Slotted Rail Guardrail Terminal

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A slotted rail terminal (SRT) for W-beam guardrails was successfully developed and crash-tested in accordance with requirements set forth in NCHRP Report 230. The SRT design is intended as a retrofit or replacement of the standard breakaway cable terminal (BCT) and has better impact performance than the eccentric loader terminal and the modified eccentric loader terminal. The slotted rail concept involves cutting three longitudinal 12.7 mm (½ in.) wide slots into the W-beam rail, one at each peak and valley in the cross section, to reduce the buckling strength while maintaining the tensile capacity. The reduced buckling strength of the slotted rail allows for controlled buckling of the rail, which greatly reduces the yaw rate of the impacting vehicle, thereby minimizing the potential for the buckled rail to directly contact or penetrate the occupant compartment. The SRT terminal is expected to be less sensitive to installation details because the buckling of the rail is controlled by the slots and is at a force level substantially lower than the unmodified W-beam rail. 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. To help reduce inventory and control cost, the SRT terminal uses many of the standard components used with the BCT and other flared terminals. In addition, the layout and configuration of the SRT terminal is similar to that of the standard BCT terminal to facilitate easy retrofit.

The development of crashworthy guardrail end terminals has long been a 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 in recent years to develop crashworthy guardrail terminals with good success. Existing safety end treatments for W-beam guardrails include: turndown, breakaway cable terminal (BCT), eccentric loader terminal (ELT), modified eccentric loader terminal (MELT), CAT, SENTRE, BRAKEMASTER, and the ET-2000.

The turndown end terminal is the least expensive of all the end treatments and has been used extensively in several states. However, it has been found that the turndown end terminals could cause impacting vehicles to ramp up and vault over the end treatment, often resulting in rollovers. For this reason, the FHWA has ruled that turndown guardrail end terminals can no longer be installed along high-speed, high-volume federal-aid highways (*1*).

Since its conception and initial testing in 1972, the BCT terminal has become the most widely used W-beam end treatment. The BCT terminal is designed to cause the W-beam rail to "gate," or buckle out of the way of an impacting vehicle, and to allow the vehicle to penetrate behind the guardrail in a controlled manner. However, because the design relies on the dynamic buckling of the W-beam rail, the impact performance of the BCT is very sensitive to installation details, such as barrier flare rate and end offset. Unfortunately, the flare rate and end offset of BCT terminals are not always installed correctly and, consequently, the BCT terminal does not have a favorable service history. Furthermore, even when installed correctly, the BCT terminal has been shown to impart unacceptably high deceleration forces on 817-kg (1,800-lb) minisize vehicles during 96.6-km/hr (60 mph) impacts and has failed to meet the evaluation criteria set forth in NCHRP Report 230 (*2*). The FHWA has recently ruled that BCT terminals will no longer be acceptable for installation along high-speed, high-volume roadways on the national highway system (*3*).

The ELT and MELT terminals are improvements over the standard BCT system. The designs are still based on the "gating" concept and rely on 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 1.22 m (4 ft) (*4*). When tested with a 457-mm (18-in.) offset, the ELT exhibited only marginally acceptable results. Like the standard BCT terminal, the ELT and MELT terminals are sensitive to installation details, and the added complexity of their designs has posed problems in field installations.

Other end treatments, such as the CAT, SENTRE, BRAKEMASTER, and ET-2000, rely on some form of energy attenuation to decelerate impacting vehicles to a safe and controlled stop. These end treatments are considerably more expensive compared with the flared terminals, such as the BCT, ELT, and MELT, and together they comprise only a small percentage of the terminals currently in use.

The slotted rail terminal (SRT) presented in this study is intended as a relatively inexpensive retrofit, or replacement, for the standard BCT terminal. Two designs have been developed based on the slotted rail concept: one intended for use on high-speed (96.6 km/hr or 60 mph) highways (5) and the other for lower-speed roadways with speed limits of 72.4 km/hr (45 mph) or less (*6*). This study presents only the design and evaluation results of the 96.6-km/hr (60-mph) SRT terminal. Development of the SRT designs began in 1992 and was completed in the spring of 1994. The terminal was tested and evaluated in accordance with NCHRP Report 230 criteria. (*2*)

DESIGN CONSIDERATIONS

The SRT terminal is intended as a retrofit and replacement to the BCT terminal, therefore, its design is based on the same gating concept. The BCT, ELT, and MELT terminals all rely on the dynamic buckling of the W-beam rail, which requires a high force level and which is difficult to control in terms of location and manner of buckling. In small car, off-center, head-on impacts with these terminals, the high buckling force caused the vehicle to yaw at a high rate, exposing the occupant compartment of the vehicle to the buckled rail. Thus, the major considerations in the design of the SRT terminal were controlling the dynamic buckling of the W-beam rail and reducing the yaw rate of the impacting vehicle to minimize the potential for the buckled rail to penetrate the occupant compartment.

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Another consideration in the design of the SRT terminal was the ease of retrofit for the standard BCT terminal. The SRT terminal should use as many standard BCT terminal components as possible and have a similar configuration and layout. The impact performance of the BCT, ELT, and MELT terminals are known to be very sensitive to installation details. One of the considerations in the design of the SRT terminal was to reduce the sensitivity of the impact performance to installation details, thus allowing for more latitude and margin of error in case the terminal is not installed exactly according to design.

Costs associated with the terminal were also a major consideration. Most guardrail installations are rarely, if ever, subjected to an impact, and the benefits of even greatly improved impact performance are often not sufficient to justify high terminal costs. Experience has shown that high construction and maintenance costs have prevented the widespread implementation of crashworthy barrier terminals. The SRT terminal is designed to keep the cost of installation and maintenance low and therefore comparable with the costs of the ELT and MELT terminals.

