Development of Guardrail Extruder Terminal

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Development of the Guardrail Extruder Terminal (GET), a low-cost end treatment for W-beam guardrails, is presented in this paper. When impacted, this end treatment causes the W-beam to be flattened and deformed in a controlled manner ahead of the impacting vehicle. The flattening process dissipates energy, and impacting vehicles are decelerated to a controlled stop. The paper discusses static and dynamic laboratory testing of extruder components as well as full-scale crash tests of the GET. The GET is shown to be in compliance with nationally recognized impact performance standards.

Highway engineers have searched for many years to find a safe and economical method of terminating strong post W-beam barriers. Early W-beam barriers were constructed with an untreated standup end, which were capable of piercing through impacting vehicles. To mitigate the hazard associated with guardrail ends, engineers with the Texas State Department of Highways and Public Transportation developed the "Texas Twist," in which the guardrail end was twisted and sloped to the ground. Although this treatment effectively solved the problem of guardrails spearing impacting vehicles, it has the potential for causing impacting vehicles to roll over (*1*,*2*).

In an effort to solve problems associated with the Texas twist, researchers developed the "Floppy End," a sloped guardrail end treatment designed to be pushed down by vehicles impacting the sloped barrier section (*3*). This treatment exhibited somewhat improved impact performance but proved to be a maintenance problem since the barrier end was frequently knocked down by roadside mowing activities. Further efforts to refine the floppy end technique have solved some of its maintenance problems (*4*,*5*). However, it continues to exhibit a tendency to cause rollover when small vehicles impact the end of the barrier.

The Breakaway Cable Terminal (BCT) is a guardrail end treatment that has gained widespread acceptance across the country (*6*). BCT end treatments rely on the dynamic buckling of a flared section of guardrail to provide a mechanism for slowing impacting vehicles in a controlled manner. As a result, the BCT is very sensitive to the way the barrier end is flared; field experience has indicated that improper flare rates are frequently employed (*7*). Furthermore, even when installed correctly, the BCT system has been shown to impart unacceptably high deceleration forces on mini-size vehicles (*8*).

An improved BCT design, the Eccentric Loader BCT (ELBCT), was recently developed and successfully crash tested with mini-size vehicles (*9*). Although this system should offer improved safety performance over the standard BCT, the flared barrier end remains a critical component of the design. Further, the ELBCT has several other important design details that may adversely affect end treatment performance if not installed correctly. Finally, the ELBCT requires significant new hardware that will raise the cost of this system.

The Sentre (*10*) and Vehicle Attenuator Terminal (VAT) (*11*) end treatments are proprietary guardrail terminals that have been introduced recently. While neither system has a great deal of service history, crash test results indicate that both terminals should perform well in the field. However, the proprietary nature and complexity of the designs increase the cost of these end treatments to an unacceptable level. As a result, proprietary end treatment deployment has been limited to sites with high accident frequencies.

Due to the high cost and the complexity of available end treatments that meet current safety standards, highway agencies continue to use sloped and BCT end treatments. Therefore, in an effort to find a more suitable alternative, the Guardrail Extruder Terminal (GET) was developed (*12*).

RESEARCH OBJECTIVES

Barrier end treatment safety standards (*13*) require that a guardrail terminal provide safe deceleration or controlled barrier penetration for vehicles impacting upstream from the beginning of the length of barrier need (LON) and barrier anchorage for redirecting vehicles impacting beyond the LON. Crash test experience has indicated that, when a vehicle penetrates a barrier end at a high rate of speed, even small deceleration forces can throw the vehicle out of control, thereby increasing the probability of a rollover. Further, vehicles traveling behind a guardrail are likely to impact the hazard that the barrier was designed to shield. Thus, it is desirable for an end treatment to provide impact attenuation to prevent high-speed penetrations of the barrier end.

Field installations of barrier end treatments have revealed that it is best to terminate guardrails along a tangent, thereby eliminating problems associated with terminating barriers on roadside slopes. If a guardrail terminal design is to be widely used, it must be relatively inexpensive and simple to construct. Thus, the primary objectives of the research reported here were to develop a guardrail end treatment design that could offer the following features:

- Meet nationally recognized safety standards (*13*),
- Be inexpensive to install and maintain,
- Perform safely when installed on a tangent section of guardrail,

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- Provide attenuation for vehicles impacting the barrier end, and
- Be simple to construct.

GUARDRAIL EXTRUDER CONCEPT

Numerous end treatment concepts were developed and subjected to a preliminary feasibility analysis. The GET was believed to be the most promising concept and was selected for further development. This concept involves placing an extruding device over the end of a straight section of W-beam guardrail (see Figure 1). When struck by an automobile, the extruder curls the W-beam around a circular arc away from the front of the impacting vehicle. Plastic deformation of the W-beam dissipates impact energy and decelerates the vehicle at an acceptable rate. Although the GET performs best for head-on impacts, it should perform well for angular impacts. When a vehicle strikes the extruder at an angle, the device need only extrude a short distance before the vehicle can safely penetrate behind the guardrail.

Preliminary evaluation of the GET concept revealed that the extrusion could be best controlled by dividing the process into two separate events. The first stage involves flattening the W-beam to reduce its section modulus, while the second involves bending the W-beam along a circular arc to project it away from the impacting vehicle. This two-stage process is depicted in Figure 2.

The section modulus of a standard 12 gauge W-beam is approximately 1.37 in^3. As the W-section is flattened, its section modulus is drastically reduced. When the depth of the beam is reduced to 1 in, its section modulus is reduced to approximately 0.4 in^3. The flattened beam can then be easily bent into a circular shape and guided away from the front of an impacting automobile.

