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EVALUATION OF EXISTING T-INTERSECTION GUARDRAIL SYSTEMS FOR EQUIVALENCY WITH *NCHRP REPORT 350* TL-2 TEST CONDITIONS

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16. Abstract

When a road or driveway intersects a highway with certain restrictive features (bridge rail, culvert …etc), it is difficult to fit the proper guardrail length (transition, length-of-need guardrail, and end treatment) along the primary roadway. Site constraints such as private driveways, state roads, and parish or county roads may intersect the primary road and not allow the placement of a properly designed guardrail length of need. In these cases, alternatives are to shorten the designed guardrail length, provide a curved or T-intersection guardrail design, or relocate the constraint blocking placement of the guardrail. This curved guardrail system is usually known as a short radius guardrail.

This study investigated the performance of previously tested short radius systems to determine if some of the previously tested short radius guardrail systems meet *NCHRP Report 350* TL- 2 evaluation criteria. A system designed and tested for Yuma County, Arizona was used as the basis for developing a short radius guardrail system that satisfies *NCHRP Report 350* TL-2.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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1.1. PROBLEM STATEMENT

When a road or driveway intersects a highway with certain restrictive features (bridge rail, culvert …etc), it is difficult to fit the proper guardrail length (transition, length-of-need guardrail, and end treatment) along the primary roadway. Site constraints such as private driveways, state roads, and parish or county roads may intersect the primary road and not allow the placement of a properly designed guardrail length of need.

In these cases, alternatives are to shorten the designed guardrail length, provide a curved or T-intersection guardrail design, or relocate the constraint blocking placement of the guardrail. This curved guardrail system is usually known as a short radius guardrail.

Numerous tests have been conducted on short radius guardrails; however none of the previous designs meet National Cooperative Highway Research Program (NCHRP) *Report 350* TL-3 *(1)*.

1.2. BACKGROUND

One of the earliest known series of tests of a short radius guardrail system was conducted by Southwest Research Institute (SwRI) per *NCHRP Report 230* guidelines in 1988 *(2)*. Later, SwRI conducted a series of tests for the Yuma County, AZ, Public Works Department and the tests were evaluated per *NCHRP Report 230* criteria (*3)*. Another series of tests were conducted by Texas Transportation Institute (TTI) per *NCHRP Report 230* and *NCHRP Report 350* guidelines under two different research projects in the early 1990s *(4, 5)*. In those tests, 178 mm (7 inches) diameter round wood posts were used in the system. The posts used in the curved section had 89 mm (3.5 inches) holes that are similar to the holes in the Controlled Released Terminal (CRT) wood post. There were no free standing posts in those tests. The weakened round wood posts broke readily once impacted by the test vehicles similar to the CRT wood post. More, recently, Midwest Roadside Safety Facility (MwRSF) embarked on testing a T-Intersection curved rail design per the *NCHRP Report 350* guidelines, but efforts to date have not been successful *(6, 7)*.

1.3. OBJECTIVE

The objective of this study is to investigate the performance of previously tested short radius systems to determine if some of the previously tested short radius guardrail systems meet *NCHRP Report 350* TL-2 evaluation criteria. The unique geometry of a short radius (T-Intersection) guardrail system makes it function more as a terminal/crash cushion rather than a longitudinal barrier. This was also articulated by researchers at MwRSF *(6)*. Hence, the terminal/crash cushion test matrix from *NCHRP Report 350* is used in this report to evaluate presented designs.

1.4. STUDY APPROACH

This study is undertaken to investigate the performance of previously tested short radius guardrail systems to determine if some of these previously tested short radius guardrail systems which would meets *NCHRP Report 350* TL-2 criteria. The study approach consists of (a) review *NCHRP Report 350* TL-2 test conditions and the crash test performed in a short radius guardrail treatment developed for Yuma County, Arizona, (b) comparison of *NCHRP Report 350* TL-2 test conditions with the Yuma County tests, and (c) discussion of the energy contribution of the free standing CRT post that were part of the original design during an impact.

1.5. NCHRP REPORT 350 TEST CONDITION

*NCHRP Report 350, "*Recommended Procedures for the Safety Performance Evaluation of Highway Features,*"* which was published in 1993, provides guidance on testing and evaluating roadside safety features. This report contains three test levels for crash cushions and terminals that place an increasing level of demand on the structural capacity of the system. Test levels 1 through 3 relate to passenger vehicles and vary by impact speed.

For T-intersection system, Test Level 2 (TL-2) matrix for terminals/crash cushions is applied herein. The conditions for this test level consist of an 820 kg (1800 lb) small car (designated as 820C in *NCHRP Report 350*) and 2000 kg (4409 lb) pickup truck (designated as 2000P in *NCHRP Report 350*) impacting the rail at 70 km/h (43.5 mph) at various angles as shown in Table 1.1. The researchers at MwRSF defined special impact points for a short radius guardrail system based on the matrix in Table 1.1 *(6)*. These same defined impact points are used in this report and are presented in Figure 1.1.

Table 1.1 *NCHRP Report 350* TL-2 Matrix for Terminals and Crash Cushions *(1)*

Feature	Feature Type[a]	Test Designation	Impact Conditions		
			Vehicle	Nominal speed (km/h)	Nominal angle, θ (deg)
Terminals and Redirective Crash Cushions	G/NG	2-30	820C	70	0
	G/NG	2-31	2000P	70	0
	G/NG	2-32	820C	70	15
	G/NG	2-33	2000P	70	15
	NG	2-36	820C	70	15
	NG	2-37	2000P	70	20
	NG	2-38	2000P	70	20
	G/NG	2-39	2000P	70	20

[a] G/NG – Test applicable to gating and nongating devices
NG - Test applicable to nongating devices

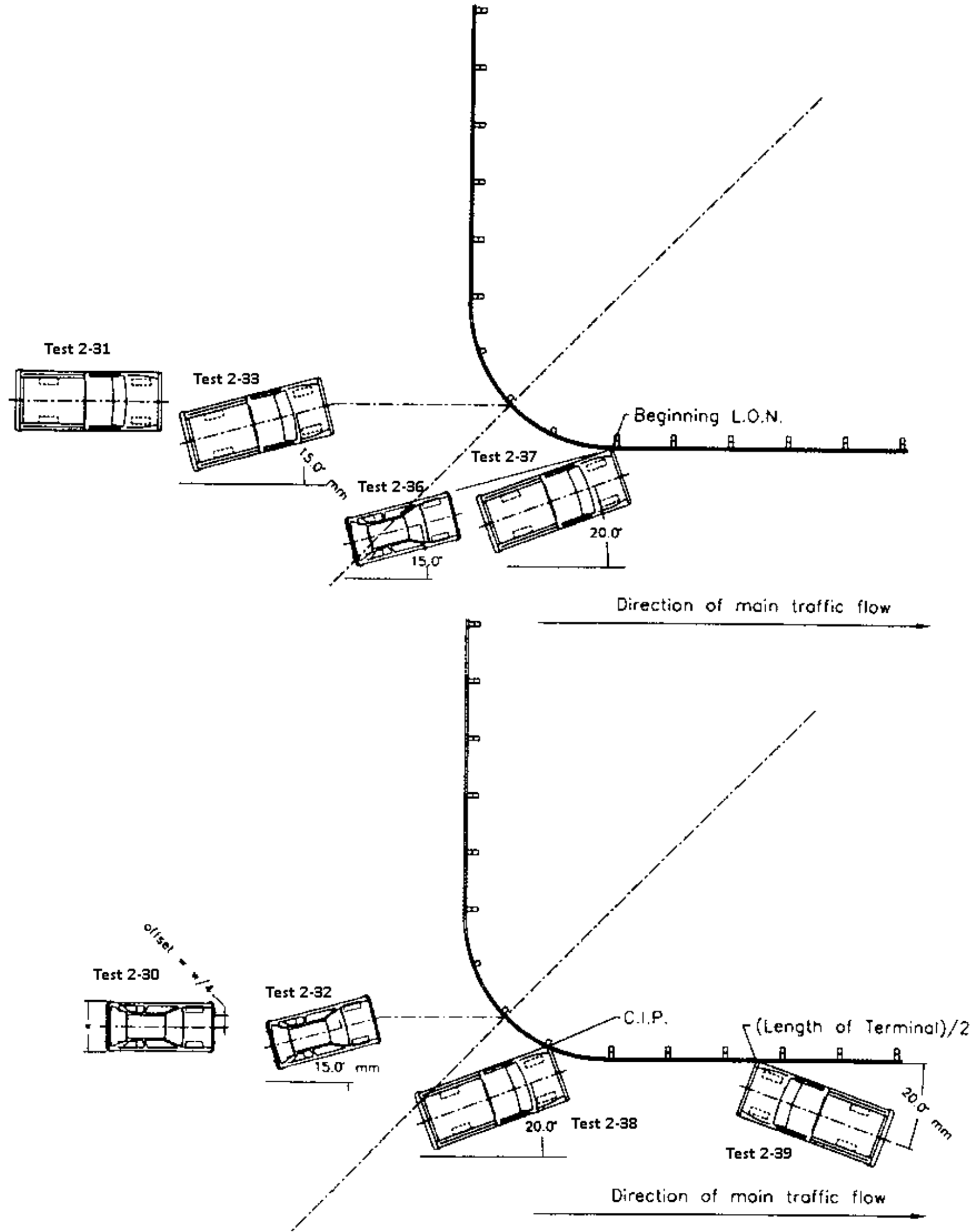


Figure 1.1 Crash test matrix for short-radius guardrail based on *NCHRP Report 350* Table 3.2 *(6)*

2. FULL-SCALE TESTING OF SHORT-RADIUS GUARDRAIL SYSTEM

Test and evaluation of T-intersection system was conducted by Southwest Research Institute for Yuma County, Arizona *(3)*. The test conditions were based on Performance Level 1 (PL-1) of the 1989 *AASHTO Bridge Specification (8)* which are summarized in Table 2.1. The test matrix used consisted of an 80.5 km/h (50 mph) impact with an 820 kg (1800 lb) small car and 72.42 km/h (45 mph) impact with a 2450 kg (5400 lb) pickup truck with various impact angles and locations.

Table 2.1 1989 *AASHTO Bridge Specification* PL-1 and PL-2 matrix *(8)*

Test Level		Vehicle	Nominal speed (mph)	Nominal angle (degree)
PL-1	small automobile	1800 lb (817 kg)	50 mph (81 km/h)	20
	pickup truck	5400 lb (2450 kg)	45 mph (72 km/h)	20
PL-2	small automobile	1800 lb (817 kg)	60 mph (97 km/h)	20
	pickup truck	5400 lb (2450 kg)	60 mph (97 km/h)	20

The test system used in the Yuma County (YC) study consisted of a 2.44 m (8 ft) radius curved section connected to a 7.62 m (25 ft) long flared on the primary road and a 3.81 m (12.5 ft) long tangent section on the secondary road. Layout of the test system is shown in Figure 2.1. Three Controlled Released Terminal (CRT) posts were installed in the curved section (Post 3, 4, and 5) at a spacing of 1.91 m (6.25 ft). Two free standing CRT posts were installed on a 2.03 m (6.67 ft) radius behind the curved section to decrease the vehicle stopping distance.

The downstream end of the rail on the primary road transitioned into a bridge rail. The guardrail on the secondary road terminated into a standard Breakaway Cable Terminal (BCT). The bridge rail consists of 0.3 m (1 ft) high concrete curb and 0.41 m (16 inches) high W 6 × 15.5 posts spaced at 1.91 m (6 ft-3 inches) center to center. The bridge rail consisted of standard 12 gauge W-beam guardrail, supported by an MC 200 x 33.9 (MC 8 × 22.8) structural steel channel extending out beyond the end of the bridge deck 1.91 m (6 ft-3 inch). Total bridge rail height was 0.69 m (27 inches) above grade.

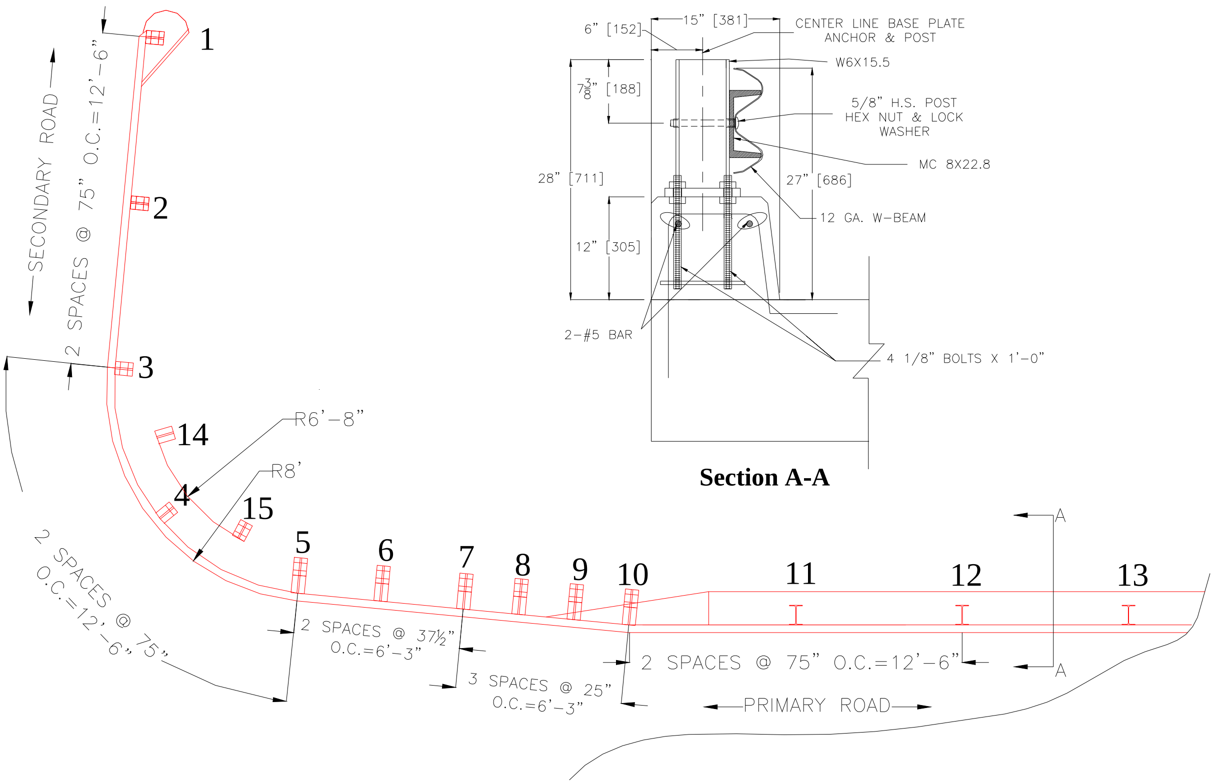


Figure 2.1 Yuma County test T-intersection installation for Test YC-1 through YC-3

The crash tests were conducted in the following order to reduce system repair between impacts as follows;

1. Tests YC-1 and YC-2 were conducted to investigate the risk of spearing and vaulting;
   YC-1: a 2439 kg (5376 lb) pickup truck with a 72.42 km/h (45 mph) velocity
   YC-2: an 897 kg (1978 lb) small car with a 80.9 km/h (50.3 mph) velocity

2. Tests YC-3, YC-4 and YC-5 were conducted to evaluate vehicle containment and barrier strength;
   YC-3 (failed) and YC-4 (modified YC-3 system):
   a 2440 kg (5380 lb) pickup truck with a 72.1 km/h (44.8 mph) velocity
   YC-5: an 898 kg (1980 lb) small car with a 71.1 km/h (44.2 mph) velocity

3. Tests YC-6 and YC-7 were conducted to investigate the risk of pocketing or wheel snag;
   YC-6: an 898 kg (1980 lb) small car with a 82.2 km/h (51.1 mph) velocity
   YC-7: a 2460 kg (5424 lb) pickup truck with a 72.74 km/h (45.2 mph) velocity

After tests YC-1 and YC-2, the system was restored to original condition. After conducting test YC-3, the test system was modified to prevent the secondary roadway terminal from releasing. Modification of the system consisted of lengthening the secondary roadside segment of the system from 3.81 m (12.5 ft) to 5.72 m (18.75 ft) as show in Figure 2.2. The summary of tests conditions and results are described in Table 2.2.

