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Termination and Transition of Temporary Concrete Barrier

by

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ABSTRACT

For the research studies described herein two new technologies were developed for temporary concrete barriers (TCBs). The first project developed an economical method for terminating and anchoring the upstream end of TCB systems. The second developed a TCB approach transition for attachment to permanent concrete median barriers. Both designs were configured for use with the Kansas F-shape TCB that is currently used by several states participating in the Midwest Pooled Fund Program. These efforts were performed in accordance with the Test Level 3 (TL-3) guidelines found in the Manual for Assessing Safety Hardware (MASH), First Edition.

The termination and anchorage system allowed for a significant reduction in the number of barrier segments required upstream from the length of need and for use in anchoring a free-standing TCB system. The anchorage system was configured to effectively constrain the end of the TCB system for impacts as far upstream as the first anchored barrier segment. Full-scale crash testing demonstrated that the impacting vehicle was safely and smoothly redirected, and the test was judged acceptable according to the TL-3 safety criteria set forth in MASH.

The approach transition was developed for attaching free-standing TCBs to permanent concrete median barriers. Evaluation of the approach transition required testing at two Critical Impact Point (CIP) locations. Full-scale crash testing demonstrated that the impacting vehicle was safely and smoothly redirected, and the testing of the approach transition was judged acceptable according to the TL-3 safety criteria set forth in MASH.

Keywords: Roadside Safety, Temporary Concrete Barrier, F-shape, Termination, Anchorage, TL-3, Crash Testing, Compliance Testing

INTRODUCTION

Temporary concrete barrier (TCB) is one of the most common types of roadside hardware found on our nation's highways. TCB systems redirect errant vehicles through a combination of various forces and mechanisms, including inertial resistance developed by the acceleration of several barrier segments, lateral friction loads, and the tensile loads developed from the mass and friction of the barrier segments upstream and downstream of the impacted region. While TCB technologies have advanced in recent years with the development of methods for limiting deflection, there exists a need for safely terminating a run of barrier segments. Two major areas that need to be addressed include the upstream end of TCB systems and the approach transition to various barrier types.

The impact behavior of TCB, when struck near the upstream end of the system, has never been investigated nor crash tested. Thus, no guidelines exist regarding the location of the beginning of length-of-need (LON) for a free-standing, TCB system. Currently, some roadway designers have assumed that the temporary barrier system was effective throughout the length of the system. However, previous full-scale crash testing has demonstrated that the beginning of LON for free-standing barriers may be a long distance away from the upstream end. Dynamic testing of such barriers has normally occurred with the vehicle striking the system between 80 and 100 ft downstream from the upstream end of a 200-ft long barrier system. During one full-scale crash test, the ends of the TCB system moved as much as 2 in. [1]. Impacts closer to the system ends would very likely increase barrier deflections and may result in pocketing, vehicle climb, and/or vehicle instabilities, such as rollovers.

This fact has led other designers to lengthen TCB systems by 80 to 100 ft and flare the system away from the roadway. Unfortunately, errant vehicles impacting these additional barrier segments may result in vehicle rollover as well. Therefore, a method was needed for shortening the distance between the TCB's upstream end and the beginning of the LON.

A strong ground anchor is one option that could allow a TCB system to achieve adequate capacity within the first one or two barrier segments and would eliminate the need for extending the system farther upstream.

Aside from the upstream termination and anchorage, TCBs often must be connected and transitioned to other types of barriers. Sometimes TCBs are connected to similarly-shaped, permanent concrete barriers while at other times, they must be connected to vertical concrete barriers, tubular steel bridge railings, W-beam guardrail, thrie-beam guardrail, and open concrete bridge railings. In addition, these transitions may occur in either roadside or median applications. Unfortunately, there has been little effort devoted to this issue, and only a roadside approach transition between rigid, safety-shaped, concrete barriers and free-standing, TCBs has been designed [2-3]. Thus, a need existed to indentify the critical approach transition and develop an effective approach transition for that application.

The research objectives were to develop two new technologies for TCBs. The first objective was to design, test, and evaluate an economical method for terminating and anchoring the upstream end of TCB systems. The termination should provide adequate anchorage to allow for the beginning of the LON to be on or near the system's first barrier segment. The second objective was to identify the most prominent transition scenario between TCB and other types of barriers and develop a TCB transition for the highest priority situation. Both designs were developed for use with the Kansas F-shape TCB [4] that is currently used by several states participating in the Midwest Pooled Fund Program. This effort was performed in accordance with the Test Level 3 (TL-3) guidelines found in the proposed Update to NCHRP Report 350, currently referred to as the Manual for Assessing Safety Hardware (MASH), First Edition [5].

TEST CRITERIA

Terminals and crash cushions, such as TCB terminations, must satisfy impact safety standards provided in MASH in order to be accepted by the Federal Highway Administration (FHWA) for use on National Highway System (NHS) new construction projects or as a replacement for existing designs not meeting current safety standards. According to Test Level 3 (TL-3) of MASH, non-gating terminals and crash cushions must be subjected to nine full-scale vehicle crash tests. The nine full-scale crash tests are test designation nos. 3-30, 3-31, 3-32, 3-33, 3-34, 3-35, 3-36, 3-37, and 3-38.

The TCB termination and anchorage system was designed with the intention of either placing an approved impact attenuator, such as sand barrels, in front of the anchorage posts or placing the anchorage system outside of the clear zone. Thus, most of the required MASH crash tests for terminals and crash cushions are unnecessary because they have been previously addressed in the prior compliance testing programs. Thus, test designation nos. 3-30 through 3-34, 3-36, and 3-38 are not intended to evaluate the safety performance of the concrete barrier or termination anchor system.

Test 3-37 is used to evaluate a crash cushion during reverse direction impacts. However, the barrier system is often flared away from the traveled way and out of the clear zone in roadside applications, thus not requiring an impact attenuator. In the occasion that the end of the barrier is inside the clear zone, an appropriate crash attenuator would be required. However, testing the compatibility of every crash attenuator on the market is not within the scope of this project. Rather, the manufacturer of a specific crash attenuator is responsible for proving satisfactory crash results during reverse impacts. Therefore, only test 3-35 was deemed applicable for evaluating the TCB termination and anchorage system.

The approach transition detailed in this research was required to satisfy two full-scale vehicle crash tests. The two tests included test designation no. 3-20, consisting of a 2,425-lb passenger car impact, and test designation no. 3-21, consisting of a 5,000-lb pickup truck impact. Previous research has demonstrated that the passenger car test was unnecessary for the transition [6-10], and test designation no. 3-21 was deemed sufficient to evaluate the approach transition.

Two Critical Impact Points (CIP's) must be evaluated for the approach transition. The first CIP is located adjacent to the point where the transition attaches to the permanent barrier and is used to evaluate snag and pocketing near the hazard. The second CIP is located near the upstream end of the transition and is used to evaluate the stiffness transition in, which can cause pocketing and vehicle instability.

TERMINATION AND ANCHORAGE OF TCB

The development of the termination and anchorage for TCB was initiated with the identification of four main design criteria for use in configuring the system. First, the termination system must develop sufficient loads to anchor the barrier system. The anchorage system should develop loads on the end barrier similar to those developed by adjacent barriers in the LON of the free-standing barrier system. It was also desired that the anchorage system develop these loads over some controlled displacement, such that the end barrier was not rigidly fixed. The controlled displacement of the anchor system would prevent the anchorage loads from becoming too high.

