DEVELOPMENT OF W-BEAM SLOTTED RAIL END TERMINAL DESIGN

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* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
DISCLAIMER

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

KEY WORDS

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

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EXECUTIVE SUMMARY

The overall objective of this study was to analyze and evaluate the impact performance of various bridge rail, guardrail, transition, and end terminal designs currently in use by the Tennessee Department of Transportation (TDOT). The project was divided into two phases. Phase I involved the evaluation of various bridge rail, guardrail, transition, and end terminal designs through theoretical analyses and computer simulation. Phase II involved the full-scale crash testing and evaluation of existing and modified designs which were selected by TDOT for further evaluation. There are three major areas in the Phase II study:

1. Crash testing and evaluation of bridge railing designs,
2. Crash testing and evaluation of W-beam guardrail to bridge parapet transition designs, and
3. Design, development, crash testing and evaluation of a W-Beam slotted rail end terminal design.

This is the third volume of the final report for Phase II of the study, summarizing the effort undertaken to design, develop, crash test and evaluate a slotted-rail end terminal design for use with standard W-beam guardrails on highways with speed limits of 45 miles per hour (72.4 km/h) or less. The scope of work included design, theoretical analysis, pendulum testing and full-scale crash testing. An end terminal design utilizing the slotted rail concept was successfully developed and crash tested in this study.
# TABLE OF CONTENTS

- Metric Conversion Table .................................................. ii
- Disclaimer ........................................................................ iii
- Key Words .......................................................................... iii
- Acknowledgments ............................................................... iii
- Executive Summary ............................................................ iv
- List of Figures ..................................................................... vii
- List of Tables ....................................................................... x

## I. Introduction ..................................................................... 1
  - 1.1 Background ................................................................. 1
  - 1.2 Study Objective and Scope .......................................... 4

## II. Slotted Rail End Terminal Design ................................. 5
  - 2.1 Slotted Rail End Terminal Design Concept .................. 5
  - 2.2 Design Criteria .......................................................... 8
  - 2.3 Final Design Details ................................................... 9
  - 2.4 Cost Estimate ............................................................ 16

## III. Study Approach .......................................................... 17
  - 3.1 Pendulum Testing ...................................................... 17
  - 3.2 Full-Scale Crash Testing ............................................. 19
    - 3.2.1 Electronic Instrumentation and Data Processing .... 22
    - 3.2.2 Photographic Instrumentation and Data Processing .. 23
    - 3.2.3 Test Vehicle Propulsion and Guidance ................. 23

## IV. Results of Pendulum and Developmental Crash Tests .... 25
  - 4.1 Pendulum Tests ........................................................ 25
  - 4.2 Developmental Crash Tests ........................................ 27
    - 4.2.1 Test Number 7199-8 ........................................ 28
    - 4.2.2 Test Number 7199-8A ....................................... 39
    - 4.2.3 Test Number 7199-11 ....................................... 48
    - 4.2.4 Test Number 7199-13 ....................................... 67
TABLE OF CONTENTS (Continued)

V. RESULTS OF COMPLIANCE CRASH TESTS ......................... 79
   5.1 TEST NUMBER 7199-7 ....................................... 79
   5.2 TEST NUMBER 7199-14 ..................................... 89
   5.3 TEST NUMBER 7199-15 ..................................... 96

VI. SUMMARY OF FINDINGS AND RECOMMENDATIONS ............... 109
   6.1 SUMMARY OF FINDINGS .................................... 109
   6.2 RECOMMENDATIONS AND DISCUSSIONS ....................... 110

REFERENCES ..................................................... 112

APPENDICES
A. DIMENSIONS AND INFORMATION OF THE TEST VEHICLES ...... A-1
B. SEQUENTIAL PHOTOGRAPHS OF THE IMPACTS ................. B-1
C. VEHICULAR ACCELERATION VERSUS TIME TRACES ............. C-1
D. VEHICULAR ANGULAR DISPLACEMENT VERSUS TIME PLOTS ...... D-1
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schematic of Slot Configuration</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Schematic of Slotted Rail End Terminal Design</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Photographs of Pendulum Testing Facility</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>Test Installation for Pendulum Testing</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>Slotted rail end treatment before test 7199-8</td>
<td>29</td>
</tr>
<tr>
<td>6</td>
<td>Vehicle prior to test 7199-8</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>Vehicle/slotted rail geometrics for test 7199-8</td>
<td>31</td>
</tr>
<tr>
<td>8</td>
<td>Vehicle/slotted rail after test 7199-8</td>
<td>33</td>
</tr>
<tr>
<td>9</td>
<td>Slotted rail end treatment after test 7199-8</td>
<td>34</td>
</tr>
<tr>
<td>10</td>
<td>Vehicle after test 7199-8</td>
<td>35</td>
</tr>
<tr>
<td>11</td>
<td>Damage to door of vehicle after test 7199-8</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>Summary of results for test 7199-8</td>
<td>37</td>
</tr>
<tr>
<td>13</td>
<td>End treatment before test 7199-8A</td>
<td>41</td>
</tr>
<tr>
<td>14</td>
<td>Vehicle before test 7199-8A</td>
<td>42</td>
</tr>
<tr>
<td>15</td>
<td>Vehicle/end treatment geometrics for test 7199-8A</td>
<td>43</td>
</tr>
<tr>
<td>16</td>
<td>Vehicle/end treatment after test 7199-8A</td>
<td>44</td>
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<tr>
<td>17</td>
<td>End Treatment after test 7199-8A</td>
<td>45</td>
</tr>
<tr>
<td>18</td>
<td>Damage at post 3</td>
<td>46</td>
</tr>
<tr>
<td>19</td>
<td>Vehicle after test 7199-8A</td>
<td>47</td>
</tr>
<tr>
<td>20</td>
<td>Summary of results for test 7199-8A</td>
<td>49</td>
</tr>
<tr>
<td>21</td>
<td>Front and rear view of slots</td>
<td>52</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
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<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>22</td>
<td>End treatment before test 7199-11</td>
<td>53</td>
</tr>
<tr>
<td>23</td>
<td>Vehicle prior to test 7199-11</td>
<td>54</td>
</tr>
<tr>
<td>24</td>
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<td>55</td>
</tr>
<tr>
<td>25</td>
<td>Test site after test 7199-11</td>
<td>56</td>
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<td>26</td>
<td>Damage to end treatment after test 7199-11</td>
<td>57</td>
</tr>
<tr>
<td>27</td>
<td>Vehicle after test 7199-11</td>
<td>59</td>
</tr>
<tr>
<td>28</td>
<td>Vehicle after being uprighted (after test 7199-11)</td>
<td>60</td>
</tr>
<tr>
<td>29</td>
<td>Undercarriage of vehicle after test 7199-11</td>
<td>61</td>
</tr>
<tr>
<td>30</td>
<td>Summary of results for test 7199-11</td>
<td>64</td>
</tr>
<tr>
<td>31</td>
<td>End treatment before test 7199-11</td>
<td>68</td>
</tr>
<tr>
<td>32</td>
<td>Vehicle before test 7199-13</td>
<td>69</td>
</tr>
<tr>
<td>33</td>
<td>Vehicle end/treatment geometrics for test 7199-13</td>
<td>70</td>
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<td>34</td>
<td>Test site after test 7199-13</td>
<td>72</td>
</tr>
<tr>
<td>35</td>
<td>End treatment after removal of vehicle for test 7199-13</td>
<td>73</td>
</tr>
<tr>
<td>36</td>
<td>Vehicle after test 7199-13</td>
<td>74</td>
</tr>
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<td>37</td>
<td>Summary of results for test 7199-13</td>
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</tr>
<tr>
<td>38</td>
<td>Slotted rail end treatment before test 7199-7</td>
<td>81</td>
</tr>
<tr>
<td>39</td>
<td>Vehicle before test 7199-78</td>
<td>82</td>
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<tr>
<td>40</td>
<td>Vehicle/slotted rail geometrics for test 7199-7</td>
<td>83</td>
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<tr>
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<td>Slotted rail end treatment after test 7199-7</td>
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<tr>
<td>42</td>
<td>Vehicle after test 7199-7</td>
<td>86</td>
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<td>43</td>
<td>Summary of results for test 7199-7</td>
<td>87</td>
</tr>
<tr>
<td>44</td>
<td>End treatment before test 7199-14</td>
<td>90</td>
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<tr>
<td>45</td>
<td>Vehicle prior to test 7199-14</td>
<td>91</td>
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<td>46</td>
<td>Vehicle/end treatment geometrics for test 7199-14</td>
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<td>Damage to end treatment after test 7199-14</td>
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<td>Summary of results for test 7199-14</td>
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<td>Slotted rail end treatment before test 7199-15</td>
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<td>Slotted rail, posts 1 and 2, before test 7199-15</td>
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<td>Details of Slotted Bearing Plate</td>
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I. INTRODUCTION

The overall purpose of this study was to analyze and evaluate the impact performance of various bridge rail, guardrail, transition, and end terminal designs currently in use by the Tennessee Department of Transportation (TDOT). The project was divided into two phases. Phase I involved the evaluation of various bridge rail, guardrail, transition, and end terminal designs through theoretical analyses and computer simulation\(^1\). Phase II involved the full-scale crash testing and evaluation of existing and modified designs which were selected by TDOT for further evaluation. There are three major areas in the Phase II study:

1. Crash testing and evaluation of bridge railing designs,
2. Crash testing and evaluation of W-beam guardrail to bridge parapet transition designs, and
3. Design, development, crash testing and evaluation of a W-Beam slotted rail end terminal design.

This is the third volume of the final report for Phase II of the study, summarizing the effort undertaken to design and develop a crashworthy slotted-rail end terminal design for use with standard W-beam guardrails for application on highways with speed limits of 45 mi/h (72.4 km/h) or less.

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. Existing guardrail end safety treatments for W-beam guardrails include: turned-down, breakaway cable terminal (BCT), eccentric loader terminal (ELT), modified eccentric loader terminal (MELT), CAT, SENTRE, BRAKEMASTER, and the ET-2000. Brief descriptions of these existing end treatments are presented as follows.
Turned-down end treatments involve sloping the end of the W-beam rail down to the ground and attaching it to a rigid foundation. The turned-down end terminal is the least expensive of all the end treatments and used extensively in a number of states. However, it has been found that the turned-down end terminal causes impacting vehicles to ramp up and vault over the end treatment, oftentimes resulting in rollovers. For this reason, the Federal Highway Administration (FHWA), in a memorandum dated June 28, 1990 from the Director of the Office of Highway Safety to the Regional Federal Highway Administrators(3), has indicated that:

- Turned-down terminals should not be used on new installations of guardrails for freeway, expressway, or other high-speed, high-volume facilities.
- Safety improvement projects, hazard elimination projects, or 3R/4R projects on high-speed, high-volume facilities should require replacement of turned-down terminals with approved terminals.
- Use of turned-down terminals on projects involving high-speed, but moderate traffic carrying facilities should be considered on a case-by-case basis or an approved State developed policy.
- Use of turned-down terminals on low-speed or any low-volume facility may be allowed based on reasonable risk management considerations.

The FHWA has thus prohibited the use of turned-down terminals for high-speed, high-volume facilities although the use of turned-down terminals is still permissible, after due risk management considerations, for low-speed or low-volume facilities.

The breakaway cable terminal (BCT) is the most widely used end treatment since its conception and initial testing in 1972. The BCT end treatment is designed to cause the W-beam guardrail to "gate" or buckle out of the way of an impacting vehicle and to allow the impacting vehicle to penetrate behind the guardrail in a controlled manner. However, since the design relies on the dynamic buckling of the W-beam rail, it has been found that the impact performance of the BCT is very sensitive to installation details, such as barrier flare rate and end offset. Consequently, the BCT end treatment has not had a favorable service history. Furthermore, even when installed correctly with a 4-ft (1.22-m) parabolic flare offset, the BCT has been shown to impart unacceptably high deceleration forces on 1,800-lb (817-kg) mini-size
vehicles during 60 mi/h (96.6 km/h) impacts and has failed to meet the evaluation criteria set forth in National Cooperative Highway Research Program (NCHRP) Report 230.\(^4\)

The eccentric loader terminal (ELT) and the modified eccentric loader terminal (MELT) are improvements over the standard BCT. The designs are still based on the "gating" concept and the dynamic buckling of the W-beam rail for energy dissipation and controlled penetration. These end treatments have been successfully crash tested in accordance with NCHRP Report 230 requirements with a flare offset of 4 ft (1.22 m) and with marginally acceptable results for a flare offset of 18 in (457 mm). The ELT and MELT end terminals suffer from similar drawbacks as the standard BCT terminal, being sensitive to installation details. Further, the mechanisms are relatively complicated and have presented problems in actual field installations. Also, the costs of these end terminals are considerably higher than that of a standard BCT terminal.

The CAT end treatment consists of overlapping guardrail sections that have a series of closely spaced slots. Guardrail segments are attached with bolts through the slots. When a vehicle impacts the end terminal, the bolts are forced to tear through the W-beam from one slot to the next. As a result, the W-beam rail segments are cut into several long ribbons as the impacting vehicle is being decelerated. This design is relatively new and does not yet have an extensive field service record. The CAT end treatment is also very costly.

The SENTRE end treatment is constructed from a series of breakaway steel guardrail posts and frangible plastic sand containers. Impacting vehicles are decelerated as the guardrail posts are broken and the sand containers are impacted. A ground cable is incorporated to direct vehicles away from the end of the barrier to which it is attached. The system is very expensive and therefore has not gained wide acceptance.

The BRAKEMASTER end treatment attenuates impact energy through friction developed when a steel clamp slides along a wire rope. The design suffers from the same problems as the CAT and SENTRE in that it is very costly.

The ET-2000 end terminal attenuates head-on impacts through the flattening and bending of the W-beam rail element which brings the impacting vehicle to a controlled stop. The primary components of the terminal are a feeder chute which provides moment resistance for the terminal during end-on impacts, and an extruder which dissipates the energy of an
impacting vehicle through plastic deformation of the W-beam rail element. One of the advantages of this end terminal is that it is designed for use on a tangent section of the guardrail with no flare or offset. This design is relatively new and does not have an extensive field service record. It is also relatively expensive which limits its use to roadways with relatively high speed and traffic volume.

With the exception of the turned-down and the standard BCT end terminals, the other end terminal designs are relatively expensive. The turned-down end terminal is no longer approved for federal-aid projects on high-speed highways. The standard BCT terminal requires a 4-ft (1.22-m) flare offset which is oftentimes not available on low-speed, low-volume highways. Furthermore, the standard BCT terminal does not meet the small car crash test requirements set forth in NCHRP Report 230. There remains, therefore, a need for an end terminal to be used with W-beam guardrails that is crashworthy, has a relatively low-cost, and is applicable to installation with reduced flare offset.

1.2 STUDY OBJECTIVE AND SCOPE

The objective for this portion of the study was to design and develop a crashworthy end terminal for use with standard W-beam guardrails on highways with speed limits of 45 mi/h (72.4 km/h) or less.

