DEVELOPMENT OF END TERMINAL FOR BOX-BEAM GUARDRAIL
PHASE II - CRASH TESTING AND EVALUATION

FINAL REPORT

By

King K. Mak, P.E.
Research Engineer

and

Dean L. Sicking, P.E.
Associate Research Engineer

Project No. RF 72020

Sponsored by

Wyoming Department of Transportation
Cheyenne, Wyoming

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Texas Transportation Institute
Texas A&M University System
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### APPROXIMATE CONVERSIONS TO SI UNITS

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#### VOLUME

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### APPROXIMATE CONVERSIONS FROM SI UNITS

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#### VOLUME

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<td>1.102</td>
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<tr>
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<td>0.0929</td>
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<td>foot-Lamberts</td>
<td>fL</td>
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* SI is the symbol for the International System of Measurement (Revised July 1989)
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 Wyoming Department of Transportation. This report does not constitute a standard, specification or regulation.

KEY WORDS

Box-Beam Guardrail, End Treatment, End Terminal, Highway Safety

ACKNOWLEDGMENTS

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I. INTRODUCTION

1.1 BACKGROUND

The development of crashworthy guardrail end terminals has long been a difficult problem for the roadside safety community. Early guardrails were constructed with untreated stand-up ends, resulting in catastrophic accidents in which rail elements speared and impaled impacting vehicles. Considerable efforts have been undertaken to develop crashworthy guardrail end terminals in recent years with good success. However, the efforts have been mainly directed at the widely used W-beam guardrails and not at box-beam guardrails. Nevertheless, some states, such as the State of Wyoming, prefer the use of box-beam guardrails to W-beam guardrails at some locations due to problems associated with snow removal and accumulation.

For box-beam guardrails, the only available end terminal treatment is the sloped-end design. The sloped-end design has been shown to have the potential for causing impacting vehicles to vault and roll over under certain impact conditions, particularly for small vehicles traveling at high speeds. Further, even when the systems perform adequately, impacting vehicles are allowed to penetrate behind the barrier at a high rate of speed. Crash test experience has indicated that when a vehicle penetrates a barrier end at a high rate of speed, even small deceleration forces (such as that caused by an uneven surface) can throw the vehicle out of control and increase the likelihood of rollover. Additionally, vehicles traveling behind a guardrail are likely to impact the hazard that the barrier was designed to shield.

The sloped-end terminal for box-beam guardrails currently used by the Wyoming Department of Transportation has not been crash tested. The New York Department of Transportation has crashed tested a similar design and found the performance to be only marginal and the terminal is considered adequate for use on highways with speed limits of 45 miles per hour (72.4 km/h) or less. The Wyoming Department of Transportation has adopted the practice of flaring box-beam guardrails considerable distances away from the travelway in order to ameliorate the safety problems associated with sloped-end terminals. This requires additional lengths of guardrails beyond the length-of-need, resulting in higher
costs. In addition, the required clear recovery area required for the flared guardrail end is oftentimes not available.

There are also a number of proprietary guardrail end treatment systems developed in recent years that have been shown to meet current safety standards and are designed to accommodate tangent installations. Some are designed specifically for W-beam guardrails and are not easily adapted for use with box-beam guardrails. Others are designed for use as crash cushions and can be used as end treatments for any barrier. However, these proprietary designs are relatively expensive and are not cost-effective for use as guardrail end terminals except in rare instances. There is, therefore, a need to develop a crashworthy end terminal for use with box-beam guardrails.

1.2 STUDY OBJECTIVES AND SCOPE

The objective of this study is to develop a crashworthy end terminal for box-beam guardrails and median barriers for use by the Wyoming Department of Transportation.

The project is divided into two phases. Phase I is a feasibility study to develop and evaluate conceptual designs and to select and recommend the most promising conceptual design for further development and crash testing. A report summarizing results of the Phase I study with recommendation on the most promising design for further development and full-scale crash testing was previously completed and submitted to the Department. Phase II of the study involved further development and full-scale crash testing and evaluation of the selected design.

This report summarizes the results of the Phase II study. Chapter II of the report outlines the study approach. Detailed descriptions of the final end terminal design is presented in Chapter III of the report. Results of the developmental tests and compliance crash tests are documented in Chapter IV of the report. Adaptation of the end terminal design for use with box-beam median barriers is documented in Chapter V of the report. Chapter VI presents the study findings, conclusions and recommendations.
II. STUDY APPROACH

2.1 STUDY APPROACH

The Phase II study was divided into three major tasks:

1. Further development of conceptual design,
2. Crash testing and evaluation of the end terminal design, and
3. Modification of end terminal design for use with box-beam median barriers.

The initial conceptual design developed under the Phase I feasibility study was further improved and modified during the course of the Phase II study. Additional dynamic testing with a bogie vehicle was conducted to determine the energy absorbing characteristics of different size fiberglass composite tubes. The results of these dynamic tests were then used in theoretical conservation of energy and momentum analyses to select the appropriate sizes of fiberglass composite tubes for use as the energy absorbing material. Design details were added, deleted, or modified in conjunction with the fabrication of the prototype installations. A full-scale developmental crash test was conducted to iron out the design details prior to compliance crash testing. Additional modifications were made to the design based on the results of the developmental crash test. A series of compliance crash tests were then conducted to evaluate the performance of the box-beam end terminal design in accordance with guidelines presented in National Cooperative Highway Research Program (NCHRP) Report 230(2). Finally, the end terminal design was further modified for use with box-beam median barriers.

Brief descriptions of the procedures used in the dynamic testing and full-scale crash testing are presented in this chapter.

2.2 DYNAMIC TESTING

Dynamic testing with a bogie vehicle is an inexpensive means of applying known dynamic loads to the energy absorbing material to evaluate its energy absorbing characteristics and buckling behavior. The bogie test vehicle, as shown in Figure 1, is basically a rolling cart ram, consisting of a steel block bolted to a frame with four aircraft tires. A plywood ram pad is attached to the front of the steel block to cushion the impact and to distribute the impact force. A cable reverse tow system was used to propel the cart
Figure 1. Photograph of Bogie Vehicle Used in Dynamic Testing.
into the test installation. Guidance of the cart was provided by concrete beams lined up on both sides of the cart's intended path.

The bogie vehicle was instrumented with an accelerometer to measure longitudinal acceleration levels. The accelerometer was strain-gauge type with a linear millivolt output proportional to acceleration. The electronic signals from the accelerometer were transmitted to a base station by means of a constant band width FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Provision was made for the transmission of calibration signals before and after the test, and an accurate time reference signal was simultaneously recorded with the data. Pressure sensitive contact switches, installed on the front of the ram pad, actuated just prior to impact by wooden dowels to indicate the elapsed time over a known distance to provide a measurement of impact velocity. The initial contact also produced an "event" mark on the data record to establish the exact instant of contact with the transition system.

After the tests, the data were played back from the tape machine, filtered with a Class 180 filter, and digitized using a microcomputer. Acceleration versus time, force versus time, and force-deflection curves were then plotted from the digitized data of the vehicle-mounted linear accelerometer. These curves were studied to evaluate the energy absorption characteristics of the composite tubes and to determine the average crush forces.

A full-scale prototype installation, fabricated and used for dynamic testing in the Phase I feasibility study, was again used in these dynamic tests. The prototype installation consisted of: (1) a 20-ft (6.1-m) long section of standard 6 in x 6 in x 3/16 in (15.2 cm x 15.2 cm x 0.48 cm) box-beam rail; (2) a 20-ft (6.1-m) long outer tube of 7 in x 7 in x 3/16 in (17.8 cm x 17.8 cm x 0.48 cm) box beam; (3) a separate impact end section; and (4) free-standing legs to support the box beams and end section. The standard 6 in x 6 in x 3/16 in (15.2 cm x 15.2 cm x 0.48 cm) box-beam rail section was welded at the downstream end to a steel plate attached to a rigid wall at the proper height above ground to simulate a standard box-beam guardrail installation. An end cap was welded to the upstream end of the box-beam section to serve as a piston for crushing the fiberglass composite tube placed inside the outer tube. The 7 in x 7 in x 3/16 in (17.8 cm x 17.8 cm x 0.48 cm) outer tube telescoped over the standard box-beam rail. Test specimens of the energy absorbing composite tubes were placed inside the outer tube.
The separate impact end section consisted of: a 4-ft (1.22-m) long section of standard 6 in x 6 in x 3/16 in (15.2 cm x 15.2 cm x 0.48 cm) box beam, an 18 in x 20 in (45.7 cm x 50.8 cm) frontal impact plate made from 1/2-in (1.27-cm) thick steel plate welded to one end of the box-beam section and reinforced with 1/2-in (1.27-cm) thick gusset plates, and an end cap welded to the other end of the box-beam section to serve as a piston for crashing the composite tubes.

Free-standing legs were used at regular intervals to support and keep the standard box-beam rail, the outer tube, and the impact end section at the proper height above the ground. Since these legs were not attached to the installation, they disengaged readily upon impact. Photographs of the test installation for dynamic testing are shown in Figure 2.

2.3 FULL-SCALE CRASH TESTING

A total of six full-scale crash tests were conducted, consisting of one developmental test, one compliance test that did not meet the evaluation criteria as outlined in NCHRP Report 230, and four compliance tests that successfully met the evaluation criteria. The one full-scale developmental crash test (test number 7202-1) involved a 4,500-pound (2,041-kg) passenger car impacting the end terminal end-on at a nominal speed of 45 miles per hour (72.4 km/h). The purpose of this developmental crash test was to iron out the design details and was conducted at a reduced impact speed of 45 miles per hour (72.4 km/h) instead of the standard 60 miles per hour (96.6 km/h).

According to guidelines presented in NCHRP Report 230, four compliance crash tests are required to evaluate the performance of a barrier end terminal design. These four crash tests, listed according to the actual test sequence, are as follows:

1. **Test Designation 45.** An 1,800-lb (817-kg) passenger car impacting the end terminal head-on with an offset of 15 inches (0.38 m) from the center of the nose at a nominal impact speed of 60 miles per hour (96.6 km/h). The objective of this test is to evaluate if the vehicle decelerations and occupant risks are within acceptable limits.

2. **Test Designation 41.** A 4,500-lb (2,041-kg) passenger car impacting the end terminal head-on at the center of the nose at the nominal speed of 60 miles per hour (96.6 km/h). The objective of this test is to evaluate the energy-absorbing/dissipation properties of the end terminal.
Figure 2. Photographs of Test Installation for Dynamic Testing.
3. **Test Designation 44.** An 1,800-lb (817-kg) passenger car impacting the installation midway between the nose and the beginning of length-of-need at a nominal impact speed and angle of 60 miles per hour (96.6 km/h) and 20 degrees. The objective of this test is to assess the stability of the vehicle when impacting the end terminal upstream of the length-of-need.

4. **Test Designation 40.** A 4,500-lb (2,041 kg) passenger car impacting the installation at the beginning of length-of-need at the nominal speed and angle of 60 miles per hour (96.6 km/h) and 25 degrees. The objective of this test is to evaluate the adequacy of the terminal anchorage.

The first compliance test (test designation number 45, test number 7202-3) with an 1,800-pound (817-kg) passenger car impacting the end terminal end-on with an offset of 15 inches (0.38 m) at a nominal speed of 60 miles per hour (96.6 km/h) failed to meet the occupant impact velocity evaluation criterion. After additional modifications to the end terminal design, this compliance crash test was then re-run (test number 7202-3A) with successful results.

All crash tests and data analysis were conducted in accordance with guidelines contained in NCHRP Report 230. Brief descriptions of the crash test and data analysis procedures are presented as follows.

### 2.3.1 Electronic Instrumentation and Data Processing

Each test vehicle was instrumented with three solid-state angular rate transducers to measure roll, pitch and yaw rates; a triaxial accelerometer at the vehicle center-of-gravity to measure longitudinal, lateral, and vertical acceleration levels, and a back-up biaxial accelerometer in the rear of the vehicle to measure longitudinal and lateral acceleration levels. The accelerometers were strain gauge type with a linear millivolt output proportional to acceleration.

The electronic signals from the accelerometers and transducers were transmitted to a base station by means of constant bandwidth FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Provision was made for the transmission of calibration signals before and after the test, and an accurate time reference signal was simultaneously recorded with the data. Pressure sensitive contact switches on the
bumper were actuated just prior to impact by wooden dowels to indicate the elapsed time over a known distance to provide a measurement of impact velocity. The initial contact also produced an "event" mark on the data record to establish the exact instant of contact with the guardrail system.