For the second design criterion, the termination system should mitigate vertical rotation and tipping of the end barrier about its longitudinal axis. Experience with safety shape barrier designs has shown that their sloped faces can allow vehicle climb and subsequent vehicle instabilities. Vertical rotation of the barrier segment about its longitudinal axis can further accentuate vehicle climb and instability. Thus, it was important to minimize the vertical rotation of the barrier.

For the third criterion, existing hardware was to be considered in order to keep state DOT hardware inventories to a minimum and save costs. Fourth, the design must attach to either end of a barrier segment, since the temporary barrier design has different loop configurations on each end. With these criteria in mind, the researchers needed to determine the appropriate design loads for configuring the anchorage and termination system.

Determination of Design Loads

It was difficult to obtain the appropriate design loads for developing the termination and anchorage system through a review of previous crash testing studies or by simple analytical expressions. Tensile load data was unavailable for barrier joints and other associated hardware when subjected to full-scale crash testing in free-standing, temporary barrier installations. In addition, estimation of the barrier's tensile loads was unreliable due to the variation and spread in friction values. Thus, the researchers used LS-DYNA [11] finite element modeling to determine the loads for analyzing and designing the termination anchor system. LS-DYNA was used to investigate the behavior of terminating the TCB system under various end segment constraints including a pinned end constraint, separate lateral and longitudinal springs, and a 3-D spring with lateral, longitudinal, and vertical constraint. Information gathered from this modeling effort was used to design the actual end anchorage system, including its structural capacity and geometric layout. Analysis of the various end constraints found that a 3-D spring defined with an initial slope that rose to 80 kips over 10 in., then held constant at 80 kips for another 10 in., and finally released or failed after 20 in. of total deflection provided sufficient anchorage for the TCB system. Simulation results showed that such an anchorage provided for stable redirection of the impacting vehicle while maintaining acceptable deflection and rotation of the impacted barrier segments. Full discussion of this simulation analysis can be found in the research report [12].

Based on the results of this analysis and the design criteria discussed in the previous section, the researchers decided that the termination and anchorage system should resist an 80 kip load over approximately 10 in. of deflection. In addition, the termination and anchorage system should provide both vertical and lateral restraint in order to control barrier deflections and rotations that could lead to vehicle instability.

Termination Anchor Concept

Several ideas were considered for the termination anchor that attempted to meet the desired design criteria and design loads. The optimum design solution consisted of a driven steel pile, similar to that used in previous cable guardrail projects. During the development of a low-tension, cable guardrail system for use near fill slopes, MwRSF researchers tested several end anchorage designs [13]. One of these anchorage systems incorporated a driven steel pile, as shown in Figure 1. During that study, the steel pile anchorage was tested and found to develop 40 kips of load over a deflection of 10 in. The researchers believed that two of driven steel piles would meet the 80-kip design load as well as meet the criteria recommending the use of existing hardware. One steel pile would be mounted upstream and in line with the centerline of the upstream barrier end. This first pile would attach near the bottom of the barrier and provide primarily a tensile constraint for the end barrier. The second steel pile would be installed with a slight lateral offset toward the traffic-side face of the barrier and would attach to the upstream barrier end near the top loop bar. This pile would provide additional tensile constraint as well as provide some lateral constraint and resistance to barrier rotations about the longitudinal axis.

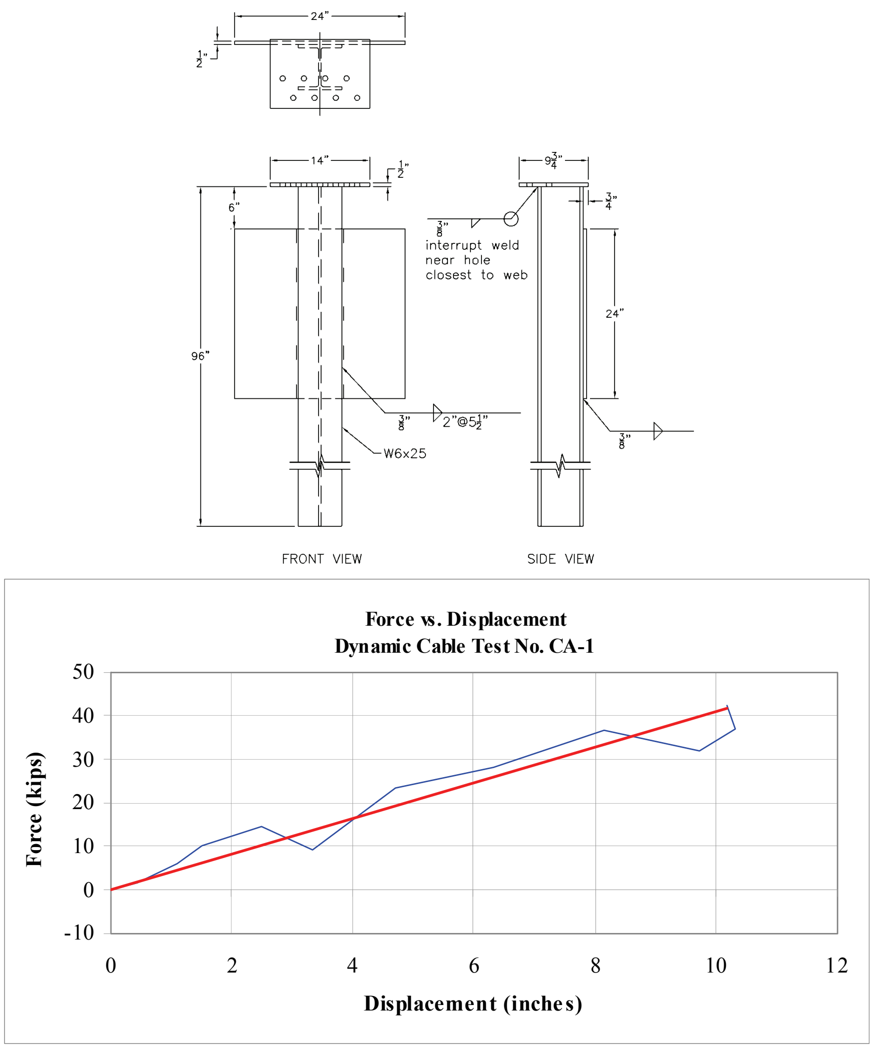


Figure 1. Single Driven Steel Pile Anchorage

The steel piles were offset from the barrier to allow for anchor displacement in the soil while developing the necessary anchor capacity. As such, a method was needed to connect the steel piles to the upstream end of the barrier. The most efficient connection method utilized cable assemblies similar to those used for anchoring W-beam guardrail systems. These cable assemblies allowed for tightening the end anchorage as well as provided some tolerance for the placement of the piles. One end of the cable assembly was designed with a threaded end that connected to a mounting bracket on top of the steel pile. The other end had as simple cable loop that would attach to a steel connection pin passing through the loops on the end of the barrier. Full details on this connection are presented in a subsequent section.

TCB Anchorage and Termination Design Details

The 156.5-ft long test installation, as shown in Figure 2, consisted of two major components: (1) twelve segments of 32-in. tall F-shape, TCB installed on a concrete surface and (2) an anchorage system composed of two ¾-in. diameter wire cables and two anchor post assemblies. Design details are shown in Figure 2.

The TCB system utilized the Kansas F-shape TCB barrier which consists of a 12.5-ft. long barrier segment with a pin and loop type connection comprised of two sets of three rebar loops on each barrier interconnection. Full details of the Kansas F-shape TCB can be found in previous reports detailing its design and testing [1,4].

