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NCTE. Volumes greater than 1000 L shall be shown in m³.

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1 °C is the symbol for the International System of Measurement.
DISCLAIMER

The contents of this report reflect the views of the authors who are solely responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Tennessee Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

KEY WORDS

Guardrail, Approach Rail, Transition, End Treatment, Terminal, Bridge Rail, Computer Simulation, Highway Safety

ACKNOWLEDGMENTS

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ABSTRACT

The objective of this study was to analyze and evaluate the impact performance of various bridge rail, guardrail, transition, and end treatment designs currently in use by the Tennessee Department of Transportation (TDOT). The project was divided into two phases. Phase I involved the evaluation of the various bridge rail, guardrail, transition, and end treatment designs through theoretical analyses and computer simulation. Where appropriate, modifications to existing designs were recommended. Phase II will involve full-scale crash testing of the existing and modified designs selected for further evaluation.

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1. INTRODUCTION

This report presents results of analytical evaluations performed on various bridge end approach guardrail transition designs, short-radius guardrail treatment designs, and guardrail end treatment designs currently in use or proposed for use by the Tennessee Department of Transportation (TDOT). The evaluation effort covered the following three major areas:

1. Bridge end approach guardrail transition designs,
2. Short-radius guardrail treatment designs, and
3. Guardrail end treatment designs.

The report is organized in a similar manner. Section II presents the evaluation results on bridge end approach guardrail transition designs. Section III summarizes the evaluation results of short-radius guardrail treatment designs while guardrail end treatment designs are covered in Section IV. A summary of the conclusions and recommendations is presented in Section V.
II. BRIDGE END APPROACH GUARDRAIL TRANSITION DESIGNS

Introduction

The primary function of a bridge rail is to prevent errant vehicles from going over the side of the bridge and to prevent the wheels of an impacting vehicle from falling between the bridge rail and the edge of the bridge deck. Thus, by their very nature, bridge rails are required to be either rigid or semi-rigid in construction. The most common types of bridge rails are reinforced concrete walls or metal rails on concrete parapets. If improperly treated, the exposed ends of these railings can present a serious safety hazard to an errant vehicle.

In most instances, an approach guardrail is used to shield the exposed end of the bridge railing and to prevent errant vehicles from getting behind the railing and encountering underlying hazards. These approach guardrails are typically much more flexible than the bridge rails to which they are attached and thus have the potential for deflecting sufficiently to allow an errant vehicle to impact the end of the rigid or semi-rigid bridge railing. A transition section is therefore used whenever there is a significant change in lateral strength from the approach guardrail to the bridge railing.

The purpose of a transition section is to provide continuity of protection where an approach guardrail joins a bridge rail. In order to achieve this continuity of protection, the lateral stiffness of the transition section should be increased smoothly and continuously from the more flexible to the less flexible system. This required increase in lateral barrier strength can be achieved by varying one or more key design parameters, including increasing guardrail beam strength, reducing post spacing, and increasing post size or embedment depth. An effective transition design is one which limits dynamic deflection and minimizes vehicle pocketing or snagging on the bridge rail end.

Standard Tennessee Transition Designs

The Tennessee Department of Transportation (TDOT) has used, prior to 1987, two basic designs for approach guardrails at bridge ends: a steel-post system and an optional wood-post system. As shown on TDOT standard drawing S-GR-20, the two designs are identical except for the types of guardrail posts utilized. The steel-post system, shown in
Figure 1, consists of a 25-ft (7.62-m) section of 10-gauge W-beam mounted at a height of 27 inches (68.6 cm) on six W6x15 posts with a standard embedment depth of 44 inches (1.12 m). The first post downstream from the beginning of the 10-gauge W-beam rail is spaced at a standard 6 ft-3 in (1.91 m) spacing. For all subsequent posts in the transition, the spacing is reduced to 3 ft-1.5 in (0.95 m). In addition, the first three posts upstream from the end of the concrete bridge parapet have 1/4 in x 8 in x 24 in (0.64 cm x 20.3 cm x 61.0 cm) steel soil plates welded five inches (12.7 cm) below the ground surface. Upstream from the transition is a standard G4(1S) guardrail, consisting of a 12-gauge W-beam mounted on W6x9 steel posts spaced at 6 ft-3 in (1.91 m).

The wood-post system, shown in Figure 2, uses two different post sizes in the transition region. The first three posts upstream from the bridge rail end are 10 in x 10 in (25.4 cm x 25.4 cm) while the remaining three posts in the transition are 8 in x 8 in (20.3 cm x 20.3 cm). All posts have a standard embedment depth of 36 inches (0.91 m) and are made from treated lumber. A standard G4(2W) guardrail precedes the transition, which incorporates a 12-gauge W-beam mounted on 6 in x 8 in (15.2 cm x 20.3 cm) wood posts at a spacing of 6 ft-3 in (1.91 m).

The two basic designs described above can be attached to a variety of concrete bridge railings. In this study, transitions to two common types of bridge railings were evaluated. One of the designs for which the transitions were analyzed was the standard TDOT concrete bridge railing shown on TDOT standard drawing K-38-151. In this design, the wingpost is a vertical concrete wall 27 inches (0.69 m) in height and 12 inches (30.5 cm) thick. The end of the wall tapers away from the roadway to a thickness of 3 inches (7.6 cm). The taper leaves a distance of 9 inches (22.9 cm) between the W-beam rail and the end of the bridge railing, thereby reducing the potential for wheel contact during an impact. Transitions to this concrete parapet are shown in Figures 1 and 2.

The other bridge railing for which the transitions were evaluated was the concrete parapet with structural tubing shown in TDOT standard drawing K-38-154A. The concrete wingpost in this design is 6 ft (1.83 m) in length and tapers from a height of 42.5 inches (1.08 m) to a height of 29.5 inches (0.75 m). The bottom of the wingpost has a sloping toe which extends 9 inches (22.9 cm) from the vertical upper face of the wall. A 9-inch (22.9-cm) taper over the last 3 ft (0.91 m) of the wingpost aligns the base of the toe with the
FIGURE 1. Standard TDO® Steel Post Transition to Vertical Concrete Parapet
FIGURE 2. Standard TDOT Wood Post Transition to Vertical Wall Concrete Parapet
traffic face of the W-beam guardrail. The guardrail is inset into a section cut out of the wingpost so that it is flush with the vertical face of the wall. The geometry of the wingpost in this design, specifically the presence of the toe, significantly increases the potential for vehicle snagging. Details of the wingwall are shown in Figure 3, and the transition design is shown in Figure 4. The safety performance of the designs described above, as well as potential retrofit modifications, are evaluated below.

Analysis of Transition Designs

The Barrier VII computer simulation model (1) was selected as the primary means for evaluating the impact performance of both the existing and modified transition designs. The Barrier VII computer simulation model is a two-dimensional simulation program that models vehicular impacts with deformable barriers. The program employs a sophisticated barrier model that is idealized as an assemblage of discrete structural members possessing geometric and material nonlinearities. It has been used successfully to simulate impacts with a variety of flexible barriers, including transitions from flexible to rigid barriers (2,3,4).

Following the guidelines presented in National Cooperative Highway Research Program (NCHRP) Report No. 230 (5), the impact conditions used to evaluate the transition designs involved a 4,500-lb (2241-kg) vehicle traveling at a speed of 60 miles per hour (96.5 km/h) and at an angle of 25 degrees to the barrier. These impact conditions simulate Test Designation 30 of NCHRP Report 230, which is the recommended test for assessing the impact performance of a transition treatment. This test examines the structural adequacy of the transition as well as the propensity for the more flexible barrier to deflect and allow a vehicle to snag on the end of the more rigid barrier.