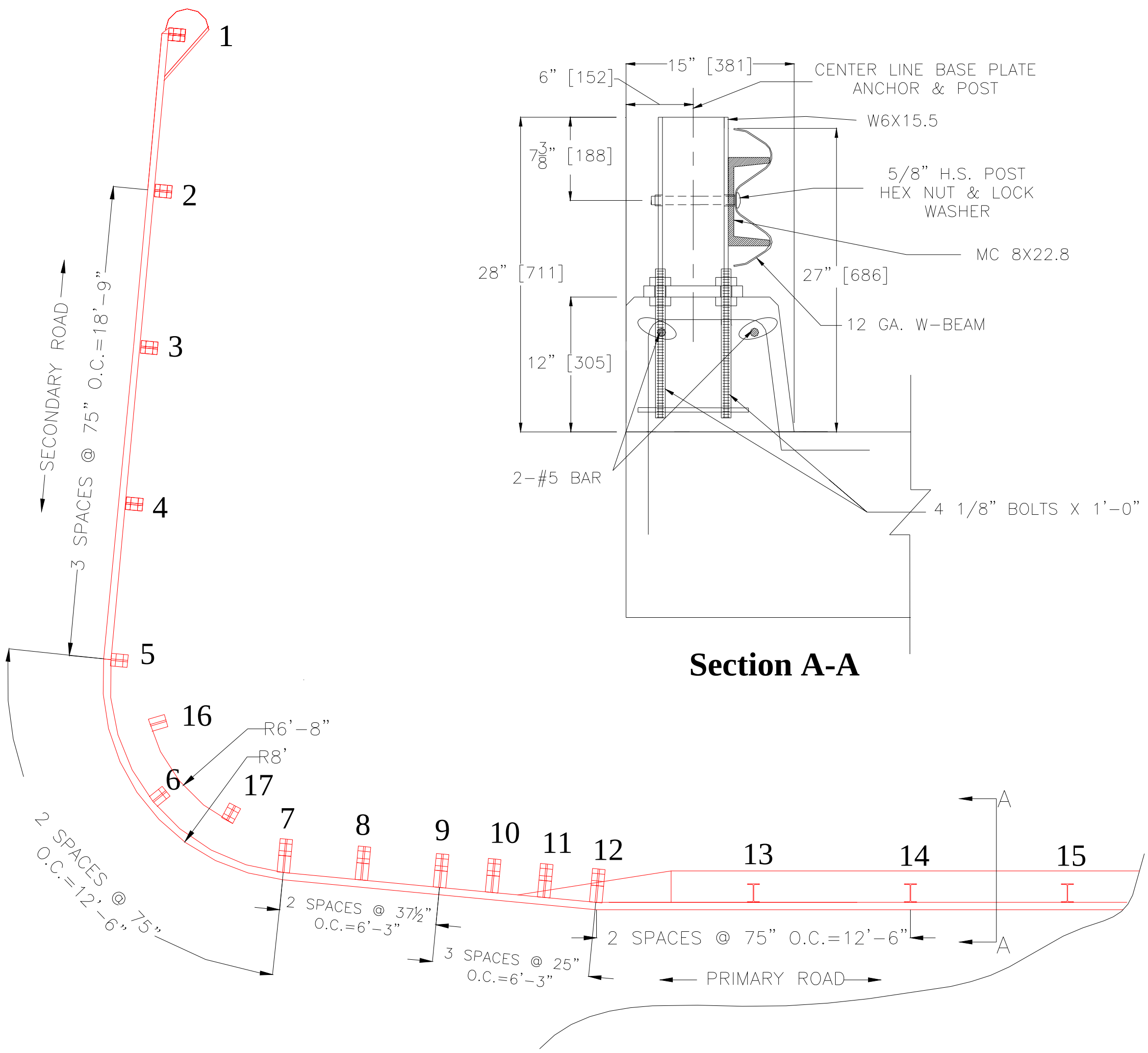


Figure 2.2 Modified Yuma County test T-intersection installation for Test YC-4 through YC-7

Table 2.2 Full-Scale Yuma County Test Results *(3)*

Test No	YC-1	YC-2	YC-3	YC-4	YC-5	YC-6	YC-7
Test Parameters for PL1 Service	5400lb/0 deg/45mph	1800lb/0 deg/50mph	5400lb/20deg/45mph	5400lb/20deg/45mph	1800lb/20deg/50mph	1800lb/20deg/50mph	5400lb/20deg/45mph
Test Vehicle	1982 Chevrolet P/U	1982 V. W. Rabbit	1984 Ford P/U	1984 Ford P/U	1982 V. W. Rabbit	1982 V. W. Rabbit	1984 Ford P/U
Gross Vehicle Weight - [lb]	5376	1978	5380	5381	1980	1980	5424
Impact Speed (film) - [mph]	45	50.3	44.8	44.9	44.2	51.1	45.2
Impact Angle - [degrees]	1.4	0.7	19.7	20.1	20.0	19.4	20.7
Exit Angle (film) - [degrees]	18.8	-12.4	Did Not Exit	Did Not Exit	Did Not Exit	-7.6	-15.4
Exit Speed (film) - [mph]	32.8	44.4	Did Not Exit	Did Not Exit	Did Not Exit	34.2	32.5
Maximum 50 msec Avg Accel (film/accelerometer)							
Longitudinal - [g's]	-2.2/-3.3	-1.8/-3.3	-6.3/-4.2	-4.0/-4.4	-4.6/-7.9	-5.8/-7.6	-4.2/-3.9
Lateral - [g's]	-2.1/-3.6	-6.1/-6.4	-4.4/2.87	3.3/4.1	1.8/2.6	-7.4/-12.3	-5.0/-5.8
Occupant Risk, NCHRP Report 230 * (film/accelerometer)							
Δ V long, - [fps] (30)	12.0/14.4	5.9/9.4	19.1/14.5	20.7/20.1	24.9/27.8	19.1/6.8	6.5/2.2
Δ V lat. - [fps] (20)	11.8/7.8	14.6/16.0	-9.5/-8.3	-14.6/-11.0	-8.2/-7.3	20.5/22.7	18.9/18.7
Ridedown Accelerations, [g's] (accel)							
Longitudinal (15)	-2.7	-0.7	-6.5	-5.6	-10.5	-0.1	-2.8
Lateral (15)	-7.1	-4.7	4	-2.9	3.3	-6.8	-8.9
NCHRP Report Evaluation							
Structural Adequacy (A, D)	Passed	Passed	Failed	Passed	Passed	Passed	Passed
Occupant Risk (E)	Passed	Passed	Passed	Passed	Passed	Marginal, lat vel. >20fps	Passed
Vehicle Trajectory (H, I)	Passed	Passed	Passed	Passed	Passed	Passed	Passed

* Numbers in parentheses are recommended in NCHRP Report 230.

2.1. TEST YC-1

Figure 2.3 and Figure 2.4 show test YC-1 impact condition and the subsequent vehicle trajectory. Once the vehicle impacted the barrier, it was redirected without any spearing or ramping as shown in Figure 2.5. Post 5 was fractured and posts 6 through 8 were deflected during the impact.

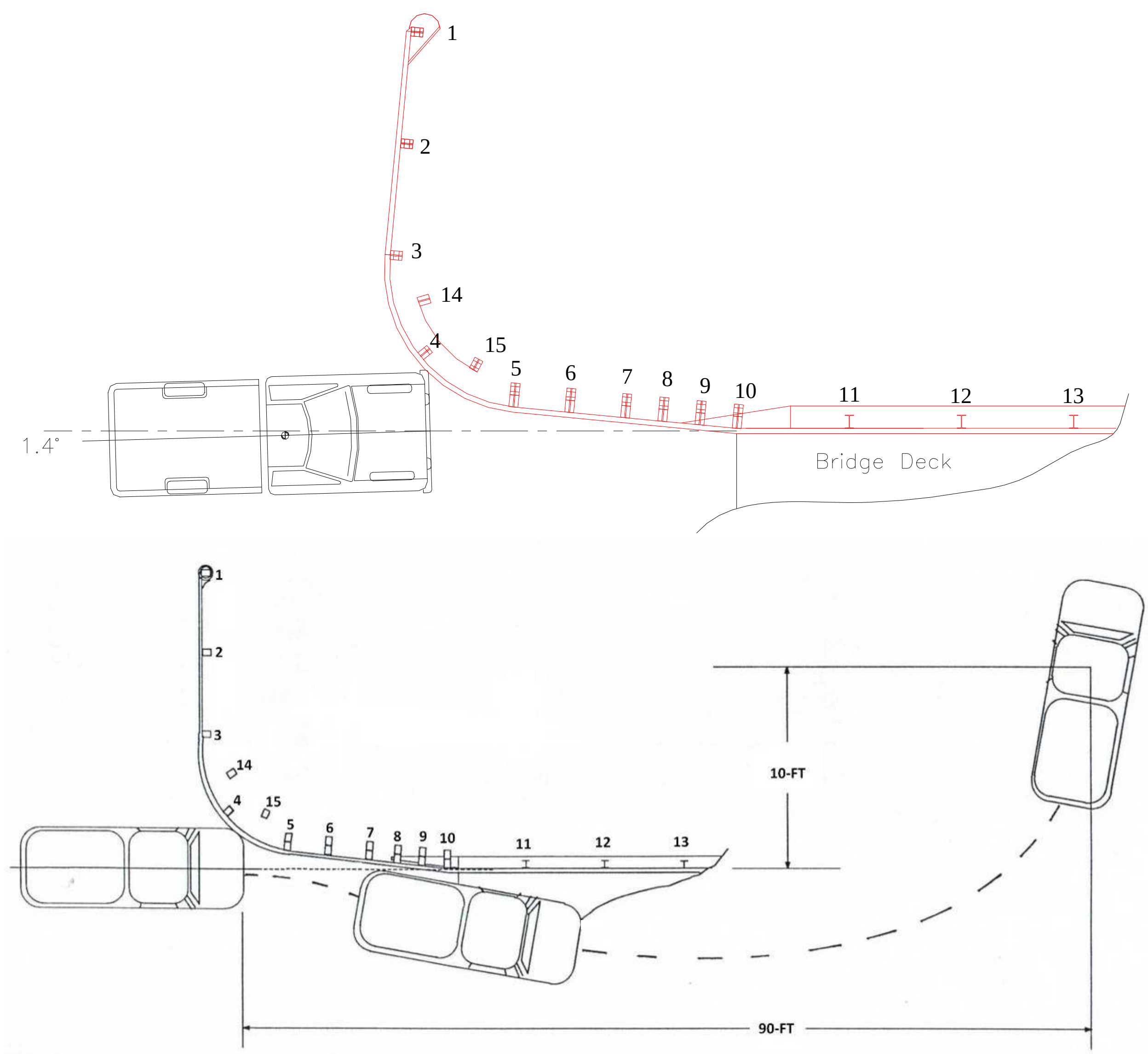
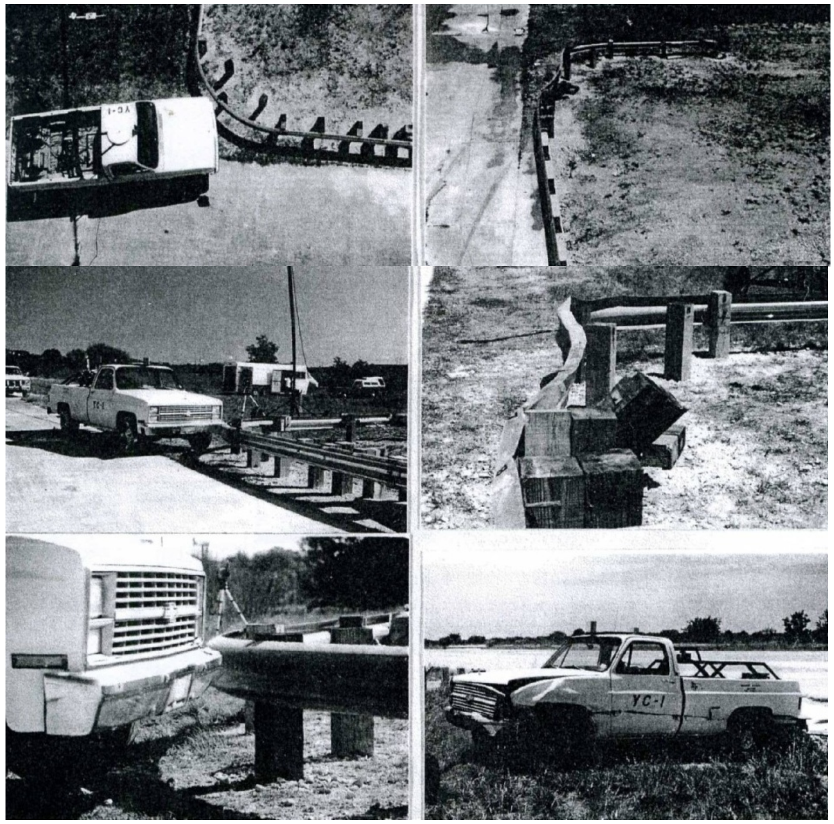


Figure 2.3 Test YC-1 (1982 Chevrolet P/U, 5376 lb pickup, 45 mph, and 1.4 degrees) -passed for structural adequacy, occupant risk, and vehicle trajectory *(3)*



(a) Before test **(b) After test**

Figure 2.4 Impact conditions and YC-1 system damage *(3)*

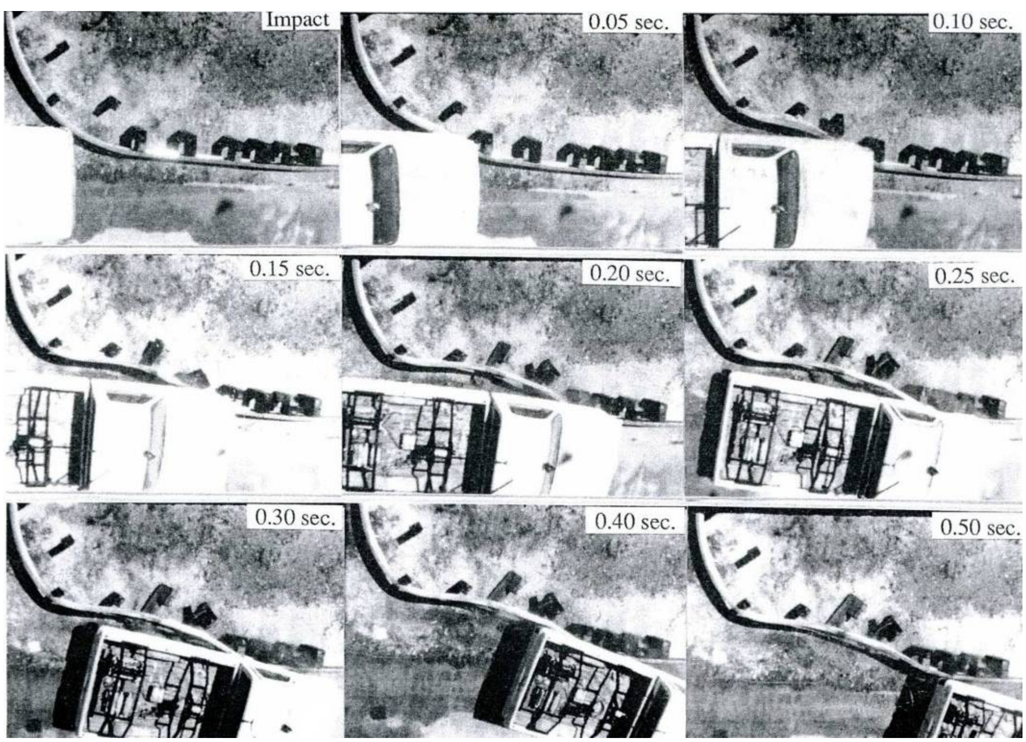


Figure 2.5 Overhead impact sequence photographs, Test YC-1 *(3)*

2.2. TEST YC-2

Figure 2.6 and Figure 2.7 show test YC-2 impact condition and the subsequent vehicle trajectory. The vehicle was redirected without any spearing or ramping as shown in Figure 2.8. Only cosmetic marks on the rail portion between posts 4 and 9 were observed.