The flattening process can be accomplished by forcing the W- beam down a metal chute with a decreasing cross section, as shown in Figure 2. The distance over which the flattening occurs was originally believed to have an effect on the forces required to push the W-beam through the extruder. This belief was based on the assumption that the angle between the flattening plates and the W-beam would affect the magnitude of sliding friction. However, static tests of several different flattening sections revealed that the W-beam contacted the flattening plates only at the narrowest opening. Since the W-beam did not contact the flattening chute along its length, the angle between the flattening plates did not affect the steady-state extrusion forces. Thus, although the angle between the W-beam and the flattening plates was found to influence the

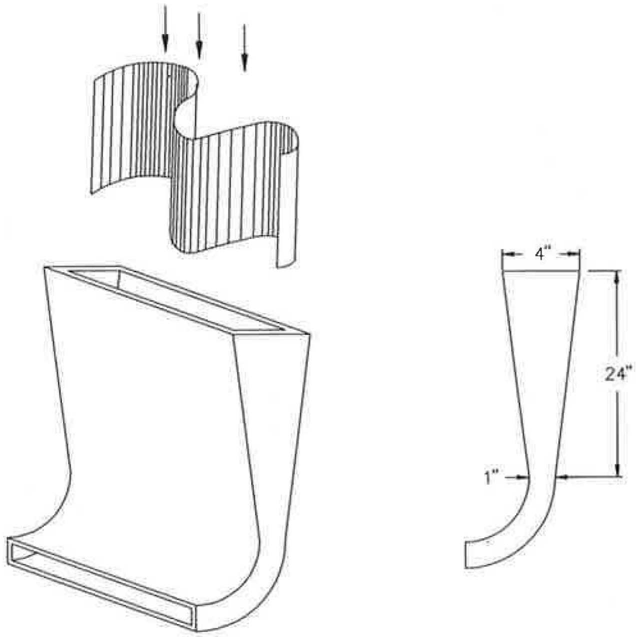

FIGURE 2 **Two-stage extrusion process.**

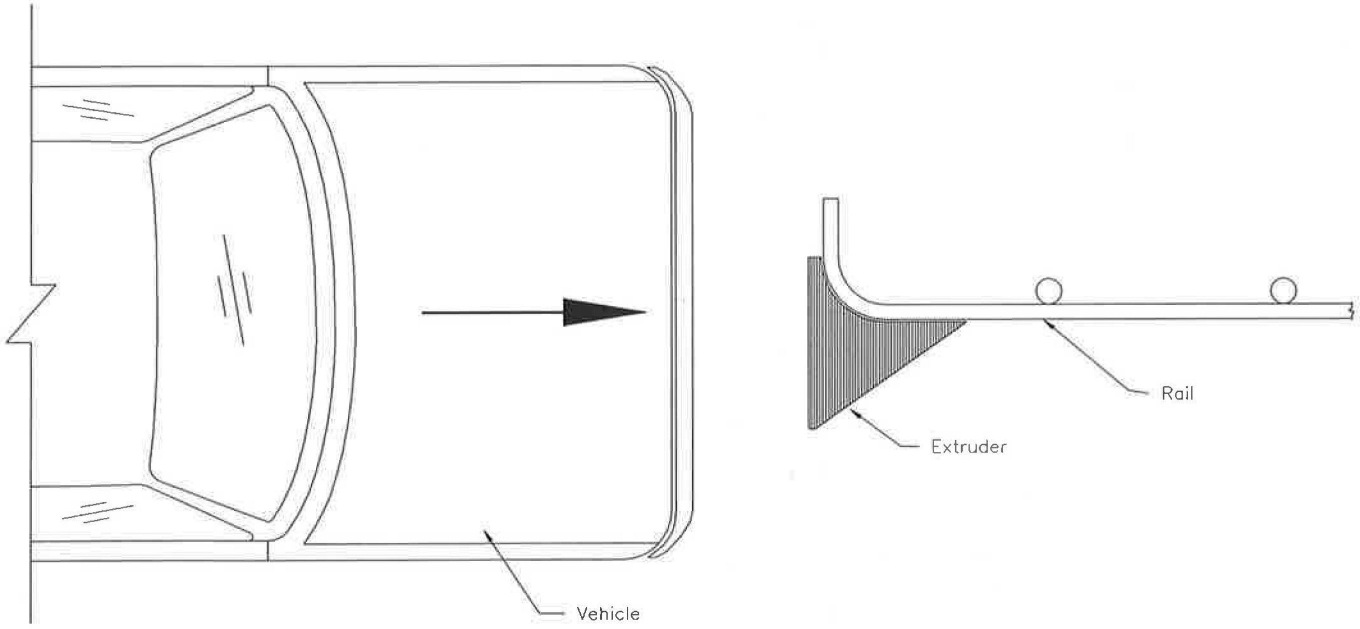

FIGURE 1 **Guardrail extruder concept.**

rate at which extrusion forces climbed, there could be no significant effect on the magnitude of steady-state extrusion forces. Figure 3 shows results of static testing of three different flattening devices. Each of these devices had an opening of 4 in on the intake end and a 1-in opening on the outlet end. Thus, the flattening angle incorporated was directly related to the length of the mechanisms. As shown in Figure 3, approximately 10 kips were required to force a W-beam through each of the three devices.

A circular bending section with a 4.5-in radius was then added to the 12- and 24-in flattening devices. Static testing was conducted to identify the effects of the bending sections on extrusion forces. Figure 4 shows that the forces required to slowly force a W-beam through the extruder varied from 9 kips to 13 kips with an average of approximately 11 kips. The 11-kip average force would correspond to a 6-g deceleration on an 1,800-lb vehicle and a 2.4-g deceleration on a full-size vehicle. These deceleration rates are well below acceptable limits (*13*).

The GET concept requires the W-beam rail to be terminated in a stand-up position similar to the BCT end treatment. Longitudinal anchorage for the BCT end treatment is provided by firmly attaching a cable between the W-beam and the bottom of the first post. This same mechanism could not be incorporated for the GET since the cable and its attachment hardware would inhibit the extrusion process. Therefore, a cable-release mechanism, shown in Figure 5, was developed to provide anchorage for the W-beam guardrail without inhibiting the operation of the extruder. The teeth on the cable-release mechanism are designed to fit into slots cut in the end of the W-beam rail element. As the extruder is pushed down the guardrail, it contacts the back of the cable-release mechanism and the wedge-shaped teeth push the mechanism out of the slots in the W-beam. However, when a vehicle impacts the side of the guardrail, the teeth bite into the slots and prevent longitudinal movement of the barrier end.