The multiplex of data channels, transmitted on one radio frequency, was received at a data acquisition station, and demultiplexed into separate tracks of Intermediate Range Instrumentation Group (I.R.I.G.) tape recorders. After the test, the data was played back from the tape machines, filtered with a SAE J211 Class 180 filter, and were digitized using a microcomputer, for analysis and evaluation of impact performance. The digitized data were then processed using two computer programs: DIGITIZE and PLOT ANGLE. Brief descriptions on the functions of these two computer programs are given below.

The DIGITIZE program uses digitized data from vehicle-mounted linear accelerometers to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 10-msec average ridedown acceleration. The DIGITIZE program also calculates a vehicle impact velocity and the change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-msec intervals in each of the three directions are computed. Acceleration versus time curves for the longitudinal, lateral, and vertical directions are then plotted from the digitized data of the vehicle-mounted linear accelerometers using a commercially available software package.

The PLOT ANGLE program uses the digitized data from the yaw, pitch, and roll rate charts to compute angular displacement in degrees at 0.00067-second intervals and then instructs a plotter to draw a reproducible plot of yaw, pitch, and roll versus time. It should be noted that these angular displacements are sequence dependent with the sequence being yaw-pitch-roll for the data presented herein. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate system being that which existed at initial impact.

2.3.2 Photographic Instrumentation and Data Processing

Photographic coverage of each test included three high-speed cameras: one overhead with a field of view perpendicular to the ground and directly over the impact point; one
placed to have a field of view parallel to and aligned with the guardrail system at the
downstream end; and a third placed behind the barrier. A flash bulb activated by pressure
sensitive tapeswitches was positioned on the impacting vehicle to indicate the instant of
contact with the guardrail system and was visible from each camera. The films from these
high-speed cameras were analyzed on a computer-linked Motion Analyzer to observe
phenomena occurring during the collision and to obtain time-event, displacement, and
angular data. A 3/4-in videotape camcorder and still cameras were used for documentary
purposes and to record conditions of the test vehicle and guardrail system before and after
the test.

2.3.3 Test Vehicle Propulsion and Guidance

The test vehicles were towed into the guardrail system using a steel cable guidance
and reverse tow system. A steel cable for guiding the test vehicles was stretched along the
impact path, anchored at each end, and threaded through an attachment to the front wheel
of the test vehicle. Another steel cable was connected to the test vehicles, passed around
a pulley near the impact point, through a pulley on the tow vehicle, and then anchored to
the ground such that the tow vehicle moved away from the test site. A 2 to 1 speed ratio
between the test and tow vehicle existed with this system. Just prior to impact with the
guardrail system, the test vehicle was released to be free-wheeling and unrestrained. The
vehicle remained free-wheeling, i.e., no steering or braking inputs, until the vehicle cleared
the immediate area of the test site, at which time brakes on the vehicle were activated to
bring the vehicle to a safe and controlled stop.
III. END TERMINAL DESIGN

A conceptual design of the energy absorbing telescoping end terminal for box-beam guardrails was developed under the Phase I feasibility study. Numerous modifications and refinements were made to the initial conceptual design during the course of this Phase II study to arrive at the final design. Discussions on the design criteria, the initial design concept, and the final design details are presented in this chapter. The various design modifications and refinements are too numerous to be described in detail and only the highlights of the modifications and refinements are presented in this report in conjunction with discussions on the results of the developmental and compliance crash tests.

3.1 DESIGN CRITERIA

According to guidelines presented in NCHRP Report 230\(^2\), barrier end terminals are required to provide safe deceleration or controlled barrier penetration for vehicles impacting upstream from the beginning of the length-of-need and barrier anchorage for redirecting vehicles impacting beyond the length-of-need. As discussed previously, controlled penetration of a barrier end at a high rate of speed could still lead to secondary collisions with serious consequences. Thus, it is desirable for a barrier end treatment to provide some level of impact attenuation. For head-on and low-angle impacts, the impact attenuation would capture the impacting vehicles and prevent barrier penetration. For higher-angle impacts that would penetrate the barrier, the impact attenuation would at least slow down the impacting vehicles significantly to minimize the potential hazard.

Another design consideration is the impact performance of the end terminal when installed tangent to the barrier. Guardrail end sections cannot always be flared away from the travelway due to lack of available space on the roadside. Also, box-beam barriers are used as median barriers as well as roadside guardrails. It would be desirable to design the end terminal to accommodate tangent installations.

Costs associated with the end terminal is also a major consideration. Roadside guardrails are relatively inexpensive and are often constructed in short segments. Costs associated with the end terminals have become a major part of the total cost of many barrier installations. For example, W-beam guardrails generally cost approximately $12 per
linear foot while the lowest-cost end terminal (i.e., turned-down end terminal) costs about $500 per installation. A typical 500-ft guardrail installation would then cost $6,000 for the guardrail and another $1,000 for the two turned-down end terminals. Other end treatments are even more expensive, costing up to $3,000 or more per unit. The cost of two of these terminals could be as high as or higher than the cost of the guardrail itself for a typical installation. Thus, the installation cost of a barrier end terminal is a very important factor and should be considered during the design process. In an effort to assure that the guardrail end terminal developed under this project would have wide applications, a goal of $1,500 or less per installation was used.

The design criteria used in the development of the new end terminal for box-beam guardrails are summarized below.

1. The end terminal will meet nationally recognized safety standards, i.e., successfully crash tested in accordance with guidelines presented in NCHRP Report 230.
2. The end terminal will perform satisfactorily when installed tangent to the barrier.
3. The end terminal will provide attenuation for vehicles impacting the barrier end.
4. The end terminal will have relatively low construction costs.

3.2 INITIAL DESIGN CONCEPT

The energy absorbing telescoping tube concept was described in the Phase I feasibility study report and is briefly summarized in this section. This concept incorporates an outer oversized tube that telescopes over the standard box-beam rail element. An energy absorbing material, i.e., a fiberglass composite tube, is placed inside the outer tube to provide a mechanism for attenuating the energy of impacting vehicles. A separate impact end section or nose piece with an impact plate assembly is employed to engage the impacting vehicle and to prevent spearing or vehicle vaulting. Anchorage is provided by two foundation tubes, similar to those used in the breakaway cable terminal (BCT) design. Tension is transmitted from the anchorage to the outer tube via a breakaway post and cable.
attachment and from the outer tube to the box-beam rail element through a tensile connector.

During end-on impacts, the impacting vehicle would first accelerate the impact end section, break away the end post, and release the cable attachment. The vehicle would next start to crush the energy absorbing material and accelerate the outer tube. The outer tube would telescope over the box-beam rail element, and continue to crush the energy absorbing material inside the outer tube until the vehicle is brought to a safe and controlled stop. For end-on impacts at an angle, the outer tube would begin to telescope over the standard box-beam rail and then bend out of the way sufficiently to act as a natural gating mechanism, allowing the impacting vehicle to continue behind the guardrail in a controlled manner. For side impacts, the end treatment would function just like a standard box-beam guardrail to contain and redirect the impacting vehicle.

3.3 FINAL DESIGN DETAILS

Figure 3 shows details of the final design that was successfully crash tested. The major components and details of the design are as follows:

1. A 24-ft (7.3-m) long, 7 in x 7 in (17.8 cm x 17.8 cm) outer tube, fabricated from 1/8-in (0.32-cm) thick sheet metal.

2. A separate end section with impact plate assembly.

3. Foundation tubes for anchorage and breakaway post and cable attachment for transmission of tension.

4. A breakaway tensile connector between the outer tube and the standard box beam.

5. Two-staged composite tubes for energy attenuation.

The outer tube is 24 ft (7.3 m) long and has outside dimensions of 7 in by 7 in (17.8 cm x 17.8 cm), fabricated from 1/8-in (0.32-cm) thick sheet metal with 3-in (7.62-cm) welds on 6-in (15.2-cm) spacing center to center, as shown in Detail G of Figure 3. The upstream end of the outer tube is reinforced with 6-in (15.2-cm) wide, 1/4-in (0.64-cm) thick steel plate collars and 24-in (61.0-cm) long continuous welding to minimize potential damage to the outer tube from minor impacts. Similarly, the downstream end of the outer tube is
Figure 3. Schematic of Final End Terminal Design.
Figure 3. Schematic of Final End Terminal Design (continued).
Figure 3. Schematic of Final End Terminal Design (continued).
reinforced with 2-in (5.1-cm) wide, 1/4-in (6.4-mm) thick steel plate collar and 12-in (30.5-cm) long continuous welding.

The outer tube telescopes over the first standard section of 6 in x 6 in x 3/16 in (15.2 cm x 15.2 cm x 0.48 cm) box-beam rail. The upstream end of the first section of the standard box beam is modified to include an end cap and steel straps welded to the outside of the box beam, as shown in Detail C of Figure 3. The end cap, made from 1/8-in (0.32-cm) thick steel plate, is welded to the end of the standard box-beam section to serve as a piston for crushing the composite tubes placed inside the outer tube. The 1-in x 1/4-in (2.54 cm x 0.64 cm) steel straps are welded to the outside of the standard box beam at the end and at 1 ft (30.4 cm) downstream from the end to reduce the free play of the 6 in x 6 in (15.2 cm x 15.2 cm) box beam inside the outer tube, which has inside dimensions of 6-3/4 in x 6-3/4 in (17.1 cm x 17.1 cm).

The separate impact end section or nose piece, as shown in Detail A of Figure 3, consists of a 3-ft (0.91-m) long section of standard 6 in x 6 in x 3/16 in (15.2 cm x 15.2 cm x 0.48 cm) box beam. A 20 in x 20 in (50.8 cm x 50.8 cm) frontal impact plate, made from 3/8-in (0.95-cm) thick steel plate, is welded to the front end of the box-beam section and reinforced with 1/2-in (1.27-cm) thick steel gusset plates. The box beam at the downstream end of the impact end section is treated similar to the upstream end of the standard box-beam section except that the 1 in x 1/4 in (2.54 cm x 0.64 cm) steel straps are welded around the end and longitudinally along the last 12 in (30.5 cm) of the box-beam section instead of a second spacer used on the standard box-beam section. The second spacer is deleted from the impact end section to prevent the possibility of the spacer snagging on the end of the outer tube.

A breakaway post and cable system similar to that used in the breakaway cable terminal (BCT) design for W-beam guardrails is used to provide anchorage for side impacts downstream from the end of the terminal. Note that the anchorage of the cable attachment to the outer tube is welded and not bolted on since protrusion of the bolts inside the outer tube would interfere with the composite tubes. Two foundation tubes with a connecting ground-level strut are used for the anchorage. However, only one wooden breakaway post is used with the first foundation tube, which also supports the impact end section of the end terminal assembly. The second foundation tube does not have a post and is used only to
increase the tensile capacity of the anchorage system. Tension is transmitted from the anchorage to the outer tube via the cable attached to the end post and the outer tube.

The outer tube transmits tension to the rest of the guardrail through a breakaway tensile connector, similar in design to that used with the ET-2000 guardrail end terminal, as shown in Detail F of Figure 3. Six lugs with teeth in one direction and sloped surfaces in the other direction are welded to the top of a 3 in x 2 in x 3/16 in (7.62 cm x 5.08 cm x 0.48 cm) x 16-3/4 in (43.5 cm) long structural tubing. Corresponding holes are cut on the bottom of the 6 in x 6 in x 3/16 in (15.2 cm x 15.2 cm x 0.48 cm) box beam for the lugs to engage. A 6-in (15.2-cm) long 2 in x 2 in x 3/16 in (5.08 cm x 5.08 cm x 0.48 cm) structural tubing is welded to the end of the outer tube on the bottom. A 1-1/4-in (3.2-cm) diameter, grade 5 all-thread bolt is used to connect the 2 in x 2 in x 3/16 in (5.08 cm x 5.08 cm x 0.48 cm) structural tubing welded to the outer tube to the 3 in x 2 in x 3/16 in (7.62 cm x 5.08 cm x 0.48 cm) structural tubing with the lugs attached to the standard box-beam section. This tensile connector is designed to transmit tension between the outer tube and the standard box beam during side impacts. For end-on impacts, the tensile connector will disengage from the standard box-beam rail, thus allowing the outer tube to freely telescope over the standard box beam.

Except for the one wooden breakaway post at the end, all other posts are the standard S3x5.7 structural steel posts normally used with box-beam guardrails. However, in order to facilitate the telescoping of the outer tube over the standard box beam, special shelf angles are used with the outer tube, as illustrated in Detail E of Figure 3. The shelf angles eliminate the need for bolting the outer tube to the posts while providing some restraint on the lateral and vertical movements of the outer tube. The first 24-ft (7.32-m) section of standard box beam downstream from the outer tube is not bolted at the first post (i.e., post 5) and 5/16-in (0.79-cm) diameter, grade 0 bolts, designed to shear upon impact, are used for the remaining three posts (i.e., posts 6, 7 and 8), as shown in Detail D of Figure 3.

