period significantly and to produce quality in-service evaluations that result in improved roadside safety hardware.

In early 1984, the Demonstration Projects Division of FHWA announced that separate federal funding was available to state highway agencies to evaluate the field performance of experimental highway safety hardware. Additional information on this program can be obtained through FHWA's division office in each state.

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Guidelines for Placement of Longitudinal Barriers on Slopes

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ABSTRACT

This research was undertaken to investigate the impact performance of longitudinal barriers when placed on sloping terrain. Tasks performed included (a) a determination of typical conditions for which longitudinal barriers are placed on sloping terrain, (b) an evaluation of the impact behavior of widely used barrier systems when placed on sloping terrain, and (c) the development of guidelines for selection and placement of barriers on sloping terrain. Crash tests and the HVOSM computer program were used to evaluate impact behavior and to develop guidelines. Factors considered in the guidelines include roadway and shoulder cross slope, cut and fill slope, barrier offset, and barrier type. It was found that W-beam and Thrie-beam barriers are more sensitive to the effects of sloping terrain than are cable barriers.

Impact behavior of a longitudinal barrier is dependent on a number of factors, including size and spacing of posts, size and mounting height of rail or beam, offset of beam from posts, embedment conditions, and roadside conditions between the edge of the traveled way and the barrier. Little is known about the effects of the latter factor, although it may have the greatest influence on performance. In general, barriers have been designed and tested for flat terrain conditions, even though roadside and median barriers are commonly placed on side slopes or behind curbs. With regard to placement of barriers on slopes, the 1977 AASHTO barrier guide (1) recommended the following:

> As a general rule, a roadside barrier should not be placed on an embankment if the slope of the embankment is steeper than 10:1. In addition, a barrier should not be placed on an embankment if the difference between the shoulder slope rate and side slope rate is greater than approximately 0.10.

Tasks performed in this study were as follows: (a) a determination of typical conditions for which longitudinal barriers are placed on nonlevel terrain, (b) an evaluation of the impact behavior of widely used barrier systems when placed on nonlevel terrain, and (c) the development of guidelines for selection and placement of barriers on nonlevel terrain. Barriers evaluated included widely used roadside and median longitudinal barriers identified in the 1977 AASHTO barrier guide (1). Nonlevel terrain considered in the evaluation concerned sloping embankments, ditches, and superelevated roadway sections.

The results of the study are summarized in this paper. Complete details can be found in a three-volume final report (2-4).

REVIEW OF CURRENT PRACTICE

At the inception of this study the researchers traveled to several states to survey current barrier placement practices and to solicit input from various state transportation personnel. It was found that there are four basic conditions for which roadside and median barriers are typically placed on nonlevel terrain. First, barriers used to shield bridge piers, overhead sign bridge supports, or other rigid objects in depressed medians or on side slopes are often placed as near to the object as the barrier design permits. In many cases this places the barrier on the side slope. Second, barriers used to shield bridge abutments or other rigid objects near the shoulder are often flared away from the shoulder and terminated. As a consequence, a portion of the barrier is placed on the side slope.

Third, roadside barriers are sometimes placed on barn-roof sections in high-fill areas. Typically, the roadside is composed of a shoulder, then a relatively flat sloped embankment (usually a 6:1 slope), which may extend up to 20 ft (6.1 m) laterally from the shoulder, and finally a relatively steep embankment (usually 2:1 or steeper). In this case the barrier is placed on the 6:1 slope to shield the steeper embankment. The last condition, which is not as common as the other conditions mentioned, involves median barriers that are placed on stepped or depressed medians in order to prevent cross-over, head-on accidents.