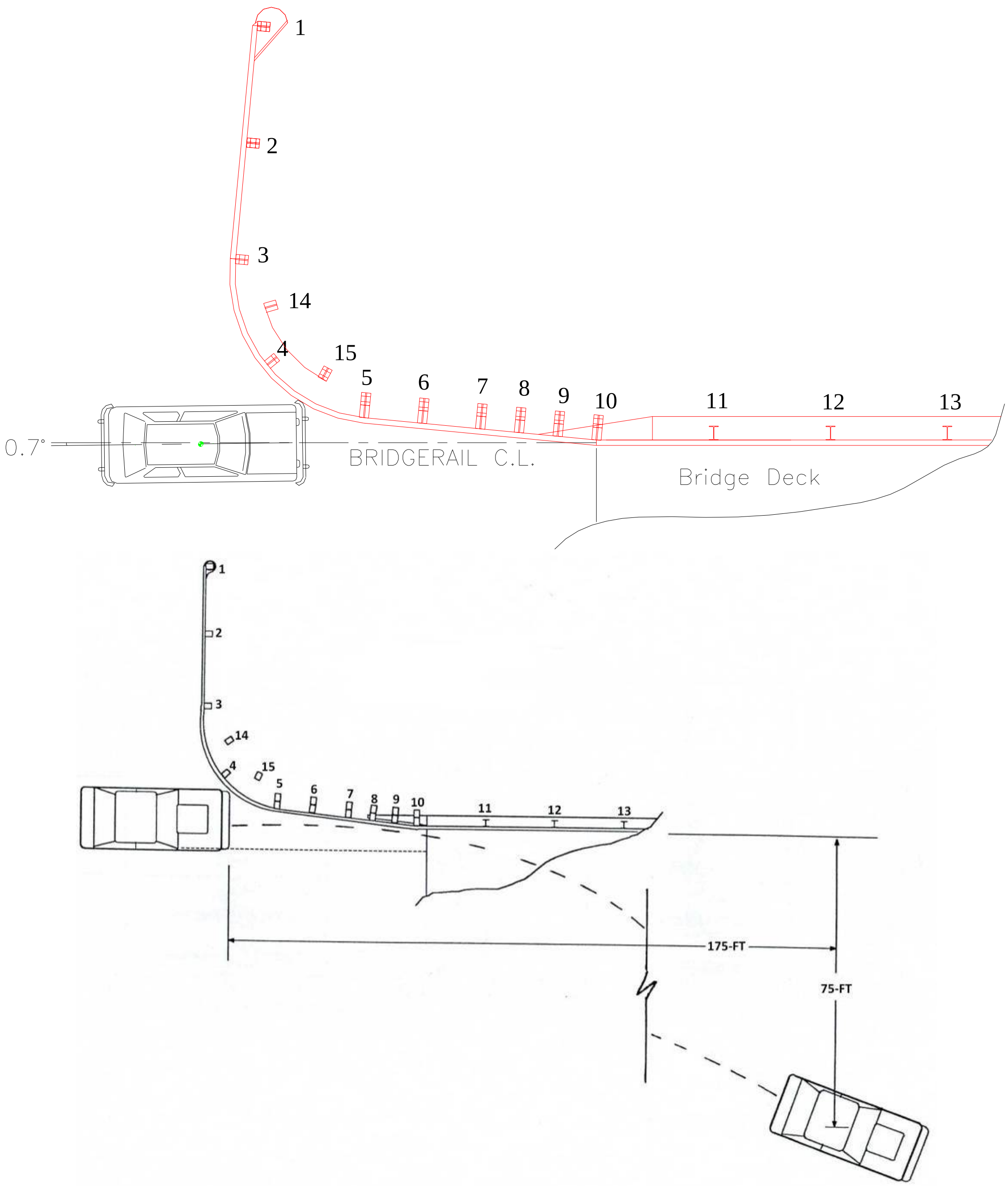


Figure 2.6 Test YC-2 (1982 V.W. Rabbit, 1978 lb mini car, 50.3 mph, and 0.7 degrees) -passed for structural adequacy, occupant risk, and vehicle trajectory *(3)*

(a) Before test **(b) After test**

Figure 2.7 Impact conditions and YC-2 system damage *(3)*

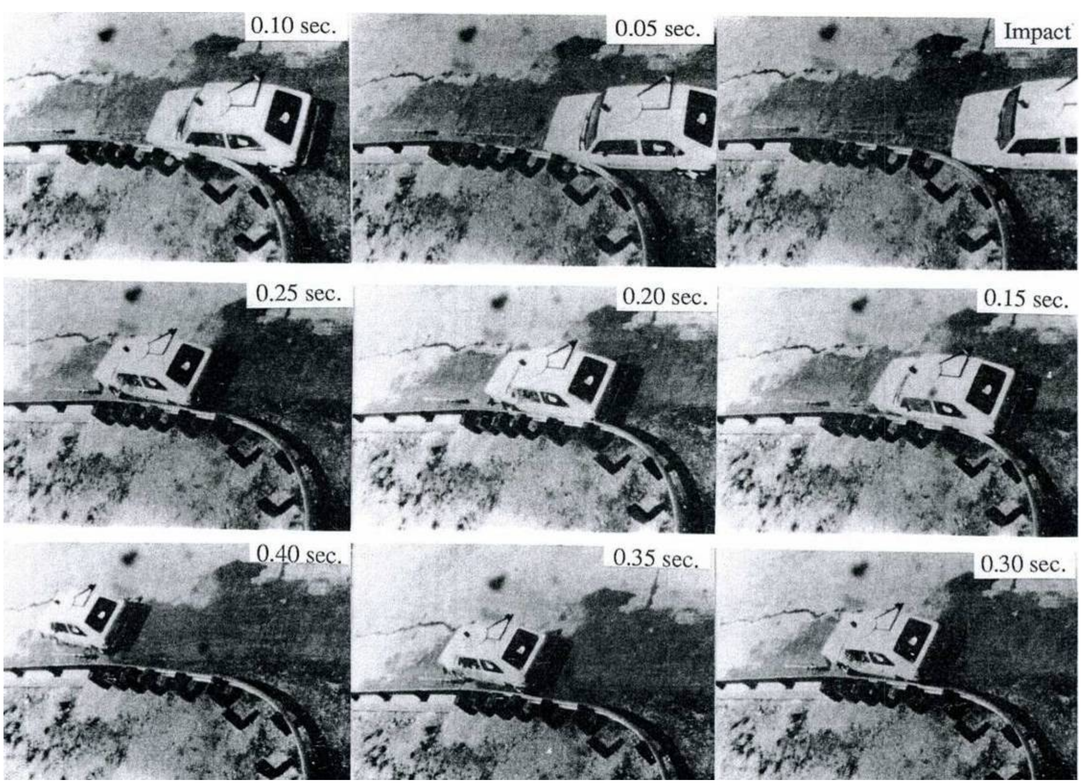


Figure 2.8 Overhead impact sequence photographs, Test YC-2 *(3)*

2.3. TEST YC-3

Figure 2.9 and Figure 2.10 show test YC-3 impact condition and the subsequent vehicle trajectory. The barrier failed to contain the vehicle as shown in Figure 2.11. Ten posts (No.1 through No. 8, No. 14, and No.15) were fractured. The termination on the secondary road failed and the released rail swung inward behind the bridge rail.

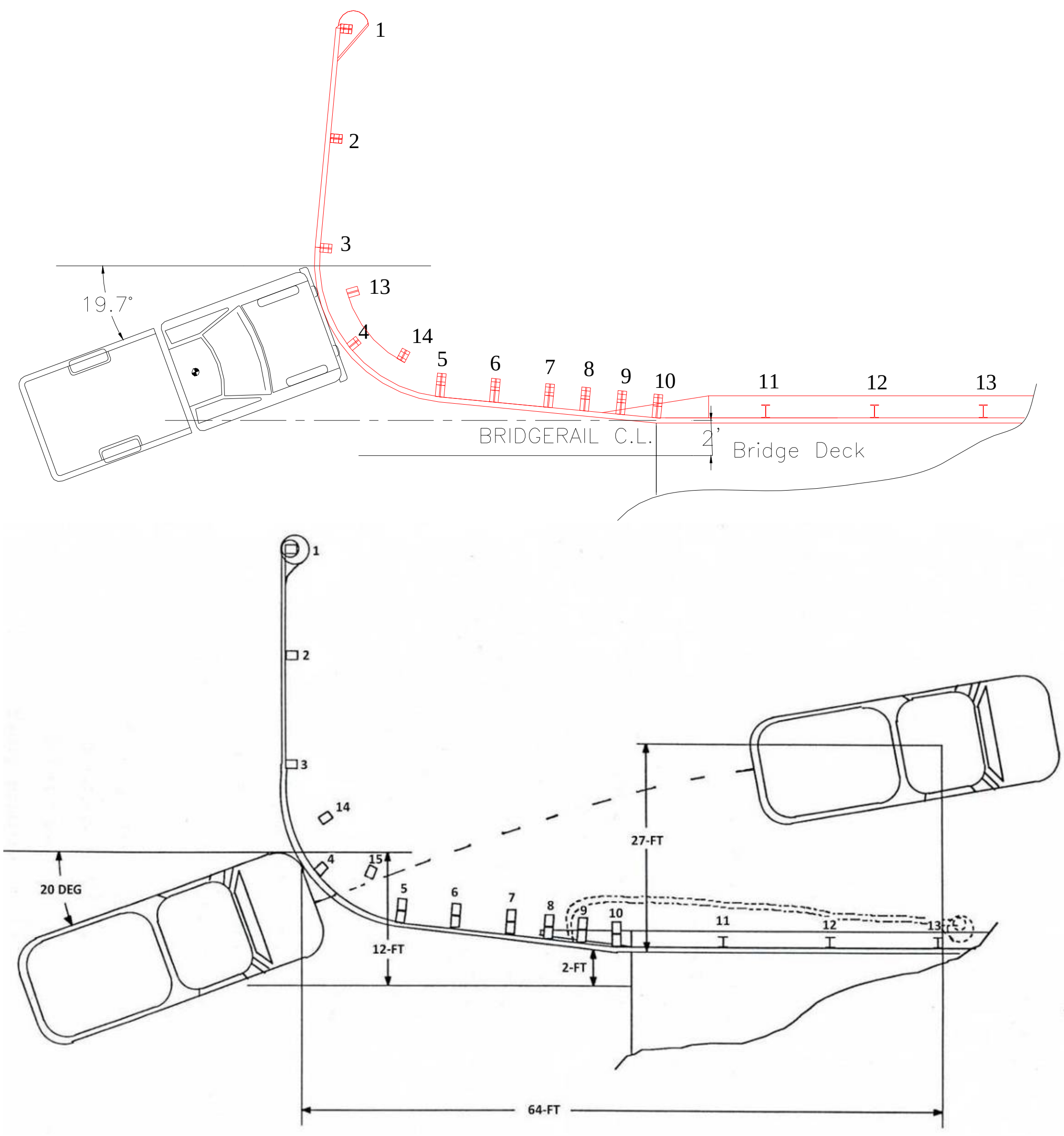
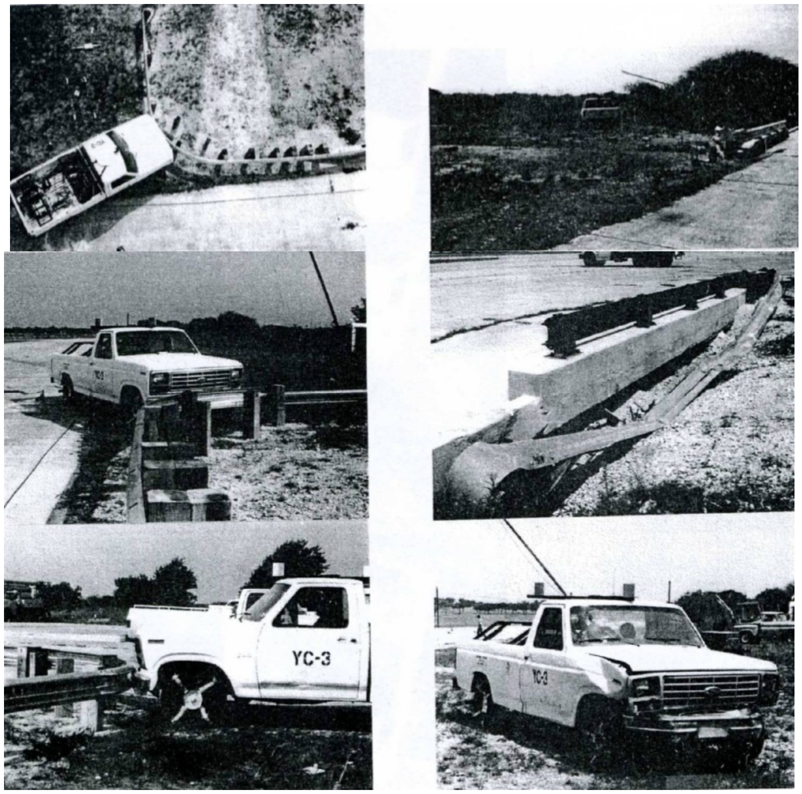