Chapter II of this report provides detailed descriptions of the design concept, design criteria, and the final end terminal design. Chapter III outlines the study approach. Results of the pendulum tests and developmental crash tests are documented in Chapter IV of the report. Chapter V presents the results of the compliance crash tests. A summary of the study findings, conclusions and recommendations is presented in Chapter VI.
II. SLOTTED RAIL END TERMINAL DESIGN

The slotted rail end terminal design developed in this study was based on the split rail end terminal design concept, previously developed under another study conducted at Texas Transportation Institute (TTI). This design concept was selected by TDOT as the basis for developing a new crashworthy end-terminal design for W-beam guardrails on highways with speed limits of 45 mi/h (72.4 km/h) or less. A number of modifications and refinements were made to the initial conceptual design during the course of this study to arrive at the final design. Discussions on the initial design concept, the design criteria, and the final design details are presented in this chapter.

2.1 SLOTTED RAIL END TERMINAL DESIGN CONCEPT

The split rail end terminal concept involves cutting longitudinal slots in the W-beam rail element to reduce its dynamic buckling strength sufficiently to safely accommodate small car impacts while maintaining sufficient capacity to stop full-size vehicles within a reasonable distance for end-on impacts and to contain and redirect impacting vehicles in side impacts with the guardrail installation. As shown in figure 1, the W-beam rail element cross-section can be cut into four relatively flat segments by placing a longitudinal slot at each peak and valley in the cross-section. The three 0.5-in (13-mm) wide longitudinal slots reduce the cross-sectional area in the slotted region from 1.99 to 1.83 in² (1,284 to 1,181 mm²), which is still greater than the cross-sectional area of 1.61 in² (1,039 mm²) through the four bolt holes at a splice. Thus, the tensile capacity of the W-beam is not reduced since the tensile capacity of the W-beam rail element at the slotted segments is still higher than that at a splice.

On the other hand, the moment of inertia of the W-beam rail element is significantly reduced by the slots. The moment of inertia of an unmodified 12-gauge W-beam rail element is approximately 2.33 in⁴ (38,182 mm⁴). In comparison, the combined moments of inertia of the four relatively flat segments is only 0.02 in⁴ (328 mm⁴). Thus, the buckling strength of a slotted W-beam cross-section is only 1 percent of that of an unmodified cross-section.

The split rail end terminal design with a 4-ft (1.22-m) parabolic flare offset over the last 37.5 ft (11.4 m) of the guardrail has successfully passed all required compliance crash tests. 
Figure 1. Schematic of slot configuration.
The test installation incorporated 27-in (686-mm) long slots and weakened wooden posts for the first eight spans, i.e., the first 50 ft (15.24 m) of guardrail installation. The wooden end post was placed in a concrete foundation and a BCT breakaway cable anchor assembly was used to connect the W-beam rail element to the end post so as to provide tensile capacity for the W-beam rail element. A ground line cable connected these weakened wooden posts to prevent rotation of the posts and to ensure clean breaks at ground level. A buffered end section was wrapped around the end of the terminal to distribute impact forces over the front of the impacting vehicles.

The slots were protected with cover plates to prevent any intrusion by the bumper or other parts of the impacting vehicle into the slots. It was found in one of the developmental crash tests that intrusion of parts of the impacting vehicle into the slots could lead to tearing, ripping, and extending of one of the slots until it reached a splice, at which point the W-beam rail element would rupture and allow the vehicle to penetrate through the guardrail. The cover plate was bolted to one end of the slotted segment while the other end of the cover plate was attached to the W-beam rail with clips that can slide relative to the W-beam, thereby allowing the slots to collapse under axially compressive loading.

Also, two intermediate posts were added in spans 3 and 4, which effectively reduced the post spacing in those spans to 3 ft-1.5 in (0.95 m). The reduced post spacing increased the lateral stiffness of the guardrail which in turn improved the capacity of the terminal to handle redirectional or side impacts by large cars. Note that these two additional posts were not attached to the W-beam rail element.

Despite the successful impact performance and the relative low cost (estimated to be $750 or less per installation), the split rail end terminal design was never adopted for field installation, probably due to concerns over aesthetics and potential installation and maintenance problems.

The original split rail end terminal concept was retained for the slotted rail end terminal design, i.e., the use of slots in the rail element to reduce the bending moment of inertia and to facilitate controlled buckling of the W-beam rail element. The emphasis of the redesign effort was to: (1) reduce the offset from 4 ft (1.22 m) to 18 in (0.46 m); (2) optimize the slot lengths; and (3) develop an alternative to replace the cover plate, which was considered a potential
maintenance problem and not aesthetically pleasing. More detailed discussions on the design criteria used in designing and developing the slotted rail end terminal design are presented in the next section.

2.2 DESIGN CRITERIA

The design criteria used in the development of this new end terminal for W-beam guardrails are summarized below:

1. Meet nationally recognized safety standards, i.e., successfully crash tested in accordance with guidelines presented in NCHRP Report 230.
2. For use on highways with speed limits of 45 mi/h (72.4 km/h) or lower.
3. Perform satisfactorily when installed with a flare offset of 18 in (0.46 m).
4. Have relatively low construction costs.

The most critical design consideration is perhaps the flare offset of the end terminal. The standard BCT terminal design requires a flare offset of 4 ft (1.22 m). A flare offset of this magnitude is oftentimes not available on low-speed, low-volume roadways due to the lack of available clear recovery area on the roadside. It would be desirable to design the end terminal for tangent application or at least to accommodate a smaller flare offset.

According to guidelines presented in NCHRP Report 230(9), barrier end treatments are required to provide safe deceleration or controlled barrier penetration for vehicles impacting upstream from the beginning of the length-of-need (LON) and barrier anchorage for redirecting vehicles impacting beyond the LON. Most existing end terminal designs are based on either the concept of gating, i.e., allowing the impacting vehicle to penetrate behind the guardrail in a controlled manner such as the standard BCT terminal, or energy attenuation, i.e., bringing the vehicle to a controlled and safe stop such as the ET-2000 terminal.

A tangent application, initially preferred by TDOT, would require the end terminal design to be based strictly on the concept of energy attenuation since there is no eccentricity in the system for the end terminal to gate. The slotted rail end terminal design does have energy attenuation capability through buckling and collapsing of the slots and would likely work well for small car end-on impacts. However, there would be some potential problems for the large car end-on crash test. In a previous test of a 4,500-lb (2,043-kg) passenger car
head-on into the split rail end terminal design with no flare offset at 60 mi/h (96.6 km/h), the vehicle ramped over the top of the end terminal and continued down the test installation on top of the guardrail for some distance before coming to rest. Even though the vehicle did not roll over or sustain excessive deceleration rates, such ramping behavior is not considered desirable.

The slotted rail end terminal design employs both of these concepts, i.e., gating and energy attenuation. Energy from the impacting vehicle is dissipated through buckling and collapsing of the slots, which slows down the impacting vehicle prior to gating. After some consideration, the flare offset distance selected for the design was 18 in (0.46 m), which is the same as that for the ELT and the MELT. This flare offset of 18 in (0.46 m) was considered as the minimum offset for the gating mechanism to function properly.

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 costs approximately $12 per linear foot while the lowest-cost end treatment (i.e., turned-down end terminal) costs about $500 per installation. A typical 500-ft (152.4-m) 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 would be as high as or higher than the total cost of the guardrail for a typical installation. Thus, the cost of the end terminal was an important factor considered during the design process.

### 2.3 FINAL DESIGN DETAILS

Figure 2 shows details of the final design of the slotted rail end terminal that was successfully crash tested. The major components of the slotted rail end terminal design are listed as follows:

1. A 25-ft (7.62-m) section of slotted W-beam rail element with four sets of slots. Slot guards are bolted to the downstream ends of the slots to minimize the potential for tearing or ripping of the rail element at the slots.
End Anchorage Assembly (See Detail C)

5 1/2" x 7 1/2" x 3'-6 1/2" Wooden Breakaway Post in Steel Foundation Tube (See Detail D)

6"x8"x6'-0" Wooden CRT Post (See Detail E)

W6x9x6'-0" Structural Steel Post (Typ.)

Tangent line projected from the face of the last two post blocks in the standard post section.

Plan

25'-0" Slotted Rail (See Detail A)

18'-9" Flare

Post not connected to rail

Standard G4(1S) Guardrail

Slotguard (See Detail B)

Ground Line

See Detail F

6'-3" 6'-3" 6'-3" 6'-3" 6'-3"

Elevation

45 MPH SLOTTED RAIL TERMINAL

Figure 2. Schematic of slotted rail end terminal design.
DETAIL A
SLOTTED RAIL ELEMENT

Slotted W-beam
3/4" Ø holes for
5/8" bolts (TYP)

SECTION A-A

Note: At locations shown, cut three 1/2" slots. One on each peak, and one in the valley of the W-beam.

DETAIL B
SLOTGUARD

NOTE: All holes 3/4" diam.

Figure 2. Schematic of slotted rail end terminal design (continued).
Figure 2. Schematic of slotted rail end terminal design (continued).
Figure 2. Schematic of slotted rail end terminal design (continued).
2. A buffered end section, similar to that used with the standard BCT terminal, is attached to the end of the slotted rail section to distribute the impact load.

3. All four posts (posts 1 through 4) within the 25-ft (7.62-m) end terminal section are wooden breakaway posts. Posts 1 and 2 are placed in steel foundation tubes while posts 3 and 4 are controlled release terminal (CRT) posts. Standard wooden or steel guardrail posts are then used from post 5 on.

4. A post spacing of 6 ft 3 in (1.95 m) is used with the end terminal section.

5. A breakaway cable attachment, similar to that used with the BCT end terminal, is used to provide anchorage for the guardrail.

6. A straight flare offset of 18 in (0.46 m) is used, starting at post 4, i.e., the offsets at posts 1, 2, 3 and 4 are 18 in (457 mm), 12 in (305 mm), 6 in (152 mm), and zero (0), respectively.

The pattern of the slots for the first 25-ft (7.62-m) section of W-beam rail element is shown in detail A of figure 2. Four sets of slots are used, one at mid-span for each of the first four spans. Note that the slots in the first span (i.e., between posts 1 and 2) are offset 2 in (51 mm) toward post 1 to accommodate the breakaway cable anchor plate. The lengths of the slots are 18 in (457 mm) for the first two spans and 12 in (305 mm) for the third and fourth spans.

The main reason for using longer slots for the first two spans is to separate the impulse of breaking the wooden end post from that of buckling and collapsing the first set of slots. The longer slots also have a slightly lower buckling force which helps to soften the initial impulse and to reduce the yaw rate of the vehicle in the early stages of the impact. Shorter slots are used in spans 3 and 4 to reduce the potential for the bumper or other parts of the impacting vehicle to protrude into the slots during redirectional impacts and to stiffen the end terminal for the large vehicle end-on impacts.

Cover plates used in the original split rail end terminal were replaced with bolt-on slot guards. The slot guard is attached to the downstream end of each set of slots to prevent extension of the slots as observed in the split rail end terminal testing. The slot guard both reinforces the W-beam rail element and provides a 45-degree deflector plate to push the rail element away from any vehicle component that intruded into the slots. The slot guard design
alleviates the perceived problems with aesthetics, installation and maintenance associated with the use of cover plates. Details of the slot guard are shown as detail B of figure 2.

A standard buffered end or terminal section, similar to that used with the standard BCT terminal, is attached to the end of the slotted rail section to distribute the impact load. The end anchorage system is also similar to that of the BCT end terminal, as shown in detail C of figure 2. A 6 in x 8 in (152 mm x 203 mm) x 5 ft (1.52 m) long steel foundation tube provides the required anchorage capacity. A cable anchorage assembly is attached to the W-beam rail element at one end and anchored to the end wooden post and the foundation tube through a hole in the base of the post.

The first two posts are 5-1/2 in x 7-1/2 in (140 mm x 191 mm) wooden breakaway posts placed in foundation tubes to ensure proper breaking of the posts. These posts were weakened with a 2-3/4-in (70-mm) diameter hole at the base, as shown in detail D of figure 2. The next two posts (posts 3 and 4) are wooden 6 in x 8 in (152 mm x 203 mm) CRT posts. Two 3-1/2-in (89-mm) diameter holes are drilled into the CRT posts, one at ground line and the other at 16 in (406 mm) below surface, to facilitate fracture of the post upon impact. Details of the CRT post are shown as detail E in figure 2.

Note that the W-beam rail element is not bolted to post 2. Instead, a shelf angle is used to support the rail element, as illustrated in detail F of figure 2. Based on crash test results, there is concern that the bolt at post 2 may not disengage properly, which would cause excessive force to build up and prevent downstream slotted sections from buckling properly. On the other hand, it was found in another crash test that, without an intermediate support between the first two sets of slots, the buckled rail element could potentially rotate downward, thus allowing the vehicle to ramp over and mount the guardrail. The shelf angle, details of which are shown in detail F of figure 2, provides support to the rail element at post 2 and eliminates the need for a bolt at that post.

This slotted rail end terminal is designed for use with a minimum flare offset of 18 in (0.46 m). As mentioned previously, a flare offset of 18 in (0.46 m) was considered as the minimum offset for the gating mechanism to function properly and was therefore selected for the design. A straight line flare starting at post 4 is used instead of the parabolic flare used
with the standard BCT end terminal. This straight flare configuration simplifies the layout and installation of the end terminal.

2.4 COST ESTIMATE

The major components of this end terminal include: (1) one 25-ft (7.62 m) section of slotted W-beam rail element, (2) four slot guards, (3) two breakaway wooden posts placed in foundation tubes, (4) two wooden CRT posts, and (5) one buffered end section. With the exception of the 25 ft (7.62-m) section of slotted W-beam rail element, the slot guards, and the two CRT posts, the other components are standard BCT end terminal components. It is difficult to estimate the actual costs of slotted rail and slot guards since these components were manually fabricated in the prototype installation and the costs are, as may be expected, much higher than what may be expected when these components are manufactured on a large scale. For example, the slots were machined manually for the prototype installations. Discussions with manufacturers indicate that, for mass production, the slots could be punched at a very low cost. However, there will be some initial tooling costs, which can be amortized over all the units manufactured and sold over the life of the special tools. Thus, the tooling cost per unit of rail element is a function of the demand.
III. STUDY APPROACH

The study approach was divided into two major tasks:

1. Further development of conceptual design, and
2. Crash testing and evaluation of the end terminal design.

As mentioned previously, a split rail end terminal design was previously developed under another study. The design concept was further improved and modified during the course of this study. Additional pendulum testing was conducted to determine the energy absorbing characteristics of different slot lengths and the effect of the slot guard. The results of these pendulum tests were then used to select the appropriate slot lengths and configurations for use with the end terminal design. Design details were added, deleted, or modified in conjunction with the fabrication of the prototype installations. A series of crash tests were then conducted to evaluate the performance of the end terminal design in accordance with guidelines presented in NCHRP Report 230. Additional modifications were made to the design based on the results of developmental crash tests.