CRASH-TEST PROGRAM

A limited crash-test program was used to evaluate the collision performance of longitudinal barriers placed on sloping terrain. The objectives of these tests were to gain insight into the effect of sloping terrain on barrier performance and to establish a limited number of data points from which placement recommendations could be developed. Tests of a standard G4(1S) W-beam roadside barrier, a standard G9 Thrie-beam roadside barrier, and a standard G1 cable roadside barrier were conducted. [Note that G4(1S), G9, and G1 are barrier notations as used in the 1977 AASHTO barrier guide (1).] The barriers in each test were placed on a 6:1 side slope at a distance of 6 or 12 ft (1.83 or 3.66 m) laterally from the edge of the shoulder. Test site geometry is shown in Figure 1. Photographs of the barriers installed at the test site are shown in Figures 2-4.

A summary of the seven crash tests conducted is given in Table 1. The tests were conducted and evaluated per recommendations of TRB Circular 191 (5). Subsequently, NCHRP Report 230 (6) was published.

Conclusions drawn as a result of these tests are as follows.

1. The G4(1S) roadside barrier system does not satisfy structural adequacy requirements (5) when placed on a 6:1 slope at 6 ft (1.83 m) or 12 ft (3.7 m) from the edge of the shoulder. In other words, the barrier, when placed as stated, will not contain and redirect a 4,500-lb (2043-kg) automobile impacting at 60 mph (96.5 km/h) and an encroachment angle of 25 degrees.
2. The G4(1S) system, when placed on a 6:1 slope 6 ft from the edge of the shoulder, will contain and smoothly redirect a 4,500-lb automobile impacting at 60 mph and an encroachment angle of 15 degrees. Although not proven by test, it is the authors' opinion that the G4(1S) system will satisfy impact severity requirements (5) under these same conditions.
3. The G4(1S) system satisfies impact severity requirements (5) when placed on a 6:1 slope 12 ft from the edge of the shoulder. In other words, the barrier, when placed as stated, will contain and smoothly redirect a 2,250-lb (1022-kg) automobile with tolerable decelerations when impacting at 60 mph and an encroachment angle of 15 degrees.
4. Post-impact vehicle trajectory was less than desirable following the G4(1S) tests in which the vehicle was redirected (tests 2 and 4). Results of these two tests could be interpreted to mean that a vehicle trajectory hazard (5) existed (i.e., after impact, trajectory of the vehicle would pose a hazard to traffic in adjacent lanes).
5. The G9 roadside barrier system does not satisfy structural adequacy requirements (5) when placed on a 6:1 slope 6 ft from the edge of the shoulder.
6. The G1 roadside barrier system, when placed on a 6:1 slope 6 ft from the edge of the shoulder, satisfied all performance specifications for a roadside barrier [i.e., structural adequacy, impact severity, and vehicle trajectory hazard (5)]. When compared to the G4(1S) system, improved performance of the G1 system is attributed to the 30-in. (76.2-cm) mounting height of the top cable [versus 27 in. (68.6 cm) for the W-beam]. The cables tend to remain at essentially the same height following impact, whereas the W-beam in the G4(1S) system rotates backward and downward, thus creating a ramp for the vehicle.

DEVELOPMENT OF PLACEMENT GUIDELINES

In the final phase of the research, a version of the computer program HVOSM (7) was used to supplement crash-test results in the development of placement guidelines. HVOSM was used to determine vehicle kinematics at the instant of impact with a given barrier. Then, based on observed vehicle behavior from the crash tests, a determination was made as to whether the vehicle would have been contained and redirected. The procedures by which this determination was made are given in the following sections.

Barrier Containment Criteria

After careful study of the crash-test film it was concluded that, for a given barrier installation, front bumper position relative to the barrier at impact was the critical factor with regard to vehicle containment and redirection. Other vehicle factors that have an influence on impact behavior include roll, pitch, and yaw rates at impact and the shape and stiffness of the bumper and sheet metal near the contact point. However, the degree to which these factors influenced containment could not be quantified with the limited number of crash tests or with the HVOSM program. Containment criteria for the various types of longitudinal barriers were thus established as follows.