Figure 2.9 Test YC-3 (1982 Chevrolet P/U, 5380 lb pickup, 44.8 mph, and 19.7 degrees) -failed for structural adequacy, passed for occupant risk, and vehicle trajectory *(3)*



(a) Before test (b) After test

Figure 2.10 Impact conditions and YC-3 system damage *(3)*

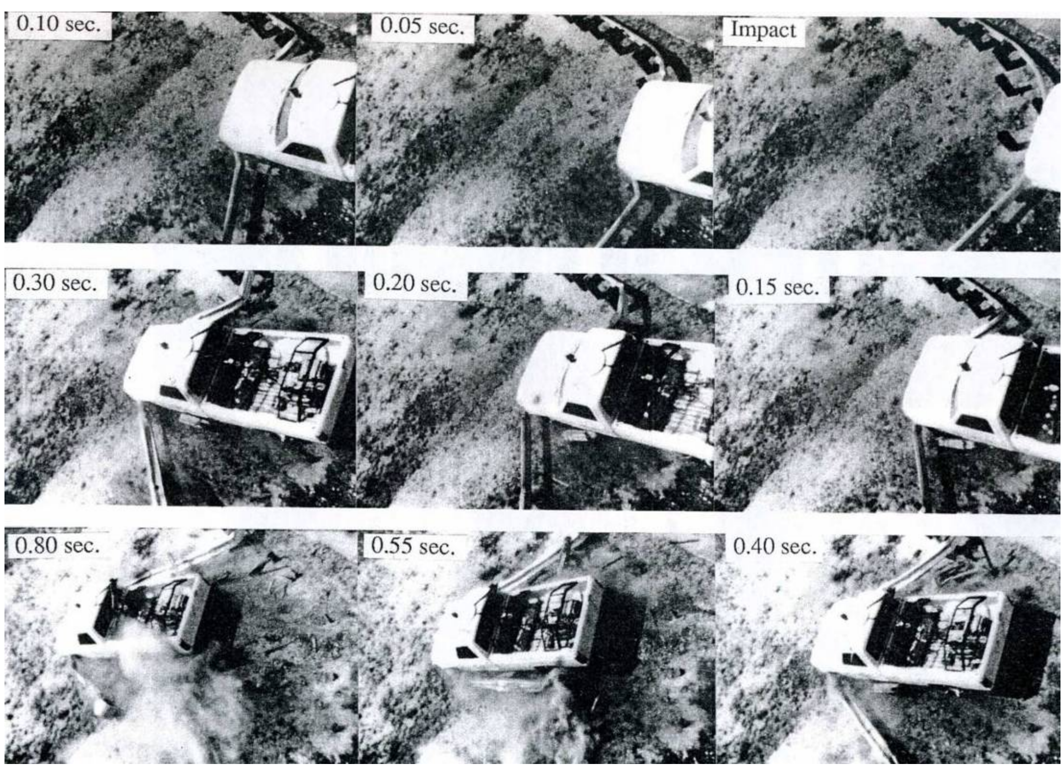


Figure 2.11 Overhead impact sequence photographs, Test YC-3 *(3)*

2.4. TEST YC-4

Since test YC-3 failed to contain the vehicle, the system was modified to prevent the secondary roadway terminal from failing and releasing the rail. Figure 2.12 and Figure 2.13 show test YC-4 impact condition and the subsequent vehicle trajectory. The vehicle was successfully contained although the barrier deflected 6.1 m (20 ft) as shown in Figure 2.14. Posts 3 through 9 as well as the two free standing posts (No. 16 and No. 17) were fractured.

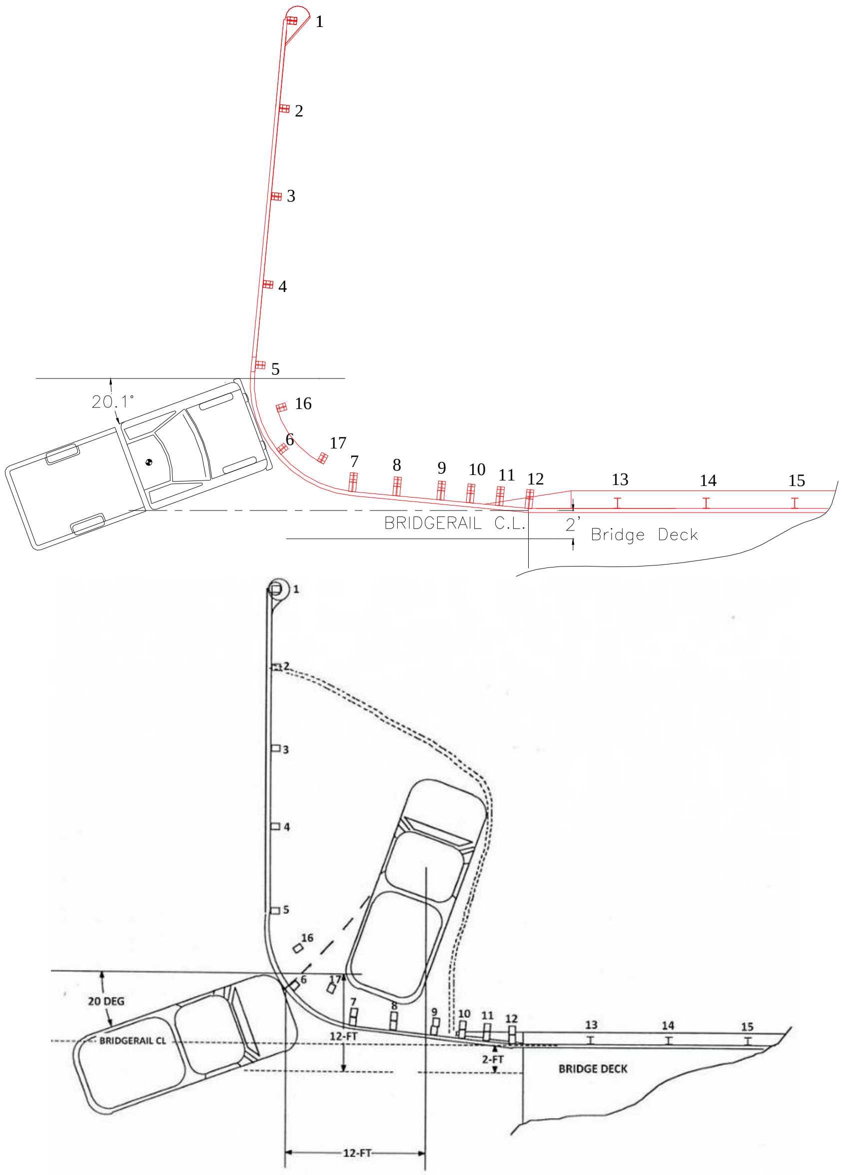
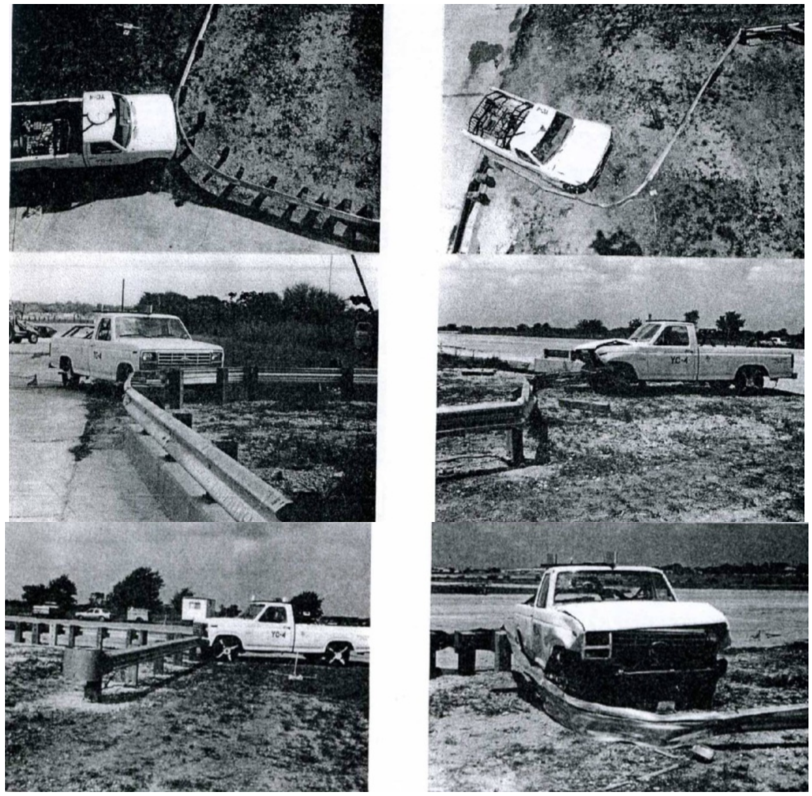


Figure 2.12 YC-4 (1982 Chevrolet P/U, 5381 lb pickup, 44.9 mph, and 20.1 degrees) -passed for structural adequacy, occupant risk, and vehicle trajectory (H, I) *(3)*



(a) Before test (b) After test

Figure 2.13 Impact conditions and YC-4 system damage *(3)*

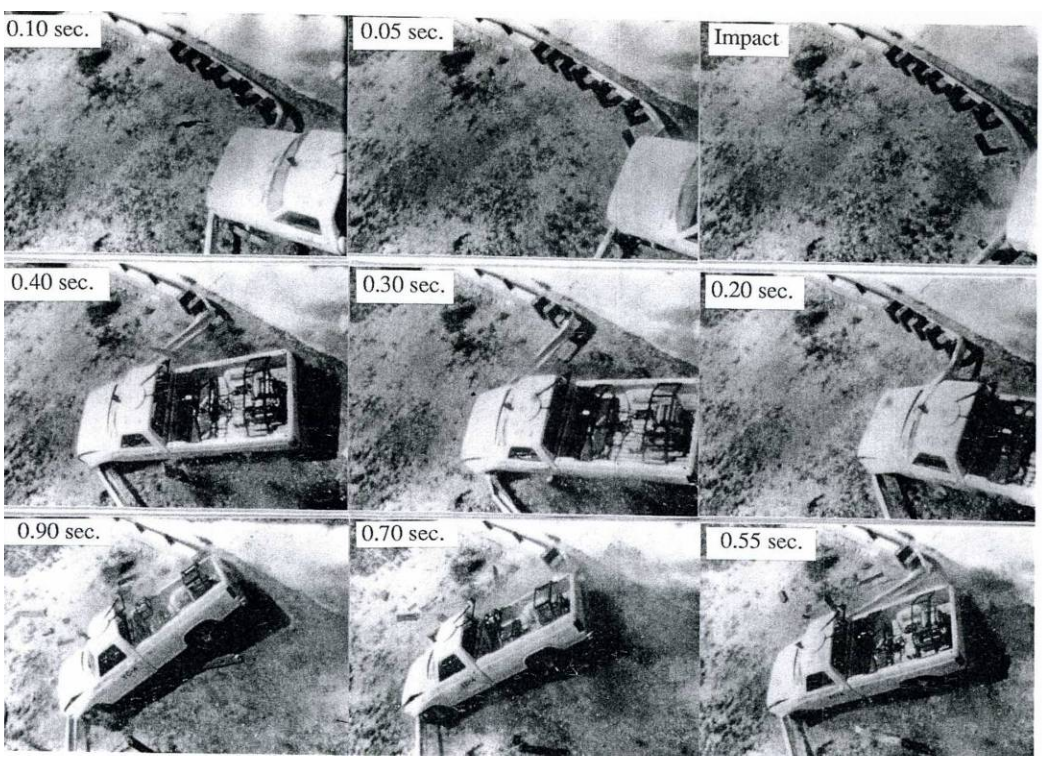


Figure 2.14 Overhead impact sequence photographs, Test YC-4 *(3)*

2.5. TEST YC-5

Figure 2.15 and Figure 2.16 show test YC-5 impact condition and the subsequent vehicle trajectory. The vehicle was successfully contained and the barrier deflected 5.49 m (18 ft) as shown in Figure 2.17. Posts 4 through 10 as well as the two free standing posts (No. 16 and No. 17) were fractured.

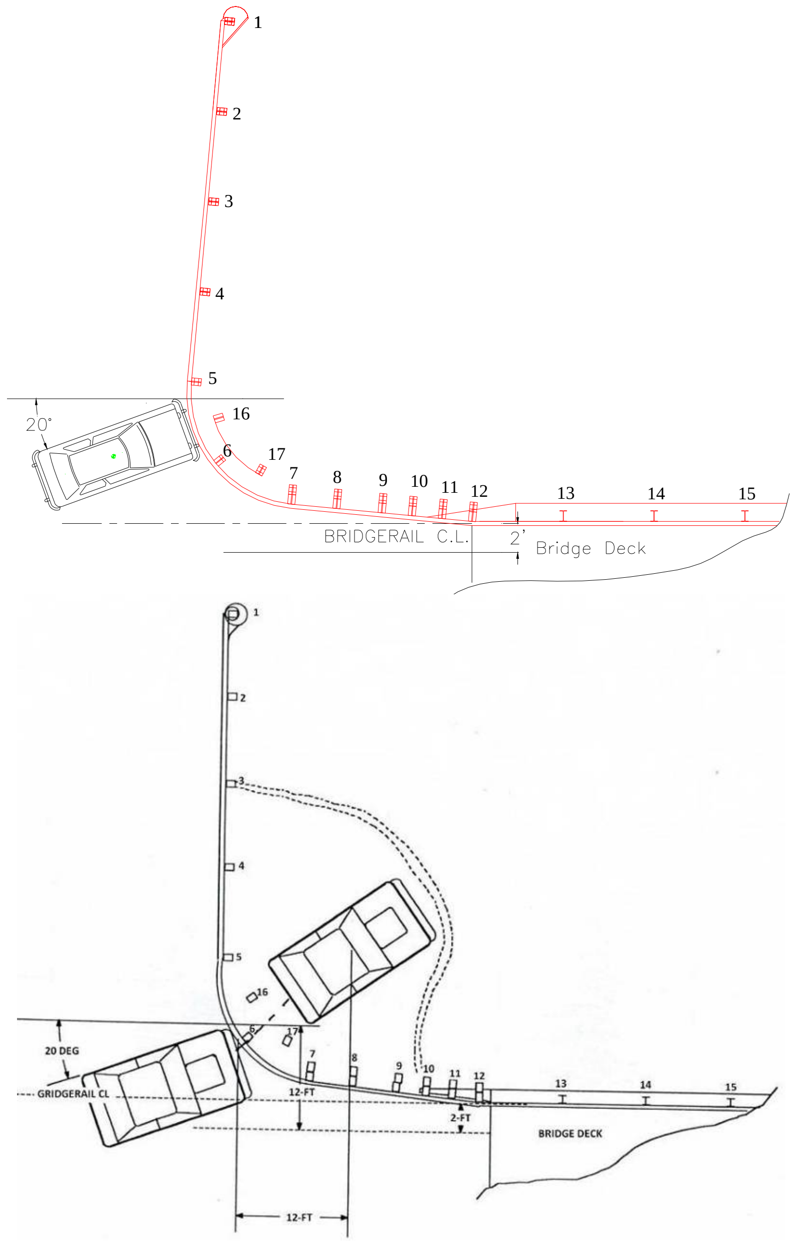
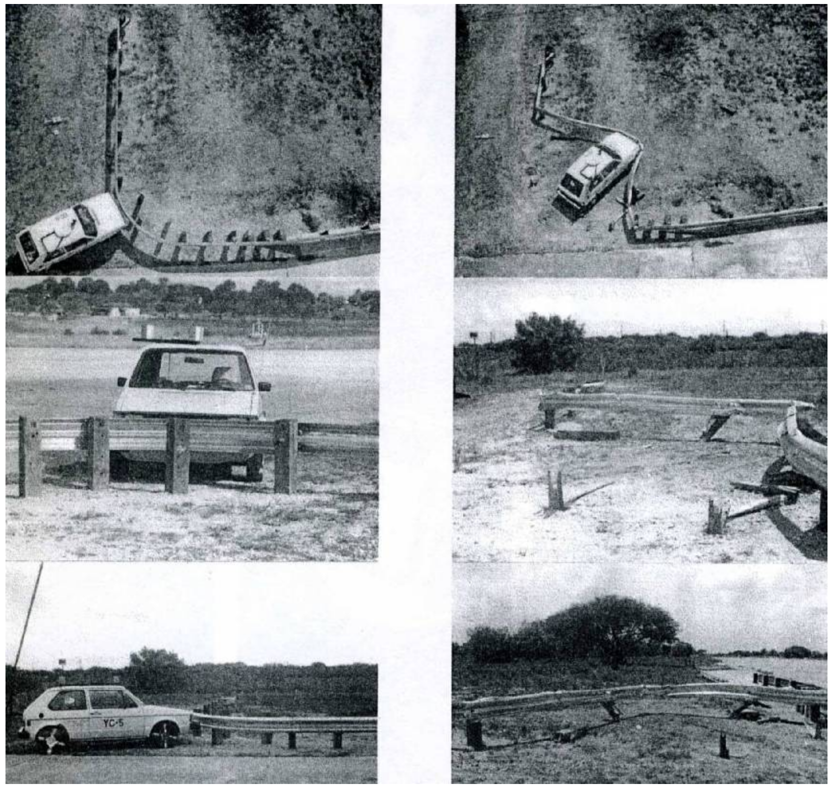


