This research was undertaken to investigate longitudinal barrier impact performance when placed on nonlevel terrain. Tasks performed in this study included 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.

This volume is an executive summary of the three-volume research report. Volume II describes full-scale crash tests conducted under this study. Volume III includes guidelines for placement of longitudinal barriers on slopes.
DEVELOPMENT OF GUIDELINES FOR PLACEMENT
OF LONGITUDINAL BARRIERS
ON SLOPES
VOLUME I. EXECUTIVE SUMMARY

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INTRODUCTION AND SCOPE

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: (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 super-elevated roadway sections.

At the inception of this study, trips were made 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. Secondly, 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. Thirdly, 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 to 1 slope) which may extend up to 20 ft (6.1 m) laterally from the shoulder, and finally a relatively steep embankment (usually 2 to 1 or steeper). In this case the barrier is placed on the 6 to 1 slope to shield the steeper embankment. The last condition, which is not as common as the other conditions mentioned, involves median barriers used to prevent cross-over, head-on accidents that are placed on stepped or depressed medians.

CRASH TEST PROGRAM

A limited crash test program was employed to evaluate the impact performance of longitudinal barriers placed on sloping terrain. The objectives of these tests were (a) to gain insight into the effect of sloping terrain on barrier performance; (b) to establish a limited number of data points from which placement recommendations could be developed; and (c) to establish a data base from which computer program GUARD (2) could be validated. Tests of a standard G4(1S)a W-beam roadside barrier, a standard G9a thrie-beam roadside barrier, and a standard G1a cable roadside barrier

---

*aBarrier notations as used in the 1977 AASHTO Barrier Guide (1).
were conducted. The barriers in each test were placed on a 6 to 1 side slope with offsets of 6 and 12 ft (1.83 and 3.66 m).

Shown in Table 1 is a summary of the seven crash tests conducted. Conclusions drawn as a result of these tests are:

(1) The G4(1S) roadside barrier system does not satisfy structural adequacy requirements when placed on a 6:1 slope at offsets through 12 ft (3.7 m). In other words, the barrier, when placed as stated, will not contain and redirect a 4500 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 and a 6 ft (1.8 m) offset, will contain and smoothly redirect a 4500 lb (2043 kg) automobile impacting at 60 mph (96.5 km/h) 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 when placed on a 6:1 slope and a 6 ft (1.8 m) offset.

(3) The G4(1S) system satisfies impact severity requirements when placed on a 6:1 slope at a 12 ft (3.7) offset. In other words, the barrier, when placed as stated, will contain and smoothly redirect a 2250 lb (1022 kg) automobile with tolerable decelerations when impacting at 60 mph (96.5 km/h) 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 existed, i.e., after impact,
<table>
<thead>
<tr>
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<th>BARRIER TYPE</th>
<th>BARRIER OFFSET (ft)</th>
<th>VEHICLE WEIGHT (lb)</th>
<th>IMPACT SPEED (mph)</th>
<th>IMPACT ANGLE (deg)</th>
<th>ADHERENCE TO PERFORMANCE SPECIFICATIONS&lt;sup&gt;c&lt;/sup&gt;</th>
<th>IMPACT SEVERITY?</th>
<th>EXIT ANGLE?</th>
<th>STRUCTURAL ADEQUACY?</th>
<th>IMPACT ADEQUACY?</th>
<th>ADHERENCE TO PERFORMANCE SPECIFICATIONS&lt;sup&gt;c&lt;/sup&gt;</th>
<th>IMPACT SEVERITY?</th>
<th>EXIT ANGLE?</th>
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<td>G4(1S)</td>
<td>6.0</td>
<td>4500</td>
<td>62.83</td>
<td>25.0</td>
<td>No&lt;sup&gt;d&lt;/sup&gt;</td>
<td>N/A</td>
<td>d</td>
<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
<td>No&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>Yes</td>
<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
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<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
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<td>Yes</td>
<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
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<td>62.9</td>
<td>26.25</td>
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<td>2300</td>
<td>58.2</td>
<td>14.75</td>
<td>Yes</td>
<td>Yes</td>
<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
<td>Yes</td>
<td>Yes</td>
<td>No&lt;sup&gt;e&lt;/sup&gt;</td>
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<td>4500</td>
<td>59.6</td>
<td>24.75</td>
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<td>N/A</td>
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</tr>
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<td>6</td>
<td>G1</td>
<td>6.0</td>
<td>2250</td>
<td>58.4</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<sup>a</sup>All barriers tested were placed on a 6:1 side slope.