Energy attenuation is provided by crushing of fiberglass/exepoxy composite tubes placed inside the outer tube. In static compressive strength tests and dynamic tests with a bogie vehicle, the composite tubes were found to be very efficient energy absorbers. The crush forces were very uniform and consistent with the peak crush forces generally within
10 percent of the average value. The specific composite tubes used with the prototype design were MMFG EXTREN Series 500 composite tubes. Similar products are available from other manufacturers. A laboratory test procedure based on static compressive strength testing, shown in Appendix A, was developed for testing of the composite tubes to ensure that the composite tubes have the required crush characteristics.

Two stages of energy attenuation are employed in the design. The first stage is intended for impacts by small vehicles, i.e., 1,800-lb (817-kg) passenger cars, and has a lower level of stiffness to provide an acceptable level of deceleration for the smaller vehicles. The second stage has a higher level of stiffness in order to handle impacts by larger and heavier vehicles, i.e., 4,500-lb (2,041-kg) passenger cars or pickup trucks. A 6-ft (1.83-m) long, 6-in (15.2-cm) diameter composite tube with a 1/8-in (0.32-cm) wall thickness was selected for the first-stage energy attenuation. Both ends of the composite tube are cut into a tulip-like shape, each approximately 6 inches (15.2 cm) in length, as shown in Detail H of Figure 3. This provides 12 inches (30.5 cm) of crush with reduced stiffness at initial impact to minimize the impulse associated with initiation of crush of the composite tube. Based on results of static and dynamic testing, the expected stiffness of the 6-in (15.2-cm) diameter, 1/8-in (0.32-cm) thick side-wall composite tube is approximately 18 kips per foot (262.8 KN/m).

The second-stage energy attenuation is provided by a 12-ft 8-in (3.86-m) long, 6-in (15.2-cm) diameter composite tube with a 1/4-in (0.64-cm) wall thickness, as shown in Detail I of Figure 3. Again, both ends of the composite tube are cut into a tulip shape, approximately 4 in (10.2 cm) in length, for proper initiation of the crush. The expected stiffness of this 6-in (15.2-cm) diameter, 1/4-in (0.64-cm) thick side-wall composite tube is approximately 35 kips per foot (508.5 KN/m).

End caps, made from 16-gage sheet metal, are used to cover the ends of the composite tubes to prevent splitting and fracturing of the composite tubes, as shown in Detail J of Figure 3. The end caps also eliminate the potential for the ends of the composite tubes to be wedged between the inside of the outer tube and the outside of the impact end section, the intermediatespacer, or the standard box-beam rail.

An intermediate spacer is used to separate the two different thickness composite tubes. The spacer, as illustrated in Detail B of Figure 3, consists of a 10-in (25.4-cm) long
section of standard 6 in x 6 in x 3/16 in (15.2 cm x 15.2 cm x 0.48 cm) box beam. End caps made from 1/8-in thick steel plate are welded to both ends of the box-beam section. Also, steel spacer straps, 1 in x 1/4 in (2.5 cm x 0.64 cm), are welded to the box beam at both ends to reduce the amount of free play inside the outer tube.

The Wyoming Department of Transportation has adopted the final design of the box-beam end terminal into their standard plans, a copy of which is shown in Appendix A. Also, detailed specifications and test procedures for the fiberglass/epoxy composite tube was prepared, a copy of which is shown as Appendix B.

3.4 COST ESTIMATE

The estimated cost for the material and fabrication of this end terminal, not including labor for installation, is approximately $2,000, including the entire end terminal assembly and the first 24-ft (7.3-m) section of the standard box-beam guardrail. This cost estimate is based on actual costs of the prototype installation after allowing for discounts when purchased in larger quantity. A breakdown of the cost estimate by major components is shown as follows:

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost ($)</th>
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<tbody>
<tr>
<td>Outer tube</td>
<td>400</td>
</tr>
<tr>
<td>24-ft section of standard box beam</td>
<td>250</td>
</tr>
<tr>
<td>Impact end section</td>
<td>200</td>
</tr>
<tr>
<td>2 foundation tubes and ground strut</td>
<td>350</td>
</tr>
<tr>
<td>Breakaway cable attachment</td>
<td>150</td>
</tr>
<tr>
<td>Breakaway tensile connector</td>
<td>150</td>
</tr>
<tr>
<td>Posts and attachments</td>
<td>200</td>
</tr>
<tr>
<td>Composite tubes and end caps</td>
<td>300</td>
</tr>
</tbody>
</table>

Subtotal 2,000

Less 35-ft length-of-need 350

Total 1,650

The estimated cost of the end terminal of $2,000 is higher than the design goal of $1,500. However, it should be noted that the end terminal includes approximately 35 ft (10.7 m) of guardrail beyond the beginning of the length-of-need. After subtracting the costs associated with this 35 ft (10.7 m) of guardrail, the net cost of the end terminal is approximately $1,650, which is fairly close to the design goal of $1,500.
IV. RESULTS OF DEVELOPMENTAL TESTS AND COMPLIANCE CRASH TESTS

4.1 DEVELOPMENTAL TESTS

As mentioned previously under "Study Approach", developmental tests, including dynamic testing with bogie vehicle and one full-scale crash test, were conducted to iron out the design details. The results of the developmental tests are summarized as follows.

4.1.1 Dynamic Testing

One concern with the conceptual design developed under the Phase I feasibility study was the observed global buckling of the fiberglass composite tubes during dynamic testing, particularly for the smaller diameter tubes intended for the first-stage energy attenuation. To minimize this potential problem with global buckling, it was decided to use the largest diameter tubes permissible, which would be 6 inches (15.24 cm), and use different wall thickness to control for the energy absorption characteristics. A 6-inch (15.24-cm) diameter, 1/4-inch (6.4-mm) wall thickness fiberglass composite tube was previously tested under the Phase I feasibility study and found to provide the desired energy absorbing characteristics for the second-stage energy attenuation.

For the first-stage energy attenuation, a 6-inch (15.24-cm) diameter, 1/8-inch (3.2-mm) wall thickness fiberglass composite tube was selected for testing and evaluation. This particular diameter and wall thickness composite tube is not a stock item and requires special order. Thus, it was not tested in the Phase I feasibility study. However, since the smaller diameter composite tubes exhibited a problem with global buckling, it was decided to evaluate this 6-in (15.24-cm) diameter, 1/8-in (3.2-mm) wall thickness composite tubes for use with the first-stage energy attenuation.

A series of five dynamic tests with a bogie vehicle was conducted on this 6-in (15.24-cm) diameter, 1/8-in (3.2-mm) wall thickness composite tubes. Also, three additional tests were conducted on the 6-in (15.24-cm) diameter, 1/4-in (6.4-mm) wall thickness composite tubes to confirm the results of the dynamic tests previously conducted under the Phase I feasibility study.

Similar to the results found with the previous dynamic tests, the crush forces were again found to be very uniform and consistent, which are highly desirable characteristics
from the standpoint of designing an energy attenuation device. The estimated dynamic crush force for the 6-inch (15.42-cm), 1/8-inch (3.2-mm) wall thickness composite tube was approximately 18 kips (80.1 KN) and that for the 6-inch (15.24-cm), 1/4-inch (6.4-mm) wall thickness composite tube was approximately 35 kips (155 KN). Global buckling was not observed with these larger diameter composite tubes. The 6-inch (15.24-cm) diameter, 1/8-inch (3.2-mm) and 1/4-inch (6.4-mm) wall thickness composite tubes were thus selected for use with the final design.

4.1.2 Full-Scale Developmental Test (Test No. 7202-1)

One full-scale developmental crash test (test number 7202-1) with a 4,500-pound (2,041-kg) passenger car impacting the end terminal end-on at a nominal speed of 45 miles per hour (72.4 km/h) was conducted to iron out the design details. Brief descriptions of this developmental crash test are presented as follows.

Photographs of the test installation for the developmental test are shown in Figures 4 and 5. A 1980 Cadillac Coupe DeVille (shown in Figure 6) impacted the end terminal end-on at a speed of 47.0 miles per hour (75.6 km/h). The vehicle was directed into the test installation using a cable reverse tow and guidance system. Test inertia mass of the vehicle was 4,500 pounds (2,041 kg). The height to the lower edge of the vehicle bumper was 12.3 in (31.1 cm) and 20.8 in (52.7 cm) to the top of the bumper. Other dimensions and information on the vehicle are given in Figure 7.

The vehicle was free wheeling and unrestrained just prior to impact. Upon impact, the front bumper of the vehicle wrapped around the frontal impact plate of the end section and began to accelerate the end section forward. Shortly thereafter, the wooden end post (post 1) fractured while the end section continued to move forward. At 0.037 second, the stoppers on the end section contacted the outer tube and the outer tube began to accelerate and telescope over the standard box-beam rail. As the outer tube continued to telescope over the standard box-beam rail, the vehicle impacted and displaced the second and third posts at approximately 0.168 second and 0.308 second, respectively. By 0.370 second, the forward movement of the outer tube stopped and the outer tube began to buckle laterally and vertically as the forward motion of the vehicle was arrested. The vehicle rebounded
Figure 4. Photographs of Test Installation Before Test 7202-1.
Figure 4. Photographs of Test Installation Before Test 7202-1 (continued).
Figure 5. Vehicle/End Terminal Geometrics Before Test 7202-1.
Figure 6. Photographs of Vehicle Before Test 7202-1.
Date: 4-10-92  Test No.: 7202-1  VIN: 60476A9205008

Make: Cadillac  Model: Coupe DeVille  Year: 1980  Odometer: 52557


Tire Condition: good _  fair _  badly worn _

Vehicle Geometry - inches

\[
a = 77.25''  \quad b = 42''  \\
c = 121''  \quad d = 54.5''  \\
e = 55.75''  \quad f = 218.75''  \\
g  \quad h = 55.26''  \\
i  \quad j = 34''  \\
k = 16.25''  \quad l = 49.75''  \\
m = 20.75''  \quad n = 4.75''  \\
o = 12.25''  \quad p = 61''  \\
r = 28.25''  \quad s = 16.25''  \\
\]

Engine Type: 8 cyl. gas  Engine CID: 6.0 LT

Transmission Type:
- Automatic or Manual
- FWD or RWD or 4WD

Body Type: 2 door

Steering Column Collapse Mechanism:
- Behind wheel units
- Convoluted tube
- Cylindrical mesh units
- Embedded ball
- NOT collapsible
- Other energy absorption
- Unknown

Brakes:
- Front: disc _  drum _
- Rear: disc _  drum X

Note any damage to vehicle prior to test:

Windshield Cracked (marked)

*\text{d} = \text{overall height of vehicle}

**Figure 7. Vehicle Properties for Test 7202-1.**
from the end terminal and came to rest approximately 2 feet (0.61 m) from the end terminal. Sequential photographs of the test are shown in Figure 8.

The end terminal was displaced forward dynamically for a maximum distance of approximately 13 ft (3.96 m) and the residual displacement was 12 ft-5.5 in (379.7 em). The maximum dynamic deflection of the rail elements was 32.3 in (82.0 cm) laterally and 19.9 in (50.6 cm) vertically. The maximum lateral residual deformation was 20.8 in (52.7 cm). In addition, the rail elements were detached from the posts at posts 2 through 7. The outer tube buckled in three places along its length. The frontal impact plate and gusset plates for the end section were damaged extensively. Damage sustained by the test installation during testing is shown in Figure 9. The first-stage 7-ft (2.13-m) long, 6-in (15.24-cm) diameter, 1/8-in (3.2-mm) wall thickness composite tube was totally crushed and the second-stage 12-ft (3.66-m) long, 6-in (15.24-cm) diameter, 1/4-in (6.4-mm) wall thickness composite tube was crushed for a length of approximately 5 ft (1.52 m).

The vehicle received relatively minor damages, as shown in Figure 10. The damage sustained was concentrated at the front center of the vehicle. The maximum crush was 16.0 in (40.6 cm) at the center of the front bumper. In addition, damage was noted to the hood, grill and radiator.

A summary of the test results and other information pertinent to this test are given in Figure 11. Occupant impact velocity in the longitudinal direction was 23.1 feet per second (7.0 m/s) and -4.2 feet per second (-1.3 m/s) in the lateral direction. The highest 10-msec average occupant ridedown accelerations were -8.3 g in the longitudinal direction and -0.6 g in the lateral direction. The maximum 50-msec average acceleration experienced by the vehicle was -7.6 g in the longitudinal direction and 0.9 g in the lateral direction. Vehicle angular displacements are plotted in Figure 12 and vehicle accelerometer traces are displayed in Figures 13 through 15.