The upstream-most barrier segment was installed with 36 in. of the downstream end placed on the concrete surface and the remainder of the barrier segment resting on soil. This end barrier was anchored by two cable assemblies that connected the end connector pin to two driven, steel pile, anchor posts. Each of the two anchor posts was a 8-ft long, W6x25 steel section with a 24-in. x 24-in. x ½-in. thick soil plate welded to the front flange and a ½-in. thick plate welded to the top of the post. The anchor posts were placed in soil with an embedment depth of 8 ft. One post was located along the longitudinal axis of the system, 45 3/8 in. upstream of the end of the first barrier. The second post was located 29 3/8 in. upstream of the first barrier and offset 11 ½ in. laterally from the traffic-side face of the barrier. The soil pit underneath the asphalt surface was comprised of a crushed limestone aggregate soil satisfying the standard soil requirements of MASH. Cable brackets were bolted to the top of the anchor posts. The cable brackets were assembled from multiple ½-in. thick, ASTM A36 steel plates welded together.

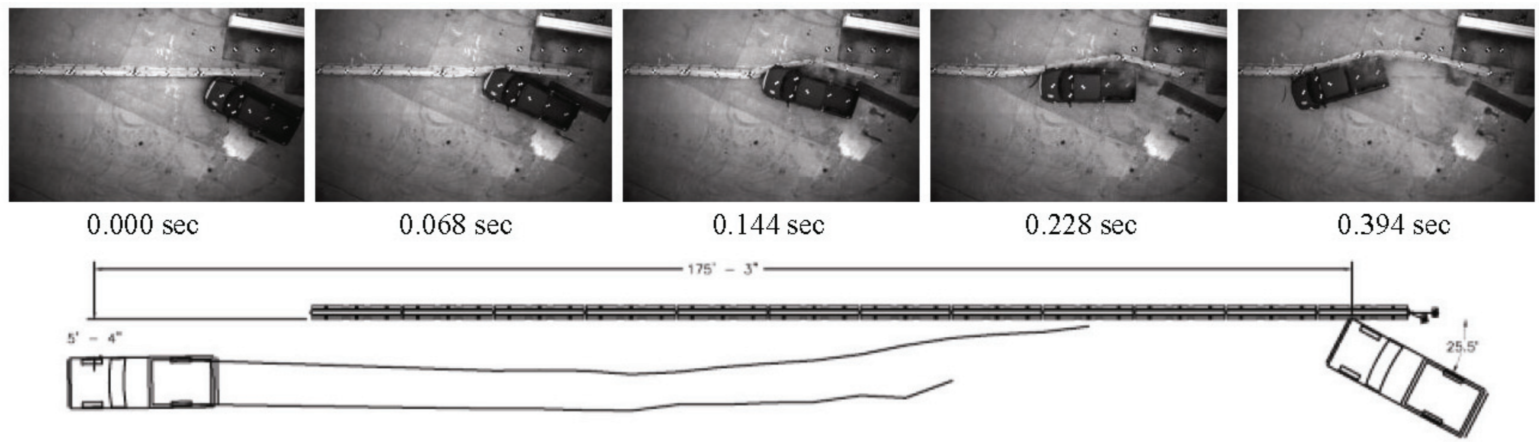
The cable assemblies were comprised of a ¾-in. diameter, 7x19 wire rope, BCT cable end fitting, a Crosby heavy-duty HT thimble, and a 115-HT mechanical splice. One 54 3/4-in. long cable assembly was aligned with the longitudinal axis of the barrier system. This cable assembly was attached with one end fixed between the lower barrier loops on an additional connection pin on the upstream end of the barrier and the other end attached to the anchor post. The end connector pin utilized a second 2 ½-in. wide x 4-in. long x ½-in. thick ASTM A36 steel plate and a ½-in. diameter x 10-in. long Grade 8 hex bolt and nut at the bottom of the pin to prevent the pin from pulling out of the barrier loops when the anchorage was loaded. The second cable assembly measured 48 3/8 in. long, and it was attached from just below the top barrier loop on the connector pin on the end of the barrier to the offset anchor post. A pin sleeve, made from 1 ½ in. Schedule 40 pipe, was used to keep the anchor cables in the correct vertical positions. The use of the pin sleeve also allowed the cable anchorages to be attached at the same vertical position on the end pin regardless of which end of the F-shape barrier was used. Thus, if the barrier ends were reversed, the offset cable would attach to the connection pin between the top two barrier loops, and the in-line cable would attach to the connection pin between the pin sleeve and lower barrier loop.

Figure 2. Termination of TCB, Test No. TTCB-1

Full-Scale Crash Testing

Test No. TTCB-1

For test no. TTCB-1, the 4,991-lb pickup truck impacted the anchored temporary barrier system at a speed of 62.9 mph and at an angle of 25.5 degrees. A summary of the test results and the sequential photographs are shown in Figure 3. Initial vehicle impact was to occur 98 3/8 in. downstream of the upstream end of barrier no. 1. The actual point of impact was 10 ¼ in. downstream of the targeted impact. After initial impact with the first barrier segment, the pickup truck began to redirect and translate downstream. As the vehicle continued to redirect, minor pitch and roll of the vehicle were observed, but the levels were well below the limits set forth in



- Test Agency .... MwRSF
- Test Number TTCB-1
- Date 6/27/07
- MASH Test Designation 3-35
- Test Article .... Termination of Temporary Concrete Barrier
- System Length .... 156 ft – 6 in.
- Temporary Concrete Barriers
  - Type .... Precast Kansas F-Shape
  - Quantity 12
  - Length .... 12 ft – 6 in.
  - Base Width .... 22.5 in.
  - Height .... 32 in.
- Anchorage Components
  - Cables .... 0.75 in. Diameter 6x19 IWRC Wire Rope
  - Cable Assembly Lengths .... 51 & 46 in.
  - Post Type W6x25
  - Post Length (Embedment) .... 8 ft
- Vehicle Make and Model .... 2003 Dodge Ram 1500 Quad Cab.
  - Curb .... 4,988 lbs
  - Test Inertial .... 4,991 lbs
  - Gross Static .... 4,991 lbs
- Impact Conditions
  - Speed .... 62.9 mph
  - Angle .... 25.5 deg
  - Impact Location .... 108 5/8 in. DS from US End of Barrier 1
- Exit Conditions
  - Speed .... 36.1 mph
  - Angle .... 15.9 deg
- Vehicle Stability .... Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.) (EDR-3)
  - Longitudinal .... 16.47 g's < 20.49 g's
  - Lateral .... 8.00 g's < 20.49 g's
- Occupant Impact Velocity
  - Longitudinal .... 13.41 ft/s < 40 ft/s
  - Lateral .... 17.15 ft/s < 40 ft/s
- THIV .... 21.74 ft/s
- PHD .... 16.78 g's
- Vehicle Damage .... Moderate
  - VDS[15] .... 1-FR-6 and 1-RD-3
  - CDC[16] .... 01-FREN2 and 01-RDES2
  - Maximum Interior Deformation .... 4.25 in. near RF corner of the floorboard
- Vehicle Stopping Distance .... 175.25 ft DS of impact, 5.3 ft laterally
- Test Article Damage .... Moderate
- Test Article Deflections
  - Permanent Set .... 66.5 in.
  - Dynamic .... NA
- Working Width .... 89.0 in.
- Maximum Roll Angle .... 14.75 deg. @ 0.693 sec

Figure 3. Summary of Test Results and Sequential Photographs, Test No. TTCB-1

the MASH safety requirements and overall stability of the vehicle was very good. By 0.228 sec, the vehicle was parallel with the system at a speed of 45.2 mph, and soil gaps were visible as the anchors were being pulled downstream. At 0.756 sec, the front bumper impacted the ground, and at 0.810 sec, the vehicle lost contact with the barrier system at 36.1 mph and an angle of 15.9 degrees until it eventually came to a stop 175 ft – 3 in. downstream of impact and 5 ft – 4 in. in front of the barrier system. A maximum permanent set deflection of 66.5 in. was measured at the downstream end of barrier no. 3.