Using these impact conditions, the critical impact locations for the TDOT bridge end approach guardrail transitions were determined. This was accomplished by simulating impacts into the transitions at various distances before the bridge rail end. The critical impact point was defined as the point at which the potential for snagging on the end of the rigid bridge railing was maximized. It should be noted that this location changes with the stiffness of the approach guardrail transition design. Stiffer approach guardrail transition designs redirect impacting vehicles more quickly and, therefore, have a critical impact point nearer to the end of the rigid bridge railing than do more flexible approach guardrail
FIGURE 3. Detail of Safety-Shaped Concrete Parapet
Figure 4. Standard TDOT Steel Post Transition to Safety-Shaped Concrete Parapet
transition systems. Consequently, both the steel-post and wood-post transitions were analyzed in this manner. Results of the Barrier VII simulations indicated that the critical impact location for both the standard steel and wood post designs was approximately 6 ft (1.83 m) from the end of the concrete wingpost.

Having found the critical impact points, the impact performance of the standard transition designs was evaluated. In order to help assess whether or not a transition system was acceptable from an impact standpoint, a performance criterion was established for maximum allowable wheel snagging on the end of the bridge wingpost. Based on average dimensions of typical passenger car tires and wheels, it was determined that up to 2 inches (5.1 cm) of contact was permissible. Such limited contact would only involve the vehicle's tire, exclusive of the actual wheel assembly. Contact greater than 2 inches (5.1 cm) could significantly increase the probability of the wheel assembly snagging on the end of the concrete wingpost which could lead to severe deceleration of the vehicle or other undesirable results.

The simulation and analysis effort included: (1) evaluation of the impact performance of both existing and modified transition designs for the vertical wall parapet, (2) modifications for the safety-shaped parapet, and (3) analysis of transition designs for lower performance levels. Results of the simulation and analysis effort are presented in the following sections.

Transition Designs for Vertical Wall Parapet

Results of the simulations indicated that both the standard TDOT steel and wood post transition designs would perform unsatisfactorily with the vertical wall parapet. Predicted values for wheel overlap on the end of the vertical wall concrete wingpost were 4.3 inches (10.9 cm) and 4.2 inches (10.7 cm) for the steel and wood post systems, respectively, as shown in Table 1. These values were greater than the 2 inches (5.1 cm) previously selected as the upper limit of wheel overlap on the end of the concrete parapet.

A significant simulation study was then undertaken in an effort to identify satisfactory modifications to the existing transition designs. Numerous potential design modifications were identified and then simulated to evaluate their effects on the impact performance. When selecting potential design modifications, several factors were considered including
Table 1. Simulation Results for Steel Post Transition Design

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<td>3.8</td>
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<tr>
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<td>2.6</td>
</tr>
<tr>
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<td>1.7</td>
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<td>Nested W-beam, W8x21 posts with 68&quot; embedment, and spacer pipe</td>
<td>8.0</td>
<td>1.2</td>
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<td>Single W-beam, W6x15 posts with 44&quot; embedment, and rubrail</td>
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<tr>
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</tr>
<tr>
<td>Nested W-beam, W6x15 posts with 44&quot; embedment, rubrail, and spacer pipe</td>
<td>9.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Single W-beam, W6x15 posts with 44&quot; embedment, 1'-6 3/4&quot; post spacing</td>
<td>10.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Single W-beam, W6x15 posts with 44&quot; embedment, 1'-6 3/4&quot; post spacing, and spacer pipe</td>
<td>8.5</td>
<td>1.8</td>
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* Standard TDOT steel post transition design.
ease of retrofitting existing installations and use of standard hardware items. The key parameters which were investigated included beam strength, post size, post strength (i.e. embedment depth), and post spacing.

The results of the more pertinent simulation runs for the various steel post transition designs are summarized in Table 1. The values for extent of snagging reported in this table reflect the fact that the concrete wingpost tapers 9 inches (22.9 cm) away from the roadway, and are estimates of how much the wheel of the vehicle will overlap the end of the bridge rail during impact. As indicated by the results shown in Table 1, the degree of snagging predicted for the steel post system can be reduced by increasing the beam strength, i.e., using a nested W-beam, increasing the post size, i.e., using W8x21 posts instead of the standard W6x15 posts, increasing the post embedment depth, i.e., from the standard 44 inches (1.12 m) embedment depth to 56 inches (1.42 m) and 68 inches (1.73 m), decreasing the post spacing, i.e., from 3 ft-1.5 in (0.95 m) to 1 ft-6.75 in (0.48 m), adding a channel rubrail and/or a spacer pipe. These changes, either individually or in combination, provide increased lateral barrier stiffness and hence reduce maximum barrier deflections and wheel snagging on the end of the bridge parapet.

Results of the computer simulation indicated three candidate modifications that would provide satisfactory impact performance. Brief discussions on each of these three candidate modifications are presented as follows. The first candidate modification is to use 8-ft (2.44-m) long W8x21 structural steel posts instead of the standard 6-ft (1.83 m) W6x15 posts for the first three posts adjacent to the concrete parapet. The post spacing would remain at 3 ft-1.5 in (0.95 m). As shown in Table 1, this modification with a single W-beam and a spacer pipe would reduce the wheel overlap on the end of the concrete wingpost would be reduced to 1.7 inches (4.3 cm). This represents a reduction of approximately 60 percent in the extent of wheel snagging from the current design. Details of the modified transition design are shown in Figure 5, and are discussed below.

The use of the W8x21 posts allows greater post strength to be achieved through increased embedment depths. The W6x15 post reaches its load carrying capacity at an embedment depth of 56 inches (1.42 m), and any greater embedment depths would simply result in yielding at the base of the post. A W8x21 post, on the other hand, has a greater section modulus and can therefore accommodate greater embedment depths without
FIGURE 5. Modified Steel Post Transition to Vertical Wall Concrete Parapet
- Larger Post Size and Embedment Depth Option
exceeding its structural capacity. In the modified design, W8x21 posts replace the first three posts adjacent to the concrete wingpost. Note that soil plates are not used with the W8x21 posts since soil plates contribute very little to the post strength (2).

The second candidate retrofit design for the steel post system is shown in Figure 6. This design incorporates two additional W6x15 structural steel posts placed between the first three existing posts to effectively reduce the post spacing near the wingwall end from 3 ft-1.5 in (0.95 m) to 1 ft-6.75 in (0.48 m). As shown in Table 1, the predicted extent of wheel contact for this system is 1.8 inches (4.6 cm) which translate into a 58 percent reduction in snagging from the standard design.

These two additional intermediate posts do not need to be connected to the W-beam rail, but should be installed such that the blockout is adjacent to the back side of the W-beam. As shown in Figure 6, the use of soil plates on the additional posts is optional. While the W6x15 steel post with soil plate may be convenient to use in retrofit situations because it is a standard TDOT barrier hardware item, previous testing has shown that the addition of a soil plate increases post capacity by only 5 percent (2).

The advantage of this design is that it eliminates the need of replacing the first three posts in the transition with the heavier, nonstandard W8x21 posts. However, the reduced post spacing decreases the clear space between posts to only 12.75 inches (32.4 cm) which may be restrictive at sites with bridge end drainage.

The third retrofit alternative for the steel post system is shown in Figure 7. In this design, a C6x8.2 channel is used as a lower rubrail to help prevent the wheel of an impacting vehicle from contacting the end of the concrete parapet. The post spacing remains at 3 ft-1.5 in (0.95 m). The rubrail section is anchored to the concrete parapet and is connected to the front flanges of the steel guardrail posts. The upstream end of the rubrail is bent and terminated behind the fifth post in the transition in order to eliminate spearing and wheel snagging during upstream impacts.