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

3.1 PENDULUM TESTING

Pendulum testing provides an inexpensive means of assessing the energy absorbing characteristics of different slot lengths and configurations. The pendulum testing facility, as shown in figure 3, consists of a structural frame for hanging of the pendulum mass. The pendulum mass weighs approximately 2,300 lb (1,044 kg) and is supported by four steel cables in such a manner as to insure continuous horizontal alignment and lateral stability of the impacting mass. The nose of the pendulum mass is outfitted with a sliding mechanism which can be used to house a honeycomb assembly to simulate the crush characteristics of selected vehicles. Since the pendulum tests conducted in this study were developmental in nature, a rigid nose cushioned with a piece of wood and a 1-1/2-in (38-mm) thick rubber pad was used instead of the honeycomb assembly.
Figure 3. Pendulum Testing Facility.
The pendulum mass can be raised to different heights using a winch mechanism to attain different impact speeds of up to a maximum of 25 mi/h (40.2 km/h). After the pendulum mass is raised to the desirable height for a pre-determined impact speed, a solenoid release hook is then activated to release the pendulum mass to initiate the test. A soil pit or a rigid steel mounting plate is available for installation of the test article into the ground, e.g., base plates for breakaway structures, posts for barriers, etc. Also, a rigid steel backup structure is available for support of the test article in the horizontal direction.

The pendulum mass was instrumented with a single accelerometer in the longitudinal direction to measure acceleration levels. The electronic signals from the accelerometer were telemetered to a base station for recording on magnetic tape and for display on a real-time strip chart. After the test, the data were filtered with a SAE J211 Class 180 filter and digitized using a microcomputer. Data analyses included plots of acceleration level versus displacement and energy dissipated versus displacement. Photographic coverage of the pendulum tests included one 3/4-in videotape camcorder and still cameras for documentary purposes.

Figure 4 shows the test configuration for the pendulum testing. W-beam rail sections, 12.5 ft (3.81 m) in length, were used as test specimens. The back end of the W-beam rail section was bolted to the rigid steel backup structure. A wooden CRT post, mounted in a steel foundation tube, supported the rail section in the middle and separated the rail element into two spans. Each test specimen had two sets of slots mid-span of the two spans. An impact plate was bolted to the front end of the W-beam rail section to minimize the potential for non-axial loading of the rail.

3.2 FULL-SCALE CRASH TESTING

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 compliance crash tests are as follows:

1. 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 mi/h (96.6 km/h) and 25 degrees. The objective of this test is to evaluate the adequacy of the terminal anchorage.
Figure 4. Test installation for pendulum testing.
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 mi/h (96.6 km/h). The objective of this test is to evaluate the energy-absorbing/dissipation properties of the end terminal.

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 mi/h (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 45.** An 1,800-lb (817-kg) passenger car impacting the end terminal head-on with an offset of 15 in (0.38 m) from the center of the nose at a nominal impact speed of 60 mi/h (96.6 km/h). The objective of this test is to evaluate the impact performance of the terminal for small-car end-on impacts.

Since the intended application of this new slotted rail end terminal design is for highways with speed limits of 45 mi/h (72.4 km/h) or less, the nominal impact speeds for these crash tests were reduced from 60 to 45 mi/h (96.6 to 72.4 km/h). Accordingly, all future references to these crash tests in this report will refer to nominal impact speeds of 45 mi/h (72.4 km/h) instead of the standard 60 mi/h (96.6 km/h).

For the purpose of evaluating the performance of this slotted rail end terminal design, only three of the four compliance crash tests were deemed necessary. Test designation 44, which involves 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 45 mi/h (72.4 km/h) and 20 degrees was considered not necessary. The rationale for this decision was that this crash test was successfully conducted with the original split rail end terminal design at a nominal speed of 60 mi/h (96.6 km/h). The modifications made to the end terminal design in this study should not affect the stability of the vehicle or occupant risk factors for this small car redirectional test. The nominal impact speed is lower at 45 mi/h (72.4 km/h). The angle of impact is also lower since the slotted rail end terminal was designed for a flare offset of 18 in (0.46 m) as compared to a flare offset of 4 ft (1.22 m) for the split rail end terminal design. It was therefore concluded that a repeat of this particular test was unnecessary and thus not
conducted. The Federal Highway Administration (FHWA) was consulted and agreed to this decision.\(^9\)

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.

### 3.2.1 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.

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 PLOTANGLE. 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-ms 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-ms 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 PLOTANGLE program uses the digitized data from the yaw, pitch, and roll rate charts to compute angular displacement in degrees at 0.00067-sec 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.

3.2.2 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 to document wheel contact on the guardrail posts and end of the concrete parapet. A flash bulb activated by pressure sensitive taperswitches 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.

3.2.3 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.
IV. RESULTS OF PENDULUM AND DEVELOPMENTAL CRASH TESTS

4.1 PENDULUM TESTS

A total of 8 pendulum tests were conducted to study the energy absorption characteristics of various slot lengths and the effect of the slot guard. Table 1 summarizes the results of the pendulum tests. Results of pendulum tests conducted in the previous study to develop the split rail end terminal are shown in table 2.

As shown in these tables, peak deceleration rates and energy dissipation from buckling and collapsing of the slots remained little changed when the slot length was varied from 12 to 60 in (305 mm to 1.52 m). It was decided not to test slot lengths shorter than 12 in (305 mm) since it was evident from the pendulum test results that the peak deceleration and energy dissipation level would increase significantly if the slot length is further reduced. Also, it is desirable to buckle the slots individually and sequentially in order to separate the impulses from buckling of each set of slots. The separation of the impulses is provided by the collapsing of the slots after the initial buckling. Slot lengths that are too short would not provide the desired separation between the impulses. On the other hand, slot lengths that are too long would increase the fabrication cost and the potential for the bumper or other parts of the impacting vehicle to intrude into the slots. After some consideration, a slot length of 12 in (305 mm) was selected for use with the slotted rail end terminal design. Note that the slot length was later modified based on results of the developmental crash tests. More detailed discussions on the modification of the slot length are presented under the descriptions of the individual crash tests.

The slot guard was found to have minimal effect on the buckling and collapsing behavior of the slots or on the peak deceleration and the energy dissipation capacity of the slotted rail element. In comparison, the cover plate used with the previous design affected the buckling and collapsing behavior of the slots, resulting in a significant increase in the energy dissipation level, i.e., higher buckling force. The use of slot guards is therefore preferred over the use of cover plates from an impact performance standpoint as well as for aesthetic and maintenance considerations.
### Table 1. Summary of Pendulum Test Results

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Slot Length (in)</th>
<th>Slot Guard</th>
<th>Peak Deceleration (g's)</th>
<th>Energy Dissipation (kip-ft) @ Displacement = 4 ft</th>
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<tbody>
<tr>
<td>1</td>
<td>24</td>
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<td>32.5</td>
<td>8.3, 12.6</td>
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<td>2</td>
<td>18</td>
<td>No</td>
<td>30.7</td>
<td>9.7, 18.5</td>
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<tr>
<td>3</td>
<td>12</td>
<td>No</td>
<td>27.8</td>
<td>8.5, 18.5</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>No</td>
<td>25.1</td>
<td>8.7, 14.3</td>
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<td>12</td>
<td>No</td>
<td>29.9</td>
<td>10.0, 18.9</td>
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<td>6</td>
<td>18</td>
<td>Yes</td>
<td>31.5</td>
<td>9.5, 20.8</td>
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<td>7</td>
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<td>30.7</td>
<td>8.3, N/A</td>
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<td>8</td>
<td>12</td>
<td>Yes</td>
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### Table 2. Summary of Previous Pendulum Test Results

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<th>Slot Length (in)</th>
<th>Cover Plate</th>
<th>Energy Dissipation (kip-ft) @ Displacement = 4 ft</th>
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<td>20/24</td>
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<td>27</td>
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<td>8.8, 24.5</td>
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26
4.2 DEVELOPMENTAL CRASH TESTS

A total of seven full-scale crash tests were conducted during the course of developing this slotted rail end terminal. Three of the crash tests were successful compliance tests and are presented in Chapter 5. The other four crash tests were termed developmental tests since they involved either tests that failed to perform satisfactorily or tests of terminal designs that were subsequently modified significantly. The results of these four developmental crash tests and subsequent modifications to the end terminal resulting from these tests are presented in the following sections.

To avoid redundancy in the reporting of the individual developmental and compliance crash tests, data items that are common to the crash tests are summarized below and will not be repeated in the individual test descriptions:

- For the 1,800-lb (817-kg) test vehicle, the empty weight was 1,800 lb (817 kg) and its test weight was 1,970 lb (894 kg), including an unrestrained Alderson Research Laboratories Hybrid II, 50th percentile male anthropomorphic dummy placed in the driver's position.

A dummy was not used with the 4,500-lb (2,043-kg) test vehicle and both the empty weight and the test weight of the vehicle were 4,500 lb (2,043 kg).

- The test vehicle was directed into the end terminal using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

- Occupant risk factors computed from digitized data from the accelerometer located at the center of gravity of the test vehicle, i.e., occupant impact velocity, the highest 0.010-second average ridedown acceleration, and the maximum 0.050-second average acceleration, are reported both in the "Summary of Results" figures and the "Performance Summary Evaluation" tables and are not repeated in the text of the test descriptions.

Furthermore, some of the data and information from the individual crash tests are presented in the appendices to keep the main body of the report concise and easier to read. The appendices include:
4.2.1 Test Number 7199-8

This crash test involved an 1,800-lb (817-kg) passenger car impacting the end terminal head-on at a nominal speed of 45 mi/h (72.4 km/h) with an offset of 15 in (0.38 m) to the center of the vehicle, i.e., the center of the vehicle was offset 15 in (0.38 m) from the center of the end terminal. The purpose of this test is to evaluate vehicle stability, occupant risk, and after-impact trajectory of the end terminal design. This is typically the most difficult test condition for any end terminal design. Note that the existing breakaway cable terminal (BCT) design has never passed this test requirement.

The end terminal constructed for this crash test differed from the final design in the following aspects:

1. A ground strut was used to connect the foundation tubes of the first two posts (posts 1 and 2).
2. Four sets of 12-in (305-mm) long slots, one each mid-span of the first four spans, were used with the W-beam rail element.
3. The slotted rail element was bolted to post 2.

Photographs of the test installation are shown in figure 5. A 1987 Chevrolet Sprint (figures 6 and 7) was used in this crash test. The vehicle impacted the terminal end-on at a speed of 44.9 mi/h (72.2 km/h) and an angle of 0 degrees. Upon impact, the buffered end section began to collapse and post 1 began to move. At 0.056 sec, the W-beam rail element began to buckle at the first set of slots mid-span between posts 1 and 2 (i.e., span 1). At 0.071 sec, the vehicle began to yaw in a clockwise rotation and, at 0.079 sec, post 1 broke off at ground level. The yaw rate of the vehicle increased substantially by 0.145 sec, and shortly thereafter, the W-beam rail element began to buckle at the second set of slots mid-span between post 2 and 3 (i.e., span 2), and post 2 broke off at ground level. The rail element at
Figure 5. Slotted rail end treatment before test 7199-8.
Figure 6. Vehicle prior to test 7199-8.
Figure 7: Vehicle/slotted rail geometrics for test 7199-8.
the post 3 location began to move laterally to the left at 0.203 sec, and then at 0.289 sec, began to move to the right. The buckled end of the rail element at the second set of slots (i.e., mid-span of span 2) formed an elbow and the driver side door impacted the elbow at 0.463 sec. The window at the driver side door broke at 0.507 sec as the rail deformed the door and intruded into the occupant compartment. The vehicle continued to yaw in a clockwise rotation and slide into the buckled rail element and subsequently came to rest against the elbow or buckled end of the rail element, as shown in figure 8.

The end terminal received moderate damage, as shown in figure 9. There was buckling of the rail element at the first two set of slots mid-span in spans 1 and 2. Posts 1 and 2 were sheared off at ground level and post 3 was leaning slightly. The bolt at post 1 was pulled through the post and the bolts at post 2 and 3 were pulled out of the rail element.

The vehicle sustained severe damage to the front and sides, as shown in figures 10 and 11. There was a maximum crush of 11.0 in (279 mm) to the front center of the vehicle at bumper height. This crush was directed toward the passenger side of the vehicle, with the motor pushed into the firewall and deforming the floorpan into the occupant compartment on the passenger side by 4.0 in (102 mm). Also on the passenger side, the A-pillar was bent, the door was bent out 2.0 in (51 mm), and there was a 1.0 in (25 mm) dent in the roof at the B-post. The door on the driver side was deformed into the occupant compartment 9.0 in (229 mm) where the elbow formed by the buckled rail element impacted the door. The upper edge of the door was bent out 2.0 in (51 mm). The steering wheel and instrument panel were damaged and the windshield was shattered. The right front strut was bent and damage was done to the front bumper, hood, grill, radiator and fan, right and left front quarter panels and the right and left doors.

A summary of the test results is presented in figure 12. This test was considered to be unsuccessful with the vehicle sliding sideways and impacting an elbow formed by the buckled W-beam rail element at the door on the driver side. Even though the vehicle had very little velocity left at that point, there was still significant intrusion into the occupant compartment which was considered unacceptable according to evaluation criteria outlined in NCHRP Report 230. Otherwise, the test met the other evaluation criteria. A summary of the evaluation criteria and results is shown in table 3.
Figure 8. Vehicle/slotted rail after test 7199-8.
Figure 9. Slotted rail end treatment after test 7199-8.
Figure 10. Vehicle after 7199-8.
Figure 11. Damage to door of vehicle after 7199-8.
Figure 12. Summary of results for test 7199-8.
### Table 3. Performance Evaluation Summary - Test 7199-8.

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Test Results</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.</td>
<td>The vehicle was brought to a controlled stop.</td>
<td>Pass</td>
</tr>
<tr>
<td>D. Detached elements, fragments of other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>There were no detached elements or debris from the end terminal that showed any potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>Pass</td>
</tr>
<tr>
<td>E. The vehicle shall remain upright during and after the collision. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.</td>
<td>The vehicle remained upright and stable throughout the test sequence. There was significant deformation and intrusion of the occupant compartment on the floorpan and the driver side door.</td>
<td>Fail</td>
</tr>
<tr>
<td>F. Impact severity shall be less than:</td>
<td>The Impact severity for the test were:</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Occupant Impact Velocity - fps</strong></td>
<td><strong>Occupant Impact Velocity - fps</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Longitudinal</strong></td>
<td><strong>Lateral</strong></td>
</tr>
<tr>
<td>Limit/Design</td>
<td>40/15</td>
<td>36/20</td>
</tr>
<tr>
<td>Occupant Ridedown Acceleration - g's</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Longitudinal</strong></td>
<td>28.3</td>
<td>6.4</td>
</tr>
<tr>
<td><strong>Lateral</strong></td>
<td>-13.6</td>
<td>-6.4</td>
</tr>
<tr>
<td>Limit/Design</td>
<td>28/15</td>
<td>20/15</td>
</tr>
<tr>
<td>H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.</td>
<td>The vehicle came to rest against the test installation. The vehicle trajectory and final rest position did not indicate any potential of intrusion into adjacent traffic lanes.</td>
<td>Pass</td>
</tr>
<tr>
<td>J. Vehicle trajectory behind the test article is acceptable.</td>
<td>The vehicle came to rest against the test installation.</td>
<td>Pass</td>
</tr>
</tbody>
</table>
The test results were then analyzed in detail to identify the problems and to devise the appropriate design modifications. The initial impulse, caused by a combination of fracturing the wooden end post and buckling the first set of slots (i.e., the mid-span slots between posts 1 and 2), was found to be too high. This caused the vehicle to yaw or rotate prematurely and excessively, which eventually resulted in the vehicle sliding sideways into the elbow formed by the buckled W-beam rail element at the second set of slots (i.e., the mid-span slots between posts 2 and 3). To reduce this initial impulse, the first set of slots, i.e., the mid-span slots between posts 1 and 2, were lengthened from 12 to 24 in (305 to 610 mm). This modification would effectively separate the impulse of breaking the wooden end post from that of buckling and collapsing the first set of slots. The longer slots also have a slightly lower buckling force, which would help to soften the initial impulse.

