Development of Kansas Guardrail to Bridgerail Transition Designs Using BARRIER VII

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BARRIER VII computer code was used to evaluate the dynamic performance of five Kansas guardrail-to-bridgerail transition designs. The simulation results were compared with those of two FHWA-approved transition designs. The test vehicle model was a 4,500-lbs, 1977 Plymouth impacting the barriers at 60 mph with an approach angle of 25°. The vehicle-crushing properties and guardrail-post stiffness had been validated using full-scale vehicle crash test data before the simulations were conducted. A methodology for wheel-snagging prediction was also proposed and validated against available test data. It was shown that reliable simulation results could be obtained if the input parameters for simulation were assessed accurately.

The safety performance of a traffic barrier design is often examined by conducting full-scale vehicle crash tests. The results are evaluated against certain criteria in terms of barrier deformations, occupant risk, and vehicle trajectory as described in *NCHRP Report 230* (*1*). The first of several crash tests on a transition design will cost approximately $20,000, while each succeeding test will cost around $10,000. On the average, three crash tests are required to confirm a satisfactory guardrail transition design. Since these crash tests are costly and are affected by many circumstantial factors, numerical simulation becomes an attractive alternative to the designers. It will be shown in this paper that it is possible to evaluate the safety performance of a guardrail transition design using an accurately calibrated computer simulation model without conducting costly full-scale vehicle crash tests.

In *Technical Advisory T5040.26*, the Federal Highway Administration (FHWA) (*2*) approved five W-Beam guardrail transition designs and two Thrie Beam guardrail transition designs for field installation. These seven designs successfully passed the recommended *NCHRP Report 230* criteria under the impact conditions of a 4,500-lb automobile at a speed of 60 mph and 25° impact angle. Highway and bridge engineers in the Kansas Department of Transportation (KDOT) favor the Thrie Beam transition designs over the W-Beam transition designs because they eliminate the use of W-Beam rubrail, which can trap drifting snow. However, neither of the two Thrie Beam designs approved by FHWA are acceptable to KDOT because one of the designs specified the use of three different sizes of posts, which creates an inventory problem, and the other design would require costly bridgerail end-wall modifications. Consequently, KDOT proposed five new guardrail transition designs for safety performance evaluation.

The computer program BARRIER VII developed by Powell (*3*, *4*) was employed in this study for comparative evaluation of guardrail-to-bridgerail transition designs. The BARRIER VII computer simulation model was first validated with full-scale vehicle crash test data, and then used to evaluate the safety performance of the Kansas transition designs in comparison to selected FHWA-approved guardrail transition designs. In addition, a methodology for wheel snagging prediction was proposed and validated against available crash test data. This method was then applied to assess the amount of wheel snagging on the ends of bridgerails in the comparative studies.

CALIBRATION OF BARRIER VII MODEL

BARRIER VII simulates the dynamic interaction behavior of an automobile impacting a deformable protective barrier composed of beams, posts, and other types of structural members. The automobile is idealized as a rigid body in the horizontal plane surrounded by cushions of discrete springs.

The BARRIER VII model was calibrated using data from full-scale vehicle crash tests on roadside traffic barriers. A discussion of the critical factors involved in the calibration process is presented herein.

Vehicle Crushing Stiffness

The model vehicle selected for crash test simulations was a 1977 Plymouth Fury weighing approximately 4,500-lb. The vehicle was representative of the full-scale crash test vehicles used by Post (*5*) and Bronstad et al. (*6*) in evaluating the safety performance of guardrail-bridgerail transition designs. The vehicle crushing stiffness was idealized by springs located at 19 contact points around the vehicle, two of which defined the locations of the wheel hubs that could contact the barrier. The idealized automobile is shown in Figure 1.

The data obtained from crash test number 3451-36 conducted by Buth et al. (*7*) on an instrumented rigid wall was used to determine the force-deflection relationship of these boundary springs. The parameters were estimated from visual observation and measurements of the vehicle structure and

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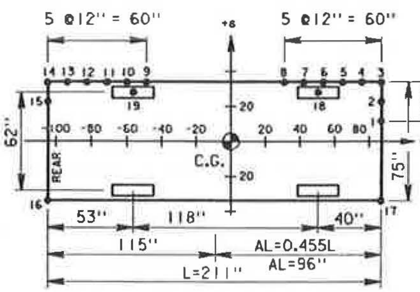
fine tuned for each contact point until simulation results compared favorably with the crash test data, as shown in Table 1.

Soil Stiffness

When an automobile impacts a guardrail, transverse and longitudinal forces are transmitted to the ground through posts. Since resistance is provided by the soil foundation, the stiffness of the posts is controlled by the soil properties.



AUTOMOBILE 1977 PLYMOUTH FURY

CONTACT POINT NO.	COORDINATES r (in.)	s (in.)
1	96.0	13.5
2	96.0	25.5
3	96.0	37.5
4	84.0	37.5
5	72.0	37.5
6	55.0	37.5
7	48.0	37.5
8	36.0	37.5
9	-55.0	37.5
10	-67.0	37.5
11	-79.0	37.5
12	-91.0	37.5
13	-103.0	37.5
14	-115.0	37.5
15	-115.0	25.5
16	-115.0	-37.5
17	96.0	-37.5
18	56.0	33.0
19	-62.0	33.0

SHEET METAL (points 1–17)
WHEEL HUBS (points 18–19)

FIGURE 1 Idealization of simulation vehicle.

TABLE 1 VEHICLE CRUSHING CALIBRATION

Test Vehicle	:	1975 Plymouth
Vehicle Weight	:	4,740 lb.
Impact Speed	:	59.8 mph
Impact Angle	:	24.0 deg.
Barrier Type	:	Concrete Wall (Instrumented)

Item	Crash Test	Simulation
Exit Speed (mph)	42.4	44.6
Exit Angle (deg)	14.0	14.6
Max 50-ms Averages:		
Impact Force (Kips)	78.3	79.6
Vehicle Lateral Acceleration (g)	15.4	15.6
Vehicle Longitudinal Acceleration (g)	9.1	11.7

Dynamic impact tests were conducted by Jeyapalan et al. (*8*) to determine the relationship between laterally applied loads and the rotational displacements of 6-in wide guardrail posts in dry soils. For all practical purposes, the load-displacement relationship can be idealized as elastic-plastic with complete failure occurring at a post deflection of 20 in. Ataullah showed that the dynamic load on a post needed to cause yielding in the soil was proportional to the bearing width of the post against the soil, assuming a parabolic soil-pressure distribution (*9*).

The full-scale vehicle crash test conducted by Post (*5*) on a single Thrie Beam bridgerail design was used to calibrate the soil-post stiffness. The simulation results are compared with field data in Table 2. The soil stiffness for various sizes of posts under lateral and longitudinal loads is shown in Figure 2.

