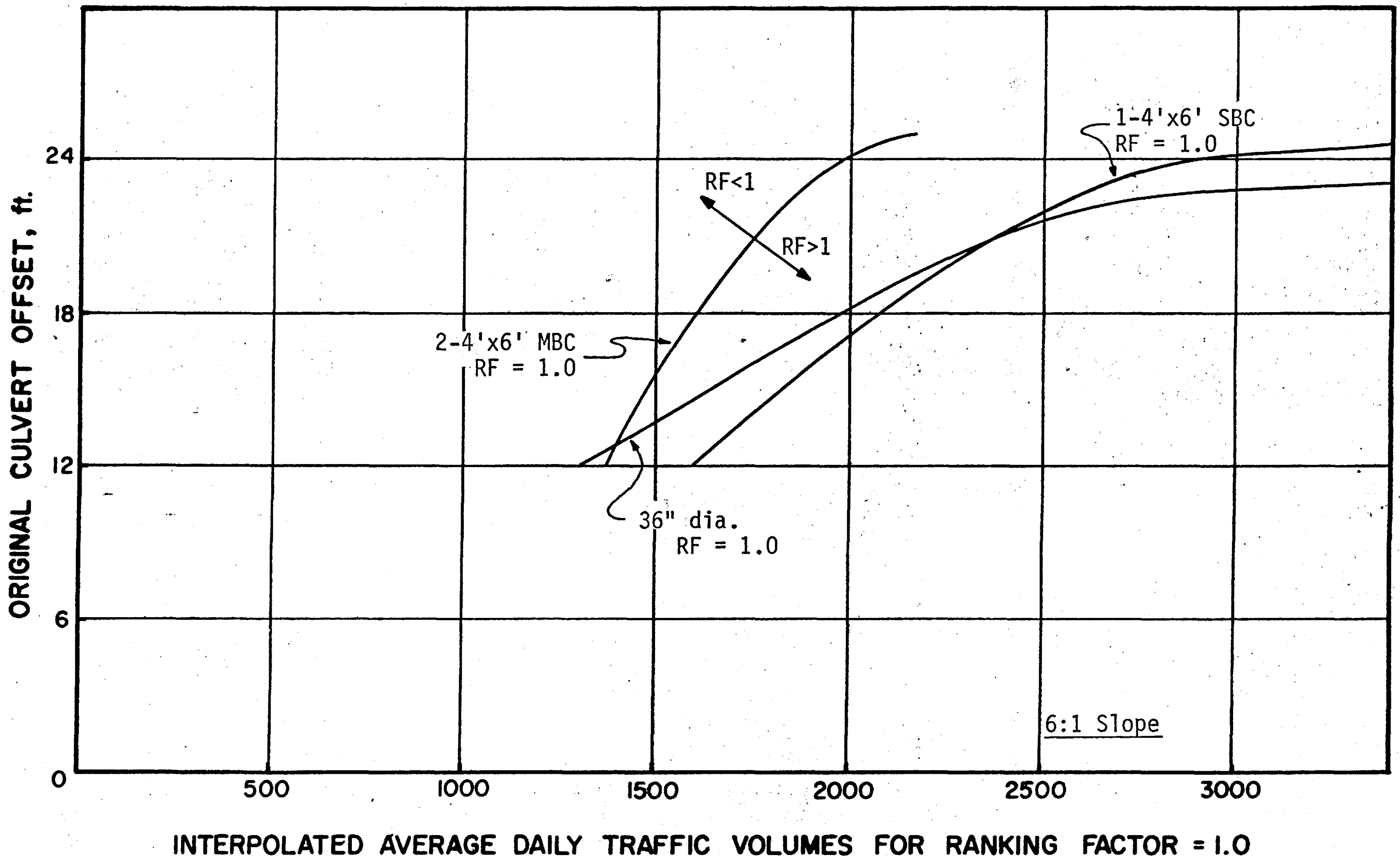


FIGURE 11. COST-EFFECTIVENESS CURVES FOR TYPICAL CULVERTS ON 6:1 SLOPES

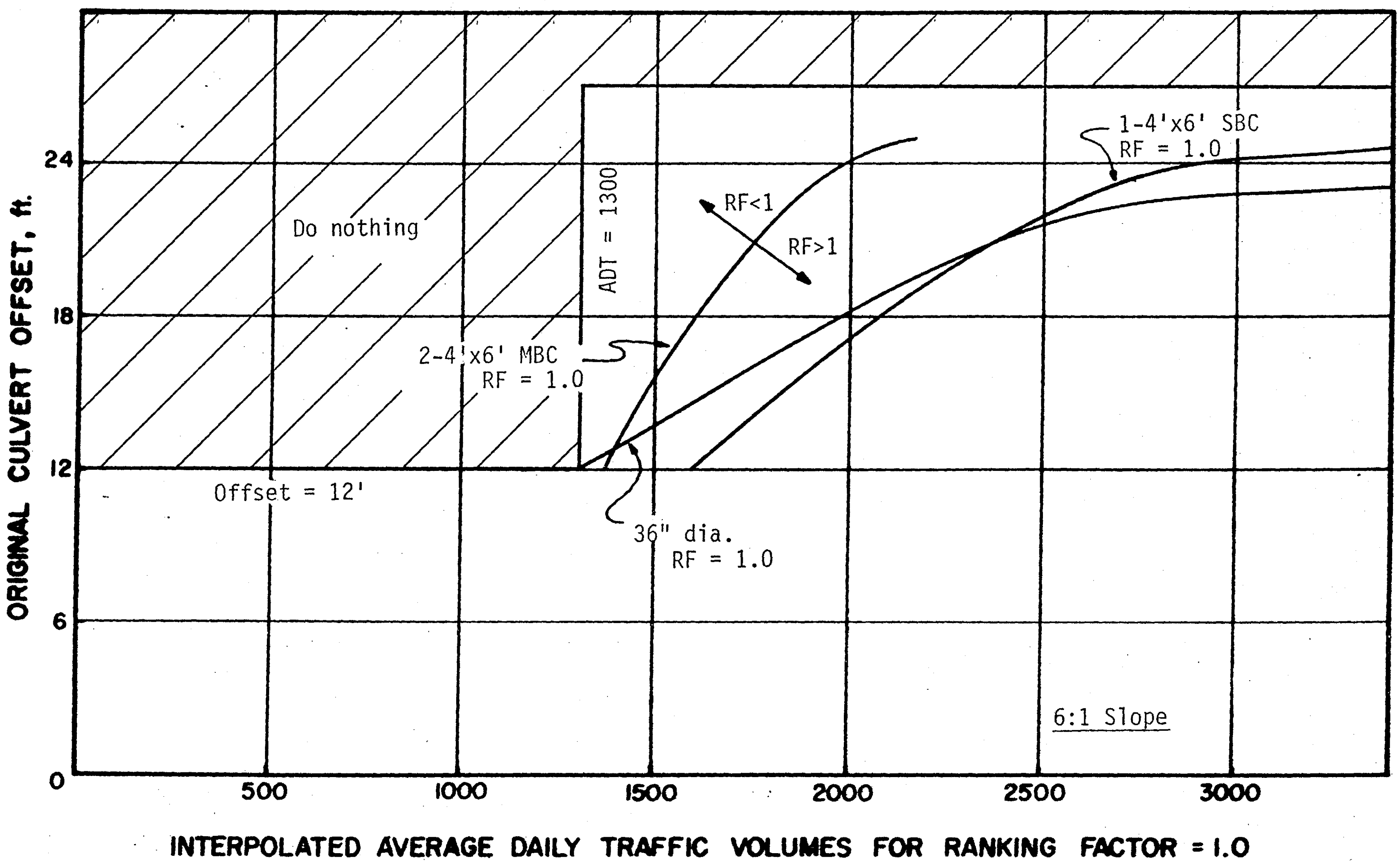


FIGURE 12. POSSIBLE DESIGN GUIDELINES FOR TYPICAL CULVERTS ON 6:1 SLOPES

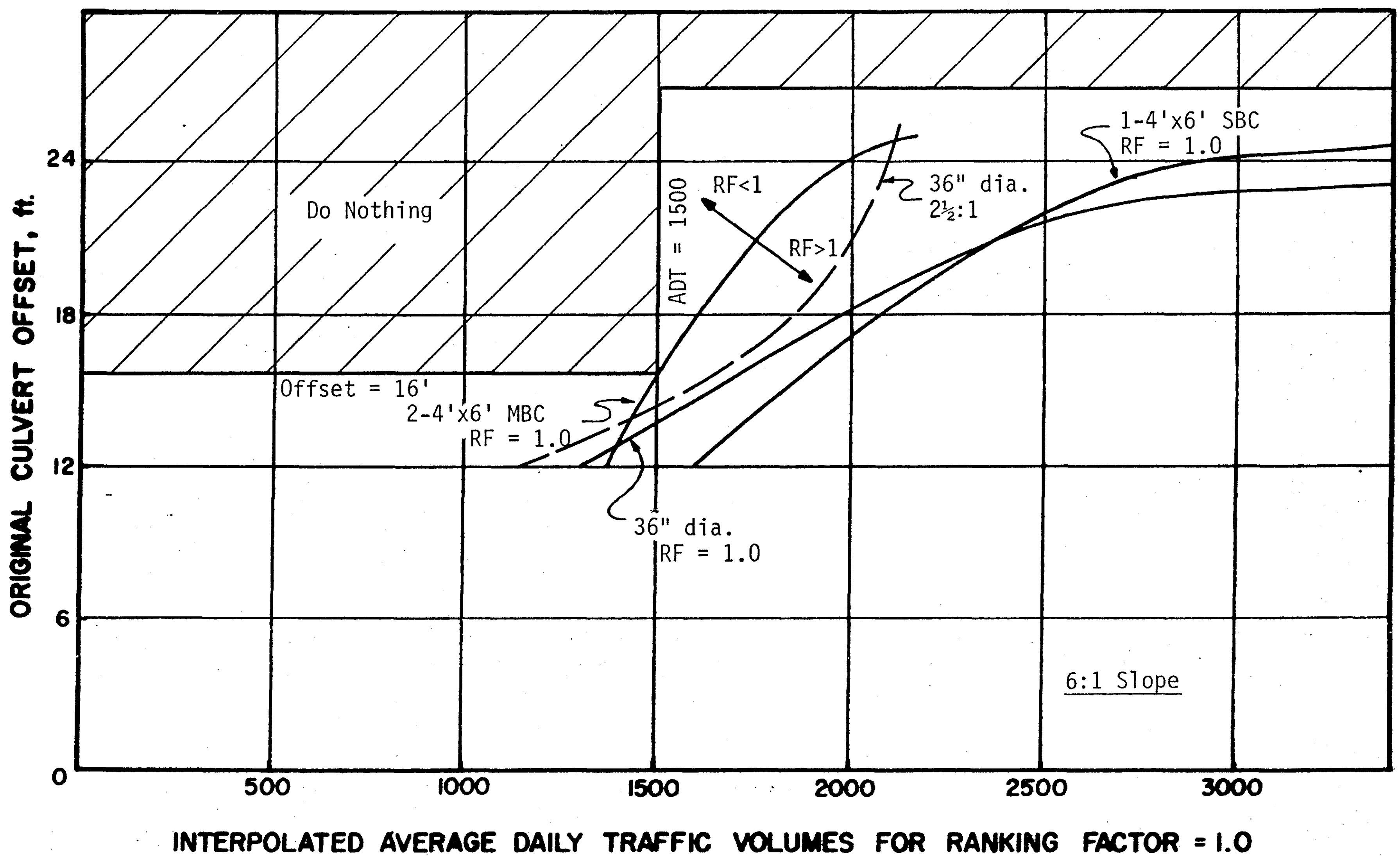


FIGURE 13. POSSIBLE DESIGN GUIDELINES FOR TYPICAL CULVERTS ON 6:1 SLOPES AND SMALL (36" DIA.) CULVERTS ON STEEP SLOPES

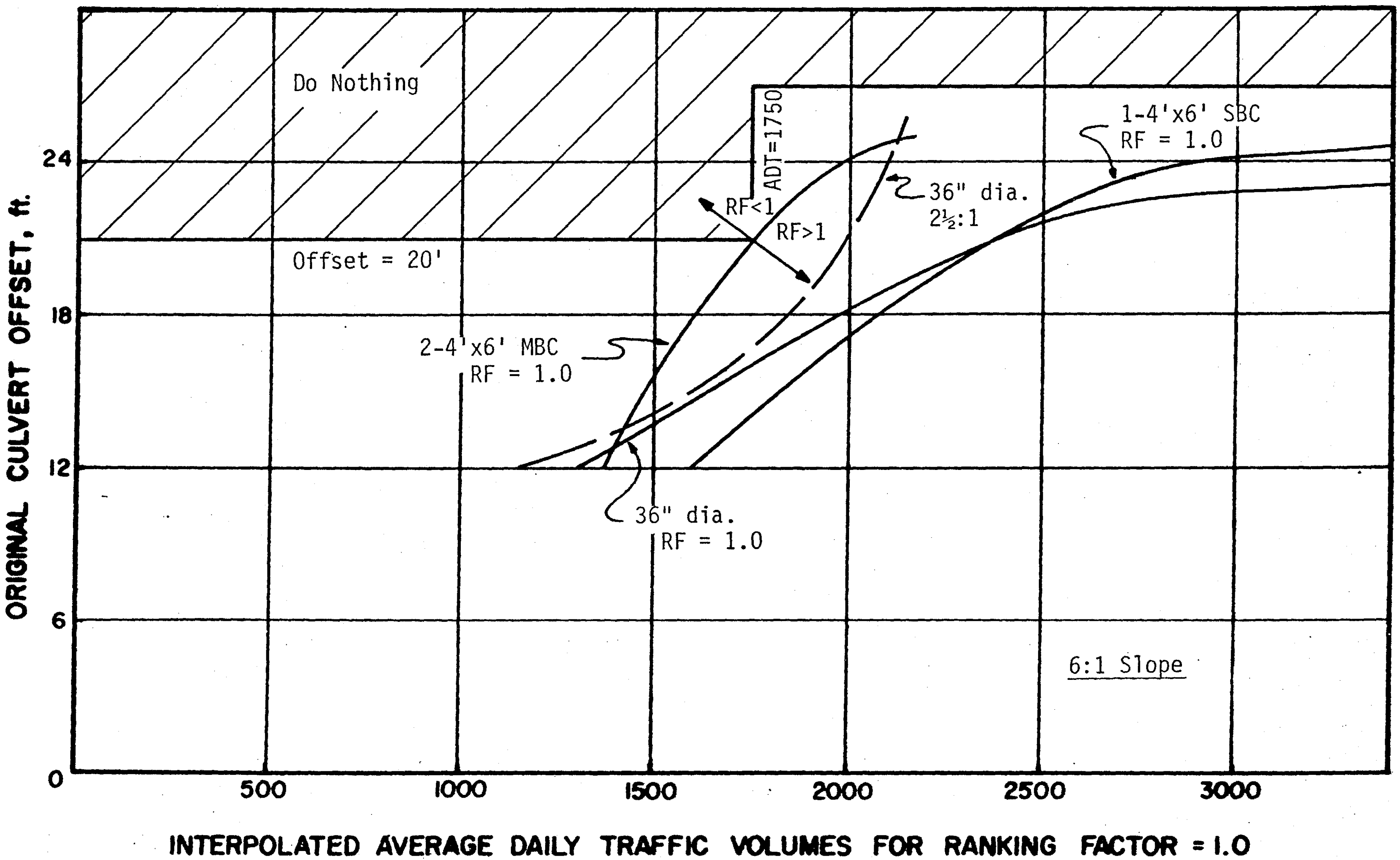


FIGURE 14. POSSIBLE DESIGN GUIDELINES FOR TYPICAL CULVERTS ON 6:1 SLOPES AND SMALL (36" DIA.) CULVERTS ON STEEP SLOPES

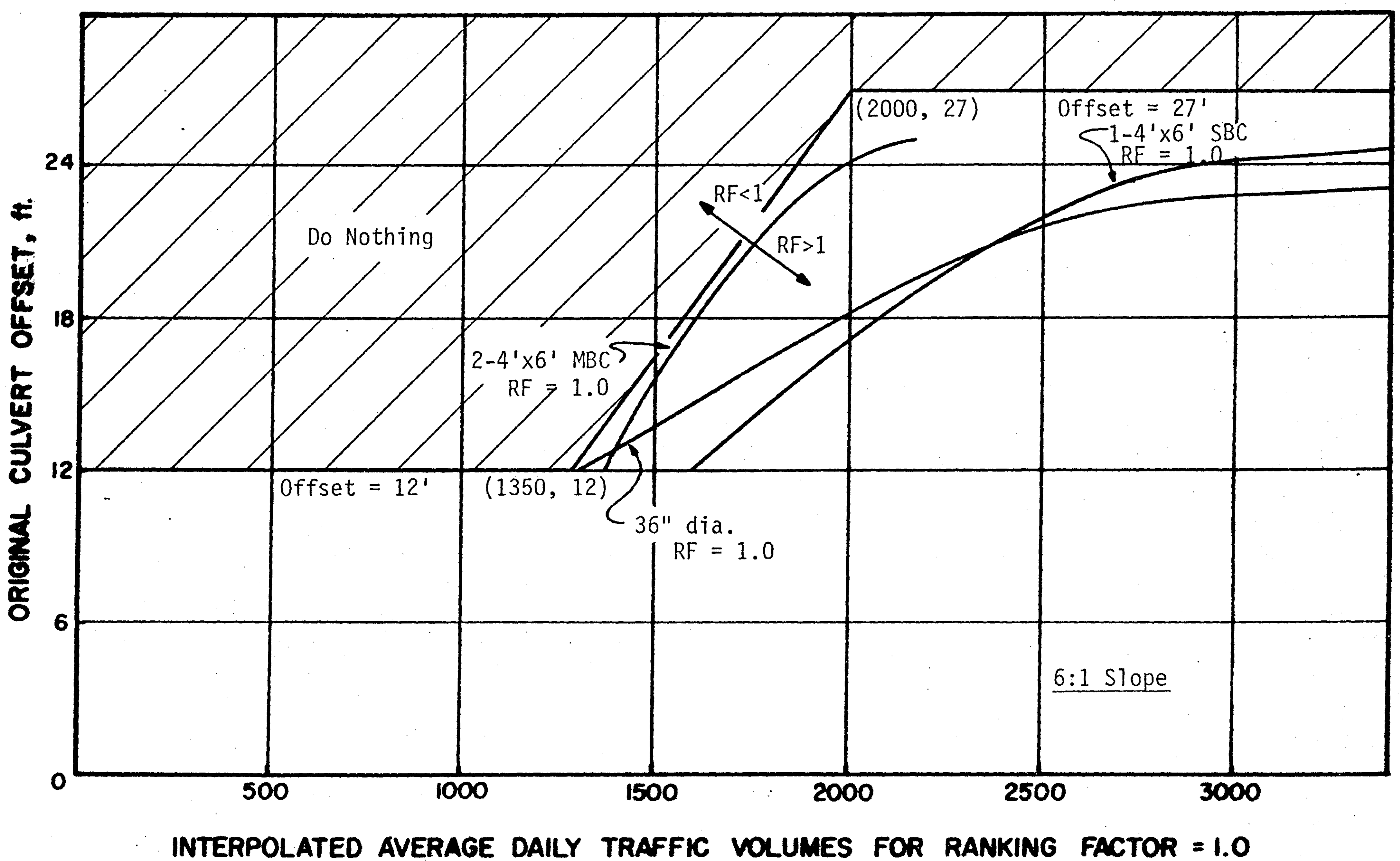


FIGURE 15. POSSIBLE DESIGN GUIDELINES FOR TYPICAL CULVERTS ON 6:1 SLOPES

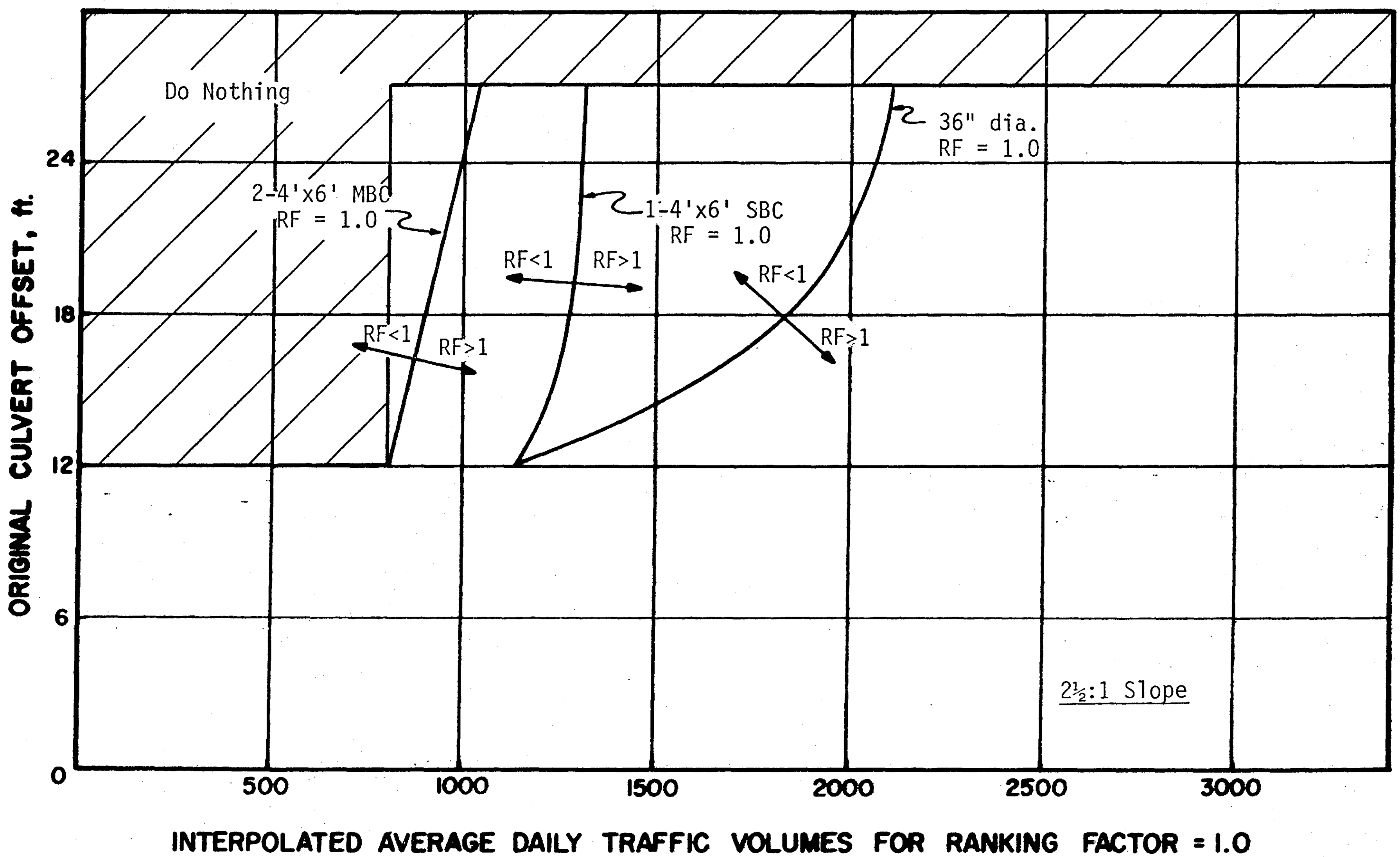


FIGURE 16. POSSIBLE DESIGN GUIDELINES FOR TYPICAL CULVERT ENDS ON STEEP SLOPES

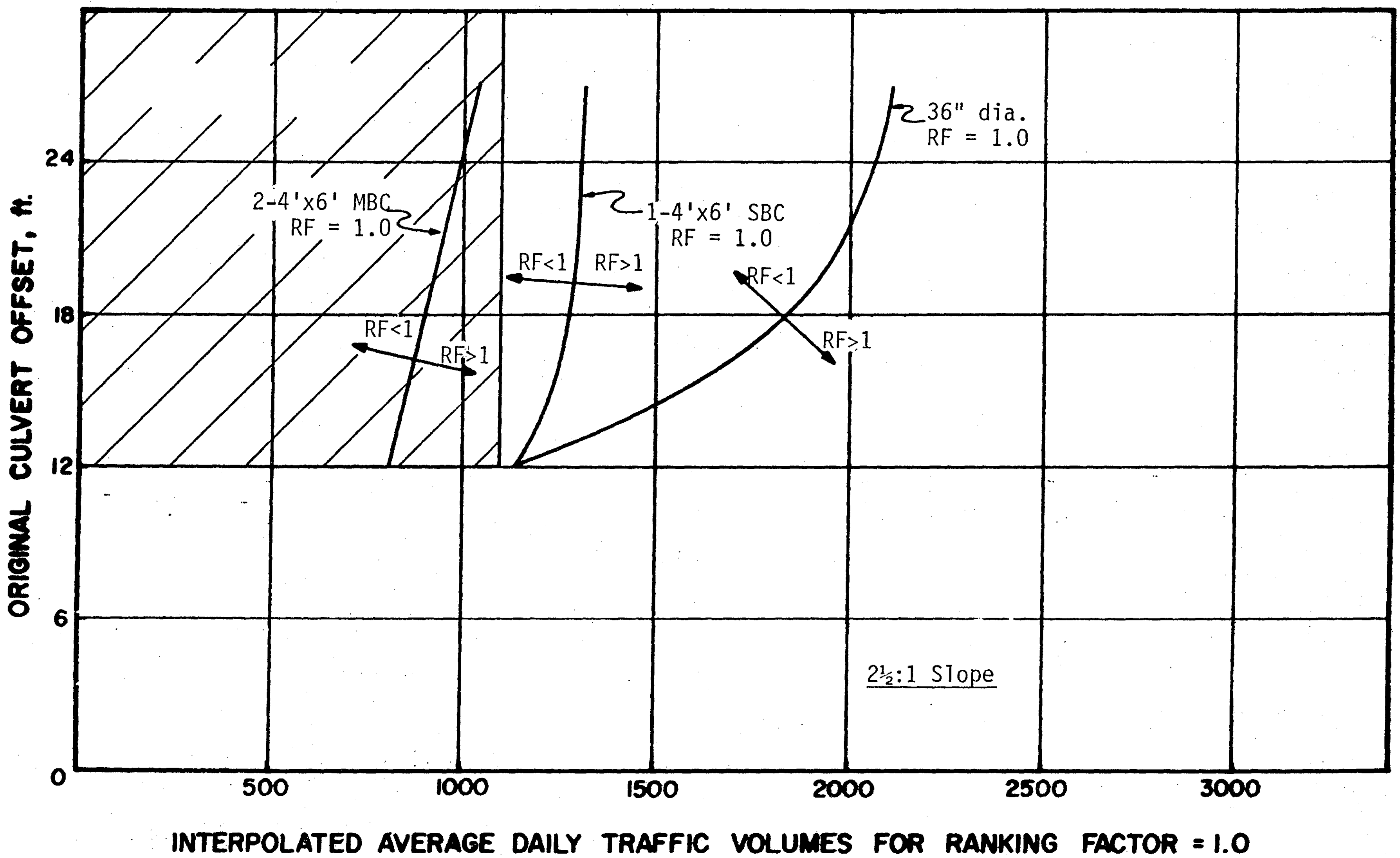


FIGURE 17. POSSIBLE DESIGN GUIDELINES FOR TYPICAL CULVERT ENDS ON STEEP SLOPES

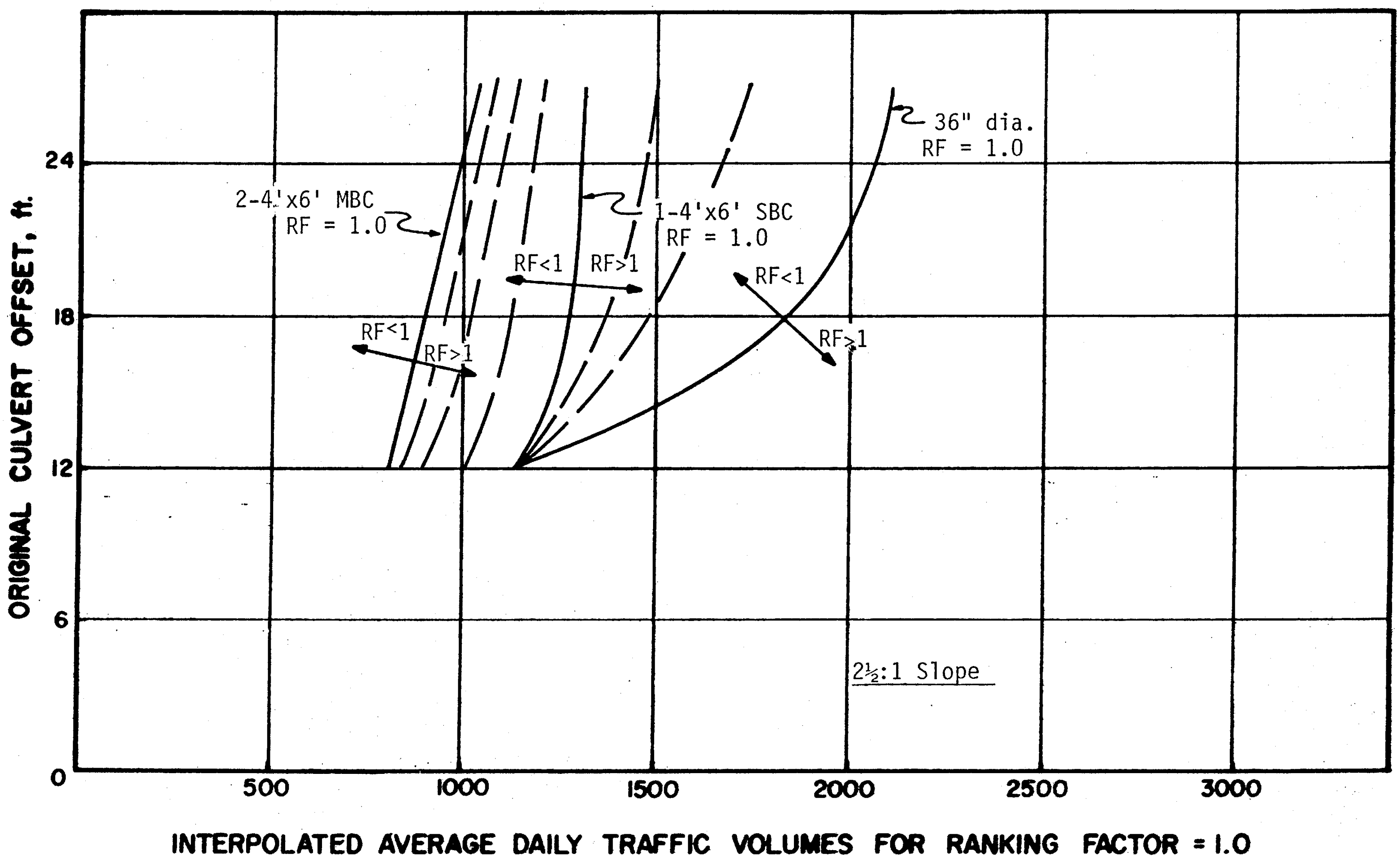


FIGURE 18. POSSIBLE DESIGN GUIDELINES FOR ALL CULVERT ENDS ON STEEP SLOPES

Figures 3 through 8 provide the necessary information for selecting the treatment means. Example design guidelines are as follows:

1. For <u>flat</u> (6:1 or flatter) slopes and culvert sizes ranging from 36 in. diameter pipe to double 4 ft x 6 ft boxes:
   a. Where traffic is 1300 ADT or less and offset is 12 ft or more, treatment is not cost-effective, as shown in Figure 12; or,
   b. Where traffic is 1500 or less and offset is 16 ft or more, treatment is not cost-effective as shown in Figure 13 (36 in. diameter pipe on steep slopes also fit the same criteria); or,
   c. Where traffic is 1750 or less and offset is 20 ft or more, treatment is not cost-effective as shown in Figure 14 (36 in. diameter pipe on steep slopes also fit the same criteria); or
   d. The "do-nothing" area could be defined to be variable with traffic and offset as shown in Figure 15.
2. For <u>steep</u> (steeper than 6:1) slopes:
   a. Where traffic volumes are 800 ADT or less, double 4 ft x 6 ft boxes and smaller size culvert ends with 12 ft or more offset cannot be cost-effectively treated as shown in Figure 16; or,
   b. Where traffic volumes are 1100 or less and offset is 12 ft or more, single 4 ft x 6 ft and smaller size culvert ends cannot be cost-effectively treated as shown in Figure 17.

These curves, particularly for steep slopes, could be further developed by estimating additional unity ranking factor curves for various culvert end areas as shown in Figure 18. Although resultant design guidelines would be more difficult to use, a designer could enter the resultant figure with a design traffic volume and culvert size and determine the cost-effective offset.

In summary, the cost-effectiveness approach can be used to determine appropriate design guidelines which identify conditions meriting treatment plus identifying the most cost-effective alternative treatment.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. Unprotected culvert ends located 27 ft or more from the pavement edge cannot be cost-effectively extended to 30 ft or safety treated for the volumes, hazard size, and slopes considered. Although not specifically identified in this study, there may be combinations of culvert size, slope rate, and traffic volume where an existing culvert may be cost-effectively extended from 27 ft to more than 30 ft from pavement edge.