It appeared that the post bolt at post 2 did not disengage properly, generating high deceleration forces before the W-beam rail element was separated from the post. A new set of 12-in (305-mm) slots were added at post 2 to minimize this potential problem. This design modification served two purposes. The first purpose was to facilitate the disengagement of the post bolt at post 2. The second purpose was to reduce (actually half) the length of the column between the mid-span slots in spans 1 and 2. Note that there was a 5.4-ft (1.65-m) long unbuckled section of W-beam rail between the first two mid-span sets of slots, which appeared to have accentuated the yawing of the vehicle.

In addition, the length of the second set of mid-span slots, i.e., between posts 2 and 3, was also increased from 12 to 24 in (305 to 610 mm) and another new set of 12-in (305-mm) slots was added at post 3. These additional modifications were precautionary measures which could further enhance the performance of the end-terminal design.

In summary, the design modifications consisted of: lengthening the first two sets of mid-span slots in spans 1 and 2 from 12 to 24 in (305 to 610 mm), and adding two new sets of 12-in (305-mm) slots at posts 2 and 3.

4.2.2 Test Number 7199-8A

After incorporating the design modifications described above in the previous test (test no. 7199-8), the small car end-on test was repeated. Again, the test involved an 1,800-lb (817-
kg) passenger car impacting the end terminal end-on at a nominal speed of 45 mi/h (72.4 km/h) with an offset of 15 in (0.38 m) to the center of the vehicle. Photographs of the test installation are shown as figure 13.

A 1986 Chevrolet Sprint (figures 14 and 15) was used in this crash test. The vehicle impacted the terminal end-on at a speed of 46.6 mi/h (75.0 km/h) and an angle of 0 degree. Shortly after the vehicle impacted the end terminal, post 1 began to move and the vehicle contacted post 1 at 0.034 sec. The first set of slots located mid-span between posts 1 and 2 began to buckle at 0.043 sec after impact and, at 0.065 sec, the vehicle began to yaw in a clockwise rotation. At 0.108 sec, the second set of slots at post 2 began to buckle. At 0.171 sec, the vehicle contacted post 2. The yaw rate of the vehicle remained little changed as the vehicle continued forward. The rail element began to buckle at the third set of slots mid-span between posts 2 and 3 at 0.198 sec. The rail element began to buckle at the fourth set of slots at post 3 and separated from post 3 at 0.224 sec. At 0.350 sec, the vehicle contacted post 3. Forward motion of the vehicle stopped at 0.511 sec; however, the vehicle continued to yaw clockwise. The vehicle rolled backwards and subsequently came to a complete stop at 1.133 sec over the post 3 location with the front of the vehicle still in contact with the guardrail, as shown in figure 16.

The end terminal received moderate damage, as shown in figures 17 and 18. There was buckling of the rail element at the first four sets of slots between posts 1 through 3. The fifth and sixth set of slots located mid-span in spans 3 and 4 were deformed but not buckled. Posts 1 and 2 sheared off at ground level and post 3 broke off just below ground level. Post 4 was not broken, but leaning slightly.

The vehicle sustained severe damage to the front as shown in figure 19. There was a maximum crush of 11.0 in (279 mm) slightly to the right of the center front of the vehicle at bumper height. This crush was directed toward the passenger side of the vehicle, with the motor pushed into the firewall deforming the floorpan into the occupant compartment on the passenger side by 3.0 in (76 mm). Also on the passenger side, there was a 0.5 in (13 mm) dent in the roof at the B-post, and there was a slight indentation in the roof near the rear on the driver side. The wheelbase was shortened by 4.0 in (102 mm) on the right side and by 2.5 in (64 mm) on the left side. The instrument panel was damaged and the windshield was
Figure 13. End treatment before test 7199-8A.
Figure 14. Vehicle before test 7199-8A.
Figure 15. Vehicle/end treatment geometrics for test 7199-8A.
Figure 16. Vehicle/end treatment after test 7199-8A.
Figure 17. End treatment after test 7199-8A.
Figure 18. Damage at post 3.
Figure 19. Vehicle after test 7199-8A.
shattered. The right and left front strut towers, the motor mounts and the master cylinder were damaged. Also damaged were the front bumper, hood, grill, radiator and fan, right and left front quarter panels and the right and left doors.

A summary of the test results is presented in figure 20. The test was judged to have met the evaluation criteria set forth in NCHRP Report 230, a summary of which is shown in table 4. The end terminal successfully brought the impacting vehicle to a safe and controlled stop. The test vehicle remained upright and stable during the entire impact sequence. There was no debris from the vehicle or barrier that might present undue hazard to other traffic. Damage to the test installation was moderate. Damage to the impacting vehicle was severe and there was some deformation in the floorpan area of the occupant compartment, but it was judged to be minor in nature and of little consequence.

It was noted that the buffered end section did not collapse as designed to distribute the loading over a wider area of the vehicle. This was caused by the overlapping of the slot for the bolt attaching one end of the nose section to the W-beam rail element with the first set of 24-in (610-mm) slots mid-span between posts 1 and 2. When the first set of slots buckled, the bolt attaching one end of the nose section to the W-beam rail element was disengaged, thus resulting in the nose section not collapsing as intended. It is unclear what effect this might have on the impact performance of the end terminal. There was some over-riding of the W-beam rail element over the engine block and the structural members of the vehicle, which might have rendered the damage to the vehicle to appear more severe. In any event, it was decided that the middle slot of the first set of slots mid-span between posts 1 and 2 would be shortened from 24 to 18 in (610 to 457 mm) so that the slot will not overlap with the bolt slot for attachment of the buffered end section and affect the behavior of the buffered end section.

4.2.3 Test Number 7199-11

The end terminal design that successfully passed the small car end-on test (test no. 7199-8A) was then tested with 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 45 mi/h (72.5 km/h). The objective of this test was to evaluate the energy-absorbing/dissipation properties of the end terminal. As mentioned above, the only change in the design of the end terminal for this test was the
Test No. ............... 7199-8A
Date .................. 10/20/92
Test Installation ......... Slotted Rail
End Treatment
Installation Length ....... 50.0 ft (15.2 m)
Test Vehicle ............ 1986 Chevrolet Sprint
Vehicle Weight
  Test Inertia ........... 1,800 lb (817 kg)
  Gross Static .......... 1,967 lb (893 kg)
Vehicle Damage Classification
  TAD .................. 12FD5
  CDC .................. 12FDW3
Maximum Vehicle Crush . 11.0 in (27.9 cm)
Impact Speed ........... 46.6 mi/h (75.0 km/h)
Impact Angle .......... 0 deg - end-on
Exit Speed ............. N/A
Exit Trajectory ........ N/A
Vehicle Accelerations
  (Max. 0.050-sec Avg)
    Longitudinal .... -10.7 g
    Lateral .......... -2.4 g
Occupant Impact Velocity
  Longitudinal ....... 23.9 ft/s (7.3 m/s)
  Lateral ........... 9.6 ft/s (2.9 m/s)
Occupant Ridedown Accelerations
  Longitudinal ....... -12.3 g
  Lateral .......... -3.1 g

Figure 20. Summary of results for test 7199-8A.
<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Test Results</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. Acceptable test article performance may be by redirection, controlled penetration, controlled stopping of the vehicle.</td>
<td>The vehicle was brought to a controlled stop.</td>
<td>Pass</td>
</tr>
<tr>
<td>D. Detached elements, fragments of other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>There were no detached elements or debris from the end terminal that showed any potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>Pass</td>
</tr>
<tr>
<td>E. The vehicle shall remain upright during and after the collision. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.</td>
<td>The vehicle remained upright and stable throughout the test sequence. There was no deformation or intrusion of the occupant compartment.</td>
<td>Pass</td>
</tr>
<tr>
<td>F. Impact severity shall be less than:</td>
<td>The Impact severity for the test were:</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>Occ. Impact Velocity - fps</td>
<td>Occ. Impact Velocity - fps</td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>Longitudinal</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>Lateral</td>
</tr>
<tr>
<td>Limit/Design</td>
<td>Limit/Design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40/15</td>
<td>30/20</td>
</tr>
<tr>
<td></td>
<td>Occup. Ridedown Acceleration - g's</td>
<td>Occup. Ridedown Acceleration - g's</td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>Longitudinal</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>Lateral</td>
</tr>
<tr>
<td>Limit/Design</td>
<td>Limit/Design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20/15</td>
<td>20/15</td>
</tr>
<tr>
<td>H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.</td>
<td>The vehicle came to rest against the test installation. The vehicle trajectory and final rest position did not indicate any potential of intrusion into adjacent traffic lanes.</td>
<td>Pass</td>
</tr>
<tr>
<td>J. Vehicle trajectory behind the test article is acceptable.</td>
<td>The vehicle came to rest against the test installation.</td>
<td>Pass</td>
</tr>
</tbody>
</table>
shortening of the middle slot of the first set of slots mid-span between posts 1 and 2 from 24 to 18 in (610 to 457 mm), as shown in figure 21. Photographs of the test installation are shown as figure 22.

A 1981 Cadillac Fleetwood (figures 23 and 24) was used in this crash test. The vehicle impacted the terminal end-on at a speed of 46.1 mi/h (74.2 km/h) and an angle of 0 degrees. The vehicle contacted post 1 at 0.029 sec after impact and the slots located between posts 2 and 3 began to buckle at 0.086 sec. As the vehicle contacted post 2 at 0.126 sec, the rail element separated from post 3. At 0.171 sec, the span between post 3 and 4 began to buckle. By this time, the vehicle was travelling behind the guardrail but continued forward in a relatively straightforward and stable manner. The vehicle contacted post 3 at 0.267 sec, and the guardrail folded and slapped the left side of the vehicle at 0.360 sec. At 0.398 sec, the vehicle contacted post 4 and shortly thereafter at 0.437 sec, a severe steer input occurred which caused the vehicle to yaw in a counterclockwise rotation at 0.460 sec. At 0.514 sec, the vehicle lost contact with the guardrail and had slowed to 21.7 mi/h (34.9 km/h). The vehicle then contacted post 5 at 0.586 sec and continued to yaw counterclockwise. As this rotation continued, the vehicle also began to roll onto its right side. The vehicle subsequently came to rest on its roof behind the rail approximately 42 ft (13 m) from the point of impact, as shown in figure 25.

The end terminal received substantial damage, as shown in figure 26. There was buckling of the rail element at the slots between posts 2 and 3, and between 3 and 4. The slots located on between post 4 and 5 were deformed but not completely buckled. Posts 1 and 2 sheared off at ground level and posts 3 and 4 broke off just below ground level. Post 5 was bent and leaning approximately 7 in (180 mm).

The vehicle sustained severe damage to the front as shown in figures 27 and 28. There was a maximum crush of 8.0 in (203 mm) slightly to the right of the center front of the vehicle at bumper height. There was damage to the left front frame and some peculiar damage to the undercarriage as shown in figure 29. Also damaged were the front bumper, hood, grill, radiator and fan, right and left front quarter panels and the right and left doors. Most of the remaining damage was due to rollover of the vehicle at the end of the impact sequence.
Figure 21. Front and rear view of slots.
Figure 22. End treatment before test 7199-11.
Figure 23. Vehicle prior to test 7199-11.
Figure 24. Vehicle/end treatment geometrics for test 7199-11.
Figure 25. Test site after test 7199-11.
Figure 26. Damage to end treatment after test 7199-11.
Figure 26. Damage to end treatment after test 7199-11 (continued).
Figure 27. Vehicle after test 7199-11.
Figure 28. Vehicle after being uprighted (after test 7199-11).
Figure 29. Undercarriage of vehicle after test 7199-11.
Figure 29. Undercarriage of vehicle after test 7199-11 (continued).
A summary of the test results is presented in figure 30. This test was considered to be unsuccessful with the vehicle rolling over. Even though the vehicle had very little velocity left at the point of rollover, it was still considered unacceptable according to evaluation criteria outlined in NCHRP Report 230. Otherwise, the test met the other evaluation criteria. A summary of the evaluation criteria and results is shown in table 5.

The vehicle rollover was totally unexpected. The end terminal functioned as designed in the early stages of the impact sequence. The rail element buckled and collapsed as the vehicle was gradually slowed down and allowed to gate behind the rail in a controlled manner. The vehicle had almost cleared the rail past post 3 when the vehicle suddenly started to yaw counterclockwise and roll to its right, coming to rest on its top. A detailed analysis of the test data was conducted to determine the cause of the rollover, including examination of the damage to the end terminal and the vehicle, and review of the electronic data and high-speed films.

It appeared that the loose end of the breakaway cable attachment was caught by the front cross member of the vehicle (as evidenced by the hole punched in the cross member shown in figure 29) while the bearing plate for the breakaway cable attachment was digging into the ground. This in effect fixed the loose end of the breakaway cable attachment in relation to the vehicle. In the mean time, the rail element formed an elbow at the slots between posts 2 and 3 and the rail was bent 180 degrees at the elbow. Since the breakaway cable attachment was attached to the rail, this in effect fixed the other end of the breakaway cable attachment. As the vehicle proceeded forward, the cable was tensioned and caught on a lip on the left front A-frame of the vehicle that was only approximately 1/2-in (12.7 mm) wide. The tensioned cable bent back the A-frame 90 degrees and in the process sheared off the bumper shock absorber attachment and broke the bumper.

