Transition from Guardrail to Concrete Bridge Rail for Low-Speed Roadways

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In recent years, many state departments of transportation have had to modify their approach guardrail–to–concrete bridge rail transition systems to comply with the testing requirements of NCHRP Report 350. Generally, these transition systems are designed and tested for use on high-speed roadways. Because no national transition designs have been developed and tested for lower-speed conditions, the same transition standard is typically applied to all roadways regardless of speed. The new transition designs represent a significant increase in installation cost and complexity over some previous designs that were acceptable under NCHRP Report 230. Thus, it may be cost-prohibitive to require use of the same design on all roadways. The purpose of this research was to develop a guardrail–to–concrete bridge rail transition that is suitable for use on lower-speed roadways and that is less expensive and complex than current designs for high-speed roadways. A low-cost transition was successfully evaluated under NCHRP Report 350 Test Level 2 (TL-2) impact conditions. It is considered suitable for use on roadways that have traffic conditions appropriate for the use of TL-2 safety hardware. Use of this system provides significant savings in material and installation cost compared with high-speed (i.e., TL-3) transitions.

On July 16, 1993, FHWA formally adopted the performance evaluation guidelines for highway safety features set forth in NCHRP Report 350 (*1*) as a guide or reference document (*Federal Register,* Volume 58, Number 135). FHWA also mandated that, starting in September 1998, only highway safety appurtenances that meet the performance evaluation guidelines set forth in NCHRP Report 350 may be used in new construction projects on the National Highway System.

Changes incorporated into the NCHRP Report 350 guidelines included new design test vehicles, expanded test matrices, and revised impact conditions. Of the most significance was the adoption of a ¾-ton (2,000-kg) pickup truck as the design test vehicle for structural adequacy tests. This change necessitated the retesting and redesign of many existing roadside safety features. Many of the guardrail–to–bridge rail transition designs tested and approved under NCHRP Report 230 (*2*) were unable to accommodate the pickup truck. Compared with passenger cars, pickup trucks have a higher center of gravity, a shorter front overhang, and a greater bumper height (see Table 1). All of these factors combine to make the pickup truck a more critical vehicle than the passenger car from the standpoint of impact performance with roadside safety features. The propensity for wheel snagging, occupant compartment deformation, and vehicle instability (i.e., rollover) is greater for the pickup truck than for the passenger car.

Full-scale crash testing of transitions with the pickup truck indicated that the design parameters required adjustment. First and foremost, the transition systems needed to be stiffened to limit vehicle snagging to tolerable levels and avoid vehicle overturn. Whereas a maximum dynamic deflection of 12 in. (305 mm) was generally sufficient for a transition system designed under NCHRP Report 230, dynamic deflection typically has to be limited to less than 6 in. (152 mm) in order to successfully accommodate the pickup truck design vehicle of NCHRP Report 350. It was further determined that additional efforts to mitigate wheel snagging were required. This effort usually takes the form of a rubrail or curb added below the transition rail element to reduce the clear opening and help prevent the wheel of the pickup from intruding underneath the transition rail. The wheels of pickup trucks have demonstrated a tendency to rotate out of plane and underneath the transition rail element. This tendency increases the severity of snagging on the posts in the transition section as well as at the end of the bridge rail parapet. Such tendencies have been observed not only for transitions with W-beam rail elements but also for those with thrie beam rail, which have a clear opening between the pavement surface and bottom edge of rail of only 10 in. (253 mm).

Stiffening of the transition systems was generally accomplished by increasing the number of posts in the transition (i.e., decreasing post spacing) or increasing the post size or length, or both. The addition of a lower rubrail or curb was also needed in most cases to prevent interaction between the wheel and transition components. Some designs further attempted to limit wheel snagging by offsetting the transition rail element from the bridge rail parapet through the use of specially fabricated offset blocks with variable dimensions. As an illustration, one commonly used guardrail–to–concrete bridge rail transition consists of a nested thrie beam rail supported on 7-ft (2.1-m) long steel or wood posts spaced at 18.75 in. (476 mm). A 4-in.-tall curb runs along the length of the nested thrie beam section. The front face of the curb is aligned with the traffic face of the wood blockout that offsets the thrie beam from the support posts. A thrie beam terminal connector and specially fabricated backup block is used to attach the downstream end of the transition to the concrete bridge rail parapet. On the upstream end, a 6-ft 3-in. (1,905-mm), 10-gauge, thrie-beam-to-W-beam transition element is used to transition the thrie beam to the standard W-beam rail section that is commonly used as the approach guardrail.