The primary considerations in the development of the slotted rail terminal were to:

- Meet nationally recognized safety standards (*2*),
- Provide controlled dynamic buckling of the W-beam rail,
- Reduce the potential for impact or penetration of the occupant compartment by the buckled rail,
- Be suitable for retrofit of the BCT terminal, and
- Be inexpensive and easy to install and maintain.

SLOTTED RAIL TERMINAL CONCEPT

The slotted rail concept, previously developed at the Texas Transportation Institute as part of another study (*7*), involves cutting longitudinal slots in the W-beam rail to reduce its dynamic buckling strength sufficiently to safely accommodate small car end-on impacts while maintaining adequate capacity to contain and redirect vehicles impacting beyond the length of need. As shown in Figure 1, the W-beam rail 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 12.7mm (½ in.) wide longitudinal slots reduce the cross-sectional area in the slotted region from 1,284 to 1,181 mm^2 (1.99 to 1.83 $in.^2$), which is still greater than the cross-sectional area of 1,039 mm^2 (1.61 $in.^2$) through the four bolt holes at a splice. Thus, the tensile capacity of the W-beam is not compromised because the tensile capacity of the W-beam rail at the slotted segments is greater than that at a splice.

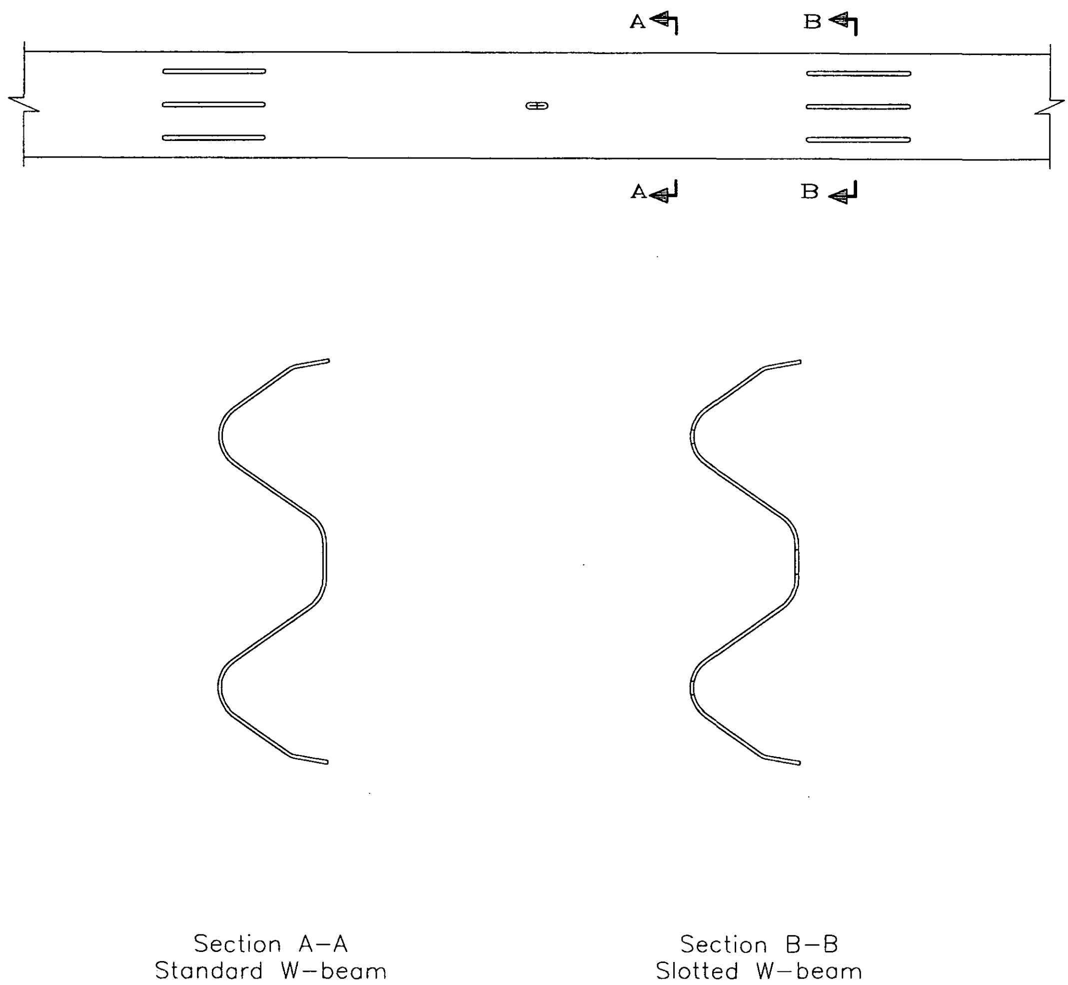

FIGURE 1 Schematic of slot configuration.

On the other hand, the moment of inertia of the W-beam rail is significantly reduced by the presence of the slots. The moment of inertia of an unmodified, 12-gauge W-beam rail is approximately 97×10^4 mm^4 (2.33 in.^{4}). In comparison, the combined moments of inertia of the four relatively flat segments is only 8,325 mm^4 (0.02 in.^{4}). Thus, the buckling strength of a slotted W-beam cross section is only 1 percent of that of an unmodified cross section. The reduced buckling strength of the slotted W-beam allows for controlled, predictable buckling of the rail.

In one of the early developmental crash tests of the slotted rail concept, it was found 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 would rupture and allow the vehicle to penetrate through the guardrail. To alleviate this potential problem, slot guards are attached to the W-beam rail at the downstream ends of each set of slots. The slot guard both reinforces the W-beam rail and provides a 45-degree deflector plate to push the rail away from any vehicle component that may intrude into the slots.

Pendulum tests were conducted to determine the dynamic buckling strength of the slotted W-beam rail, the results of which are summarized in Table 1. Energy dissipation from buckling and collapsing of the slots showed little variation when the slot length was varied from 305 mm to 1.52 m (12 to 60 in.). The same is true for the peak deceleration. Additionally, the slot guard was found to have minimal effect on the buckling and collapsing behavior of the slots or on the peak deceleration or the energy dissipation characteristics of the slotted rail.