In summary, the general behavior and performance of the end terminal design in the developmental test is very encouraging. The test installation received moderate damage. There was no debris or detached elements that could pose potential hazard to the impacting vehicle or to adjacent traffic. The vehicle was brought to a safe and controlled stop with relatively minor damage. There was no deformation or intrusion into the occupant compartment. The vehicle remained upright and stable during the test sequence. Occupant
Figure 8. Sequential Photographs of Test 7202-1.
Figure 8. Sequential Photographs of Test 7202-1 (continued) (overhead and frontal views).
Figure 8. Sequential Photographs of Test 7202-1 (continued) (behind rail view).
Figure 9. Photographs of Test Installation After Test 7202-1.
Figure 10. Photographs of Vehicle After Test 7202-1.
Test No .................. 7202-1.
Date ...................... 04/10/92.
Test Installation .......... Wyoming End Treatment
Installation Length ........ 200 ft. (61.0 m)
Test Vehicle ............... 1980 Cadillac Coupe Deville
Vehicle Weight
   Test Inertia ............. 4500 lb (2041 kg)
Vehicle Damage Classification
   TAD ..................... 12-FC-4
   CDC ..................... 12FCEW2
Maximum Vehicle Crush. .... 16.0 in (40.6 cm)
Maximum Perm End Treatment Displacement .... 149.5 in (379.7 cm)
Impact Speed ............. 47.0 mi/h (75.6 km/h)
Impact Angle .............. 0.0 deg
Exit Speed ............... N/A
Exit Trajectory .......... N/A
Vehicle Accelerations
   (Max. 0.050-sec Avg)
      Longitudinal ........ -7.6 g
      Lateral .............. 0.9 g
Occupant Impact Velocity
   Longitudinal ........... 23.1 ft/s (7.0 m/s)
   Lateral ............... -4.2 ft/s (-1.3 m/s)
Occupant Ridedown Accelerations
   Longitudinal .......... -8.3 g
   Lateral ............... -0.6 g

Figure 11. Summary of Results for Test 7202-1.
Figure 12. Vehicle Angular Displacements for Test 7202-1.
CRASH TEST 7202-1
Class 180 Filter

Figure 13. Longitudinal Accelerometer Trace for Test 7202-1.
CRASH TEST 7202-1
Class 180 Filter

Figure 14. Lateral Accelerometer Trace for Test 7202-1.
CRASH TEST 7202-1
Class 180 Filter

Figure 15. Vertical Accelerometer Trace for Test 7202-1.
impact velocities and ridedown accelerations were within the recommended limits set forth in NCHRP Report 230.

Based on the results of the developmental crash test, a number of modifications that would further improve on the performance of the end terminal design were identified and incorporated into the end terminal design for subsequent crash tests. Brief descriptions of the design modifications are presented as follows.

It appeared that portions of the first-stage 6-in (15.24-cm) diameter, 1/8-in (3.2-mm) thick composite tube were caught between the outer tube and the impact end section and between the outer tube and the intermediate spacer, resulting in some reduction in the energy absorbing capability of the composite tube. The problem was attributed to the design of the end caps for the composite tubes. The end caps for the composite tubes were welded to the downstream end of the impact end section, both ends of the intermediate spacer, and the upstream end of the standard box beam. It is believed that the ends of the 6-inch (15.24-cm), 1/8-inch (3.2-mm) wall thickness composite tube were either not properly seated in the end caps or became dislodged during the impact, thus allowing portions of the composite tube to be wedged between the outer tube and the impact end section and between the outer tube and the intermediate spacer.

This wedging phenomenon adversely affected the crushing and energy absorbing capability of the composite tubes and should be eliminated. The end cap detail was therefore modified so that the end caps would be directly attached onto the ends of the composite tubes to eliminate this potential wedging problem. This modification in the end cap design also simplifies the installation process since it is no longer necessary to ensure that the composite tubes are properly seated within the end caps welded to the downstream end of the impact end section, both ends of the intermediate spacer, and the upstream end of the standard box beam. It also simplifies the process of cleanup of the debris from the crushed composite tubes after an impact since the crushed composite tubes basically stayed in one piece.

The 7 in x 7 in x 1/8 in (17.8 cm x 17.8 cm x 0.32 cm) outer tube was damaged in both the developmental crash test and the bogie vehicle tests to the extent that it cannot be reused. While this does not affect the performance of the end terminal, it does increase the repair costs after an impact. A number of modifications were made to strengthen the outer
tube and to reduce the likelihood of damage to the outer tube. The spacing between the 3-in (7.62-cm) skip welds for the outer tube was decreased from 12 in (30.5 cm) to 6 in (15.24 cm) center to center. The upstream end of the outer tube was reinforced with a 6-in (15.2-cm) wide, 1/4-in (0.64-cm) thick steel plate collar and 24-in (61.0-cm) long continuous welding. Similarly, the downstream end of the outer tube was reinforced with a 2-in (5.1-cm) wide, 1/4-in (0.64-cm) thick steel plate collar and 12-in (30.5-cm) long continuous welding. Also, 1-1/2 in (3.8 cm) thick rubber blocks were added to the stoppers on the impact end section to cushion the initial impact between the stoppers and the upstream end of the outer tube.

It was observed during the developmental crash test that the rail elements moved both upward and outward during the impact sequence and the outer tube eventually buckled at its connection to the standard box-beam rail. The buckling to the outer tube could prevent the composite tube from crushing further. To minimize the lateral and vertical movements of the outer tube, the shelf angles holding the outer tube to the posts were redesigned with a lip on the top. Also, for the first 24-ft (7.32-m) section of standard box-beam rail, 5/16-in (7.9-mm) diameter, grade 0 bolts that would readily shear upon impact were used to attach the box beam to the posts at posts 6, 7 and 8. Note that the first post of the standard box-beam rail downstream from the outer tube (i.e., post 5) was not bolted to reduce the resistance at the initiation of the telescoping of the outer tube.

The vertical and lateral movement of the outer tube and the subsequent buckling during the developmental crash test also raised the concern that the original design of the tensile connector between the outer tube and the standard box-beam rail (i.e., overlapping metal collars around the ends of the outer tube and the end of the standard box-beam rail) may not function properly. A more positive breakaway tensile connector, similar to that used with the ET-2000 W-beam guardrail end treatment, was therefore adopted in the design, details of which are previously described under Section 3.3 on "Final Design Details" in Chapter III.

4.1.3 First Compliance Test (Test No. 7202-3)

The design modifications described above were incorporated into the prototype test installation for the compliance crash tests. The first compliance test conducted (test number
7202-3) was NCHRP Report 230 test designation 45, involving an 1,800-lb (817-kg) passenger car impacting the end terminal head-on with an offset of 15 inches (0.38 m) from the center of the nose at a nominal impact speed of 60 miles per hour (96.6 km/h). This test was considered as the most critical test and was therefore selected as the first compliance crash test to be conducted. As it turned out, this test failed to meet the evaluation criteria as outlined in NCHRP Report 230, thus resulting in further modifications to the end terminal design. Consequently, this crash test was considered as a developmental test rather than an actual compliance crash test. Brief descriptions of this crash test and the resulting modifications to the end terminal design are presented as follows.

Photographs of the test installation are shown as Figures 16 and 17. A 1986 Yugo GV (shown in Figure 18) impacted the end terminal end-on with a 15 in (38.1 cm) offset left of the vehicle centerline at 60.7 miles per hour (97.7 km/h). The vehicle was directed into the test installation using a cable reverse tow and guidance system. The test inertia mass of the vehicle was 1,800 pounds (817 kg) and the gross static mass of the vehicle was 1,965 pounds (892 kg). The height to the lower edge of the vehicle bumper was 14.0 in (35.6 cm) and 19.3 in (48.9 cm) to the top of the bumper. Other dimensions and information on the vehicle are given in Figure 19.

The vehicle was free wheeling and unrestrained just prior to impact. Upon impact, the front bumper of the vehicle wrapped around the frontal impact plate of the end section and began to accelerate the end section forward. Shortly thereafter, the wooden end post (post 1) fractured while the end section continued to move forward. At 0.034 second, the stoppers on the end section contacted the outer tube and the outer tube began to accelerate and telescope over the standard box-beam rail. At 0.105 second, the unrestrained dummy impacted the windshield. At approximately 0.144 second, the vehicle impacted and displaced the second post. The forward movements of the outer tube and the vehicle were arrested at approximately 0.191 second and the vehicle began to yaw counterclockwise, buckling the outer tube in the process. The rear wheels of the vehicle became airborne during the rotation and the right front wheel also momentarily became airborne. The vehicle rotated for a total of approximately 160 degrees and came to rest behind the installation approximately 15 ft (4.57 m) downstream and 12 feet (3.66 m) lateral of the
Figure 16. Photographs of Test Installation Before Test 7202-3.
Figure 16. Photographs of Test Installation Before Test 7202-3 (continued).
Figure 17. Vehicle/End Terminal Geometries Before Test 7202-3.
Figure 18. Photographs of Vehicle Before Test 7202-3.
Date: 5-13-92  Test No.: 7202-3  VIN: VX1BA1217GK325052
Make: YUGO  Model: G.V.  Year: 1986  Odometer: 
Tire Condition: good  rear accelerometer fair  badly worn
Height of vehicle 
Vehicle Geometry - inches 
4-wheel weight for c.g. det. 
Mass - pounds  Curb  Test Inertial  Gross Static
M_1  1187  1166  1249
M_2  616  634  721
M_T  1803  1800  1970
Note any damage to vehicle prior to test: 

* = overall height of vehicle

Figure 19. Vehicle Properties for Test 7202-3.
initial point of impact, as shown in Figure 20. Sequential photographs of the test are shown in Figure 21.

The end terminal was displaced forward dynamically for a maximum distance of 7 ft-3 in (2.21 m) and the residual displacement was 6 ft-6.8 in (2.0 m). The maximum lateral dynamic deflection of the rail was 21.2 in (54.0 cm). Maximum lateral residual deformation was 14.4 in (36.6 cm). The rail was detached from the first five posts. Damage sustained during testing is shown in Figure 22. The first-stage 7-ft (2.13-m) long, 6-in (15.24-cm) diameter, 1/8-in (3.2-mm) wall thickness composite tube was totally crushed and the second-stage 12-ft (3.66-m) long, 6-in (15.24-cm) diameter, 1/4-in (6.4-mm) wall thickness composite tube was crushed for a length of approximately 4 in (10.2 cm).

The vehicle received moderate damage, as shown in Figure 23. The damage sustained was concentrated at the front of the vehicle. The maximum crush was 13.0 in (33.0 cm) at the left quarter of the front bumper. Damage was extensive to the front of the vehicle. Other damage included: a bent steering column and deformed dashboard resulting from impact by the unrestrained dummy, detached left front seat, and a cracked transmission housing.

A summary of the test results and other information pertinent to this test are given in Figure 24. Occupant impact velocity in the longitudinal direction was 41.9 feet per second (12.8 m/s) and -4.8 feet per second (-1.5 m/s) in the lateral direction. The highest 10-msec average occupant ridedown accelerations were -17.7 g in the longitudinal direction and 1.1 g in the lateral direction. The maximum 50-msec average acceleration experienced by the vehicle was -17.1 g in the longitudinal direction and 3.1 g in the lateral direction. Vehicle angular displacements are plotted in Figure 25 and vehicle accelerometer traces are displayed in Figures 26 through 28.