Vehicle damage was moderate, and the most extensive damage was concentrated at the right-front corner of the pickup truck where the quarter panel and bumper were crushed inward. The right-front tire was detached from the pickup truck and was resting flat underneath the right-side occupant compartment. Damage to the barrier system was also moderate. The most extensive barrier damage occurred to barrier no. 2 where cracks were found through the entire cross section of the barrier spanning the middle 60 in. of barrier no. 2. The data from the string potentiometer mounted on the anchors showed maximum dynamic anchor deflections of 5.28 in. for the offset anchorage and 6.19 in. for the in-line anchorage. Post test damage photographs are shown in Figure 4.

Test no. TTCB-1 was determined to be acceptable according to the TL-3 safety performance criteria found in MASH using test designation no. 3-35.

Figure 4. Post Test Damage, Test No. TTCB-1

TCB APPROACH TRANSITION TO MEDIAN BARRIER

At the onset of this project, the Midwest States' Regional Pooled Fund states were surveyed. The states were given eight types of commonly used TCB transitions and invited to add their own as desired. For each transition, the states were asked to (1) identify the usefulness of the transition, (2) identify the approximate percentage of all temporary barrier transitions that each type composes, and (3) rank the transition types in order of importance.

After compiling the state responses, the various transition needs were organized into a limited number of design categories. Priorities for the project were assigned based on: (1) the importance of the transition to the states participating in the Pooled Fund Program; (2) the number of different systems that can be addressed simultaneously; and (3) the potential for the development of a successful design. According to the responses, the most useful transitions were those connecting TCBs to safety shape and vertical permanent concrete barriers. The highest percentage of all of the transitions currently in use were those connecting TCBs to permanent concrete safety shape barriers and tubular steel bridge railings. In rank of importance, transitions to permanent concrete safety shape barriers were again at the top, followed by transitions to W-beam guardrail.

As the most popular in all three categories, the transition between TCBs and permanent concrete safety shape barriers was chosen for development of a transition solution. Realizing that such a transition may be applicable to more than one type of permanent concrete barrier, the researchers expanded the scope of the design to include vertical concrete parapets, safety shape parapets, and single-slope barriers, but intending to only test the most critical. Since an NCHRP Report No. 350 compliant design for the transition between TCB and permanent safety shaped barriers for roadside applications was recently developed [2-3], a median application was selected for this study. An end-to-end barrier transition was selected as opposed to an offset-overlap barrier transition, because it was deemed the more common and more useful type of transition. Therefore, it was decided to design of an end-to-end transition between free-standing TCBs and permanent concrete barrier for median applications.

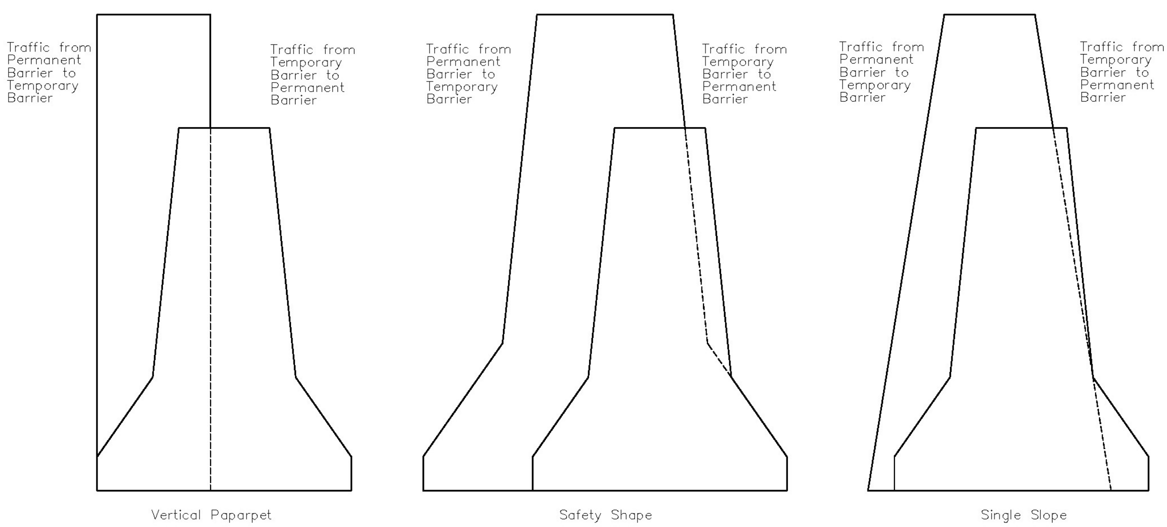
The preliminary transition design was based on the previously-developed, roadside approach transition between free-standing TCB and rigid F-shape barrier. Thus, the design utilized varying numbers of steel pins driven through holes in the toe of the barrier in order to provide for the stiffness transition and thrie beam sections to connect the final temporary barrier section to the permanent barrier. Because the new transition was intended for use in medians, the steel pins would be required on both sides of the barriers rather than solely on the traffic-side face. In addition, some form of transition piece would be required to prevent vehicle snag on the permanent barrier due to the difference in the barrier heights.

Determination of Critical Rigid Barrier Geometry

The next phase of the research was to determine the type of permanent concrete barrier that would be the most critical in a transition. To make this determination, the shapes of various permanent median barrier designs were compared to the shape of both the narrow and wide versions of the 32-in. tall F-shape temporary barrier. The following comparisons were completed:

1. 32-in. F-shape temporary barrier to 32-in. and 42-in. F-shape and New Jersey (NJ)-shape median barriers;
2. 32-in. F-shape temporary barrier to 32-in. and 42-in. Texas (TX) and California (CA) single-slope median barriers;
3. 32-in. F-shape temporary barrier to 32-in. and 42-in. vertical median barriers;
4. Wide, 32-in. F-shape temporary barrier to 32-in. and 42-in F-shape and NJ-shape median barriers;
5. Wide, 32-in. F-shape temporary barrier to 32-in. and 42-in. TX and CA single-slope median barriers; and
6. Wide, 32-in. F-shape temporary barrier to 32-in. and 42-in. vertical median barriers.

From the comparison of the various shapes, it was determined that the 42-in. tall CA single-slope median barrier provided the worst case situation. Comparison of the F-shape temporary barrier geometry with the single-slope barrier showed that there was a high potential for vehicle snag on the sides of the permanent barrier as well as on the 10 in. height difference of the barriers, as shown in Figure 5. It was determined that shifting the temporary barrier toward the traffic-flow side of the single-slope so that the slope breakpoint at the top of the toe of the temporary barrier lines up with the traffic-side face of the permanent single slope would help alleviate some of the snag potential on the single-slope barrier. This asymmetrical placement would only present a safety concern if the temporary barrier were used to separate traffic flowing in the same direction, such as in a gore area. However, it was believed that this situation would be better treated with a barrier end treatment.



Note: (1) The 32" temporary F–shape barrier is shown as the front barrier.