Figure 2.15 YC-5 (1982 V.W. Rabbit, 1980 lb mini car, 44.2 mph, and 20 degrees) -passed for structural adequacy, occupant risk, and vehicle trajectory *(3)*



(a) Before test **(b) After test**

Figure 2.16 Impact conditions and YC-5 system damage *(3)*

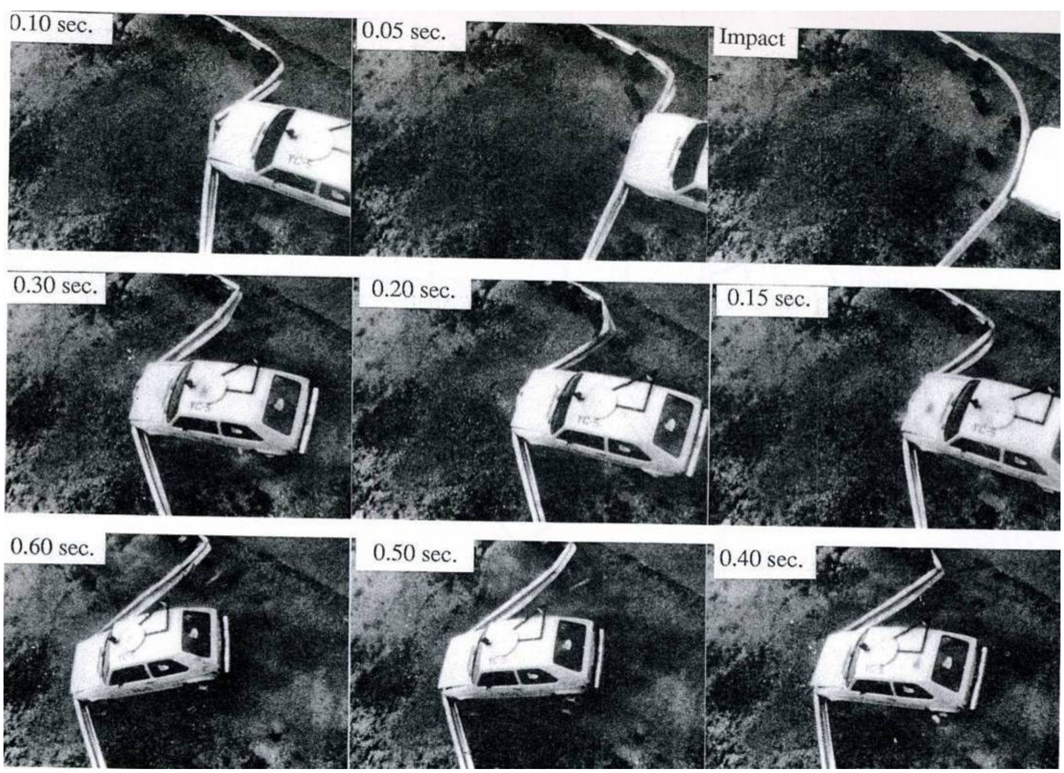


Figure 2.17 Overhead impact sequence photographs, Test YC-5 *(3)*

2.6. TEST YC-6

Figure 2.18 and Figure 2.19 show test YC-6 impact condition and the subsequent vehicle trajectory y. The vehicle impacted the barrier and was redirected without pocketing as shown in Figure 2.20. Only cosmetic damage on the rail and the concrete curb were observed in the impact area.

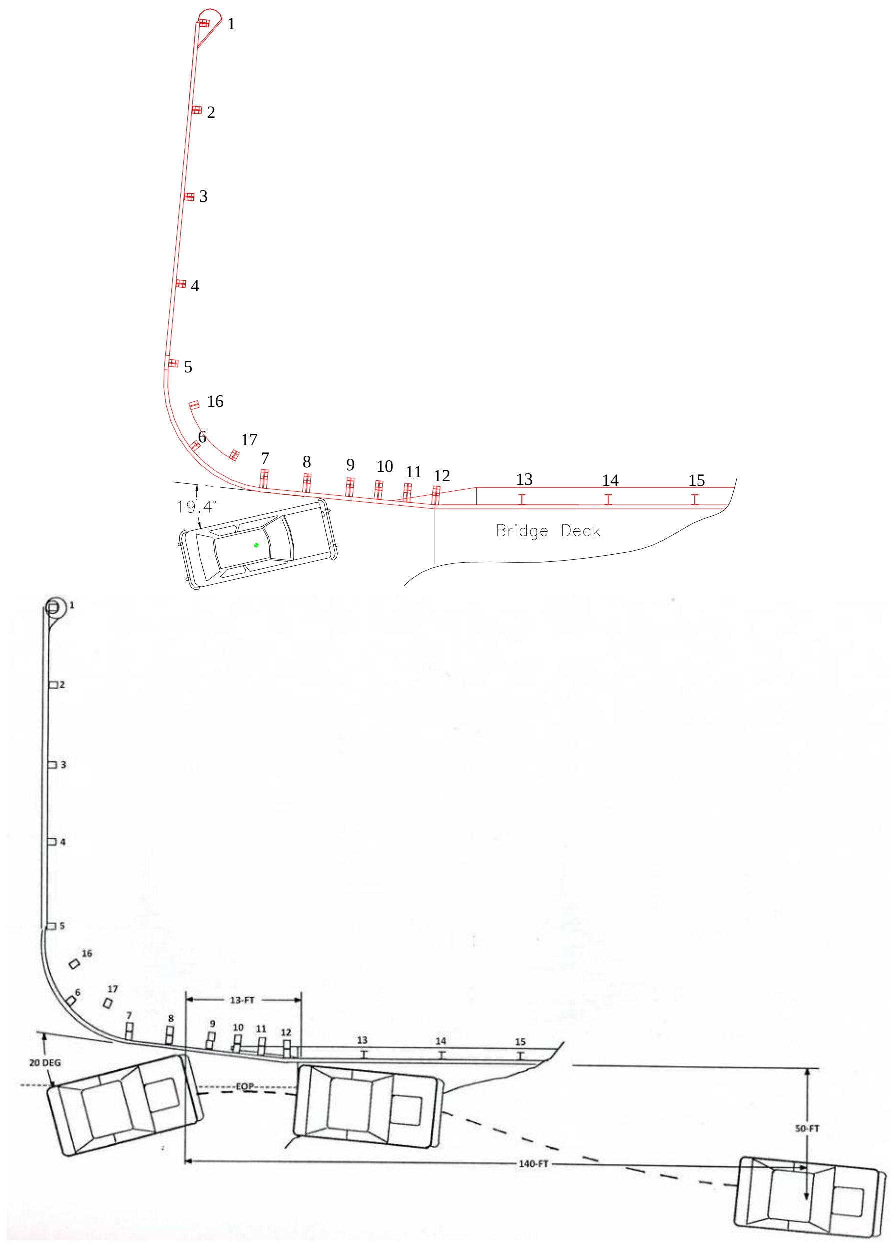
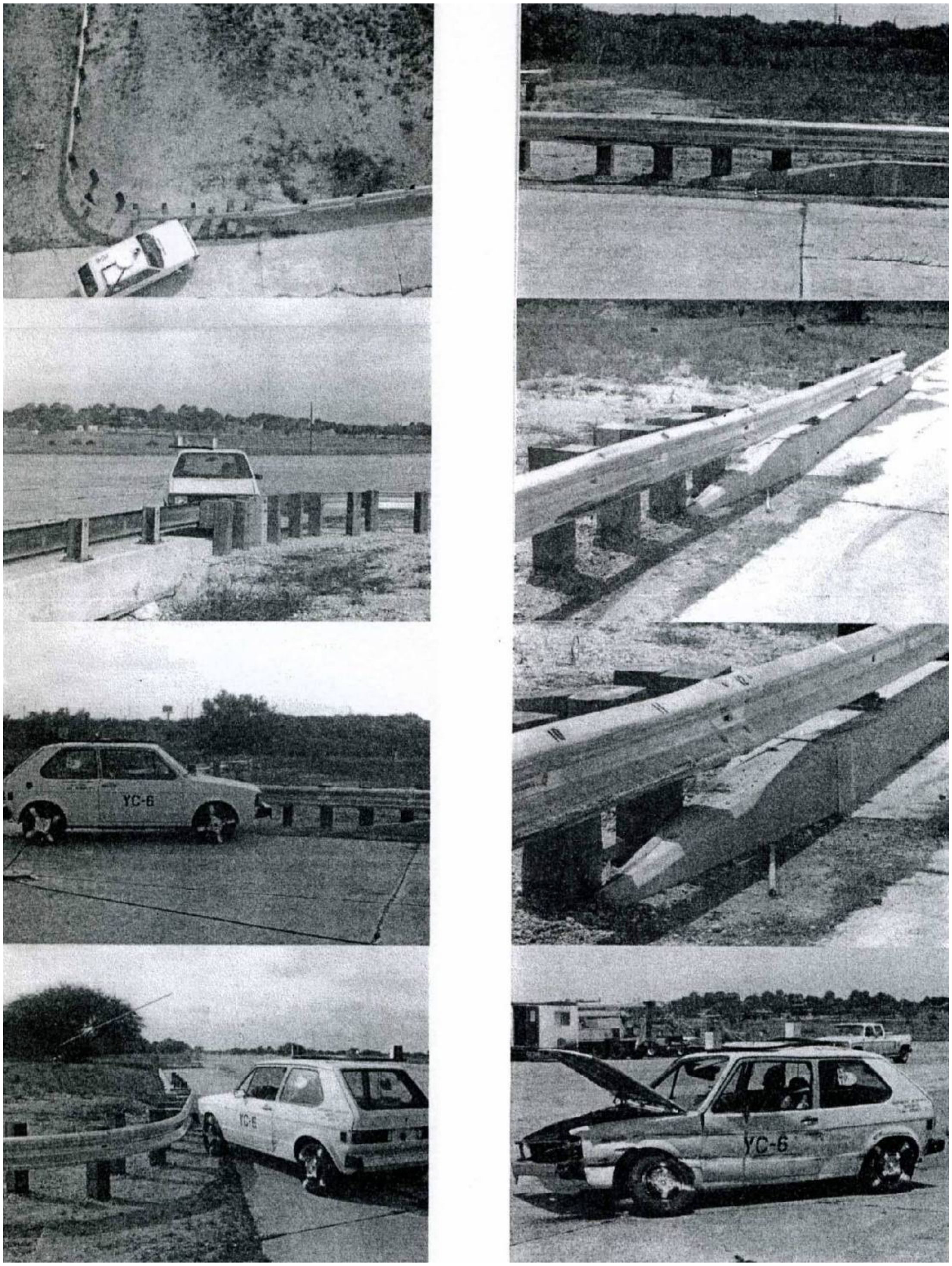


Figure 2.18 YC-6 (1982 V.W. Rabbit, 1980 lb mini car, 51.1 mph, and 19.4 degrees) -passed for structural adequacy and vehicle trajectory -marginals for occupant risk *(3)*