Pendulum testing of the cable anchor used in BCT end treatments has indicated that the breakaway wood BCT post is capable of developing a 42-kip dynamic restraining force (*11*). Laboratory testing of the new cable-release mechanism indicated that the new device could develop a 38-kip static force. This static load capacity should translate into a dynamic load capacity well above the 42 kips provided by the breakaway post incorporated in the BCT end treatment.

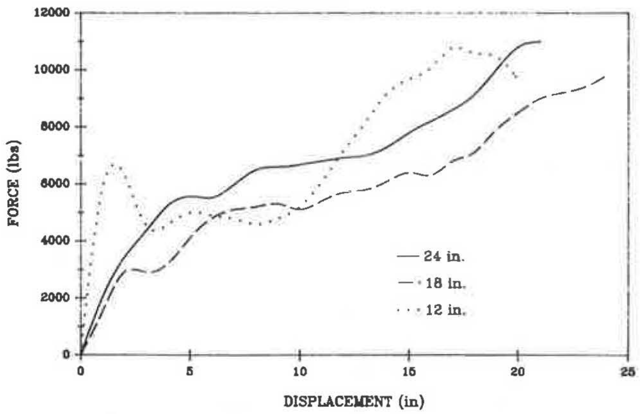

FIGURE 3 Static test results for W-beam flattening devices.

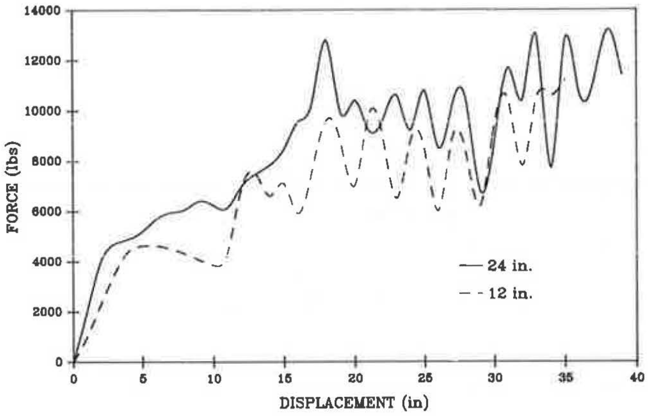

FIGURE 4 Static test results for W-beam extruders.

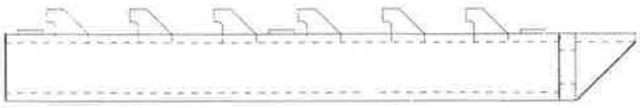

FIGURE 5 Cable-release mechanism.

TERMINAL DESIGN

A preliminary GET was developed by constructing a protective steel box around the extruding devices shown in Figure 4. As shown in Figure 6, the protective box incorporated a ½-in-thick rectangular steel impact plate to reduce damage to the device during impact. Steel plates and angles were incorporated to safely transfer loads from the impact plate into the extrusion device. Further, due to its heavy weight, steel legs were tack welded to the bottom of the extrusion device. These legs should also help assure proper mounting height for the extruder. Steel angles were also welded to the extruder with one leg of the angle extending in front of the impact plate. These angles were designed to provide an interlock between the extruder and an impacting vehicle, thereby preventing the extruder from slipping along the front of the impacting vehicle.

Dynamic load effects on extrusion forces were investigated with two low-speed crash tests: MBP-1 and MBP-2. These tests were run at 35 mph with a 4,276-lb vehicle and at 47 mph with a 4,340-lb vehicle, respectively. Figure 7 shows force deflection characteristics of the GET during these two low-speed tests. Note that dynamic loads were not greatly different from static test results and that impact speed had no significant effect on dynamic extruder forces. Zinc galvanizing is believed to behave as a lubricant during the extrusion process, which explains the small differences between static and dynamic test results.

Preliminary analysis of the energy dissipation characteristics of the GET revealed that a large automobile impacting at 60 mph could extrude as much as 50 ft of guardrail before coming to a stop. However, a bolted guardrail splice normally found within the first 25 ft of the guardrail end would likely inhibit extruder performance. Thus, the preliminary GET design incorporated a welded lap splice at the end of the first 25-ft section of W-beam. Further, previous testing of guardrail end treatments has shown that unweakened wooden guardrail posts can impart unacceptably high decelerations on small vehicles. Therefore, two ⅜-in holes were drilled in the first nine guardrail posts at the ground line and 18 in below ground. This scheme, first incorporated in the controlled release terminal (CRT) end treatment (*5*), is designed to provide weakened post cross sections at points of maximum moment for posts embedded in both stiff soil (ground surface) and soft soil (18 in below ground surface).

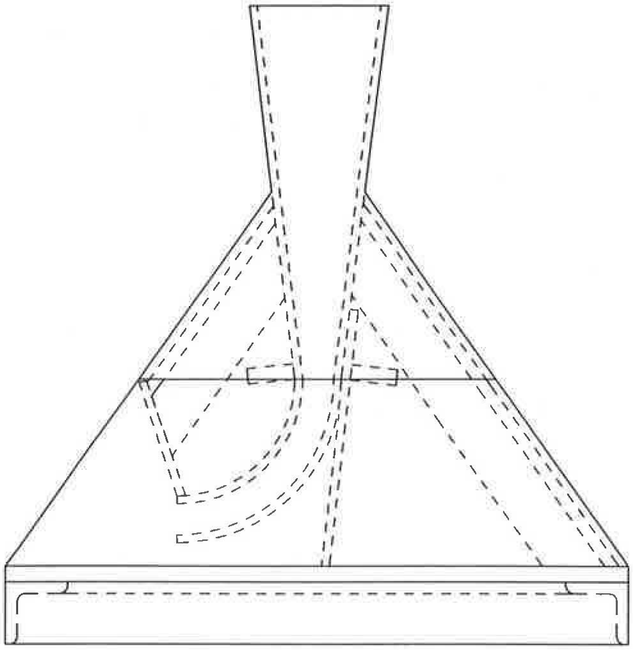

FIGURE 6 Guardrail extruder.

A 6-in by 8-in wood post, similar to those used in the BCT, was used in the leading post position to assure proper strength characteristics for impacts with the side of the W-beam. The leading post was placed in a concrete footing to provide adequate anchorage for the W-beam. Although never tested during its development, the anchorage system used on some modern BCT designs, consisting of two driven steel box tubes attached with a steel channel, could be incorporated into the GET design. Such a system would eliminate the need for a concrete footing and require 6-in by 8-in posts in the first two positions.