2. AASHTO guidelines (1) suggest that steep (1:1 or steeper) drop-offs, with or without permanent bodies of water, warrant protection only if the drop-off is greater than 2 ft in depth. In this regard, small (e.g., 18- or 24-in. diameter pipes) culverts with heights of 2 ft or less should not be considered as severe as larger culverts. For these installations, ends should be sloped, preferably to match side slopes, stabilized with flush riprap if necessary, and the surrounding area should be smoothly contoured to decrease potential impact severity and improve crashworthiness.
3. The provision of flat (6:1 or flatter) slopes allows for possible driver action to avoid culvert-end collisions. Comparisons of Figure 3 with Figure 4, Figure 5 with Figure 6, and Figure 7 with Figure 8 reveal the impact of steep versus flat slopes in identifying traffic and offset conditions which merit treatment of culvert ends.

4. Figures 3 through 8 identify cost-effective treatments for various culvert conditions. The following general conclusions may be made regarding particular treatment methods:

   (a) For both flat and relatively steep side slopes, leaving the culvert unprotected was the most cost-effective alternative for traffic volumes less than 750 and culvert offset distances greater than 12 ft.

   (b) When culvert extension is cost-effective, it is desirable that the culvert be extended 30 ft or more from the roadside. In general, it was found that when safety treatment is warranted, culvert extension is a cost-effective method -- although not always the most cost-effective. However, special circumstances not considered in this study, such as where needed right-of-way is unavailable or costly, may preclude culvert extension.

   (c) Grates for relatively flat sloped culvert ends were not found to be cost-effective due to the large grate area and resultant high cost. For steep slopes, however, grates were found either to be competitive with culvert extension or clearly the most cost-effective alternative as shown in Figures 3, 5, and 7. Where possible, standardization of grate shape and structural design may be expected to reduce "in-place" costs and further enhance its attractiveness as a safety treatment. Simple, shop-fabricated grates designed for heavy (4500 lbs) passenger car loading have demonstrated field performance, both from hydraulic and impact standpoints. Reportedly, such a design has been accidently impacted by a loaded truck with successful results although grate deformation did occur.

(d) For the traffic volumes, slopes, and hazard sizes and locations studied, guardrail protection was found to be a cost-effective safety treatment only for the double box culvert and moderate traffic volumes (greater than 2000 ADT) and the single box culvert and high traffic volumes (greater than 20,000 ADT). However, even for these culvert sizes and traffic volumes, guardrail protection was not found to be the most cost-effective alternative. Generally, guardrail protection appears to be a more competitive alternative as the slope becomes steeper and as the hazard size increases. In this regard, for culverts larger than the double 4 ft x 6 ft considered in this study, shielding by guardrail might be the most cost-effective solution.

5. Figures 10 and 11 may be used to develop design guidelines for new location or upgrading existing facilities as exemplified in Figures 12 through 18. When such guidelines are combined with the information regarding the most effective means of treatment as shown in Figures 3 through 8, a comprehensive, sound design policy is possible.