TABLE 2 SOIL STIFFNESS CALIBRATION

Test Vehicle	:	1977 Plymouth Fury
Vehicle Weight	:	4,400 lb.
Impact Speed	:	61 mph
Impact Angle	:	24 deg.
Barrier Type	:	Single Thrie Beam Transition
Impact Point	:	Between Posts No. 2 & 3
Soil Type	:	Dry Silty Clay (CL)

Item	Crash Test	Simulation
Exit Speed (mph)	39	36
Exit Angle (deg)	11	10
Max Dynamic Barrier Deflection (in.)	14	12

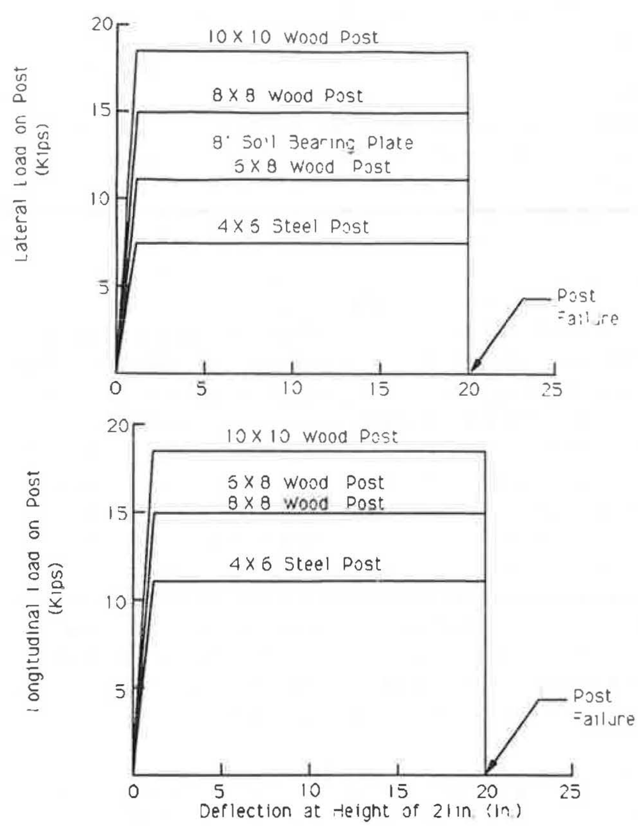


FIGURE 2 Idealized soil stiffness for various size posts in dry silty clay soil.

Vehicle Snagging Potential

In W-Beam guardrail transition designs without a rubrail and Thrie Beam guardrail transition designs, snagging of the front wheel hub and rim can occur on the end of concrete bridgerail walls.

Bligh et al. (*10*) determined and verified with full-scale vehicle crash tests that BARRIER VII can be used to predict vehicle snagging for W-Beam transitions without a rubrail by plotting the path of the undeformed wheel hub as shown in Figure 3a. This finding indicates that the wheel hub and rim are able to slide under the W-Beam guardrail member easily.

Insight into vehicle wheel hub and rim snagging on the end of a concrete bridgerail wall with a single Thrie Beam guardrail transition design was provided by Post (*5*) after conducting full-scale vehicle crash tests for Nebraska. The severity of snagging shown in Figure 4 was reported as moderate. Snagging occurred as a result of localized plastic deformations of the lower part of the Thrie Beam in the vicinity of the wheel hub and rim, thereby allowing the deformed section to wrap 3 in around the end of the tapered bridgerail wall.

A sketch illustrating the concept of vehicle snagging on the end wall of a bridgerail with a Thrie Beam transition is shown in Figure 3b. After local plastic deformations in the Thrie Beam begin, the path of the deformed wheel hub is assumed to remain parallel to the path of the undeformed wheel hub due to a constant load on the wheel hub.

The BARRIER VII simulation of the paths of the undeformed and deformed wheel hubs is shown in Figure 5. The local plastic deformations in the Thrie Beam began about 8 in beyond post no. 1. The predicted 3½ in of snagging on the tapered end wall compares well with the 3 in of snagging measured in the crash test.

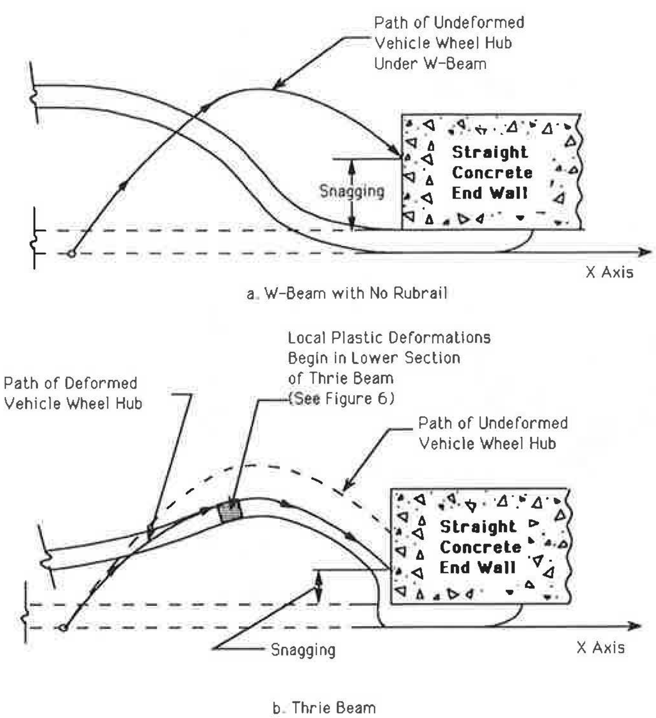


FIGURE 3 Vehicle snagging methodology (not to scale).

VALIDATION OF BARRIER VII MODEL WITH SwRI CRASH TESTS

The BARRIER VII model was validated by the use of data of full-scale vehicle crash tests on the guardrail transition designs conducted by Bronstad et al. (*6*).

Among the 11 transition designs crash tested, three designs with bridgerail end walls similar to end walls in Kansas were selected for the validation study. These designs were

1. Test T-5: Double W-Beam with wood posts, W-Beam rubrail, and straight concrete bridgerail end wall;
2. Test T-1: Single Thrie Beam with wood posts and straight concrete bridgerail end wall; and
3. Test T-7: Single Thrie Beam with steel posts and straight concrete bridgerail end wall.

The results from the SwRI crash tests and the BARRIER VII simulations are compared in Tables 3 through 5. The vehicle exit angle in Test T-1 (Table 4) was lower than predicted by BARRIER VII, probably due to the slight rotation of the damaged end wall in the crash test.