Figure 5. F-Shape TCB Alignment with Median Barrier

Determination of CIP

Two Critical Impact Points (CIP's) needed to be evaluated for the approach transition. The first CIP was located adjacent to the point where the transition attaches to the permanent barrier and was used to evaluate snag and pocketing near the hazard. This CIP was defined in MASH as 51

5/8 in. upstream of the upstream end of the permanent barrier. The second CIP was located near the upstream end of the transition and was used to evaluate the stiffness transition in, which can cause pocketing and vehicle instability. LS-DYNA was used to determine the impact point for the full-scale crash test evaluating the second CIP. For this CIP, there is a potential for barrier deflections and rotations that could result unstable vehicle behavior or override of the system. A detailed model of the approach transition was built and impacted at various locations along the barrier to determine the CIP. Four different cases are presented herein to demonstrate the selection of the CIP:

Case A- Impact 40 1/4 -in. upstream of the joint between the third and fourth barrier upstream of the rigid barrier;
Case B- Impact 1/2 barrier length upstream from Case A;
Case C- Impact 1 barrier length upstream from Case A; and
Case D- Impact 1½ barrier lengths upstream from Case A.

Determination of the CIP considered evaluation of the vehicle stability as well as examination of barrier motions such as displacement and roll and yaw rotations. Case A exhibited relatively limited barrier motion and although the vehicle exhibited the most pitch, that motion did not cause any significant indication of the vehicle becoming unstable. Thus, Case A was ruled out for the CIP. Impacts downstream of Case A were expected to produce even lower barrier motions due to the increased constraint on the barriers in the transition. Case D appeared to have the smoothest vehicle redirection and thus was ruled out for the CIP. Cases B and C demonstrated somewhat similar behavior, but the researchers concluded that Case C had larger barrier motions and slightly more vehicle roll than observed in Case B. Thus, Case C was chosen as the CIP for test no. TCBT-2. Further details on the selection of the CIP can be found in the research report [14].

It should be noted that the downstream CIP adjacent to permanent barrier was chosen to be 4.3 ft upstream of the permanent barrier. This value was based on guidance for CIP values for rigid barriers and TCB provided in Table 2.6 in MASH. It represents the distance upstream of a post or joint in a rigid barrier that has increased potential for vehicle snag. Due to the high stiffness of the anchored TCB sections adjacent to the permanent barrier, it was believed that this CIP location would be sufficient to determine the potential for snag on the rigid median barrier.

TCB Approach Transition to 42-in. High Single-Slope Barrier Design Details

Design details for the TCB approach transition to a 42-in. high single-slope barrier are shown in Figure 6. The test installation consisted of a rigid parapet, four transition barriers, eight free-standing barriers on the upstream end, and a transition cap. The transition and free-standing barriers were installed on a 3-in. thick asphalt pad.

The transition utilized a varied spacing of the asphalt pin tie-down system to create a transition in stiffness over a series of four barrier segments. The asphalt pins were 1.5-in. diameter x 38 1/2-in long ASTM A36 steel pins with 3-in. x 3-in. x 0.5-in. ASTM A36 steel cap plates. These pins were installed in the holes on both the front and back face of the four barriers in the transition section of the installation. The first barrier in the transition (the one adjacent to the free-standing barrier) had a single pin at the downstream end on both the front and back sides. The second barrier had pins installed at the two outermost hole locations on both the front and back faces. The final two barriers had all three pins installed on both the front and back faces.

In order to reduce the potential for vehicle snag at the joint between the pinned barriers and the rigid parapet, a transition cap and nested thrie beam sections were added. The nested 12-gauge thrie beam was bolted across both sides of the barrier at the joint between the pinned barrier and the rigid parapet. The 12-gauge, ASTM A36 steel cap was 6 1/16 in. and 8 1/8 in. wide at the top and bottom, respectively, with a height of 10 in. and a length of 49 11/16 in. Four 12-gauge ASTM A36 gussets were stitch welded on three sides inside the cap.

The TCB system utilized the Kansas F-shape TCB barrier which consists of a 12.5-ft. long barrier segment with a pin and loop type connection comprised of two sets of three rebar loops on each barrier interconnection. Full details of the Kansas F-shape TCB can be found in previous reports detailing its design and testing [1,4].

The single-slope permanent concrete barrier was 21.5 in. and 8 in. wide at the base and top, respectively, with an overall height of 42 in. from the ground to the top of the barrier. The single-slope concrete barrier had a overall length of 13 ft – 4 in.

Figure 6. TCB Approach Transition to 42-in. High Single-Slope Barrier

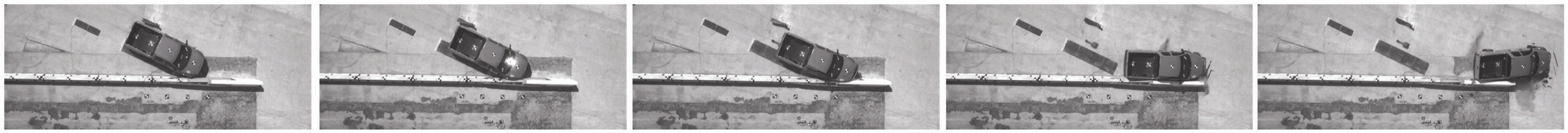
Full-Scale Crash Testing

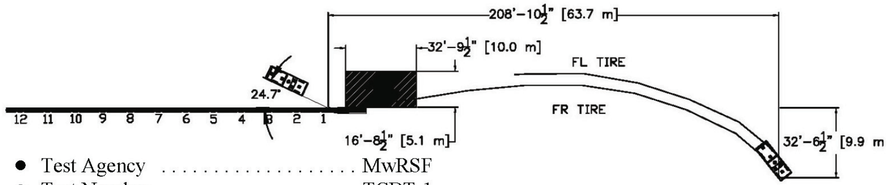
Test No. TCBT-1

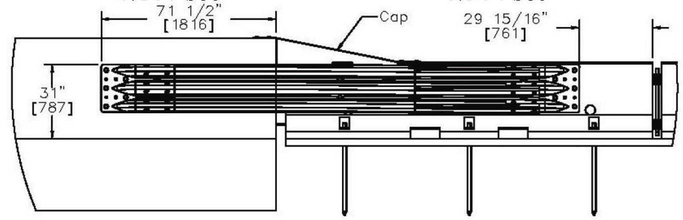
Test no. TCBT-1 was performed to evaluate the transition adjacent to the permanent median barrier. A summary of the test results and the sequential photographs are shown in Figure 7. The 5,175-lb pickup truck, with the dummy placed in the right-front seat, impacted the TCB to permanent barrier transition, at a speed of 62.5 mph and at an angle of 24.7 degrees. Initial vehicle impact was to occur 51 5/8 in. upstream from the upstream end of the permanent barrier. Actual vehicle impact occurred 56 3/8 in. upstream from the upstream end of the permanent barrier. As the vehicle impacted the system and began to redirect, the right-front fender engaged the slope of the steel transition cap on the final temporary barrier segment and was prevented from snagging on the single slope barrier. By 0.034 sec, the right-front corner of the vehicle reached the permanent concrete barrier, but snagging of the vehicle was mitigated by the reduced deflection of the temporary barrier segment and the thrie beam section. The vehicle continued to redirect and yaw counter clockwise and became parallel with the barrier system at 0.188 sec with a resultant velocity of 49.8 mph. The vehicle continued to redirect with minimal pitch and roll motions until exiting the barrier system at 0.318 sec with a trajectory angle of 4.2 degrees and a resultant velocity of 48.6 mph. The final position of the vehicle was determined to be 208 ft - 10 1/2 in. downstream of impact and 32 ft - 6 1/2 in. laterally behind the traffic-side face of the system.