In selecting the slot lengths for use with the SRT terminal, consideration was given to the separation of the impulses caused from the buckling of each set in order to minimize the yaw rate of the small car during offset, end-on impacts. This separation of the impulses is provided by the collapsing of the slots after buckling has been initiated. Additionally, it is desirable to select the length and location of the slots such that each set of slots buckles individually and sequentially. Slot lengths that are too short may not provide the desired separation between the buckling impulses. On the other hand, slot lengths that are too long may increase the potential for the bumper or other parts of the impacting vehicle to intrude into the slots. After some consideration, slot lengths of 305 mm (12 in.) and 686 mm (27 in.) were selected for use with the SRT terminal design.

SLOTTED RAIL TERMINAL DESIGN

Figure 2 presents details of the design of the SRT terminal, and Figure 3 includes photographs of the terminal. Brief descriptions of the major components of the SRT terminal design are as follows.

Five sets of slots are used over the first 7.62 m (25 ft) of rail, which may consist of one 7.62-m (25-ft) section or two 3.81-m (12-ft 6-in.) sections of W-beam rail. The slots of the first set are 0.69 m (27 in.) long and are located between Posts 1 and 2. The slots of the second set are 305 mm (12 in.) long and are located at Post 2. The slots of the third set are 0.69 m (27 in.) long and are located between Posts 2 and 3. The slots of the fourth and fifth sets are both 305 mm (12 in.) long and are located between Posts 4 and 5 and between Posts 6 and 7, respectively.

The reason for using longer slots for the first and third sets of slots is to provide longer strokes after initial buckling of these slots,

TABLE 1 Summary of Pendulum Test Results

Slot Length mm (in.)	Slot Guard	Energy Dissipation, KJ (kip-ft)	
		Initial	@ Displacement = 1.22 m (4 ft)
305 (12)	No	12.5 (9.3)	25.4 (18.7)
381 (15)	No	11.8 (8.7)	19.4 (14.3)
457 (18)	No	13.2 (9.7)	25.1 (18.5)
610 (24)	No	11.3 (8.3)	17.1 (12.6)
914 (36)	No	8.9 (6.6)	21.4 (15.8)
1219 (48)	No	11.7 (8.6)	26.3 (19.4)
1524 (60)	No	10.7 (7.9)	18.7 (13.8)
305 (12)	Slot Guard	11.8 (8.7)	31.5 (23.2)
381 (15)	Slot Guard	11.3 (8.3)	N/A
457 (18)	Slot Guard	12.9 (9.5)	28.2 (20.8)

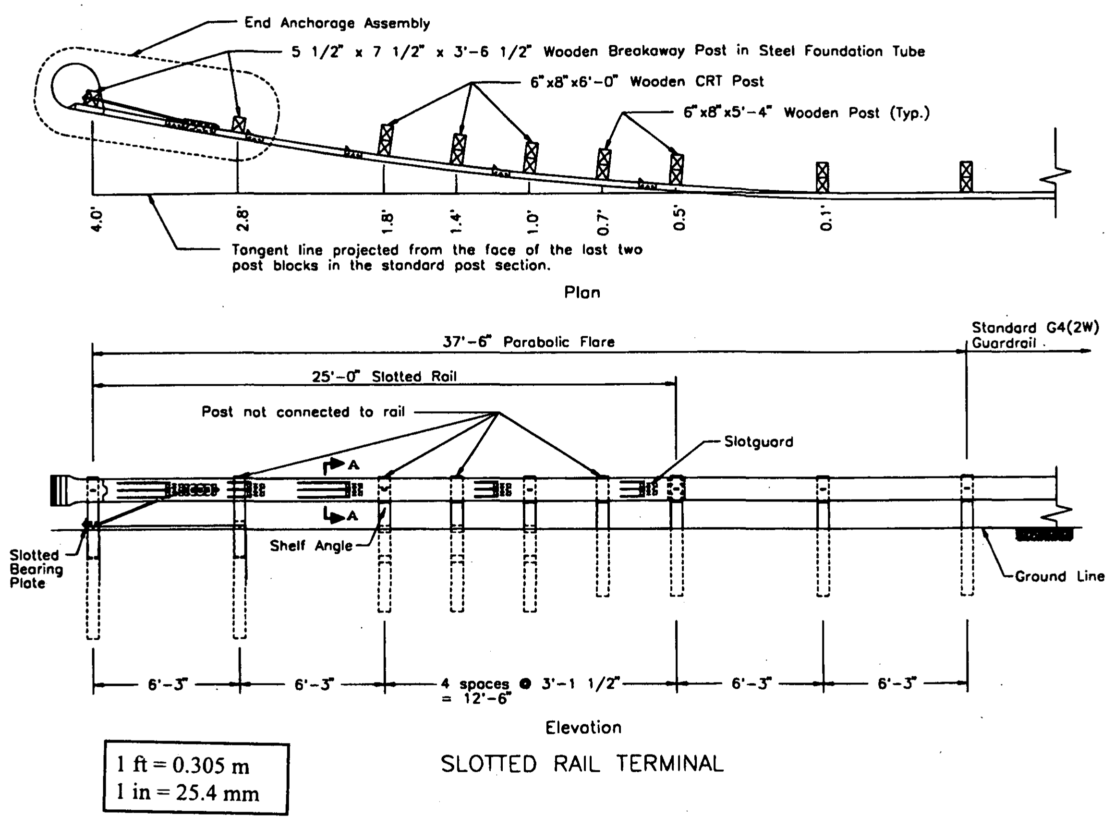

FIGURE 2 Schematic of SRT design.

which helps separate the impulses and reduce the yaw rate of the vehicle in the early stages of impact. The second set of slots at Post 2 is intended to facilitate bending or buckling of the rail at Post 2, thereby reducing the length of the W-beam column created between the first and third set of slots. Shorter slots are used for the fourth and fifth sets of slots (*a*) to reduce the potential for the bumper or other parts of the impacting vehicle to protrude into the slots during redirectional impacts and (*b*) to stiffen the end terminal for large vehicle end-on impacts.