In summary, the occupant impact velocity of 41.9 ft/s (12.8 m/s) in the longitudinal direction was above the maximum allowable limit of 40 ft/s (12.2 m/s) set forth in NCHRP Report 230. Otherwise, the end terminal perform satisfactorily. There were moderate damage to the vehicle and rail installation. There were no debris or detached elements that could pose potential hazard to the impacting vehicle or to adjacent traffic. There was minimal deformation or intrusion into the occupant compartment. The vehicle remained upright and stable during the test sequence and after exiting from the rail.
Figure 20. Resting Position of Vehicle After Test 7202-3.
Figure 21. Sequential Photographs of Test 7202-3 (perpendicular view).
Figure 21. Sequential Photographs of Test 7202-3 (continued) (overhead and down the rail views).
Figure 21. Sequential Photographs of Test 7202-3 (continued) (overhead and down the rail views).
Figure 22. Photographs of Test Installation After Test 7202-3.
Figure 22. Photographs of Test Installation After Test 7202-3 (continued).
Figure 23. Photographs of Vehicle After Test 7202-3.
Figure 23. Photographs of Vehicle After Test 7202-3 (continued).
<table>
<thead>
<tr>
<th>Test No</th>
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</tr>
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<tbody>
<tr>
<td>Date</td>
<td>05/13/92</td>
</tr>
<tr>
<td>Test Installation</td>
<td>Wyoming End Treatment</td>
</tr>
<tr>
<td>Installation Length</td>
<td>200 ft. (61.0 m)</td>
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<tr>
<td>Test Vehicle</td>
<td>1986 Yugo</td>
</tr>
<tr>
<td>Vehicle Weight</td>
<td>1800 lb (816 kg)</td>
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<tr>
<td>Test Inertia</td>
<td></td>
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<td>Vehicle Damage Classification</td>
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<td>TAD</td>
<td>12-FC-6</td>
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<tr>
<td>CDC</td>
<td>12FCAW2</td>
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<tr>
<td>Maximum Vehicle Crush</td>
<td>13.0 in (33.0 cm)</td>
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<tr>
<td>Maximum Perm End Treatment</td>
<td>78.8 in (200.0 cm)</td>
</tr>
<tr>
<td>Impact Speed</td>
<td>60.7 mi/h (97.7 km/h)</td>
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<tr>
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<td>0.0 deg</td>
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<tr>
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<td>N/A</td>
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<tr>
<td>Vehicle Accelerations</td>
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<tr>
<td>(Max. 0.050-sec Avg)</td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>-17.1 g</td>
</tr>
<tr>
<td>Lateral</td>
<td>3.1 g</td>
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<tr>
<td>Occupant Impact Velocity</td>
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<tr>
<td>Longitudinal</td>
<td>41.9 ft/s (12.8 m/s)</td>
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<tr>
<td>Lateral</td>
<td>-4.8 ft/s (1.5 m/s)</td>
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<tr>
<td>Occupant Ridedown Accelerations</td>
<td></td>
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<tr>
<td>Longitudinal</td>
<td>-17.7 g</td>
</tr>
<tr>
<td>Lateral</td>
<td>1.1 g</td>
</tr>
</tbody>
</table>

Figure 24. Summary of Results for Test 7202-3.
Axes are vehicle fixed. Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll

Figure 25. Vehicle Angular Displacements for Test 7202-3.
Figure 26. Longitudinal Accelerometer Trace for Test 7202-3.
Figure 27. Lateral Accelerometer Trace for Test 7202-3.
Figure 28. Vertical Accelerometer Trace for Test 7202-3.
Despite the higher than acceptable occupant impact velocity in the longitudinal direction, the end terminal basically performed as designed. Review of the electronic data and photographic coverage of the crash test indicated that the initial impulse was too high which in turn resulted in the unacceptable longitudinal occupant impact velocity. The initial impulse reflected the combined effect of accelerating the impact end section, breaking of the end post, initial crushing of the first-stage composite tube, and acceleration of the outer tube, all within a very short time period of 35 to 40 milli-seconds. In order to reduce the magnitude of this initial impulse, the end terminal design was modified to provide better staging of the sequence of events.

The 7 in x 7 in x 1/8 in (17.8 cm x 17.8 cm x 3.2 mm) outer tube was lengthened from 22 ft (6.7 m) to 24 ft (7.3 m). The impact end section was shortened from 4 ft (1.22 m) to 3 ft (0.91 m). The end post and the two foundation tubes were moved back 1 ft (30.5 cm) to accommodate these changes. The spacing between the first two posts was increased from 7 ft-8 in (2.34 m) to 8 ft-8 in (2.64 m). The first-stage 6-in (15.24-cm) diameter, 1/8-in (3.2-mm) wall thickness composite tube was shortened from 7 ft (2.13 m) to 6 ft (1.83 m) by reducing the length of the tulip cut at the ends of the composite tube from 12 in (30.5 cm) to 6 in (15.24 cm). The second-stage 6-in (15.24-cm) diameter, 1/4-in (6.4-mm) wall thickness composite tube was lengthened from 12 ft (3.66 m) to 12 ft-8 in (3.86 m). The net effect of these changes is an empty space of 2 ft-6 in (76.2 cm) prior to the impact end section engaging the first-stage composite tube. This empty space allowed the acceleration of the impact end section, breaking of the end post, and acceleration of the outer tube to occur prior to initiation of the crushing of the composite tube, thus reducing the magnitude of the initial impulse.

Also, both the frontal impact plate and the reinforcing gusset plates for the end section were damaged extensively in this crash test and in the developmental crash test to the extent that the end section had to be rebuilt after each test. The damage was attributed to insufficient strength for the gusset plates and the frontal impact plate. While the damage to the frontal impact plate and the gusset plates does not affect the impact performance of the end terminal, it is desirable to minimize the damage and the associated repair costs. The design of the impact end section was therefore modified to use 1/2-inch (1.27-cm) thick steel plates for the frontal impact plate and the gusset plates.
These design modifications were incorporated into the test installation for the compliance crash tests.

4.2 COMPLIANCE CRASH TESTS

As mentioned previously, four compliance crash tests are required to evaluate the performance of an end terminal design, according to guidelines presented in NCHRP Report 230. These four crash tests, listed according to the actual test sequence, are as follows:

1. **Test Designation 45.** An 1,800-lb (817-kg) passenger car impacting the end terminal head-on with an offset of 15 inches (0.38 m) from the center of the nose at a nominal impact speed of 60 miles per hour (96.6 km/h).

2. **Test Designation 41.** A 4,500-lb (2,041-kg) passenger car impacting the end terminal head-on at the center of the nose at the nominal speed of 60 miles per hour (96.6 km/h).

3. **Test Designation 44.** An 1,800-lb (817-kg) passenger car impacting the installation midway between the nose and the length of need at a nominal impact speed and angle of 60 miles per hour (96.6 km/h) and 20 degrees.

4. **Test Designation 40.** A 4,500-lb (2,041 kg) passenger car impacting the installation at the beginning of length-of-need at the nominal speed and angle of 60 miles per hour (96.6 km/h) and 25 degrees.

4.2.1 Repeat of First Compliance Crash Test (Test No. 7202-3A)

The first compliance test, i.e., test designation 45 with an 1,800-lb (817-kg) passenger car impacting the end terminal head-on with an offset of 15 inches (0.38 m) from the center of the nose at a nominal impact speed of 60 miles per hour (96.6 km/h), was repeated after incorporating the design modifications as described above. Photographs of the test installation are shown as Figures 29 and 30. A 1988 Yugo GVL (shown in Figure 31) impacted the end terminal end-on with a 15 in (38.1 cm) offset to the left of the vehicle centerline at 58.1 miles per hour (93.5 km/h). The vehicle was directed into the test installation using a cable reverse tow and guidance system. Test inertia mass of the vehicle was 1,800 pounds (817 kg) and the gross static mass was 1,965 pounds (892 kg). The height
Figure 29. Photographs of Test Installation Before Test 7202-3A.
Figure 30. Vehicle/End Terminal Geometries Before Test 7202-3A.
Figure 31. Photographs of Vehicle Before Test 7202-3A.
to the lower edge of the vehicle bumper was 14.3 in (36.2 cm) and 19.8 in (50.2 cm) to the
top of the bumper. Other dimensions and information on the vehicle are given in Figure
32.

The vehicle was free wheeling and unrestrained just prior to impact. Upon impact,
the front bumper of the vehicle wrapped around the frontal impact plate of the end section
and began to accelerate the end section forward. Shortly thereafter, the wooden end post
(post 1) fractured while the end section continued to move forward. At approximately 0.025
second, the stoppers on the impact end section contacted the outer tube and the outer tube
began to accelerate and telescope over the standard box-beam rail. Shortly thereafter at
0.028 second, the outer tube buckled at its connection with the impact end section. The
outer tube continued to telescope over the standard box-beam rail, seemingly unaffected by
the local buckling. The vehicle impacted and displaced the second post at approximately
0.170 second. The outer tube ceased forward movement at approximately 0.200 second and
began to buckle as the vehicle yawed counterclockwise. The rear wheels of the vehicle
became airborne during the rotation and the right front wheel also momentarily became
airborne. The vehicle rotated for a total of approximately 120 degrees and came to rest
behind the installation approximately 14 ft (4.27 m) downstream and 11 feet (3.35 m) lateral
of the initial point of impact, as shown in Figure 33. Sequential photographs of the test are
shown in Figure 34.

The end terminal was displaced forward dynamically for a maximum distance of
approximately 9-1/2 ft (2.90 m) and the residual displacement was 8 ft-10.3 in (269.9 cm).
The maximum lateral dynamic deflection of the rail was 27.0 in (68.6 cm). Maximum lateral
residual deformation was 15.6 in (39.6 cm). The end section, with the thicker frontal impact
plate and gusset plates, received only superficial damage. The rail was detached from the
first five posts. Damage sustained by the test installation is shown in Figure 35. The first­
stage 6-ft (1.83-m) long, 6-in (15.24-cm) diameter, 1/8-in (3.2-mm) wall thickness composite
tube was totally crushed and the second-stage 12 ft-8 in (3.86-m) long, 6-in (15.24-cm)
diameter, 1/4-in (6.4-mm) wall thickness composite tube was crushed for a length of
approximately 5 in (12.7 cm).

The vehicle received moderate damages, as shown in Figure 36. The damage
sustained was concentrated at the front of the vehicle. The maximum crush was 9.5 in (24.1
Date: 5-15-92  Test No.: 7202-3A  VIN: VX1BB1222KK439667
Make: Yugo  Model: GVL  Year: 1988  Odometer: 20695

Tire Condition: good  fair  badly worn

Vehicle Geometry - inches
a 60.25"  b 26.00"

Engine Type: 4 cyl.
Engine CID: 1100 cc
Transmission Type: Manual or Automatic
Body Type: Hatch
Steering Column Collapse Mechanism:

Note any damage to vehicle prior to test:

* d = overall height of vehicle

Figure 32. Vehicle Properties for Test 7202-3A.
Figure 33. Final Resting Position of Vehicle After Test 7202-3A.
Figure 34. Sequential Photographs of Test 7202-3A (overhead and frontal views).
Figure 34. Sequential Photographs of Test 7202-3A (continued) (overhead and frontal views).
Figure 34. Sequential Photographs of Test 7202-3A (continued) (perpendicular view).
Figure 35. Photographs of Test Installation After Test 7202-3A.
Figure 35. Photographs of Test Installation After Test 7202-3A (continued).
Figure 36. Photographs of Vehicle After Test 7202-3A.
cm) at the left quarter of the front bumper. Damage was sustained to the front right and left fenders, hood, bumper, grill, radiator and fan. In addition, a hole was noted in the transmission and the floor pan and the roof were slightly deformed.

A summary of the test results and other information pertinent to this test are given in Figure 37. Occupant impact velocity in the longitudinal direction was 32.5 feet per second (9.9 m/s) and -4.0 feet per second (-1.2 m/s) in the lateral direction. The highest 0.10 second occupant ridedown accelerations were -14.9 g in the longitudinal direction and 1.4 g in the lateral direction. The maximum 0.050-second average acceleration experienced by the vehicle was -15.3 g in the longitudinal direction and 2.4 g in the lateral direction. Vehicle angular displacements are plotted in Figure 38 and vehicle accelerometer traces are displayed in Figures 39 through 41.

In summary, the behavior of the end terminal was very similar to that of the previous test (test 7202-3). However, the modifications to the end terminal design reduced the occupant impact velocity in the longitudinal direction to 32.5 ft/s (9.9 m/s), which was above the design limit of 30 ft/s (9.14 m/s), but below the maximum allowable occupant impact velocity of 40 ft/s (12.2 m/s) set forth in NCHRP Report 230. There were no debris or detached elements that could pose potential hazard to the impacting vehicle or to adjacent traffic. There was minimal deformation and intrusion into the occupant compartment. The vehicle remained upright and stable during the test sequence and after exiting from the rail.

4.2.2 Second Compliance Crash Test (Test No. 7202-2)

Photographs of the test installation are shown in Figures 42 and 43. A 1981 Cadillac Sedan (shown in Figure 44) impacted the end terminal end-on at 58.0 miles per hour (93.3 km/h). The vehicle was directed into the test installation using a cable reverse tow and guidance system. Test inertia mass of the vehicle was 4,500 pounds (2,041 kg). The height to the lower edge of the vehicle bumper was 13.5 in (34.3 cm) and 21.3 in (54.0 cm) to the top of the bumper. Other dimensions and information on the vehicle are given in Figure 45.

