Development of a New End Treatment for Steel-Backed Timber Guardrail: Phase I Conceptual Design

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This working paper summarizes recent efforts and findings derived from NCAC research. It is intended to solicit feedback on the approach, scenarios analyzed, findings, interpretations, and implications for practice reported by the research team. The statements contained herein do not necessarily reflect the views or policy of the FHWA. Please forward comments or questions to the authors noted above. These efforts will ultimately be documented and made available to advance research efforts related to this topic and guidance for practice.

ABSTRACT
The purpose of this research is to determine the feasibility of developing a new aesthetic, crashworthy terminal for the steel-backed timber (SBT) guardrail system for use by the National Park Service and others along park roads and scenic highways. Two conceptual designs, a flared non-energy absorbing concept and a parallel energy absorbing concept, were developed using the same materials that are used for the SBT barrier. Component testing was done using a pendulum and the results from the tests were used to calibrate computer models. Computer simulations were then conducted using FE models of the SBT barrier system to evaluate the two end-terminal designs under different impact conditions. The simulations indicated that the two designs would be likely to pass NCHRP Report 350 testing and evaluation criteria at test level 2 (TL-2).
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INTRODUCTION

To preserve the natural look of its scenic roads, the National Park Service (NPS) does not routinely install the same types of traffic barriers commonly used on most public roads throughout the country. Rather than the standard galvanized steel W-beam or the concrete safety shape barrier, aesthetic barriers such as the steel-backed timber (SBT) guardrail (Figure 1 - a) and the rough stone masonry guardwall have been developed and tested for use in the Parks and other scenic areas. Currently, the only end treatments available for use with the SBT barrier are flared, buried in backslope and sloped into the ground designs (not recommended for a leading edge end treatment since they have the potential to launch an impacting vehicle and cause rollover).

This study investigated the feasibility of developing a crashworthy end terminal for the steel-backed timber guardrail that would be acceptable to the NPS from an aesthetic viewpoint and would meet current NCHRP Report 350 crash test criteria for an end terminal at test level 2 (TL-2).

![a – Typical SBT Guardrail](image1)
![b – Typical SBT End-Treatment](image2)

Figure 1: Typical Steel Backed Timber Guardrail Installation

BACKGROUND

Steel-Backed Timber Guardrail

The steel-backed timber guardrail is a strong post barrier system consisting of 10-inch x 12-inch x 7-foot long timber posts spaced on 10-foot centers. These posts support 6-inch x 10-inch beams with their tops set at 27 inches above the ground surface. To provide the tensile strength needed to contain and redirect a vehicle impacting the barrier at a relatively high speed and angle, the timber beams are backed by a continuous steel strap, 3/8-inches thick x 6-inches deep. The rails, with the backing straps, are interconnected using 6-inch x 9-inch x 3/8-in splice plates. These plates are bolted to the rail ends and posts. This connection effectively prevents the beams from separating at their joints when the railing is hit, and thus minimizes the possibility that a vehicle will penetrate the barrier or directly impact a support post. The steel backed timber guardrail has been successfully tested to NCHRP Report 350 test level 3 (TL-3), i.e., it has demonstrated, through full-scale crash tests, that it is capable of containing and redirecting a 2000-kg (4400-pound) pickup truck striking it at 100 km/h (62 mph) at an angle of 25-degrees [1].
Common End Terminal Designs

The terminology commonly used to describe the various types of barrier terminals has led to some confusion. While the descriptions “parallel” and “flared” (referring to the physical layout of the terminal posts in relation to the edge of the roadway) are readily understandable, the terms “gating”, “non-gating”, “energy-absorbing”, and “non-energy absorbing” are less clear and are occasionally misused. A gating terminal is one which is designed to allow vehicular penetration into the area behind and beyond the terminal itself when it is struck on the end at a 15-degree angle. In other words, the terminal posts and its beam elements push away readily on impact (similar to opening a gate), thus letting the vehicle through. By contrast, a non-gating terminal will usually contain and redirect a vehicle in a similar impact, keeping it on or very near the roadway and not allowing significant penetration behind the terminal. From a practical viewpoint, all current, crashworthy, free-standing W-beam terminals are gating designs. In contrast, virtually all crash cushions (which are often used to terminate median barrier installations) are non-gating designs.