Bolt-on slot guards are attached to the W-beam rail at the downstream end of each set of slots to prevent the bumper or other parts of the impacting vehicle from intruding into and extending the slots. The slot guard reinforces the W-beam rail and provides a 45-degree deflector plate to push the rail away from any vehicle component that may intrude into the slots.

The end anchorage system is similar to that of the ELT and MELT terminals. Two steel foundation tubes connected with a ground channel strut provide the required anchorage capacity. A BCT cable anchorage assembly is attached to the W-beam rail at one end and is anchored through a hole in the base of the wooden end post. A buffered end section, similar to that used with the BCT terminal, is attached to the end of the slotted rail section to distribute the impact load.

A slotted bearing plate is used to distribute the forces in the cable to the wooden end post and foundation tube. The standard bearing plate arrangement used with the BCT cable assembly does not allow the bearing plate to separate from the cable after the wooden end post is broken from impact by the vehicle. Tests have shown that the bearing plate, after releasing from the wooden end post, can potentially be thrown up underneath the vehicle and become caught on the undercarriage. This restrains the forward movement of the vehicle resulting in the vehicle yawing rapidly and coming to an abrupt stop. To eliminate this potential problem, a slotted configuration is incorporated into the bearing plate so the bearing plate can separate from the cable if the wooden end post breaks. To keep the cable anchor bearing plate from being displaced from its proper position should the cable become slack, two lag screws, or bent nails, are used to secure the bearing plate to the wooden end post.

A parabolic flare with an end offset of 1.22 m (4 ft) is used, identical to that used with the BCT terminal. The first five posts (Posts 1–5) are wooden breakaway posts. Posts 1 and 2 are placed in foundation tubes, and Posts 3, 4, and 5 are controlled release terminal (CRT) posts. Standard wooden or steel guardrail posts are then used from Post 6 on. A post spacing of 1.91 m (6 ft 3 in.) is used with the first two spans, followed by four spans of 0.95 m (3 ft 1½ in.) post spacing. The rest of the end terminal section and the standard length-of-need section use the standard 1.91 m (6 ft, 3 in.) post spacing. The W-beam rail is not bolted to Posts 2, 3, 4, or 6. A shelf angle is added at Post 3 to provide intermediate support to the rail between Posts 1 and 5.

COMPLIANCE TESTING

According to guidelines presented in NCHRP Report 230, four compliance crash tests are required to evaluate the performance of

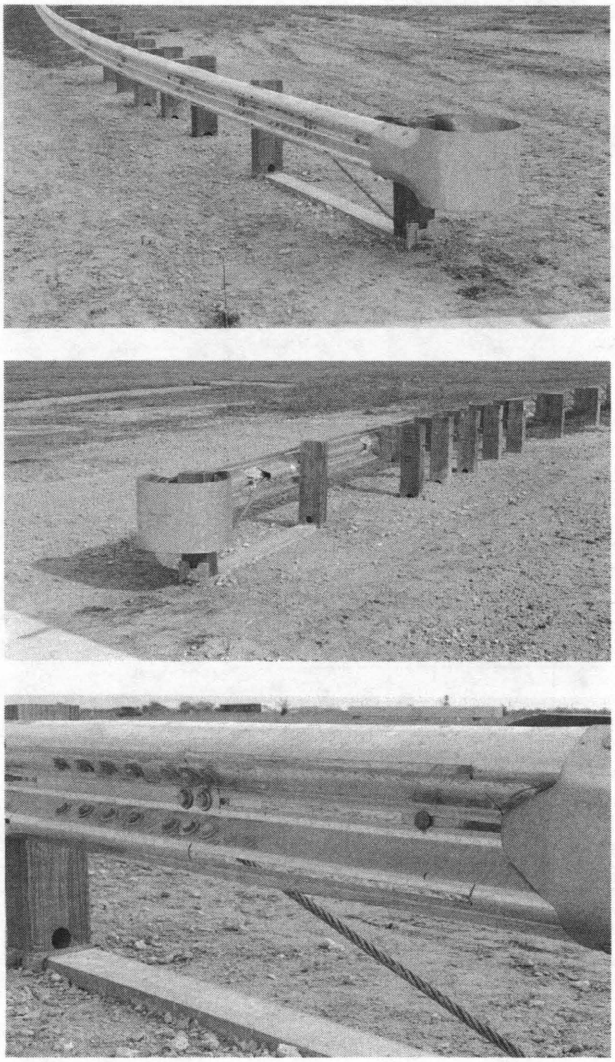

FIGURE 3 Photographs of SRT.

a barrier end terminal design. To evaluate the performance of this SRT terminal design, only three of the four compliance crash tests were deemed necessary. The small car redirective test was considered unnecessary because this crash test was successfully conducted with other BCT-type terminal designs with similar flares and end offsets, and the modifications made to the SRT terminal design should not affect the stability of the vehicle or occupant risk factors for this test. The FHWA agreed with this assessment.

The SRT terminal successfully passed all three recommended crash tests as summarized in Table 2. Sequential photographs for each of the tests are presented in Figure 4.

Large Car Length-of-Need Test

The first compliance crash test involved a 1981 Cadillac Sedan weighing 2,041 kg (4,500 lb) and impacting the test installation at the beginning of length-of-need, which was selected to be at Post 3, or 3.81 m (12.5 ft) downstream from the nose of the terminal. At impact, the test vehicle was traveling at a speed of 91.7 km/hr (57.0 mph) and at an angle of 22.5 degrees relative to the length-of-need section and 30.3 degrees relative to the terminal section. The usual objective of this test is to evaluate the structural adequacy of the guardrail and terminal anchorage. An additional objective of this test was to evaluate the effectiveness of the slot guard in preventing the slots from being extended and thereby resulting in penetration of the vehicle through the W-beam rail.

