Guardrail End Treatments in the 1990s

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An attempt is made to objectively review the most important characteristics of most commercially available and widely implemented terminals or end treatments for guardrail installations. These characteristics include collision performance in the testing and roadside environments, maintenance characteristics, and costs. Field experience with these devices is reviewed. An effort is made to compare performance, use, and costs to aid interested parties in selecting the most cost-effective terminals to meet specific needs.

Roadside safety has improved spectacularly since the mid-1960s. Functional life-saving structures have been developed rapidly in response to readily perceived needs. An exception to these achievements is end treatments or terminals for W-section guardrails.

When it was recognized in the mid-1960s that unprotected or unmodified guardrail ends were lethal roadside hazards (Figure 1), the highway community moved toward what appeared at the time to be a good, economical solution—the turned-down end. Turning the first section of the W-beam down and anchoring it at ground level certainly solved the spearing problem. Turndowns were considered good practice to enhance "the forgiving roadside" and were widely implemented throughout the United States (*1,2*).

With the momentum of AASHTO safety publications, the inertia of the research community, and the lack of good alternatives working to its advantage, turndowns continued to be implemented in many states. Concern for the ramping problem resulted in the development of a variation that was included in the 1977 barrier guide as an experimental design (*3,4*). It was designed to prevent severe ramping by collapsing when stuck head-on. It represents another example of good performance when struck head-on by a full-size vehicle, but marginal performance when struck by a small car. Efforts to improve performance by Hirsch and Buth (*4*), Hinch (*5*), and FHWA had limited success and neither GEET1 nor controlled releasing terminals (CRTs) have been used in significant numbers.

By the 1970s, the problem of ramping and capsizing was recognized (*6*). After Southwest Research Institute (SwRI) demonstrated this problem, it began development of the breakaway cable terminal (BCT) (*7*). BCT showed great promise in early tests with full-sized vehicles (*8*). The head-on 15-in. offset test with a 1,800-lb vehicle at 60 mph, which became a required test in 1981, was a problem (*9*). This was demonstrated in the early 1980s by FHWA (*10*).

The 4-ft offset, 37.5-ft parabolic flare was a prominent and important feature in the development of BCT. If there had been better alternatives to the BCT at that time, it might not have received such wide acceptance. It has several virtues: it was low cost, was relatively simple to install, and was the only operational terminal in the 1977 barrier guide (*3*).

It is estimated that 45 states have installed approximately 450,000 BCTs since 1972. Over time two problems began to emerge. Some state departments of transportation (DOTs) were not installing BCTs according to the recommended design drawings and the 1977 barrier guide. In some cases, state standards allowed installation with only 1 ft of flare, and in others, BCTs were installed with no flare at all. Furthermore, vehicles were not impacting the terminal in the same way in which the crash tests were conducted. The result was collisions in which BCTs did not perform well (*11–13*).

Continued testing of BCTs after initial implementation was conducted to (a) reduce costs, and (b) develop the steel post, slipbase alternative. Only after the FHWA program in the early 1980s was there a definite need recognized to change the basic BCT design. BCT-type devices such as the eccentric loader terminal (ELT) and the modified eccentric loader terminal (MELT) (Figure 2) are products of those efforts. The 18-in. offset test has not yet been tested.

In a memorandum of June 28, 1990, FHWA declined participation in any new installation of turndowns in high-speed, high-volume facilities (*14*). Turndowns have been used almost exclusively in a number of states. Texas recently completed a study of statewide accident data that may illustrate the shortcomings of the turndown. Texas has now changed the policy of constructing turndowns on high-speed, high-volume roadways, and Ohio is entering a new rehabilitation phase of replacing many turndowns. California (*15*) has recently evalu-

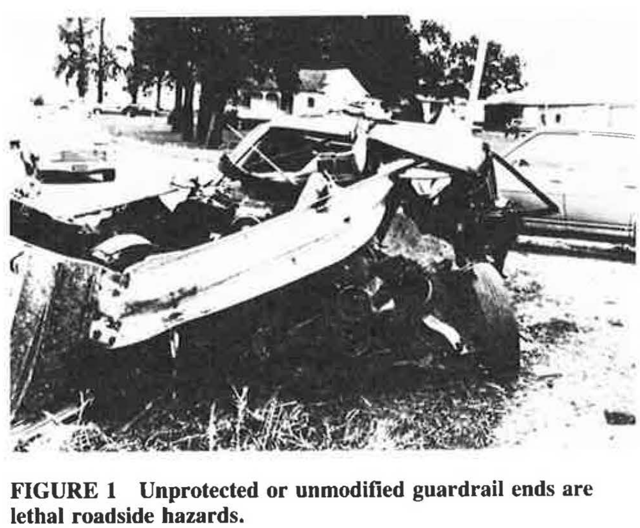

FIGURE 1 Unprotected or unmodified guardrail ends are lethal roadside hazards.

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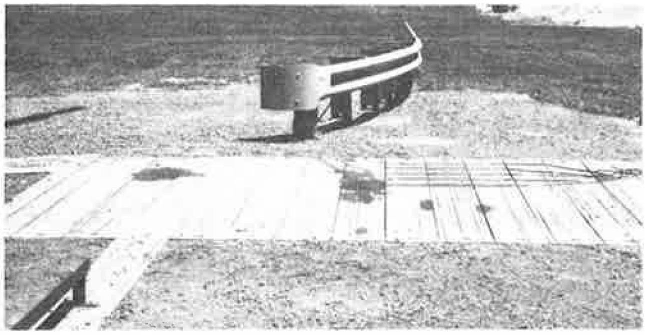


FIGURE 2 MELT (*29*).