(a) Before test **(b) After test**

Figure 2.19 Impact conditions and YC-6 system damage *(3)*

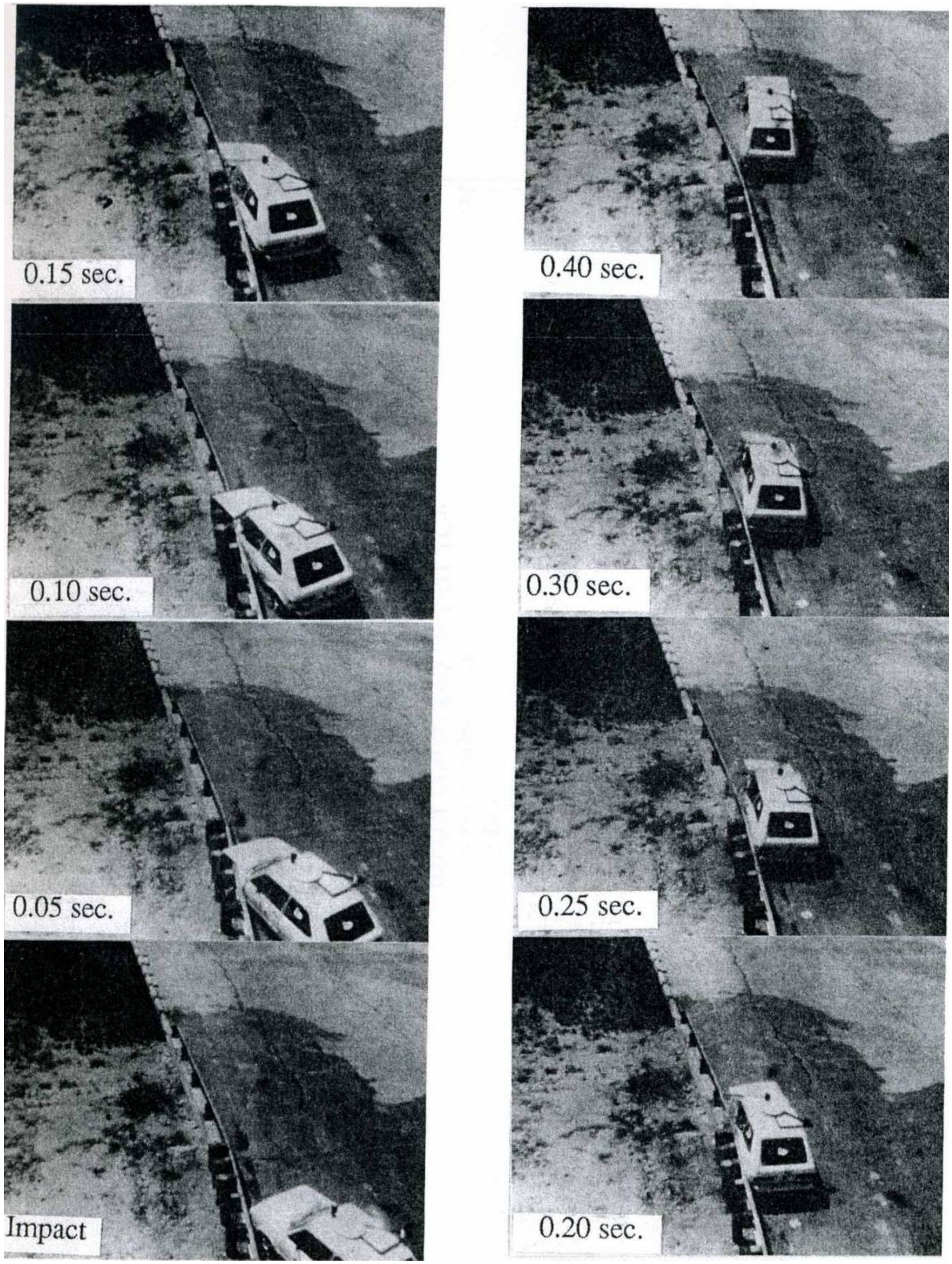
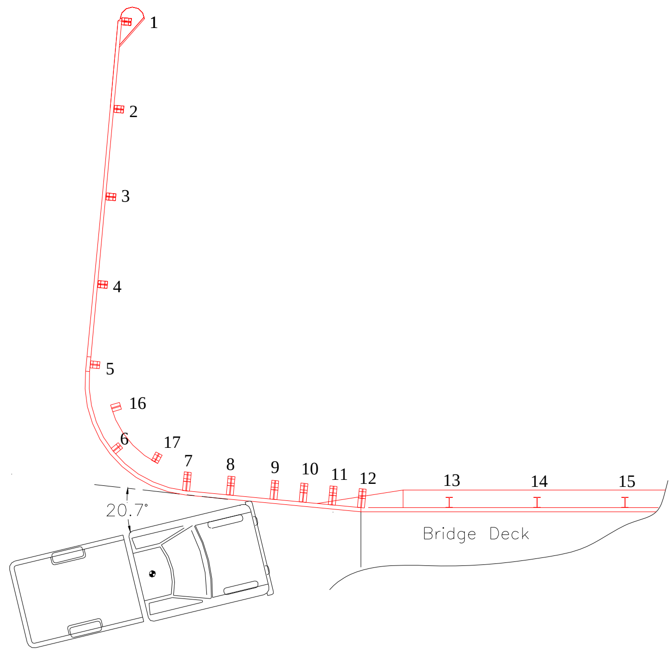


Figure 2.20 Overhead impact sequence photographs, Test YC-6 *(3)*

2.7. TEST YC-7

Figure 2.21 and Figure 2.22 show test YC-7 impact condition and the subsequent vehicle trajectory. The vehicle impacted the barrier and was redirected without pocketing as shown in Figure 2.23. No posts were fractured, however, the rail area next to post No. 9 was deformed due to impact.



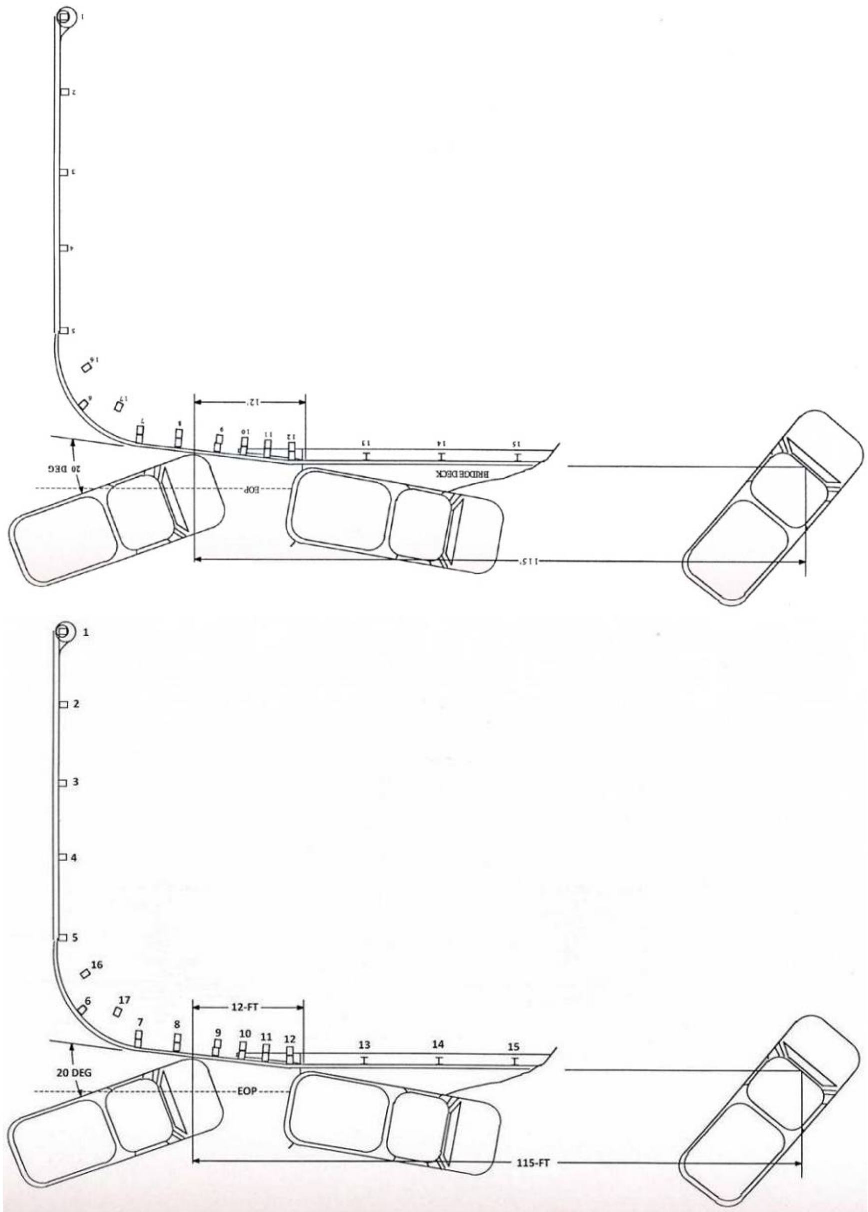
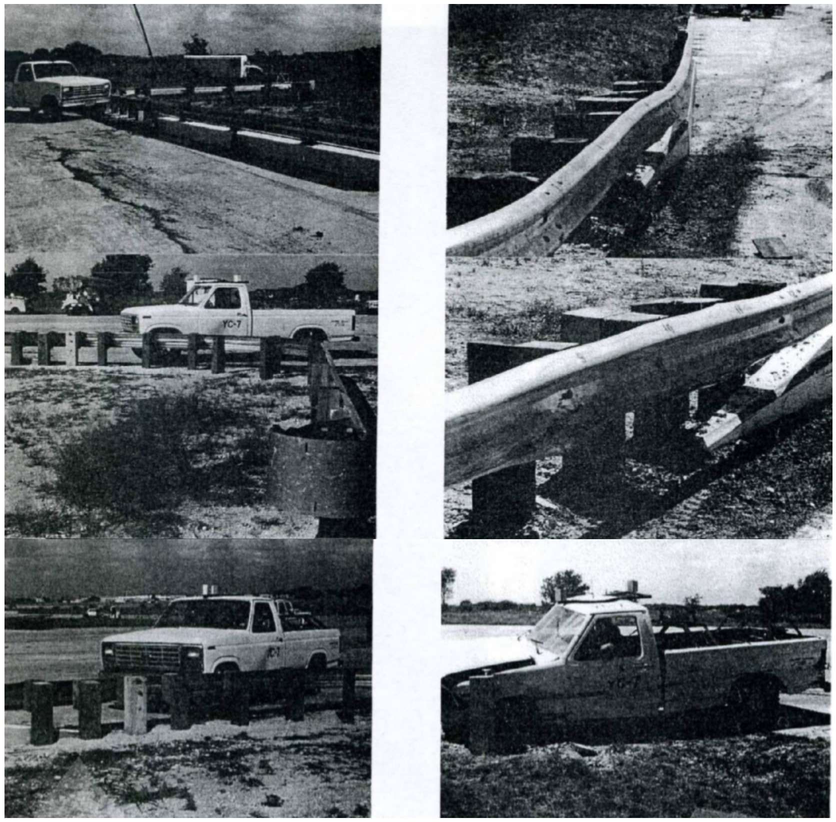


Figure 2.21 YC-7 (1982 Chevrolet P/U, 5424 lb pickup, 45.2 mph, and 20.7 degrees) - passed for structural adequacy, occupant risk, and vehicle trajectory *(3)*



(a) Before test **(b) After test**

Figure 2.22 Impact conditions and YC-7 system damage *(3)*

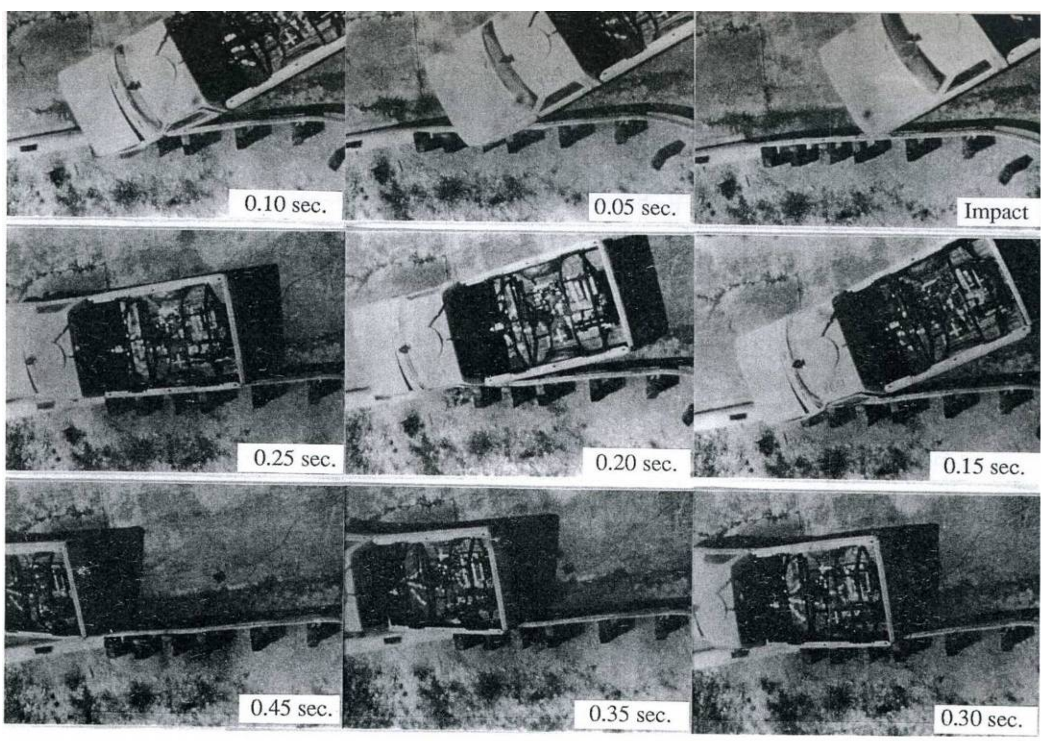


Figure 2.23 Overhead impact sequence photographs, Test YC-7 *(3)*

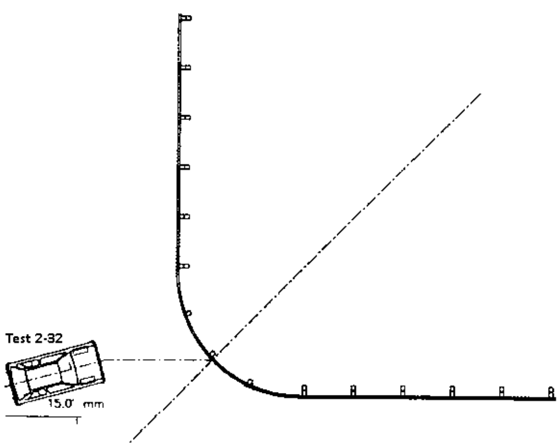
3. COMPARISON OF YUMA COUNTY TESTS WITH *NCHRP REPORT 350* TL-2 IMPACT CONDITIONS

NCHRP Report 350 TL-2 impact conditions for terminals and crash cushions are compared to the Yuma County (YC) test conditions. Specifically, tests YC-5, YC-4, YC-6, and YC-7 are compared to *NCHRP Report 350* test designation 2-32, 2-33, 2-36, and 2-37, respectively. The comparison is shown in Figure 3.1 below.

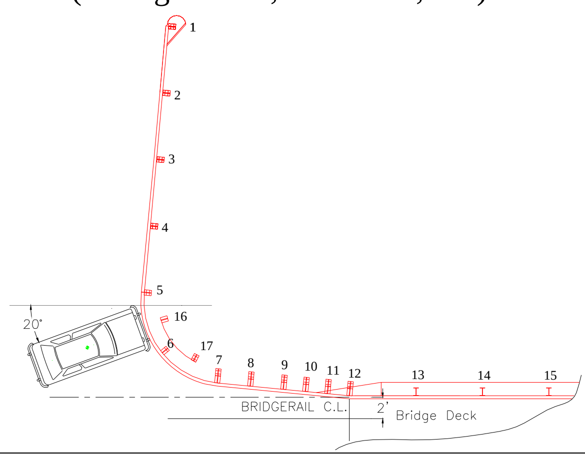
As illustrated in Figure 3.1, tests YC-5, YC-4, YC-6, and YC-7 have more severe impact conditions (due to increased vehicle mass and/or velocity) than required in *NCHRP Report 350* test conditions and have similar impact locations compared to those recommended by MwRSF researchers.