The impacting vehicle was contained and smoothly redirected by the terminal. All occupant risk factors were well within the recommended limits in NCHRP Report 230. The test vehicle remained upright and stable throughout the test. As shown in Figure 5, damage to the guardrail was moderate considering the severity of the impact. The foundation tube at Post 1 was displaced longitudinally 50.8 mm (2 in.). Posts 3–5 were broken off at ground level, and Posts 6 and 7 were split along their longitudinal axis. The rail element was damaged and partially flattened in the impact area. The maximum dynamic deflection of the rail was 1.0 m (3.3 ft), and the maximum permanent deflection was 0.8 m (2.7 ft), located approximately midspan of Posts 5 and 6. Damage to the vehicle, shown in Figure 5, also was moderate, concentrated at the right front quarter. Maximum crush was 340 mm (13.4 in.) at the right front corner of the vehicle. There was no deformation or intrusion into the occupant compartment.

The vehicle was in contact with the installation for 7.9 m (26.0 ft). The vehicle exited the installation at a speed of 39.2 km/hr (24.4 mph) and at an angle of 15.1 degrees. The vehicle came to rest 26.2 m (86.0 ft) downstream from the initial point of impact and 4.6 m (15 ft) in front of the installation. The change in velocity of the vehicle was 52.5 km/hr (32.6 mph) and the exit angle was 15.1 degrees, these are higher than the recommended limit of 24.1 km/hr (15 mph) and 60 percent of the impact angle (13.5 degrees). However, vehicle trajectory after loss of contact with the guardrail indicated that the vehicle would not have posed a hazard to adjacent traffic.

The major concern with this test was the potential for the vehicle bumper or other parts of the vehicle to intrude into the slots and tear or rip the rail. The slot guard was specifically designed to prevent this. Results of this crash test demonstrated that the slot guards perform as designed in preventing the slots from being torn or ripped apart.

Small Car Head-On Test

The second compliance test involved an end-on impact by a 1988 Chevrolet Sprint, weighing 817 kg (1,800 lb). The test vehicle hit the terminal at a speed of 99.4 km/hr (61.8 mph) and at an angle of 0 degrees relative to the tangent of the length-of-need section. The centerline of the vehicle was offset 381 mm (15.0 in.) toward the traffic face from the centerline of the wooden end post. This orientation will cause the vehicle to rotate clockwise into the rail, maximizing the potential for the buckled rail to hit and penetrate the occupant compartment of the impacting vehicle. In addition to vehicle trajectory, the primary objective of this test was to evaluate occupant risk for small car, end-on impacts.

On impact, the end post (Post 1) was fractured at ground level, releasing the cable anchor mechanism as designed. The vehicle was smoothly decelerated as it proceeded forward, buckling the first, third, and fourth sets of slots and breaking Posts 1–5 at ground level. The vehicle first yawed clockwise and then began to yaw counterclockwise, apparently the result of the left front tire or undercarriage of the vehicle engaging some of the broken posts and debris. The vehicle lost contact with the installation near Post 6,

TABLE 2 Summary of Compliance Crash Test Results

Description		Large Car, Redirection Test	Small Car, Head-On Test	Large Car, Head-On Test
Vehicle Weight		2,043 kg (4,500 lb)	817 kg (1,800 lb)	2,043 kg (4,500 lb)
Impact Conditions	Speed	91.7 km/h (57.0 mph)	99.4 km/h (61.8 mph)	97.6 km/h (60.6 mph)
	Angle	22.5 deg.	0	0
	Offset	N/A	381 mm (15 in.)	0
Exit Conditions	Speed	39.2 km/h (24.4 mph)	37.5 km/h (23.3 mph)	83.1 km/h (51.7 mph)
	Angle	15.1 deg.	15.6 deg.	2.3 deg.
Total Length of Contact		7.9 m (26.0 ft)	9.1 m (30.0 ft)	9.5 m (31.3 ft)
Maximum Dynamic Deflection		1.0 m (3.3 ft)	7.5 m (24.5 ft)	7.6 m (24.9 ft)
Occupant Impact Velocity	Longitudinal	8.1 m/s (26.7 ft/s)	8.4 m/s (27.4 ft/s)	3.8 m/s (12.5 ft/s)
	Lateral	4.6 m/s (15.0 ft/s)	2.6 m/s (8.6 ft/s)	No Contact
Ridedown Acceleration	Longitudinal	-10.3 g	-9.4 g	-6.7 g
	Lateral	-10.8 g	13.5 g	No Contact

traveling at a speed of 37.5 km/hr (23.3 mph) and at an angle of 15.6 degrees relative to the tangent section and was still yawing in a counterclockwise direction. The vehicle came to rest behind the rail facing Post 11, 16 m (52.5 ft) downstream from the point of impact and oriented 120 degrees from the vehicle's initial direction of travel.

The terminal performed as designed, first smoothly decelerating the vehicle and then allowing the vehicle to penetrate behind the guardrail in a controlled manner. As a result of the low buckling strength of the slotted rail, the vehicle exhibited a minimal amount of yaw during the impact sequence. Thus, even though an elbow was formed at the third set of slots of the buckled rail, the orientation of the vehicle was such that it merely sideswiped the slot guard on the back side of the rail, resulting in minor damage to the left rear door. All occupant risk factors were well within the recommended limits in NCHRP Report 230. The occupant impact velocity in the longitudinal direction was 8.4 m/sec (27.4 ft/sec), which is less than the design value of 9.1 m/sec, (30 ft/sec) and below that for most existing end terminals.

The test vehicle remained upright and stable during the impact sequence and after exiting from the installation. The vehicle yawed counterclockwise near the end of impact sequence, apparently as a result of the left front tire or undercarriage of the vehicle becoming engaged with some of the broken posts and debris. However, the vehicle had slowed significantly with most of the impact energy attenuated at that point, and the yaw rate was considered moderate.