COMPARATIVE STUDIES

FHWA Guardrail Transition Designs (Base Controls)

Of the seven guardrail transition designs approved by FHWA in *Technical Advisory T5040.26*, two designs were selected as base control designs for the comparative studies using the BARRIER VII model simulation. The two designs had bridgerail end walls that were most representative of the straight vertical end walls in Kansas. The designs selected were as follows:

1. Double W-Beam with rubrail, steel posts, and straight concrete bridgerail end wall, with design details shown in Figure 6;
2. Double W-Beam with rubrail, wood posts and straight concrete bridgerail end wall, with design details shown in Figure 7.

Kansas Guardrail Transition Designs

The five Kansas designs on which simulations were conducted were as follows:

1. Double Thrie Beam, steel posts and straight concrete bridgerail end wall.
2. Double Thrie Beam, wood posts and straight concrete bridgerail end wall.
3. Single Thrie Beam, steel posts with base plates, and straight concrete bridgerail end wall.
4. Double W-Beam, steel posts, rubrail, and straight concrete bridgerail end wall.
5. Combination Double/Single Thrie Beam, steel posts, and tapered concrete bridgerail end wall.

The details of these designs are shown in Figures 8 through 12, respectively.

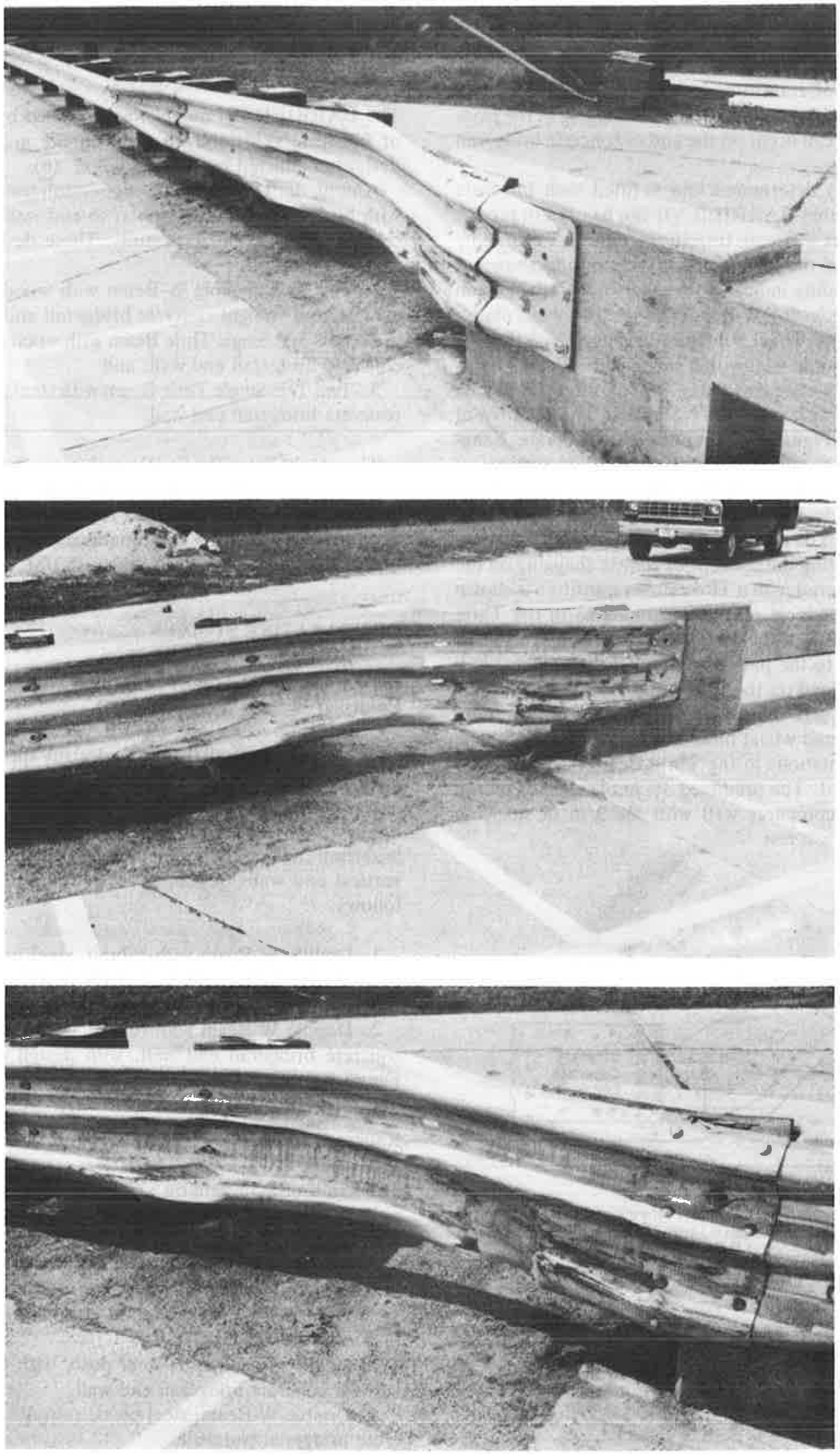


FIGURE 4 Vehicle snagging on Nebraska single Thrie Beam transition design (test no. 3).