This combination of events resulted in the left front of the vehicle being held in place, causing the vehicle to yaw violently in a counterclockwise rotation. In the meantime, the suspension on the left front of the vehicle was first compressed and then released to provide a impetus of rolling to the right. The right front tire turned to the left sharply and dug into the ground as the vehicle yawed counterclockwise and rolled to the right. This combination of kinematics resulted in the rollover of the vehicle.
<table>
<thead>
<tr>
<th>Test No.</th>
<th>7199-11</th>
<th>Impact Speed</th>
<th>46.1 mi/h (74.2 km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>01/26/93</td>
<td>Impact Angle</td>
<td>0 deg - end-on</td>
</tr>
<tr>
<td>Test Installation</td>
<td>Slotted Rail</td>
<td>Exit Speed</td>
<td>21.7 mi/h (34.9 km/h)</td>
</tr>
<tr>
<td></td>
<td>End Treatment</td>
<td>Exit Trajectory</td>
<td>N/A - Vehicle rollover</td>
</tr>
<tr>
<td>Installation Length</td>
<td>50.0 ft (15.2 m)</td>
<td>Vehicle Accelerations</td>
<td>(Max. 0.050-sec Avg)</td>
</tr>
<tr>
<td>Test Vehicle</td>
<td>1981 Cadillac</td>
<td>Longitudinal</td>
<td>-6.4 g</td>
</tr>
<tr>
<td>Vehicle Weight</td>
<td>Fleetwood</td>
<td>Lateral</td>
<td>2.2 g</td>
</tr>
<tr>
<td>Test Inertia</td>
<td>4,500 lb (2,043 kg)</td>
<td>Occupant Impact Velocity</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>Gross Static</td>
<td>4,500 lb (2,043 kg)</td>
<td>Lateral</td>
<td>N/A</td>
</tr>
<tr>
<td>Vehicle Damage Classification</td>
<td></td>
<td>Occupant Ridedown Accelerations</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>TAD</td>
<td>12FL5 &amp; 3R&amp;T4</td>
<td>Lateral</td>
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</tr>
<tr>
<td>CDC</td>
<td>12FYEK3 &amp; 00TPD04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Vehicle Crush</td>
<td>8.0 in (20.3 cm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 30. Summary of results for test 7199-11.
<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Test Results</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.</td>
<td>The vehicle was brought to a controlled stop.</td>
<td>Pass</td>
</tr>
<tr>
<td>D. Detached elements, fragments of other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>There were no detached elements or debris from the end terminal that showed any potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>Pass</td>
</tr>
<tr>
<td>E. The vehicle shall remain upright during and after the collision. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.</td>
<td>The vehicle rolled over.</td>
<td>Fail</td>
</tr>
<tr>
<td>F. Impact severity shall be less than:</td>
<td>The Impact severity for the test were:</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Occupant Impact Velocity - fps</strong></td>
<td><strong>Occupant Impact Velocity - fps</strong></td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>Lateral</td>
</tr>
<tr>
<td></td>
<td>40/15</td>
<td>30/20</td>
</tr>
<tr>
<td></td>
<td><strong>Occupant Ridedown Acceleration - g's</strong></td>
<td><strong>Occupant Ridedown Acceleration - g's</strong></td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>Lateral</td>
</tr>
<tr>
<td></td>
<td>20/15</td>
<td>20/15</td>
</tr>
<tr>
<td>H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.</td>
<td>The vehicle came to rest against the test installation. The vehicle trajectory and final rest position did not indicate any potential of intrusion into adjacent traffic lanes.</td>
<td>Pass</td>
</tr>
<tr>
<td>J. Vehicle trajectory behind the test article is acceptable.</td>
<td>The vehicle rolled over and came too rest behind the test installation.</td>
<td>Pass</td>
</tr>
</tbody>
</table>
The initial concern with this large vehicle end-on test was that the vehicle would proceed through the first four wood posts without gating, i.e., going behind the barrier, and the vehicle would then ramp on the first steel post (post 5) and get on top of the barrier. This did not happen and the vehicle almost cleared the barrier at post 3 and would have completed the gating process had the sequence of events described above not occurred. It is believed that what happened was an occurrence of extremely low probability and unrelated to the slotted rail end terminal design.

However, even though the rollover was not caused by the slotted rail design and the rollover was considered a freakish occurrence, there remained the fact that the vehicle did roll over and the design did not pass the test. The end terminal design would have to be modified and tested again. It was therefore decided to use the opportunity to optimize the design and to cut down on the cost of the installation.

The key change in the design was to increase the post spacing of the terminal from 6 ft-3 in (1.91 m) to 12 ft-6 in (3.81 m). The rationale for this change was twofold. First, there was a study underway with the Washington Department of Transportation to crash test and evaluate a 12 ft-6 in (3.81 m) post spacing W-beam guardrail system intended for use on roadways with speed limit of 45 mi/h (72.4 km/h) or lower. The advantage of increasing the post spacing was of course lower cost since the number of posts and blockouts would be halved. If the guardrail system with the increased post spacing was shown to perform satisfactorily, that could become the new standard for guardrails on roadways with speed limit of 45 mi/h (72.4 km/h) or lower. It seemed logical that the slotted rail end terminal should also be designed for the 12 ft-6 in (3.81 m) post spacing instead of the 6 ft-3 in (1.91 m) post spacing.

Second, the use of the 12 ft-6 in (3.81 m) post spacing for the slotted rail end terminal could greatly reduce the cost of the end terminal by eliminating the following details from the design: (1) one foundation tube and post at post 2, (2) the ground strut, (3) the post and blockout at post 4, and (4) two set of slots at posts 2 and 3.

With the change to the 12 ft-6 in (3.81 m) post spacing for the end terminal, there were only two posts and two spans in the end terminal section: an end post (post 1) which was a breakaway wooden post placed in a foundation tube and a CRT post for post 2. The beginning
of the standard guardrail now began with post 3. The offset remained at 18 in (0.46 m) with a straight flare, i.e., the offsets at posts 1, 2 and 3 were 18, 9 and 0 in (457, 229 and 0 mm), respectively.

There were two sets of slots in each span. The length of the two sets of slots in span 1 (i.e., between posts 1 and 2) was reduced from 24 to 18 in (610 to 457 mm). This resolved the problem of unequal lengths for the first set of slots. The length of the second set of slots was similarly shortened to minimize the potential for the second set of slots to buckle prior to the first set of slots, which might adversely affect the performance of the end terminal.

4.2.4 Test Number 7199-13

The modified end terminal design with the 12 ft-6 in (3.81 m) post spacing, as described above, was again crash tested and evaluated with the small car end-on test, similar to test nos. 7199-8 and 7199-8A. The crash test involved an end-on impact by an 1,800-lb (817-kg) passenger car at a nominal speed of 45 mi/h (72.4 km/h) with an offset of 15 in (381 mm) to the center of the vehicle. Photographs of the test installation are shown as figure 31.

A 1988 Yugo (figures 32 and 33) was used in this crash test. The vehicle impacted the terminal end-on at a speed of 44.6 mi/h (71.8 km/h) and an angle of 0 degrees. Upon impact, the rail began to buckle at the point where the buffered end section bolts to the back of the W-beam rail element. The vehicle contacted post 1 at 0.032 sec after impact. The first two sets of slots located between posts 1 and 2 began to buckle at 0.049 sec and the rail section rotated downward at the first set of slots. Shortly thereafter, the vehicle began to yaw clockwise when maximum engagement with post 1 occurred. As the vehicle continued forward, the guardrail separated from post 2 at 0.103 sec. At 0.241 sec, the left front tire struck the rail as the vehicle passed over the rail section and began to climb atop the rail. Meanwhile, the vehicle continued to yaw clockwise. The left front tire struck the post 2 blockout at 0.374 sec and by 0.645 sec, the vehicle was airborne.

At 0.859 sec, the vehicle was traveling atop the rail oriented approximately perpendicular to the installation when post 3 (first post of the standard guardrail section) was struck. The top of post 3 impacted the vehicle at the floor pan near the longitudinal center of gravity of the vehicle. At this point, only the right front tire of the vehicle was in contact with
Figure 31. End treatment before test 7199-13.
Figure 32. Vehicle before test 7199-13.
Figure 33. Vehicle/end treatment geometrics for test 7199-13.
the ground. At 1.053 sec, the vehicle rolled to the left and the left front tire made contact with the ground while the other tires were airborne. Shortly thereafter, the vehicle impacted post 4 in the rear left quarter panel of the vehicle in front of the rear wheel at rocker panel level. The left side of the vehicle snagged on post 4 and came to rest atop the installation with the front tires in contact with the ground and the rear tires elevated, as shown in figure 34. The vehicle at final rest was oriented at an angle of approximately 135 degrees from the initial direction of travel.

As can be seen in figure 35, the end terminal received a moderate amount of damage. The first two sets of slots between posts 1 and 2 were buckled and bent. Posts 1 and 2 were sheared off at ground level. The foundation tube for post 1 was bent in the rear and displaced 1.5 in (38 mm). Post 3 and 4 in the standard section of the guardrail were bent and displaced to a small degree.

The vehicle sustained severe damage to the front as shown in figure 36. There was a maximum crush of 12.6 in (320 mm) at the right front quarter point of the vehicle. There was extensive damage to the uni-body of the vehicle. The floorpan had numerous dents and tears. The roof, dashboard, right side A and B-pillar, and the entire front of the vehicle was bent.

A summary of the test results is presented in figure 37. This test was considered to be unsuccessful with the vehicle ramping and mounting the guardrail, resulting in a near rollover prior to coming to rest on top of the guardrail. Even though the vehicle did not roll over and technically the test results met all evaluation criteria outlined in NCHRP Report 230, the behavior of the vehicle was considered unacceptable, as indicated in the performance evaluation summary shown in table 6.

Again, the test data were analyzed in detail to determine the causes for the ramping and to devise appropriate design modifications. It appeared from review of the high speed films that the first two sets of slots buckled nicely and the end post broke off cleanly upon impact. However, once the slots buckled, they essentially acted like hinges and allowed the rail to rotate downward at the first set of slots. The right front tire of the vehicle caught on the buckled rail, causing the vehicle to yaw clockwise at a high yaw rate. The vehicle then mounted the ramp formed by the rail while continuing to yaw at a high rate, causing the
Figure 34. Test site after test 7199-13.
Figure 35. End treatment after removal of vehicle for test 7199-13.
Figure 36. Vehicle after test 7199-13.
Test No. ............... 7199-13
Date .................. 04/13/93
Test Installation .... Slotted Rail
                      End Treatment
Installation Length ... 50.0 ft (15.2 m)
Test Vehicle .......... 1988 Yugo
Vehicle Weight
  Test Inertia ......... 1,800 lb (816 kg)
  Gross Static ......... 1,966 lb (892 kg)
Vehicle Damage Classification
  TAD .................. 12FC3
  CDC .................. 12FCEK3 & O0UYDW2
Maximum Vehicle Crush .. 12.6 in (32.0 cm)
Impact Speed ........ 44.6 mi/h (71.8 km/h)
Impact Angle .......... 0 deg - end-on
Exit Speed ........... Came to rest on rail
Exit Trajectory ..... N/A
Vehicle Accelerations
  (Max. 0.050-sec Avg)
    Longitudinal .... -13.7 g
    Lateral ........... 2.0 g
Occupant Impact Velocity
  Longitudinal ....... 25.0 ft/s (7.6 m/s)
  Lateral ........... 3.5 ft/s (1.1 m/s)
Occupant Ridedown Accelerations
  Longitudinal ........ -5.1 g
  Lateral ............. -5.5 g

Figure 37. Summary of results for test 7199-13.

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Test Results</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.</td>
<td>The vehicle was brought to a controlled stop.</td>
<td>Pass</td>
</tr>
<tr>
<td>D. Detached elements, fragments of other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>There were no detached elements or debris from the end terminal that showed any potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>Pass</td>
</tr>
<tr>
<td>E. The vehicle shall remain upright during and after the collision. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.</td>
<td>The vehicle ramped and mounted the guardrail and came to rest on top of the test installation. There was no deformation or intrusion of the occupant compartment.</td>
<td>Fail</td>
</tr>
<tr>
<td>F. Impact severity shall be less than:</td>
<td>The Impact severity for the test were:</td>
<td>Pass</td>
</tr>
<tr>
<td>Occupant Impact Velocity - fps</td>
<td>Occupant Impact Velocity - fps</td>
<td>Pass</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>Longitudinal</td>
<td></td>
</tr>
<tr>
<td>40/15</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td>Lateral</td>
<td></td>
</tr>
<tr>
<td>30/20</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Occupant Ridedown Acceleration - g's</td>
<td>Occupant Ridedown Acceleration - g's</td>
<td>Pass</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>Longitudinal</td>
<td></td>
</tr>
<tr>
<td>20/15</td>
<td>-5.1</td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td>Lateral</td>
<td></td>
</tr>
<tr>
<td>20/15</td>
<td>-5.5</td>
<td></td>
</tr>
<tr>
<td>H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.</td>
<td>The vehicle came to rest on top of the test installation. The vehicle trajectory and final rest position did not indicate any potential of intrusion into adjacent traffic lanes.</td>
<td>Pass</td>
</tr>
<tr>
<td>J. Vehicle trajectory behind the test article is acceptable.</td>
<td>The vehicle came to rest on top of the test installation.</td>
<td>Pass</td>
</tr>
</tbody>
</table>
vehicle to roll to the left side. The vehicle attained a high roll angle, but did not roll over, and eventually came to rest on top of the guardrail.

Part of the problem could be attributed to the 12 ft-6 in (3.81 m) post spacing, which eliminated the intermediate post between the first two sets of slots. With the 6 ft-3 in (1.91 m) post spacing design previously tested, the post bolt at the intermediate post (i.e., post 2) held the rail element up long enough before disengaging to prevent the downward rotation.

The end terminal design was again modified to resolve this problem of the W-beam rail buckling downward. The resulting design was the final design which was subsequently crash tested with satisfactory results. Details of the final design are previously described in Section 3.3, "Final Design Details," and will not be repeated herein. Brief discussions on the more significant modifications are presented as follows:

1. The post spacing was changed back to 6 ft-3 in (1.91 m). The first two posts (posts 1 and 2) were breakaway posts placed in foundation tubes and posts 3 and 4 were CRT posts to ensure proper breakaway characteristics.

2. The ground strut between the two foundation tubes at posts 1 and 2 was eliminated. The standard BCT design without the ground strut had been shown to perform satisfactorily in redirectional impacts at impact speeds of 60 mi/h (96.6 km/h). Since the slotted rail end terminal was designed for impacts of only 45 mi/h (72.4 km/h), there should be adequate anchorage capacity without the ground strut.

3. The offset remained at 18 in (457 mm) with a straight flare starting at post 4, i.e., the offsets at posts 1, 2, 3 and 4 were 18, 12, 6, and 0 in (457, 305, 152, and 0 mm), respectively.

4. The two sets of slots at posts 2 and 3 were eliminated. These two sets of slots were incorporated into the design after the first small car end-on test failed to perform satisfactorily. The key reason for the set of slots at post 2 was to facilitate the disengagement of the post bolt at post 2. The concern over proper disengagement of the post bolt was alleviated by removing the post bolt at post 2. The slots at post 3 was purely a precautionary move and should not have any significant effect on the performance of the end terminal.
5. A shelf angle was added to post 2 to provide support for the rail element and to minimize the potential of any downward buckling.
V. RESULTS OF COMPLIANCE CRASH TESTS

As mentioned previously, the following three compliance crash tests were considered necessary to evaluate the performance of this end terminal design according to requirements set forth in NCHRP Report 230:

1. 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 45 mi/h (72.4 km/h) and 25 degrees.