6. Other observations and conclusions can be made from this study if the information presented in Figures 3 through 10 and Appendices A, B, and C is used in conjunction with cost information available to the various highway departments or agencies. These conclusions may or may not occur with those presented in this report.

V. FUTURE CONSIDERATIONS

In view of the research findings, the authors suggest the following items be considered in future studies:

1) apply the cost-effectiveness model to different culvert designs, slope conditions, and higher traffic volumes;
2) refine the model to include hazards beyond the 30 ft clear distance for fill sections with slopes steeper than 6:1;
3) develop a computer program with simple input data such as culvert size and type, fill section slope, culvert end offset, safety treatment, costs and restrictions (e.g., in some cases extending to 30 ft is not possible), traffic volume, etc., to provide more flexibility in design alternatives and to reduce the computations required. and
4) incorporate encroachment data for low volume roads as they become available.

APPENDICES

APPENDIX A
A DISCUSSION OF THE COST-EFFECTIVENESS MODEL

The cost-effectiveness model used in this study calculates the present value of each alternative over a given period of time, taking into account the initial costs, maintenance costs, and accident costs. The model can be expressed by the equation:

$$C_T = C_I + C_D(C_F)(K_T) + C_M(K_T) + C_{OVD}(C_F)(K_T) - C_S(K_J) \qquad \text{(A1)}$$

where:

C_T = total present worth associated with the alternative (present dollar),

C_I = initial cost of the alternative (present dollar),

C_D = average damage cost per accident incurred to the alternative (present dollar),

C_M = average maintenance cost per year for the alternative (present dollar),

C_{OVD} = average occupant injury and vehicle damage cost per accident (present dollar),

C_S = estimated salvage value of the alternative (future dollar),

C_F = collision frequency (accidents per year),

K_T, K_J = economic factors for some current interest rate.

The model is structured around an accident prediction technique used to estimate the frequency at which a roadside hazard will be struck over a given period of time. This is introduced into the model by the variable C_F. Mathematically, the collision frequency is given by the expression:

$$C_F = \frac{E_F}{10,560} \left[(L + 62.9) \cdot P(Y \geq A) + 5.14 \sum_{J=1}^{J=W} P\left[Y \geq A + 6.0 + \frac{2J-1}{2} \right] \right] \qquad (A2)$$

where:

- A = distance from edge of the traveled way to the hazard (offset),
- L = hazard length (dimension parallel to the traveled way),
- W = hazard width (dimension perpendicular to the traveled way),
- E_F = encroachment frequency (encroachments per mile per year), these values are taken from the literature (2),
- Y = the lateral displacement in feet, of the encroaching vehicle, measured from the edge of the traveled way to the longitudinal face of the hazard, and
- $P[Y \geq ..]$ = probability of a vehicle lateral displacement greater than some value. The values are taken from the literature (3).

Equation (A2) may be implemented directly into Equation (A1), however, it should be noted that computation of the collision frequency for multiple objects requires special procedures. Reference should be made to the literature (1) for illustrations of these procedures.

To calculate the collision frequencies for the hazards in the alternatives considered in this study, it was necessary to make three idealizations. These are shown in Figures A1, A2, and A3. Note that these hazard zones apply to both 2½:1 and 6:1 slopes.