DEVELOPMENTAL TESTING

Five full-scale crash tests were undertaken to identify other design features required to meet safety requirements (*13*). Important extruder performance problems and associated design modifications identified during development testing are described below.

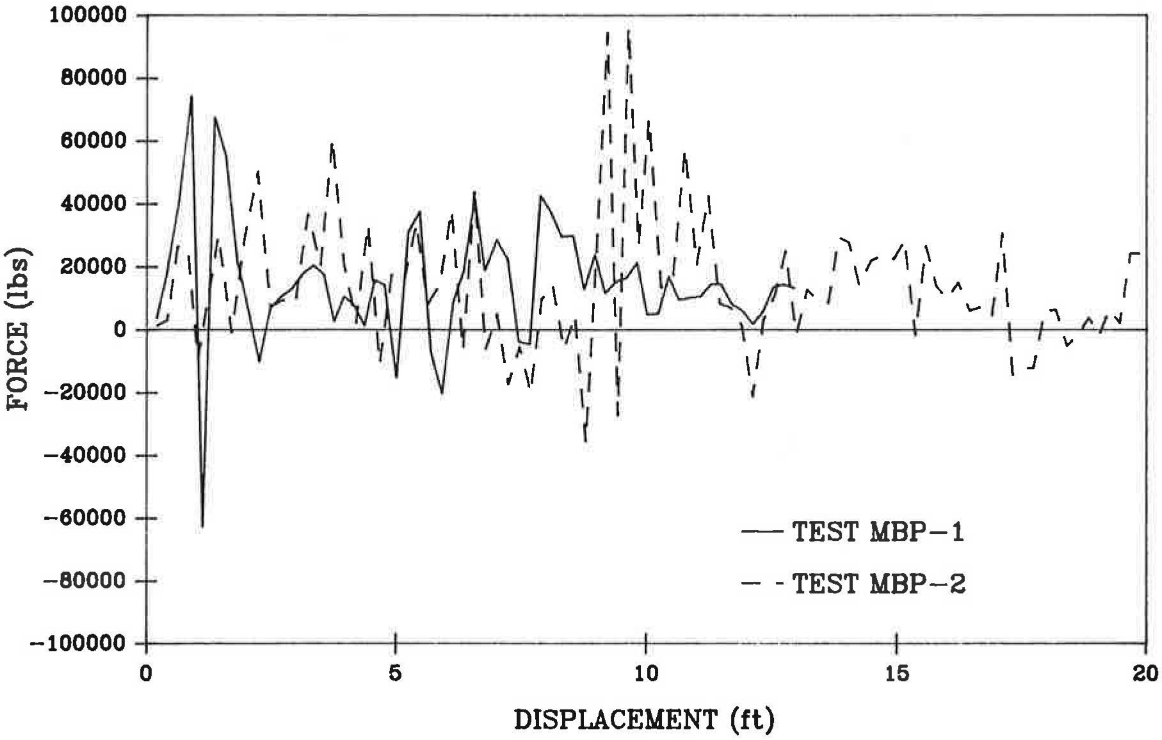

FIGURE 7 Low-speed crash tests.

Extruder Rotation

Head-on impact tests of the GET indicated that the extruder had a tendency to rotate as it was pushed down the guardrail. After the extruder rotated approximately 35° relative to the guardrail, the W-beam became wedged in its mouth and the device stopped functioning properly. Several design modifications were made in an attempt to solve this problem. The most important of these changes involved adding a feeder chute to the mouth of the extruder, as shown in Figure 8. The feeder chute increased the stabilizing moment that the guardrail could exert on the extruder, and the flared mouth of the chute reduced the possibility of the W-beam becoming wedged in the opening. These modifications virtually eliminated all rotation of the extruder during subsequent testing.

Another modification incorporated to reduce extruder pitch rotations involved adding rubber dock bumper pads to the top of the impact plate. Since the center of an automobile's bumper impacts the extruder below its center of gravity, the dock bumpers were added to help distribute initial impact forces upward. This design change is not considered to be critical to extruder performance.

Unsuccessful design modifications aimed at reducing extruder rotations included modifying the extruder to bend the W-beam toward the roadway instead of away from it and weakening W-beam-to-post attachments. As the W-beam exits the extruder, it is projected to the side and thereby exerts a side force on the extruder. Further, posts impacting the side of the extruder impart lateral forces in the same direction. Therefore, it was believed that reversing the direction of W-beam bending could reduce net side forces on the side of the extruder and eliminate its tendency to rotate.

Surprisingly, changing the direction of W-beam bending significantly increased extrusion forces. Static test results indicated that bending the W-beam toward the roadway increased average extrusion forces from 11 kips to 15 kips. As a result of the large increase in extrusion forces and the problems associated with projecting extruded guardrail across the roadway, this solution to the extruder rotation problem was abandoned. Another important finding from these development tests was that extruder performance was not sensitive to the guardrail post attachment. Therefore, standard button head guardrail post bolts were used in the final GET design. Figure 9 shows a typical GET installation incorporating the final extruder design.

Breakaway Posts

Development testing indicated that the weakened guardrail posts did not break properly when impacted by mini-size vehicles. When small vehicles impacted the GET, a post often rotated downward instead of breaking along one of the weakened cross sections. As the post leaned over, it provided a ramp for the front of the vehicle that could initiate rollover. Proper post breakage could be assured if post rotation could be eliminated. Previous dynamic testing of guardrail posts indicated that these posts rotated about a point approximately 28 in below ground. Forces required to rotate a guardrail post would be greatly increased by forcing the post to rotate about a point at the ground surface. The post-rotation problem was therefore eliminated by passing a cable around the footing under the first post and through the ground-line holes of the next three posts. Bearing plates were then placed behind posts