Damages sustained by the terminal and vehicle are shown in Figure 6. The first, third, and fourth set of slots were buckled, and the second and fifth set of slots did not activate. Posts 1–5 were broken off at ground level, and Posts 6 and 7 were slightly displaced laterally. The foundation tube was bent at Post 1 and disturbed at Post 2. The vehicle received moderate damage, most of which was concentrated at the front of the vehicle. The maximum crush was 240 mm (9.5 in.) at bumper height near the front center of the vehicle. There was 159 mm (6.3 in.) of deformation into the occupant compartment in the fire wall area near the floor pan on the driver's side. 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 behind and adjacent to the test installation and did not pose any hazard to adjacent traffic.

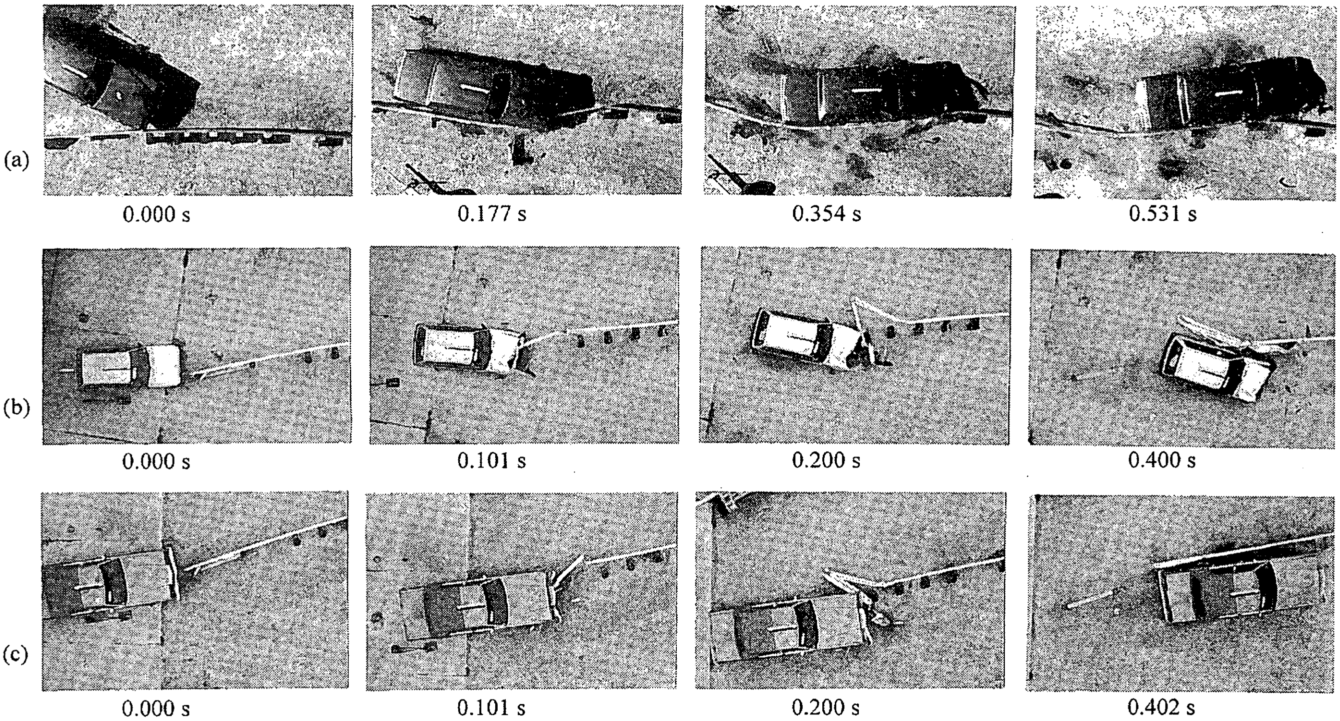

FIGURE 4 Sequential photographs of compliance crash tests: (*a*) large car length-of-need test, (*b*) small car end-on test, and (*c*) large car end-on test.

Large Car Head-On Test

The third compliance crash test involved a 1980 Lincoln Continental, weighing 2,041-kg (4,500 lb). The vehicle hit the end terminal head on at a speed of 97.6 km/hr (60.6 mph) and at an angle of 0 degrees relative to the tangent section of rail. The centerline of the vehicle was aligned with the centerline of the end post. The objective of this test was to evaluate the terminal performance during high-speed, head-on impacts with full-size automobiles.

On impact, the end post was fractured at ground level, releasing the cable anchor mechanism as designed. The vehicle was smoothly decelerated as it proceeded forward, buckling the first four sets of slots and breaking Posts 1–5 at ground level. As the vehicle continued forward, the left front tire made contact with the top of Posts 6, 7, and 8. The vehicle was traveling at 83.1 km/hr (51.7 mph) with an exit trajectory of 2.3 degrees as the vehicle lost contact with Post 8. After the vehicle exited from the guardrail, it landed on the right front tire and began to slide and yaw counterclockwise. The vehicle subsequently turned back toward the barrier and hit the guardrail again near Post 19 and came to rest 51.8 m (170 ft) from the point of initial impact.

The terminal performed as designed, first smoothly decelerating the vehicle and then allowing the vehicle to penetrate behind the guardrail in a controlled manner. Although not required as part of the evaluation criteria, 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 and after exiting the installation. There was some roll and pitch of the vehicle as it traversed over some of the broken posts and debris, but the extent of the roll and pitch was relatively moderate and did not affect the stability of the vehicle.

Damage sustained by the terminal and vehicle is shown in Figure 7. The first through fourth sets of slots were buckled. The fifth set of slots was bent but did not buckle. Posts 1–5 were broken off at ground level, and Posts 6 and 7 were slightly displaced laterally. The foundation tube for the end post was slightly disturbed. The vehicle received moderate damage, most of which was concentrated at the front of the vehicle. Maximum crush was 440 mm (17.3 in.) at bumper height near the front center of the vehicle. There was no deformation into the occupant compartment.