<sup>b</sup>Distance from outer edge of shoulder to face of barrier.

<sup>c</sup>See Section V-A of Volume II for discussion of performance specifications.

<sup>d</sup>Vehicle vaulted over barrier.

<sup>e</sup>Subjective evaluation.

<sup>f</sup>Vehicle penetrated through fractured rail element.

N/A - Not Applicable.

Metric Conversions:

1 ft = 0.305 m
1 lb = 0.454 kg
1 mph = 1.609 km/h
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 (3) when placed on a 6:1 slope at a 6 ft (1.8 m) offset.

(6) The G1 roadside barrier system, when placed on a 6:1 slope at a 6 ft (1.8 m) offset, satisfied all performance specifications for a roadside barrier, i.e., structural adequacy, impact severity, and vehicle trajectory hazard (3). 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 remained at essentially the same height following impact while the W-beam in the G4(1S) system rotated backward and downward, creating a ramp for the vehicle.

USE OF HVOSM

In the final phase of the research, a version of computer program HVOSM (4) was used to supplement crash test results in the development of placement guidelines. HVOSM was used to accurately determine vehicle kinematics upon impact with the 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.

BARRIER CONTAINMENT CRITERIA

After careful study of the crash test film, it was concluded that 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 velocity of the point of contact 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. Containment criteria for the various types of longitudinal barriers was established as follows.

W-Beam and Thrie-Beam Barrier

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 rail's top corrugation, and (b) vehicle containment and redirection with a W-beam or thrie-beam barrier is likely if the midheight of the bumper impacts between the centers of the rail's lower and upper corrugation. Although there were no cases of underriding in the tests, it was assumed that vehicle underride of a W-beam or thrie-beam is likely if the midheight of the bumper impacts below the center of the rail's lower corrugation. The consequences of underride could be vehicle snagging on a post and/or vehicle submarining under the barrier. Such problems can be reduced by the addition of a rub rail.

Sample containment criteria are illustrated in Figure 1 for a W-beam barrier. The above criteria and those that follow are predicated on a vehicle striking the barrier at a weight, speed, and angle equal to or less than 4500 lb (2043 kg), 60 mph (96.5 km/h), and 25 degrees, respectively.
Override if midheight of bumper above center of top corrugation at impact.

Containment and redirection if midheight of bumper impacts within this zone.

Underride if midheight of bumper below center of lower corrugation at impact.

<table>
<thead>
<tr>
<th>BARRIER</th>
<th>a (in)</th>
<th>b (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G4(1W)</td>
<td>7.625</td>
<td>17.063</td>
</tr>
<tr>
<td>G4(2W)</td>
<td>7.625</td>
<td>17.063</td>
</tr>
<tr>
<td>G4(1S)</td>
<td>7.625</td>
<td>17.063</td>
</tr>
<tr>
<td>G4(2S)</td>
<td>7.625</td>
<td>17.063</td>
</tr>
<tr>
<td>MB4W</td>
<td>7.625</td>
<td>20.063</td>
</tr>
<tr>
<td>MB4S</td>
<td>7.625</td>
<td>17.063</td>
</tr>
</tbody>
</table>

**Metric Conversions**

1 in. = 2.54 cm

Figure 1. Containment Criteria, W-beam Barrier.
Cable Barrier

Two full-scale crash tests of type G1 roadside cable barrier were conducted on nonlevel terrain. Upon 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 is 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 (5) showed that upon 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, box-beam guardrail behaves similarly to cable barrier in many respects. Upon impact the box-beam separates from the weak posts in the impact zone. 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

Guidelines for testing impact performance of longitudinal barriers are contained in NCHRP Report 230. These guidelines recommend a test with a 4500 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 1800 lb (817 kg) vehicle impacting at 60 mph (96.5 km/h) 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 [6] have shown that guardrail impacts at 25 degrees are rare occurrences, and the design of guardrail for this severe event may not always be warranted. Guardrail performance standards should be selected based on a cost-effective analysis of each guardrail system. Therefore, in the interest of allowing engineers options for use in such analyses, three sets of performance standards were selected as follows:

**Case 1** - Barrier must contain and smoothly redirect both full-size and mini-size automobiles at an impact speed of 60 mph (96.5 km/h) and impact angles up to 25 degrees.