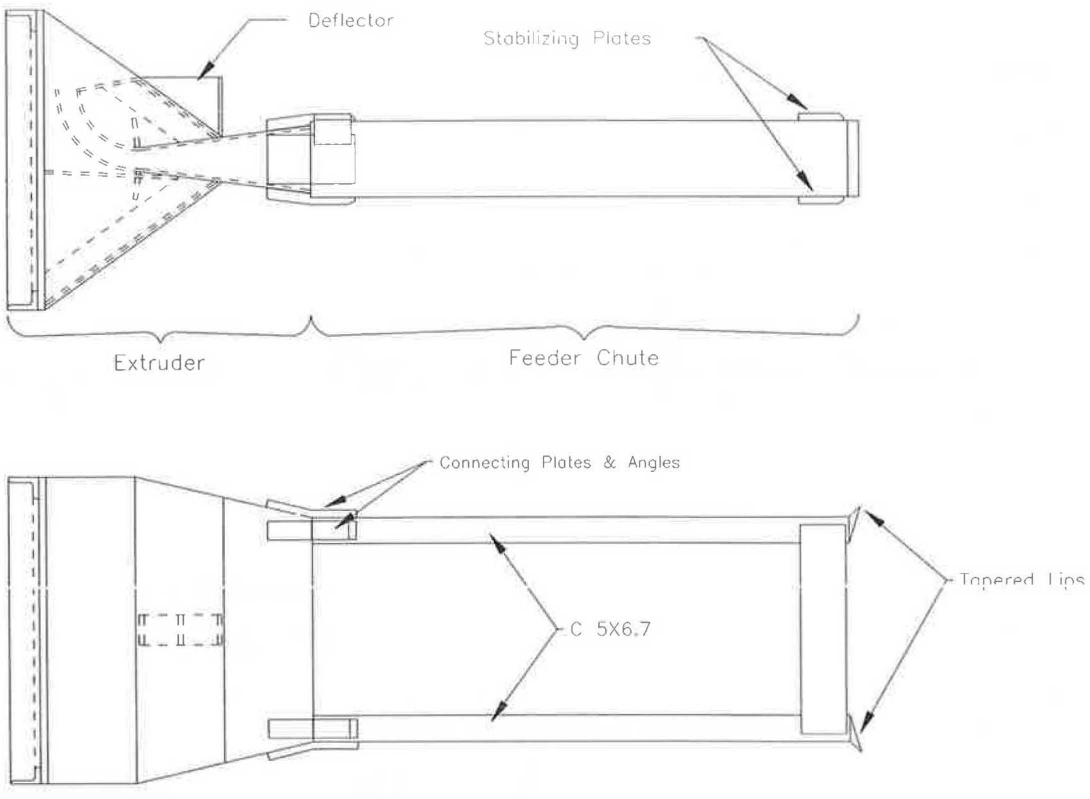

FIGURE 8 Guardrail extruder with feeder chute.

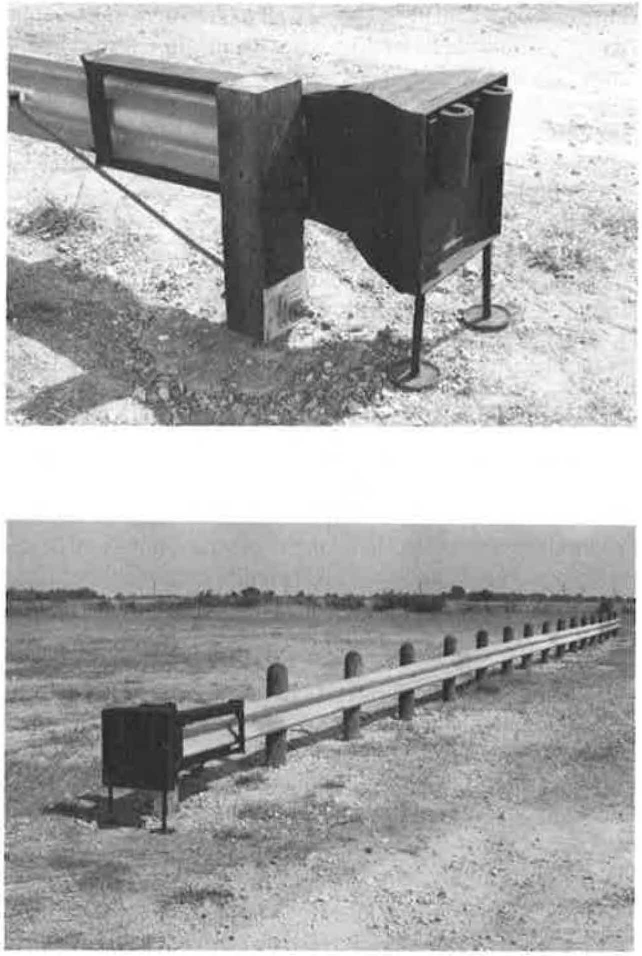

FIGURE 9 Guardrail extruder terminal.

2 through 4 and attached to the ground-line cable. This cable effectively eliminated post movement at the ground line and forced the posts to break at the weakened cross section. Figure 10 shows a sketch of the ground-line cable system.

Another design modification incorporated to promote post breakage involved placing an impact surface on the side of the extruder. This metal surface was designed to promote quick post breakage, thereby reducing lateral and longitudinal post movements as the extruder passed in front of the post. Figure 11 shows a sketch of the guardrail post impact surface.

COMPLIANCE TESTING

NCHRP Report 230 (*13*) requires four full-scale crash tests of barrier end treatments. Two of the tests are designed to study head-on impact performance of the end treatment, and the remaining tests investigate the redirective capacity of the barrier near the end treatment. The GET successfully passed all four of the recommended crash tests, as summarized in Table 1 and described below.