The presence of the rubrail increases the lateral stiffness of the transition so that increased post strength or reduced post spacing is no longer required to achieve acceptable impact performance. In other words, this option eliminates the need to add additional W6x15 posts or replace the existing ones with heavier and longer W8x21 posts.
Figure 6. Modified Steel Post Transition to Vertical Wall Concrete Parapet — Reduced Post Spacing Option
STEEL SPACER TUBE
6" I.D. x 12" LONG
SCHEDULE 40 GALVANIZED
PIPE (SEE DETAIL A)

W6x15x6'-0" FIRST THREE POSTS
W6x9x6'-0"

C6x8.2 RUB RAIL

25' W-BEAM
6 SPA. @ 3'-1 1/2"
6'-3"

1/4" x 8" x 2'-4"
SOIL PLATE
FIRST THREE POSTS ONLY

FiGURE 7. Modified Steel Post Transition to Vertical Wall Concrete Parapet
- Rubrail Option
Although the simulation results indicated that the predicted amount of wheel snagging for this design would be 2.9 inches (7.37 cm), which exceeds the established limit of 2 inches (5.1 cm), this is not necessarily a true indicator of impact performance for the rubrail option. The maximum dynamic deflections shown in the first column of Table I are measured at the midheight of the W-beam rail element. By nature of the post rotation, the deflections observed at the height of the channel rubrail are significantly less than these values. Also, since the wheel of the impacting vehicle cannot penetrate beyond the face of the rubrail, the actual severity of snagging is somewhat less than the values presented in Table 1. It is, therefore, concluded that the rubrail alternative should provide acceptable impact performance.

Note that, for all three candidate retrofit designs, a 6-inch (15.2-cm) diameter steel spacer pipe is placed between the wingpost and rail elements. The function of the steel pipe is to provide a controlled collapsible spacer between the flared portion of the wingwall and the guardrail beam elements to help minimize deflections and prevent local yielding of the rail around the end of the parapet. The spacer pipe initially resists deflection of the W-beam near the end of the wingwall, and then begins to collapse as the vehicle approaches the spacer and the dynamic loads become more severe. In absence of the spacer tube, the W-beam is free to deflect laterally until it comes in contact with the wingwall, thus reducing the effectiveness of the 9-inch (22.9-cm) flare. The spacer tube is connected to the W-beam rail with a single 5/8-inch (1.6-cm) button head bolt. The W-beam may be predrilled or drilled in the field to accommodate the spacer pipe.

Note also that the use of nested W-beam would further enhance the impact performance by decreasing the amount of snagging on the end of the concrete parapet. However, since the degree of snagging predicted for the single rail transition described above was either already below the established limit of 2 inches (5.1 cm) or considered acceptable in the case of the rubrail alternative, additional beam strength is not necessary to achieve acceptable impact performance. Also, testing has shown that a single W-beam rail is capable of withstanding the severe dynamic loading that occurs during impact (6). With the use of a single W-beam, backup plates are required at all non-splice post locations. The importing of backup plates in steel post guardrail systems has been demonstrated in full-scale crash testing (7). In the absence of backup plates, the W-beam element has a
tendency to yield locally and pocket around the guardrail post resulting in severe snagging, vehicle ramping, and/or rupture of the rail element.

In summary, any of the three candidate designs discussed above should provide an acceptable retrofit for the standard TDOT steel post guardrail transition design. The selection of the design for implementation is primarily a question of economics and other site specific considerations such as drainage requirements. The reduced post spacing alternative is probably the most economical since it does not require any modification to the existing installations. The drawback is that the reduced post spacing would decrease the clear space between posts to only 12.75 inches (32.4 cm) which may be restrictive at sites with bridge end drainage.

The other two alternative designs retain the post spacing of 3 ft-1.5 in (0.95 m), but would require some modifications to the existing installations. For the larger post size and embedment depth alternative, the first three posts would have to be replaced. For the rubrail alternative, holes would have to be drilled in the concrete parapet (and in the posts if not already predrilled) to accommodate the rubrail addition. Again, the choice of which alternative design to use is primarily a consideration of economics and specific site requirements.

The simulation study effort was then repeated for the wood post system with similar results, as summarized in Table 2. Again, results of the simulation indicated the same three candidate modifications would provide satisfactory impact performance. The first alternative is to increase the embedment depth of the first three 10 in x 10 in (25.4 cm x 25.4 cm) wood posts from 36 inches (0.91 m) to 56 inches (1.42 m). This would reduce the extent of wheel snagging by 57 percent to 1.8 inches (4.57 cm). Figure 8 shows the modified transition design.

As shown in Table 2, the simulation results predict even better impact performance for the reduced post spacing option. By installing two additional 10 in x 10 in (25.4 cm x 25.4 cm) posts adjacent to the bridge rail end, the post spacing is reduced from 3 ft-1.5 in (0.95 m) to 1 ft-6.75 in (0.48 m), and the extent of snagging is reduced by a remarkable 93 percent. Details of this design are shown in Figure 9. The only drawback of this system is the severe limitation in clear space between adjacent posts. The available clear distance of 8.75 inches (22.2 cm) may be unsatisfactory at sites with drainage at the bridge end.
## Table 2. Simulation Results for Wood Post Transition Design

<table>
<thead>
<tr>
<th>System Description</th>
<th>Max. Deflection (in.)</th>
<th>Extent of Snagging (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single W-beam, 10&quot;x10&quot; posts with 36&quot; embedment*</td>
<td>11.8</td>
<td>4.2</td>
</tr>
<tr>
<td>Nested W-beam, 10&quot;x10&quot; posts with 36&quot; embedment</td>
<td>11.6</td>
<td>3.7</td>
</tr>
<tr>
<td>Single W-beam, 10&quot;x10&quot; posts with 44&quot; embedment</td>
<td>10.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Nested W-beam, 10&quot;x10&quot; posts with 44&quot; embedment</td>
<td>9.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Single W-beam, 10&quot;x10&quot; posts with 56&quot; embedment, and spacer pipe</td>
<td>8.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Nested W-beam, 10&quot;x10&quot; posts with 56&quot; embedment, and spacer pipe</td>
<td>7.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Single W-beam, 10&quot;x10&quot; posts with 36&quot; embedment, and rubrail</td>
<td>10.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Single W-beam, 10&quot;x10&quot; posts with 36&quot; embedment, rubrail, and spacer pipe</td>
<td>8.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Nested W-beam, 10&quot;x10&quot; posts with 36&quot; embedment, rubrail, and spacer pipe</td>
<td>7.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Single W-beam, 10&quot;x10&quot; posts with 36&quot; embedment, and 1'-6 3/4&quot; post spacing</td>
<td>8.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Single W-beam, 10&quot;x10&quot; posts with 36&quot; embedment, 1'-6 3/4&quot; post spacing, and spacer pipe</td>
<td>7.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

* Standard TDOT wood post transition design
FIGURE 2. Modified Wood Post Transition to Vertical Wall Concrete Parapet
- Larger Post Embedment Depth Option
FIGURE 9. Modified Wood Post Transition to Vertical Wall Concrete Parapet - Reduced Post Spacing Option
A rubrail system, similar to that described for the steel post transition, is also a candidate alternative. However, due to the difference in blockout depth between the two systems, the rubrail intersects the tapered wingpost at different locations. In order to use the same rubrail section for both wood and steel post transitions, small 2-inch (5.08-cm) spacer blocks would have to be utilized for the wood design. Otherwise, a different rubrail section would have to be fabricated to accommodate each design. The predicted amount of wheel snagging for this design, as shown in Table 2, is 1.8 inches (4.6 cm) which represents a decrease of 57 percent from the standard design. This design should provide acceptable impact performance and is another option for consideration at sites where drainage requirements necessitate a larger clear space than that provided by the reduced post spacing option.

As with the steel post designs, a 6-inch (15.2-cm) diameter steel spacer pipe between the flared portion of the wingwall and the guardrail beam elements is utilized to help minimize deflections and prevent local yielding of the rail around the end of the parapet. Also, a single W-beam element is used with all three alternative designs. The use of nested W-beam rail elements would further reduce the extent of wheel snagging, but considered unnecessary since the extent of wheel snagging for all three alternative designs with single rail element is less than the limit of 2 inches (5.1 cm).