W-Beam and Thrie-Beam Barriers

Four crash tests of a type G4(1S) W-beam barrier and one test of a type G9 Thrie-beam barrier were conducted on nonlevel terrain. After careful analysis of the high-speed film of the tests, it was concluded that (a) vehicle override of a W-beam or Thrie-beam barrier is likely if the midheight of the bumper impacts above the center of the top corrugation of the rail, and (b) vehicle containment and redirection with a W-beam or Thrie-beam barrier are likely if the midheight of the bumper impacts between the centers of the lower and upper corrugation of the rail. Although there were no cases of underriding in the tests, it was assumed that vehicle underride of a W-beam or Thrie-beam barrier is

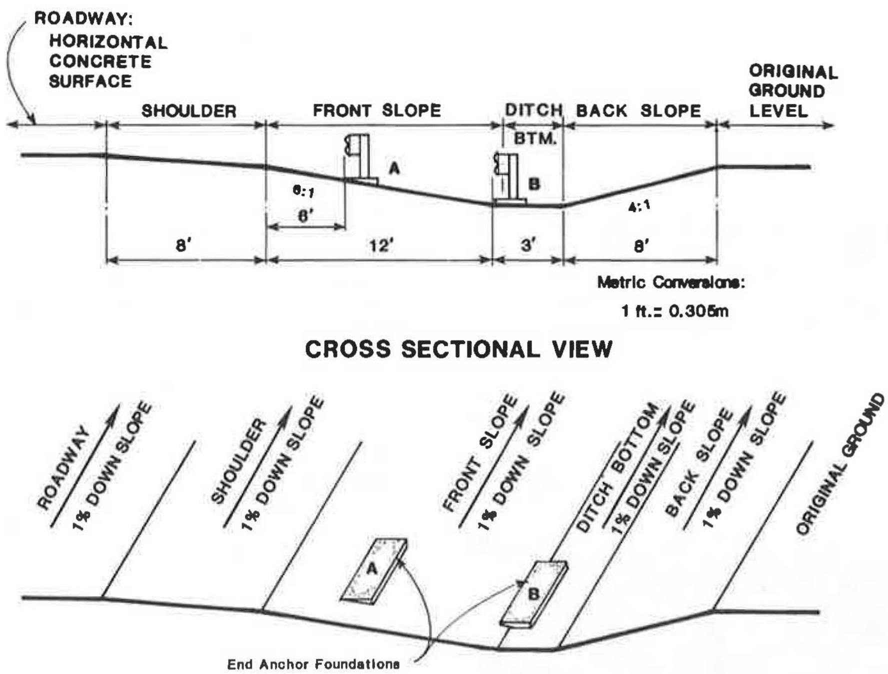


FIGURE 1 Test site geometry.