Test MB-6

The first compliance test involved a 1979 Honda Civic impacting the GET head on at 60 mph with the GET offset 15 in away from the roadway. It was believed that offsetting the vehicle in this manner would increase the probability of the test vehicle yawing away from the guardrail end at a high rate of speed. The test vehicle was smoothly decelerated as 13.2 ft of guardrail was forced through the extruder. After the forward motion of the vehicle was virtually stopped, the vehicle began to yaw slowly away from the roadway. The test

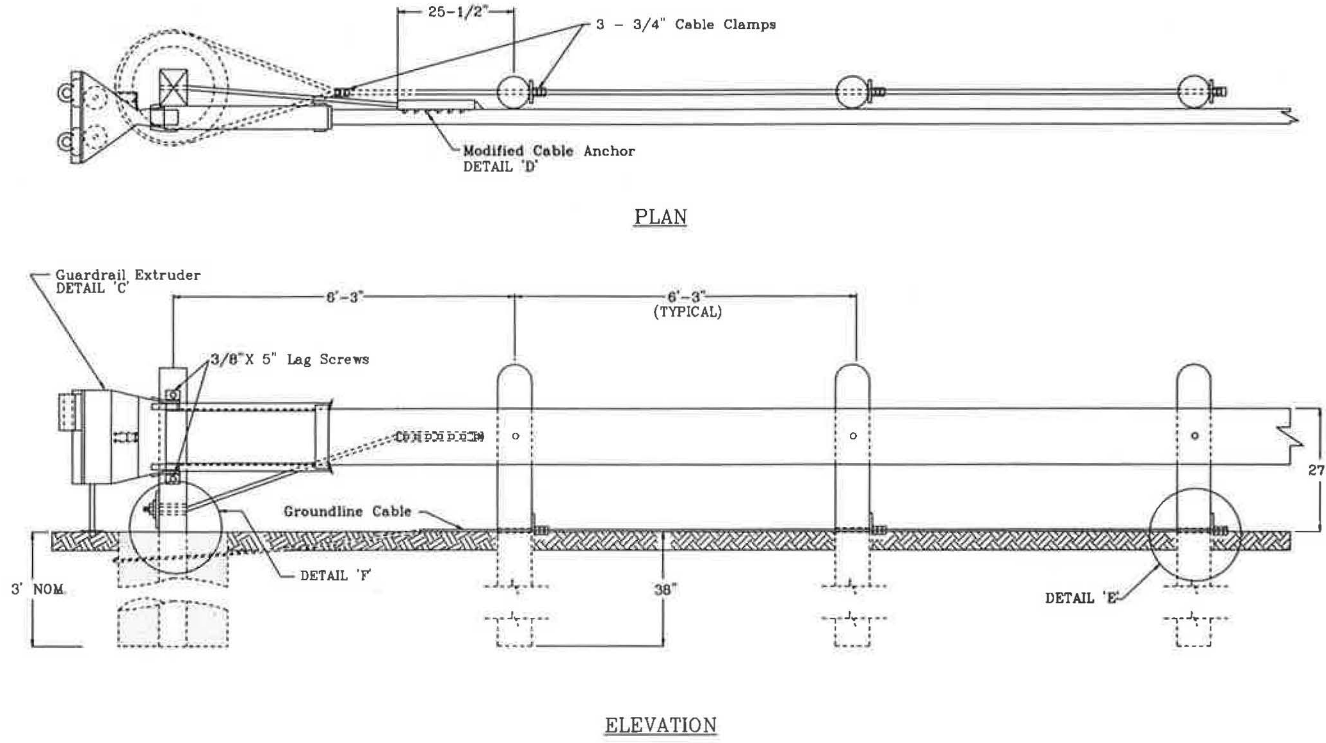

FIGURE 10 Ground-line cable system.

vehicle exhibited no tendency to roll over and came to rest within 30 ft of the original guardrail end. The maximum roll angle during this test was less than 5°, and all occupant severity measures were within recommended limits (*13*). Figure 12 shows the test vehicle and end treatment after test MB-6.

Test MB-7

Test MB-7 evaluated the performance of the GET for head-on impacts with full-size automobiles. This test involved a 4,500-lb vehicle impacting the extruder head on at 61.6 mph. The terminal performed well and decelerated the test vehicle to a smooth stop over 45 ft. The test vehicle exhibited no tendency to ride over the end treatment, and all occupant-impact severity measures were well below recommended limits. The test vehicle and end treatment after test MB-7 are shown in Figure 13.

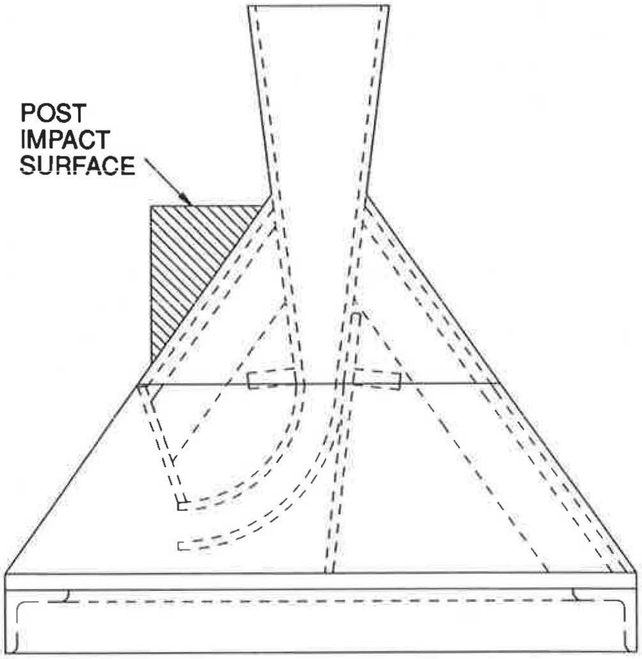

FIGURE 11 **Post impact surface.**

Note that, as discussed previously, the splice between the first and second 25-ft segments of guardrail was welded to eliminate bolts that may inhibit extruder performance. As shown in Figure 14, the test vehicle was traveling at approximately 38 mph when the extruder encountered the welded splice. At this point, high deceleration forces would likely have developed if a bolted splice had been incorporated. Thus, the GET system cannot be expected to perform acceptably with a bolted splice at this point in the guardrail system. However, the test vehicle was decelerated to 25 mph after extruding 37.5 ft of guardrail. Further, if the test vehicle had weighed 4,500 lb and impacted at 60 mph, as required by *NCHRP Report 230* (*13*), it would have decelerated to less than 20 mph after extruding 37.5 ft of guardrail. Although the extrusion process would be restricted by a bolted splice connection, severe deceleration forces would not likely develop when the impacting vehicle is traveling at speeds less than 20 mph. A full-scale crash test should be conducted to verify the safety performance of a GET with a bolted splice 37.5 ft from the end. Syro Steel Company, a leading guardrail manufacturer in Ohio, has indicated that a 37.5-ft length of guardrail could be purchased at a cost only modestly more than that of 37.5 ft of guardrail cut in shorter lengths. Such a design modification would allow the terminal to be constructed without field welding a guardrail splice.