As in the case with the steel post systems, the choice of which alternative design to use is primarily a consideration of economics and specific site requirements. The reduced post spacing alternative is the most economical since it does not require any modification to the existing installations, but it severely decreases the clear space between posts which may be restrictive at sites with bridge end drainage. The other two alternative designs retain the post spacing of 3 ft-1.5 in (0.95 m), but would require some modifications to the existing installations. For the larger post embedment depth alternative, the first three posts would have to be replaced. For the rubrail alternative, holes would have to be drilled in the concrete parapet (and in the posts if not already predrilled) to accommodate the rubrail addition.
Modifications for Safety-Shaped Parapet

All of the modified transition designs, as described above and shown in Figures 5 through 9, have a high probability of meeting NCHRP Report 230 test requirements when connected to a vertical wall parapet with a 9-inch (22.9-cm) flare. However, these modified designs may not perform satisfactorily when used with the safety-shaped concrete parapet (shown previously in Figure 3) since the geometry of the safety-shaped parapet significantly increases the potential for vehicle contact on the exposed end of the barrier.

The upper face of the safety-shaped concrete railing tapers away from the roadway in the same fashion as the vertical wall parapet, but the inset of the W-beam into the concrete wall effectively reducing the taper from 9 inches (22.9 cm) to 6 inches (15.2 cm). In addition, the toe of the barrier is only tapered back to the traffic face of the W-beam rail. Therefore, any deflection in the transition system would permit the wheel of the impacting vehicle to snag on the exposed end of the lower sloped face of the barrier. This could result in severe decelerations of the vehicle or other undesirable results. On the other hand, the toe on the concrete rail has a vertical rise of only 4 1/2 inches (11.4 cm) at which point it slopes away from the roadway toward the face of the wall. It is possible that an impacting wheel might be able to jump or ride over the toe without imparting severe decelerations to the vehicle.

It should be noted that the analysis effort associated with the safety-shaped concrete parapet is not based on the results of simulation studies. Current computer simulation models are unable to accurately model the interaction between the wheel of an impacting vehicle and the end of a concrete barrier. While the Barrier VII computer simulation model can predict the amount of wheel snagging or overlap with the end of the barrier, the severity of impacting the sloped toe cannot be determined without a full-scale crash test. Thus, the analysis effort was based primarily on past experience with similar transition designs.

There is little question that the safety-shaped concrete parapet has a high potential for wheel snagging, particularly on the sloped toe. A number of modifications were, therefore, considered for use with the safety-shaped concrete parapet to reduce the potential of wheel contact with the sloped toe of the concrete barrier. One proposed retrofit alternative consists of blocking out the W-beam rail from the concrete wingwall using
fabricated wood or steel spacer blocks and using a channel rubrail section. Figures 10 and 11 illustrate how this design would work for a steel post system with the larger post size and embedment depth alternative or the reduced post spacing alternative, respectively.

As shown in Figures 10 and 11, two separate blocks are used to block out the W-beam rail from the concrete wingwall. The purpose of the first block is to "fill in" the existing cut out, making it flush with the concrete wall at a point before the taper begins. The dimensions of this block are 3 1/4 in x 2 ft-2 in x 1 ft-1 in (8.3 cm x 66.0 cm x 33.0 cm). The second block is placed on top of the first block to further increase the distance between the W-beam rail and the exposed toe of the concrete barrier. This block is tapered toward the bridge parapet to reduce the possibility of snagging when impacted from the opposite direction. The terminal end shoe is bolted through the blockouts and into the existing anchor insert assembly. The use of these blockouts will provide a distance of 6 1/4 inches (15.9 cm) between the W-beam rail and the vertical face of the toe. It should be noted that no bridge deck area will be sacrificed for this modification. The face of the concrete toe, before being tapered, still extends beyond the face of the blocked out W-beam railing.

To further decrease the probability of wheel snagging on the end of the parapet, a C6x8.2 channel is added as a lower rubrail. The rubrail is carried past the flared section of the wingwall and terminated on the sloped face of the toe. In order to maintain a vertical face for the rubrail, a triangular wood or steel block is required as well as a specially fabricated steel end shoe for terminal connection, as shown in Figures 10 and 11. Note that the rubrail is also blocked out the same distance as the W-beam rail element and the upstream end of the rubrail is bent and terminated behind a post in order to eliminate spearing and wheel snagging during upstream impacts.

Since the rail elements are blocked further out at the connection to the concrete parapet, it is necessary to transition the rail elements back to their normal position. This can be accomplished in one of two ways. The first option, shown in Figure 10, is to gradually increase the blockout distance on succeeding guardrail posts until the proper distance is reached. Special blocks made from structural steel tubing ranging in depth from 8 to 12 inches (20.3 to 30.5 cm) and 22 inches (55.9 cm) in length are used on the first three posts for both the W-beam and channel rubrail to achieve the desired blockout distance. The use a single 22-inch (55.9-cm) section of structural tubing to accommodate both W-
FIGURE 10. Fabricated Steel Post Transition to Safety-Shaped Concrete Parapet - Blockout Cotion with Larger Post Size and Embedment Depth
FIGURE 11. Modified Steel Post Transition to Safety—Shaped Concrete Parapet - Blockout Option with Reduced Post Spacing
beam and rubrail elements eliminates the need for separate blockouts for the W-beam and the rubrail.

Another option to accommodate the transition is to reposition the guardrail posts in a staggered manner. This would eliminate the need for the special blockouts and would allow for a more gradual offset of the W-beam if so desired. For the larger post size and embedment depth alternative, this would be a better option since the use of the W8x21 steel posts already necessitates the removal of the existing posts and replacing the new posts in this manner would not require much additional effort. Note that, for the reduced post spacing alternative, no special blockouts are necessary for the two additional posts since they can be positioned such that the faces of the blockouts are adjacent to the back sides of the W-beam and channel rubrail, as shown in Figure 11.

It should be noted that, as in all the previous designs, a steel spacer pipe is utilized to improve impact performance near the bridge end. However, due to the geometry of the safety-shaped parapet, an 8-inch (20.3-cm) diameter pipe is used rather than the 6-inch (15.2-cm) pipe.

Another feasible retrofit modification for the safety-shaped concrete wingwall is to remove the toe from the end of the wall by breaking out the concrete as shown in Figure 12. By transitioning the toe of the wall in this manner, the surface area of the exposed end of the concrete parapet and, hence, the degree of vehicle snagging will be significantly reduced. While this modification should dramatically improve the impact performance of the original design, it still may not provide satisfactory impact performance. As mentioned previously, the W-beam rail is inset into the side of the safety-shaped barrier, which in effect reduces the distance between the W-beam and the end of the concrete barrier from 9 to 6 inches (22.9 to 15.2 cm). Thus, to further improve impact performance, it is recommended that a 3-inch (7.6-cm) blockout be placed underneath the W-beam end shoe. This would increase the effective blockout distance from the W-beam rail to the edge of the concrete barrier to 9 inches (22.9 cm) and render the various alternatives for the vertical concrete parapet directly applicable to the safety-shaped parapet.

Yet another alternative for retrofitting the safety-shaped wingwall involves the use of a precast concrete curb as shown in Figure 13. The downstream end of the curb is doweled into the end of the concrete barrier and has a cross section which matches the
FIGURE 12. Modified Steel Post Transition to Safety-Shape Concrete Parapet
- Concrete toe removed option with larger post size and embedment depth
FIGURE 13. Modified Steel Post Transition to Safety-Shaped Concrete Parapet
- Precast Curb Option with Larger Post Size and Embedment Depth
slope of the toe. The curb extends into the transition a distance of 6 ft (1.83 m) and the back side of the curb is flush with the front flange of the first two guardrail posts. The height of the curb tapers from 12 inches (30.5 cm) at the downstream end to 6 inches (15.2 cm) on the upstream end.

The purpose of the curb is to prevent the wheel of the impacting vehicle from penetrating behind the barrier face, thereby eliminating the potential for wheel snagging on the exposed end of the concrete barrier. The design shown in Figure 13 should adequately perform its intended function and provide good impact performance when impacted near the bridge end. However, it could pose a problem for sites with bridge end drainage. Also, it is possible for a wheel assembly to be wedged between the curb and the W-beam rail element for vehicles impacting upstream from the beginning of the curb. However, full-scale crash testing of similar designs have not shown this to be a problem (8). In any event, the actual behavior of the vehicle would have to be evaluated with a full-scale crash test.