![Figure 2: Typical Steel Rail Terminals](image)

Energy-absorbing terminals are those designed to stop an impacting vehicle safely in a relatively short distance in a direct end-on hit. All crash cushions are energy-absorbing devices. Commonly used W-beam terminals that also absorb energy are the Extruder Terminal (ET-series) (upper left photograph in Figure 2), the Sequential Kinking Terminal (SKT), and the Flared Energy Absorbing Terminal (FLEAT) (upper right photograph in Figure 2). In general, the ET-series and the SKT terminal are installed parallel to the roadway or with a relatively short offset/flare. Non-energy absorbing terminals are designed to break away in an end-on hit without abruptly stopping or overturning an impacting vehicle, but they are not designed to reduce the vehicle's speed substantially. Thus, vehicles can travel a significant distance behind and essentially parallel to the rail in a high-speed impact. The most common non-energy absorbing W-beam terminal is the Slotted Rail Terminal (SRT), shown in the two lower photographs in Figure 2. The first post in most non-energy absorbing terminals is typically flared 4 feet more from the roadway than the barrier itself.

Report 350 Required Testing for End Terminals

Although revised crash testing procedures are in final draft form and are expected to be adopted by the AASHTO in the near future, any appurtenance tested and accepted for use under NCHRP Report 350 criteria will remain acceptable for use in the U.S. Since NCHRP Report 350 remains the accepted
guidance in the interim period, it will be used in this study. Report 350 outlines the criteria used to determine the crashworthiness of roadside features, including traffic barriers and their terminals. Both the specific tests required for various appurtenances and the evaluation criteria for each of those tests are identified. If a feature meets all test requirements, it is considered acceptable for use on any public road in the United States. For a test level 2 (TL-2) design, all tests are run at an impact speed of 70 km/h (42 mph). For a non-redirective guardrail terminal in particular, seven tests are specified. These are the following:

- 2-30 - 820-kg car @ 0-degrees on the terminal end
- 2-31 - 2000-kg pickup truck @ 0-degrees on the terminal end
- 2-32 - 820-kg car @ 15-degrees on the terminal end
- 2-33 - 2000-kg pickup truck @ 15-degrees on the terminal end
- 2-34 - 820-kg car @ 15 degrees at the critical impact point (CIP)
- 2-35 - 2000-kg pickup truck @ 20-degrees at the beginning length of need (LON), the point at which containment and redirection of the vehicle is expected
- 2-39 - 2000-kg pickup truck @ 20-degrees in the reverse direction, between the LON point and the end of the terminal

CONCEPTUAL DESIGN DEVELOPMENT

Design Requirements

The design requirements for a new SBT guardrail end terminal are twofold: (1) the proposed design must meet NCHRP Report 350 test and evaluation criteria for a test level 2 (TL-2) guardrail terminal, and (2) it must be similar in appearance to the steel-backed timber guardrail, i.e., rustic and unobtrusive in its natural setting. To meet the latter requirement, design efforts were focused on using the same materials as those used in the guardrail itself, modified only as necessary to meet Report 350 test and evaluation criteria.

Non-Energy Absorbing Conceptual Design

There are two primary concerns for developing a crashworthy end terminal for any post and beam guardrail system. First, the posts must be designed to yield in a predictable manner without stopping the vehicle too abruptly or causing it to become unstable and eventually overturning. Second, the beam elements themselves must also fail predictably and not penetrate into the passenger compartment. The commonly-used W-beam terminal, the SRT, accomplishes the first design goal by using weakened timber posts or breakaway/yielding steel posts throughout the terminal length. The second design goal is met by cutting slots into the W-beam itself to weaken its beam or column strength, causing the W-beam to fold in an end-on hit in lieu of penetrating the passenger compartment of the vehicle. Thus, by modifying the posts and the beam used in the steel-backed timber guardrail, both design requirements can likely be met.

The SRT uses 6-inch x 8-inch wood posts with holes drilled at the ground line to ensure predictable and consistent breakaway characteristics. Since the standard posts for the steel-backed timber guardrail are 12-inches x 10-inches in cross-section, sawing these in half along their length would create two posts, each of which has cross-sectional dimensions of 6-inches x 10-inches - similar in size to the SRT posts. By then varying the size of the drilled ground-line hole in the larger posts, similar breakaway
characteristics would result. Using the same width posts in both the terminal and the timber guardrail itself would make the change in post size virtually unnoticeable to the majority of passing motorists. As described below, computer simulation was then used to "fine-tune" the proposed design.