Most transition systems have been crash tested under Test Level 3 (TL-3) of NCHRP Report 350, which is the basic test level required to receive approval of the system for use on high-speed roadways. Since no national transition designs have been developed for lower-speed conditions, most states typically apply the same transition standard to all roadways regardless of speed or traffic volume. However, the new transition designs developed to comply with NCHRP Report

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TABLE 1 Comparison of Critical Test Vehicle Dimensions

Vehicle Property	Vehicle Type	
	2000P[1]	4500S[2]
C.G. height (in.)	28	22
Front overhang (in.)	31	43
Bumper height[3] (in.)	18–28	12–21

C.G. = center of gravity
[1]4,409-lb (2000-kg) pickup truck; NCHRP Report 350 design vehicle
[2]4,500-lb (2040-kg) passenger sedan; NCHRP Report 230 design vehicle
[3]Range: bottom edge–upper edge

350 represent a significant increase in installation cost and complexity over designs previously acceptable under NCHRP Report 230. Beyond the cost of installing more posts at a deeper embedment, the addition of a curb may require modification of the bridge end drainage, particularly in retrofit and upgrade applications.

For these reasons, it may be cost-prohibitive to require use of the high-speed, TL-3 guardrail–to–concrete bridge rail transition systems on low-speed roadways. The primary purpose of this research was to develop a transition suitable for use on lower-speed roadways that is less expensive and complex than the high-speed transition designs that comply with NCHRP Report 350. The design alternatives were compared using computer simulation, and the selected design was subjected to a full-scale crash test to assess compliance with NCHRP Report 350 performance criteria. The testing was conducted at an impact speed of 43.5 mph (70 km/h), which conforms to NCHRP Report 350 Test Level 2 (TL-2) impact conditions. Approval as a TL-2 system would make the transition suitable for use on many lower-speed roadways or roadways with traffic conditions appropriate for the use of TL-2 safety hardware.

TRANSITION DESIGN

The researchers met with Texas Department of Transportation (DOT) personnel and discussed design requirements and constraints associated with the development of a TL-2 transition from a standard strong-post W-beam approach guardrail to a rigid concrete bridge parapet. Emphasis was placed on developing a system that is low-cost and simple to install and maintain. Further, it was requested that the system incorporate standard hardware items to the extent possible. It was also desirable for the height of the transition to be 27 in. (686 mm). This height would greatly simplify the upstream transition from the approach guardrail to the transition section and enable the transition to be connected to existing 27-in.-tall bridge rails (used by Texas DOT and other states) without major modification to the bridge rail parapet. Although a 27-in.-tall transition section was not feasible for TL-3 impact conditions, it was believed that the reduced impact severity associated with the lower TL-2 impact speed made a 27-in.-tall transition a realistic possibility.

Analyses were performed to assess the ability of selected design concepts to meet NCHRP Report 350 impact performance criteria before any full-scale crash tests were conducted. Computer simulation techniques were used to support the analysis efforts. The program utilized in the computer modeling effort was Barrier VII (*3*), which is a two-dimensional code that models vehicular impacts with deformable barriers. The program employs a sophisticated barrier model that is idealized as an assemblage of discrete structural members possessing geometric and material nonlinearities. It has been used successfully to simulate impacts with a variety of flexible roadside barriers, including transitions from flexible to rigid barriers (*4–7*).

A simulation study was undertaken to evaluate and compare design alternatives. Use of the simulation code provided more-detailed understanding of the influence of these key transition design parameters on dynamic barrier deflection and the severity of wheel snagging on the end of the concrete parapet. Key parameters investigated included post spacing, post size, and post embedment depth. The objective was to determine a more optimal lateral barrier stiffness for TL-2 impact conditions. Three transition designs were evaluated as part of the computer simulation effort. For each case, the approach guardrail was assumed to be a strong-post W-beam guardrail. The 12-gauge W-beam rail was mounted to 6-ft-long, W6 × 9 steel posts at a height of 27 in. to the top of the rail, providing a post embedment depth of 44 in. The posts were spaced on 6-ft-3-in. centers and 8-in.-deep offset blocks were incorporated between the rail and posts. The concrete bridge rail parapet was modeled as a rigid block to represent the worst-case condition.