FIGURE 3 BRAKEMASTER.

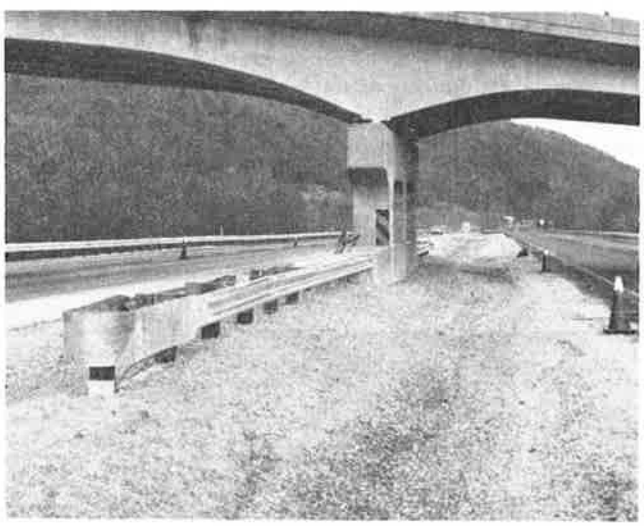


FIGURE 4 CAT installation.

ated eight terminal devices, including BCT. California noted the limitations of BCTs, but has not restricted their use as long as there is space for the full 4-ft flare. California has also approved use of ELT with a 4-ft flare and has declined its use with a 1.5-ft flare.

A design called Sentre (safety barrier end treatment) has been available for several years, but its cost has remained at

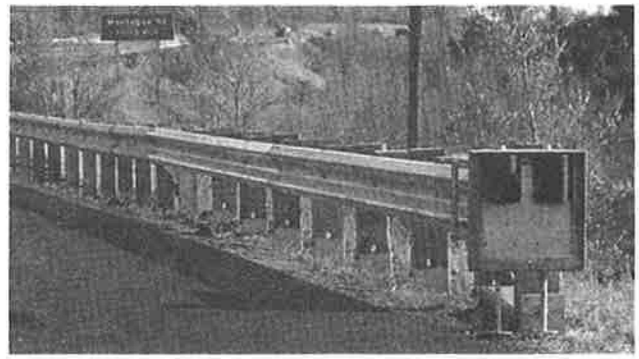


FIGURE 5 ET-2000, guardrail extruder terminal.

a level considered prohibitive in many states in all but the most accident-prone locations.

With significant questions regarding the adequacy of the lower-cost and most widely used terminals, three new devices have recently reached the market. They are BRAKEMASTER, CAT (crash-cushion attenuating terminal), and ET-2000, shown in Figures 3–5. These devices, described in more detail in the following section, meet safety requirements, but are more expensive than BCTs and turndowns.

OPERATIONAL EXPERIENCE

Figure 6 shows the periods during which various designs were used. The blunt end has been in use from the beginning and for decades has been recognized as an extremely hazardous roadside object. However, it has never been replaced on low-volume highways and is still being constructed in some counties and municipalities.

The turndown has been widely applied since the late 1960s but is now slowly being replaced in some states. Many states are still satisfied with BCTs. This satisfaction may be because care has been taken to ensure compliance with the 4-ft flare requirement or because the accident experience has not been documented and evaluated. The other five terminals are still

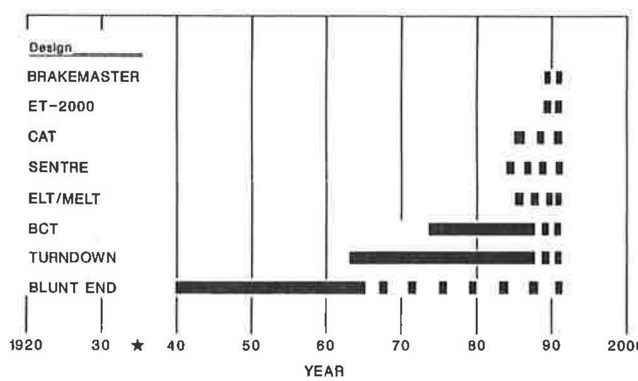


FIGURE 6 Periods of use for various end treatments.

relatively new, but significant positive operational experience should be acknowledged for Sentre and CAT. ET-2000 is rapidly gaining that experience.

BCT Design and Installation

Since the original BCT design drawing was introduced in 1972, a number of changes or alternatives to this design have been developed by NCHRP (*8,16,17*):

- An end-post size change from 8 × 8 in. to 6 × 8 in.,
- A steel, slip-base post alternative,
- Recommended omission of the steel nose diaphragms, and
- Steel tube foundation alternative to concrete footings.

Other known changes to the design have been incorporated into state standards and are not considered advisable:

- Reduction or omission of the 4-ft lateral offset, use of a straight taper in lieu of a parabolic flare at the end, or both;
- Use of a 10-gauge W-beam; and
- Use of a rub rail within the 37.5-ft flare length, sometimes with increased beam height.