Test 9429A-1

The capacity of the GET for redirecting vehicles impacting along the side was then tested with a mini-size automobile. During this test, an 1,800-lb vehicle impacted the barrier 6.25 ft from the end at a speed of 59.5 mph and an angle of 15°. The test vehicle was redirected smoothly and, although there was some contact between the test vehicle's tires and the guardrail posts, no significant snagging was observed. All occupant severity measures were well within recommended safety limits, and the test was considered to be successful. Furthermore, no signs of distress were observed in the guardrail where the cable-release mechanism was attached.

TABLE 1 SUMMARY OF GUARDRAIL EXTRUDER TERMINAL CRASH TESTS

					TEST RESULTS				
		IMPACT CONDITIONS			OCCUPANT IMPACT VELOCITY		RIDEDOWN ACCELERATION		
TEST NO.	VEHICLE WEIGHT (lbs)	SPEED (mph)	ANGLE (deg)	OFFSET (in.)	LONG. (ft/sec)	LAT. (ft/sec)	LONG. (g's)	LAT. (g's)	COMMENTS
MB-6	1,785	58.7	0	15	29.0	12.5	15.5	2.1	Vehicle decelerated smoothly to a stop
MB-7	4,600	61.6	0	0	19.8	0	8.2	0	Vehicle decelerated smoothly to a stop
9429A-1	1,780	59.1	15.6	0	15.9	17.0	1.4	10.3	Vehicle redirected smoothly
9429A-2	4,410	58.9	24.9	0	23.2	16.5	6.2	8.5	Vehicle redirected smoothly

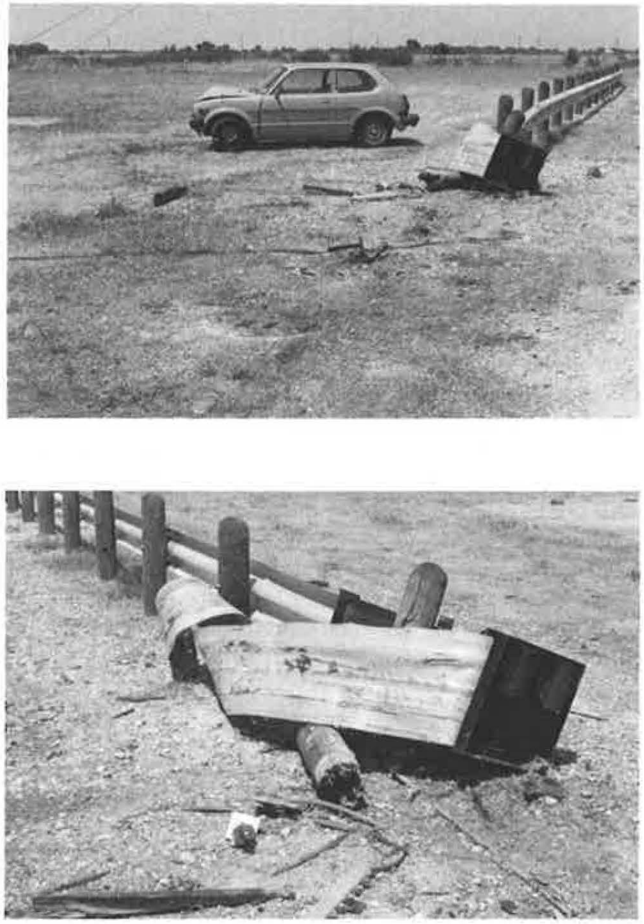

FIGURE 12 Vehicle and treatment after test MB-6.

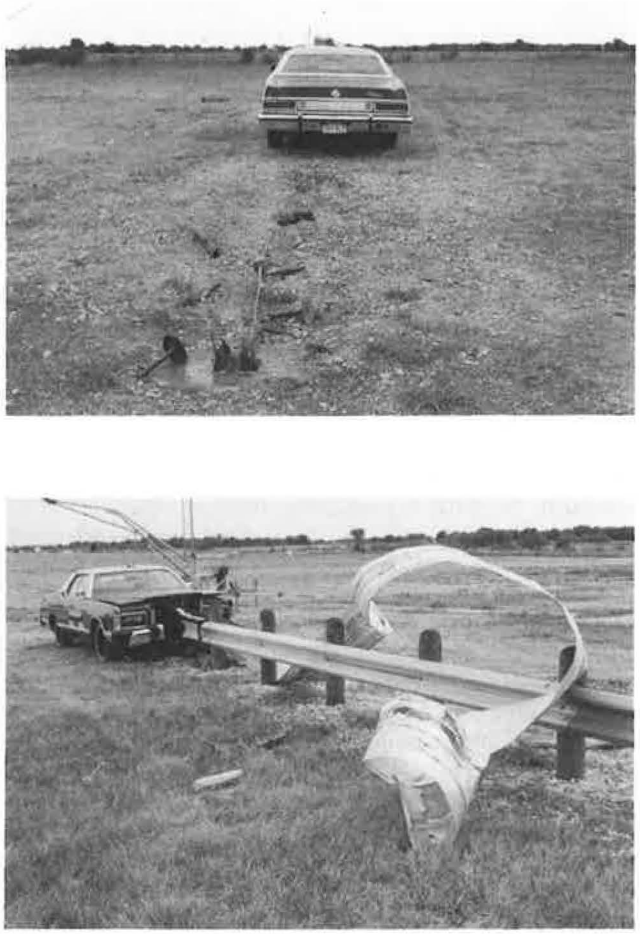

FIGURE 13 Vehicle and treatment after test MB-7.