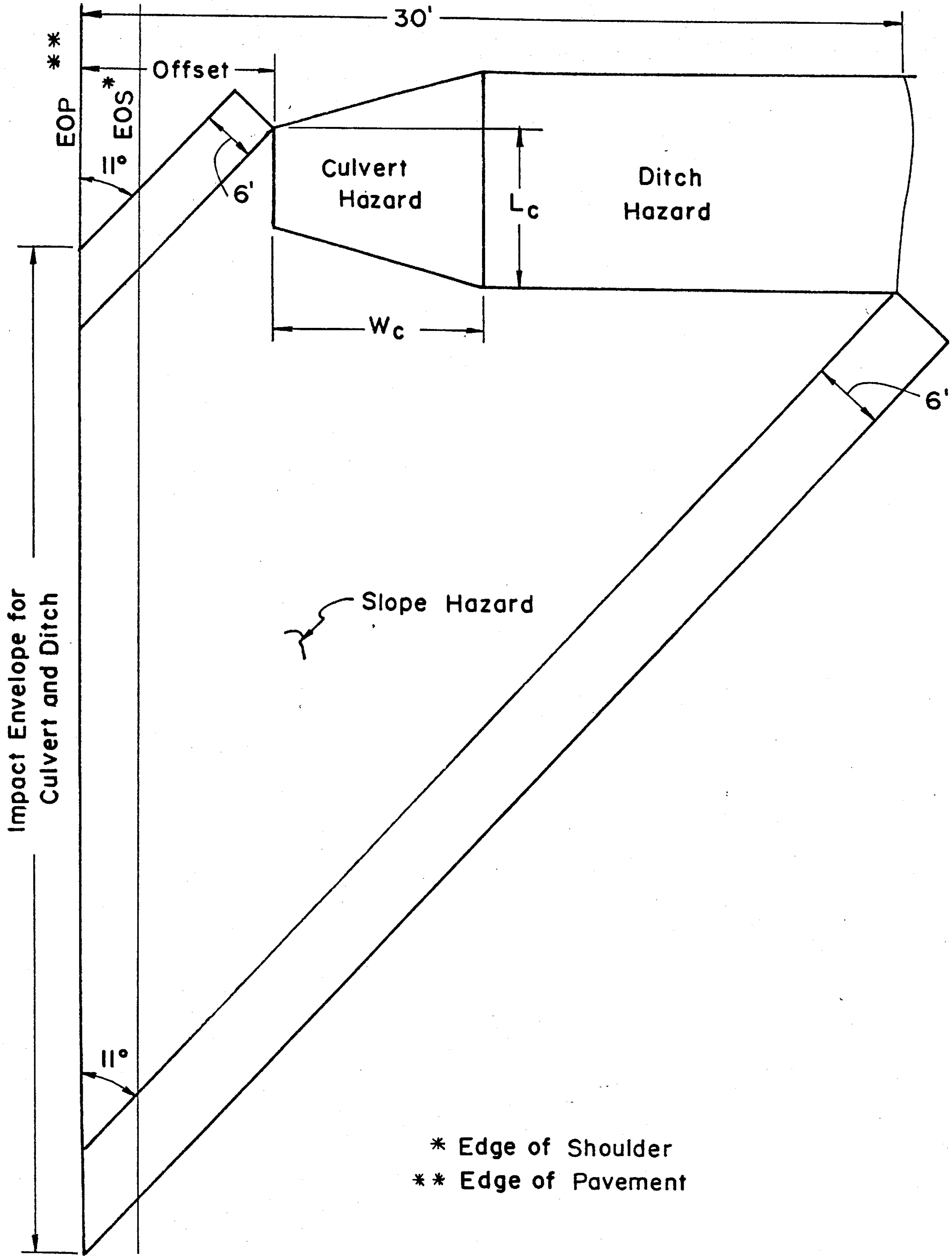


FIGURE A1. HAZARD ENVELOPE FOR AN UNPROTECTED CULVERT AND DITCH

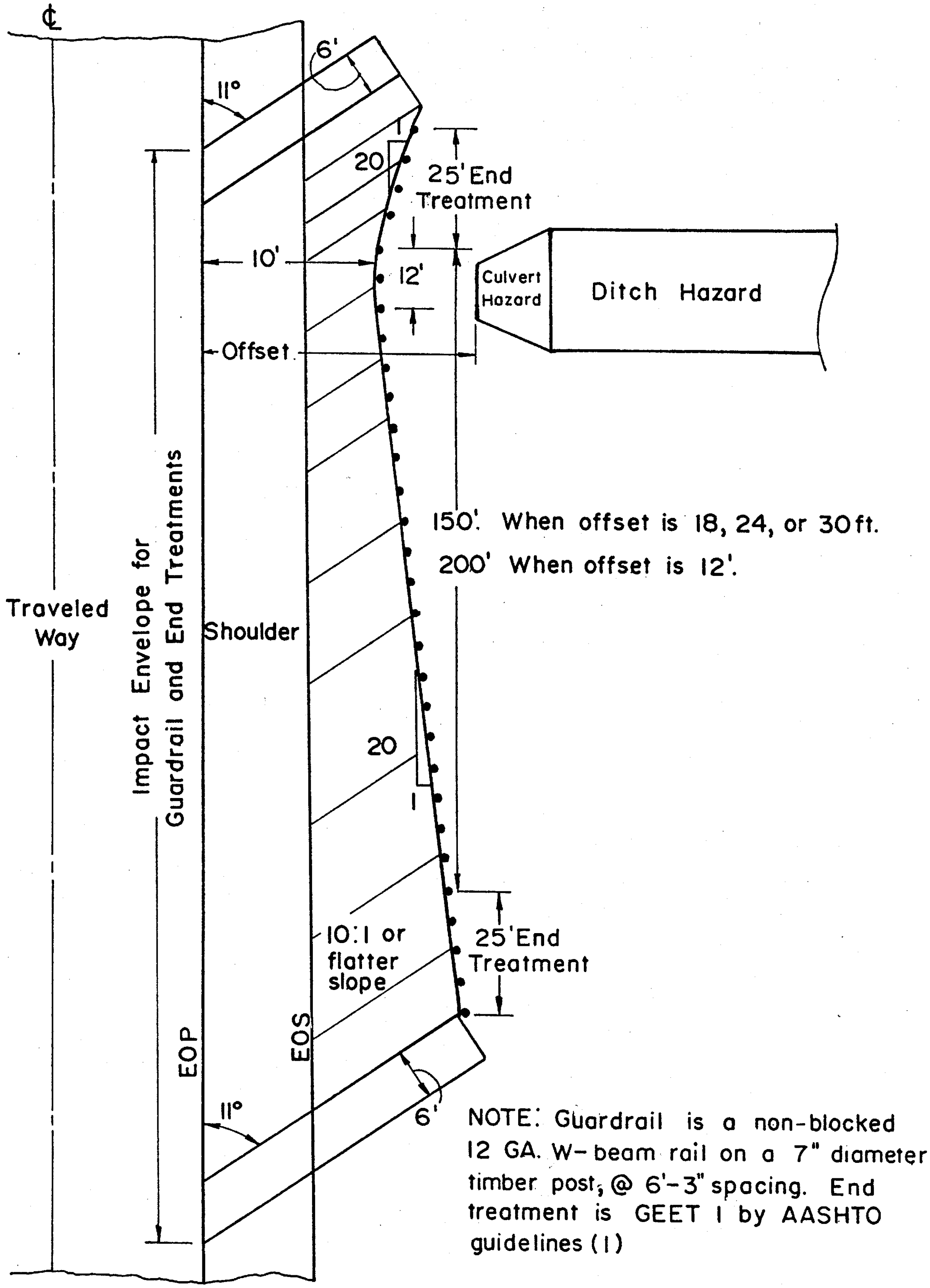


FIGURE A2. HAZARD ENVELOPE FOR GUARDRAIL PROTECTED CULVERT

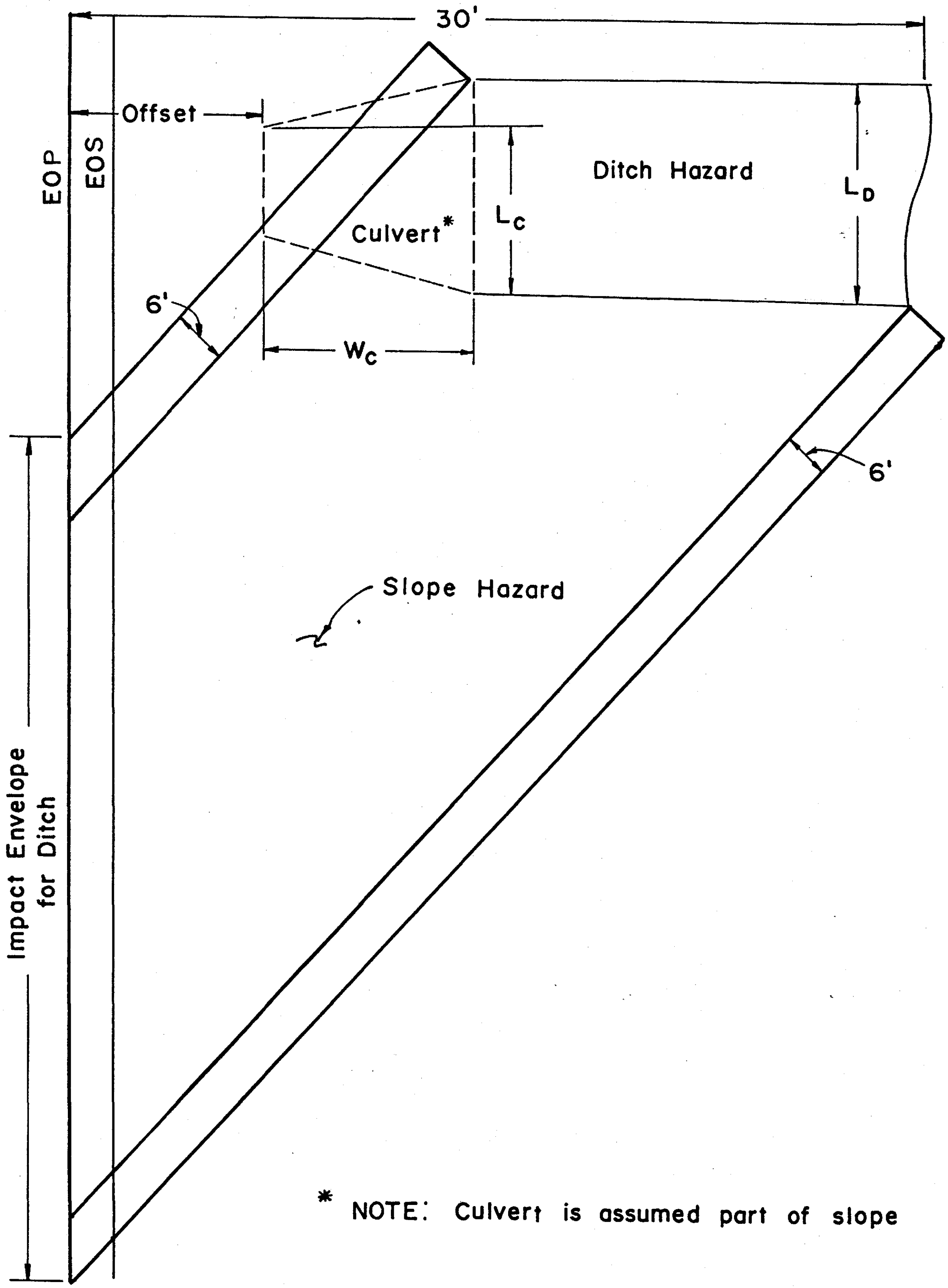


FIGURE A3. HAZARD ENVELOPE FOR GRATE PROTECTED CULVERT

Table A1 contains a summary of the variables that would be substituted into Equation (A2) to obtain C_F for the various hazards. It should be noted for hazards located both inside and outside the 30 ft. zone, that only the length and width inside this zone is considered when calculating C_F.

As stated in Chapter II, it was assumed that no vehicle redirection will occur on 2½:1 slopes. Since the model assumes a chance of redirection in the zone from the edge of the traveled way (EOTW) and the lateral face of the hazard, certain special procedures must be followed. The basic procedure is to project all hazards to the edge of the shoulder at an 11^o angle. The length used in Equation (A2) would be the projected length along the edge of the shoulder. These variable values are also shown in Table A1.

To obtain the average occupant injury and vehicle damage cost per accident (C_{OVD}), the criteria in Table A2 was used (4). Severity indices were assigned to each hazard based on a survey sent to fifteen personnel from the Texas Transportation Institute, Texas State Department of Highways and Public Transportation and the United States Department of Transportation, Federal Highway Administration (5). Each person was asked to evaluate the relative severity of each hazard considered in the study based on the criteria in Table A2. The averages of the responses received were then assigned to each hazard to obtain C_{OVD}. See Appendix B for particular values of the severity index and C_{OVD}.