Vehicle damage was moderate, and damage was concentrated on the right-front corner of the vehicle. The right-front corner, hood, and bumper were deformed inward. Major sheet metal deformations were found above the right-side wheel well and along the lower portion of the right-side doors. The right-front wheel was detached from the vehicle. Barrier damage consisted of scrapes and contact marks on the TCB, permanent barrier, and the thrie beam section, cracking of temporary barrier sections, and deformed thrie beam. The maximum lateral permanent set barrier deflection was 1/4 in. at the downstream end of barrier no. 1. The maximum lateral dynamic barrier deflection was 2.6 in. on middle of the non-impact-side of the thrie beam, as determined from high speed digital video analysis. Post test damage photographs are shown in Figure 8.

Test no. TCBT-1was determined to be acceptable according to the TL-3 safety performance criteria found in MASH using test designation no. 3-21.







- Test Agency . . . . MwRSF
- Test Number TCBT-1
- Date 4/4/2008
- MASH Test Designation 3-21
- Appurtenance . . . . Temporary Concrete Barrier to Permanent Concrete Barrier Transition
- Total Length . . . . 166 ft - 10 in.
- Key Elements - Temporary Barriers
  - Description . . . . Kansas F-shape
  - Length . . . . 12 ft - 6 in.
  - Base Width . . . . 22.5 in.
  - Height . . . . 32 in.
- Key Elements - Permanent Barrier
  - Description . . . . California Single Sloped Concrete Barrier
  - Top Width . . . . 8 in.
  - Base Width . . . . 21.5 in.
  - Height . . . . 42 in.
- Key Elements - Cap
  - Length . . . . 68 7/16 in.
  - Height . . . . 10 in.
- Type of Soil . . . . None
- Test Vehicle
  - Type/Designation 2270P
  - Make and Model . . . . 2002 Dodge Ram 1500 Quad Cab
  - Curb . . . . 4,971 lbs
  - Test Inertial . . . . 5,006 lbs
  - Gross Static . . . . 5,175 lbs
- Impact Conditions
  - Speed . . . . 62.5 mph
  - Angle . . . . 24.7 degrees
  - Impact Location . . . . 56 3/8 in. upstream of permanent barrier

- Exit Conditions
  - Speed . . . . 48.6 mph
  - Angle . . . . 4.2 degrees
  - Exit Box Criterion . . . . Pass
- Post-Impact Trajectory
  - Vehicle Stability . . . . Satisfactory
  - Stopping distance . . . . 208 ft - 10.5 in. downstream 32 ft - 6.5 in. laterally behind
- Occupant Impact Velocity
  - Longitudinal . . . . -22.68 ft/s < 40 ft/s
  - Lateral . . . . 26.99 f/s < 40 ft/s
- Occupant Ride Down Acceleration
  - Longitudinal . . . . -4.66 g's < 20.49 g's
  - Lateral . . . . 6.76 g's < 20.49 g's
- THIV (not required) . . . . 31.69 ft/s
- PHD (not required) . . . . 7.66 g's
- Test Article Damage . . . . Moderate
- Test Article Deflections
  - Permanent Set . . . . N/A
  - Dynamic . . . . 2.6 in.
  - Working Width . . . . 24 7/8 in.
- Vehicle Damage . . . . Moderate
  - VDS 1-RFQ-5
  - CDC 01-RFEE5
  - Maximum Deformation . . . . 6 in. at front-center floorboard
- Angular Displacement
  - Roll . . . . N/A
  - Pitch . . . . N/A
  - Yaw . . . . -31.8 degrees

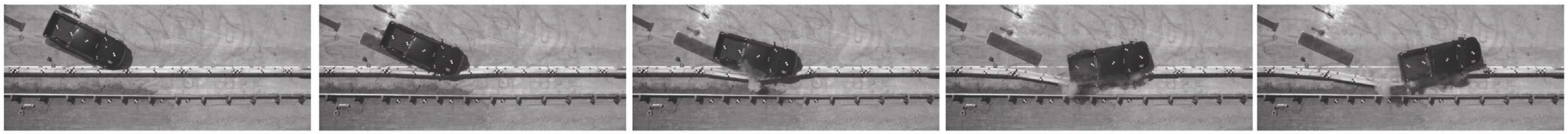
Figure 7. Summary of Test Results and Sequential Photographs, Test No. TCBT-1

Figure 8. Post Test Damage, Test No. TCBT-1

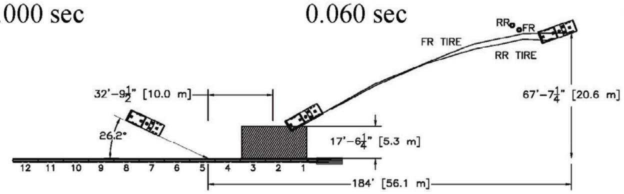
Test No. TCBT-2

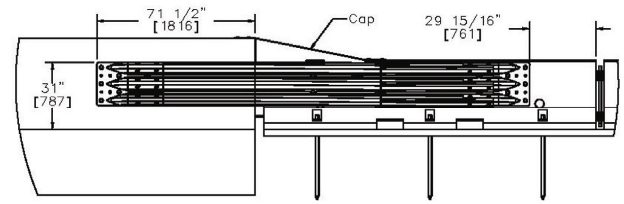
Test no. TCBT-2 was performed to evaluate the upstream end of the approach transition. A summary of the test results and the sequential photographs are shown in Figure 9. The 5,160-lb pickup truck, with the dummy placed in the right-front seat, impacted the TCB to permanent concrete barrier transition at a speed of 62.2 mph and at an angle of 26.2 degrees. Initial vehicle impact was to occur 3 ft - 4 1/4 in. upstream from the downstream end of barrier no. 5. Actual vehicle impact occurred 3 ft - 5 1/4 in. upstream from the downstream end of barrier no. 5. After impact with the barrier system, the front right corner of the vehicle crushed inward and the vehicle began to redirect. By 0.070 sec, the impact of the vehicle with barrier no. 4 caused a large crack to form near the midspan of barrier no. 4 that fractured the barrier into two pieces connected by the portions of the reinforcing steel. The vehicle continued to redirect with the front of the vehicle pitching upward as the right-front corner of the vehicle climbed the sloped face of the deflected temporary barrier segments. By 0.206 sec, the vehicle had become parallel to the system with a resultant velocity of 50.1 mph. At 0.260 sec, the rear of the vehicle impacted the upstream half of barrier no. 4. Impact with the fractured barrier segment caused the right rear wheel of the vehicle to snag the fractured barrier and pitch the rear of the vehicle upward rapidly. The vehicle exited the barrier at 0.346 sec at a trajectory angle of 14.0 degrees and a resultant velocity of 43.0 mph. The vehicle came to rest 184 ft downstream from impact and 67 ft - 1/4 in. laterally away from the traffic-side face of the barrier.