CONCLUSIONS AND RECOMMENDATIONS

An SRT for W-beam guardrails was successfully developed and crash-tested in accordance with requirements in NCHRP Report 230. The slotted rail concept involves cutting three longitudinal 1.3 cm (½ in.) wide slots into the W-beam rail, one at each peak and valley in the cross section. A slot guard is attached to the W-beam rail at the downstream end of each set of slots to prevent extension of the slots and rupture of the rail.

Even though the ELT, MELT, and SRT terminals all meet the recommended design limits for occupant impact velocity and ridedown accelerations set forth in NCHRP Report 230, the SRT terminal is believed to offer a significant improvement over these other systems. The slotted feature of the SRT terminal provides controlled and predictable dynamic buckling of the W-beam rail, whereas the ELT and MELT terminals rely on the buckling behavior of a long, unmodified, eccentrically loaded W-beam rail. The buckling load for the SRT terminal is significantly less than that required by the other two terminals. This reduced buckling load substantially reduces vehicular yaw during the impact sequence,

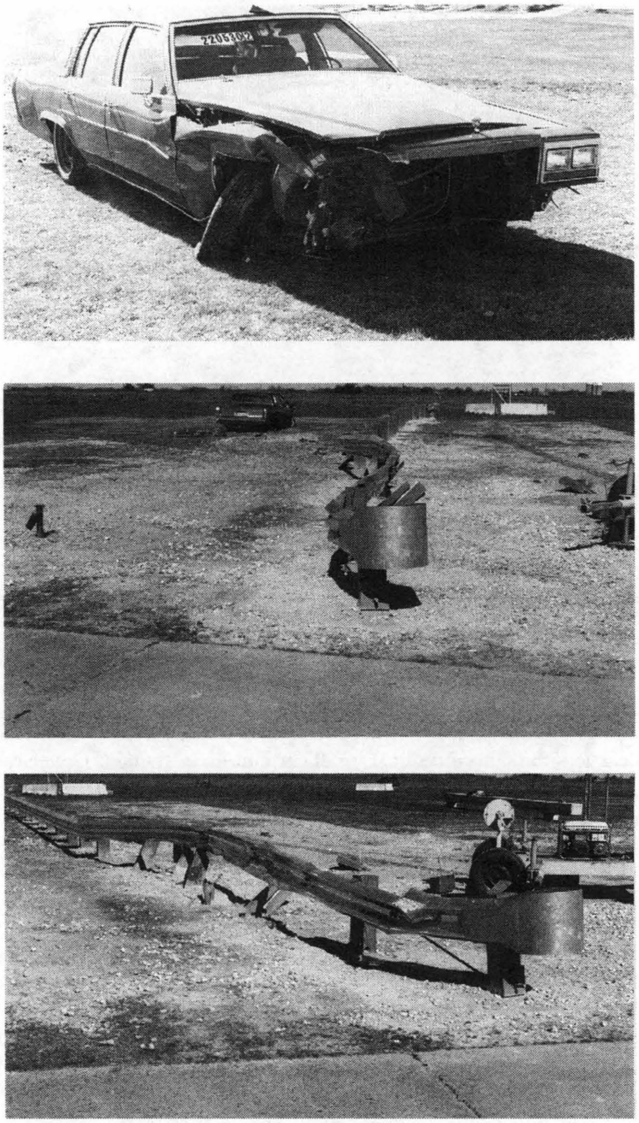

FIGURE 5 Damaged test vehicle and terminal after large car, redirection test.

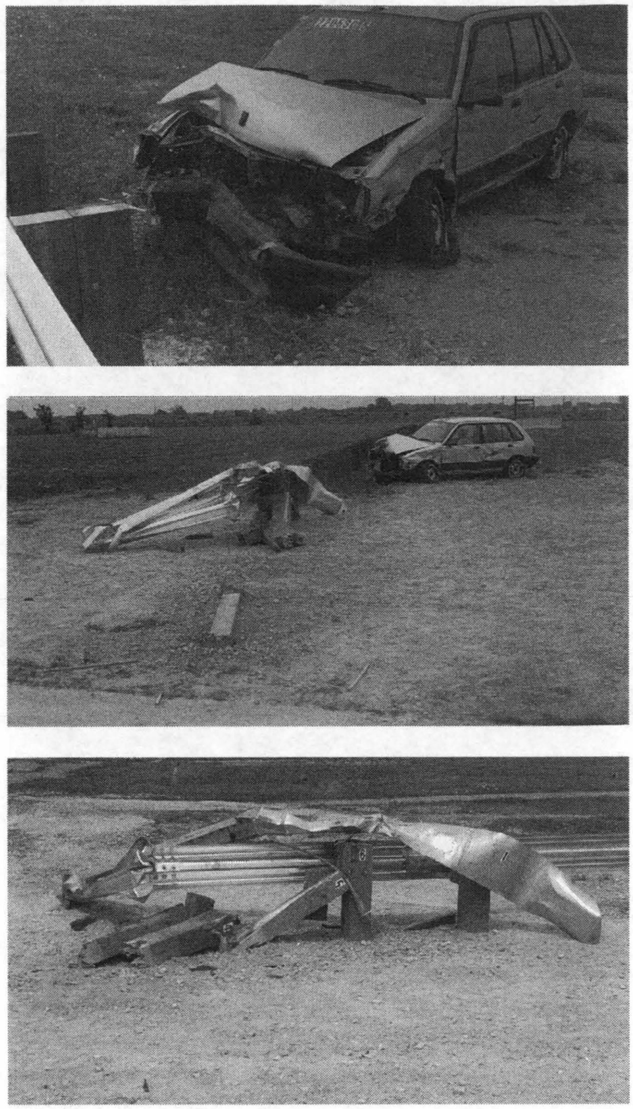

FIGURE 6 Damaged test vehicle and terminal after small car, end-on test.

which in turn minimizes the potential for secondary impact with bent or kinked rail elements that could result in penetration of the occupant compartment. Reduced yaw motion also reduces the potential for vehicle rollover after the terminal impact. The long column length in the ELT and MELT terminal designs results in the buckled W-beam rail initially rebounding away from the impacting vehicle and then forcefully recontacting the side of the vehicle. This type of behavior is much less pronounced with the SRT because of to the relatively short lengths of rail present between the slotted sections. Furthermore, because buckling of the rail for the SRT terminal is controlled by the slots, the impact performance of the SRT terminal is expected to be much less sensitive and more forgiving to installation variations and tolerances.