The first and simplest transition alternative (Option 1) involves nesting the last 12.5 ft of W-beam rail adjacent to the bridge parapet and reducing the post spacing to 37.5 in. (half the standard strong-post guardrail post spacing) along this section. Thus, this design is only 12.5 ft long and requires only one additional section of W-beam rail and two additional standard guardrail line posts. The purpose of the nested W-beam is to help minimize localized deflections of the W-beam rail element around the end of the rigid parapet. No rubrail or curb was utilized.

The second design (Option 2) is similar to the first except that the post spacing over the last 6-ft 3-in. span (i.e., the span adjacent to the parapet) is further reduced to 18.75 in. (one-fourth the standard spacing). The post spacing along the initial 6-ft 3-in. span on the upstream end of the transition remains at 37.5 in. All other details remain the same. Thus, a total of four additional standard line posts are required for this option.

The third design alternative (Option 3) is similar to Option 1 except that the standard 6-ft-long W6 × 9 steel guardrail posts are replaced with 7-ft-long W8 × 13 steel posts spaced at 37.5 in. along the 12.5-ft-long transition section. The post at the upstream end of the transition is still a standard line post. Thus, three of the larger, longer posts are required in place of the standard line posts.

The simulated impacts involved a 4,409-lb (2,000-kg) pickup truck striking the transition at a speed of 43.5 mph (70 km/h) and an angle of 25 degrees. Several simulations were conducted for each transition system. The impact location was incrementally varied along the transition to determine the location that maximizes the wheel contact with the end of the rigid bridge parapet. This point was defined to be the critical impact point (CIP) for the transition.

Results of the simulation study are shown in Table 2. Each transition system was evaluated at its critical impact location. The primary variable evaluated in the simulations was maximum dynamic rail

TABLE 2 Barrier VII Simulation Results for TL-2 Transition

Option	Deflection (in.)	Snagging[1] (in.)	CIP[2] (ft)
1	4.9	6.5	6.0
2	2.8	6.4	5.5
3	3.5	5.6	6.0

[1]Wheel overlap on end of bridge parapet
[2]Distance upstream from end of bridge parapet

deflection. As mentioned previously, most high-speed TL-3 transition systems that have been successfully crash tested in accordance with NCHRP Report 350 have had a maximum dynamic deflection less than 6 in.

On the basis of the predicted dynamic deflections, all three design options are considered to have a high probability of meeting NCHRP Report 350 evaluation criteria for TL-2 impact conditions. The maximum dynamic deflection for Option 1 was 4.9 in. As a result of the stronger posts, the estimated dynamic deflection for Option 3 was reduced to 3.5 in. The stiffest system was Option 2. The 18.75-in. post spacing adjacent to the parapet resulted in a deflection of only 2.8 in. The stiffness of the system also moved the CIP 6 in. closer to the end of the parapet.

The amount of wheel overlap on the end of the concrete parapet ranged from 5.6 in. to 6.5 in. Although this degree of contact is significant, it was believed to be within an acceptable range for a TL-2 impact. The severity of a TL-2 impact at 43.5 mph (70 km/h) is only 49% of that of a TL-3 impact at 62.2 mph (100 km/h).

Option 1 was selected for full-scale crash testing in consultation with Texas DOT personnel. Option 1 is the simplest and least expensive of the three alternatives evaluated and was believed to have a high probability of meeting TL-2 impact conditions.

FULL-SCALE CRASH TEST

A full-scale crash test was conducted to evaluate the safety performance of the selected TL-2 transition. The recommended test for evaluation of the impact performance of a transition section in NCHRP Report 350 is Test 21, which involves a 4,409-lb (2,000-kg) pickup truck striking the CIP of the transition section at an angle of 25 degrees. The test is intended to evaluate the strength of the transition section (i.e., its ability to contain and redirect the 4,409-lb vehicle), vehicle stability, and occupant risk (e.g., extent of occupant compartment deformation or intrusion).