2. Test designation 45. An 1,800-lb (817-kg) passenger car impacting the end terminal head-on with an offset of 15 in (0.38 m) from the center of the nose at a nominal impact speed of 45 mi/h (72.4 km/h).

3. 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 45 mi/h (72.4 km/h).

The final design, as presented previously under Section 3.3, "Final Design Details", successfully met all the evaluation criteria. This chapter presents the results of the compliance crash tests.

5.1 TEST NUMBER 7199-7

The first compliance crash test involved a 4,500-lb (2,041-kg) passenger car impacting the test installation at the beginning of length-of-need, which was selected to be at post 3 or 12.5 ft (3.81 m) from the end of the end terminal, at the nominal speed and angle of 45 mi/h (72.4 km/h) and 25 degrees. The usual objective of this test is to evaluate the adequacy of the terminal anchorage, which was not an area of concern for the slotted rail end terminal. The anchorage capacity of the slotted rail end terminal was similar to that of the BCT, which has been shown to be adequate for impacts of 60 mi/h (96.6 km/h). Since the design speed for this slotted rail end terminal was only 45 mi/h (72.4 km/h), there was really no question about the adequacy of the anchorage capacity. Instead, the key objective of this test is to evaluate the effectiveness of the slot guard to keep the slots from being torn or ripped apart.
Note that this crash test was the first to be conducted and the end terminal design as tested in this crash test was slightly different from the final design as follows:

1. A ground strut was used to connect the foundation tubes between posts 1 and 2.
2. Four sets of 12-in (305-mm) long slots, one each mid-span of the first spans, were used with the W-beam rail element.
3. The slotted rail element was bolted to post 2.

However, these variations from the final design should not have any effect on the performance of the end terminal for redirectional impacts. As mentioned previously, the anchorage capacity of the slotted rail end terminal without the ground strut is similar to that of a standard BCT, which has been shown to be adequate for impacts of 60 mi/h (96.6 km/h). Also, since the point of impact (beginning of length-of-need) was at post 3 for this test, changes in the design upstream of post 3, such as the longer slots in spans 1 and 2 and the removal of the post bolt at post 2, should not have any effect on the outcome of this test. Thus, even though there were some minor differences between the end terminal in this crash test and the final design, there was no reason to repeat this test for the final design.

Photographs of the test installation are shown in figure 38. A 1982 Cadillac Sedan (figures 39 and 40) was used for this crash test. The vehicle impacted the end terminal at post 3 (the beginning of length-of-need) at a speed of 47.9 mi/h (77.1 km/h) and an angle of 23.9 degrees. At 0.035 sec after impact, the rail began to buckle at the location of the slots between posts 3 and 4. The vehicle began to redirect at 0.048 sec after impact. At 0.101 sec, the vehicle contacted post 4 and post 4 broke off near ground level at 0.111 sec. The rail then began to buckle at the location of the slots between posts 4 and 5 at 0.128 sec. The guardrail reached a maximum dynamic deflection of 2.0 ft (0.6 m) at 0.202 sec. The vehicle contacted post 5 at 0.219 sec and, at 0.293 sec, the right front tire aired out as it contacted post 5. By 0.303 sec, the vehicle was travelling parallel to the guardrail at a speed of 28.9 mi/h (46.5 km/h). The rear of the vehicle impacted the guardrail at 0.574 sec. The vehicle lost contact with the guardrail at 0.738 sec, travelling at a speed of 22.4 mi/h (36.0 km/h) with an exit angle of 15.3 degrees. As the vehicle exited the rail, the vehicle yawed clockwise due to damage to the right front wheel. At 2.498 sec, the vehicle impacted the guardrail again.
Figure 38. Slotted rail end treatment before test 7199-7.
Figure 39. Vehicle before test 7199-7.
Figure 40. Vehicle/slotted rail geometrics for test 7199-7.
between posts 14 and 15 and subsequently came to rest against the guardrail. Damage to the guardrail and vehicle due to this secondary impact was very minor in comparison to that from the initial impact.

As can be seen in figure 41, the end terminal received moderate damage from the impact. Post 4 broke off and posts 3, 5 and 6 were pushed back and to the side. Post 5 had tire marks on the face, the blockout was bent and the bolt was pulled out of the rail. Maximum dynamic deflection of the guardrail was 2.0 ft (0.6 m) and the maximum permanent deformation was 1.7 ft (0.5 m). The vehicle was in contact with the rail for a total distance of 18.0 ft (5.5 m).

The vehicle sustained damage to the front and right side as shown in figure 42. Maximum crush at the left front corner at bumper height was 10.25 in (260 mm). The right tie rod and lower right A-arm were damaged. Also damage was done to the front bumper, hood, grill, right front quarter panel, right door, right rear quarter panel, rear bumper, and the right front and rear tires and rims.

A summary of the test results is presented in figure 43. The test was judged to have met the evaluation criteria set forth in NCHRP Report 230, a summary of which is shown in table 7. The installation successfully contained and redirected the impacting vehicle. All occupant risk factors were well within the recommended limits set forth in NCHRP Report 230. The test vehicle remained upright and stable during the impact period and after leaving the test installation. There was no debris from the vehicle or barrier that might present undue hazard to other traffic. Damage to the guardrail was moderate. Damage to the impacting vehicle was also moderate and there was no deformation or intrusion into the occupant compartment.

The change in velocity of the vehicle was 25.5 mi/h (41.0 km/h) and the exit angle 15.3 degrees, which are higher than the recommended limit of 15 mi/h (24.1 km/h) and 60 percent of the impact angle (14.3 degrees). However, vehicle trajectory after loss of contact with the guardrail indicated that the vehicle would not have posed a hazard to adjacent traffic since the vehicle returned to the roadside and impacted the guardrail again in a secondary impact.

The major concern with this test was the potential of the vehicle bumper or other parts of the vehicle intruding into the slots and tearing or ripping the rail apart along the slots. The
Figure 41. Slotted rail end treatment after test 7199-7.
Figure 42. Vehicle after test 7199-7.
<table>
<thead>
<tr>
<th>Test No.</th>
<th>7199-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>08/27/92</td>
</tr>
<tr>
<td>Test Installation</td>
<td>Slotted Rail End Treatment</td>
</tr>
<tr>
<td>Installation Length</td>
<td>50.0 ft (15.2 m)</td>
</tr>
<tr>
<td>Test Vehicle</td>
<td>1982 Cadillac Sedan</td>
</tr>
<tr>
<td>Vehicle Weight</td>
<td></td>
</tr>
<tr>
<td>Test Inertia</td>
<td>4,500 lb (2,043 kg)</td>
</tr>
<tr>
<td>Gross Static</td>
<td>4,500 lb (2,043 kg)</td>
</tr>
<tr>
<td>Vehicle Damage Classification</td>
<td></td>
</tr>
<tr>
<td>TAD</td>
<td>01RFQ5 &amp; 01RD3</td>
</tr>
<tr>
<td>CDC</td>
<td>01FREK2 &amp; 01RFES3</td>
</tr>
<tr>
<td>Maximum Vehicle Crush</td>
<td>10.25 in (16.0 cm)</td>
</tr>
<tr>
<td>Max. Dyn. Rail Deflection</td>
<td>2.0 ft (0.6 m)</td>
</tr>
<tr>
<td>Max. Perm. Rail Deformation</td>
<td>1.7 ft (0.5 m)</td>
</tr>
<tr>
<td>Impact Speed</td>
<td>47.9 mi/h (77.1 km/h)</td>
</tr>
<tr>
<td>Impact Angle</td>
<td>23.9 deg</td>
</tr>
<tr>
<td>Exit Speed</td>
<td>22.4 mi/h (36.0 km/h)</td>
</tr>
<tr>
<td>Exit Trajectory</td>
<td>15.3 deg</td>
</tr>
<tr>
<td>Vehicle Accelerations</td>
<td>(Max. 0.050-sec Avg)</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>-3.8 g</td>
</tr>
<tr>
<td>Lateral</td>
<td>3.9 g</td>
</tr>
<tr>
<td>Occupant Impact Velocity</td>
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<tr>
<td>Longitudinal</td>
<td>19.2 ft/s (5.9 m/s)</td>
</tr>
<tr>
<td>Lateral</td>
<td>-12.0 ft/s (3.7 m/s)</td>
</tr>
<tr>
<td>Occupant Ridedown Accelerations</td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>-5.5 g</td>
</tr>
<tr>
<td>Lateral</td>
<td>5.9 g</td>
</tr>
</tbody>
</table>

Figure 43. Summary of results for test 7199-7.
<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Test Results</th>
<th>Pass/ Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Test article shall smoothly redirect the vehicle; the vehicle shall not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.</td>
<td>The test article contained and smoothly redirected the vehicle.</td>
<td>Pass</td>
</tr>
<tr>
<td>D. Detached elements, fragments of other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>There were no detached elements or debris from the end terminal that showed any potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>Pass</td>
</tr>
<tr>
<td>E. The vehicle shall remain upright during and after the collision. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.</td>
<td>The vehicle remained upright and stable during the entire impact sequence. There was no deformation or intrusion of the occupant compartment.</td>
<td>Pass</td>
</tr>
<tr>
<td>F. Impact severity shall be less than:</td>
<td>The impact severity for the test were:</td>
<td>Pass</td>
</tr>
<tr>
<td><strong>Occupant Impact Velocity - fps</strong></td>
<td><strong>Occupant Impact Velocity - fps</strong></td>
<td></td>
</tr>
<tr>
<td>Longitudinal 40/15</td>
<td>Longitudinal 19.2</td>
<td></td>
</tr>
<tr>
<td>Lateral 30/20</td>
<td>Lateral 12.0</td>
<td></td>
</tr>
<tr>
<td>Limit/Design</td>
<td>Limit/Design</td>
<td></td>
</tr>
<tr>
<td><strong>Occupant Ridedown Acceleration - g's</strong></td>
<td><strong>Occupant Ridedown Acceleration - g's</strong></td>
<td></td>
</tr>
<tr>
<td>Longitudinal 20/15</td>
<td>Longitudinal -5.5</td>
<td></td>
</tr>
<tr>
<td>Lateral 20/15</td>
<td>Lateral 5.9</td>
<td></td>
</tr>
<tr>
<td>H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.</td>
<td>The vehicle exited the test installation with a speed of 22.4 mi/h (36.0 km/h) and an exit angle of 15.3 degrees which were higher than the recommended limits. However, the vehicle trajectory and final rest position did not indicate any potential of intrusion into adjacent traffic lanes.</td>
<td>Pass</td>
</tr>
</tbody>
</table>
slot guard was specifically designed to prevent this from occurring. Results of this crash test demonstrated that the slot guards perform as designed in preventing the slots from being torn or ripped apart.

5.2 TEST NUMBER 7199-14

The second compliance test involved an end-on impact by an 1,800-lb (817-kg) passenger car at a nominal speed of 45 mi/h (72.4 km/h) with an offset of 15 in (0.38 m) to the center of the vehicle. The objective of this test is to evaluate the impact performance of the terminal for small-car end-on impacts.

Photographs of the test installation are shown in figure 44. A 1988 Yugo (figures 45 and 46) was used in this crash test. The vehicle impacted the terminal end-on at a speed of 45.7 mi/h (73.6 km/h) and an angle of 0 degrees. The vehicle contacted post 1 at 0.031 sec after impact, thereafter the vehicle began to yaw clockwise. The first set of slots located between posts 1 and 2 began to buckle at 0.039 sec. At 0.065 sec, the rail began to separate from post 2. Shortly thereafter, at 0.119 sec, the rail began to buckle at the second set of slots located between posts 2 and 3 and displaced the rail away from post 3. By 0.160 sec, the rail began to buckle at the third set of slots located between posts 3 and 4. As the vehicle contacted post 2 at 0.179 sec, the rail element formed an elbow between post 2 and 3. At approximately 0.369 sec, the vehicle contacted the third post. Shortly thereafter, the driver side door of the vehicle sideswiped the elbow formed by the rail section. The vehicle continued to travel forward with the left side of the vehicle sideswiping the elbow formed by the rail section until it came to rest against post 4, oriented approximately 57 degrees to the length of need section of the guardrail. Photographs of the test installation and vehicle after impact are shown in figure 47.

As can be seen in figure 48, the end terminal received substantial damage. The first three sets of slots mid-span between posts 1 and 2, posts 2 and 3, and posts 3 and 4 were buckled. Posts 1, 2 and 3 were sheared off at ground level.

The vehicle sustained severe damage to the front as shown in figure 49. There was a maximum crush of 14.0 in (356 mm) offset to the right of the center front of the vehicle. In addition, the outside of the driver side door was crushed inward 4.0 in (102 mm) and there was
Figure 44. End treatment before test 7199-14.
Figure 45. Vehicle prior to test 7199-14.
Figure 46. Vehicle/end treatment for test 7199-14.
Figure 47. Test site after test 7199-14.
Figure 48. Damage to end treatment after test 7199-14.
Figure 49. Vehicle after test 7199-14.
1.0 in (25.4 mm) of intrusion into the passenger compartment near the bottom of the driver side door. Also damaged were the front bumper, hood, grill, radiator and fan, right and left front fenders, roof and floor pan.

A summary of the test results is presented in figure 50. The test was judged to have met the evaluation criteria set forth in NCHRP Report 230, a summary of which is shown in table 8. The end terminal successfully brought the vehicle to a controlled and safe stop. All occupant risk factors were well within the recommended limits set forth in NCHRP Report 230. The test vehicle remained upright and stable during the impact sequence. There was no debris from the vehicle or end terminal that might present undue hazard to other traffic. Damage to the end terminal was substantial. Damage to the impacting vehicle was severe and there was approximately 1.0 in (25.4 mm) of intrusion into the occupant compartment near the bottom of the driver side door. However, the extent of intrusion into the occupant compartment was considered minor and did not pose any significant hazard to the occupant. The vehicle came to rest against the test installation and did not pose any hazard to adjacent traffic.

5.3 TEST NUMBER 7199-15

This third compliance crash test involved a 4,500-lb (2,043-kg) passenger car impacting the end terminal head-on at the center of the nose at the nominal speed and angle of 45 mi/h (72.5 km/h) and 0 degree. The objective of this test is to evaluate the energy-absorbing/dissipation properties of the end terminal.