TABLE A1. VALUES FOR CALCULATING THE COLLISION FREQUENCY (C_F)

Alternative Description with Hazards	Variables for Calculating C_F		
	A[1]	L[2]	W[2]
Unprotected Culvert[3] and Ditch on 2½:1 Slope:			
1) Culvert	8 ft.	L_C + 5.14 W_C	0
2) Ditch	8 ft.	123 - 5.14(W_C + Offset)	0
3) Slope	10 ft.	(15 or -35 ft.) - L_C + 5.14(Offset)	1 ft.
Unprotected Culvert[3] and Ditch on 6:1 Slope:			
1) Culvert	Offset	L_C	W_C
2) Ditch	Offset + W_C + 6 ft.	1 ft.	24 ft. - (Offset + W_C)
3) Slope	--[4]	--[4]	--[4]
150 ft. of Guardrail Protection on Any Slope[5]:			
1) Approach guardrail and end treatment	14 ft.	175 ft.	1 ft.
2) Departure guardrail and end treatment	11 ft.	-6 ft.	1 ft.
200 ft. of Guardrail Protection on Any Slope[5]:			
1) Approach guardrail and end treatment	14 ft.	175 ft.	1 ft.
2) Departure guardrail and end treatment	12 ft.	44 ft.	1 ft.
Grate Protection[6] [7] on 2½:1 Slope			
1) Ditch	8 ft.	L_D + 154 ft. - 5.14(Offset + W_C)	0
2) Slope	10 ft.	(-16 or -66 ft.) - L_D + 5.14(Offset + W_C)	1 ft.
Grate Protection[6] [7] on 6:1 Slope			
1) Ditch	Offset + W_C	L_D	30 ft. - (Offset + W_C)
2) Slope	--[4]	--[4]	--[4]

[1]For values of A greater than 30 ft., $C_F = 0$. [2]Only the length and width within a 30 ft. clear zone is considered. [3]Refer to Figure A1. [4]This is done by first finding C_F for the slope protected by either 150 or 200 ft. of guardrail. Next, subtract the C_F for the culvert and the C_F for the ditch from this value to obtain the C_F for a 6:1 slope. [5]Refer to Figure A2. [6]Refer to Figure A3. [7]Since the grate is assumed to be traversable, it is also assumed to be part of the slope, so that there are only two hazards, namely, the ditch and the slope.

TABLE A2. SEVERITY INDEX AND ACCIDENT COST

Severity Index	% PDO Accidents	% Injury Accidents	% Fatal Accidents	Total Accident Cost (C_{OVD})
0	100	0	0	$ 700
1	85	15	0	2,095
2	70	30	0	3,490
3	55	45	0	4,885
4	40	59	1	8.180
5	30	65	5	16,710
6	20	68	12	30,940
7	10	60	30	66,070
8	0	40	60	124,000
9	0	21	79	160,000
10	0	5	95	190,000

APPENDIX B

APPLICATION OF MODEL

Input Data

This appendix presents the particular values assigned to each variable in Equation (A1). Values of C_F are not given since the technique used to calculate these values is presented in Appendix A. A summary of all costs is given by each alternative. A constant value for K_T = 8.514 is used for all alternatives based on a 10% rate of return over a 20-year term.

Alternative I - The Unprotected Culvert

A) Assumptions

1) $C_I = 0$ (no initial costs)

2) $C_D = 0$ (no damage to culvert upon impact)

3) $C_M = 0$ (no maintenance costs)

4) $C_S = 0$ (no salvage value after 20 years)

B) Revised form of equation (A1):

$$C_T = 8.514\left[(C_F C_{OVD})_{SLOPE} + (C_F C_{OVD})_{CULVERT} + (C_F C_{OVD})_{DITCH}\right] \quad \text{(B1)}$$

where:

$(C_F C_{OVD})_{SLOPE}$ = collision frequency times the occupant and vehicle damage caused by the slope;

$(C_F C_{OVD})_{CULVERT}$ = collision frequency times the occupant and vehicle damage caused by the culvert; and

$(C_F C_{OVD})_{DITCH}$ = collision frequency times the occupant and vehicle damage caused by the ditch.

C) Summary of other costs

1) See Table B1.

TABLE B1. SEVERITY INDICES AND ACCIDENT COSTS FOR THE UNPROTECTED CULVERT*

Culvert Type	$(C_{OVD})_{SLOPE}$	$(C_{OVD})_{CULVERT}$	$(C_{OVD})_{DITCH}$
36 in. pipe on 2½:1 slope	$5900 (3.3)**	$16,710 (5.0)	$7400 (3.8)
36 in. pipe on 6:1 slope	$2500 (1.3)	$16,710 (5.0)	$6000 (3.4)
4' x 6' single box on 2½:1 slope	$5900 (3.3)	$28,100 (5.8)	$10,000 (4.2)
4' x 6' single box on 6:1 slope	$2500 (1.3)	$28,100 (5.8)	$6400 (3.5)
4' x 6' multi-box on 2½:1 slope	$5900 (3.3)	$42,500 (6.3)	$7400 (3.8)
4' x 6' multi-box on 6:1 slope	$2500 (1.3)	$42,500 (6.3)	$4900 (3.0)

*Based on the criteria in Table A2.
**Severity index in parenthesis.

Alternative II - Extending Existing Culvert to 30 Ft

A) Assumptions

1) Wing wall must be replaced.

2) Fill must be added for smooth transition between slopes.

B) Revised form of equation (A1):

$$C_T = C_{T30} + C_{WW} + C_{EXT} + C_{FILL} \quad \text{(B2)}$$

where:

C_{T30} = total cost of unprotected culvert with 30 ft. original offset

C_{WW} = cost of wing wall

C_{EXT} = cost of extending the culvert pipe or box; and

C_{FILL} = cost of fill material.

c) Summary of other costs

1) See Tables B2, B3, and B4

TABLE B2. COST OF WING WALLS (C_{WW})

Culvert Type	C_{WW} for 2½:1 Slope	C_{WW} for 6:1 Slope
36 in. pipe	$260	$620
4' x 6' single box	$460	$1100
4' x 6' multi-box	$450	$1100

TABLE B3. COST OF EXTENDING THE CULVERT PIPE OR BOX TO 30 FT FINAL OFFSET (C_{EXT})

Culvert Type	Original Offset		
	12 ft.	18 ft.	24 ft.
36 in. pipe on 2½:1 and 6:1 slopes*	$450	$300	$150
4' x 6' single box on 2½:1 and 6:1 slopes**	$1710	$1140	$570
4' x 6' multi-box on 2½:1 and 6:1 slopes***	$2970	$1980	$990

*Based on $25/ft.

**Based on $95/ft.

***Based on $165/ft.

TABLE B4. COST OF FILL FOR EXTENDING THE CULVERT TO 30 FT FINAL OFFSET (C_{FILL})*

Culvert Type	Original Offset		
	12 ft.	18 ft.	24 ft.
36 in. pipe on 2½:1 slope	$820	$1100	$1300
36 in. pipe on 6:1 slope	$470	$520	$570
4' x 6' single box on 2½:1 slope	$900	$1200	$1300
4' x 6' single box on 6:1 slope	$540	$550	$580
4' x 6' multi- box on 2½:1 slope	$930	$1200	$1400
4' x 6' multi-box on 6:1 slope	$550	$560	$580

*Based on $2.35/yd.^{3}

Alternative III - Guardrail Protection

A) Assumptions

1) C_I = (Length)($13/ft.)

2) C_D = $225

3) C_{OVD} = $5900 (S.I. = 3.3)

4) C_M = (Length)($1.50/ft.)

B) Revised form of equation (A1):

$$C_T = C_I + 8.514 \left[(C_D + C_{OVD})(C_{F_{AP}} + C_{F_{DP}}) + C_M\right] \quad \text{(B3)}$$

where:

C_I = total initial cost of barrier proper and end treatments ($3250 or $2600);

C_D = damage cost to barrier proper and end treatments after a collision ($225);

C_{OVD} = occupant and vehicle damage cost caused by barrier proper and end treatments ($5900);

C_M = total maintenance cost of barrier proper and end treatments ($375 or $300);

$C_{F_{AP}}$ = collision frequency for the approach guardrail and end treatment; and

$C_{F_{BP}}$ = collision frequency for the departure guardrail and end treatment.

Alternative IV - Grate Protection

A) Assumptions

1) C_D = 0 (no damage to grate upon impact)

2) $C_M = \$100$

3) $C_S = 0$ (no salvage value after 20 years)

B) Revised form of equation (A1):

$$C_T = C_I + 8.514\left[(C_F C_{OVD})_{SLOPE} + (C_F C_{OVD})_{DITCH} + C_M\right] \quad \text{(B4)}$$

where:

$(C_F C_{OVD})_{SLOPE}$ and $(C_F C_{OVD})_{DITCH}$ are defined previously.

C) Summary of other costs

1) See Table B1 for $(C_{OVD})_{SLOPE}$ and $(C_{OVD})_{DITCH}$.

2) See Table B5 for C_I.

TABLE B5. INITIAL COST OF GRATE PROTECTION*

Culvert Type	C_I on 2½:1 Slope	C_I on 6:1 Slope
36 in. pipe	\$600	\$6900
4' x 6' single box	\$1300	\$13,800
4' x 6' multi-box	\$2000	\$19,100

*Includes only the cost of the grate.

Ranking Factor

The ranking factor is a ratio of the benefits received by using a particular alternative to the costs incurred by the highway department or agency associated with the installation of that alternative. The following formula may be used for determining a ranking factor, R:

$$R = \frac{C_{T_H} - C_{T_I}}{C_{TD_I}} \qquad (B5)$$

where:

C_{T_H} = total cost associated with the unprotected culvert;

C_{T_I} = total cost associated with the selected alternative; and

C_{TD_I} = total cost to the highway department or agency associated with selected alternative.

To obtain C_{TD_I} for each alternative simply substitute $C_{OVD} = 0$ into equations (B1), (B2), (B3), and (B4). This will then give for the unprotected culvert:

$$C_{TD_I} = 0 \qquad (B6)$$

extending to 30 ft.:

$$C_{TD_I} = C_{WW} + C_{EXT} + C_{FILL} \qquad (B7)$$

guardrail protection:

$$C_{TD_I} = C_I + 8.514\left[(C_D)(C_{F_{AP}} + C_{F_{DP}}) + C_M\right] \qquad (B8)$$

and for grate protection:

$$C_{TD_I} = C_I + 8.514 \left[C_M \right] \qquad \text{(B9)}$$

where all variables are as previously defined.

Tables B6, B7 and B8 list the direct costs for each alternative based on equations (B7), (B8), and (B9).

TABLE B6. DIRECT COSTS FOR EXTENDING A CULVERT TO 30 FT FINAL OFFSET

Culvert Type	Original Offset		
	12 ft.	18 ft.	24 ft.
36 in. pipe on 2½:1 slope	$1500	$1700	$1700
36 in. pipe on 6:1 slope	$1500	$1400	$1300
4' x 6' single box on 2½:1 slope	$3100	$2800	$2400
4' x 6' single box on 6:1 slope	$3400	$2800	$2300
4' x 6' multi-box on 2½:1 slope	$4300	$3600	$2800
4' x 6' multi-box on 6:1 slope	$4600	$3600	$2600

TABLE B7. DIRECT COSTS FOR GUARDRAIL PROTECTION OF 36 IN. PIPE, 4 FT x 6 FT SINGLE BOX, AND 4 FT x 6 FT MULTI-BOX (2) CULVERTS ON 2½:1 AND 6:1 SLOPES

ADT	OFFSET = 12 FT.	OFFSET = 18.24 or 30 FT.
750	$6500	$5200
1500	$6600	$5300
2250	$6700	$5300
3000	$6700	$5400
15000	$6700	$5400
20000	$6900	$5500

TABLE B8. DIRECT COSTS FOR GRATE PROTECTION

Culvert Type	C_{TD_I} for 2½:1 Slope	C_{TD_I} for 6:1 Slope
36 in. pipe	$1500	$7700
4' x 6' single box	$2100	$14,600
4' x 6' multi-box	$2900	$20,000

Using this information, ranking factors were calculated for each alternative. The alternative with the highest ranking factor is the most desirable since it returns the largest benefits for the lowest total direct costs. Ranking factors for leaving a culvert unprotected is theoretically 1.0 since $C_{T_H} = C_{T_I}$ and $C_{TD_I} = 0$. Thus alternatives with ranking factors less than 1.0 are undesirable since an unprotected culvert has a higher ranking factor.

Figures 3 through 8 are based on the alternative with the highest ranking factor. The unprotected culvert was assumed to have a ranking of 1.0 since it was one of the alternatives considered.

APPENDIX C
SUPPORTING DATA

This appendix contains all the data necessary to obtain Figures 3 through 8. These data can also be used in conjunction with the information presented in Appendices A and B to obtain new criteria for different direct costs. See Appendix D for further discussion.

Tables C1 through C6 present the ranking factors for each alternative by each culvert design considered in the study. Tables C7 through C12 list the total costs for each alternative by each culvert design. Tables C13 through C18 list the direct costs for extending each of the culvert designs. Note that ranking factors, direct costs and total costs are given in each table for extending culverts to 18, 24, and 30 ft. Although this study was concerned primarily with extending to 30 ft, it may not be possible where there are limited right of ways or other extenuating circumstances. Thus it may be feasible to extend the culvert to 18 or 24 ft where other alternatives are not possible. Again see Appendix D for further discussion.