The relevant NCHRP Report 350 test designation for TL-2 is Test 2-21. The nominal impact speed for this test is 43.5 mph (70 km/h). In accordance with the recommendations of NCHRP Report 350, the BARRIER VII simulation program was used to select the CIP. As indicated in Table 2, the CIP for Option 1 was determined to be 6 ft upstream from the end of the bridge parapet. All crash test, data analysis, and evaluation and reporting procedures followed under this project were generally in accordance with guidelines presented in NCHRP Report 350.

Test Article Description

Texas DOT permits the use of three different post types in its guardrail systems: W6 × 9 steel posts, 7-in. (178-mm) diameter round wood posts, and 6-in. by 8-in. (152-mm by 203-mm) rectangular wood posts. In consultation with Texas DOT and FHWA's Office of Safety, it was determined that the W6 × 9 steel post would constitute the most critical condition in regard to post snagging and would therefore be used in the full-scale crash test. By using the most critical post type, it was agreed that a successful result would also be applicable to the other post types.

Upon decision of the post type, a prototype transition installation was constructed to include an appropriate length of bridge parapet and approach guard fence and a single guardrail terminal. The bridge parapet constructed for the test was a 15-ft-long section of Texas Type T501 traffic rail. This rail is 32 in. high and has a Jersey safety shape profile. The toe of the safety shape incorporates a vertical taper over the last 3 ft of the parapet to help reduce wheel contact.

A 12.5-ft-long section of nested, 12-gauge W-beam rail was attached to the face of the T501 concrete parapet using a W-beam terminal connector. The nested W-beam rail was twisted into the sloped traffic face of the parapet, and the terminal connector was attached to the parapet using four 0.825-in.-diameter, A325 hex head through bolts.

The nested W-beam was mounted to support posts at a height of 27 in. to the top of the rail. The first post was located 27.5 in. upstream from the end of the bridge rail end, and the next three posts making up the transition were spaced 37.5 in. on center. Each of the four posts in the transition section were standard 6-ft-long, W6 × 9 steel guardrail posts embedded 44 in. in NCHRP Report 350 standard soil. The nested W-beam rail was offset from the posts using standard 6-in. by 8-in. by 14-in. routed wood blockouts.

A 25-ft length of standard strong-post W-beam guardrail was attached to the upstream end of the transition. It consisted of a single 12-gauge W-beam rail supported on W6 × 9 steel posts spaced 6 ft 3 in. apart. The W-beam rail was offset from the posts by using 6-in. by 8-in. by 14-in. routed wood blockouts. The installation was terminated using a 37.5-ft-long ET-PLUS guardrail terminal. The completed test installation is shown in Figure 1.

Test Vehicle

A 1998 Chevrolet Cheyenne was used for the crash test. Test inertia weight of the vehicle was 4,515 lb (2,050 kg), and its gross static weight was 4,515 lb (2,050 kg). The height to the lower edge of the vehicle bumper was 14.9 in. (378 mm), and the height to the upper edge of the bumper was 23.4 in. (595 mm). The vehicle was directed into the installation by using a cable reverse tow and guidance system and was released to be freewheeling and unrestrained just before impact.

Test Description

The vehicle, traveling at a speed of 42.7 mph (68.8 km/h), struck the transition 70.5 in. (1,790 mm) upstream from the end of the concrete parapet at an impact angle of 26.8 degrees. The vehicle began

FIGURE 1 Transition system before crash test.

to redirect at 0.037 s, and the left front tire contacted the end of the concrete parapet at 0.067 s. At 0.121 s, the left front tire deflated, and at 0.233 s the vehicle lost contact with the rail element. At 0.287 s, the vehicle was traveling parallel with the transition at 29.8 mph (47.9 km/h).

The rear of the vehicle contacted the transition at 0.365 s and then contacted the end of the parapet at 0.392 s. At 0.557 s, the vehicle lost contact with the transition while traveling at 27.4 mph (44.1 km/h) and an exit angle of 15.7 degrees. Brakes on the vehicle were applied 1.9 s after impact, and the vehicle subsequently came to rest in an upright manner 90 ft (27.4 m) downstream from the impact with the rear of the vehicle aligned with the traffic face of the rail.