Photographs of the test installation are shown in figures 51 and 52. A 1981 Cadillac (figures 53 and 54) was used in this crash test. The vehicle impacted the end terminal end-on at a speed of 46.8 mi/h (75.3 km/h) and an angle of 0 degrees. The vehicle contacted post 1 at 0.032 sec after impact and the first set of slots between posts 1 and 2 began to buckle shortly thereafter. Also, the rail began to twist or rotate counterclockwise about the longitudinal rail axis. The second set of slots located between posts 2 and 3 began to buckle at 0.092 sec. At 0.144 sec after impact, the vehicle contacted post 2. As the vehicle continued moving forward, the third set of slots between posts 3 and 4 began to deform at 0.207 sec. At 0.224 sec, the rail pulled away from posts 3 and 4. By 0.268 sec, the fourth set of slots
Test No. ............... 7199-14
Date ............... 04/27/93
Test Installation ........ Slotted Rail
End Treatment
Installation Length ........ 50.0 ft (15.2 m)
Test Vehicle ........ 1988 Yugo
Vehicle Weight
Test Inertia ........ 1,800 lb (816 kg)
Gross Static ........ 1,967 lb (892 kg)
Vehicle Damage Classification
TAD ........ 12FR2
CDC ........ 12FREK4 & 11LPEW2
Maximum Vehicle Crush ........ 14.0 in (35.6 cm)

Impact Speed ........ 45.7 mi/h (73.6 km/h)
Impact Angle ........ 0 deg/15° offset to traffic face
Exit Speed ........ N/A
Exit Trajectory ........ N/A
Vehicle Accelerations
(Max. 0.050-sec Avg)
  Longitudinal ........ -9.9 g
  Lateral ........ -3.8 g
Occupant Impact Velocity
  Longitudinal ........ 28.9 ft/s (8.8 m/s)
  Lateral ........ -7.2 ft/s (2.2 m/s)
Occupant Ridedown Accelerations
  Longitudinal ........ -6.5 g
  Lateral ........ -3.6 g

Figure 50. Summary of results for test 7199-14.
<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Test Results</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.</td>
<td>The vehicle was brought to a controlled stop.</td>
<td>Pass</td>
</tr>
<tr>
<td>D. Detached elements, fragments of other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>There were no detached elements or debris from the end terminal that showed any potential for penetrating the passenger compartment or present undue hazard to other traffic.</td>
<td>Pass</td>
</tr>
<tr>
<td>E. The vehicle shall remain upright during and after the collision. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.</td>
<td>The vehicle remained upright and stable throughout the test sequence. There was minor intrusion of 1 in (2.54 cm) into the occupant compartment near the bottom of the driver side door.</td>
<td>Pass</td>
</tr>
<tr>
<td>F. Impact severity shall be less than:</td>
<td>The Impact severity for the test were:</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>Occupant Impact Velocity - fps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>Lateral</td>
</tr>
<tr>
<td>Limit/Design</td>
<td>40/15</td>
<td>30/20</td>
</tr>
<tr>
<td>Occupant Ridedown Acceleration - g's</td>
<td>Longitudinal</td>
<td>Lateral</td>
</tr>
<tr>
<td>Limit/Design</td>
<td>20/15</td>
<td>20/15</td>
</tr>
<tr>
<td>H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.</td>
<td>The vehicle came to rest against the test installation. The vehicle trajectory and final rest position did not indicate any potential of intrusion into adjacent traffic lanes.</td>
<td>Pass</td>
</tr>
<tr>
<td>J. Vehicle trajectory behind the test article is acceptable.</td>
<td>The vehicle came to rest against the test installation.</td>
<td>Pass</td>
</tr>
</tbody>
</table>
Figure 51. Slotted rail end treatment before test 7199-15.
Figure 52. Slotted rail, posts 1 and 2, before test 7199-15.
Figure 53. Vehicle before test 7199-15.
Figure 54. Vehicle/end treatment geometrics for test 7199-15.
located between posts 4 and 5 began to buckle. Hinges were formed at the buckled second, third and fourth sets of slots and the rail began to move laterally outward from the installation. As the vehicle continued forward, an elbow was formed at the buckled fourth set of slots. Upon contact with post 4 at 0.448 sec, the vehicle began to yaw counterclockwise. The vehicle then impacted post 5 and the elbow formed at the buckled fourth set of slots at 0.611 sec. The vehicle yawed counterclockwise and came to rest near post 5, oriented approximately 75 degrees to the length-of-need section of the guardrail. Photographs of the test installation and vehicle at final rest are shown in figure 55.

As can be seen in figure 56, the end terminal received substantial damage. All four sets of slots were buckled and posts 1 through 4 were all sheared off at ground level. Also, post 5 was bent and twisted.

The vehicle sustained severe damage to the front as shown in figure 57. There was a maximum crush of 13.0 in (330 mm) at the center front of the vehicle. The left front wheel was pushed rearward 9.5 in (241 mm) and the front subframe severely bent from impact with post 5 and the elbow formed at the buckled fourth set of slots. Other notable damage sustained were to the front bumper, hood, grill, radiator and fan, and right and left front fenders.

A summary of the test results is presented in figure 58. The test was judged to have met the evaluation criteria set forth in NCHRP Report 230, a summary of which is shown in table 9. The end terminal successfully brought the vehicle to a controlled and safe stop. The vehicle did not gate, which was somewhat unexpected based on the results of the developmental test (test no. 7199-11), but not surprising given the offset of only 18 in (457 mm). The vehicle impacted post 5, which was the beginning of the standard guardrail section, resulting in a counterclockwise yaw. However, the highest 0.010-sec average ridedown acceleration in the longitudinal direction was only -4.7 g, well below the 20 g limit set forth in NCHRP report 230. The other occupant risk factors were also well within the limits set forth in NCHRP Report 230. The vehicle remained upright and stable during the impact sequence. There was no debris from the vehicle or the end terminal that might present undue hazard to other traffic. Damage to the end terminal was substantial. Damage to the impacting vehicle was severe, but there was no or intrusion into the occupant compartment. The vehicle came to rest against the test installation and did not pose any hazard to adjacent traffic.
Figure 55. Test site after test 7199-15.
Figure 56. Slotted rail end treatment after test 7199-15.
Figure 57. Vehicle after test 7199-15.
Test No. ................. 7199-15
Date ................. 05/14/93
Test Installation ........ Slotted Rail
End Treatment
Installation Length ........ 50.0 ft (15.2 m)
Test Vehicle ........ 1981 Cadillac
Vehicle Weight
  Test Inertia ........ 4,500 lb (2,041 kg)
  Gross Static ........ N.A.
Vehicle Damage Classification
  TAD ......... 12FC5
  CDC .......... 12FCEW2
Maximum Vehicle Crush ........ 13.0 in (33.0 cm)

Impact Speed ........ 46.8 mi/h (75.3 km/h)
Impact Angle ........ 0 deg
Exit Speed ........ N/A
Exit Trajectory ........ N/A
Vehicle Accelerations
  (Max. 0.050-sec Avg)
    Longitudinal ........ -4.7 g
    Lateral ........ -2.0 g
Occupant Impact Velocity
  Longitudinal ........ 19.8 ft/s (6.0 m/s)
  Lateral ........ 5.3 ft/s (1.6 m/s)
Occupant Ridedown Accelerations
  Longitudinal ........ -5.7 g
  Lateral ........ -0.9 g

Figure 58. Summary of results for test 7199-15.
<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Test Results</th>
<th>Evaluation Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptable test article performance may be by redirection, controlled stopping, or controlled stopping on the test article.</td>
<td>The vehicle was brought to a controlled stop.</td>
<td>Pass</td>
</tr>
<tr>
<td>Detached elements, fragments of other debris from the test article, or debris from the end terminal compartment or present above hazard to other traffic.</td>
<td>There were no detached elements or debris on the passenger compartment.</td>
<td>Pass</td>
</tr>
<tr>
<td>The vehicle remained upright and stable throughout the test sequence. There was no deformation or intrusion of the occupant compartment.</td>
<td>The vehicle remained upright and stable throughout the test sequence.</td>
<td>Pass</td>
</tr>
<tr>
<td>The impact severity for the test were:</td>
<td>The impact severity was:</td>
<td></td>
</tr>
<tr>
<td>Occupant Impact Velocity - Lateral FPE</td>
<td>19.8 longitudinal</td>
<td></td>
</tr>
<tr>
<td>Occupant Rideshock Acceleration - Lateral</td>
<td>5.7 longitudinal</td>
<td></td>
</tr>
<tr>
<td>Occupant Impact Velocity - Longitudinal FPE</td>
<td>30/20 longitudinal</td>
<td></td>
</tr>
<tr>
<td>Occupant Rideshock Acceleration - Longitudinal</td>
<td>20/15 longitudinal</td>
<td></td>
</tr>
<tr>
<td>The vehicle remained upright and stable and after the collision, the final stopping position shall include a minimum distance, if at all, into adjacent traffic lanes.</td>
<td>The vehicle came to rest against the test installation. The vehicle trajectory and final stopping position did not indicate any potential of intrusion into adjacent traffic lanes.</td>
<td>Pass</td>
</tr>
<tr>
<td>J. Vehicle trajectory behind the test article is acceptable.</td>
<td>The vehicle came to rest against the test installation.</td>
<td>Pass</td>
</tr>
</tbody>
</table>
VI. SUMMARY OF FINDINGS AND RECOMMENDATIONS

6.1 SUMMARY OF FINDINGS

- A slotted rail end terminal for W-beam guardrails, designed for use on highways with speed limits of 45 mi/h (72.4 km/h) or lower and with a flare offset of as little as 18 in (0.46 m), was successfully developed and crash tested under this study. The slotted rail end terminal design is suitable for both new construction and retrofit of existing W-beam guardrail installations.

- The slotted rail end terminal design was based on a concept developed under a previous study, which was further refined and developed in this study. The design concept is based on the use of three longitudinal 1/2-in (12.7 mm) slots cut into the W-beam rail element, one at each peak and valley in the cross section, to reduce the buckling strength of the W-beam rail element while maintaining the tensile capacity of the rail element. A slot guard is attached to the downstream end of each set of slots to prevent extension of the slots and rupture of the rail. The slot guard both reinforces the W-beam rail element and provides a 45-degree deflector plate to push the rail element away from any vehicle component that intruded into the slots. The modified design alleviates the perceived problems with aesthetics, installation and maintenance associated with the original split rail end terminal.

- Other than the slotted W-beam rail element and the slot guards, the slotted rail terminal utilizes standard components used with the BCT terminal.

- The design was subjected to the required compliance crash tests and successfully met with guidelines and evaluation criteria set forth in NCHRP Report 230 for impact speed of 45 mi/h (72.5 km/h).

- The estimated cost for the end terminal assembly is expected to be slightly higher than the standard BCT terminal, but substantially lower than other end terminals currently available. A more exact cost estimate for the slotted rail end terminal is not possible at this time since the costs for the slotted rail element and the slot guards are a function of the manufacturing process.
6.2 RECOMMENDATIONS AND DISCUSSIONS

- In one of the large car head-on tests in this study (test no. 7199-11) and in another crash test on a box-beam median barrier end terminal\(^{(2)}\), it was observed that the cable anchor bearing plate, after releasing from the wooden end post, was thrown up underneath the vehicle and caught on the undercarriage of the vehicle. This restrained the forward movement of the vehicle, resulting in the vehicle yawing rapidly and coming to an abrupt stop.

To eliminate this potential of the cable anchor bearing plate being caught or snagged on some part of the undercarriage of the vehicle, a slotted bearing plate, as shown in figure 59, has been designed so that the bearing plate would separate from the cable anchor upon breaking of the wooden end post. A 4 in. x 3 in. x 3/8 in (102 mm x 76 mm x 9.5 mm) plate washer is used with the slotted bearing plate. Also, to avoid the cable anchor bearing plate being displaced from the proper position when the cable is loosened, two 1/4-in (6.4-mm) diameter lag screws are used to attach the bearing plate to the wooden end post.

While the slotted bearing plate was not tested under this study, it has been successfully tested in two length-of-need strength tests involving a 4,500-lb (2,043-kg) passenger cars impacting a box-beam median barrier end terminal at the nominal speed and angle of 60 mi/h (96.6 km/h) and 25 degrees\(^{(8)}\). The incorporation of the slotted bearing plate into the slotted rail terminal design is therefore recommended.

- While the slotted rail end terminal design has been successfully crash tested and shown to meet all 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 slotted rail end terminal 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.
Figure 59. Slotted bearing plate detail
REFERENCES


6. Letter from Mr. Lawrence A. Staron, Chief, Federal-Aid and Design Division, to King K. Mak, dated March 26, 1993.

7. Test no. 7202-6, conducted under TTI project no. RF 7202, "Development of End Terminal for Box-Beam Guardrail, Phase II - Crash Testing and Evaluation".

8. Test nos. 7202-8 and 7202-9, conducted under TTI project no. RF 7202, "Development of End Terminal for Box-Beam Guardrail, Phase II - Crash Testing and Evaluation".
APPENDIX A

DIMENSIONS AND INFORMATION
OF THE TEST VEHICLES
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>Vehicle properties for test 7199-8</td>
<td>A-3</td>
</tr>
<tr>
<td>A-2</td>
<td>Vehicle properties for test 7199-8A</td>
<td>A-4</td>
</tr>
<tr>
<td>A-3</td>
<td>Vehicle properties for test 7199-11</td>
<td>A-5</td>
</tr>
<tr>
<td>A-4</td>
<td>Vehicle properties for test 7199-13</td>
<td>A-6</td>
</tr>
<tr>
<td>A-5</td>
<td>Vehicle properties for test 7199-7</td>
<td>A-7</td>
</tr>
<tr>
<td>A-6</td>
<td>Vehicle properties for test 7199-14</td>
<td>A-8</td>
</tr>
<tr>
<td>A-7</td>
<td>Vehicle properties for test 7199-15</td>
<td>A-9</td>
</tr>
</tbody>
</table>
Date: 9-4-92 Test No.: 7199-8 VIN: JG1MR6153H12739327
Make: Chevrolet Model: Sprint Year: 1987 Odometer: 6843
Tire Condition: good __ fair X __ badly worn __

Vehicle Geometry - inches
a 60.25" b 26.5"
c 92.5" d* 53.25"
e 24.25" f 143.25"
g ________ h 38.7"
i ________ j 28.5"
k 14.5" l 43.5"
m 20" n 6.5"
o 9.25" p 52.5"
r 21" s 13.125"

Engine Type: 3 cyl
Engine CID: 1.0 liter
Transmission Type: Manual
FWD
Body Type: 5 Door Hatch
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

4-wheel weight for c.g. det.  
\[ \ell f \text{536} \quad \ell r \text{386} \quad \ell r \text{368} \]

Mass - pounds Curb Test Inertial Gross Static
\[ \begin{array}{cccc}
M_1 & 981 & 1046 & 1135 \\
M_2 & 597 & 754 & 835 \\
M_T & 1578 & 1800 & 1970 \\
\end{array} \]

Note any damage to vehicle prior to test:
Crack in windshield (marked)

*d = overall height of vehicle

Figure A-1. Vehicle properties for test 7199-8.
Date: 10-20-92  Test No.: 7199-8A  VIN: JG1MR2151HK742677
Make: Chevy  Model: Sprint  Year: 1986  Odometer: 81641
Tire Condition: good  fair  X  badly worn
Vehicle Geometry - inches
a  60.25"  b  26"
c  88.5"  d* 52.25"
e  25"  f  139.25"
g  h  35.1"
i  j  27.5"
k  15"  l  37"
m  18.5"  n  6.5"
o  11.25"  p  53"
r  21.5"  s  13.25"
Engine Type: 3 cyl gas
Engine CID: 1.0 Liter
Transmission Type: Automatic
FWD
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