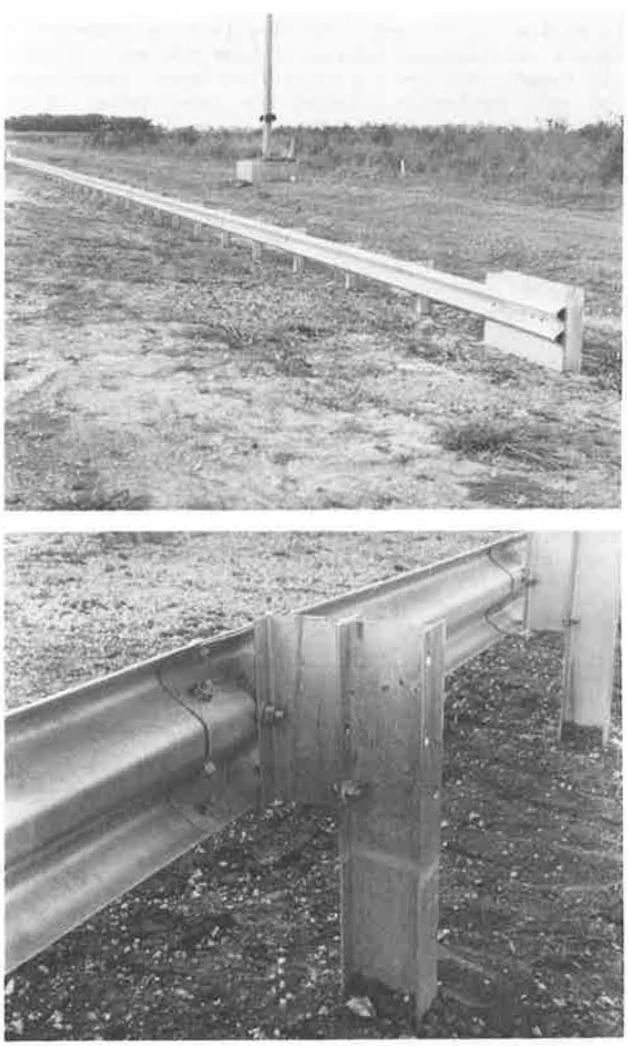


FIGURE 2 G4(1S) barrier installed on 6:1 slope.

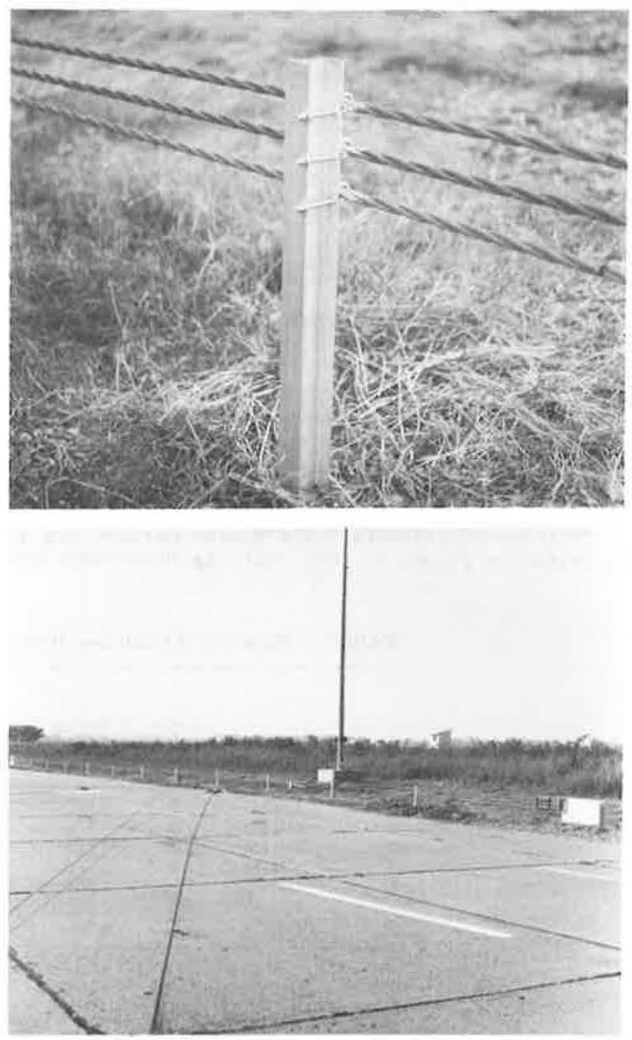


FIGURE 3 G1 cable rail details.