RANKING FACTORS FOR EXTENDING A CULVERT

FOR A 36 IN. DIAMETER PIPE ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	0.21	-0.15	0.36	-0.92	-0.24	-0.32
1500.0	1.43	0.70	1.72	-0.84	0.52	0.36
2250.0	2.55	1.48	2.98	-0.76	1.21	0.98
3000.0	3.77	2.33	4.34	-0.66	1.97	1.66
15000.0	3.86	2.40	4.44	-0.67	2.03	1.71
20000.0	5.73	3.70	6.54	-0.54	3.20	2.76

TABLE C1. RANKING FACTORS FOR A 36 INCH PIPE CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR GUARDRAIL VS. UNPROTECTED

FOR A 36 IN. DIAMETER PIPE ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.78	-0.83	-0.85	-1.07
1500.0	-0.57	-0.67	-0.70	-1.15
2250.0	-0.38	-0.52	-0.57	-1.21
3000.0	-0.18	-0.36	-0.43	-1.23
15000.0	-0.17	-0.35	-0.42	-1.29
20000.0	0.14	-0.11	-0.20	-1.38

TABLE C1 (CONTINUED). RANKING FACTORS FOR A 36 INCH PIPE CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR GRATE PROTECTION VS. UNPROTECTED

FOR A 36 IN. DIAMETER PIPE ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	0.07	-0.27	-0.19	-1.00
1500.0	1.14	0.47	0.62	-1.00
2250.0	2.13	1.15	1.36	-1.00
3000.0	3.19	1.88	2.17	-1.00
15000.0	3.28	1.94	2.23	-1.00
20000.0	4.92	3.07	3.48	-1.00

TABLE C1 (CONTINUED). RANKING FACTORS FOR A 36 INCH PIPE CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR EXTENDING A CULVERT
FOR A 36 IN. DIAMETER PIPE ON A 6 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	-0.26	-0.07	0.15	-0.57	-0.23	-0.51
1500.0	0.45	0.67	1.29	-0.13	0.54	-0.02
2250.0	1.11	1.73	2.35	0.27	1.26	0.43
3000.0	1.64	2.66	3.50	0.70	2.03	0.91
15000.0	1.69	2.73	3.59	0.73	2.09	0.95
20000.0	3.00	4.17	5.35	1.40	3.26	1.70

TABLE C2. RANKING FACTORS FOR A 36 INCH PIPE CULVERT ON A 6:1 SLOPE

RANKING FACTORS FOR GUARDRAIL VS. UNPROTECTED
FOR A 36 IN. DIAMETER PIPE ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.95	-1.00	-1.09	-1.22
1500.0	-0.89	-1.00	-1.18	-1.42
2250.0	-0.85	-1.00	-1.25	-1.61
3000.0	-0.79	-1.00	-1.33	-1.80
15000.0	-0.78	-1.01	-1.35	-1.83
20000.0	-0.72	-1.00	-1.46	-2.12

TABLE C2 (CONTINUED). RANKING FACTORS FOR A 36 INCH PIPE CULVERT ON A 6:1 SLOPE

RANKING FACTORS FOR GRATE PROTECTION VS. UNPROTECTED
FOR A 36 IN. DIAMETER PIPE ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.79	-0.86	-0.92	-1.00
1500.0	-0.58	-0.71	-0.83	-1.00
2250.0	-0.38	-0.58	-0.75	-1.00
3000.0	-0.17	-0.44	-0.67	-1.00
15000.0	-0.16	-0.43	-0.66	-1.00
20000.0	0.17	-0.21	-0.53	-1.00

TABLE C2 (CONTINUED). RANKING FACTORS FOR A 36 INCH PIPE CULVERT ON A 6:1 SLOPE

RANKING FACTORS FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	-0.23	-0.30	0.29	-0.71	0.07	0.03
1500.0	0.53	0.40	1.57	-0.42	1.14	1.07
2250.0	1.24	1.05	2.76	-0.15	2.13	2.02
5000.0	2.00	1.75	4.05	0.15	3.20	3.06
15000.0	2.06	1.80	4.15	0.17	3.28	3.14
20000.0	3.24	2.88	6.12	0.62	4.93	4.73

TABLE C3. RANKING FACTORS FOR A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR GUARDRAIL VS. UNPROTECTED

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.50	-0.51	-0.61	-1.06
1500.0	-0.01	-0.03	-0.22	-1.15
2250.0	0.43	0.40	0.13	-1.21
3000.0	0.91	0.86	0.50	-1.28
15000.0	0.95	0.89	0.52	-1.29
20000.0	1.64	1.58	1.08	-1.39

TABLE C3 (CONTINUED). RANKING FACTORS FOR A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR GRATE PROTECTION VS. UNPROTECTED
FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	0.46	0.18	0.15	-1.00
1500.0	1.91	1.36	1.30	-1.00
2250.0	3.26	2.45	2.37	-1.00
3000.0	4.71	3.63	3.52	-1.00
15000.0	4.82	3.72	3.61	-1.00
20000.0	7.07	5.54	5.38	-1.00

TABLE C3 (CONTINUED). RANKING FACTORS FOR A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 6 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	-0.46	-0.24	-0.06	-0.57	-0.26	-0.46
1500.0	0.21	0.52	0.88	-0.14	0.47	0.07
2250.0	0.77	1.23	1.75	0.25	1.15	0.57
3000.0	1.37	1.99	2.69	0.66	1.89	1.11
15000.0	1.42	2.05	2.76	0.72	1.94	1.15
20000.0	2.35	3.22	4.20	1.38	3.08	1.98

TABLE C4. RANKING FACTORS FOR A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

RANKING FACTORS FOR GUARDRAIL VS. UNPROTECTED

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.74	-0.82	-0.99	-1.22
1500.0	-0.47	-0.64	-0.96	-1.42
2250.0	-0.24	-0.48	-0.95	-1.61
3000.0	0.02	-0.31	-0.92	-1.66
15000.0	0.05	-0.31	-0.93	-1.83
20000.0	0.41	-0.04	-0.90	-2.12

TABLE C4 (CONTINUED). RANKING FACTORS FOR A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

RANKING FACTORS FOR GRATE PROTECTION VS. UNPROTECTED
FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.79	-0.86	-0.92	-1.00
1500.0	-0.59	-0.72	-0.83	-1.00
2250.0	-0.40	-0.59	-0.76	-1.00
3000.0	-0.19	-0.45	-0.68	-1.00
15000.0	-0.17	-0.44	-0.67	-1.00
20000.0	0.15	-0.22	-0.54	-1.00

TABLE C4 (CONTINUED). RANKING FACTORS FOR A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

RANKING FACTORS FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET	A=12 FT.	A=12 FT.	A=12 FT.	A=18 FT.	A=18 FT.	A=24 FT.
FINAL OFFSET	A=18 FT.	A=24 FT.	A=30 FT.	A=24 FT.	A=30 FT.	A=30 FT.
ADT						
750.0	-0.54	-0.45	0.35	-0.60	0.41	0.51
1500.0	-0.08	0.11	1.70	-0.20	1.82	2.03
2250.0	0.35	0.62	2.95	0.18	3.12	3.42
3000.0	0.81	1.17	4.30	0.58	4.55	4.93
15000.0	0.85	1.21	4.41	0.61	4.64	5.05
20000.0	1.56	2.06	6.49	1.23	6.81	7.38

TABLE C5. RANKING FACTORS FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR GUARDRAIL VS. UNPROTECTED

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.21	-0.11	-0.27	-1.08
1500.0	0.58	0.78	0.45	-1.13
2250.0	1.28	1.57	1.10	-1.21
3000.0	2.03	2.41	1.79	-1.28
15000.0	2.09	2.46	1.83	-1.29
20000.0	3.19	3.72	2.86	-1.39

TABLE C5 (CONTINUED). RANKING FACTORS FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR GRATE PROTECTION VS. UNPROTECTED
FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	0.67	0.71	0.48	-1.00
1500.0	2.75	2.42	1.96	-1.00
2250.0	4.48	4.00	3.33	-1.00
3000.0	6.35	5.72	4.81	-1.00
15000.0	6.50	5.85	4.92	-1.00
20000.0	9.38	8.48	7.20	-1.00

TABLE C5 (CONTINUED). RANKING FACTORS FOR A 4' X 5' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

RANKING FACTORS FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 6 TO 1 SLOPE

ORIGINAL OFFSET	A=12 FT.	A=12 FT.	A=12 FT.	A=18 FT.	A=18 FT.	A=24 FT.
FINAL OFFSET	A=18 FT.	A=24 FT.	A=30 FT.	A=24 FT.	A=30 FT.	A=30 FT.
ADT						
750.0	-0.24	-0.09	0.11	-0.41	-0.06	-0.23
1500.0	0.52	0.82	1.22	0.17	0.89	0.53
2250.0	1.22	1.66	2.24	0.71	1.76	1.24
3000.0	1.98	2.57	3.34	1.30	2.71	2.01
15000.0	2.04	2.64	3.43	1.34	2.78	2.07
20000.0	3.20	4.04	5.13	2.24	4.23	3.25

TABLE C6. RANKING FACTORS FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

RANKING FACTORS FOR GUARDRAIL VS. UNPROTECTED

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.44	-0.56	-0.83	-1.22
1500.0	0.12	-0.13	-0.65	-1.42
2250.0	0.61	0.26	-0.50	-1.61
3000.0	1.14	0.68	-0.33	-1.80
15000.0	1.19	0.69	-0.33	-1.83
20000.0	1.97	1.32	-0.08	-2.12

TABLE C6 (CONTINUED). RANKING FACTORS FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

RANKING FACTORS FOR GRATE PROTECTION VS. UNPROTECTED

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	-0.75	-0.83	-0.90	-1.00
1500.0	-0.50	-0.66	-0.80	-1.00
2250.0	-0.27	-0.50	-0.70	-1.00
3000.0	-0.03	-0.33	-0.60	-1.00
15000.0	-0.01	-0.32	-0.59	-1.00
20000.0	0.38	-0.05	-0.44	-1.00

TABLE C6 (CONTINUED). RANKING FACTORS FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

TOTAL COST OF AN UNPROTECTED CULVERT

FOR A 36 IN. DIAMETER PIPE ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	3400.00	2500.00	2400.00	1300.00
1500.0	6700.00	5100.00	4900.00	2500.00
2250.0	9800.00	7400.00	7200.00	3700.00
3000.0	13200.00	10000.00	9600.00	5000.00
15000.0	13400.00	10100.00	9800.00	5100.00
20000.0	18600.00	14000.00	13600.00	7100.00

TABLE C7. TOTAL COST DATA FOR A 36 INCH PIPE CULVERT ON A 2½:1 SLOPE

C21

TOTAL COST FOR EXTENDING A CULVERT

FOR A 36 IN. DIAMETER PIPE ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET	A=12 FT.	A=12 FT.	A=12 FT.	A=18 FT.	A=18 FT.	A=24 FT.
FINAL OFFSET	A=18 FT.	A=24 FT.	A=30 FT.	A=24 FT.	A=30 FT.	A=30 FT.
ADT						
750.0	3200.00	3500.00	2800.00	3500.00	2900.00	3000.00
1500.0	5700.00	6000.00	4100.00	6000.00	4200.00	4300.00
2250.0	6100.00	8200.00	5300.00	8200.00	5400.00	5500.00
3000.0	10600.00	10700.00	6500.00	10700.00	6700.00	6700.00
15000.0	10800.00	10900.00	6600.00	10900.00	6800.00	6800.00
20000.0	14700.00	14600.00	6600.00	14600.00	8700.00	8800.00

TABLE C7 (CONTINUED). TOTAL COST DATA FOR A 36 INCH PIPE CULVERT ON A 2½:1 SLOPE

TOTAL COST OF A GUARDRAIL PROTECTED CULVERT

FOR A 36 IN. DIAMETER PIPE ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	8500.00	6900.00	6900.00	6900.00
1500.0	10500.00	8600.00	8600.00	8600.00
2250.0	12400.00	10200.00	10200.00	10200.00
3000.0	14400.00	11900.00	11900.00	11900.00
15000.0	14500.00	12100.00	12100.00	12100.00
20000.0	17700.00	14700.00	14700.00	14700.00

TABLE C7 (CONTINUED). TOTAL COST DATA FOR A 36 INCH PIPE CULVERT ON A 2½:1 SLOPE

TOTAL COST OF A GRATE PROTECTED CULVERT

FOR A 36 IN. DIAMETER PIPE ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	3300.00	2900.00	2700.00	2700.00
1500.0	5100.00	4400.00	4000.00	4000.00
2250.0	6700.00	5800.00	5200.00	5200.00
3000.0	8500.00	7200.00	6500.00	6500.00
15000.0	8700.00	7300.00	6500.00	6500.00
20000.0	11500.00	9600.00	8500.00	8500.00

TABLE C7 (CONTINUED). TOTAL COST DATA FOR A 36 INCH PIPE CULVERT ON A 2½:1 SLOPE

TOTAL COST OF AN UNPROTECTED CULVERT
FOR A 36 IN. DIAMETER PIPE ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	2300.00	1700.00	1200.00	600.00
1500.0	4600.00	3300.00	2400.00	1100.00
2250.0	6700.00	4800.00	3500.00	1600.00
3000.0	9000.00	6500.00	4700.00	2200.00
15000.0	9200.00	6600.00	4800.00	2200.00
20000.0	12800.00	9200.00	6600.00	3100.00