The vehicle was free wheeling and unrestrained just prior to impact. Upon impact, the front bumper of the vehicle wrapped around the frontal impact plate and began to accelerate the end section. Shortly thereafter, the wooden end post (post 1) fractured and
Test No .................. 7202-3A
Date ..................... 05/25/92
Test Installation ........ Wyoming End Treatment
Installation Length ..... 200 ft. (61.0 m)
Test Vehicle .......... 1988 Yugo
Vehicle Weight
Test Inertia ........ 1800 lb (816 kg)
Vehicle Damage Classification
TAD ....................... 12-FC-5
CDC ....................... 12FCEW2
Maximum Vehicle Crush. .. 9.5 in (2.9 cm)
Maximum Perm End Treatment Displacement ........ 106.3 in (269.9 cm)

Impact Speed .......... 58.1 mi/h (93.5 km/h)
Impact Angle .......... 0.0 deg
Exit Speed ............. N/A
Exit Trajectory ........ N/A
Vehicle Accelerations
(Max. 0.050-sec Avg)
Longitudinal .......... -15.3 g
Lateral ................. 2.4 g
Occupant Impact Velocity
Longitudinal .......... 32.5 ft/s (9.9 m/s)
Lateral ................ -4.0 ft/s (1.2 m/s)
Occupant Ridedown Accelerations
Longitudinal .......... -14.9 g
Lateral ................ 1.4 g

Figure 37. Summary of Results for Test 7202-3A.
Axes are vehicle fixed.
Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll

Figure 38. Vehicle Angular Displacements for Test 7202-3A.
CRASH TEST 7202-3A
Class 180 Filter

Figure 39. Longitudinal Accelerometer Trace for Test 7202-3A.
CRASH TEST 7202-3A
Class 180 Filter

Figure 40. Lateral Accelerometer Trace for Test 7202-3A.
Figure 41. Vertical Accelerometer Trace for Test 7202-3A.
Figure 42. Photographs of Test Installation Before Test 7202-2.
Figure 42. Photographs of Test Installation Before Test 7202-2 (continued).
Figure 43. Vehicle/End Terminal Geometrics Before Test 7202-2.
Figure 44. Photographs of Vehicle Before Test 7202-2.
Date: 5-27-92    Test No.: 7202-2    VIN: 1G6AD69N689149606

Make: Cadillac    Model: Sedan    Year: 1981    Odometer: 37193


Tire Condition: good __    fair __    badly worn __

Vehicle Geometry - inches
a 76.25"    b 39.50"

c 122.00"    d* 57.25"
e 57.00"    f 218.50"
g ______    h 57.0"
i ______    j 34.25"
k 17.00"    l 54.00"
m 21.25"    n 4.75"
o 13.50"    p 62.25"
r 28.25"    s 16.25"

Engine Type: 8 cyl.
Engine CID: 5.7 liter
Transmission Type: Automatic or Manual
FWD or RWD or 4WD

Body Type: __

Steering Column Collapse Mechanism:
- Behind wheel units
- Convoluted tube
- Cylindrical mesh units
- Embedded ball
- NOT collapsible
- Other energy absorption
- Unknown

Brakes:
Front: disc X drum
Rear: disc __ drum X

* = overall height of vehicle

Figure 45. Vehicle Properties for Test 7202-2.
the end section continued to move forward. At 0.027 second, the stoppers on the impact end section contacted the outer tube and the outer tube began to accelerate and telescope over the standard box-beam rail. As the outer tube continued to telescope over the standard box-beam rail, the vehicle impacted and displaced the second and third post at approximately 0.157 sec and 0.289 sec, respectively. By 0.377 sec, the outer tube ceased its forward movement and began to buckle upward and outward as the vehicle continued forward. Meanwhile, the vehicle pitched forward and yawed counter-clockwise slightly. The vehicle then rebounded from the end terminal and came to rest approximately 2.3 feet (0.70 m) from the end terminal. Sequential photographs of the test are shown in Figure 46.

The end terminal was displaced forward dynamically for a maximum distance of 15 ft-1.25 in (4.60 m) and the residual displacement was 14 ft-8.5 in (4.48 m). The maximum dynamic deflection of the rail was 7.9 in (20.1 cm) laterally and 16.2 in (41.1 cm) vertically. Maximum residual deformation was 3.6 in (9.1 cm) laterally and 8.8 in (22.3 cm) vertically. In addition, the rail was detached from the first seven posts. Also, posts downstream from post 7 were pushed backward slightly due to movement in the box-beam rail as the outer tube was buckled. Damage sustained by the test installation is shown in Figure 47.

The vehicle received moderate damages, as shown in Figure 48. The damage sustained was concentrated at the front center of the vehicle. The maximum crush was 24.0 in (61.0 cm) at the center of the front bumper. Damage was noted to the hood, left and right front fenders, and grill and radiator. In addition, a hole was found in the transmission pan.

A summary of the test results and other information pertinent to this test are given in Figure 49. The maximum 50-msec average acceleration experienced by the vehicle was -11.1 g in the longitudinal direction and 1.1 g in the lateral direction. Occupant impact velocity in the longitudinal direction was 25.5 feet per second (7.7 m/s) and -5.5 feet per second (-1.7 m/s) in the lateral direction. The highest 10-msec occupant ridedown accelerations were -11.6 g in the longitudinal direction and -1.1 g in the lateral direction. Vehicle angular displacements are plotted in Figure 50 and vehicle accelerometer traces are displayed in Figures 51 through 53.

In summary, the end terminal performed satisfactorily by bringing the vehicle to a safe and controlled stop. The vehicle and rail installation sustained moderate damage.
Figure 46. Sequential Photographs of Test 7202-2 (overhead and frontal views).
Figure 46. Sequential Photographs of Test 7202-2 (continued) (overhead and frontal views).
Figure 46. Sequential Photographs of Test 7202-2 (continued) (perpendicular view).
Figure 47. Photographs of Test Installation After Test 7202-2.
Figure 47. Photographs of Test Installation After Test 7202-2 (continued).
Figure 48. Photographs of Vehicle After Test 7202-2.
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</tr>
<tr>
<td>Test Installation</td>
<td>Wyoming End Treatment</td>
</tr>
<tr>
<td>Installation Length</td>
<td>200 ft. (61.0 m)</td>
</tr>
<tr>
<td>Test Vehicle</td>
<td>1981 Cadillac Sedan</td>
</tr>
<tr>
<td>Vehicle Weight</td>
<td>4500 lb (2041 kg)</td>
</tr>
<tr>
<td>Test Inertia</td>
<td>4500 lb (2041 kg)</td>
</tr>
<tr>
<td>Vehicle Damage Classification</td>
<td>12-FC-4</td>
</tr>
<tr>
<td>TAD</td>
<td>12-FC-4</td>
</tr>
<tr>
<td>CDC</td>
<td>12FCEW2</td>
</tr>
<tr>
<td>Maximum Vehicle Crush.</td>
<td>24.0 in (61.0 cm)</td>
</tr>
<tr>
<td>Maximum Perm End Treatment Displacement</td>
<td>176.5 in (448.3 cm)</td>
</tr>
<tr>
<td>Impact Speed</td>
<td>58.0 mi/h (93.3 km/h)</td>
</tr>
<tr>
<td>Impact Angle</td>
<td>0.0 deg</td>
</tr>
<tr>
<td>Exit Speed</td>
<td>N/A</td>
</tr>
<tr>
<td>Exit Trajectory</td>
<td>N/A</td>
</tr>
<tr>
<td>Vehicle Accelerations</td>
<td>(Max. 0.050-sec Avg)</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>-11.1 g</td>
</tr>
<tr>
<td>Lateral</td>
<td>1.1 g</td>
</tr>
<tr>
<td>Occupant Impact Velocity</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>Lateral</td>
<td>-5.5 ft/s (-1.7 m/s)</td>
</tr>
<tr>
<td>Occupant Ridedown Accelerations</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>Lateral</td>
<td>-1.1 g</td>
</tr>
</tbody>
</table>

Figure 49. Summary of Results for Test 7202-2.
Axes are vehicle fixed.
Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll

Figure 50. Vehicle Angular Displacements for Test 7202-2.
CRASH TEST 7202-2
Class 180 Filter

Figure 51. Longitudinal Accelerometer Trace for Test 7202-2.
CRASH TEST 7202-2
Class 180 Filter

![Lateral Accelerometer Trace for Test 7202-2](image)

**Figure 52.** Lateral Accelerometer Trace for Test 7202-2.
Figure 53. Vertical Accelerometer Trace for Test 7202-2.
There were no debris or detached elements that could pose potential hazard to the impacting vehicle or to adjacent traffic. There was no deformation or intrusion into the occupant compartment. The vehicle remained upright and stable during the test period. Occupant impact velocities and ridedown accelerations were within the recommended limits set forth in NCHRP Report 230.

4.2.3 Third Compliance Crash Test (Test No. 7202-5)

Photographs of the test installation are shown in Figures 54 and 55. A 1987 Yugo GV (shown in Figure 56) impacted the test installation 1 ft (0.3 m) upstream of post 2, or 8 ft-8 in (2.64 m) downstream from the beginning of the end terminal, at an impact speed of 62.3 miles per hour (100.3 km/h) and at an angle of 20.7 degrees. The vehicle was directed into the test installation using a cable reverse tow and guidance system. Test inertia mass of the vehicle was 1,800 pounds (817 kg) and the gross static mass was 1,965 pounds (892 kg). The height to the lower edge of the vehicle bumper was 14.0 in (35.6 cm) and 19.8 in (50.2 cm) to the top of the bumper. Other dimensions and information on the vehicle are given in Figure 57.

The vehicle was free wheeling and unrestrained just prior to impact. Upon impact, the outer tube began to deform laterally and the vehicle began to redirect. As the vehicle proceeded down the rail, the vehicle continued to redirect with a counterclockwise yaw. At the same time, the right front wheel of the vehicle underrode the box-beam rail and directly impacted posts 3 through 6. The contact between the right front wheel of the vehicle and the posts imparted a clockwise rotation to the vehicle, which counteracted against the counterclockwise yaw and redirection of the vehicle. At approximately 0.427 second, the vehicle began to yaw clockwise. The vehicle exited the rail installation as a result of the clockwise yaw, with the front of the vehicle remaining in contact with the rail installation as the vehicle exited. Due to the manner under which the vehicle exited from the rail installation, the exit speed and angle of the vehicle were considered not applicable and were not determined. The vehicle continued to rotate clockwise after exiting from the rail installation for approximately 120 degrees and came to rest approximately 150 feet (45.7 m) downstream from the point of initial impact and 4 feet (1.2 m) laterally in front of the rail.
Figure 54. Photographs of Test Installation Before Test 7202-5.
Figure 55. Vehicle/End Terminal Geometrics Before Test 7202-5.
Figure 56. Photographs of Vehicle Before Test 7202-5.
Date: 6-10-92  Test No.: 7202-5  VIN: VXIBA1211HK361742

Make: YUGO  Model: GV  Year: 1987  Odometer: 37567


Tire Condition: good ___  fair X  badly worn ___

H=24.75" Vehicle Geometry - inches
a  60.25"  b  25.5"

c  84.75"  d  55.75"

e  23.5"  f  133.75"

g ___  h  32.06"

i ___  j  30.75"

k  15"  l  31"

m  19.75"  n  2"

o  14"  p  51.75"

r  22.25"  s  14.25"

Engine Type: 4 cyl gas

Engine CID: 1.1 L.

Transmission Type: Automatic or Manual

FWD or RWD or 4WD

Body Type: 3 door

Steering Column Collapse Mechanism:

Behind wheel units
Convoluted tube
Cylindrical mesh units
Embedded ball
NOT collapsible
Other energy absorption
Unknown

Brakes:
Front: disc X drum
Rear: disc ___ drum X

Note any damage to vehicle prior to test:

Windshield cracked (marked)

* d = overall height of vehicle

Figure 57. Vehicle Properties for Test 7202-5.
installation. The vehicle was in contact with the rail installation for a total length of 24.7 ft (7.5 m). Sequential photographs of the test are shown in Figure 58.

Posts 2 through 6 were bent and the rail element was detached from these posts. The wooden end post and the anchorage assembly was undamaged, but the two foundation tubes were moved approximately 1.25 in (3.2 cm) in the soil at the top. The breakaway tensile connector remained attached and undamaged. The outer tube was buckled approximately 89 in (226.1 cm) downstream from the upstream end of the outer tube. The maximum lateral dynamic deflection of the rail was 26.8 in (68.0 cm) and the maximum lateral residual deformation was 18.1 in (46.0 cm). Damage sustained by the rail installation is shown in Figure 59.

The vehicle received moderate damages, as shown in Figure 60. The damage sustained was concentrated at the right front quarter of the vehicle. Maximum crush was 5.5 in (14.0 cm) at the right front corner the vehicle. The right front wheel and strut assembly was pushed rearward 5.8 in (14.6 cm). Other notable damage was sustained to the hood, grill, bumper and right door. In addition, the roof and floor pan were dented on the right side of the vehicle and the windshield was displaced from its frame.