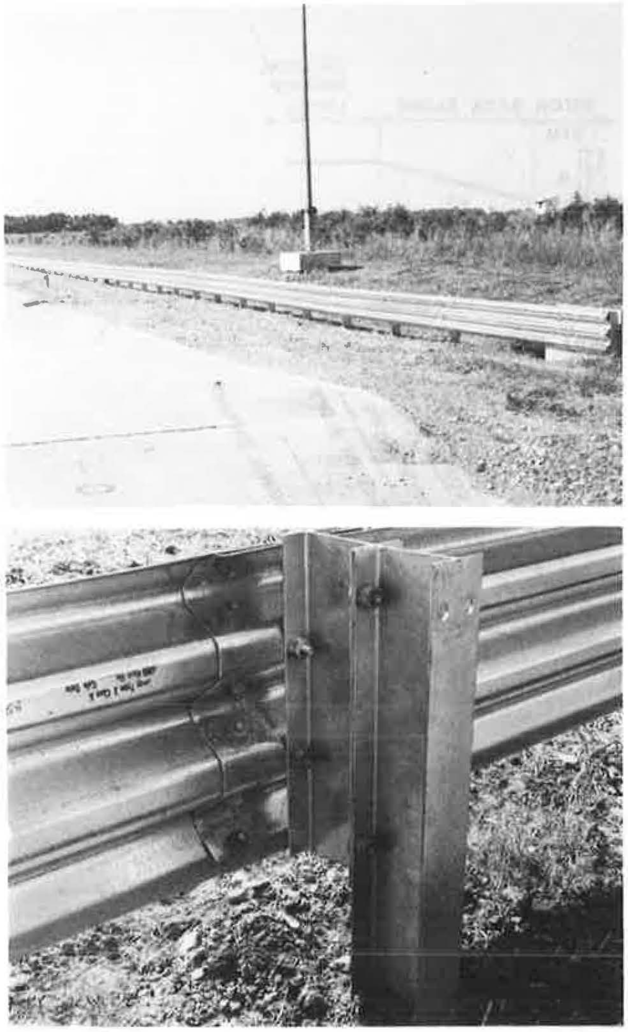


FIGURE 4 G9 barrier installed on 6:1 slope.

likely if the midheight of the bumper impacts below the center of the lower corrugation of the rail. The consequences of underride could be vehicle snagging on a post or vehicle submarining under the barrier or both. Such problems could be reduced by the addition of a lower (rub) rail.

Containment criteria for a W-beam barrier are illustrated in Figure 5. The criteria previously discussed and those that follow are predicated on a vehicle striking the barrier at a weight, speed, and angle equal to or less than 4,500 lb (2043 kg), 60 mph (96.5 km/h), and 25 degrees, respectively.

Cable Barrier

Two full-scale crash tests of the type G1 roadside cable barrier were conducted on nonlevel terrain. On analysis of these tests it was concluded that (a) vehicle override of a cable barrier is likely if the midheight of the bumper is above the top cable on impact, and (b) vehicle containment and redirection are likely if at impact the midheight of the bumper is below the top cable and the upper corner of the right front fender is above the lower cable. Analysis of these and other cable barrier tests (8) indicated that on contact the cable(s) creases the sheet metal and it typically remains in the crease during contact. Such behavior enables a cable barrier to redirect a vehicle even if the bumper is below the cable. When the upper corner of the right front fender is below the lower cable, it is assumed that underride will occur.

Box-Beam Barrier

No tests have been conducted on box-beam barriers placed on nonlevel terrain. However, their behavior is similar to the cable barrier in many respects. On impact the box-beam separates from the weak posts in the impact zone and is not pulled down. Furthermore, the rail typically creases the sheet metal of the vehicle and remains in the crease during contact. Therefore, it was decided to apply the cable guardrail criteria for the development of placement guidelines to box-beam guardrail. Thus for box-beam guardrail it was assumed that if the bumper midheight impacts below the top of the box-beam, the vehicle will not override; and if the upper front corner of the vehicle fender is above the base of the box-beam, the vehicle will not underride.

Barrier Performance Standards

Current guidelines for evaluating the collision performance of longitudinal barriers are contained in NCHRP Report 230 (6). These guidelines recommend a test with a 4,500-lb (2043-kg) vehicle impacting at 60 mph (96.5 km/h) and 25 degrees as the critical test of vehicle containment, and a test with an

TABLE 1 Summary of Crash Test Results

Test No.	Barrier Type	Barrier Offset[a] (ft)	Vehicle Weight (lb)	Impact Speed (mph)	Impact Angle (degree)	Adherence to Performance Specifications[b]: Structural Adequacy?	Impact Severity?	Exit Angle?
1	G4(1S)	6.0	4,500	62.83	25.0	No[c]	NA	–[c]
2	G4(1S)	6.0	4,500	63.30	14.75	Yes	Yes	No[d]
3	G4(1S)	12.0	4,500	62.9	26.25	No[e]	NA	–[e]
4	G4(1S)	12.0	2,300	58.2	14.75	Yes	Yes	No[d]
5	G1	6.0	4,500	59.6	24.75	Yes	NA	Yes
6	G1	6.0	2,250	58.4	17.25	Yes	Yes	Yes
7	G9	6.0	4,500	62.0	26.0	No[c]	NA	–[c]