Other observed installation errors include the following:

- Not building 4-ft offset, 37.5-ft parabolic flare as shown on standard,
- Installing end on steep slope or near slope break,
- Lack of consideration of run-out for vehicles impacting or narrowly missing terminal (too short),
- Installing beam too high or too low,
- Inadequate foundation for end posts (could be due to poor geometrics, concrete material, weak soil, etc.), and
- Use of a square washer not in compliance with the plans.

Examples of proper and improper installations are shown in Figure 7.

BCT Accident Experience

New Jersey (*11*) and Indiana (*12*) both reported adverse accident experience with straight or moderately flared BCTs. Both reported more satisfactory results when the full 4-ft offset flare was constructed. The latest reports from Kentucky (*13,18*) recommend using the BCTs where the full 4-ft offset can be obtained. Other states have related satisfactory experience with the BCT.

Among the notable problem areas in addition to those attributed to improper installation are impacts with the side of a vehicle and impacts in which the beam enters the wheel well area. BCTs, like all terminals, were developed using frontal impact and do not perform well in side impacts. In addition, when the beam goes between the wheel and the engine, an area of minimal resistance is encountered. This has resulted in penetration into the passenger compartment.

IMPLEMENTATION PROBLEMS

The most significant problem for the BCT is the 4-ft offset, 37.5-ft long parabolic flare. In many observed cases, there was adequate space to accommodate this critical geometry, but it was not done. This failure is often associated with sloping terrain problems. It is sometimes judged that it is safer to reduce the offset distance than to carry the flare down sloping terrain, but this is probably incorrect in most cases.

The foregoing paragraphs lead to the conclusion that the BCT is not always dependable. The FHWA memorandum of March 27, 1991, called for multistate financing of research to improve BCTs (*19*). This is an ongoing study.

TURNDOWNS

Griffin (*20*) sought to determine if, and to what degree, turned-down guardrail ends constitute a safety problem. He attempted to estimate the number of vehicles that overturned on turned-down guardrail ends in Texas in one year and the number of people who were seriously injured in accidents involving turned-down guardrail ends.

These accidents were drawn from the 190,512 accidents reported to have occurred on the Texas highway system in 1989. Of these 190,512 accidents, 4,047 (2.1 percent) were alleged to involve an impact with a guardrail. Of these, 100 were fatal accidents, although the guardrails (or their turned-down ends) may have had little or nothing to do with the fatalities.

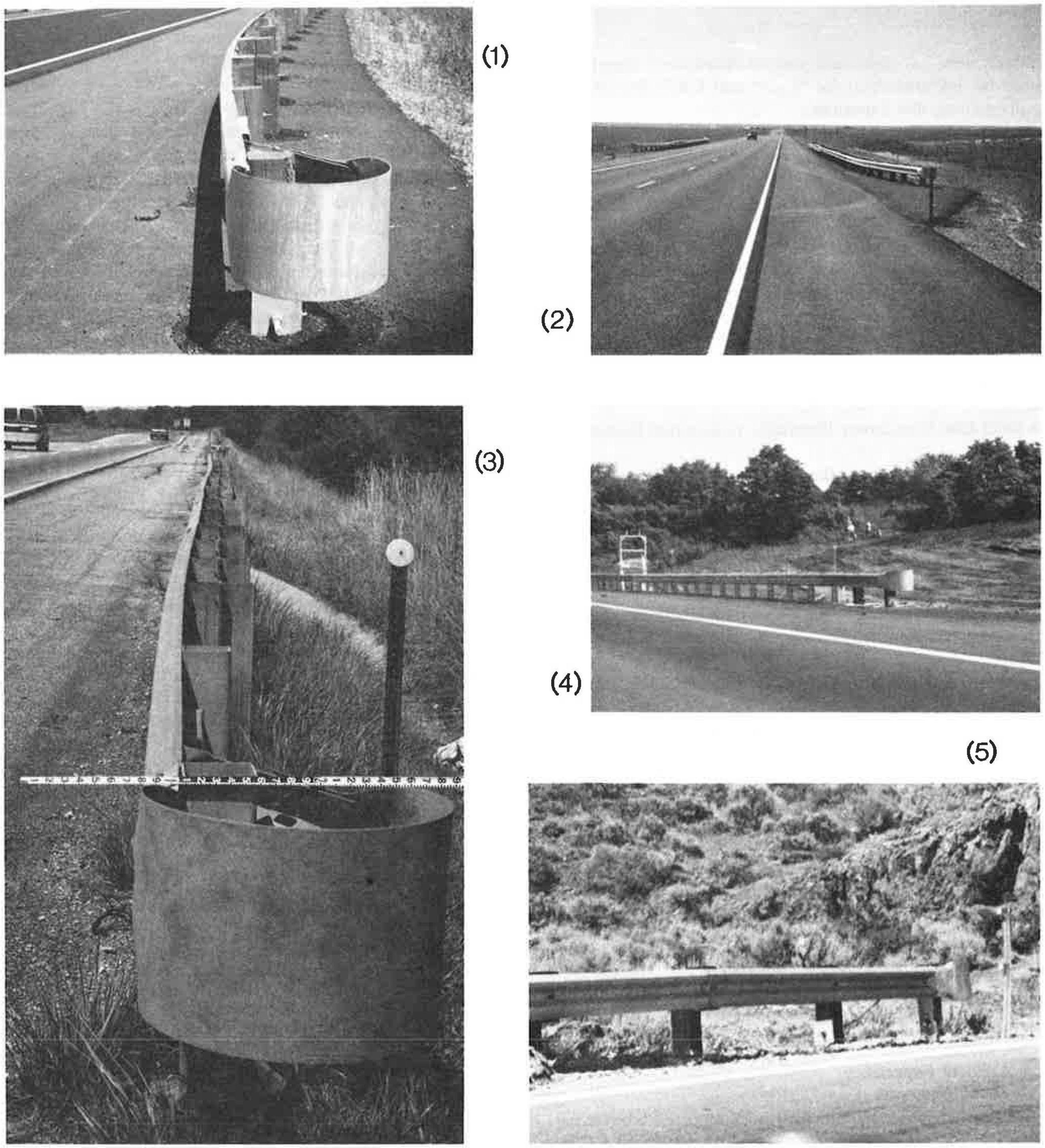
The police accident reports for all 100 fatal accidents and a 25 percent sample of the remaining 3,947 nonfatal accidents were reviewed to answer two questions: Was the point of impact in the accident with the end of the rail (i.e., on a turned-down end) or somewhere else on the rail? and Did the vehicle overturn?