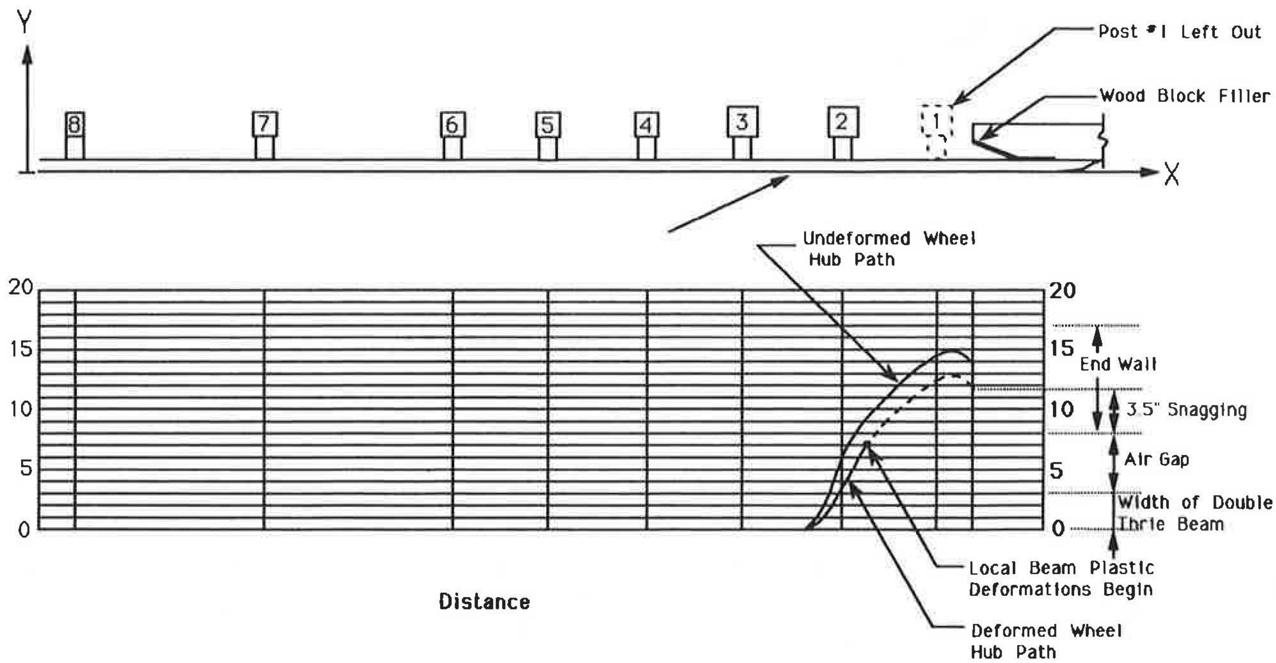


FIGURE 5 Vehicle snagging prediction based on BARRIER VII simulation.

TABLE 3 BARRIER VII VALIDATION: SwRI CRASH TEST T-5

Test Vehicle	:	1978 Plymouth
Vehicle Weight	:	4,700 lb.
Impact Speed	:	58.9 mph
Impact Angle	:	25.8 deg.
Transition Type	:	Double W-Beam with Wood Posts
Impact Point	:	Post No. 5
Soil Type	:	Dry

Item	Crash Test	Simulation
Exit Speed (mph)	40.5	36.0
Exit Angle (deg)	8.0	6.7
Max Dynamic Barrier Deflection (in.)	10.9	11.1
Max 50-ms Averages:		
Vehicle Lateral Acceleration (g)	11.9	13.6
Vehicle Longitudinal Acceleration (g)	11.1	16.4

TABLE 4 BARRIER VII VALIDATION: SwRI CRASH TEST T-1

Test Vehicle	:	1978 Plymouth
Vehicle Weight	:	4,658 lb.
Impact Speed	:	61.5 mph
Impact Angle	:	25.2 deg.
Transition Type	:	Single Thrie Beam with Wood Posts
Impact Point	:	Between Posts No.4 & 5
Soil Type	:	Dry

Item	Crash Test	Simulation
Exit Speed (mph)	43.8	38.1
Exit Angle (deg)	11.2	17.0
Max Dynamic Barrier Deflection (in.)	9.4	9.6

TABLE 5 BARRIER VII VALIDATION: SwRI CRASH TEST T-7

Test Vehicle	:	1978 Dodge
Vehicle Weight	:	4,675 lb.
Impact Speed	:	58.9 mph
Impact Angle	:	25.1 deg.
Transition Type	:	Single Thrie Beam with Steel Posts
Impact Point	:	Between Posts No.8 & 9
Soil Type	:	Dry

Item	Crash Test	Simulation
Exit Speed (mph)	40.2	41.1
Exit Angle (deg)	5.7	5.0
Max Dynamic Barrier Deflection (in.)	13.9	16.9

Comparison of FHWA and Kansas Transition Designs

In all of the FHWA and Kansas guardrail transition designs simulated in the comparative study, the post spacings were approximately identical. The first four posts from the end of the bridgerail were spaced 1 ft, 6¾ in on centers; the next four posts were spaced 3 ft, 1½ in on centers; and the remaining posts were spaced 6 ft, 3 in on centers.

The vehicle impact conditions used in the comparative simulation study were in accordance with the criteria in *NCHRP Report 230*. The impact conditions were 4,500-lb vehicle weight, 60 mph impact speed, and 25° impact angle.

The potential for vehicle wheel snagging on the end of a bridgerail of the two FHWA-approved designs and the five Kansas transition designs was investigated in detail using BARRIER VII simulation. The two base control designs were impacted at posts 2, 3, 4, and 5. As expected, wheel snagging

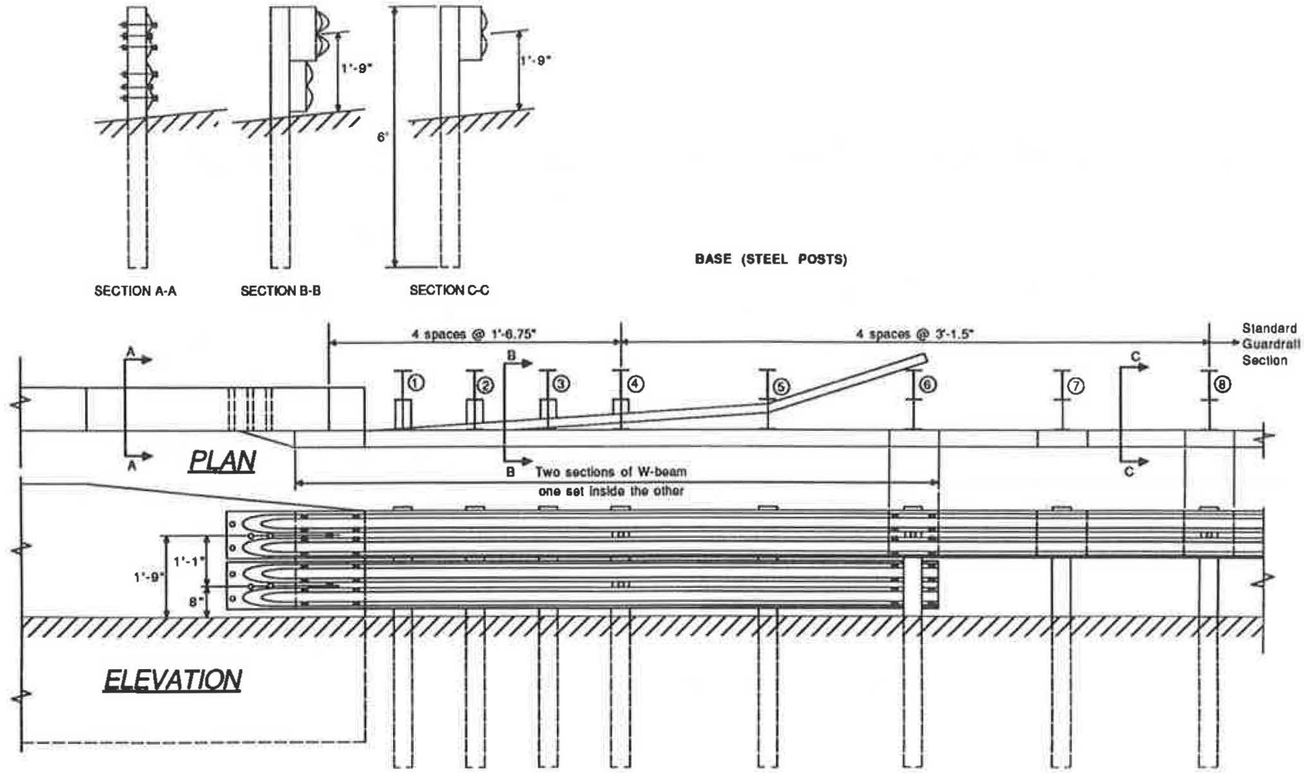


FIGURE 6 FHWA double W-Beam transition: steel posts and rubrail (base control).