4-wheel weight for c.g. det.  l f  553  r f  533  l r  357  r r  357
Mass - pounds  Curb  Test Inertial  Gross Static
M₁  1053  1086  1161
M₂  542  714  806
M₀  1577  1800  1967

Note any damage to vehicle prior to test:

*A d = overall height of vehicle

Figure A-2. Vehicle properties for test 7199-8A.
Date: 1-26-93        Test No.: 7199-11        VIN: 1G6AB6991B9228724
Make: Cadillac      Model: Fleetwood       Year: 1981         Odometer: 68882
Tire Condition: good __ fair X badly worn __

Vehicle Geometry - inches
a 77.5"  b 40"

4-wheel weight for c.g. det.   \( e_f 1192 \) \( r_f 1173 \) \( e_r 1069 \) \( r_r 1066 \)

Mass - pounds Curb          Test Inertial Gross Static
\( M_1 \) 2375             2365
\( M_2 \) 1714             2135
\( M_T \) 4089             4500

Note any damage to vehicle prior to test:

\*d = overall height of vehicle

Figure A-3. Vehicle properties for test 7199-11.
Date: 4-13-93  Test No.: 7199-13  VIN: VX1BB1214JK405753

Make: Yugo  Model: GVL  Year: 1988  Odometer: 50601

Tire Size: 145R13  Ply Rating:  Bias Ply:  Belted:  Radial: 

Tire Condition: good  fair  badly worn

Vehicle Geometry - inches
a 151  b 68.5
c 215.5  d* 141
e 62.5  f 346.5
g 20  h 85.5
i ----  j 80.8
k ----  l ----
m 50.3  n 7.4
o 37.2  p 128.5
r 56  s 36.4

Engine Type: 4 Cyl Gasoline
Engine CID: 1100 CC
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 √ drum __
Rear: disc __ drum √

Note any damage to vehicle prior to test:

\( d = \text{overall height of vehicle} \)

Figure A-4. Vehicle properties for test 7199-13.
Date: 8-28-92    Test No.: 7199-7    VIN: 1G6AD6985C9226526

Make: Cadillac    Model: Sedan    Year: 1982    Odometer: 

Tire Size:      Ply Rating:      Bias Ply:      Belted:      Radial: 

Tire Condition: good 

fair 

badly worn 

Vehicle Geometry - inches 

\[ a = 77'' \quad b = 39.5'' \]

\[ c = 121.5'' \quad d = 55.5'' \]

\[ e = 56.5'' \quad f = 217'' \]

\[ g = \quad h = \quad i = \quad j = 33'' \]

\[ k = 15.75'' \quad \ell = 53'' \]

\[ m = 21.5'' \quad n = 4.75'' \]

\[ o = 12'' \quad p = 62.25'' \]

\[ r = 28.5'' \quad s = 16.25'' \]

Engine Type: 8 cyl gas

Engine CID: 

Transmission Type:

Automatic 

Manual

Body Type: 4 Door Sedan

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

4-wheel weight for c.g. det. \[ M_1 = 2160 \quad M_2 = 1878 \quad M_T = 4038 \]
\[ \ell_f = 1180 \quad \ell_r = 1140 \quad M_1 = 2263 \quad M_2 = 2237 \quad M_T = 4500 \]

Note any damage to vehicle prior to test:

- Cracked windshield (marked)

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

---

Figure A-5. Vehicle properties for test 7199-7.
Date: 4-27-93  Test No.: 7199-14  VIN: VX1BB1219JK408566
Make: Yugo  Model: GVL  Year: 1988  Odometer: 39154
Tire Size: P155/80R13  Ply Rating:  Bias Ply:  Belted:  Radial: 
Tire Condition: good  fair  badly worn
Vehicle Geometry - inches
a 57.5  b 27.5  c 85.25  d 56.5  e 25  f 137.75  g 27  h 31.5  i 30.5  j 30.5
k 31.7  l  
m 20.5  n 2.25  o 13  p 51.75  r 23  s 14.75
Engine Type: V4 Gasoline  Engine CID: 1.1 L  Transmission Type: 
Ax Ax Ax 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

Figure A-6. Vehicle properties for test 7199-14.
Date: 5-14-93  Test No.: 7199-15  VIN: 1G6AD479489191542
Make: Cadillac  Model: Coupe  Year: 1981  Odometer: 16665
Tire Size: P225 R15  Ply Rating:  Bias Ply:  Belted: X  Radial: 
Tire Condition: good  fair X  badly worn 

Vehicle Geometry - inches
a 74.75  b 41
c 121  d* 55.5
e 56.25  f 218.25
g  h 57.7
i 33.75
j  k 17.25  l 53
m 20.25  n 4.25
o 12  p 62
r 28  s 16.25

Engine Type: V-8 Gasoline  Engine CID: 6.0
Transmission Type: Automatic or M or RWD or 4W
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

* = overall height of vehicle

Figure A-7. Vehicle properties for test 7199-15.
APPENDIX B

SEQUENTIAL PHOTOGRAPHS OF THE IMPACTS
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>Sequential photographs for test 7199-8 (overhead and frontal views)</td>
<td>B-3</td>
</tr>
<tr>
<td>B-2</td>
<td>Sequential photographs for test 7199-8 (side view)</td>
<td>B-5</td>
</tr>
<tr>
<td>B-3</td>
<td>Sequential photographs for test 7199-8A (overhead and frontal views)</td>
<td>B-6</td>
</tr>
<tr>
<td>B-4</td>
<td>Sequential photographs for test 7199-8A (side view)</td>
<td>B-8</td>
</tr>
<tr>
<td>B-5</td>
<td>Sequential photographs for test 7199-11 (overhead and side views)</td>
<td>B-9</td>
</tr>
<tr>
<td>B-6</td>
<td>Sequential photographs for test 7199-13 (overhead and frontal views)</td>
<td>B-11</td>
</tr>
<tr>
<td>B-7</td>
<td>Sequential photographs for test 7199-13 (behind the rail view)</td>
<td>B-13</td>
</tr>
<tr>
<td>B-8</td>
<td>Sequential photographs for test 7199-7 (overhead and frontal views)</td>
<td>B-14</td>
</tr>
<tr>
<td>B-9</td>
<td>Sequential photographs for test 7199-7 (side view)</td>
<td>B-16</td>
</tr>
<tr>
<td>B-10</td>
<td>Sequential photographs for test 7199-14 (overhead and frontal views)</td>
<td>B-17</td>
</tr>
<tr>
<td>B-11</td>
<td>Sequential photographs for test 7199-14 (behind the rail view)</td>
<td>B-19</td>
</tr>
<tr>
<td>B-12</td>
<td>Sequential photographs for test 7199-15 (overhead and frontal views)</td>
<td>B-20</td>
</tr>
<tr>
<td>B-13</td>
<td>Sequential photographs for test 7199-15 (side view)</td>
<td>B-22</td>
</tr>
</tbody>
</table>
Figure B-1. Sequential photographs for test 7199-8.
(overhead and frontal views)
Figure B-1. Sequential photographs for test 7199-8 (continued) (overhead and frontal views).
Figure B-2. Sequential photographs for test 7199-8.
(side view)
Figure B-3. Sequential photographs for test 7199-8A. (overhead and frontal views)
Figure B-3. Sequential photographs for test 7199-8A (continued) (overhead and frontal views).
Figure B-4. Sequential photographs for test 7199-8A. (side view)
Figure B-5. Sequential photographs for test 7199-11. (overhead and side views)
Figure B-5. Sequential photographs for test 7199-11 (continued) (overhead and side views).
Figure B-6. Sequential photographs for test 7199-13. (overhead and frontal views)
Figure B-6. Sequential photographs for test 7199-13 (continued)
(overhead and frontal views).
Figure B-7. Sequential photographs for test 7199-13.
(behind the rail view)
Figure B-8. Sequential photographs for test 7199-7, (overhead and frontal views)
Figure B-8. Sequential photographs for test 7199-7 (continued) (overhead and frontal views).
Figure B-9. Sequential photographs for test 7199-7. (side view)
Figure B-10. Sequential photographs for test 7199-14 (continued) (overhead and frontal views).
Figure B-10. Sequential photographs for test 7199-14. (overhead and frontal views) cont.
Figure B-11. Sequential photographs for test 7199-14. (behind the rail view)
Figure B-12. Sequential photographs for test 7199-15. (overhead and frontal views).

B-20
Figure B-12. Sequential photographs for test 7199-15 (continued) (overhead and frontal views).
Figure B-13. Sequential photographs for test 7199-15.
(side view)
APPENDIX C

VEHICULAR ACCELERATION
VERSUS TIME TRACES

C-1
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>Longitudinal accelerometer trace for test 7199-8</td>
<td>C-3</td>
</tr>
<tr>
<td>C-2</td>
<td>Lateral accelerometer trace for test 7199-8</td>
<td>C-4</td>
</tr>
<tr>
<td>C-3</td>
<td>Vertical accelerometer trace for test 7199-8</td>
<td>C-5</td>
</tr>
<tr>
<td>C-4</td>
<td>Longitudinal accelerometer trace for test 7199-8A</td>
<td>C-6</td>
</tr>
<tr>
<td>C-5</td>
<td>Lateral accelerometer trace for test 7199-8A</td>
<td>C-7</td>
</tr>
<tr>
<td>C-6</td>
<td>Vertical accelerometer trace for test 7199-8A</td>
<td>C-8</td>
</tr>
<tr>
<td>C-7</td>
<td>Longitudinal accelerometer trace for test 7199-11</td>
<td>C-9</td>
</tr>
<tr>
<td>C-8</td>
<td>Lateral accelerometer trace for test 7199-11</td>
<td>C-10</td>
</tr>
<tr>
<td>C-9</td>
<td>Vertical accelerometer trace for test 7199-11</td>
<td>C-11</td>
</tr>
<tr>
<td>C-10</td>
<td>Longitudinal accelerometer trace for test 7199-13</td>
<td>C-12</td>
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<td>Lateral accelerometer trace for test 7199-13</td>
<td>C-13</td>
</tr>
<tr>
<td>C-12</td>
<td>Vertical accelerometer trace for test 7199-13</td>
<td>C-14</td>
</tr>
<tr>
<td>C-13</td>
<td>Longitudinal accelerometer trace for test 7199-7</td>
<td>C-15</td>
</tr>
<tr>
<td>C-14</td>
<td>Lateral accelerometer trace for test 7199-7</td>
<td>C-16</td>
</tr>
<tr>
<td>C-15</td>
<td>Vertical accelerometer trace for test 7199-7</td>
<td>C-17</td>
</tr>
<tr>
<td>C-16</td>
<td>Longitudinal accelerometer trace for test 7199-14</td>
<td>C-18</td>
</tr>
<tr>
<td>C-17</td>
<td>Lateral accelerometer trace for test 7199-14</td>
<td>C-19</td>
</tr>
<tr>
<td>C-18</td>
<td>Vertical accelerometer trace for test 7199-14</td>
<td>C-20</td>
</tr>
<tr>
<td>C-19</td>
<td>Longitudinal accelerometer trace for test 7199-15</td>
<td>C-21</td>
</tr>
<tr>
<td>C-20</td>
<td>Lateral accelerometer trace for test 7199-15</td>
<td>C-22</td>
</tr>
<tr>
<td>C-21</td>
<td>Vertical accelerometer trace for test 7199-15</td>
<td>C-23</td>
</tr>
</tbody>
</table>

C-2
Figure C-2. Lateral accelerometer trace for test 7199-8.
Figure C-4. Longitudinal accelerometer trace for test 7199-8A.
Figure C-5. Lateral accelerometer trace for test 7199-8A.
Figure C-6. Vertical accelerometer trace for test 7199-8A.
Figure C-7. Longitudinal accelerometer trace for test 7199-11.
Figure C-9. Vertical accelerometer trace for test 7199-11.
Figure C-10. Longitudinal accelerometer trace for test 7199-13.
CRASH TEST 7199-13
Accelerometer at center-of-gravity

Figure C-11. Lateral accelerometer trace for test 7199-13.
Figure C-12. Vertical accelerometer trace for test 7199-13.
Figure C-13. Longitudinal accelerometer trace for test 7199-7.
CRASH TEST 7199-7
Class 180 Filter

Figure C-14. Lateral accelerometer trace for test 7199-7.
Figure C-15. Vertical accelerometer trace for test 7199-7.
CRASH TEST 7199-14
Accelerometer at center-of-gravity

Figure C-16. Longitudinal accelerometer trace for test 7199-14.
CRASH TEST 7199-14
Accelerometer at center-of-gravity

Figure C-17. Lateral accelerometer trace for test 7199-14.
CRASH TEST 7199-14
Accelerometer at center-of-gravity

Figure C-18. Vertical accelerometer trace for test 7199-14.
Figure C-19. Longitudinal accelerometer trace for test 7199-15.
Figure C-20. Lateral accelerometer trace for test 7199-15.
Figure C-21. Vertical accelerometer trace for test 7199-15.
APPENDIX D

VEHICULAR ANGULAR DISPLACEMENTS
VERSUS TIME PLOTS
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>Vehicle angular displacements for test 7199-8</td>
<td>D-3</td>
</tr>
<tr>
<td>D-2</td>
<td>Vehicle angular displacements for test 7199-8A</td>
<td>D-4</td>
</tr>
<tr>
<td>D-3</td>
<td>Vehicle angular displacements for test 7199-11</td>
<td>D-5</td>
</tr>
<tr>
<td>D-4</td>
<td>Vehicle angular displacements for test 7199-13</td>
<td>D-6</td>
</tr>
<tr>
<td>D-5</td>
<td>Vehicle angular displacements for test 7199-7</td>
<td>D-7</td>
</tr>
<tr>
<td>D-6</td>
<td>Vehicle angular displacements for test 7199-14</td>
<td>D-8</td>
</tr>
<tr>
<td>D-7</td>
<td>Vehicle angular displacements for test 7199-15</td>
<td>D-9</td>
</tr>
</tbody>
</table>
Figure D-1. Vehicle angular displacements for test 7199-8.

Axes are vehicle fixed. Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll
Axes are vehicle fixed. Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll

Figure D-2. Vehicle angular displacements for test 7199-8A.
Figure D-3. Vehicle angular displacements for test 7199-11.

Axes are vehicle fixed.
Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll
Axes are vehicle fixed. Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

Figure D-4. Vehicle angular displacements for test 7199-13.
Axes are vehicle fixed. Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll

Figure D-5. Vehicle angular displacements for test 7199-7.
Axes are vehicle fixed. Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

Figure D-6. Vehicle angular displacements for test 7199-14.
Axes are vehicle fixed.
Sequence for determining orientation is:
1. Yaw
2. Pitch
3. Roll

Figure D-7. Vehicle angular displacements for test 7199-15.