The answers led to the following conclusion (*20*).

> It is estimated on the Texas state-maintained highway system in a typical year some 736 accidents occur on turned-down guardrail ends. 278 of these vehicles overturn, 43 individuals are killed and another 85 sustain incapacitating (A-Level) injuries. These are considered unsatisfactory statistics.
>
> It should also be understood that the degree to which vehicle overturns and driver/occupant deaths and injuries could be reduced by replacing turned-down guardrail ends with other end treatments (e.g., breakaway cable terminals) is unknown. The analyses contained in this report suggest that fatal accidents on turned-down guardrail ends tend to be associated with high speeds, drunk driving, darkness, sleeping/fatigued drivers, etc.

IMPROVED TERMINALS

Throughout the 1970s and early 1980s BCTs and turndowns were rapidly deployed. Without good field information these end treatments seemed to be adequate. Their advantages over the blunt end were clear. Widespread implementation of the turndown and BCT also occurred before there was a recognized test matrix for terminals. Few terminal tests were conducted according to NCHRP Report 153 (*21*) before 1981 when NCHRP Report 230 (*9*) was published. SwRI demon-



(1) Parabolic flared BCT. PROPER
(2) Parabolic flared BCT, local shoulder widening*.
(3) Straight steel slip base post BCT (offset < 9"). IMPROPER
(4) Straight wood post BCT (0 offset). IMPROPER
(5) Cable tension member across the wrong diagonal of the first opening. IMPROPER

* Since the grade of the soil is not at the same grade of the ACP shoulder addition the vehicle trajectory just before impact may be adversely affected.

FIGURE 7 Properly and improperly installed BCTs.

strated the poor characteristics of turndowns as early as 1969 and in other tests in 1982 showed that BCTs did not perform well when struck by small cars (*10*). Attempts to modify these popular treatments resulted in the eccentric loader BCT, GEET1 and CRT, but in terms of implementation, success was limited.

Sentre

Leading developments in the early 1980s was Energy Absorption Systems, Inc., with Sentre. Sentre consisted of overlapping segments of Thrie beam guardrail mounted on blocked out steel posts with slipbases. "Sandbox" inertia elements absorbed some energy, and a redirection cable moved a collapsing Sentre laterally. Sentre performed well in tests required in NCHRP Report 230 (*22*) and has also performed well in the field. Through 1987, 31 collisions with Sentre were documented by the manufacturer. Performance was judged to be good in 29 cases and marginal in 2 cases. As of July 1991, there were 475 Sentre installations in 19 states. A fact summary sheet is shown in Figure 8.

CAT

The race was on for a high-performance end treatment at reasonable cost as problems with BCT and turndown became better understood. The next entry was developed by FHWA, SwRI, Syro Steel Company. The design was originally called

GUARDRAIL END TREATMENT
FACT SUMMARY

NAME SENTRE

MANUFACTURER(S) Energy Absorption Systems, Inc.

DEVELOPER(S) Energy Absorption Systems, Inc.

DEVELOPMENT PERIOD 1981 **to** 1983 (Basic System)

NUMBER OF DEVELOPMENT CRASH TESTS 22 basic, and 11 supplimental performance tests.

DATE OF FIRST FIELD INSTALLATION December, 1983.

STATES USING THE DEVICE Oklahoma, Texas, Indiana, Illinois, Delaware, Maryland, Michigan, District of Columbia, Utah, New Mexico, Arizona, Connecticut, New Hampshire, Pennsylvania, and Vermont; also Nevada, Hawaii, Iowa, and Washington.

APPROXIMATE NUMBER OF DEVICES NOW IN USE 475

FIELD COLLISION EXPERIENCE See attached. The impact data has not been collected by the state DOTs since the SENTRE system was accepted as operational by FHWA on April 7, 1989.