Note: All barriers tested were placed on a 6:1 side slope. NA = not applicable. Metric conversions: 1 ft = 0.305 m, 1 lb = 0.454 kg, and 1 mph = 1.609 km/h.

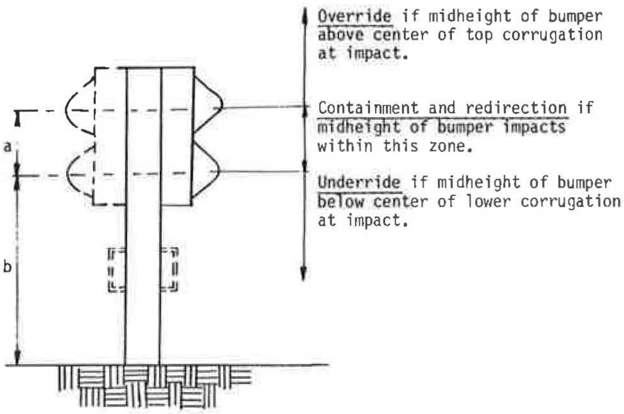
[a]Distance from outer edge of shoulder to face of barrier.

[b]See Section V-A, *(3)* for discussion of performance specifications.

[c]Vehicle vaulted over barrier.

[d]Subjective evaluation.

[e]Vehicle penetrated through fractured rail element.



BARRIER	a (in)	b (in)
G4(1W)	7.6	17.1
G4(2W)	7.6	17.1
G4(1S)	7.6	17.1
G4(2S)	7.6	17.1
MB4W	7.6	20.1
MB4S	7.6	17.1

Metric Conversions

1 in. = 2.54 cm

FIGURE 5 Containment criteria, W-beam barrier.

1,800-lb (817-kg) vehicle impacting at 60 mph and 15 degrees as a test of impact severity. However, these tests are conducted on flat ground, and impacts at other angles or with smaller vehicles may be more severe when the barrier is placed on nonlevel terrain. In addition, other studies (9) have demonstrated that longitudinal barrier impacts at 25-degree angles are rare occurrences, and the design of barriers for this severe event may not always be warranted. Barrier warrants and performance standards can be based on a cost-effectiveness or benefit/cost analysis, in which the probability of encroachment conditions is considered. Therefore, in the interest of allowing engineers options for use in such analyses, three sets of performance standards were selected:

Case 1--barrier must contain and smoothly redirect both full- and mini-sized automobiles at an impact speed of 60 mph and impact angles up to 25 degrees;

Case 2--barrier must contain and redirect a full-sized automobile at an impact speed of 60 mph and impact angles up to 25 degrees, and a mini-sized automobile at an impact speed of 60 mph and impact angles up to 15 degrees; and

Case 3--barrier must contain and redirect both full- and mini-sized automobiles at an impact speed of 60 mph and impact angles up to 15 degrees.

Initially, the researchers believed that the guidelines should be based on nationally recognized performance standards, such as those given in NCHRP Report 230 (6). Such standards are incorporated in case 2. For all practical purposes, NCHRP Report 230 assumes the barriers will be tested on flat approach areas. For such conditions, it is believed that most barriers satisfying the case 2 criteria will satisfy the case 1 criteria. However, after analysis of the data from the present study, it became obvious that for a nonlevel approach there are impact conditions for which the two standards are not mutually satisfied. As such, it is the authors' opinion that the case 1 standard should be used in lieu of the case 2 standard for nonlevel barrier placement. The case 3 standard is believed to more accurately reflect the large majority of real-world accidents. It may also be viewed as a lower service level standard.