Of the three alternative designs discussed above, the special blockout and rubrail design appears to be the most promising. This can be used in conjunction with the larger post size and embedment depth alternative or the reduced post spacing alternative to provide acceptable impact performance for transitions to the safety-shaped concrete parapet.

Analysis of Transitions for Lower Performance Levels

As discussed above, analysis of the standard TDOT transition designs indicated that the current designs were not adequate to withstand a Multiple Service Level 2 (MSL 2) impact, i.e., a 4500-lb (2241-kg) vehicle impacting the transition at 60 mi/h (96.5 km/h) and 25 degrees (5). However, since these designs are installed on roadways with various functional classifications, it is valuable to know under what impact conditions the current designs will perform satisfactorily.

Toward this goal, additional Barrier VII simulation runs were made using various impact conditions for both the TDOT standard steel and wood post transition designs. Results of the analysis indicated that, for the vertical wall parapet, the standard transition designs exhibited acceptable impact performance when impacted by a 4500-lb (2241-kg) vehicle traveling at 45 mi/h (72.4 km/h) and 25 degrees. The existing designs also exhibited satisfactory performance when impacted by a 4500-lb (2241-kg) vehicle at 60 mi/h (96.5
km/h) and 15 degrees, which correspond to a Multiple Service Level 1 (MSL 1) impact in NCHRP Report 230 (5). No wheel snagging was predicted to occur for either the standard steel or wood post transition designs. The critical impact location for both of these impact conditions was determined to be 4 1/2 ft (1.37 m) upstream from the end of the concrete barrier.

While the impact performance of the standard TDOT transition designs appear to be satisfactorily for impact speeds up to and including 45 mi/h (72.4 km/h) for the vertical wall concrete parapet with a 9-inch (22.9-cm) taper, it would be marginal at best for the safety-shaped concrete parapet. Under the impact conditions of a 4500-lb (2241-kg) vehicle at 45 mi/h (72.4 km/h) and 25 degrees, wheel snagging of 7.2 and 6.3 inches were predicted for the standard steel and wood post transition designs, respectively, when connected to the safety-shaped concrete parapet. This is due to the geometry of the safety-shaped parapet as discussed in the previous section. On the other hand, the wheel snagging would occur at the toe of the concrete parapet and the resulting severity may be much lower. Although it is not possible to precisely predict the impact performance of the standard transition designs when connected to the safety-shaped concrete parapet without full-scale crash tests, it is evident from the simulation results that the impact performance would be marginal at best.
III. SHORT-RADIUS GUARDRAIL TREATMENT DESIGNS

Introduction

Whenever a secondary roadway or driveway intersects a primary roadway in an area where a guardrail needs to be installed, a special end treatment problem exists. In such instances, the guardrail cannot be extended past the length of need and terminated in a conventional fashion. The only practical solution is to use a short-radius guardrail treatment, i.e., to bend the guardrail in a tight radius through a 90-degree turn and extending it down the secondary roadway. This section examines the current TDOT designs on short-radius guardrail treatments and recommends modifications when appropriate.

Prior to evaluating short-radius guardrail treatment designs, it is necessary to first establish the intended purpose of the short-radius guardrail treatments. There are basically two primary applications for short-radius guardrail treatments. The first is to simply terminate the guardrail when the presence of a driveway or other secondary roadway prevents the use of other types of end treatments. The sole intent of such a design is to prevent spearing, ramping, or other undesirable results associated with improperly terminated guardrails. Where a clear recovery area is available behind the short-radius guardrail so that vehicle containment is not necessary, the vehicle is not kept from penetrating behind the barrier if an impact occurs along the curved section of the guardrail. An in-line anchor is generally used by TDOT to provide anchorage for redirecting vehicles that impact along the tangent section of guardrail.

The second type of application for a short-radius guardrail is one in which vehicle containment, in addition to guardrail termination, is of vital importance. Such a need exists wherever a clear recovery area is not available behind the short-radius guardrail, e.g., the presence of a bridge rail end or other hazards. Under these circumstances, it is necessary to strictly limit vehicle travel behind the barrier due to the presence of hazards. Vehicle containment of this nature can be accomplished by providing adequate anchorage and runout distance along the secondary roadway. Although the need for such treatments is quite common, there is a lack of acceptable designs from which to choose.
In the sections to follow, the standard TDOT designs will be discussed and modifications will be recommended when appropriate.

**In-Line Guardrail Anchor**

Wherever a private drive or public road intersects a main roadway at a point where a guardrail is required, TDOT terminates the guardrail with their standard design, shown in Figure 14, page 33, which incorporates an in-line guardrail anchor (TDOT standard drawing S-GR-18A). The standard design includes a short-radius bend from the primary roadway to the secondary roadway over a 12 1/2-ft (3.81-m) section of guardrail. The guardrail installation is terminated along the secondary roadway immediately after the short-radius curve. An in-line anchor consisting of a standard cable assembly connected to a breakaway wood post is used along the main roadway where the tangent section of guardrail begins. A standard G4(1S) guardrail, consisting of W6x9 steel posts and a W-beam rail, begins at the first post downstream from the in-line anchor. The W6x9 steel posts and blockouts are also used along the curved section of guardrail.

The in-line anchor should perform satisfactorily for its intended function of maintaining tension to the W-beam at tangent locations to redirect impacting vehicles. It should be noted that the in-line anchor is an essential part of the short-radius guardrail design since no anchorage is provided along the upstream end. Removal of the in-line anchor could allow vehicle pocketing or penetration to occur along the tangent section of the barrier under severe impact conditions. Also, since no upstream anchorage along the secondary roadway is provided, the purpose of the short-radius curve section is simply to terminate the guardrail installation. Vehicles impacting the short-radius section would not be contained, but would be allowed to penetrate behind the barrier. A clear recovery area is therefore needed behind the short-radius guardrail.

Full-scale crash testing of short-radius guardrail designs along the curved section of the guardrail (2) indicated a propensity for the impacting vehicle to deflect the posts in front of its path, forming a ramp which could eventually launch the vehicle and lead to vehicle ramping, rollover, or other undesirable results. In order to eliminate this potential ramping problem, it is necessary to use breakaway posts along the curved section of rail. The breakaway posts will fracture upon impact and allow the impacting
FIGURE 14. Standard TDOT In-Line Guardrail Anchor
6" x 8" WEAKENED POST

PRIVATE DRIVE OR PUBLIC ROAD

MAIN ROADWAY

FIGURE 15. Modified n-Line Guardrail Anchor
vehicle to safely penetrate behind the barrier and come to a controlled stop. A modified in-line anchor design with breakaway posts along the curved section of guardrail, is shown in Figure 15. Note that details of the standard in-line anchor design remain unchanged with the exception of the breakaway posts.

Short-Radius Guardrail Treatments

For applications in which vehicle containment is warranted, a short-radius guardrail treatment with adequate upstream anchorage along the secondary roadway is required. An acceptable design can be characterized by two requirements. First, the short-radius guardrail treatment should have the structural capacity to contain a large, i.e., 4,500 lb (2241 kg), vehicle within a reasonable stopping distance. For certain locations, it may be necessary to strictly limit vehicle travel behind the barrier due to the presence of severe hazards behind the barrier. Secondly, the short-radius guardrail treatment should be able to decelerate a small, i.e., 1800 lb (816 kg), vehicle in such a manner that occupant severity criteria as outline in NCHRP Report 230 (5) would be satisfied.

In a previous study at TTI (3), the Barrier VII computer simulation program was used to analyze the short-radius guardrail treatment problem. The major design parameters investigated include post strength, post spacing, and guardrail beam strength around the curve. As mentioned above, it was determined that breakaway or weakened posts should be used along the curved section of guardrail. The purpose of the weakened posts is to allow them to fracture or break away and thus prevent vehicle ramping during head-on impacts. The breakaway mechanism is achieved by drilling two 3 1/2-inch (8.9-cm) diameter holes through a standard 6 in x 8 in (15.2 cm x 20.3 cm) wood post. One hole is located 16 inches (40.6 cm) below grade and the other is located at ground level. Since these weakened posts are designed to fracture upon impact, they possess very little energy absorbing capability. Therefore, the post spacing around the curved section of the guardrail is not a critical variable in the short-radius guardrail design and a standard spacing of 6 ft-3 in (1.91 m) can be maintained.