**Case 2** - Barrier must contain and redirect a full-size automobile at an impact speed of 60 mph (96.5 km/h) and impact angles up to 25 degrees, and a mini-size automobile at an impact speed of 60 mph (96.5 km/h) and impact angles up to 15 degrees.

**Case 3** - Barrier must contain and redirect both full-size and mini-size automobiles at an impact speed of 60 mph (96.5 km/h) and impact angles up to 15 degrees.
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 shown in Table 2. Note there are 26 combinations. Roadway cross slopes varied from +48 to 1 to -10 to 1; shoulder cross slopes varied from +20 to 1 to -10 to 1; and embankment slopes varied from +4 to 1 to -4 to 1.

VEHICLE PARAMETERS

To establish adherence to the selected performance standards, it was necessary to evaluate the trajectory and attitude of two automobile types, namely a full-size car and a mini-subcompact car. Furthermore, it was necessary to evaluate vehicle behavior for 60 mph (96.5 km/h) encroachments at angles up to 25 degrees for the roadway/roadside conditions selected for analysis. Encroachment angles of 7.5 degrees, 15 degrees, and 25 degrees were therefore simulated.

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 was satisfied. This led to the
### TABLE 2. ROADWAY/ROADSIDE GEOMETRIC PARAMETERS

<table>
<thead>
<tr>
<th>$\hat{a}_t$</th>
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<th>-20</th>
<th>-10</th>
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<tr>
<td>$a_s$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+20</td>
<td>+20</td>
<td>+20</td>
</tr>
<tr>
<td>$a_e$</td>
<td>+4</td>
<td>+4</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>-4</td>
<td>-4</td>
<td>-4</td>
</tr>
</tbody>
</table>

TRAVELWAY 100'  SHOULDER 12'  EMBANKMENT 1000'

Positive sloping downward to right.

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

Metric Conversion: $1 \text{ ft} = 0.305 \text{ m}$
development of a series of placement guidelines for the three performance
standards (cases) for each of the five barrier categories studied. (See
Table 4, Volume III for barrier categories.)

Figure 2 shows one of the series of placement guidelines. This
figure 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: (1) 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 (2) 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
similar to that used on the MB4W barrier system. Barrier override is
predicted for combinations of offset and embankment slope not within the
above two zones, and consequently barrier placement is not recommended in
this zone.

Use of the guidelines is illustrated in the following examples, both
of which are for a Case 1 performance standard:

Example 1:

Barrier: G4(2W)

Travelway slope: 48 to 1
Shoulder slope: 20 to 1
Embankment slope: 6 to 1
Desired offset: 20 ft (6.1 m) or 8 ft (2.4 m) off shoulder

From Figure 2, it is determined that barrier placement at this offset
is not recommended. For acceptable performance, the barrier should
FIGURE 2

BARRIER CATEGORY C, PLACEMENT ON NONLEVEL TERRAIN

TRAVELWAY SLOPE = 48:1   CASE - 1   SHOULDER SLOPE = 20:1

LEGEND

ZONES OF ACCEPTABLE USE

- BARRIER CATEGORY C
- BARRIER CATEGORY C WITH RUBLRAIL

EMBANKMENT SLOPE (6:1)

EXAMPLE 1

EXAMPLE 2

LATERAL OFFSET, D, (FT.)

* POSITIVE AS SHOWN
be placed 16.5 ft (5.0 m) or less (5.0 m) or less from the travelway
or 4.5 ft (1.4 m) or less from the shoulder.

Example 2:
Same as Example 1 except embankment slope equals 8 to 1. From
Figure 2, 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 program 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 75 figures, according to one of five barrier categories and one of three performance standards. The reader should refer to Volume II for details of the crash test program and to Volume III 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 the barrier containment criteria. The assumptions are believed to be conservative in general, i.e., the containment criteria probably overstate the likelihood of vehicle override or underride. However, additional research involving crash tests and computer simulations may be necessary to ascertain the validity of these assumptions. Discretion is therefore advised in the application of the findings and placement criteria.

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

1. Impact performance of a longitudinal barrier is sensitive to the slope of the approach area in front of the barrier.
2. Where possible, the area between the travelway and the face of the barrier should be flat and unobstructed to afford an errant
motorist room to stop or regain control prior to striking the barrier. If struck, the barrier can be expected to perform better if the approach area is flat.

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

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 level of service, nature and frequency of predicted accidents, societal costs, and initial and maintenance costs.
REFERENCES