Damage to Test Installation

Damage sustained by the transition system is shown in Figure 2. The lower corrugation of the W-beam was gouged and flattened in the immediate vicinity of the impact. Tire marks were found on the end of the parapet extending 3.5 in. (90 mm) from the traffic face. No tire marks were observed on the posts. The maximum dynamic deflection of the transition during the test was 2.6 in. (65 mm). The maximum residual deformation was 1.6 in. (42 mm) near Post 13. The working width was 17.6 in. (448 mm), and the total length of contact of the vehicle with the transition was 106 in. (2,704 mm).

(a)

(b)

FIGURE 2 Damage to transition system after crash test: two views.

FIGURE 3 Damage to vehicle after crash test.

Vehicle Damage

The vehicle damage is shown in Figure 3. Structural damage was imparted to the left lower A-arm, left outer tie-rod end, left frame rail. Also damaged were the front bumper, grill, radiator, fan, left front quarter panel, left door, left rear bed, and rear bumper, and the right rear wheel rim was deformed. The windshield sustained stress cracks induced by deformation of the vehicle. The left front tire was cut and the wheel rim was deformed. Maximum exterior crush to the vehicle was 17.7 in. (450 mm) in the frontal plane at the left front corner near bumper height. In the occupant compartment, the floor pan was deformed and separated slightly at the seam with the left toe pan. Maximum occupant compartment deformation was only 0.4 in. (11 mm) in the left floor pan area.

Occupant Risk Factors

Data from the accelerometer located at the vehicle center of gravity were digitized for evaluation of occupant risk criteria. Only the occupant impact velocity and ridedown accelerations in the longitudinal axis are required from these data for evaluation of Criterion L of NCHRP Report 350; however, both longitudinal and lateral data are reported for information purposes. In the longitudinal direction, the occupant impact velocity was 18.7 ft/s (5.7 m/s) at 0.128 s, the highest 0.010-s occupant ridedown acceleration was −5.5 *g* from 0.128 to 0.138 s, and the maximum 0.050-s average acceleration was −7.4 *g* between 0.077 s and 0.127 s. In the lateral direction, the occupant impact velocity was 20.7 ft/s (6.3 m/s) at 0.128 s, the highest 0.010-s occupant ridedown acceleration was 3.8 *g* from 0.415 to 0.425 s, and the maximum 0.050-s average was 8.0 *g* between 0.069 and 0.119 s. These data and other pertinent information from the test are summarized in Figure 4.

Assessment of Test Results

An assessment of the test based on the applicable NCHRP Report 350 safety evaluation criteria is provided in Table 3. As shown, the transition was judged to meet all required impact performance criteria for a TL-2 impact.

0.000 s

(a)

0.243 s

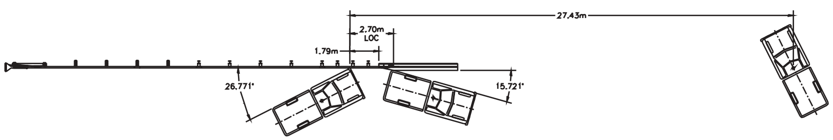
(b)

0.730 s

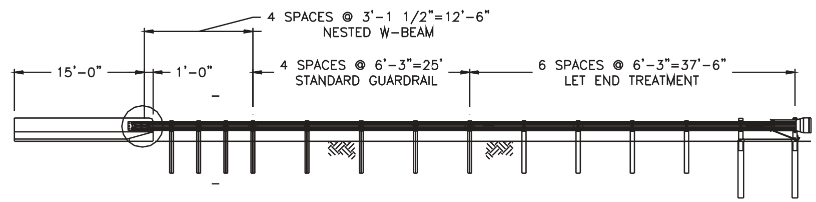
(c)

2.432 s

(d)



(e)



(f)