The SRT design is intended as a retrofit or replacement of the standard BCT terminal. Hence, the SRT design uses many of the standard components common to the BCT terminal. Because the SRT also uses features common to other end treatments, such as a foundation strut and weakened CRT posts, the need for inventory of new components is minimized and the cost of the terminal is kept low. Also of significance in terms of facilitating easy retrofit of existing terminals is that the parabolic flare of the SRT terminal is identical to that of the BCT terminal. The site grading requirement for the SRT terminal should also be similar to that of the BCT terminal (i.e., the SRT terminal should be installed on an essentially level site that has a relatively clear runout area behind and beyond the gating portion of the terminal to ensure proper performance).

Although production and installation costs are extremely difficult to quantify, the material cost for the slotted rail terminal is expected to be comparable with that of the ELT or MELT, with manufacturers' estimates in the range of $900 to $1,100. The installation cost

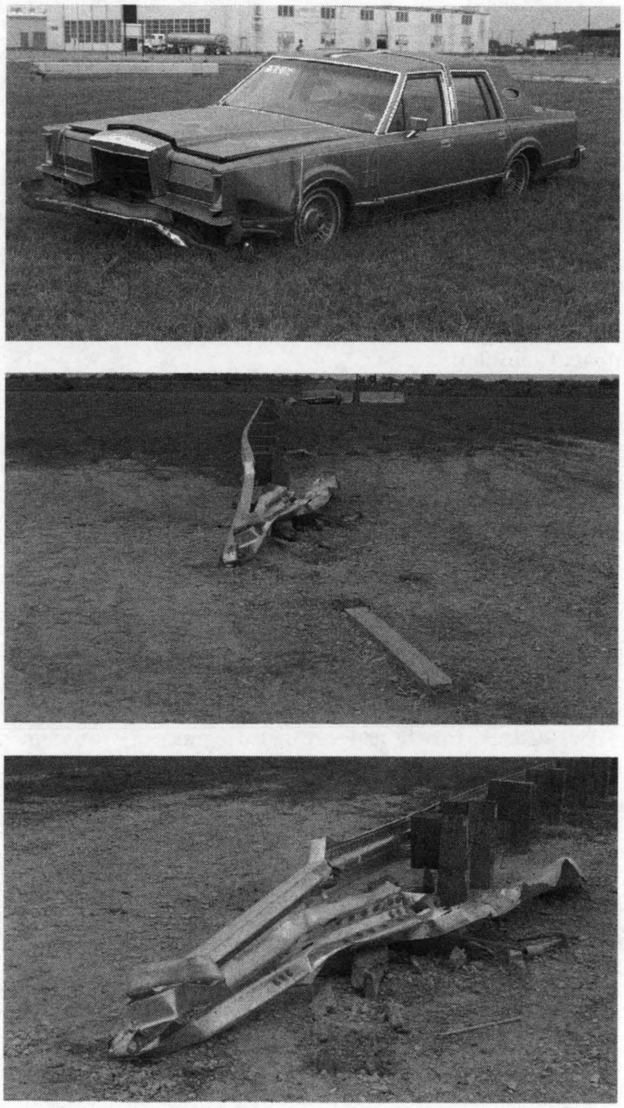

FIGURE 7 Damaged test vehicle and terminal after large car, end-on test.

should be similar to that of the BCT terminal, probably in the range of $200 to $300.

The SRT has been approved by FHWA for use on federal-aid highway projects (*8*). The terminal is offered as a proprietary item and is available for field implementation. As with any new roadside safety device, in-service evaluations to monitor the installation activities and accident experience are recommended to identify and resolve any unforeseen installation, maintenance, or safety problems in a timely manner.

REFERENCES

1. Willett, T. O. Guidelines of Applications of the AASHTO Roadside Design Guide on Federal-Aid Highway Projects. Memorandum, Sept. 7, 1990.
2. Michie, J. D. *NCHRP Report 230: Recommended Procedure for the Safety Performance Evaluation of Highway Appurtenances.* TRB, National Research Council, Washington, D.C., March 1981.
3. Carlson, E. D. Traffic Barrier Safety Policy and Guidance. Memorandum, Sept. 29, 1994.
4. Meczkowski, L. C., *Evaluation of Improvements to Breakaway Cable Terminal.* Report FHWA-RD-91-065. FHWA, U.S. Department of Transportation, Washington, D.C., 1991.
5. Mak, K. K., R. P. Bligh, and W. C. Menges. *W-Beam Slotted End Terminal Design,* Final Report, TTI Project No. 220530. Texas Transportation Institute, Texas A&M University System, College Station, May 1994.
6. Mak, K. K., and R. P. Bligh. *Development of W-Beam Slotted Rail End Terminal Design,* Research Report RF 7199-3F. Texas Transportation Institute, Texas A&M University System, College Station, May 1994.
7. Sicking, D. L., A. B. Qureshy, R. P. Bligh, H. E. Ross, Jr., and C. E. Buth. *Development of New Guardrail End Treatments,* Research Report 404-1F. Texas Transportation Institute, Texas A & M University System, College Station, Oct. 1988.
8. Sillan, S. I. Letter to King K. Mak. Federal-Aid and Design Division, FHWA, U.S. Department of Transportation, Washington, D.C., June 24, 1994.

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