TABLE C8. TOTAL COST DATA FOR A 36 INCH PIPE CULVERT ON A 6:1 SLOPE

TOTAL COST FOR EXTENDING A CULVERT

FOR A 36 IN. DIAMETER PIPE ON A 6 TO 1 SLOPE

ORIGINAL OFFSET	A=12 FT.	A=12 FT.	A=12 FT.	A=18 FT.	A=18 FT.	A=24 FT.
FINAL OFFSET	A=18 FT.	A=24 FT.	A=30 FT.	A=24 FT.	A=30 FT.	A=30 FT.
ADT						
750.0	2600.00	2400.00	2100.00	2300.00	2000.00	1900.00
1500.0	4200.00	3600.00	2600.00	3500.00	2500.00	2400.00
2250.0	5700.00	4700.00	3100.00	4600.00	3000.00	2900.00
3000.0	7400.00	5900.00	3700.00	5800.00	3600.00	3500.00
15000.0	7500.00	6000.00	3700.00	5900.00	3600.00	3500.00
20000.0	10100.00	7600.00	4600.00	7700.00	4500.00	4400.00

TABLE C8 (CONTINUED). TOTAL COST DATA FOR A 36 INCH PIPE CULVERT ON A 6:1 SLOPE

TOTAL COST OF A GUARDRAIL PROTECTED CULVERT
FOR A 36 IN. DIAMETER PIPE ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	8500.00	6900.00	6900.00	6900.00
1500.0	10500.00	8600.00	8600.00	8600.00
2250.0	12400.00	10200.00	10200.00	10200.00
3000.0	14400.00	11900.00	11900.00	11900.00
15000.0	14500.00	12100.00	12100.00	12100.00
20000.0	17700.00	14700.00	14700.00	14700.00

TABLE C8 (CONTINUED). TOTAL COST DATA FOR A 36 INCH PIPE CULVERT ON A 6:1 SLOPE

TOTAL COST OF A GRATE PROTECTED CULVERT

FOR A 36 IN. DIAMETER PIPE ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	8400.00	8300.00	8300.00	8300.00
1500.0	9100.00	8800.00	8800.00	8800.00
2250.0	9700.00	9300.00	9300.00	9300.00
3000.0	10400.00	9900.00	9900.00	9900.00
15000.0	10400.00	9900.00	9900.00	9900.00
20000.0	11500.00	10800.00	10800.00	10800.00

TABLE C8 (CONTINUED). TOTAL COST DATA FOR A 36 INCH PIPE CULVERT ON A 6:1 SLOPE

TOTAL COST OF AN UNPROTECTED CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	5200.00	4200.00	3700.00	1300.00
1500.0	10500.00	8400.00	7400.00	2500.00
2250.0	15300.00	12300.00	10900.00	3700.00
3000.0	20500.00	16600.00	14600.00	5000.00
15000.0	20900.00	16900.00	14900.00	5100.00
20000.0	29000.00	23400.00	20600.00	7100.00

TABLE C9. TOTAL COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

TOTAL COST FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	5500.00	5900.00	4300.00	5400.00	4000.00	3600.00
1500.0	9800.00	9600.00	5600.00	9200.00	5300.00	4900.00
2250.0	13700.00	13000.00	6800.00	12600.00	6500.00	6100.00
3000.0	17900.00	16800.00	8100.00	16300.00	7800.00	7400.00
15000.0	18200.00	17000.00	8200.00	16600.00	7900.00	7500.00
20000.0	24700.00	22800.00	10100.00	22300.00	9800.00	9400.00

TABLE C9 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

TOTAL COST OF A GUARDRAIL PROTECTED CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	8500.00	6900.00	6900.00	6900.00
1500.0	10500.00	8600.00	8600.00	8600.00
2250.0	12400.00	10200.00	10200.00	10200.00
3000.0	14400.00	11900.00	11900.00	11900.00
15000.0	14500.00	12100.00	12100.00	12100.00
20000.0	17700.00	14700.00	14700.00	14700.00

TABLE C9 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

TOTAL COST OF A GRATE PROTECTED CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	4300.00	3800.00	3400.00	3400.00
1500.0	6400.00	5600.00	4700.00	4700.00
2250.0	8400.00	7100.00	5900.00	5900.00
3000.0	10500.00	8800.00	7100.00	7100.00
15000.0	10700.00	9000.00	7200.00	7200.00
20000.0	13900.00	11600.00	9200.00	9200.00

TABLE C9 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

TOTAL COST OF AN UNPROTECTED CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	3700.00	2600.00	1800.00	600.00
1500.0	7400.00	5200.00	3500.00	1100.00
2250.0	10800.00	7600.00	5100.00	1600.00
3000.0	14500.00	10200.00	6900.00	2200.00
15000.0	14800.00	10400.00	7000.00	2200.00
20000.0	20500.00	14500.00	9800.00	3100.00

TABLE C10. TOTAL COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

TOTAL COST FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 6 TO 1 SLOPE

ORIGINAL OFFSET	A=12 FT.	A=12 FT.	A=12 FT.	A=18 FT.	A=18 FT.	A=24 FT.
FINAL OFFSET	A=18 FT.	A=24 FT.	A=30 FT.	A=24 FT.	A=30 FT.	A=30 FT.
ADT						
750.0	4400.00	4300.00	3900.00	3700.00	3300.00	2800.00
1500.0	7000.00	6100.00	4500.00	5500.00	3900.00	3400.00
2250.0	9400.00	7700.00	5000.00	7100.00	4400.00	3900.00
3000.0	12000.00	9500.00	5500.00	8900.00	5000.00	4400.00
15000.0	12200.00	9600.00	5600.00	9000.00	5000.00	4500.00
20000.0	16300.00	12300.00	6400.00	11700.00	5600.00	5300.00

TABLE C10 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

TOTAL COST OF A GUARDRAIL PROTECTED CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	8500.00	6900.00	6900.00	6900.00
1500.0	10500.00	8600.00	8600.00	8600.00
2250.0	12400.00	10200.00	10200.00	10200.00
3000.0	14400.00	11900.00	11900.00	11900.00
15000.0	14500.00	12100.00	12100.00	12100.00
20000.0	17700.00	14700.00	14700.00	14700.00

TABLE C10 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

TOTAL COST OF A GRATE PROTECTED CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	15300.00	15200.00	15200.00	15200.00
1500.0	16000.00	15700.00	15700.00	15700.00
2250.0	16600.00	16200.00	16200.00	16200.00
3000.0	17300.00	16800.00	16800.00	16800.00
15000.0	17300.00	16800.00	16800.00	16800.00
20000.0	18400.00	17700.00	17700.00	17700.00

TABLE C10 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

TOTAL COST OF AN UNPROTECTED CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	7100.00	6400.00	5500.00	1300.00
1500.0	14300.00	12700.00	11000.00	2500.00
2250.0	20900.00	18600.00	16100.00	3700.00
3000.0	28000.00	24900.00	21600.00	5000.00
15000.0	28600.00	25400.00	22000.00	5100.00
20000.0	39600.00	35200.00	30400.00	7100.00

TABLE C11. TOTAL COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

TOTAL COST FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	6100.00	8500.00	5600.00	7600.00	4900.00	4100.00
1500.0	14400.00	14000.00	6900.00	13100.00	6100.00	5300.00
2250.0	20300.00	19100.00	8100.00	18200.00	7300.00	6500.00
3000.0	26600.00	24500.00	9300.00	23700.00	8600.00	7800.00
15000.0	27100.00	25000.00	9400.00	24100.00	8700.00	7900.00
20000.0	30900.00	33400.00	11400.00	32600.00	10700.00	9800.00

TABLE C11 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

TOTAL COST OF A GUARDRAIL PROTECTED CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	8500.00	6900.00	6900.00	6900.00
1500.0	10500.00	8600.00	8600.00	8600.00
2250.0	12400.00	10200.00	10200.00	10200.00
5000.0	14400.00	11900.00	11900.00	11900.00
15000.0	14500.00	12100.00	12100.00	12100.00
20000.0	17700.00	14700.00	14700.00	14700.00

TABLE C11 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

TOTAL COST OF A GRATE PROTECTED CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	4700.00	4300.00	4100.00	4100.00
1500.0	6500.00	5800.00	5400.00	5400.00
2250.0	8100.00	7100.00	6600.00	6600.00
3000.0	9900.00	8600.00	7900.00	7900.00
15000.0	10100.00	8700.00	7900.00	7900.00
20000.0	12800.00	11000.00	9900.00	9900.00

TABLE C11 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

TOTAL COST OF AN UNPROTECTED CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	5600.00	4000.00	2600.00	600.00
1500.0	11300.00	7900.00	5200.00	1100.00
2250.0	16500.00	11600.00	7500.00	1600.00
3000.0	22100.00	15600.00	10100.00	2200.00
15000.0	22500.00	15900.00	10300.00	2200.00
20000.0	31200.00	22000.00	14300.00	3100.00

TABLE C12. TOTAL COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

TOTAL COST FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 6 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	6200.00	5900.00	5100.00	4900.00	4200.00	3200.00
1500.0	10100.00	8500.00	5700.00	7500.00	4700.00	3700.00
2250.0	13600.00	10900.00	6200.00	9900.00	5200.00	4300.00
3000.0	17600.00	13500.00	6600.00	12500.00	5800.00	4800.00
15000.0	18100.00	13700.00	6800.00	12700.00	5800.00	4800.00
20000.0	24200.00	17600.00	7600.00	16800.00	6700.00	5700.00

TABLE C12 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

C42

TOTAL COST OF A GUARDRAIL PROTECTED CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	8500.00	6900.00	6900.00	6900.00
1500.0	10500.00	8600.00	8500.00	8600.00
2250.0	12400.00	10200.00	10200.00	10200.00
3000.0	14400.00	11900.00	11900.00	11900.00
15000.0	14500.00	12100.00	12100.00	12100.00
20000.0	17700.00	14700.00	14700.00	14700.00

TABLE C12 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

TOTAL COST OF A GRATE PROTECTED CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 6 TO 1 SLOPE

ADT	A=12FT.	A=18FT.	A=24FT.	A=30FT.
750.0	20600.00	20500.00	20500.00	20500.00
1500.0	21300.00	21100.00	21100.00	21100.00
2250.0	21900.00	21600.00	21600.00	21600.00
3000.0	22600.00	22100.00	22100.00	22100.00
15000.0	22700.00	22200.00	22200.00	22200.00
20000.0	23700.00	23000.00	23000.00	23000.00

TABLE C12 (CONTINUED). TOTAL COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

TOTAL DIRECT COST FOR EXTENDING A CULVERT

FOR A 36 IN. DIAMETER PIPE ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET	A=12 FT.	A=12 FT.	A=12 FT.	A=18 FT.	A=18 FT.	A=24 FT.
FINAL OFFSET	A=18 FT.	A=24 FT.	A=30 FT.	A=24 FT.	A=30 FT.	A=30 FT.
ADT						
750.0	700.00	1100.00	1500.00	1100.00	1700.00	1700.00
1500.0	700.00	1100.00	1500.00	1100.00	1700.00	1700.00
2250.0	700.00	1100.00	1500.00	1100.00	1700.00	1700.00
3000.0	700.00	1100.00	1500.00	1100.00	1700.00	1700.00
15000.0	700.00	1100.00	1500.00	1100.00	1700.00	1700.00
20000.0	700.00	1100.00	1500.00	1100.00	1700.00	1700.00

TABLE C13. DIRECT COST DATA FOR A 36 INCH PIPE CULVERT ON A 2½:1 SLOPE

TOTAL DIRECT COST FOR EXTENDING A CULVERT
FOR A 36 IN. DIAMETER PIPE ON A 6 TO 1 SLOPE

ORIGINAL OFFSET	A=12 FT.	A=12 FT.	A=12 FT.	A=18 FT.	A=18 FT.	A=24 FT.
FINAL OFFSET	A=18 FT.	A=24 FT.	A=30 FT.	A=24 FT.	A=30 FT.	A=30 FT.
ADT						
750.0	900.00	1200.00	1500.00	1100.00	1400.00	1300.00
1500.0	900.00	1200.00	1500.00	1100.00	1400.00	1300.00
2250.0	900.00	1200.00	1500.00	1100.00	1400.00	1300.00
3000.0	900.00	1200.00	1500.00	1100.00	1400.00	1300.00
15000.0	900.00	1200.00	1500.00	1100.00	1400.00	1300.00
20000.0	900.00	1200.00	1500.00	1100.00	1400.00	1300.00

TABLE C14. DIRECT COST DATA FOR A 36 INCH PIPE CULVERT ON A 6:1 SLOPE

TOTAL DIRECT COST FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	1300.00	2100.00	3100.00	1700.00	2800.00	2400.00
1500.0	1300.00	2100.00	3100.00	1700.00	2800.00	2400.00
2250.0	1300.00	2100.00	3100.00	1700.00	2800.00	2400.00
3000.0	1300.00	2100.00	3100.00	1700.00	2800.00	2400.00
15000.0	1300.00	2100.00	3100.00	1700.00	2800.00	2400.00
20000.0	1300.00	2100.00	3100.00	1700.00	2800.00	2400.00

TABLE C15. DIRECT COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 2½:1 SLOPE

TOTAL DIRECT COST FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. SINGLE BOX CULVERT ON A 6 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	1800.00	2500.00	3400.00	2000.00	2800.00	2300.00
1500.0	1800.00	2500.00	3400.00	2000.00	2800.00	2300.00
2250.0	1800.00	2500.00	3400.00	2000.00	2800.00	2300.00
3000.0	1800.00	2500.00	3400.00	2000.00	2800.00	2300.00
15000.0	1800.00	2500.00	3400.00	2000.00	2800.00	2300.00
20000.0	1800.00	2500.00	3400.00	2000.00	2800.00	2300.00