Since the timber beam element in the steel-backed timber guardrail cannot be weakened by cutting slots in it, another method was devised to reduce the beam or column strength of the rail. By cutting the 6-inch x 10-inch beam into shorter segments and making these cuts at a 45-degree angle, it was believed that the segments would readily separate in an end-on hit and be pushed away from the impacting vehicle with little likelihood of penetration. The conceptual design for the non-energy absorbing SBT end-terminal is shown in Figure 3. Computer simulations were used to determine the best way to attach these beam segments to the support posts and to determine the amount of energy needed to collapse them. These simulations were then verified through pendulum tests.

Energy Absorbing Conceptual Design

The most commonly used energy absorbing gating terminal designs were developed for W-beam guardrails. They slow a vehicle in a head-on hit by deforming and bending the W-beam rail element as the "impact head" is pushed along the rail. The posts supporting the beam element are weakened (wood posts) or designed to yield on contact (steel posts) so the vehicle's speed is gradually reduced and it remains relatively stable until brought to a stop. Because any type of metal energy-absorbing element would be unlikely to meet the aesthetic design requirement, and any timber element would be unlikely to absorb a significant amount of impact energy unless the terminal was significantly longer than approximately 50 feet, emphasis was initially placed on developing a non-energy absorbing design. An energy absorbing terminal for the steel-backed timber guardrail, using the same methodology described in the previous section, was developed (Figure 4). Since the requirement for end-terminal in the study is aimed at meeting the lower speed TL-2 condition, it was feasible to slow down the vehicle with reasonable length. The energy absorption is achieved through breaking of the wood posts, movement of the soil, crush of the vehicle, and pullout of the bolts connecting the rails to splice plates. The optimum barrier length, post cross section, ground level post hole size, number of lag bolts connecting the rails to splice plates, and rail angled cuts were determined using iterative computer simulations.
The performances of the conceptual designs were evaluated and optimized using computer crash simulations using LS-DYNA finite element code [3, 4]. The response of these conceptual designs is significantly influenced by the behavior of the wood and soil materials during the crash event. To ensure that the responses of these two materials were accurately captured, several pendulum tests were conducted and used to validate the model. These tests were conducted on wood posts, soil, and sub-components of the end-terminal. These tests were then used to validate the model results. A full-scale crash test of the SBT guardrail, which had been previously conducted by the Texas Transportation Institute, was also used to calibrate and validate the computer models. The specific tests used to calibrate and validate the computer models are described in the following sub-sections.

**Wood Material Model Calibration**

To characterize wood post failure and develop a material model that can predict the behavior of the wood, two pendulum tests were conducted at the Federal Highway Administration (FHWA) Federal Outdoor impact laboratory (FOIL). The tests consisted of a 2000-kg (4500-lbs) rigid pendulum impacting a wood post. The wood post was rigidly constrained using a steel structure. The tested wood posts were 150 mm (6 in) in width, 200 mm (8 in) in depth, and 1000 mm (40 in) in length. The posts were impacted at a height of 550 mm (22 in) from its constrained end. The pendulum impacted speed was 24 km/hr (15 mph). The pendulum was instrumented with three triaxial accelerometers to measure its response during the impact. High-speed digital cameras were used to capture the crash sequence. Two repeat tests were conducted to check the consistency of the data and variation in the wood material. A computer model representing the pendulum test setup was created and used for the material calibration. Using this computer model, iterative simulations with varied wood material properties, constitutive models, and element formulations were carried out and the results were compared the pendulum test data. The wood model behavior was found to be sensitive to mesh size (element size) and element formulation. Additionally, the wood failure was found to be significantly affected by the moisture content percentage. After several iterations, a numerical model that closely captures the wood behavior was achieved, i.e., the simulation results fall within the envelope of the two repeated tests. Comparisons between the pendulum test and simulation using this material model are shown in Figure 5.
Soil Material Model Calibration