NCHRP Report 350	Yuma County, Arizona

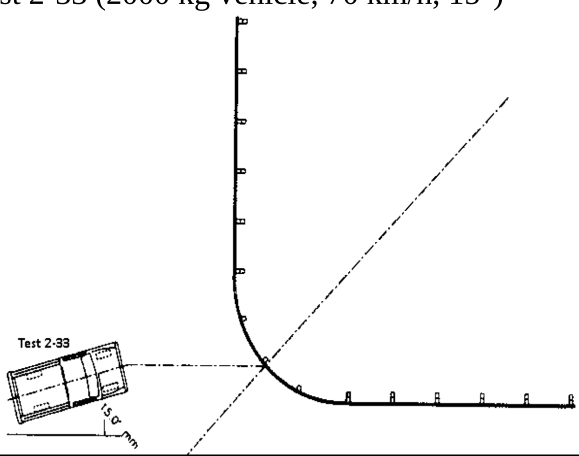
Test 2-32 (820 kg vehicle, 70 km/h, 15°)



YC-5 (898 kg vehicle, 71.1 km/h, 20°)



Test 2-33 (2000 kg vehicle, 70 km/h, 15°)



YC-4 (2440 kg vehicle, 72.1 km/h, 20.1°)

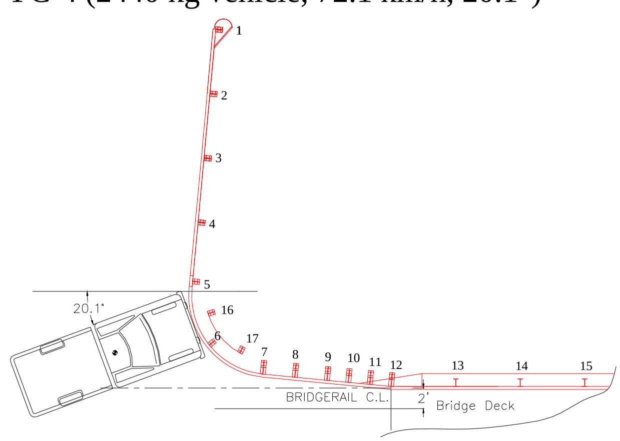
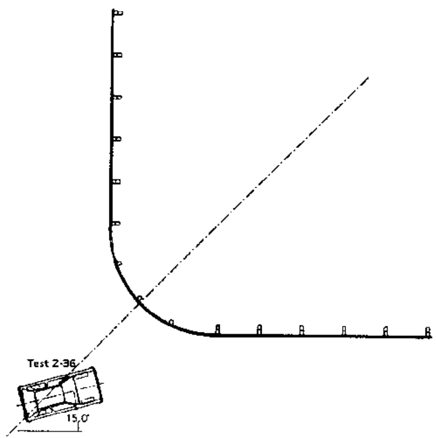
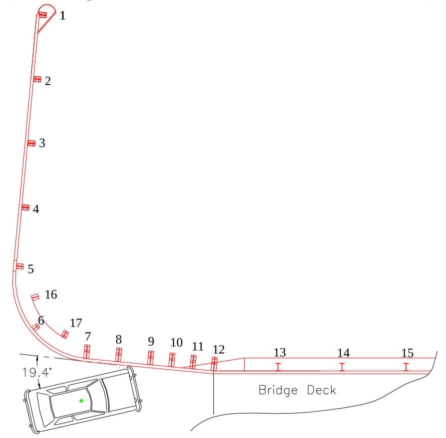


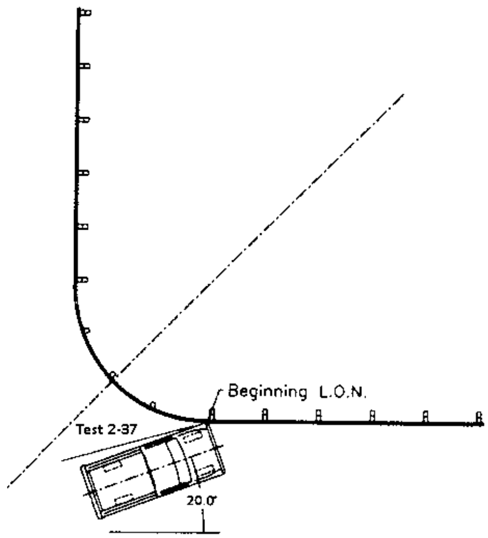
Figure 3.1 Comparison of *NCHRP Report 350* TL-2 and YC test.

NCHRP Report 350	YUMA , Arizona
Test 2-36 (820 kg vehicle, 70 km/h, 15°).	YC-6 (898 kg vehicle, 82.2 km/h, 19.4°)





NCHRP Report 350	YUMA , Arizona
Test 2-37 (2000 kg vehicle, 70 km/h, 15°)	YC-7 (2460 kg vehicle, 72.7 km/h, 20.7°)



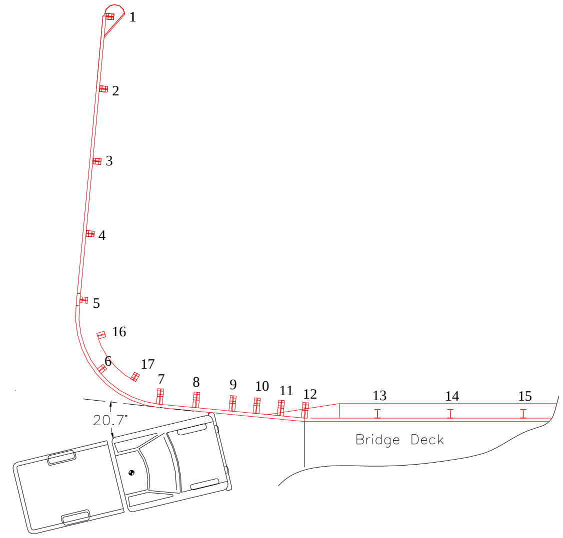


Figure 3.1 Comparison of *NCHRP Report 350* TL-2 and YC test (continued).

The remaining *NCHRP Report 350* test designations that cannot be compared directly to existing crash tests are 2-30, 2-31, 2-38, and 2-39, which are shown in Figure 3.2. *NCHRP Report 35*0 Test 2-39 specifies a 70 km/h (43.5 mph) reverse direction impact with a 2000P vehicle at an angle of 20 degrees at the midpoint of the tangent section of rail along the primary roadway as shown in Figure 3.2. Test 2-39 is intended to evaluate the performance of a terminal or crash cushion for a “reverse” hit. Reverse direction evaluates potential for snagging on a terminal anchor assembly or crash cushion. The short radius guardrail does not have an anchorage assembly along the primary roadway. This condition is no different than impacting a standard guardrail in the opposite direction. In fact, it can be argued that it is less severe since the short radius flares away from the impacting vehicle.

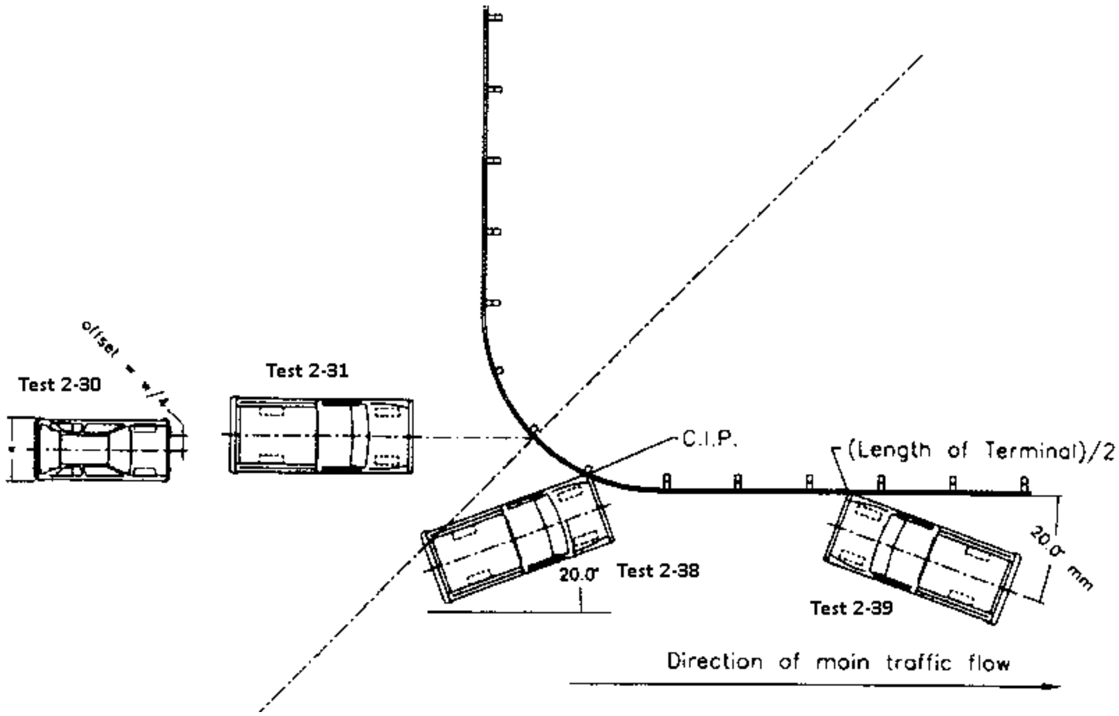


Figure 3.2 Remaining *NCHRP Report 350* test conditions

Under *NCHRP Report 350* Test 2-30, the 820C test vehicle impacts the curved section (terminal) head-on with ¼ point offset at a speed of 70 km/h (43.5 mph). Under *NCHRP Report 350* Test 2-31, the 2000P test vehicle impacts the curved section (terminal) head-on at a speed of 70 km/h (43.5 mph). These two tests are considered less severe than *NCHRP Report 350* Tests 2-32 and 2-33 which impact the curved section at an angle of 15 degrees relative to the tangent section of rail along the primary roadway.

Furthermore, *NCHRP Report 350* Test 2-30 falls within the impact envelope of YC-2 and YC-5 as shown in Figure 3.3. Similarly, *NCHRP Report 350* Test 2-31 falls within the impact envelope of YC-1 and YC-4 as shown in Figure 3.4. Therefore, the researcher team concludes that *NCHRP Report 350* Tests 2-30 and 2-31 conditions are satisfied using the aforementioned YC tests.

NCHRP Report 350 Test 2-38 specifies a 70 km/h (43.5 mph) impact with a 2000P vehicle at an angle of 20 degrees at the Critical Impact Point (CIP). While Test 2-37 is intended primarily to evaluate structural adequacy and vehicle trajectory criteria, Test 2-38 differs in purpose from Test 2-37 in that it is intended to evaluate the potential for pocketing or snagging at the bridge rail end. Since *NCHRP Report 350* Test 2-38 falls within the impact envelope of YC-4 and YC-7 as shown in Figure 3.5, the researchers conclude that *NCHRP Report 350* Test 2-38 conditions are satisfied.