Although post spacing was found to be inconsequential, guardrail beam strength was determined to be a significant factor in the behavior of the short-radius guardrail.
Analysis of the Barrier VII simulation runs indicated some potential problems regarding the use of W-beam rail along the short-radius treatment. Plots of deflected barrier shapes indicated a tendency for the rail to kink at several locations. This kinking, if it occurs, could potentially result in rupture of the rail or the formation of a "point" or "spear" which could cause deeper penetration into the vehicle. In a series of crash tests conducted on short-radius guardrail treatments (2), kinking of the W-beam rail could be observed. In one test, the W-beam rail ruptured in the location of the impacted post and the vehicle penetrated through the railing. The beam failure was attributed to snagging of the bolt head in the slot of the W-beam which initiated the tearing. Although no other rail failures were observed, the kinking in the rail was quite evident.

Simulation results of the short-radius guardrail treatment utilizing a nested W-beam around the curve indicated better overall performance than the single W-beam system. Although plots of deflected barrier shapes showed some evidence of kinking, the degree of kinking was considerably less than that seen in the single W-beam runs. Furthermore, the potential for this kinking to cause rail rupture is reduced since the strength of the nested W-beam is twice that of the single rail.

Another important parameter in the design of a short-radius guardrail treatment is the runout distance along the secondary roadway. For the standard Breakaway Cable Terminal (BCT), the anchorage at the upstream end is provided by a cable running from the guardrail to the base of the first post. Although this post is weakened for head-on impacts into the end terminal, it generally provides sufficient tension in the rail to redirect vehicles impacting along a tangent section of guardrail. In the case of the short-radius guardrail, however, a more serious impact condition exists. The terminal needs to provide sufficient anchorage to contain a vehicle impacting head-on into the curved section of the guardrail. If the runout distance is inadequate, the torsional forces developed in the anchor post can be sufficient to cause complete failure of the anchorage system.

This type of behavior was observed during a crash test of a short-radius guardrail system which was impacted headon in the curved section by a 4500-lb (2241-kg) vehicle traveling at 60 mi/h (96.6 km/h) (2). The installation consisted of a W-beam rail with weakened wood posts along the curve, a 25-ft (7.62-m) runout distance along the
secondary roadway, and a BCT end anchor installed on a tangent. All of the wood posts on the secondary roadway fractured during impact, and the vehicle was not contained. The result of this test clearly indicated that a 25-ft (7.62-m) runout distance, in combination with a standard BCT end terminal, is not capable of containing vehicles impacting at high speeds.

Obviously, the runout distance required to contain a vehicle varies with the impact conditions. The more severe the impact, the greater the required runout distance. Although a runout distance of 25 ft (7.62 m) proved to be inadequate for a BCT end anchor, longer runout distances should yield satisfactory results. Shown in Figure 16 is a short-radius guardrail treatment for high speed impacts. The design incorporates a 25-ft (7.62-m) section of nested W-beam around the curve, and a 37.5-ft (11.43-m) runout distance along the secondary roadway terminated with a standard BCT anchor assembly. Although this design has not been subjected to full-scale crash testing, it has a high probability of passing NCHRP Report 230 test criteria (5). The nested W-beam should reduce the potential for rail rupture, and the weakened wood posts along the curved section should prevent ramping of the vehicle during head-on impacts. In addition to being able to contain vehicles impacting head-on into the curved section of the rail, this design provides a standard BCT end treatment on a 4-ft (1.22-m) flare to protect vehicles traveling on the secondary roadway as well.

When a shorter runout distance is necessary due to physical constraints, such as right-of-way restrictions, the BCT end anchor assembly can be modified for use with a 25-ft (7.62-m) section of guardrail along the secondary roadway. The modified design, shown in Figure 17, uses a second cable which is attached to the end anchor cable and the foundation of the second BCT post (2). The attachment to the foundation of the second post is not breakaway and, therefore, it provides a positive anchor for the installation even if all of the posts on the secondary roadway fail. In addition, failure of the end post releases the first cable as designed for end-on impacts from the secondary roadway. It should be noted that the performance of the BCT as an end treatment is highly sensitive to the flare rate. If a 4-ft (1.22-m) flare is unattainable due to roadside slopes or right-of-way restrictions, an alternate end treatment which can be used on a
FIGURE 16. Short-Radius Guardrail with BCI Anchor
Barrier components with F, P, and RE prefixes are found in latest edition of "A Guide to Standardized Highway Barrier Rail Hardware," a report prepared and approved by the AASHTO-AGC-ARTBA Joint Cooperative Committee.

Note: This terminal is intended only for low speed impacts.

FIGURE 17. Modified BCT for Short-Radius Guardrail Treatment (2)
FIGURE 18. Short-Radius Guardrail for Short Runout Distance
tangent or with a smaller flare should be utilized. Alternate end treatments are discussed in detail in the next section of the report.

In extreme cases, when vehicle containment is necessary and less than 25 ft (7.62 m) of runout distance is available, design compromises would have to be made. Figure 18 shows one such design for intersections with low-volume, low-speed roadways such as a private drives or county roads. As in the previous designs, a nested W-beam and weakened wood posts are utilized around the short-radius bend. However, due to the extremely short runout distance, a conventional end anchor treatment cannot be employed. Instead, positive anchorage is provided by using a modified type 13 terminal (deadman anchor) with only a 12 1/2-ft (3.81-m) runout distance. Another, perhaps more attractive alternative, would be to use the modified BCT end anchor shown in Figure 17 on a 12 1/2-ft (3.81-m) tangent section of guardrail.
IV. GUARDRAIL END TREATMENT DESIGNS

Introduction

Highway safety engineers have been searching for many years to find a safe and economical method to terminate W-beam guardrail. Safety standards for barrier end treatments (§) require that a guardrail terminal provide safe deceleration or controlled barrier penetration for vehicles impacting upstream from the beginning of the length of barrier need and adequate barrier anchorage for redirecting vehicles impacting beyond the length of need.

One of the earliest W-beam anchorage systems employed a cable assembly running from an anchor plate on the back side of the W-beam to a concrete deadman embedded beneath the groundline. This is similar in design to TDOT's modified type 13 terminal (see TDOT standard drawings M-101-148 and S-GR-19). While this design provides adequate anchorage for redirecting vehicles impacting beyond the length of need, it could pose a potential safety hazard for end-on impacts. The cable mechanism cannot release and, therefore, it "reinforces" the W-beam against buckling. Even at low speeds, these untreated guardrail ends could impart severe decelerations to vehicle occupants and have been found to be capable of spearing and piercing through impacting vehicles.

There are several designs currently available that would greatly improve safety performance in end-on impacts and still provide adequate anchorage for redirection impacts. The primary option considered by TDOT for use wherever possible is to bury the guardrail end and anchorage assembly in a cut backslope or a berm. This option eliminates spearing at guardrail ends, provides needed guardrail anchorage, usually provides a generous terminal offset, and is probably the least expensive of the various treatments. However, its use is limited to only those sites that are suitable for this treatment and there are a number of design considerations that can adversely affect its performance. For sites where the use of the "buried in backslope" option is not appropriate, there are a number of end terminals available that have been successfully crash tested and approved by FHWA for field use, such as the breakaway cable terminal (BCT), eccentric loader BCT (ELT) and modified eccentric loader BCT (MELT), the
split rail end terminal, and the ET-2000 end terminal. This section will discuss these various guardrail end terminals, with particular interest on an economical end treatment design for low service level roadways which TDOT could use to replace the modified type 13 terminal described above.