Similar pendulum tests were performed to characterize the soil material and calibrate the soil material model. These tests consisted of a 2,000-kg (4,400-lb) mass impacting a wood post embedded in soil at an impact speed of 16 km/hr (10 mph). The soil used in the tests was chosen such that it meets the NCHRP Report 350 specifications for standard soil. It was compacted in accordance to the guidelines listed in Report 350. The soil was compacted in 6 in vertical height increments. A nuclear gauge was used to measure the density and moisture content of the soil after each increment. A minimum density of 95% compaction was achieved for each compaction increment. The post cross-section used in the soil pendulum tests was similar to the one used in the wood post pendulum tests described in the previous section (150 mm x 200 mm). The post embedment in soil was 1,100 mm (43 in) and its height above ground was 730 mm (28.75 in). The pendulum impacted the post at a height of 550 mm (21.5 in) from ground level. A total of six tests were conducted. Data from these tests were used to find the most appropriate constitutive model and material properties that would represent the NCHRP Report 350 standard soil. A computer model, representing the pendulum test setup, was created and used for the soil material calibration. The wood material model, which was validated using the wood pendulum tests, was used for the wood post model. Using the computer model, simulations with varied soil constitutive models and material properties were performed and the results were compared to the pendulum test data. The process was repeated until the soil response from the simulations was close to
the responses observed in repeated pendulum tests. Comparisons between the pendulum test and simulation using this material model are shown in Figure 6.

**Figure 6: Soil Pendulum Test and Simulation Comparison**

End-Terminal Component Tests

In addition to the wood and soil pendulum tests, two components tests were conducted on sub-sections of the conceptual energy-absorbing end-terminal design. The purpose of these tests was to validate the computer model results at the sub-system level. The two tests consisted of impacting sections of the end-terminal designs with the 2000-kg (4400-lb) pendulum. The soil used in the tests was similar to the one used in the soil tests described in the previous section of this report. The compaction procedure was also similar to the one used in the soil test. The end-terminal sub-sections were constructed from components of an SBT guardrail. The setup from one of the component tests is shown in Figure 7. Each of the two tested sub-sections was made up of four wood posts and three rail segments. The first three posts were half the size of the SBT guardrail posts (254 mm x 152 mm x 2.133 m (10 in x 6 in x 7 ft)). The last post was of similar size to the SBT posts (254 mm x 305 mm x 2.133 m (10 in x 12 in x 7 ft)). Similarly, the first two wood rails were about half the length of the SBT rail (152 mm x 254 mm x 3.035 m (6 in x 10 in x 9 ft 11.5 in)). The third rail was of equal length to the SBT rail (152 mm x 254 mm x 3.035 m (6 in x 10 in x 9 ft 11.5 in)). The wood blockouts, splice plates, bolts, and washers used in the tested section were similar to ones from the SBT guardrail.
In the tested section of the end-terminal, holes were drilled in the first three posts at ground level. The purpose of these holes was to weaken the posts and consequently reduce the impact forces and accelerations. The holes’ diameter was 100 mm (4 in) for the first component test and 50 mm (2 in) in the second tests. Additionally, the rails were cut at 45 degrees at the splice. The reason for these cuts was to eliminate the column strength of the horizontal beam, thereby pushing the wood rail elements away from the vehicle during the impact and reducing the risk for intrusions into the occupant compartment. The two component tests were identical except for the size of the holes in the posts and the impact speeds, which were 15 mph for the first test and 10 mph for the second test.
Computer models representing the end-terminal sub-systems were created and combined with the pendulum model. Finite element simulations using the same impact speed as the pendulum tests were carried out and the results were compared to the test data. The wood and soil material models, calibrated in the previous two sections, were used in the sub-system models. The simulations showed similar behavior to the tests. Figure 8 shows a comparison of the simulation results for one of the sub-system tests.

CONCEPTUAL DESIGN EVALUATIONS

Upon completing the model calibrations and validations, the research efforts focused on developing, optimizing, and evaluating the two end-terminal conceptual designs, namely a parallel, energy absorbing end-terminal and a flared, non-energy absorbing end-terminal. Both designs were optimized and evaluated against NCHRP Report 350 test level 2 (TL-2) guidelines for end-terminals. The design descriptions and evaluations are described in the following sections of the report.

Energy Absorbing Conceptual Design

In developing the end-terminal conceptual designs, the overall aesthetics of the barrier were considered in addition to its crash worthiness and safety performance. The designs needed to blend with the SBT guardrail, so non-natural materials were avoided. To achieve these criteria, similar components to the SBT barrier were used for the end-terminal designs. Some of the components were modified to achieve a design that meets the safety requirements for end-terminals. The posts were weakened by reducing their size (cross-section) and adding holes at ground level. The rail lengths were also shortened to reduce the potential for occupant compartment intrusions. The post spacing was decreased to achieve maximum energy absorption while minimizing the end-terminal length. Additionally, the rails were cut at a 45 degree angle such that they would be pushed away from the vehicle during impact.