Roadway and Roadside Geometric Parameters

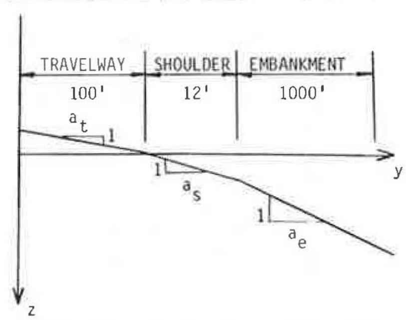
Geometric parameters that influence the trajectory and attitude of a vehicle encroaching on the roadside include roadway cross slope, shoulder width and cross slope, and embankment slope. There are wide ranges of each parameter that occur in the field, and their possible combinations are infinite. Simulation of all possible combinations obviously could not be done; therefore, it was necessary to carefully select a matrix of parameters that would encompass most combinations of interest. The matrix chosen is given in Table 2. Note there are 26 combinations. Roadway cross slopes varied from +48:1 to -10:1, shoulder cross slopes varied from +20:1 to -10:1, and embankment slopes varied from +4:1 to -4:1.

Vehicle Parameters

To establish adherence to the selected performance standards, it was necessary to evaluate vehicle behavior for 60 mph (96.5 km/h) encroachments at angles up to 25 degrees for the roadway and roadside conditions selected for analysis. Encroachment angles of 7.5, 15, and 25 degrees were therefore simulated.

TABLE 2 Roadway and Roadside Geometric Parameters

a_t	+48	-20		-10	
a_s	+20	+20	-20	+20	-10
a_e	+ 4	+ 4	+ 4	+ 4	+ 4
	+ 6	+ 6	+ 6	+ 6	+ 6
	+ 8	+ 8	+ 8	+ 8	+ 8
	+10	+10	+10	+10	+10
	- 8	- 8		- 8	
	- 4	- 4		- 4	



Positive sloping downward to right.

Note: A positive slope is one that slopes downward as one moves in +y direction.

Metric Conversion

1 ft = 0.305 m

Placement Guidelines

HVOSM simulations were used to determine vehicle position and velocity relative to roadside terrain. For each roadside encroachment condition studied, the researchers determined those regions of the embankment for which the barrier containment criteria were satisfied. This led to the development of a series of placement guidelines for the three performance standards (cases) for each of the five barrier categories studied. The categories are given in the following table:

Barrier Category	Corresponding Barrier Types
A	G1, MB3
B	G3
C	G4(1W), G4(2W), G4(1S), G4(2S), MB4S
D	G9, MB9
E	MB4W

Figure 6 shows one of the series of placement guidelines. A total of 75 such figures were necessary to present all possible combinations. Figure 6 presents placement guidelines for category C type barriers [G4(1W), G4(2W), G4(1S), G4(2S), and MB4S] for the case 1 performance standard and the given roadway and shoulder slope. Two zones are depicted: (a) combinations of barrier offset, measured from the edge of the travelway to the face of the barrier, and embankment slope in which acceptable barrier performance is predicted; and (b) combinations of barrier offset and embankment slope in which vehicle underride may occur. Placement of the barrier in the latter zone is acceptable if provisions are made to prevent potential underride (e.g., by the use of a rub rail, similiar to that used on the MB4W barrier system). Barrier override is predicted for combinations of offset and embankment slope not within the two zones just mentioned; consequently, barrier placement is not recommended in this zone.

Use of Figure 6 is illustrated in the following examples, both of which obviously assume a case 1 performance standard.

Example 1: barrier = G4(2W), travelway slope = 48:1, shoulder slope = 20:1, embankment slope = 6:1, and desired offset = 20 ft (6.1 m) from the travelway or 8 ft (2.4 m) off shoulder. From Figure 6 it is determined that barrier placement at this offset is not recommended. For acceptable performance, the barrier should be placed 16.5 ft (5.0 m) or less from the travelway or 4.5 ft (1.4 m) or less from the edge of the shoulder.