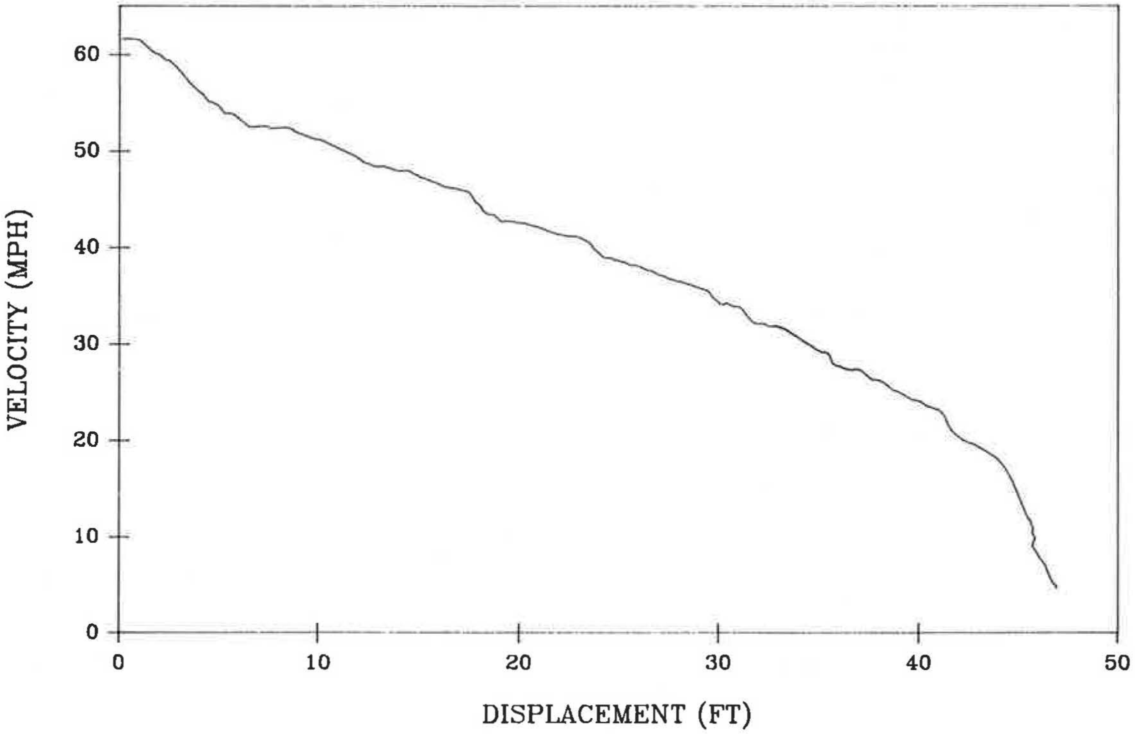

FIGURE 14 Velocity-displacement relationship for test MB-7.

Test 9429A-2

The final compliance test in this series involved a full-size vehicle impacting the end treatment 12.5 ft from the end at 60 mph and 25°. The end treatment again performed very well, even though the test vehicle deflected the barrier sufficiently to allow significant wheel contact with the guardrail posts. Much of the barrier deflection was attributable to 3 in of movement observed in the concrete footing under the leading guardrail post. The footing movement could have caused as much as 1 ft of lateral barrier deflection. Excessive barrier deflection allowed the rear wheels of the vehicle to ride up on the base of a guardrail post.

Although no large snagging forces were generated, the exit velocity for this test was somewhat lower than that recommended by *NCHRP Report 230* evaluation criterion I (*13*). This criterion mandates that a vehicle should not be redirected into the traveled way at a speed less than 75 percent of its impact speed. Thus, test evaluation is based on a subjective judgment of whether the test vehicle has been redirected back to the traveled way. During the subject crash test, the test vehicle exited the barrier at an angle of less than 6° and then quickly steered back to the barrier. It is believed that this test vehicle would not have encroached significantly onto adjacent traffic lanes; therefore, the test was considered to be a success.

For test 9429A-2, the change in vehicle velocity exceeded the 15-mph value recommended in *NCHRP 230* evaluation criterion I (*13*). Although meeting this criterion is desirable, it is believed that strict compliance with this factor is not critical. This criterion requires subjective evaluation based on whether or not the vehicle is judged to have been redirected into or stopped while in adjacent traffic lanes. In the test described herein, the test vehicle returned to the side of the road after a short time interval and was not projected across traffic lanes. Depending on the existence and the width of a shoulder, the test vehicle may or may not be judged to have briefly encroached on adjacent traffic lanes.

The primary intent of evaluation criterion I is to prevent the redirected vehicle from becoming a potential hazard to other traffic. It should be noted that, at this time, there is no evidence that post-impact trajectory is a serious problem. Furthermore, impacting the transition at such a severe speed and angle is a low-probability event. Although, as stated above, the change in vehicle velocity exceeded the recommended value of 15 mph, the occupant-impact velocity and ridedown acceleration were both within maximum acceptable limits (*13*) for this test. This fact further supports the opinion that the severity of impact was well within tolerance limits.

CONCLUSIONS AND RECOMMENDATIONS

The GET has been tested and was shown to satisfy the requirements of *NCHRP Report 230*. The total cost of the GET should be relatively low. Extruders used in the testing were originally constructed for approximately $500 each. The cable-release mechanism was constructed for approximately $250. Remaining hardware items should cost less than $250, and installation of this system should be easier than widely used BCT end treatments. Therefore, the entire cost of the GET should be less than $1,500. Further, key components of the GET are very durable. No significant damage was sustained by the extruders or the cable-release mechanism during any of the 11 full-scale crash tests conducted during GET development.

The GET captures a vehicle impacting the end of the barrier and safely decelerates it to a stop rather than allowing the vehicle to penetrate the barrier at a high rate of speed. This aspect of the GET represents a significant safety improvement over other low-cost end treatment devices, such as the BCT. In addition, the GET is designed to be installed on a tangent section and therefore can be used at sites where flared treatments are inappropriate.

Based on the potential safety improvement and low cost offered by the GET, it is recommended for immediate implementation as an experimental device. Construction activities and accident histories should be monitored to quickly identify any remaining construction, maintenance, or safety problems.

All GET testing reported in this paper involved guardrail mounted on 7-in round wood posts. Although this system successfully passed *NCHRP Report 230* test standards, it is believed that the GET would perform better on a blocked-out system since barrier redirection performance may be improved.

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