**Breakaway Cable Terminal**

The breakaway cable terminal (BCT) has evolved through the years since its conception and initial testing in 1972 (9). Since that time, the BCT has gained widespread acceptance across the country due to its low cost (typically around $300 per installation for materials). The TDOT has adopted the BCT as a standard guardrail end treatment, as shown in TDOT standard drawing S-GR-18A.

The BCT end treatment, shown in Figure 19, relies on the dynamic buckling of a flared segment of guardrail to reduce the stiffness of the barrier hardpoint and provide a mechanism for slowing down vehicles in a controlled manner. Extensive testing and analysis of these systems has indicated that the dynamic buckling of the W-beam element is very sensitive to a number of construction details, particularly the flare rate. Furthermore, even when installed correctly on a 4-ft (1.22-m) flare, the BCT system has been shown to impart unacceptably high deceleration forces on mini-size (1800-lb or 896-kg) vehicles during high speed impacts (10).

For lower service level roadways, the standard BCT end treatment should exhibit satisfactory impact performance for a mini-size vehicles provided that the standard 4-ft (1.22-m) flare is maintained. However, it is often the case that right-of-way restrictions or problems associated with terminating barriers on roadside slopes preclude the use of the 4-ft (1.22-m) flare. Under these circumstances, it is desirable to terminate the guardrail along a tangent or using a smaller flare. As mentioned above, the BCT is highly sensitive to changes in the way the barrier is flared. Even for low-speed impacts, a BCT end treatment installed on a 2-ft (0.61-m) flare can lead to spearing, high rates of deceleration, and other unacceptable results. In these instances, either an alternate design or a modified design should be utilized to improve impact performance.
FIGURE 19. Standard BCI End Treatment
Eccentric Loader Breakaway Cable Terminal

The Eccentric Loader BCT (ELT) was developed as an improvement to the standard BCT, offering improved safety performance, particularly for mini-sized vehicles. There are a number of differences between the ELT and the standard BCT designs. The most obvious difference is the nose of the ELT which has a fabricated structural steel lever surrounded by a vertical section of corrugated steel pipe. The modified nose induces a moment at the end of the W-beam to facilitate buckling of the W-beam and prevents the end of the W-beam from slicing into an impacting vehicle. Other differences include the use of a blockout on the second post, no rail attachment bolts for the second through sixth posts, and use of weakened wooden posts with slightly different offsets. All of these changes combine to make the ELT a "softer" terminal and it was successfully crash tested with mini-sized vehicles (11,12).

The ELT was also successfully tested with a flare of 1.5 ft (0.46 m), but the results were marginal and the 4-ft (1.22-m) offset remains the preferred design. The 1.5-ft (0.46-m) flare is recommended for use only in locations where the 4-ft (1.22-m) offset cannot be reasonably obtained and vehicle penetration behind and beyond the terminal is acceptable. Note that, in addition to the difference in the alignment, the 1.5-ft (0.46-m) flare ELT differs from the 4-ft (1.22-m) version in the number of posts and in the locations of post-to-rail attachments.

The ELT was recently modified with a simplified nose piece and successfully crash tested. The new nose piece consists of two diaphragms bolted into the standard BCT nose piece. The ELT with the new nose piece is referred to as the modified ELT or MELT.

Both the ELT and MELT are still sensitive to the way the barrier is flared. Also, they have several other important design details that may adversely affect impact performance if not correctly installed. Furthermore, these systems require a number of new hardware components which raise the cost of this system substantially over the standard BCT (typical cost per installation is around $900 for materials).
Split Rail End Terminal

Another relatively inexpensive modification to the BCT end treatment is known as the split rail end terminal (13). As shown in Figure 20, the split rail concept involves cutting three longitudinal slots in the W-beam rail to reduce its dynamic buckling strength. The buckling force is controlled by adjusting the number and length of the slotted sections. These variables are selected such that the end terminal can safely decelerate a small car as well as stop a large car within a reasonable stopping distance.

As an illustration, consider the case where three 0.5-inch (1.27-cm) wide longitudinal slots are cut into the W-beam rail. The total cross-sectional area of the slotted region is reduced from 1.99 in$^2$ (12.8 cm$^2$) to 1.83 in$^2$ (11.8 cm$^2$). However, when considering that the cross-sectional area of the W-beam through the four bolt holes of a splice is only 1.61 in$^2$ (10.4 cm$^2$), the slotted segment of the rail actually has a greater tensile capacity than a standard W-beam rail at a splice joint. On the other hand, the moment of inertia of a standard 12-gauge W-beam rail is approximately 2.33 in$^4$ (97.0 cm$^4$), while the combined moment of inertia of the four strips comprising the slotted cross section is only 0.02 in$^4$ (0.83 cm$^4$). This translates into a buckling strength for the slotted W-beam that is only 1 percent of that of an unmodified W-beam rail.

Considerable analysis and testing of this concept with various slotted rail configurations were conducted to optimize the performance of the end treatment for high-speed impacts with both large and small vehicles (13). In the course of testing, it was found that during oblique impacts, the vehicle could engage the slotted sections, causing them to extend and eventually leading to rupture of the rail. To remedy this problem, the cover plates shown in Figure 20 were used to "shield" the slots during oblique impacts into the rail. The clips on the downstream end of the cover plates allow them to slide along the W-beam and eventually disengage as the slotted regions of rail buckle during an end-on impact.

The split rail concept was developed with the intent of improving the impact performance of the standard BCT. Thus, testing of this design conducted in the prior study (12) was done mostly on installations with a 4-ft (1.22-m) flare. Further development and compliance testing would be necessary to evaluate the impact performance of the slotted rail design with reduced flare distances. However, based on
FIGURE 20. Slotted-Rail Concept for BCT End Treatment (9)
the results of the previous study, there is reason to believe that the slotted rail concept would work with reduced flare distances or perhaps even on a tangent, particularly at lower impact speeds. Also, the additional cost over that of a standard BCT would be fairly small, probably in the order of $200.

ET-2000 End Terminal

Another alternative to the BCT is the innovative end treatment known commercially as the ET-2000 end terminal. The ET-2000 end terminal was originally developed by TTI (13) and is now a proprietary system manufactured by Syro Steel Corporation. This end treatment is designed to be installed along a tangent, thereby eliminating the problems associated with flared treatments discussed earlier. Rather than permitting high-speed penetrations behind the barrier as in the case of the BCT and its variations, the ET-2000 end terminal provides an impact attenuation mechanism which brings the impacting vehicle to a controlled stop. As shown in Figure 21, the primary components of the terminal are a feeder chute and an extruder. The purpose of the feeder chute is to provide moment resistance for the terminal during end-on impacts. This prevents rotation of the terminal on the guardrail and thus promotes smooth feeding of the rail into the extruder.

The extruder section of the ET-2000 end terminal consists of a "squeezer" section and a "bender" section. The squeezer section is designed to flatten the W-beam rail to a depth of 1 inch (2.54 cm), thereby virtually eliminating any bending strength of the rail element. The bender section then bends the relatively flat W-beam around a circular arc and extrudes it out behind the guardrail where it does not pose a hazard to other traffic. Plastic deformation of the guardrail during these two processes dissipates the energy of the impacting vehicle in a smooth and controlled manner, eventually bringing the vehicle to a complete stop. Breakaway wood posts are used along the first 50 ft (15.2 m) of guardrail to facilitate fracture and prevent ramping as the guardrail is extruded and the vehicle travels along the guardrail installation.

This design was successfully tested with both a large and small car at 60 mi/h (96.5 km/h). The large car extruded approximately 45 ft (13.7 m) of guardrail before coming to a smooth stop. The small car was smoothly decelerated over a distance of 12.5
ft (3.81 m). The terminal performed very well in both tests and the vehicles exhibited no tendency to ride or ramp over the end treatment.

The only disadvantage of this unique end treatment is its cost. Currently, the ET-2000 end terminal costs about $1,500 per installation which includes the end terminal and the first 37.5 ft (11.4 m) of guardrail. Although the number of breakaway posts could be reduced for lower-speed impacts, this would not greatly affect the total cost of the installation.