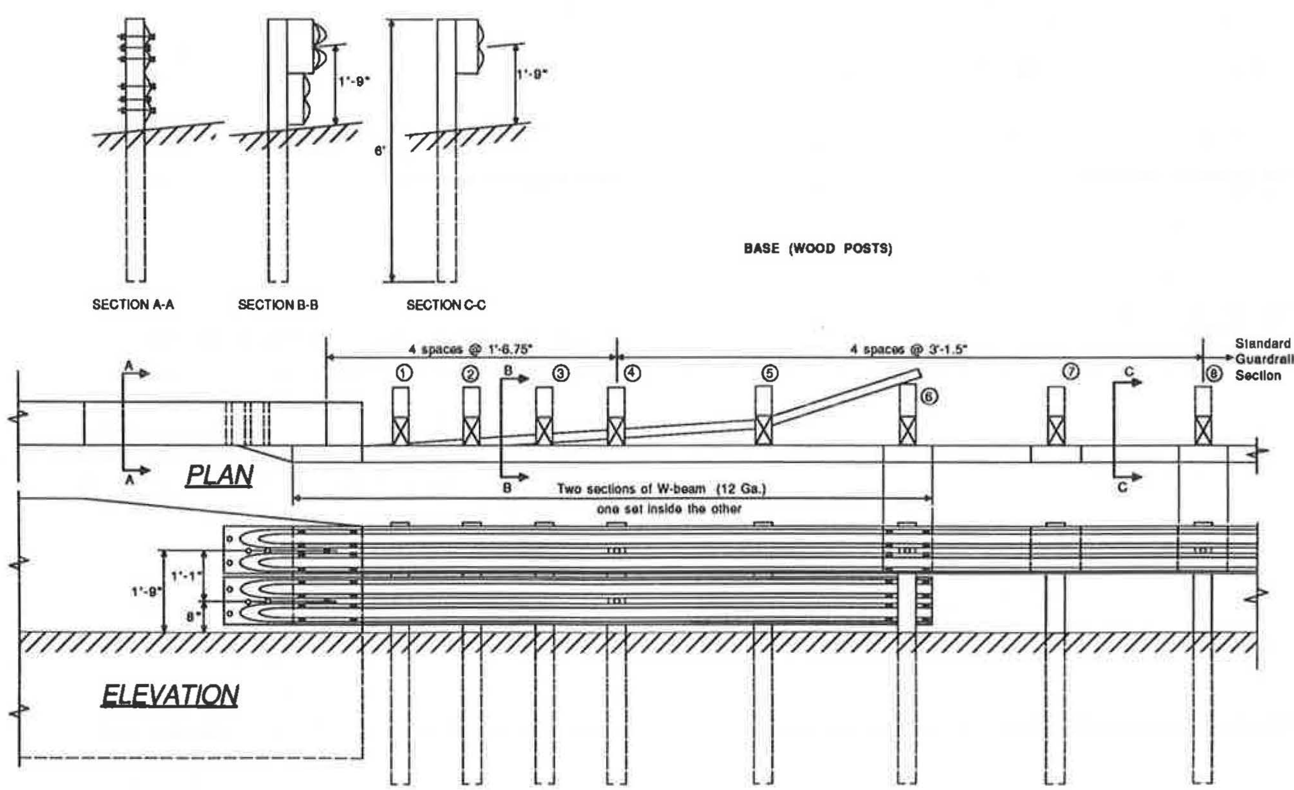


FIGURE 7 FHWA double W-Beam transition: wood posts and rubrail (base control).

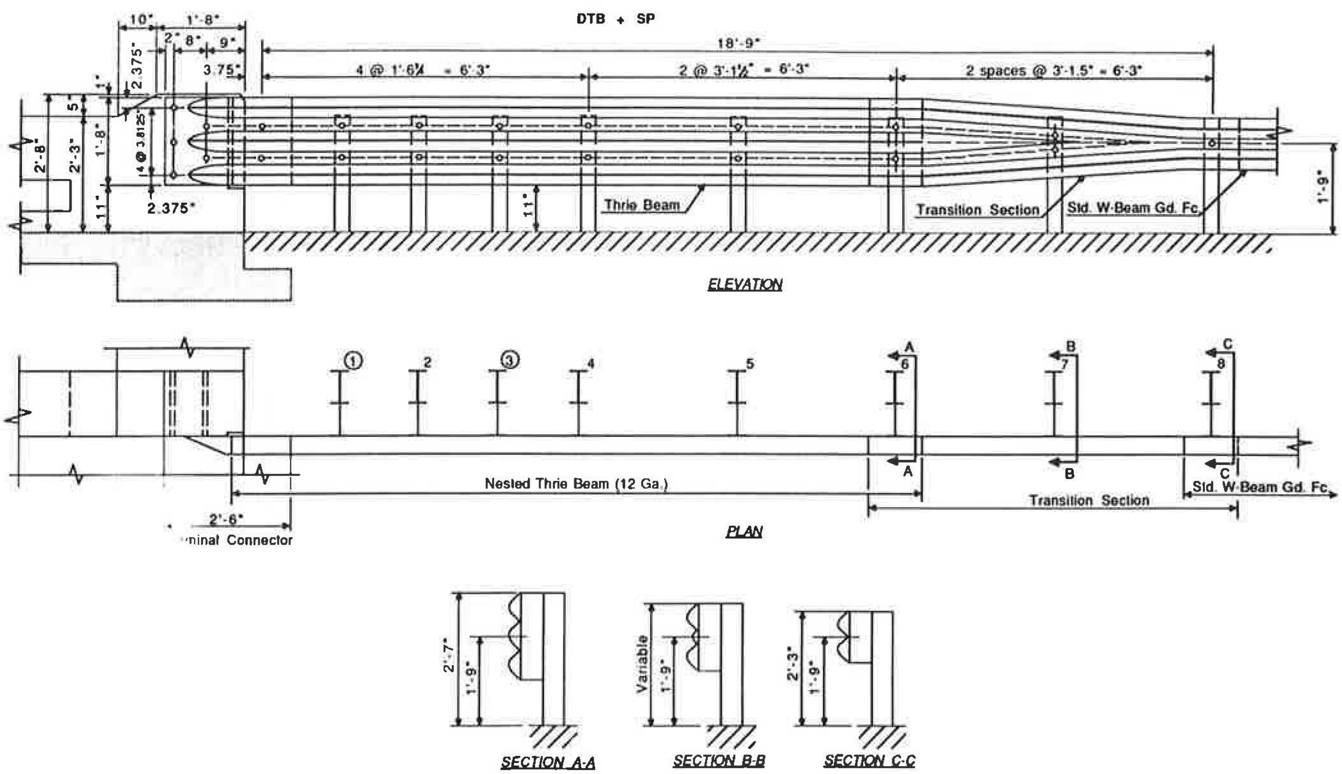


FIGURE 8 Kansas double Thrie Beam: steel posts and straight end wall.