THIS DEVICE IS A STANDARD IN THE FOLLOWING STATES
(see addendum sheet attached)

*** COST OF HARDWARE (a)** (see addendum sheet attached)

*** COST OF INSTALLING (b)** (see addendum sheet attached)

*** COST OF DEVICE INSTALLED (c)** (see addendum sheet attached)

COST OF RESTORATION (see addendum sheet attached)
(Subsequent to a major collision)

INDIVIDUAL PROVIDING INFORMATION J. M. Essex, Vice President, Sales

***** **It is understood that (a), (b) and (c) are not independent. In some cases only (c) may be available.**

FIGURE 8 **Fact summary sheet for Sentre** (***continued on next page***).

THIS DEVICE IS A STANDARD IN THE FOLLOWING STATES:

Accepted by FHWA as "operational highway hardware" on April 7, 1989. Several states have this system as one of their operational end treatments and it remains to the designer's decision as to which end terminal he specifies for a site.

COST OF HARDWARE (a):

Range depends upon anchorage option chosen. From $1700 to $4850.

COST OF INSTALLING (b):

Range depends upon anchorage option chosen and contractor capability. From $500 to $2500.

COST OF DEVICE INSTALLED (c):

Range depends on amount of preliminary site work required by specification. Early bid prices were non-typical due to installations being "experimental".

COST OF RESTORATION (Subsequent to a major collision):

Range estimated from $100 to $1700. Based on severity of impact up to design limits.

FIGURE 8 *(continued).*

The Shredder, but evolved through the designation of vehicle attenuating terminal to CAT. CAT met NCHRP Report 230 requirements and was a good step toward reasonable cost. CAT has been evaluated using 4,500- and 1,800-lb automobiles and a 5,400-lb pickup (*23–26*). CAT can be installed parallel to the road without flaring.

Projected cost is about $3,700. The 42 collisions now reported indicate good field performance. An installation is shown in Figure 4, and a fact summary sheet is shown in Figure 9.

ELT

FHWA has continued efforts to make variations of the BCT acceptable. ELT was the first stage of BCT evolution (*27*). ELT has also been evaluated for an end-on impact with a 5,400-lb pickup (*28*). Because of the problems in implementing the 4-ft flare, both 4-ft and 1.5-ft flare offset designs were tested. The results of these tests fundamentally meet the NCHRP Report 230 criteria, but the 1.5-ft flare offset design was considered marginal. A fact summary sheet for ELT is shown in Figure 10.

MELT

FHWA has recently designated MELT as operational (*29*). MELT is an FHWA design that differs from ELT in the nose piece. MELT functions reasonably well with a 4-ft flare, but head-on performance remains a concern when the flare is reduced to 1.5-ft, which has not been tested (*29*). FHWA officials believe that MELT should perform as well as ELT. The main advantage of MELT in comparison with high-performance terminals is its cost, projected to be about $1,000, excluding earthwork. The main disadvantages of MELT are possibly the same shortcomings of all BCT designs.

ET-2000

ET-2000 was developed progressively by the Texas Transportation Institute, Texas DOT, and SYRO. ET-2000 meets the criteria in NCHRP Report 230 (*30*). This device works in a unique way. A die at the end of the rail acts as an extruder in a vehicle collision. The die bends the W-section 90 degrees, flattens it, and projects it out away from the vehicle. The cost of installation is about $2,300. A fact summary sheet is shown in Figure 11.

BRAKEMASTER

BRAKEMASTER, from Energy, is shown in Figure 3 and functions in the following way. The forward structural elements of the terminal include a unique braking mechanism on a heavy longitudinal cable. When a vehicle strikes BRAKEMASTER head-on, the braking mechanism is pushed

GUARDRAIL END TREATMENT
FACT SUMMARY

NAME CAT (For use as a crash cushion, median terminal, shoulder terminal)

MANUFACTURER(S) Syro Steel Company - Girard, Ohio & Centerville, Utah

DEVELOPER(S) Southwest Research Institute (SwRI)

DEVELOPMENT PERIOD January 1983 **to** January 1988

NUMBER OF DEVELOPMENT CRASH TESTS 32

DATE OF FIRST FIELD INSTALLATION November 1986

STATES USING THE DEVICE Alaska, Arizona, California, Colorado, Connecticut, Delaware, Illinois, Indiana, Kentucky, Maine, Maryland, Michigan, Minnesota, Missouri, Nebraska, New Hampshire, New Mexico, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Texas, Utah, Virginia, Washington, West Virginia, Wyoming. Also Canada

APPROXIMATE NUMBER OF DEVICES NOW IN USE 800 (576)

(42)
FIELD COLLISION EXPERIENCE 59 impacts reported to date with no fatalities resulting from impacting the C-A-T. Accident data was compiled and submitted to the FHWA. On June 4, 1990 FHWA moved the C-A-T from experimental to operational. Numbers in parentheses are those associated with CATs used as terminals.

THIS DEVICE IS A STANDARD IN THE FOLLOWING STATES About 40% of the above states bid the C-A-T regularly.

*** COST OF HARDWARE (a)** $3300 terminal - $4700 crash cushion

*** COST OF INSTALLING (b)** $400 terminal - $600 crash cushion

*** COST OF DEVICE INSTALLED (c)** $3700 terminal - $5300 crash cushion

COST OF RESTORATION $3000.00
(Subsequent to a major collision)

INDIVIDUAL PROVIDING INFORMATION John C. Durkos, Syro Steel Company

*** It is understood that (a), (b) and (c) are not independent. In some cases only (c) may be available.**

FIGURE 9 Fact summary sheet for CAT.

down the cable and the side W-beam sections telescope. BRAKEMASTER has performed well in NCHRP 230 testing (*31*). An average installation costs about $5,000. A fact summary sheet is shown in Figure 12.