Example 2: same as example 1, except embankment slope equals 8:1. From Figure 6 it is determined that barrier placement is acceptable for the desired offset.

CONCLUSIONS

Detailed guidelines were developed for placement of widely used roadside and median barriers on roadside and median slopes. A limited crash-test program coupled with an extensive computer simulation effort was used in formulating the guidelines. Parameters included in the formulation were vehicle size and weight, vehicle encroachment speed and angle, roadway cross slope, shoulder cross slope, embankment slope, barrier dimensions, barrier impact characteristics, and barrier offset from the edge of the travelway. The guidelines are contained in a series of figures according to one of five barrier categories and one of three performance standards. Reference should be made to the FHWA publications: Volume II (3) for details of the crash-test program and Volume III (4) for details of the placement guidelines.

In arriving at the findings and conclusions of the study, certain assumptions had to be made with regard to barrier containment criteria (i.e., the ability of a barrier to contain and smoothly redirect an impacting vehicle). The assumptions are believed to be conservative in general, in that they probably overstate the likelihood of a vehicle to override or underride a barrier on nonlevel terrain. However, additional research involving crash tests and computer simulations may be necessary to ascertain the validity of these assumptions.

General conclusions reached during the course of the research were as follows.

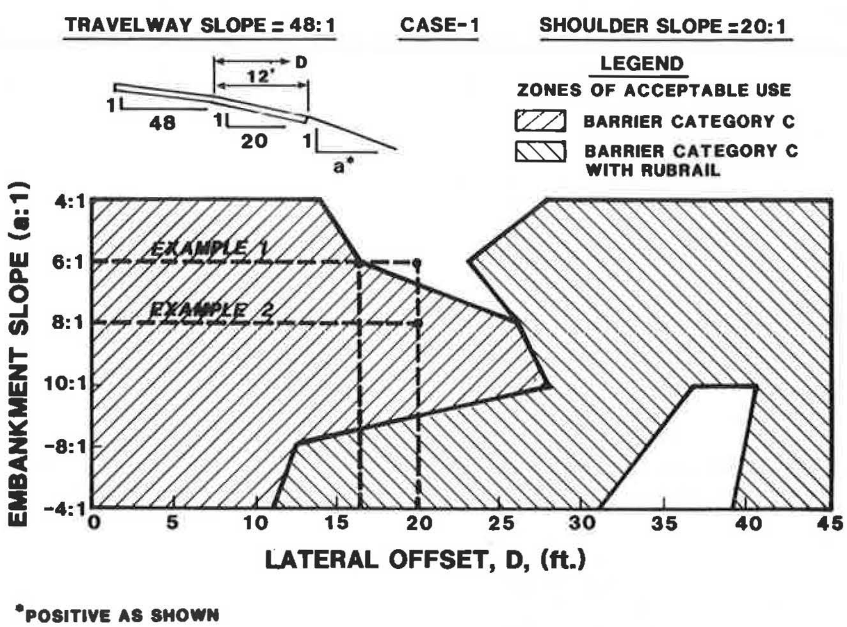


FIGURE 6 Barrier category C, placement on nonlevel terrain.

1. Impact performance of a longitudinal barrier is sensitive to the slope of the approach area in front of the barrier.

2. Impact performance of W-beam and Thrie-beam longitudinal barriers is more sensitive to variations in approach slope than are cable barriers.

3. Where possible, the area between the travelway and the face of the barrier should be flat and unobstructed to afford an errant vehicle room to stop or regain control before striking the barrier. If struck, the barrier can be expected to perform better if the approach area is flat.

4. Regardless of where a longitudinal barrier is placed, the distance between the barrier and the hazard being shielded should not be less than the dynamic deflection of the barrier.

5. Use of the placement guidelines presented herein should be made in conjunction with a cost-effective evaluation of guardrail need. The evaluation should consider factors such as barrier, initial costs, maintenance costs, level of service, nature and frequency of predicted accidents, and societal costs.

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