A summary of the test results and other information pertinent to this test are given in Figure 61. Occupant impact velocity in the longitudinal direction was 21.6 feet per second (6.6 m/s) and -17.7 feet per second (-5.4 m/s) in the lateral direction. The highest 10-msec occupant ridedown accelerations were -7.1 g in the longitudinal direction and 9.7 g in the lateral direction. The maximum 50-msec average acceleration experienced by the vehicle was -4.6 g in the longitudinal direction and 6.5 g in the lateral direction. Vehicle angular displacements are plotted in Figure 62 and vehicle accelerometer traces are displayed in Figures 63 through 65.

In summary, the end terminal rail installation safely contained and redirected the impacting vehicle. There were moderate damages to the vehicle and rail installation. There were no debris or detached elements that could pose potential hazard to the impacting vehicle or to adjacent traffic. There was minimal deformation or intrusion into the occupant compartment. The vehicle remained upright and stable during the test sequence and after exiting from the test installation. Occupant impact velocities and ridedown accelerations were within the recommended limits set forth in NCHRP Report 230.
Figure 58. Sequential Photographs of Test 7202-5 (overhead and frontal views).
Figure 58. Sequential Photographs of Test 7202-5 (continued) (overhead and frontal views).
Figure 58. Sequential Photographs of Test 7202-5 (continued) (perpendicular view).
Figure 59. Photographs of Test Installation After Test 7202-5.
Figure 59. Photographs of Test Installation After Test 7202-5 (continued).
Figure 60. Photographs of Vehicle After Test 7202-5.
Test No ............... 7202-5.
Date ............... 06/10/92.
Test Installation .......... Wyoming End Treatment Rail Installation
Installation Length .......... 200 ft. (61.0 m)
Test Vehicle .......... 1987 Yugo
Vehicle Weight
Test Inertia .......... 1800 lb (816 kg)
Vehicle Damage Classification
TAD ............... 01-RFQ-5
CDC ............... 01RFEM3
Maximum Vehicle Crush. .......... 5.0 in (12.7 cm)
Maximum Perm End Treatment Displacement .......... N/A
Impact Speed .......... 62.3 mi/h (100.3 km/h)
Impact Angle .......... 20.7 deg
Exit Speed .......... N/A
Exit Trajectory .......... N/A
Vehicle Accelerations
(Max. 0.050-sec Avg)
Longitudinal .......... -4.6 g
Lateral .......... 6.5 g
Occipant Impact Velocity
Longitudinal .......... 21.6 ft/s (6.6 m/s)
Lateral .......... -17.7 ft/s (5.4 m/s)
Occipant Ridedown Accelerations
Longitudinal .......... -7.1 g
Lateral .......... 9.7 g

Figure 61. Summary of Results for Test 7202-5.
Figure 62. Vehicle Angular Displacements for Test 7202-5.
CRASH TEST 7202-5
Class 180 Filter

Figure 63. Longitudinal Accelerometer Trace for Test 7202-5.
Figure 64. Lateral Accelerometer Trace for Test 7202-5.
Figure 65. Vertical Accelerometer Trace for Test 7202-5.
4.2.4 Fourth Compliance Crash Test (Test No. 7202-4)

Photographs of the test installation are shown in Figures 66 and 67. A 1981 Cadillac Sedan DeVille (shown in Figure 68) impacted the end terminal installation at the beginning of length of need, which was selected to be at post 3 or 15 ft-8 in (4.77 m) from the beginning of the end terminal, at an impact speed of 61.7 miles per hour (99.3 km/h) and at an angle of 25.3 degrees. The vehicle was directed into the test installation using a cable reverse tow and guidance system. Test inertia mass of the vehicle was 4,500 pounds (2,041 kg). The height to the lower edge of the vehicle bumper was 12.5 in (31.8 cm) and 21.8 in (55.2 cm) to the top of the bumper. Other dimensions and information on the vehicle are given in Figure 69.

The vehicle was free wheeling and unrestrained just prior to impact. Upon impact, the box-beam rail was pushed up and over the top of the posts, but the rail remained in contact with the vehicle. As the vehicle continued forward, the right front wheel of the vehicle contacted and ran over the posts. At approximately 0.284 second, the rear of the vehicle contacted the rail. Shortly thereafter, the vehicle began to yaw clockwise and the rear of the vehicle lost contact with the rail at 0.490 second. The vehicle continued to yaw clockwise and slid along the rail until it came to rest against the rail approximately 145 ft (44.2 m) downstream from the point of impact. The vehicle was oriented approximately 15 degrees with respect to the rail at final rest. Total length of vehicle to rail contact was 61.7 ft (18.8 m). Sequential photographs of the test are shown in Figure 70.

Posts two through twelve were bent and the rail element was detached from these posts. The wooden end post and the anchorage assembly was undamaged. The breakaway tensile connector remained attached and undamaged. The outer tube was bent and required replacement. The maximum lateral dynamic deflection of the rail was 78.5 in (1.99 m). Maximum lateral residual deformation was 51.8 in (1.32 m). Damage sustained during testing is shown in Figure 71.

The vehicle received moderate damages, as shown in Figure 72. The damage sustained was concentrated at the right front quarter of the vehicle, although the entire right side of the vehicle sustained minor dents and scrapes. The maximum crush was 9.0 in (22.9 cm) at the right front corner the vehicle. Other notable damage was sustained to the hood,
Figure 66. Photographs of Test Installation Before Test 7202-4.
Figure 66. Photographs of Test Installation Before Test 7202-4 (continued).
Figure 67. Vehicle/End Terminal Geometrics Before Test 7202-4.
Figure 68. Photographs of Vehicle Before Test 7202-4.
Date: 6-12-92  Test No.: 7202-4  VIN: 1G6AD6990B9226389
Make: Cadillac  Model: Sedan de Ville  Year: 1981  Odometer: 18131
Test Inertial Gross Static
4-wheel weight
for c.g. det.  \( M_1 \)  2377  2449  
\( M_2 \)  1783  2051  
\( M_T \)  4160  4500

Note any damage to vehicle prior to test:

* \( d \) = overall height of vehicle

Figure 69. Vehicle Properties for Test 7202-4.
Figure 70. Sequential Photographs of Test 7202-4 (overhead and frontal views).
Figure 70. Sequential Photographs of Test 7202-4 (continued) (overhead and frontal views).
Figure 70. Sequential Photographs of Test 7202-4 (continued) (perpendicular view).
Figure 71. Photographs of Test Installation After Test 7202-4.
Figure 71. Photographs of Test Installation After Test 7202-4 (continued).
Figure 72. Photographs of Vehicle After Test 7202-4.
Figure 72. Photographs of Vehicle After Test 7202-4 (continued).
and bumper. The fuel tank was punctured and the floor pan dented on the left side at the rear passenger compartment area.

A summary of the test results and other information pertinent to this test are given in Figure 73. Occupant impact velocity in the longitudinal direction was 13.6 feet per second (4.2 m/s) and -11.4 feet per second (-3.5 m/s) in the lateral direction. The highest 10-msec occupant ridedown accelerations were -4.5 g in the longitudinal direction and 8.1 g in the lateral direction. The maximum 50-msec average acceleration experienced by the vehicle was -2.8 g in the longitudinal direction and 4.3 g in the lateral direction. Vehicle angular displacements are plotted in Figure 74 and vehicle accelerometer traces are displayed in Figures 75 through 77.

In summary, the end terminal rail installation safely contained and redirected the impacting vehicle. There were moderate damages to the vehicle and rail installation. There were no debris or detached elements that could pose potential hazard to the impacting vehicle or to adjacent traffic. There was minimal deformation or intrusion into the occupant compartment. The vehicle remained upright and stable during the test sequence and after exiting from the test installation. Although not required as part of the evaluation criteria, occupant impact velocities and ridedown accelerations were within the recommended limits set forth in NCHRP Report 230.
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<td>Test Installation</td>
<td>Wyoming End Treatment, Rail Installation</td>
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<td>Installation Length</td>
<td>200 ft. (61.0 m)</td>
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<td>Test Vehicle</td>
<td>1981 Cadillac</td>
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<td>Vehicle Weight</td>
<td></td>
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<tr>
<td>Test Inertia</td>
<td>4500 lb (2041 kg)</td>
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<td>Vehicle Damage Classification</td>
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<td>TAD</td>
<td>01-RFQ-5</td>
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<td>CDC</td>
<td>01RF EW2</td>
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<tr>
<td>Maximum Vehicle Crush</td>
<td>9.0 in (22.9 cm)</td>
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<tr>
<td>Maximum Perm End Treatment Displacement</td>
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<tr>
<td>Impact Speed</td>
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<td>Impact Angle</td>
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<tr>
<td>Exit Speed</td>
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<tr>
<td>Exit Trajectory</td>
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<td>Vehicle Accelerations</td>
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<td>Occasional Impact Velocity</td>
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<tr>
<td>Lateral</td>
<td>-11.4 ft/s (3.5 m/s)</td>
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<tr>
<td>Lateral</td>
<td>8.1 g</td>
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Figure 73. Summary of Results for Test 7202-4.
Axes are vehicle fixed.
Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll

Figure 74. Vehicle Angular Displacements for Test 7202-4.
Figure 75. Longitudinal Accelerometer Trace for Test 7202-4.
Figure 76. Lateral Accelerometer Trace for Test 7202-4.
CRASH TEST 7202-4
Class 180 Filter

Figure 77. Vertical Accelerometer Trace for Test 7202-4.
V. MEDIAN BARRIER APPLICATION

5.1 BACKGROUND

After the successful design, development, and crash testing of the telescopic energy absorbing end terminal for use with box-beam guardrails, a request was received from the Department to modify the existing design or to develop a new design for use as an end terminal for box-beam median barriers. After some preliminary evaluation, it was decided that the existing end terminal design for the box-beam guardrail can be readily adapted for use with the median barrier application. The concept was to transition from the 8 in x 6 in (20.3 cm x 15.24 cm) box-beam rail for the median barrier to the 6 in x 6 in (15.24 cm x 15.24 cm) box-beam rail for the guardrail so that the same end terminal can be used for both applications. This eliminated the need for developing and testing a new design which is both time consuming and expensive. Also, this would eliminate the need for keeping parts of two different end terminals in the inventory, thus simplifying the maintenance requirements.

5.2 DESIGN CONSIDERATIONS

The major differences between the standard box-beam median barrier and box-beam guardrail designs are as follows:

1. Box-beam rail element. The median barrier uses a 8 in x 6 in (20.3 cm x 15.24 cm) box-beam rail element while the guardrail uses a 6 in x 6 in (15.24 cm x 15.24 cm) box-beam rail element.

2. Post positioning and attachment. Both the box-beam median barrier and guardrail use S3x5.7 posts, but the positioning of the posts in relation to the box-beam rail element and the attachment details are different. For the box-beam median barrier, the posts are positioned in the middle of the box-beam rail element. Paddles are attached to the top of the posts which fit into slots built into the bottom of the rail element. For the box-beam guardrail, the posts are positioned on the back side, i.e., non-traffic side, of the rail element. Shelf angles are used to attach the rail element to the posts by bolting the rail element to the shelf angles which are in turn bolted to the posts.
In order to adapt the end terminal design for the box-beam guardrail to the median barrier application, these design differences between the standard box-beam median barrier and guardrail need to be taken into consideration. Specifically, the following three design modifications were made to the end terminal design for median barrier applications:

1. Design a connecting sleeve to transition from the 8 in x 6 in (20.3 cm x 15.24 cm) box beam rail element for the median barrier to the 6 in x 6 in (15.24 cm x 15.24 cm) box beam for the guardrail,
2. Redesign the shelf angles and bolting attachments for the end terminal to allow for positioning of the posts in the middle of the box beam instead of on the side, and
3. Reposition the breakaway tensile connector to minimize potential of damage to the connector from impact with the posts.

These design modifications are considered relatively minor and should not affect the impact performance of the end terminal. Thus, it is the opinion of the project staff that retesting of the end terminal for median barrier application is not necessary and therefore not recommended. As for the transition between the box-beam median barrier and the box-beam guardrail, crash testing of the transition design is also considered unnecessary since there is only minor difference in stiffness between the 8 in x 6 in (20.3 cm x 15.24 cm) and 6 in x 6 in (15.24 cm x 15.24 cm) box beams.