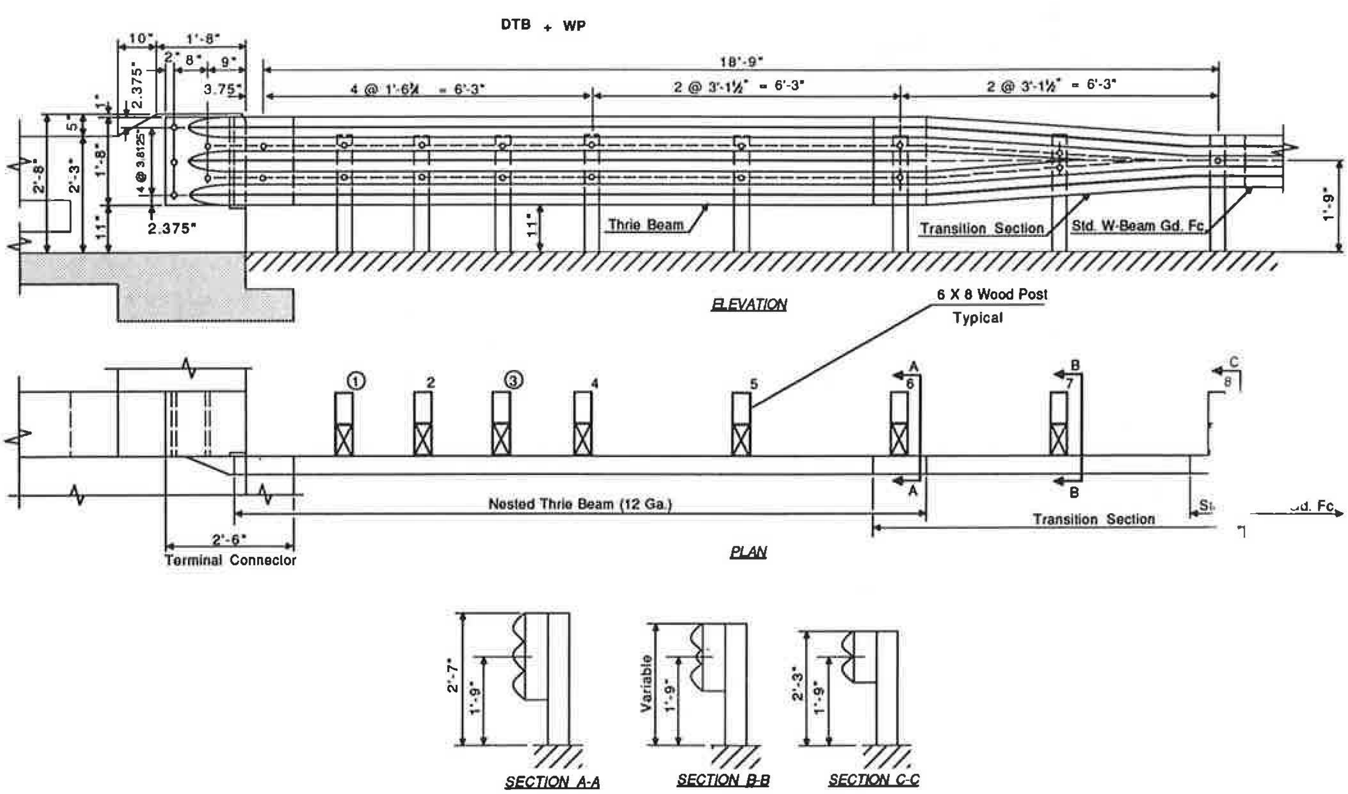


FIGURE 9 Kansas double Thrie Beam: wood posts and straight end wall.