TRENDS IN TERMINAL USE

A comparison of the various terminal designs now in use is presented in Table 1. It is based on data from the manufacturers and FHWA. Of devices with good performance, Sentre has been used the longest, more than 7 years. The installation rate of Sentre is mid-range at 63 per year. Next in longevity, ELT and MELT, have the lowest installation rate at seven. CAT, in use for 5 years, has the highest installation rate at 123. BRAKEMASTER, in use for 2 years, has an installation rate averaging 29. Finally, ET-200, in use for 1 year, has an installation rate of 88. In field experience, only Sentre and CAT could be called field-proven devices. ELT and MELT, BRAKEMASTER, and ET-2000 all need additional exposure before they can be so categorized. For an independent evaluation of the performance of these terminals, the reader may refer to work by Jewel et al. (*15*).

CONCLUSION

In the highway safety field, the engineer responsible for "forgiving roadsides" is in an unaccustomed position relative to guardrail end treatments. After decades of confronting the

GUARDRAIL END TREATMENT
FACT SUMMARY

NAME ELT

MANUFACTURER(S) Not proprietary (Syro, Trinity, Mission, etc.)

DEVELOPER(S) Southwest Research Institute and FHWA

DEVELOPMENT PERIOD ____________ to ____________

NUMBER OF DEVELOPMENT CRASH TESTS ____________

DATE OF FIRST FIELD INSTALLATION 1986

STATES USING THE DEVICE South Dakata, Utah, Washington, Michigan and New Jersey.

APPROXIMATE NUMBER OF DEVICES NOW IN USE 35 (50)*

FIELD COLLISION EXPERIENCE One hit in South Dakota a few weeks after installation. Results were good.

* As per a meeting of January 14, 1992 with FHWA engineers there may be fifty of these installations in the U.S. and up to 300 in Canada

THIS DEVICE IS A STANDARD IN THE FOLLOWING STATES None

* COST OF HARDWARE (a) (Syro)

* COST OF INSTALLING (b) Varies

* COST OF DEVICE INSTALLED (c) $1000

COST OF RESTORATION $1200
(Subsequent to a major collision)

INDIVIDUAL PROVIDING INFORMATION Richard Powers, FHWA, (202) 366-1320

* It is understood that (a), (b) and (c) are not independent. In some cases only (c) may be available.

FIGURE 10 Fact summary sheet for ELT.

necessity of choosing between marginally performing systems, the engineer is now confronted with an array of choices. These choices are systems with vastly improved performance characteristics. This conclusion assumes that proving-ground testing will relate well to field experience. A few of the new designs have significant field exposure, but others are young in application.

In an effort to summarize the performance of current designs, the following categories are proposed:

- I Unacceptable performance,
- II Improved performance based on comparisons with Category I with questionable field experience,
- III Marginal performance based on compliance testing with questionable field experience or lack of field experience,
- IV Acceptable performance based on compliance testing but without significant field experience, and
- V Acceptable performance based on compliance testing and field experience.

The various competing systems were categorized on the basis of compliance crash testing and field experience. The costs were supplied by FHWA, Energy, and Syro. These data are shown in Figure 13. The figure shows the trade-off between cost and performance. At this time, as costs per system increase, the field-verified performance level increases. The

GUARDRAIL END TREATMENT
FACT SUMMARY

NAME ET-2000 (For use as a shoulder terminal for guardrail)

MANUFACTURER(S) Syro Steel Company - Girard, Ohio and Centerville, Utah

DEVELOPER(S) Texas Transportation Institute (TTI)

DEVELOPMENT PERIOD September 1985 to June 1989

NUMBER OF DEVELOPMENT CRASH TESTS 14

DATE OF FIRST FIELD INSTALLATION June 1990

STATES USING THE DEVICE Illinois, Minnesota, Missouri, Texas and Utah.

APPROXIMATE NUMBER OF DEVICES NOW IN USE 105

FIELD COLLISION EXPERIENCE Only one hit has been reported to date. A 1984 Mazda pickup truck impacted the ET-2000 end-on. The estimated speed was 60 mph and the driver was not injured.

THIS DEVICE IS A STANDARD IN THE FOLLOWING STATES Texas and Utah now, but many in addition to the above plan to incorporate.

* COST OF HARDWARE (a) $1,900.00

* COST OF INSTALLING (b) $400.00

* COST OF DEVICE INSTALLED (c) $2,300.00

COST OF RESTORATION $500.00
(Subsequent to a major collision)

INDIVIDUAL PROVIDING INFORMATION John C. Durkos, Syro Steel Company

* It is understood that (a), (b) and (c) are not independent. In some cases only (c) may be available.

FIGURE 11 Fact summary sheet for ET-2000.

placement of various terminals in the proposed categories is somewhat subjective.