General Information		**Impact Conditions**		**Test Article Deflections** (in.)	
Test Agency	Texas Transportation Institute	Speed (mi/h)	42.7 (68.8 km/h)	Dynamic	2.6 (65 mm)
Test No.	445643-2	Angle (deg)	26.8	Permanent	1.6 (42 mm)
Date	02/12/03	**Exit Conditions**		Working Width	17.6 (448 mm)
Test Article		Speed (mi/h)	27.4 (44.1 km/h)	**Vehicle Damage**	
Type	Transition	Angle (deg)	15.7	Exterior	
Name	TxDOT TL-2 Transition	**Occupant Risk Values**		VDS	11FL3
Installation Length (ft)	12.5 (3.8 m)	Impact Velocity (ft/s)		CDC	11FLEW3
Material or Key Elements	T501 Concrete Parapet With Nested W-Beam Transition	x-direction	18.7 (5.7 m/s)	Maximum Exterior	
		y-direction	20.7 (6.3 m/s)	Vehicle Crush (in.)	17.7 (450 mm)
Soil Type and Condition	Standard Soil, Dry	THIV (mi/h)	17.9 (28.9 km/h)	Interior	
Test Vehicle		Ridedown Accelerations (*g*)		OCDI	LF0001000
Type	Production	x-direction	-5.5	Max. Occ. Compart.	
Designation	2000P	y-direction	3.8	Deformation (in.)	0.4 (11 mm)
Model	1998 Chevrolet Cheyenne 2500 P/U	PHD (*g*=s)	9.2	**Post-Impact Behavior**	
Mass (lb)		ASI	1.07	(during 1.0 s after impact)	
Curb	4862 (2208 kg)	Max. 0.050-s Average (*g*)		Max. Yaw Angle (deg)	44.0
Test Inertial	4515 (2050 kg)	x-direction	-7.4	Max. Pitch Angle (deg)	-9.8
Dummy	N/A	y-direction	8.0	Max. Roll Angle (deg)	-13.4
Gross Static	4515 (2050 kg)	z-direction	-3.0		

(g)

FIGURE 4 Summary of test results (THIV = theoretical head impact velocity, PHD = post-impact head deceleration, ASI = acceleration severity index, VDS = vehicle damage scale, CDC = collision damage classification, OCDI = occupant compartment deformation index, TxDOT = Texas Department of Transportation).

TABLE 3 Performance Evaluation of TL-2 Transition

NCHRP Report 350 Test 2-21 Evaluation Criteria	Test Results	Assessment
Structural adequacy		
A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	The transition contained and redirected the 2000P pickup truck. The 2000P pickup truck did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 2.6 inches (65 mm).	Pass
Occupant risk		
D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 0.4 inch (11 mm) in the left floorpan area.	Pass
F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.	The vehicle remained upright during and after the collision event.	Pass
Vehicle trajectory		
K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	The vehicle came to rest upright 90 ft (27 m) downstream of impact with the rear of the vehicle aligned with the traffic face of the rail.	Pass*
L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 *g*.	Longitudinal occupant impact velocity was 18.7 ft/s (5.7 m/s) and longitudinal ridedown acceleration was –5.5 *g*.	Pass
M. The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.	Exit angle at loss of contact was 15.7 degrees, which was 59 percent of the impact angle.	Pass*

*Criteria K and M preferable, not required.

SUMMARY AND CONCLUSIONS

Most states, including Texas, have typically applied the same transition standard to all roadways regardless of speed or traffic volume. However, to meet NCHRP Report 350 impact performance requirements for TL-3 impact conditions, transition systems had to be raised in height and stiffened considerably and a rubrail or curb included. As a result, these new transition designs represent a significant increase in installation cost and complexity over many previous designs that were approved under NCHRP Report 230. Thus, it becomes cost-prohibitive to require use of this system on all roadways.

A new TL-2 nested W-beam transition was successfully developed. As summarized in Table 3, the new TL-2 nested W-beam transition met all the requirements of NCHRP Report 350. It is considered suitable for use on roadways that have traffic conditions appropriate for the use of TL-2 safety hardware. The transition is entirely composed of standard hardware components and is significantly less expensive and complex to install than the high-speed, TL-3 transition systems being used by state departments of transportation. Damage to the system after the design crash test was relatively minor and required only minimal repair, indicating that the transition should be easy to maintain. Implementation of the system should result in a significant savings in both material and installation cost compared with TL-3 designs. The 27-in. mounting height greatly simplifies the ability to connect the transition to some existing bridge rails. Elimination of the curb detail helps save money and eliminates the need for modifying bridge end drainage in retrofit or upgrade situations.

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