TABLE C16. DIRECT COST DATA FOR A 4' X 6' SINGLE BOX CULVERT ON A 6:1 SLOPE

TOTAL DIRECT COST FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 2-1/2 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	1700.00	3000.00	4300.00	2100.00	3600.00	2800.00
1500.0	1700.00	3000.00	4300.00	2100.00	3600.00	2800.00
2250.0	1700.00	3000.00	4300.00	2100.00	3600.00	2800.00
3000.0	1700.00	3000.00	4300.00	2100.00	3600.00	2800.00
15000.0	1700.00	3000.00	4300.00	2100.00	3600.00	2800.00
20000.0	1700.00	3000.00	4300.00	2100.00	3600.00	2800.00

TABLE C17. DIRECT COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 2½:1 SLOPE

TOTAL DIRECT COST FOR EXTENDING A CULVERT

FOR A 4 X 6 FT. MULTI-BOX CULVERT ON A 6 TO 1 SLOPE

ORIGINAL OFFSET FINAL OFFSET ADT	A=12 FT. A=18 FT.	A=12 FT. A=24 FT.	A=12 FT. A=30 FT.	A=18 FT. A=24 FT.	A=18 FT. A=30 FT.	A=24 FT. A=30 FT.
750.0	2200.00	3400.00	4600.00	2400.00	3600.00	2600.00
1500.0	2200.00	3400.00	4600.00	2400.00	3600.00	2600.00
2250.0	2200.00	3400.00	4600.00	2400.00	3600.00	2600.00
3000.0	2200.00	3400.00	4600.00	2400.00	3600.00	2600.00
15000.0	2200.00	3400.00	4600.00	2400.00	3600.00	2600.00
20000.0	2200.00	3400.00	4600.00	2400.00	3600.00	2600.00

TABLE C18. DIRECT COST DATA FOR A 4' X 6' MULTI-BOX (2) CULVERT ON A 6:1 SLOPE

APPENDIX D
SAMPLE CALCULATIONS

Example 1:

Given: A 4 ft x 6 ft double box culvert is located on a 2½ fill section rural highway with an average daily traffic of 2250. The end of the culvert is 24 ft from the edge of the traveled way and has no other hazards on the slope or around the culvert and ditch. There are no restrictions on the type of safety treatment which may be used.

Required: Determine the most cost-effective alternative.

Solution: a) 1) Select Figure 10 (2½:1 slope).

2) Enter with ADT = 2250 and Offset = 24 ft.

3) The point ADT = 2250 and A = 24 ft falls to the right of the line for two 4 ft x 6 ft MBC. Therefore, safety treatment is recommended.

4) Select Figure 7 (4 ft x 6 ft multi-box (2) culvert on a 2½:1 slope).

5) Enter with ADT = 2250 and Offset = 24 ft.

6) Safest alternative is either extend to 30 ft or grate protection.

Example 2:

Given: A 36-in. diameter pipe culvert is located on a 2½:1 fill section rural highway with an average daily traffic of 1500. The end of the culvert is 18 ft from the edge of the traveled way and has no other hazards on the slope or around the culvert and ditch. There are no restrictions on the type of safety treatment which may be used.

Required: Determine the total costs and ranking factors for a) the unprotected culvert; b) extending the culvert end to 30 ft; c) guardrail protection; and d) grate protection for the direct costs listed in Tables B6 through B8; e) repeat steps a) through d) for 30% decreased direct costs in extending and grate treatments; f) determine most cost-effective alternative for no increase or decrease in direct costs and for 30% decreased direct costs.

Solution: a) Unprotected Culvert

From Table C7:

C_T = \$5100 (ADT = 1500, A = 18 ft)

R = 1.0 (see Appendix B for discussion)

b) Extend Culvert End to 30 ft

From Table C7:

C_T = \$4200 (ADT = 1500, A_O = 18 ft, A_F = 30 ft)

From Table C1:

R = 0.52 (ADT = 1500, A_O = 18 ft, A_F = 30 ft)

c) Guardrail Protection:

From Table C7:

C_T = \$8600 (ADT = 1500, A = 18 ft)

From Table C1:

R = -0.67

d) Grate Protection

From Table C7:

C_T = \$4400

From Table C1:

R = 0.47

e) 1) Unprotected Culvert (no direct costs involved)

C_T = \$5100

R = 1.0

2) Extend Culvert End to 30 ft (30% decrease in direct costs)

From Table C13 or Table B6:

C_{TD} = \$1700

To calculate the new total costs:

C_T = \$4200 - (30%)(\$1700)

C_T = \$3690

Using Equation (B5) to calculate the ranking factor:

$$R = \frac{\$5100 - \$3690}{(70\%)(\$1700)}$$

$R = 1.18$

3) Guardrail Protection (no decrease in direct costs)

$C_T = \$8600$

$R = -0.67$

4) Grate Protection (30% decrease in direct costs)

From Table B8:

$C_{TD} = \$1500$

$C_T = \$4400 - (30\%)(\$1500)$

$C_T = \$3900$

$$R = \frac{\$5100 - \$3900}{(70\%)(\$1500)}$$

$R = 1.14$

f) No increase or decrease in direct costs.

From parts a) - d):

$C_T = \$5100$, $R = 1.0$ for unprotected culvert;

$C_T = \$4200$, $R = 0.52$ for extending to 30 ft;

$C_T = \$8600$, $R = -0.67$ for guardrail protection; and

$C_T = \$4400$, $R = 0.47$ for grate protection.

Based entirely on total costs, extending appears to be the most cost-effective solution; however, it has a ranking factor less than 1.0. This means that more money must be spent than will be received in benefits by extending to 30 ft. Thus, the most cost-effective alternative is to leave the culvert unprotected. This can also be determined by entering Figure 3 with ADT = 1500 and Offset = 18 ft.

30% decrease in direct costs

From part e):

$C_T = \$5100$ $R = 1.0$ for unprotected culvert;

C_T = $3960   R = 1.18 for extending to 30 ft;

C_T = $8600   R = -0.67 for guardrail protection; and

C_T = $3900   R = 1.14 for grate protection

Based on total costs and ranking factors, extending appears to be the best alternative. However, the total cost and ranking factor for grate protection is so near that of extending, that either alternative is considered the most cost-effective.

Example 3:

Given: A 4 ft x 6 ft single box culvert is located on a 6:1 fill section rural highway with an average daily traffic of 3000. The end of the culvert is 12 ft from the edge of the traveled way and has no hazard on the slope or around the culvert and ditch. Right-of-way space is limited so that the culvert can be extended a maximum of 24 ft from the edge of the traveled way.

Required: Determine the most cost-effective alternative.

Solution:

1) Select Figure 11 (6:1 slope).
2) Enter with ADT = 3000 and Offset = 12 ft.
3) The point ADT = 3000 and A = 12 ft falls to the right of the line for one 4 ft x 6 ft SBC. Therefore safety treatment is recommended.
4) Select Figure 6 (4 ft x 6 ft single box culvert on a 6:1 slope).
5) Enter with ADT = 3000 and Offset = 12 ft.
6) Safest alternative is to extend to 30 ft.

This alternative is not possible due to limited right-of-way; thus, the alternative with the next highest ranking factor is the most desirable. Extending the culvert end to 18 or 24 ft might also be a possible treatment. From Table C4:

R = 1.0   for unprotected culvert;

R = 2.69   for extending culvert end to 30 ft (not a possible alternative);

R = 1.99 for extending culvert end to 24 ft;

R = 1.37 for extending culvert end to 18 ft;

R = 0.02 for guardrail protection; and

R = -0.19 for grate protection.

For this, extending to 24 ft clearly provides the second highest ranking factor next to extending to 30 ft. Thus, the culvert end should be extended to a final offset of 24 ft to obtain the second most cost-effective solution. This same procedure can be applied to other situations in which the recommended alternatives in Figures 3 through 8 cannot be implemented.

Example 4:

Given: A portion of highway has been designed for an average daily traffic of 20,000 and will be located on a 6:1 fill section. A 4 ft x 6 ft single box culvert is necessary for drainage under the roadway at Station 1+00. All hazards within 50 ft of the traveled way and 100 ft on either side of the culvert have been removed. The culvert end cannot be closer than 12 ft and no farther than 30 ft from the edge of the traveled way. Assuming no initial costs for an unprotected culvert with a 12 ft offset, it has been determined that the following additional costs are necessary: $3500 for an 18 ft offset, $7000 for a 24 ft offset, and $11,000 for a 30 ft offset. All costs include labor and material for extending the culvert and for the necessary fill to maintain a 6:1 slope.

Required: Determine the most cost-effective culvert end offset and/or safety treatment at Station 1+00.

Solution: The general procedure is to determine the total cost and ranking factor at each offset for the unprotected, guardrail protected, and grate protected culvert. The costs given above must be used in conjunction with the costs given in Appendices B and C.

1) The Unprotected Culvert (see Table C10)

12 ft Offset:

C_T = \$20,500 (from Table C10)

C_{TD} = \$0

R = 1.0

18 ft Offset:

C_T = \$3500 + \$14,500 = \$18,000

C_{TD} = \$3500

$$R = \frac{\$20,500 - \$18,000}{\$3500} = 0.71$$

24 ft Offset:

C_T = \$7000 + \$9800 = \$16,800

C_{TD} = \$7000

$$R = \frac{\$20,000 - \$16,800}{\$7000} = 0.53$$

30 ft Offset:

C_T = \$11,000 + \$3100 = \$14,100

C_{TD} = \$11,000

$$R = \frac{\$20,500 - \$14,100}{\$11,000} = 0.58$$

2) <u>The Guardrail Protected Culvert</u> (see Tables B7 and C10)

12 ft Offset:

C_T = \$17,700 (from Table C10)

C_{TD} = \$6900 (from Table B7)

$$R = \frac{\$20,500 - \$17,700}{\$6900} = 0.41$$

18 ft Offset:

C_T = \$14,700 + \$5500 + \$3500 = \$23,700

C_{TD} = \$5500 + \$3500 = \$9000

$$R = \frac{\$20,500 - \$23,700}{\$9000} = -0.36$$

24 ft Offset:

C_T = \$14,700 + \$5500 + \$7000 = \$27,200

C_{TD} = \$5500 + \$7000 = \$12,500

$$R = \frac{\$20,500 - \$27,200}{\$12,500} = -0.54$$

30 ft Offset:

C_T = \$14,700 + \$5500 + \$11,000 = \$31,200

C_{TD} = \$5500 + \$11,000 = \$16,500

$$R = \frac{\$20,500 - \$31,200}{\$16,500} = -0.65$$

3) Grate Protected Culvert (see Tables B8 and C10)

12 ft Offset:

C_T = \$18,400 (from Table C10)

C_{TD} = \$14,600 (from Table B8)

$$R = \frac{\$20,500 - \$18,400}{\$14,600} = 0.14$$

18 ft Offset:

C_T = \$17,700 + \$3500 = \$21,200

C_{TD} = \$14,600 + \$3500 = \$18,100

$$R = \frac{\$20,500 - \$21,200}{\$18,100} = -0.04$$

24 ft Offset:

C_T = \$17,700 + \$7000 = \$24,700

C_{TD} = \$14,600 + \$7000 = \$21,600

$$R = \frac{\$20,500 - \$24,700}{\$21,600} = -0.19$$

30 ft Offset:

C_T = \$17,700 + \$11,000 = \$28,700

C_{TD} = \$14,600 + \$11,000 = \$25,600

$$R = \frac{\$20,500 - \$28,700}{\$25,600} = -0.32$$

From these calculations, the most cost-effective alternative, based on ranking factor, is to leave the culvert unprotected at a 12 ft offset distance (C_T = $20,500; R = 1.0). Based on total costs, the best alternative is to leave the culvert unprotected using a 30 ft offset (C_T = $14,100; R = 0.58). Note that the additional initial costs used in this example greatly influence the final results since they are a large percentage of the total and direct costs. Care should be taken in estimating these costs in order to obtain correct results.

APPENDIX E

REFERENCES

1. Guide for Selecting, Locating, and Designing Traffic Barriers, Part I, American Association of State Highway and Transportation Officials, 1977, pp. 15-21, 156-186, 222.

2. Hutchinson, J. W. and Kennedy, T. W., "Medians of Divided Highways - Frequency and Nature of Vehicle Encroachments," Bulletin 487, University of Illinois Engineering Experiment Station, 1966.

3. Glennon, J. C., "Roadside Safety Improvement Program on Freeways - A Cost-Effectiveness Priority Approach," National Cooperative Highway Research Program Report 148, 1974, 64 pp.

4. Weaver, G. D., Post, E. R., and French, D. D., "Cost-Effectiveness Program for Roadside Safety Improvements on Texas Highways - Volume 2: Computer Program Documentation Manual," Research Report 15-1, Texas Transportation Institute and Texas Highway Department, February 1975.

5. Memorandum to T. J. Hirsch, R. M. Olson, E. L. Marquis, G. D. Weaver, C. E. Buth, D. L. Ivey, J. E. Martinez, M. E. James, D. L. Woods, and G. E. Hayes, Texas Transportation Institute; Harold Cooner, Ray Ratcliff, and Gerald Peck, Texas State Department of Highways and Public Transportation; and C. P. Damon, Federal Highway Administration, from Terry L. Kohutek of Texas Transportation Institute, Texas A&M University, April 5, 1977, concerning the severity index of various roadside hazards.