The following are additional observations from Figure 13:

- If field-verified performance is most important, the choice is probably between Sentre and CAT. They may be economically justified in areas in which many collisions occur.
- If MELT moves into Category V, the cost advantages would be considerable.
- Any end condition in Category I should be replaced or modified as quickly as is economically feasible.
- Any terminal in Category II (turndowns and nonflared BCTs) should be gradually phased out, with emphasis placed on those sites where collisions are most likely. The exception to this may be low-volume rural roads in low-exposure locations.
- There will probably soon be four systems in Category V, contingent on continued good field experience with Sentre and CAT, and with developing good field experience with BRAKEMASTER and ET-2000. This should result in a brisk competition resulting in design improvements and cost reductions.

There are still problems in accurately predicting terminal performance, and costs will vary widely and change often. Known performance levels and costs are now approaching the

GUARDRAIL END TREATMENT
FACT SUMMARY

NAME BRAKEMASTER

MANUFACTURER(S) Energy Absorption Systems, Inc.

DEVELOPER(S) Energy Absorption Systems, Inc.

DEVELOPMENT PERIOD 1987 to 1989

NUMBER OF DEVELOPMENT CRASH TESTS 62

DATE OF FIRST FIELD INSTALLATION November, 1989

STATES USING THE DEVICE South Carolina, Colorado, Kentucky, Wisconsin, Minnesota, Tennessee, and Pennsylvania; also Oregon and Alabama.

APPROXIMATE NUMBER OF DEVICES NOW IN USE 50

FIELD COLLISION EXPERIENCE (see attached summary)

THIS DEVICE IS A ~~STANDARD~~ OPERATIONAL IN THE FOLLOWING STATES Accepted as "experimental" by FHWA on October 30, 1989.

* COST OF HARDWARE (a) (see addendum sheet attached)

* COST OF INSTALLING (b) (see addendum sheet attached)

* COST OF DEVICE INSTALLED (c) (see addendum sheet attached)

COST OF RESTORATION (see addendum sheet attached)
(Subsequent to a major collision)

INDIVIDUAL PROVIDING INFORMATION J. M. Essex, Vice President, Sales

* It is understood that (a), (b) and (c) are not independent. In some cases only (c) may be available.

ADDENDUM SHEET:

COST OF HARDWARE (a):

Range based on anchorage option chosen; from $3000 to $5000.

COST OF INSTALLING (b):

Range based on anchorage option chosen; from $500 to $1500.

COST OF DEVICE INSTALLED (c):

Range based on site work specified and contractor capability. Not available from manufacturer. Number of systems specified to be bid will influence this price also.

COST OF RESTORATION:

From $200 to $2800.

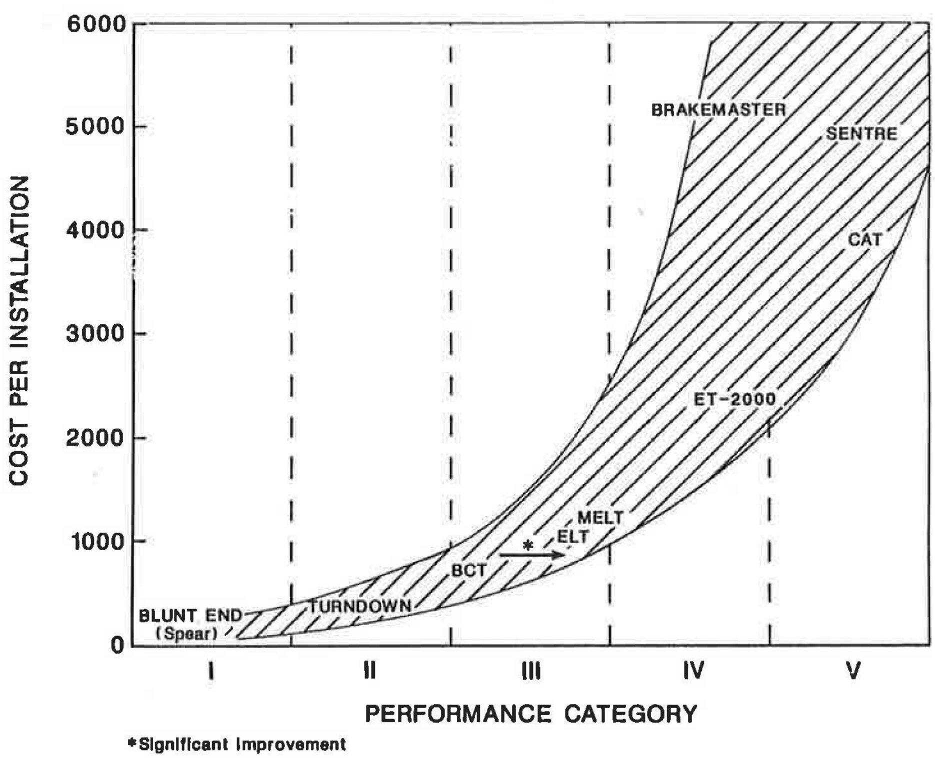
FIGURE 12 Fact summary sheet for BRAKEMASTER.

TABLE 1 Terminal Installations in Use in the United States

	Number of Terminals Installed	First Installation (Year)	Time in use (Years)	Average Installation Rate in U.S. (Inst. per yr.)
TURNDOWN	More than 450,000	1963	28	---
BCT	More than 450,000	1973	18	---
ELT	50	1986	5	10
MELT	0	---	---	---
BRAKEMASTER	50	Nov., 1989	1.7	29
CAT	576	Nov., 1986	4.7	123
ET-2000	105	June, 1990	1.2	88
SENTRE	475	Dec., 1983	7.6	63

point, however, at which benefit-cost analysis can be used to determine which systems are most appropriate for specific sites or classes of sites (*32,33*). That should be the next step.