Vehicle damage was moderate, and the damage was concentrated on the right side of the vehicle. The right-front corner including the front bumper and the right-front fender were deformed inward. The right-front wheel assembly disengaged from upper and lower control arms. Sheet metal deformation and contact marks were noted along the entire right side of the vehicle. The right-rear wheel disengaged from the vehicle. System damage consisted of scrapes, contact marks, and concrete spalling on TCB and asphalt pin deflections, cracking of temporary barrier sections, and a fractured temporary barrier. As noted above, barrier no. 4 was cracked and fractured near the midspan of the barrier, and some of the longitudinal rebar was fractured. Deformation of several concrete temporary barrier loop joints and connection pins were noted in the impact region. The maximum lateral permanent set barrier deflection was 34 in. at the



0.000 sec 0.060 sec 0.120 sec 0.246 sec 0.322 sec





- ●Test Agency . . . . MwRSF
- ●Test Number TCBT-2
- ●Date 4/23/2008
- ●MASH Test Designation 3-21
- ●Appurtenance . . . . Temporary Concrete Barrier to Permanent Concrete Barrier Transition
- ●Total Length . . . . 166 ft - 10 in.
- ●Key Elements - Temporary Barriers
  - Description . . . . Kansas F-shape
  - Length . . . . 12 ft - 6 in.
  - Base Width . . . . 22 1/2 in.
  - Height . . . . 32 in.
- ●Key Elements - Permanent Barrier
  - Description . . . . California Single Sloped Concrete Barrier
  - Top Width . . . . 8 in.
  - Base Width . . . . 21 1/2 in.
  - Height . . . . 42 in.
- ●Key Elements - Cap
  - Length . . . . 68 7/16 in.
  - Height . . . . 10 in.
- ●Type of Soil . . . . None
- ●Test Vehicle
  - Type/Designation 2270P
  - Make and Model . . . . 2003 Dodge Ram 1500 Quad Cab
  - Curb . . . . 4,905 lbs
  - Test Inertial . . . . 4,990 lbs
  - Gross Static . . . . 5,160 lbs
- ●Impact Conditions
  - Speed . . . . 62.2 mph
  - Angle . . . . 26.2 degrees
  - Impact Location . . . . 41 1/4 in. upstream from the downstream end of barrier no. 5
- ●Exit Conditions
  - Speed . . . . 43.0 mph
  - Angle . . . . 14.0 degrees
  - Exit Box Criterion . . . . Failed
- ●Post-Impact Trajectory
  - Vehicle Stability . . . . Satisfactory
  - Stopping distance . . . . 184 ft downstream 67 ft - 7 1/4 in. laterally in front
- ●Occupant Impact Velocity (EDR-3)
  - Longitudinal . . . . -12.78 ft/s < 40 ft/s
  - Lateral . . . . 18.56 ft/s < 40 ft/s
- ●Occupant Ride Down Acceleration (EDR-3)
  - Longitudinal . . . . -18.69 g's < 20.49 g's
  - Lateral . . . . 13.29 g's < 20.49 g's
- ● THIV (not required) . . . . 20.58 ft/s
- ● PHD (not required) . . . . 19.00 g's
- ● Test Article Damage . . . . Moderate
- ●Test Article Deflections
  - Permanent Set . . . . 34 in.
  - Dynamic . . . . 44.3 in.
  - Working Width . . . . 55.8 in.
- ●Vehicle Damage . . . . Moderate
  - VDS 1-RD-6
  - CDC 01-RDEE9
  - Maximum Deformation . . . . 2 1/2 in. at the front-right floorboard
- ●Angular Displacement
  - Roll . . . . 7.8 degrees
  - Pitch . . . . -27.5 degrees
  - Yaw . . . . -38.2 degrees

Figure 9. Summary of Test Results and Sequential Photographs, Test No. TCBT-2

downstream end of barrier no. 5, as measured in the field. The maximum lateral dynamic barrier deflection was 34 in. at the upstream end of barrier no. 5, as determined from high-speed digital video analysis. Post test damage photographs are shown in Figure 10.

Test no. TCBT-2 was determined to be acceptable according to the TL-3 safety performance criteria found in MASH using test designation no. 3-21.

Figure 10. Post Test Damage, Test No. TCBT-2

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Termination and Anchorage System

A termination and anchorage system was designed for use with the upstream end of free-standing, TCB and later was evaluated using full-scale vehicle crash testing. This termination and anchorage system allowed for a significant reduction in the number of barrier segments required upstream from the length of need and for use in anchoring a free-standing TCB system. The anchorage system was configured to effectively constrain the end of the TCB system for impacts as far upstream as the first anchored barrier segment. Full-scale crash testing demonstrated that the impacting vehicle was safely and smoothly redirected, and the test was judged acceptable according to the TL-3 safety criteria set forth in MASH.

As presented herein, the new termination and anchorage system provides users with increased safety and flexibility during placement of TCB systems. The termination and anchorage system should result in shorter installation lengths for TCBs, fewer vehicle impacts into the barrier system, and an overall reduction in the cost of the installation. While this research and development effort was successful, there are some comments that need to be made regarding implementation of the new system. Additional comments and recommendations pertaining to the use of this system were omitted from this paper due to space constraints, but they can be found in the research report detailing this effort [12].

The termination and anchorage system described herein was designed for use with the Kansas F-shape TCB system. Therefore, it should not be used with other TCB systems or joint designs without further study. Although it is very likely that this termination and anchorage system can be adapted to other approved TCB systems, it is first necessary to consider several factors, such as barrier connections, segment lengths, reinforcement, and geometry.

Finally, it should be noted that the termination and anchorage system described herein was developed as an upstream anchorage for TCB used in roadside applications. The anchorage was not designed for use as a downstream anchorage nor as an anchorage for use in TCB installations involving traffic on both sides of the barrier, such as in medians or gore areas. The termination and anchorage system is not recommended for use on the downstream end of a TCB installation because the effects of vehicle interaction with the cable assemblies during impacts near the end of the barrier system are largely unknown. Unlike guardrail terminals, the anchor cables in this design do not include a release mechanism for impacts near the downstream end of the system. As such, it is not known what type of behavior and interaction would result between the vehicle and the barrier during an impact with the end of the barrier system when a downstream anchorage was installed. The use of the offset cable anchor to provide resistance to vertical barrier rotation makes the anchorage design directional by nature. As such, impacts on the side of the barrier without the offset anchor near the end of the TCB installation will result in different anchorage performance than observed in the test described herein. In this type of impact, the offset anchor cable would not develop tension or load until a significant amount barrier translation was observed, thus rendering that cable anchorage largely ineffective.

Median Barrier Approach Transition

The second barrier system developed during the TCB research described herein was an approach transition between free-standing TCBs and permanent concrete median barriers. An analysis of common median barrier geometries identified the critical median barrier design for the approach transition as the 42-in. tall CA single-slope median barrier due to its height as compared to the F-shape TCB. Evaluation of the approach transition required testing at two CIP locations. The first was a CIP to evaluate vehicle interaction with the permanent barrier and the second was a CIP to evaluate the stiffness transition near the upstream end of the system. Full-scale crash testing at both CIP locations demonstrated that the impacting vehicle was safely and smoothly redirected, and the testing of the approach transition was judged acceptable according to the TL-3 safety criteria set forth in MASH. This new design provides a means of safely transitioning from free-standing TCBs to permanent median barriers.

As noted in the discussion of the termination and anchorage design, the approach transition described herein was designed for use with the Kansas F-shape TCB system. Therefore, it should not be used with other TCB systems or joint designs without further study. In order to adapt the design for use with other temporary barrier designs, the design factors noted previously for the termination and anchorage system would need to be considered.