![Sequential Images – Test 2-31 – Energy Absorbing](image)
Iterative simulations with varied post size, hole size, rail size, and post spacing were carried out to achieve an optimum energy absorbing end-terminal design that would meet the evaluation criteria for TL-2 of Report 350. The design consisted of eight (8) rail segments. The rails were 1.5-m long, half the length of the original SBT barrier rails. The posts were also half the width of the original posts (150 mm). The post spacing was 1.5 m and the total length of end-terminal was (12 m). The model was evaluated under the six test designations that are require for a gating terminal. The simulations showed that this design is likely to meet all Report 350 requirements for the TL-2 condition. Occupant risk values from the six simulations are listed in Table 1. Summary results from one of the simulations are presented in Figures 9 and 10.

![Figure 10: Velocity (left) and Acceleration (right) Plots – Test 2-30 - Energy Absorbing](image)

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<th>Impact Condition (TL-2)</th>
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Non-Energy Absorbing Conceptual Design

Using the same procedure followed in creating the energy absorbing design, a non-energy absorbing flared end-terminal for the SBT guardrail was developed. This design is very similar to the energy absorbing design. It uses similar components to the SBT barrier. The posts were weakened by reducing their size and adding holes at ground level so that they would breakaway during the impact. The rail lengths were also shortened to permit a smoother flaring of the end-terminal and to reduce the potential for occupant compartment intrusions. Again, the rails were cut at a 45 degree angle so that they would be pushed away from the vehicle during impact.

Iterative simulations with varied post size, hole size, rail size, and post spacing were carried out to achieve an optimum end-terminal design that would meet the evaluation criteria for TL-2 of Report 350. The design consisted of eight (8) rail segments. The rails were half the length of the original SBT barrier rails (1.5m). The posts were also half the width of the original posts (150 mm). The post spacing was 1.5 m and the total length of end-terminal was (12 m). The total flaring distance was 2 m. The design was evaluated under the six test designations that are required for a gating terminal. The simulations showed the design meeting all Report 350 requirements for TL-2 condition. Occupant risk values from the six simulations are listed in Table 1.

SUMMARY

Based on the results of the computer simulations and pendulum tests that were conducted, an aesthetic, crashworthy terminal design for the steel-backed timber guardrail appears to be feasible. Full-scale crash testing with both an 820-kg passenger car and a 2000-kg pickup truck will be required to confirm the crashworthiness of a final design. In this regard, NCHRP Report 350 tests 2-30 and 2-31 will need to be conducted. Test 2-32 will also be required. If the car used in test 2-32 passes safely through the terminal without significant decelerations and with low roll, pitch, and yaw angles, it is likely that test 2-33 (the same test, but with the larger pickup truck) can be waived. Tests 2-34 and 2-35 will be required to ascertain crash performance at the critical impact point and to verify the beginning barrier length of need point, respectively. Test 2-39 can be waived if the terminal is to be installed beyond the recommended clear zone distance for opposite-direction traffic, as will likely be the case on most low volume, low speed scenic roads. Thus, the minimum number of full-scale tests that may be required is five.

The pendulum tests (and associated simulations) of the partial system suggest that the energy-absorbing design will work and pass TL-2. Because pendulum testing cannot fully replicate an actual vehicular crash in which the vehicle may remain in contact with the terminal for a significant distance, the need to conduct full-scale tests exists. The analyses suggest that the flared, non-energy absorbing terminal will have the better chance of successfully passing the TL-2 test series. This is because the vehicle will impact only the few posts at the end of the terminal before passing behind the barrier and debris build-up is not likely to cause vehicular instability. On the other hand, a parallel, energy-absorbing design in which a vehicle impacting the end head-on travels directly along the line of the barrier will create much more debris and will need to be relatively long to slow a vehicle safely without overturning before it reaches the first solid line post.

Based upon the findings of this effort, it was recommended that the National Park Service and the Eastern Federal Lands Division of the Federal Highway Administration proceed with the full-scale testing of the flared, non-energy absorbing design for the steel-backed timber guardrail terminal. Efforts are underway to conduct these tests in the latter part of 2009.
REFERENCES