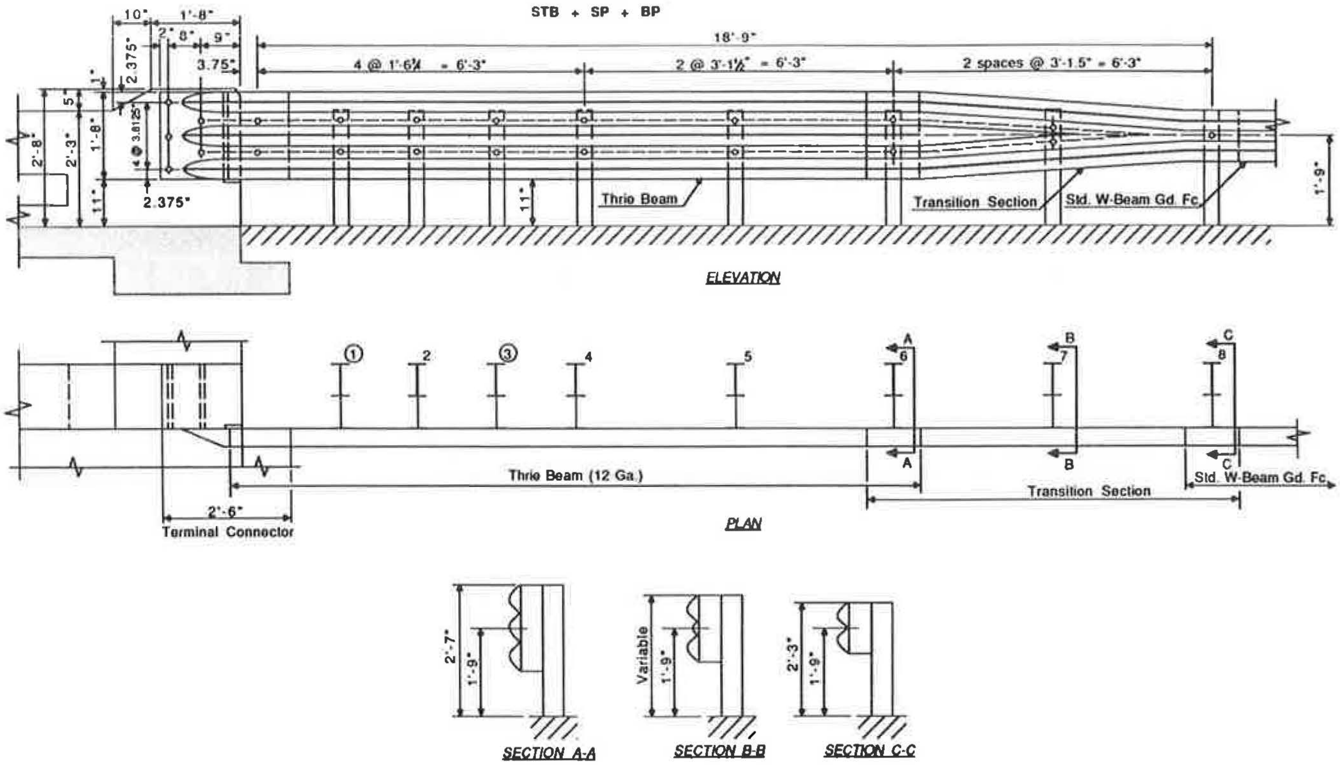


FIGURE 10 Kansas single Thrie Beam: steel posts with base plates and straight end wall.

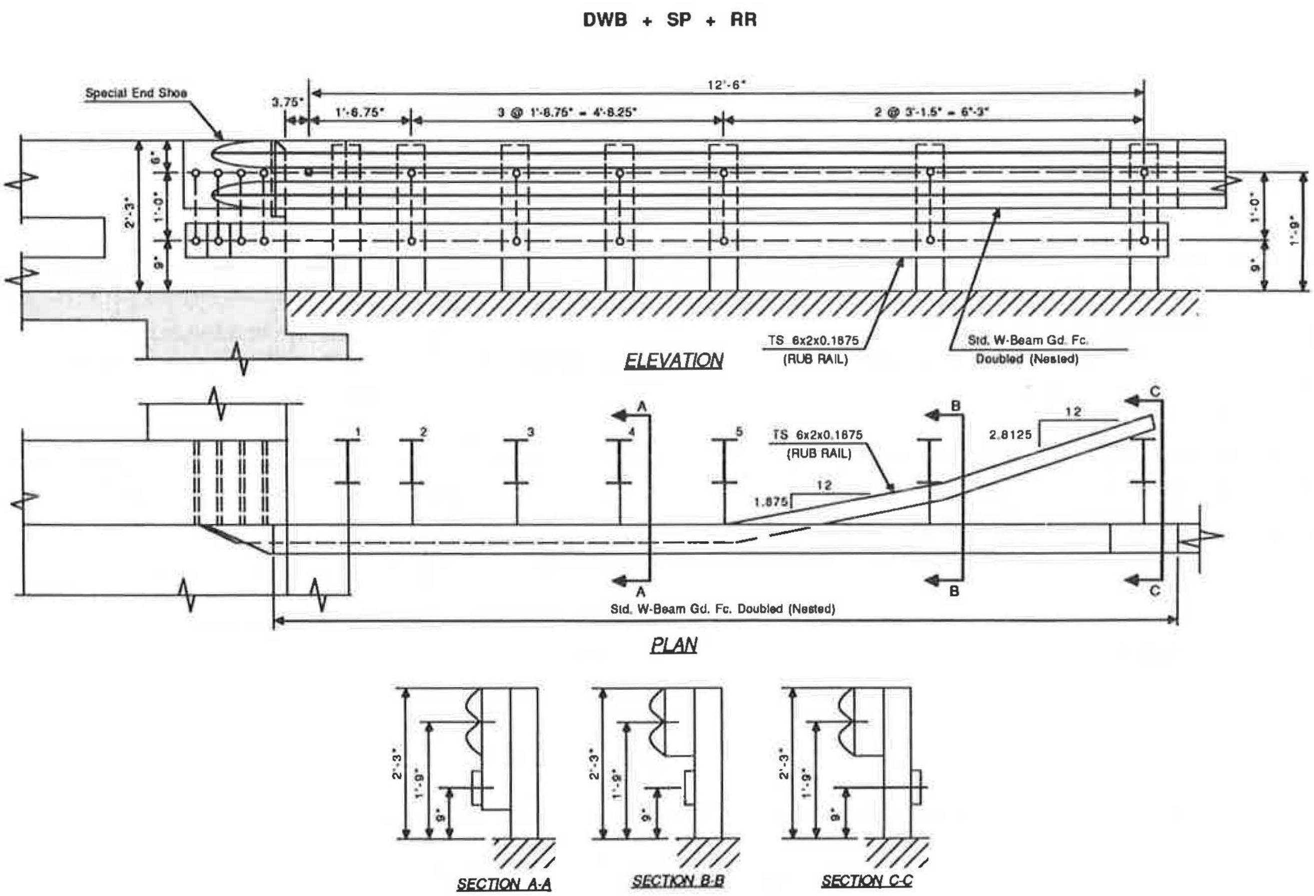


FIGURE 11 Kansas double W-Beam: steel posts and rubrail with straight end wall.

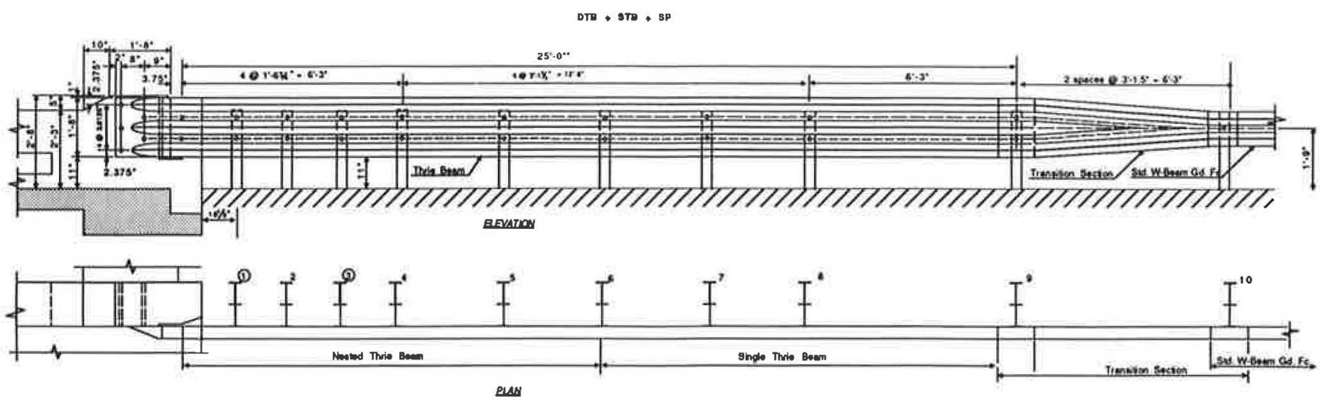


FIGURE 12 Kansas double/single Thrie Beam: steel posts and tapered end wall.