The approach transition design between free-standing and permanent concrete median barrier detailed in this report should be applied when designers are attaching free-standing TCB in the median to permanent concrete barriers or tie-down temporary barrier systems that provide a high degree of constraint on lateral deflection. This requires that the approach transition be applied when free-standing F-shape temporary barriers are connected to permanent concrete barrier, the bolt-through tie-down system for concrete roadways, or the asphalt pin tie-down system. When the approach transition is used in conjunction with the bolt-through tie-down system or the asphalt pin tie-down system, the thrie beam guardrail on the downstream end of the transition is not necessary due to the similar stiffness and deflection levels of the tie-down barriers and the transition. Use of the thrie beam sections is required when the system is attached to rigid barriers to reduce the potential for vehicle snag.

It should also be noted that the approach transition design used pins on both sides of the barrier due to the system's application in the median. However, the researchers cannot recommend using anchorage on both sides of the temporary barrier segment in order to create a median installation of TCB with limited deflection without further testing. There are concerns that placing anchorage on back side of the barrier can induce increased vertical rotation of the barrier segments which could increase the potential for vehicles to climb the sloped barrier face and become unstable.

The approach transition design was tested with the 42-in. tall, CA single-slope median barrier because this barrier was identified as the most critical barrier design for the transition. However, there are other permanent concrete median barriers that can be attached to the approach transition as long as the following guidelines are applied.

1. If the permanent median barrier is 32-in. high, the sloped, steel transition cap is not required for the transition. For barriers with heights greater than 32-in. high, the steel transition cap if required. The cap design can be adjusted for different height and shape

barriers as long as adjusted cap provides equivalent slope, permanent barrier coverage, barrier overlap, structural capacity, and anchorage as the original design.

2. Alignment of the temporary barrier system with the permanent barrier may also change when the transition is applied to different permanent barrier geometries, as shown in Figure 5. When attaching to a single-slope barrier profile, the slope break point between the toe of the barrier and the main face of the barrier should be aligned flush with the oncoming traffic side of the single-slope barrier. For safety shape barriers, the toe of the temporary barrier should be aligned flush with the toe of the oncoming traffic side of the median barrier. Vertical median barriers require that the toe of the temporary barrier segments on the reverse direction traffic side be aligned with the base of the permanent barrier on the reverse direction traffic side. These alignments will prevent vehicle snag for oncoming traffic on the permanent median barrier while preventing snag on the toe of the barrier for reverse direction impacts.
3. The thrie beam sections that span the gap between the end of the temporary barrier and the permanent median barrier should be used in all instances.

Finally, the researchers also believe that the bolt-through tie-down system developed previously could be safely applied to transitions on concrete surfaces using the configuration developed herein. The asphalt pin and bolt-through tie-down systems are believed to possess similar lateral restraint and thus can be interchanged in the transition design as needed.

DISCLAIMER

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ACKNOWLEDGEMENTS

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REFERENCES

1. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, R.W., Reid, J.D., and Coon, B.A., Performance Evaluation of the Free-Standing Temporary Barrier – Update to NCHRP 350 Test No. 3-11 (2214TB-1), submitted to the National Cooperative Highway Research Program, Transportation Research Report TRP-03-173-06, Midwest Roadside Safety Facility, University of Nebraska- Lincoln, October 2006.

2. Bielenberg, B.W., Faller, R.K., Rohde, J.R., Ried, J.D., Sicking, D.L., and Holloway, J.C., Development of Tie-Down and Transition Systems for Temporary Concrete Barrier on Asphalt Road Surfaces, Final Report to the Midwest State's Regional Pooled Regional Pooled Fund Program, Transportation Research Report No. TRP-03-180-06, Midwest Roadside Safety Facility, University of Nebraska Lincoln, February 23, 2007.

3. Bielenberg, R.W., Faller, R.K., Sicking, D.L., Rohde, J.R., and Reid, J.D., "Tie-Downs and Transitions for Temporary Concrete Barriers", Paper No. 06-1276, Transportation Research Record No. 1984, Transportation Research Board, Washington, D.C., December 2006.

4. Polivka, K.A., Faller, R.K., Rohde, J.R., Holloway, J.C., Bielenberg, B.W., and Sicking, D.L., Development and Evaluation of a Tie-Down System for the Redesigned F-Shape Concrete Temporary Barrier, Final Report to the Midwest State's Regional Pooled Fund Program, Transportation Research Report No. TRP-03-134-03, Project No. SPR-3(017)-Year 13, Project Code: RPFP-03-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, August 22, 2003.

5. Manual for Assessing Safety Hardware, First Edition, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2009.

6. Buth, C.E., Hirsch, T.J., and McDevitt, C.F., Performance Level 2 Bridge Railings, Transportation Research Record No. 1258, Transportation Research Board, National Research Council, Washington, D.C., 1990.

7. Guide Specifications for Bridge Railings, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1989.

8. Bronstad, M.E., Calcote, L.R., and Kimball, C.E., Jr., Concrete Median Barrier Research-Vol.2 Research Report, Report No. FHWA-RD-77-4, Submitted by the Office of Research and Development, Federal Highway Administration, Performed by Southwest Research Institute, San Antonio, TX, March 1976.

9. Buth, C.E., Campise, W.L., Griffin III, L.I., Love, M,L., and Sicking, D.L., Performance Limits of Longitudinal Barrier Systems-Volume I: Summary Report, FHWA/RD-86/153, Final Report to the Federal Highway Administration, Office of Safety and Traffic Operations

R&D, Performed by Texas Transportation Institute, Texas A&M University, College Station, TX, May 1986.

10. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, B.W., Reid, J.D., and Coon, B.A., Performance Evaluation of the Permanent New Jersey Safety Shape Barrier - Update to NCHRP 350 Test No. 3-10 (2214NJ-1), Final Report to the Transportation Research Board, National Research Council, National Cooperative Highway Research Program (NCHRP), NCHRP Project No. 22-14(2), Transportation Research Report No. TRP-03-177-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, October 13, 2006.

11. Hallquist, J. O., LS-DYNA Keyword Users Manual: Version 940, Livermore California, Livermore Software Technology Corporation, June 1997.

12. Bielenberg, R.B., Rosenbaugh, S.K., Faller, R.K., Reid, J.D., Rohde, J.R., Sicking, D.L.. Lechtenberg, K.A., and Holloway, J.C., Termination and Anchorage of Temporary Concrete Barriers, Draft Report to the Midwest State's Regional Pooled Fund Program, Transportation Research Report No. TRP 03-209-09, Midwest Roadside Safety Facility, University of Nebraska Lincoln, June 12, 2009.

13. Nelson, R.M., Sicking, D.L., Faller, R.K., Reid, J.D., Rohde, J.R., Polivka, K.A., and Hascall, J.A., Evaluation of Alternate Cable Anchor Designs and Three-Cable Guardrail Adjacent to Steep Slope, Final Report to the Midwest State's Regional Pooled Fund Program, Transportation Research Report No. TRP 03-155-05, Project No. SPR-3(017)-Year 10, Project Code: RPFP-00-06, Midwest Roadside Safety Facility, University of Nebraska Lincoln, February 3, 2005.

14. Wiebelhaus, M.J., Terpsma, R.J., Lechtenberg, K.A., Reid, J.D., Faller, R.K., Bielenberg, R.B., Rohde, J.R., and Sicking, D.L., Development of Temporary Concrete Barrier to Permanent Concrete Median Barrier Approach Transition, Draft Report to the Midwest State's Regional Pooled Fund Program, Transportation Research Report No. TRP 03-208-09, Midwest Roadside Safety Facility, University of Nebraska Lincoln, July 8, 2009.