The highway engineer is now blessed by good choices in the selection of guardrail terminals. Since there has been much said about meeting NCHRP 230 experimental requirements and in gaining field experience for the terminals under consideration, perhaps both writers and readers might consider the following statement by Leonardo da Vinci "Experience does not ever err, it is only your judgment that errs in promising itself results which are not caused by your experiments."



*Significant Improvement

Note: Median costs are plotted for Sentre and BRAKEMASTER. Depending on site characteristics, Sentre may vary ± 50%, while BRAKEMASTER may vary ± 30%.

FIGURE 13 Current costs and performance categories.

ACKNOWLEDGMENT

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DISCUSSION

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Although the authors of this paper present an accurate chronology of guardrail terminal evolution, they fail to discuss specific reasons for alleged dissatisfaction with some of the commonly used generic appurtenances. Thus, the paper leads one to the conclusion that proprietary terminals should be used regardless of their cost. Although terminals such as turndowns and BCTs do not perform well under all circumstances, many years of accumulated experience have revealed that they perform satisfactorily most of the time, particularly when installed and maintained properly and when careful attention is given to site selection and grading. Site considerations should include such exposure and risk factors as traffic volumes and speeds and the selection of an appropriate level of service.

The newer proprietary terminals in general do have superior energy-absorbing capabilities and have exhibited good in-service performance in their limited exposure to date. It is important to note, however, that all terminals have inherent limitations and that none will perform satisfactorily over the entire spectrum of possible impacts. Highway agencies would be well advised to keep current on the latest developments in the barrier terminal field, to become familiar with the advantages and disadvantages of each system, and to select the most cost-effective terminal for each specific site. A continuing performance evaluation of all in-service terminals will provide invaluable information in the on-going selection process.

DISCUSSION

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In the abstract of this paper, the authors indicate that the paper provides an objective review of guardrail terminals and aid for selecting cost-effective terminals to meet specific needs.

The criteria upon which the objective review is based are highly subjective in that there is no demonstrated correlation between the review criteria and actual field performance. Presumably, the authors will argue that crash test results are objective. I would suggest that the current test procedures, with tests conducted on flat, level ground with tracking vehicles impacting over a narrow range in speed and angle, basically provide rough go, no-go screening and provide little basis for discriminating between various terminal types because they fall far short of examining the full range of service conditions. Thus, until laboratory practices are changed, the only valid basis I see for rating terminals would be cogent, comparative statistical analyses of their field performance.

Information presented in the paper on field performance is primarily anecdotal, except for work by Griffin on the "Texas twist" terminal. Griffin deserves recognition for his work; it should provide guidance and encouragement to others. However, his results neither support nor argue against continued use of the Texas twist because there is no information presented on how well the alternatives might work. What his results do show is that striking a Texas twist terminal can be hazardous. Work by others, notably that by Agent and Pigman, show hazardous results from striking other types of terminals. Several of the terminals cited in the paper have not been in service long enough to have demonstrated their safety performance. Therefore, from the information presented, there is no basis on which an objective assessment of the relative safety performance of the various terminals can be made. Nevertheless, the authors are correct in suggesting the need for objective guidance in the selection of guardrail terminals. The problem is that much more field evaluation of terminal performance is needed to form a basis for such guidance.

This paper does not provide aid in selecting cost-effective terminals to meet specific needs, even though this needed aid is promised in the abstract.

My expectation is that even the terminals the authors suggest as superior performers, if subjected to field evaluation, would be shown to represent significant hazards, though, possibly, they would not be shown to be as hazardous as some of the existing alternatives.

Readers who are in a position to do so should institute field evaluation programs of terminals and use the evaluation results to develop procedures for selecting cost-effective guardrail terminals for given site conditions. I also submit that further improvement in guardrail terminals is needed and that properly designed field evaluations of existing terminals would reveal their shortcomings and provide bases for performance goals for new terminals.

I further suggest that if such evaluations are undertaken that they be extensive, detailed, and include the following considerations:

- Terrain geometries at terminal sites;
- The fact that terminals are impacted by many types of vehicles traveling at various combinations of speeds, angles, orientations, and yaw rates (side-on impacts are probably important);
- Unreported contacts, which will be essential for the analysis of field performance; and
- Site traffic speed, mix, offset, and approach alignment.

AUTHORS' CLOSURE

The authors are grateful to Powers and Hatton for their insightful discussions, their help in clarifying several areas during the writing and review process, and their direct contributions to this paper.

Although the authors are not in total agreement with every point Powers and Hatton make, the areas of agreement are certainly dominant, and readers are advised to consider all the reviewers' points carefully when deciding what weight to give the conclusions and opinions presented by the authors.

Concerning both reviewers' suggestions that field evaluations of terminals be continued or initiated to provide the data for benefit-cost comparisons, the authors could not be more in agreement. To this end, comparisons of the newer devices with the older turndown and BCT devices will only be possible if these new devices are installed in sufficient numbers to obtain meaningful accident data. Field performance is the ultimate evaluation. Only through careful evaluation of performance can the indications of testing be confirmed or rejected and can the relative effectiveness of safety systems be accurately determined.