In summary, the standard BCT design with a 4-ft (1.22-m) offset did not perform satisfactorily in crash tests with 1800-lb (896-kg) vehicles at 60 mi/h (96.5 km/h), but should perform adequately for lower service and speed roadways, provided that the 4-ft (1.22-m) offset can be maintained. However, the standard BCT would not perform satisfactorily with offsets less than 4 ft (1.22 m). A number of better performing end terminals are available, including the ELT/MELT, the split rail BCT, and the ET-2000 end terminal. Selection of which design to use is a matter of economics, site requirements, and preference.

All these improved end terminal designs would work for lower service level conditions and with less than 4 ft (1.22 m) offset. The split rail end treatment is the least expensive of these designs, but it would require additional compliance testing to make sure that it would perform satisfactorily with reduced flare distances or along a tangent. While the ELT/MELT can be used with a 1.5-ft (0.46-m) offset, the 4-ft (1.22-m) offset is the preferred design since crash test results using the reduced offset was very marginal. The ET-2000 end terminal is designed for installation along a tangent, and uses an impact attenuation mechanism to bring impacting vehicles to a smooth and controlled stop. The drawback with the ET-2000 end terminal is its high initial cost.
V. SUMMARY

This report presents the results of analytical evaluations of existing bridge end approach guardrail, short-radius guardrail treatment, and guardrail end treatment designs currently in use or proposed for use by TDOT. Potential problems associated with the current designs have been identified and modified designs have been recommended for consideration as potential remedies to these deficiencies. When possible, retrofit designs were developed to minimize the cost of upgrading the current designs. In cases where more than one alternative is presented, it will be at the discretion of TDOT engineers to determine which alternative best complements their existing designs and operations. Although the designs and alternatives presented in this report were carefully analyzed, it is anticipated that a full-scale crash testing program encompassing selected new and modified designs will be necessary to ensure compliance with nationally accepted guidelines.

A summary of the evaluation results and recommended modifications is presented as follows:

BRIDGE END APPROACH GUARDRAIL TRANSITION DESIGNS

- Both the steel and the wood post guardrail transition systems used by TDOT prior to 1987 allow too much deflection and have a high potential for wheel snagging at the end of the concrete parapet under the impact conditions of a 4500-lb (2241-kg) vehicle impacting at a speed of 60 mi/h (96.5 km/h) and at an angle of 25 degrees. However, the systems would work fine under less severe impact conditions such as 45 mi/h (72.4 km/h) and 25 degrees or 60 mi/h (96.5 km/h) and 15 degrees when used with the vertical wall concrete parapet.

- Three alternative retrofit designs are found to have satisfactory impact performance for the steel-post system:
  1. Larger post size and embedment depth. Replace the first three 6-ft (1.83-m) W6x15 posts with 8-ft (2.44-m) W8x21 posts.
  2. Reduced post spacing. Add two W6x15 posts between the first three existing posts to effectively reduce the post spacing from 3 ft-1.5 in (0.95 m) to 1 ft-6.75 in (0.48 m).
3. Addition of Rubrail. Add a C6x8.2 channel rubrail.

Note that, for all three alternative designs, a 6-in (15.2-cm) diameter spacer pipe is placed between the W-beam rail and the face of the concrete parapet to help reduce deflections and prevent local yielding of the rail around the end of the parapet.

For the wood-post system, three similar modifications are found to provide satisfactory impact performance:

1. Larger post embedment depth. Increase the embedment depth for the first three 10 in x 10 in (25.4 cm x 25.4 cm) posts from 36 inches (0.91 m) to 56 inches (1.42 m).

2. Reduced post spacing. Add two 10 in x 10 in (25.4 cm x 25.4 cm) posts between the first three existing posts to effectively reduce the post spacing from 3 ft-1.5 in (0.95 m) to 1 ft-6.75 in (0.48 m).

3. Addition of Rubrail. Add a C6x8.2 channel rubrail.

Again, a 6-in (15.2-cm) diameter spacer pipe is placed between the W-beam rail and the face of the concrete parapet for all three alternative designs.

The choice of which alternative design to use is primarily a consideration of economics and specific site requirements. The reduced post spacing alternative is the most economical since it does not require any modification to the existing installations, but it severely decreases the clear space between posts which may be restrictive at sites with bridge end drainage. The other two alternative designs retain the post spacing of 3 ft-1.5 in (0.95 m), but would require some modifications to the existing installations. For the larger post embedment depth alternative, the first three posts would have to be replaced. For the rubrail alternative, holes would have to be drilled in the concrete parapet (and in the posts if not already predrilled) to accommodate the rubrail addition.

These recommended transition designs would likely meet the safety requirements when connected to a vertical wall parapet with a 9-inch (22.9-cm) flare, but not necessarily for the safety-shaped concrete parapet because of the geometry that could significantly increase the potential for wheel contact on the exposed end of the concrete wingpost. Three alternative modifications are suggested:
1. Block out the W-beam rail further from the face of concrete parapet using fabricated wood or steel spacer blocks and add a C6x8.2 channel rubrail.
2. Remove the toe from the end of the parapet by breaking out the concrete and use a 3-in (7.6-cm) blockout underneath the W-beam end shoe.
3. Use a precast curb with a cross section matching that of the toe of the parapet to reduce the potential for wheel snagging.

The first alternative of blocking out the W-beam rail and adding a rubrail appears to be the most promising. This can be used in conjunction with the larger post size and embedment depth alternative or the reduced post spacing alternative to provide acceptable impact performance for transitions to the safety-shaped concrete parapet.

SHORT-RADIUS GUARDRAIL TREATMENT

- The standard TDOT short-radius guardrail treatment with the in-line anchor would perform satisfactorily at locations where penetration behind the barrier is acceptable, provided that breakaway posts are used along the curved section of the rail.

- For locations where vehicle containment is required, a nested W-beam rail with breakaway posts is recommended for the curved section of the rail. A standard BCT anchor, a modified BCT anchor, or a modified type 13 terminal may be used with the short-radius guardrail depending on the characteristics of the intersecting secondary roadway, such as availability of runout distance and flare distance, traffic speed and volume, etc.

GUARDRAIL END TREATMENT

- The standard BCT design with a 4-ft (1.22-m) offset did not perform satisfactorily in crash tests with 1800-lb (896-kg) vehicles at 60 mi/h (96.5 km/h), but should perform adequately for lower service and speed roadways, provided that the 4-ft (1.22-m) offset can be maintained. However, the standard BCT would not perform satisfactorily with offsets less than 4 ft (1.22 m).

- The preferred guardrail end treatment option of TDOT is to bury the guardrail end and anchorage assembly in a backslope or berm, provided that the site is suitable for this treatment. If the "buried in backslope" option is not appropriate,
there are a number of better performing end terminals available, including the ELT/MELT, the split rail BCT, and the ET-2000 end terminal. Selection of which design to use is a matter of economics, site requirements, and preference. All these improved end terminal designs would work for lower service level conditions and with less than 4 ft (1.22 m) offset. The split rail end treatment is the least expensive of these designs, but it would require additional compliance testing to make sure that it would perform satisfactorily with reduced flare distances or along a tangent. While the ELT/MELT can be used with a 1.5-ft (0.46-m) offset, the 4-ft (1.22-m) offset is the preferred design since crash test results using the reduced offset was very marginal. The ET-2000 end terminal is designed for installation along a tangent, and uses an impact attenuation mechanism to bring impacting vehicles to a smooth and controlled stop. The drawback with the ET-2000 end terminal is its high initial cost.
REFERENCES


APPENDIX A

TDOT STANDARD DRAWINGS
GUARDRAIL TERMINAL ANCHOR TYPE 1

ITEM NO. 70-40-04-04

NOTE:
- All bolts shall be galvanized or equivalent.
- All nuts shall be galvanized or equivalent.
- All structural members shall be designed in accordance with the latest edition of the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges.

DETAIL "B" FOR ALTERNATE FITTINGS

TERMINAL ANCHORS

TYPE 1

Sketch showing application of railing end treatment on divided highway.