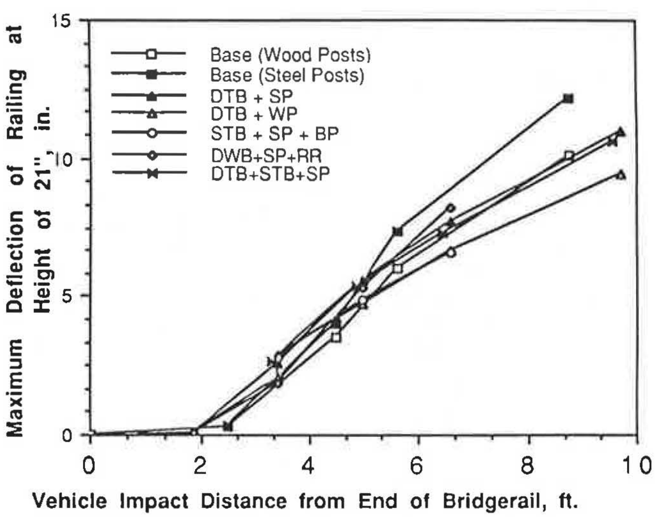


FIGURE 13 Comparison of FHWA and Kansas transition deflections.

did not occur. Kansas design no. 1 was impacted at posts 1, 2, 3, 4, and 5, and wheel snagging was predicted to occur in the cases of posts 2 and 3. Kansas design no. 2 was impacted at posts 1, 2, 3, 4, and 5, and wheel snagging was predicted to occur in the cases of posts 2 and 3. Kansas design no. 3 was impacted at posts 2, 3, and 4, and wheel snagging was predicted to occur in the cases of posts 2 and 3. Kansas design no. 4 was impacted at posts 1, 2, 3, 4, and 5, and no wheel snagging occurred. Kansas design no. 5 was impacted at posts 2, 3, 4, and 5, and no wheel snagging occurred. The amount of wheel snagging occurring in those cases was in the range of 1 to 3 in.

Out of the four Kansas Thrie Beam transition designs simulated, only design No. 5 showed the promise of no vehicle wheel snagging.

The comparison of the vehicle point of impact from the bridgerail end wall versus maximum guardrail transition deflection and vehicle exit speed for the FHWA base control designs and the KDOT designs are shown in Figures 13 and 14, respectively.

Referring to Figure 13, the following comparisons were reached in regard to the maximum guardrail transition deflections for vehicle impacts of 4 ft and beyond the end of the bridgerail wall.

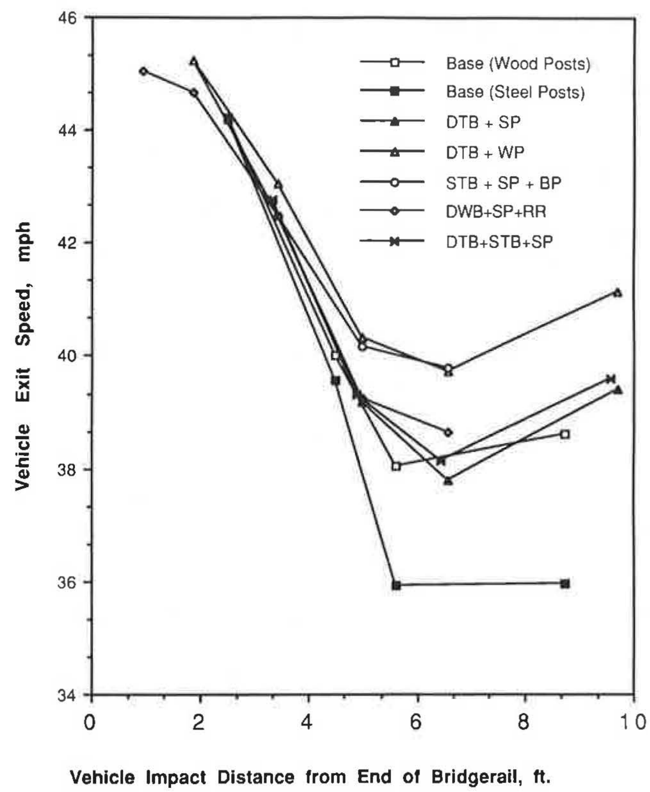


FIGURE 14 Comparison of FHWA and Kansas vehicle exit speeds.

1. All five of the Kansas designs were stronger than the FHWA design with steel posts.
2. The Kansas double Thrie Beam design with wood posts and the Kansas single Thrie Beam design with steel posts and base plates were both stronger than the FHWA design with wood posts.
3. The Kansas double Thrie Beam design with steel posts, the Kansas double/single Thrie Beam design with steel posts and tapered end wall, and the FHWA design with wood posts were all equal in strength.

4. The Kansas double W-beam design with steel posts and rubrail had a strength between the FHWA designs with steel posts and wood posts.

Referring to Figure 14, the following comparisons were reached about the vehicle exit speed in which no vehicle wheel snagging was predicted to have occurred.

The Kansas double/single Thrie Beam transition design with steel posts and tapered bridgerail end wall, and the Kansas Double W-Beam transition design with steel posts, rubrail, and straight bridgerail end wall had higher vehicle exit speeds than the FHWA transition designs with steel posts and wood posts.

The higher the vehicle exit speed, the lower is the change in vehicle speed, and consequently the risk of occupant injury would be lower.

CONCLUSIONS AND RECOMMENDATIONS

Satisfactory Transition Designs

The comparative BARRIER VII simulation study showed that two of the five Kansas guardrail transition designs would provide equal or better performance than the FHWA approved double W-Beam guardrail transition design with steel posts, W-Beam rubrail, and straight bridgerail end wall. The two Kansas designs were

1. Kansas double/single Thrie Beam design with steel posts and tapered bridgerail end wall; and
2. Kansas double W-Beam design with steel posts, channel rubrail, and straight bridgerail end wall.

In this study, it was predicted that vehicle wheel snagging would not occur on FHWA and Kansas double W-Beam transition designs with a rubrail. Also, it was shown that vehicle wheel snagging would not occur on the Kansas double Thrie Beam transition design with a tapered bridgerail end wall. Since vehicle wheel snagging will not occur, it is recommended that the two Kansas transitions defined above be approved by the FHWA for field installation without conducting full-scale vehicle crash tests.

Promising Transition Design

In this study, it was shown that vehicle wheel snagging would occur on the Kansas single Thrie Beam transition design with steel posts, 8-in wide soil bearing plates and straight bridgerail end wall. However, this design promises to be a satisfactory design if the single Thrie Beam member is replaced by a double Thrie Beam member.

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