5.3 MEDIAN BARRIER END TERMINAL DESIGN DETAILS

Figure 78 shows a schematic of the end terminal design for use with box-beam median barrier applications. The end terminal design is basically the same as that for the box-beam guardrail except for the three modifications mentioned above. Design features that are common between the guardrail and median barrier applications are previously described in Section 3.3, "Final Design Details" and will not be repeated herein. More detailed descriptions of the three design modifications are presented as follows.

As shown in Detail MB-1 of Figure 70, the 8 in x 6 in (20.3 cm x 15.24 cm) box beam rail element for the median barrier is directly transitioned into the 6 in x 6 in (15.24 cm x 15.24 cm) box beam rail element of the end terminal at the splice, using the standard splice plate for the 6 in x 6 in (15.24 cm x 15.24 cm) box beam rail (see Detail MB-1-1).
Figure 78. Schematic of Median Barrier End Terminal Design Details.
the difference in width between the two box-beam rail elements, there is an 1-in (2.54-cm) protrusion on both sides of the rail element at the rail element. These protrusions are protected by two end caps bolted to the 8 in x 6 in (20.3 cm x 15.24 cm) box-beam rail element (see Detail MB-1-2) to minimize any snagging that may be caused by these protrusions.

Except for the wooden end post, all the S3x5.7 posts for the end terminal are positioned in the middle of the box-beam rail element for median barrier applications. The 6 in x 6 in (15.24 cm x 15.24 cm) box-beam rail element is attached to posts 6, 7 and 8 using an angle attachment and shear bolts, as shown in Detail MB-2 of Figure 70. The angle attachment consists of a 2-in (5.1 cm) long, 8 in x 4 in x 3/8 in (20.3 cm x 10.2 cm x 9.5 mm) angle is attached to the top of the post. The box-beam rail element is then attached to the top of the angles using 8 in (20.3 cm) long, 5/16-in (7.9-mm) diameter, grade 0 bolts that are designed to shear off upon impact. Note that the box-beam rail element is again not attached to post 5 as with the guardrail end terminal design. The 7 in x 7 in (17.8 cm x 17.8 cm) outer tube are attached to the posts 2, 3 and 4 with redesigned shelf angles, as shown in Detail MB-3 of Figure 70. There are two shelf angles for each post, one on each side of the post. The shelf angles are fabricated from 1/8-in (3.2-mm) thick sheet metal and have lips on the top to provide some restraint against lateral and vertical movements.

The breakaway tensile connector was relocated from the bottom to the top of the rail elements. This relocation of the breakaway tensile connector is needed to prevent direct impact of the tensile connector with the posts since the posts are positioned in the middle of the box beam. This relocation of the breakaway tensile connector is intended to reduce the potential for damaging the tensile connector and is not expected to affect its performance.
VI. SUMMARY OF FINDINGS AND RECOMMENDATIONS

6.1 SUMMARY OF FINDINGS

- A conceptual design for a crashworthy end terminal to the box-beam guardrail was previously developed under the Phase I feasibility study. The design uses a telescoping tube concept with fiberglass composite tubes as the energy absorption medium. The end terminal design is suitable for tangent installation and capable of stopping a range of vehicle, from an 1,800-pound (817-kg) mini-sized passenger car to a 4,500-pound (2,043 kg) vehicle from 60 mi/h (96.5 km/h). The conceptual design was improved and refined through further evaluation and developmental testing. The final design was then subjected to the required compliance crash tests in accordance with guidelines presented in NCHRP Report 230. Results of the compliance crash tests indicated that the end terminal design meets with all required evaluation criteria set forth in NCHRP Report 230.
- The end terminal design was adapted for use with box-beam median barriers, with minor design modifications.
- The estimated cost for the end terminal assembly, including the first 35 ft (10.7 m) of barrier length of need, is $2,000.

6.2 RECOMMENDATIONS AND DISCUSSIONS

- While the box-beam barrier end terminal design has been successfully crash tested and shown to meet all required evaluation criteria set forth in NCHRP Report 230, there may be unforeseen problems encountered in actual field applications. It is therefore recommended that the impact performance of this box-beam barrier end terminal design be monitored for a period of time to identify any problems that may show up in actual field installations. This would allow for timely correction of any identified problems, including minor design modifications, if necessary.
- There was some expressed interest by the Wyoming Department of Transportation to use the median barrier end terminal design configuration for both median barrier and roadside guardrail applications in order to reduce the number of barrier components that have to be stockpiled. Since the design configurations are
practically identical for median barrier and roadside guardrail applications, there is no foreseeable problem with using the median barrier end terminal design configuration for both applications, if so desired.

- The box-beam barrier end terminal is designed for tangent applications. However, there are situations where the end terminal may not be installed on a tangent, such as on curves and flared sections. For such non-tangent applications, the following guidelines are recommended:

1. The end terminal section, i.e., the end section with the impact plate assembly, the outer tube, and the first section of standard box beam, must be installed on a straight line in order for the end terminal to function properly. Also, the end terminal should be installed on relatively flat ground, e.g., a sideslope of no more than 10:1.

2. The end terminal can be installed on a curve or on a flare provided that the effective flare rate is no more than 10:1. This recommendation is based on engineering judgement that the end terminal will function properly up to an impact angle of 17 to 18 degrees. For high-speed impacts of greater than 17 or 18 degrees, the outer tube would begin to telescope and then bend out of the way sufficiently to act as a natural gating mechanism, allowing the vehicle to continue behind the barrier in a controlled manner.
REFERENCES


APPENDIX A

STANDARD PLANS FOR WYOMING BOX-BEAM END TERMINAL
GENERAL NOTES

1. DETAILS SHOWN ARE FOR A TYPICAL LEFT HAND INSTALLATION.
2. AS DEFINED IN THE SCHEMATIC LAYOUTS ON THIS SHEET.
3. FOR A RIGHT HAND INSTALLATION, ALL POSTS INCLUDING THE WOOD POST ARE LOCATED ON THE OPPOSITE SIDE OF THE GUARDRAIL AWAY FROM TRAFFIC.

2. SEE PLANS FOR SPECIFIC GUARDRAIL LAYOUTS.

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END STANDARD BOX BEAM END TERMINAL (WY-BET)

BEGIN PAY LENGTH WY-BET TERMINAL

GUARDRAIL PAY LENGTHS

(SEE PLANS FOR DETAILS)
FABRICATION NOTES

1. 2-1/2" venting and pick-up holes may be drilled into each end of end section on bottom to facilitate galvanization.
2. Weld 1" x 1/4" straps at corners to seal.
3. 1" x 1/4" straps overlap T56 x 6 x 3/16 by 1/4".
4. Maintain a 1/8" gap between end cap and 1" x 1/4" straps for welding.
1. 6" x 8" BREAKAWAY WOOD POST DIMENSIONS ARE NOMINAL. ACTUAL DIMENSIONS ARE 5 1/2" x 7 3/4".
2. BREAKAWAY CABLE SHALL BE TAUGHT.
SHEAR BOLT SHEAR BOLT REFLECTIVE ANGLE AND SHEAR BOLT POST ANGLE ATTACHMENT DETAILS  
SHEAR BOLTS FOR POSTS (5), (3) & (3)  
(PPOST (5) DOES NOT USE SHEAR BOLT OR SHEAR BOLT ANGLE)  
SHEAR BOLT POST ANGLE DETAIL  
(PPOSTS (5), (3) & (3)  
SHELF ANGLE ATTACHMENT DETAILS  
SHELF ANGLE FOR 7 X 7 OUTER TUBE  
(PPOSTS (3), (3) & (3)  
SHELF ANGLE FOR 7 X 7 X 1/8 OUTER TUBE  
SHEAR BOLT REFLECTIVE ANGLE DETAIL  
(PPOSTS (5), (3), (3) & (3)  
ALTERNATE REFLECTIVE WASHER MATERIAL MAY BE USED WITH SPECIFIC APPROVAL. WHITE REFLECTIVE SHEETING SHALL BE PROVIDED ON BOTH SIDES OF REFLECTORS EXCEPT FOR FOUR-LANE DIVIDED HIGHWAYS OR AS OTHERWISE SHOWN. YELLOW REFLECTIVE SHEETING SHALL BE PROVIDED ON ONE SIDE OF REFLECTORS LOCATED IN THE INSIDE SHOULDERS OF FOUR-LANE DIVIDED HIGHWAYS. WHITE REFLECTIVE SHEETING SHALL BE PROVIDED ON ONE SIDE OF REFLECTORS LOCATED IN THE OUTSIDE SHOULDERS OF FOUR-LANE DIVIDED HIGHWAYS.
**COMPOSITE TUBE END CAP DETAIL**

**TYPICAL TULIP DETAIL**

**COMPOSITE TUBE DETAILS**

**INTERMEDIATE SPACER DETAILS**

**UPSTREAM END OF FIRST SECTION OF STANDARD 6X6 BOX BEAM DETAILS**

**FABRICATION NOTES:**
1. WELD P X 1/4" STRAPS AT CORNERS TO SEAL.
2. F X 1/4" STRAPS OVERLAP 156 X 6 X 3/16 BY 1/4".
3. MAINTAIN A 1/8" GAP BETWEEN END CAP AND P X 1/4" STRAPS FOR WELDING.

**STANDARD 6X6 BOX BEAM DETAILS**

**COMPOSITE TUBE END CAPS ATTACHED TO COMPOSITE TUBE WITH DUCT TAPE**

**COMPOSITE TUBE END CAPS ATTACHED TO COMPOSITE TUBE WITH DUCT TAPE**

**5/32" X 5/32" X 1/4" END CAP - ONE EACH END**

**SHEET 3 OF 7**
APPENDIX B

SPECIFICATIONS AND TEST PROCEDURE FOR COMPOSITE TUBE
APPENDIX B

SPECIFICATIONS AND TEST PROCEDURE FOR COMPOSITE TUBE

The fiberglass/epoxy composite tubes used in the Wyoming box-beam telescopic energy-absorbing end terminal are MMFG Extren series 500 extruded fiberglass structural tubes. Two stages of energy attenuation are employed in the design: the first stage consists of a 6-in diameter composite tube with a 0.125-in wall thickness and the second stage a 6-in diameter composite tube with a 0.25-in wall thickness.

Equivalent fiberglass/epoxy composite tubes produced by other manufacturers are also acceptable provided that the material complies with the following specifications and exhibits comparable energy dissipation properties:

1. The fiberglass/epoxy composite tube shall be manufactured using the "pultrusion" process and consists of a glass fiber reinforced resin matrix with a glass resin ratio of approximately 50 percent. The resin shall consist of isophthalic polyester and glass reinforcement shall include the following three varieties:
   a. A surface mat shall be used on all exterior surfaces for chemical resistance and containment of other reinforcement fibers.
   b. Continuous glass strand rovings shall be used internally for longitudinal strength.
   c. Continuous strand mats shall be used internally for transverse strength.

2. The composite material shall exhibit the following minimum mechanical properties:
   a. Ultimate Tensile Strength:
      (Longitudinal Coupon) 30,000 psi
      (Transverse Coupon) 7,000 psi
      (Full Section in Bending) 20,000 psi
   b. Ultimate Compressive Strength:
      (Longitudinal Coupon) 30,000 psi
      (Transverse Coupon) 15,000 psi
      (Full Section in Bending) 20,000 psi
   c. Ultimate Shear Strength 4,500 psi
   d. Ultimate Breaking Strength 30,000 psi
e. Modulus of Elasticity
(Full Beam Section in Bending) 2.5 x 10^6 psi

f. Barcol Hardness 50

3. The energy dissipation properties of the alternate fiberglass/epoxy composite tube shall be evaluated using static compressive testing. Each test specimen shall be 24 inches in length with a 4-in long tulip shape cut into one end of the test specimen. The test specimen shall be crushed statically at a rate of 2 inches per minute and the total crush length shall be no less than 12 inches. A minimum of three (3) static compressive tests should be conducted. The results of each test shall meet the following static energy dissipation properties:

First Stage Energy Absorber (equivalent to the 6-in diameter composite tube with 0.125-in wall thickness)

- Average Crush Force, $F_a$ 18 ± 2 kips
- Maximum Compressive Force, $P$ 26 kips
- Allowable Compressive Force Variation, $V$ ± 2.5 kips

Second Stage Energy Absorber (equivalent to the 6-in diameter composite tube with 0.25-in wall thickness)

- Average Crush Force, $F_a$ .41 ± 3 kips
- Maximum Compressive Force, $P$ 55 kips
- Allowable Compressive Force Variation, $V$ ± 5 kips

Definitions of the average crush force, $F_a$, maximum compressive force, $P$, and allowable compressive force variation, $V$, are illustrated in Figure A-1.
Static Crush Test
Pultruded Fiber-Glass Tube

Graph showing force (kip) vs. displacement (in.) for a static crush test on a pultruded fiber-glass tube.