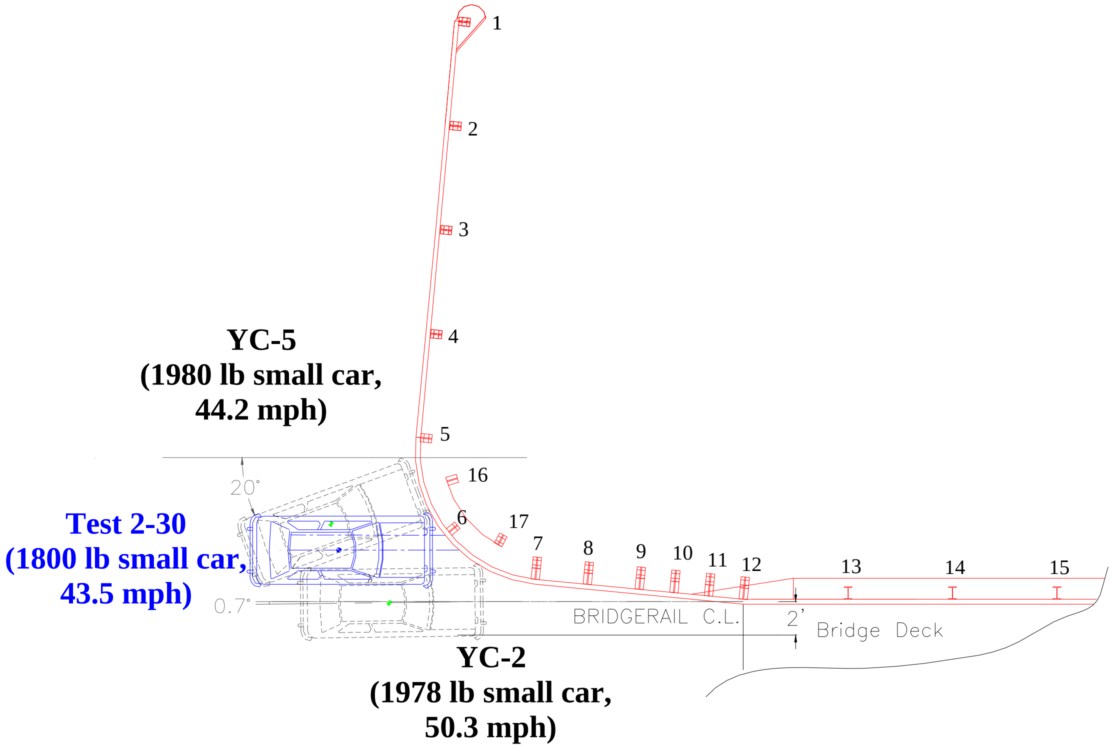


Figure 3.3 ***NCHRP Report 350*** **Test 2-30 along with YC-2 and YC-5 tests**

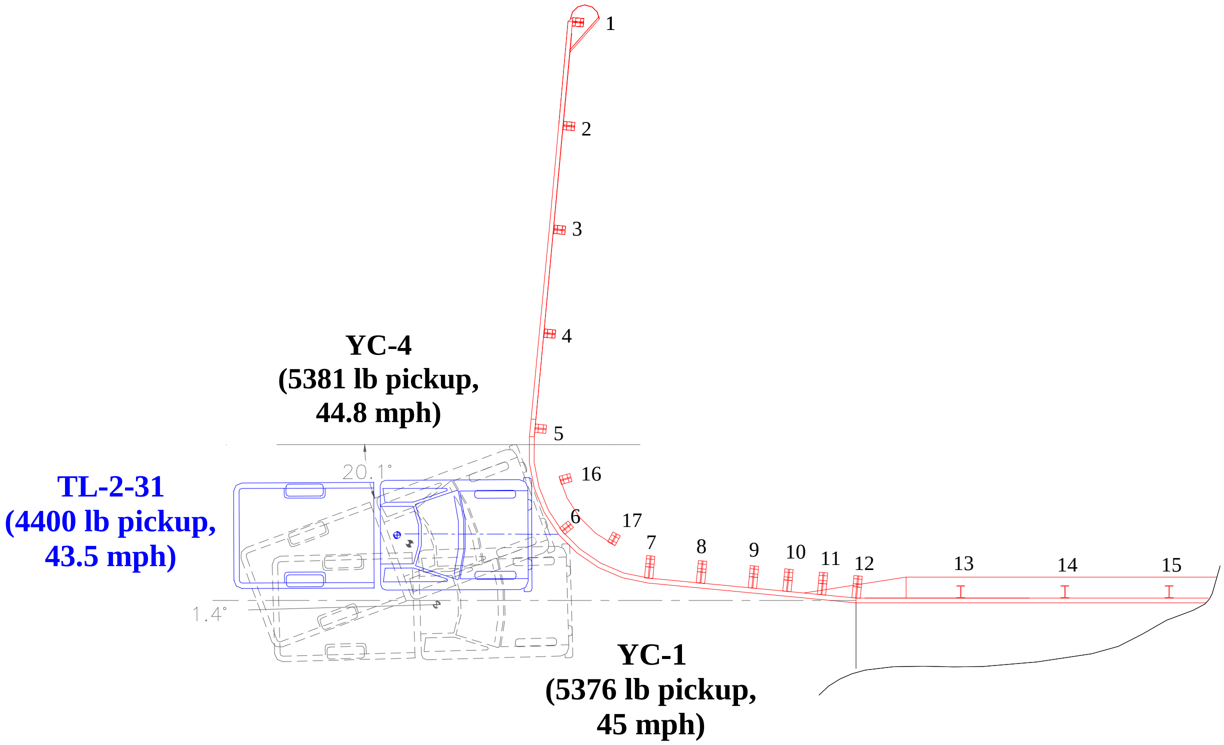


Figure 3.4 ***NCHRP Report 350*** **Test 2-31 along with YC-1 and YC-4 tests**

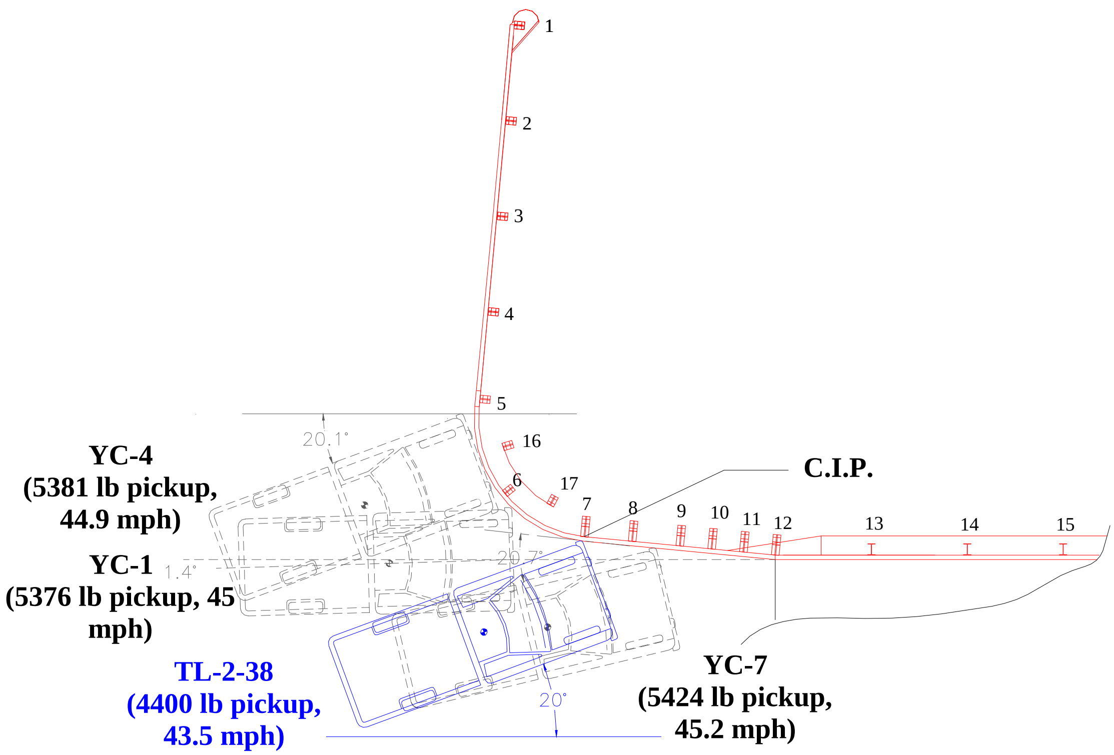


Figure 3.5 *NCHRP Report 350* Test 2-38 along with YC-4 and YC-7 tests.

4. FREE STANDING POSTS ENERGY CONTRIBUTION

Yuma County short radius guardrail design incorporates two free-standing CRT posts behind the curved rail to dissipate energy if the impacting vehicle and reduce the stopping distance. A literature review was performed to quantity the energy dissipation contribution of the CRT post during an impact and the results are summarized in this section.

In 1995, Texas Transportation Institute (TTI) conducted dynamic pendulum tests on CRT posts to evaluate their performance *(9)*. Tests were conducted along the strong axis (0 degree impact angle), along the weak axis (with 90 degrees impact angle), and along a diagonal of the post using a 1066 kg (2350 lb) pendulum as shown in Figure 4.1. The energy absorbed by the posts is shown in Table 4.1. The average energy dissipated for strong, weak, and diagonal axis impacts was calculated to be 11.59 kJ (8.55 kip-ft), 11.53 kJ (8.5 kip-ft), and 10.66 kJ (7.86 kip-ft), respectively.

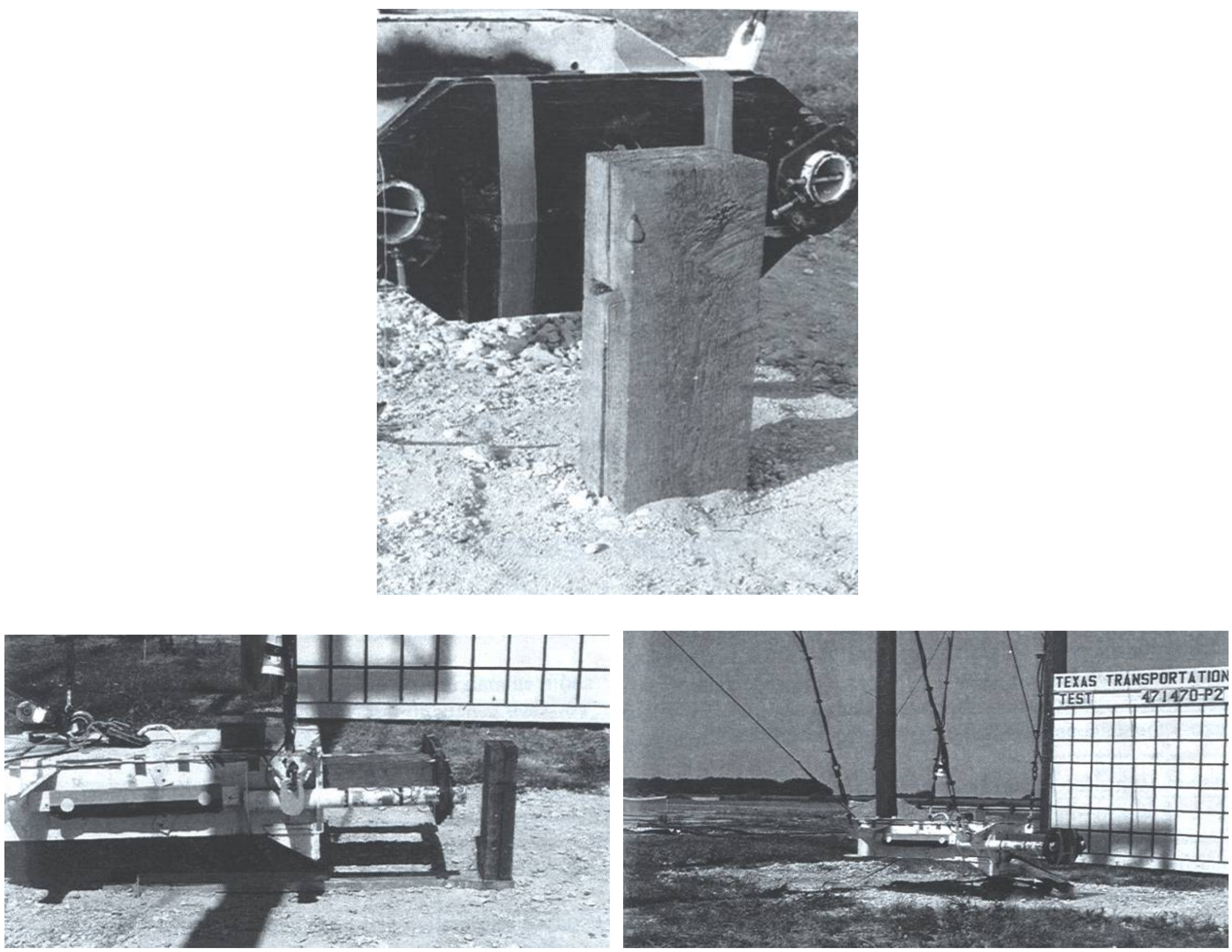


Figure 4.1 Pendulum equipment used for impact test

Table 4.1 Energy Results for TTI 471470 Tests *(9)*

Impact Axis	Test No.	Absorbed Energy (kJ)	Absorbed Energy (kip-ft)
Strong	471470-P26	11.87	8.76
	471470-P27	11.31	8.34
	Average	*11.59*	*8.55*
Weak	471470-P22	14.66	10.81
	471470-P23	8.40	6.19
	Average	*11.53*	*8.50*
Diagonal	471470-P30	7.37	5.44
	471470-P31	13.94	10.28
	Average	*10.66*	*7.86*

In 2001, TTI performed another set of dynamic pendulum tests similar to the ones conducted in TTI Project 471470 *(10)*. The energies dissipated by the CRT posts are shown in Table 4.2. The average energy dissipated for strong, weak, and diagonal axis impacts was calculated to be 14.03 kJ (10.35 kip-ft), 8.12 kJ (5.99 kip-ft), and 13.27 kJ (9.79 kip-ft), respectively.

Table 4.2 Energy Results for TTI 1458 Tests *(10)*

Impact Axis	Test No.	Absorbed Energy (kJ)	Absorbed Energy (kip-ft)
Strong	A	18.92	13.95
	B	13.04	9.62
	C	10.12	7.46
	Average	*14.03*	*10.35*
Weak	A	5.70	4.20
	B	5.93	4.37
	C	12.73	9.39
	Average	*8.12*	*5.99*
Diagonal	A	14.33	10.57
	B	12.21	9.01
	Average	*13.27*	*9.79*

MwRSF performed dynamic impact testing on CRT wood posts placed in a rigid sleeve *(11)* as shown in Figure 4.2(a). Three sets of tests (MNCRT 1~9) were conducted along the strong axis (0 degree impact angle), along the weak axis (90 degrees impact angle), and along the diagonal axis using a 728 kg (1605 lb) bogie. Figure 4.2(b) shows typical damage of a post due to a bogie impact. The energy dissipated by the posts is presented in Table 4.3. Since the CRT posts were placed in a rigid sleeve, the energy dissipation is significantly less than the energy measured in the pendulum tests of CRT posts placed in soil.

(a) Bogie and Test Setup

(b) Post impact Images (strong axis)

Figure 4.2 Dynamic impact testing (MNCRT) *(11)*

Table 4.3 Average Energy Results for MNCRT-1~9 *(11)*

Impact Axis	Test No.	Absorbed Energy (kJ)	Absorbed Energy (kip-ft)
Strong	MNCRT-1~3	2.56	1.89
Weak	MNCRT-4~6	2.38	1.754
Diagonal	MNCRT-7~9	3.34	2.46

The kinetic energy, K_E, of a moving vehicle is calculated using the following equation:

$$K_E = \frac{1}{2} m v^2 \tag{1}$$

where ,

m : Mass of vehicle
v : Velocity of impact

For example, the kinetic energy for the 2000P vehicle impacting at a velocity of 70 km/h (43.5 mph) is calculated as:

$$K_E = \frac{1}{2}(2,000kg)(19.44m/s)^2 = 378.15kJ \tag{2}$$

The kinetic energy of an 820C vehicle traveling at 70 km/h (43.5 mph) is calculated to be 155 kJ (114.35 ft-kips) as summarized in Table 4.4.

Based on the two TTI pendulum impact studies, the average energy absorbed by a single CRT post energy impacted about its strong axis is 12.81 kJ (9.45 kip-ft). This is 8.3% and 3.4% of the initial kinetic energy of the 820C and 2000P vehicles, respectively.

Table 4.4 Energy Results for 820C and 2000P Vehicle

	Velocity	Energy (kJ)	Energy (kip-ft)	Single CRT Avg. Absorbed Post Energy (12.81 kJ) as a Percentage of Vehicle K_E	Estimated Two Free Standing CRT Post Energy as a Percentage of Vehicle K_E
820C	70 km/h	155	114.32	8.3 %	16.6 %
2000P	70 km/h	378.15	278.91	3.4 %	6.8 %

Since impact conditions do not guarantee both posts breaking about their strong axes, these percentages represent an upper bound on the effectiveness of the free-standing CRT posts. Further, under many impact scenarios, one or both posts may be missed altogether. Maximum deflection of the barrier is controlled by the pick-up truck. If dynamic deflection is assumed to be proportional to the kinetic energy of the impacting vehicle, removal of the two CRT posts would result in an increase in deflecting from 6.1 m (20 ft) to 6.52 m (21.4 ft). Hence, it is the researcher's opinion that these two free standing CRT posts can be removed with no significant change in the performance of this system.

5. SUMMARY AND CONCLUSION

This study is undertaken to investigate the performance of previously tested short radius guardrail systems to determine if some of these previously tested short radius guardrail systems which would meets *NCHRP Report 350* TL-2 criteria. The evaluations performed in this study indicate that the Yuma County short radius guardrail design meets *NCHRP Report 350* TL-2 criteria. The study approach consists of (a) a review *NCHRP Report 350* TL-2 test conditions and the crash test performed on a short radius guardrail treatment developed for Yuma County, Arizona, (b) comparison of *NCHRP Report 350* TL-2 test conditions with the Yuma County tests, and (c) discussion of the energy contribution of the free standing CRT post that were part of the original design. As a result of this research, the following conclusions are made:

1- The 820C small car crash test for *NCHRP Report 350* Tests 2-32 and 2-36 conditions were satisfied by tests YC-5 and YC-6, respectively. For the 2000P pick-up truck, *NCHRP Report 350* Tests 2-33 and 2-37, were satisfied by tests YC-4 and YC-7, respectively.

2- *NCHRP Report 350* Tests 2-30, 2-31 and 2-38 conditions are satisfied by a cluster of Yuma County tests.

3- *NCHRP Report 350* Test 2-39 is considered unnecessary based on engineering review.

4- Previously conducted dynamic impact tests on CRT posts were studied to assess their energy dissipation contribution during an impact. Percentage of dissipated energy by the two free standing posts during an impact with a 2000P vehicle is approximately 7% of the initial vehicle kinetic energy. The T-intersection system developed for Yuma County can be modified to remove two free standing CRT posts behind the curved section without significantly changing system performance.

6. RECOMMENDATIONS

6.1. MINIMUM T-INTERSECTION DETAILS

A recommended *NCHRP Report 350* TL-2 T-intersection system detail is presented in Figure 6.1. The T-intersection system is a 690 mm (27 inches) high rail system. The nose section of this T-intersection system consists of a 3.82 m (12½ ft) curved W-beam segment which has a 2.44 m (8 ft) radius. The curved section is attached to a straight W-beam section on the secondary road via common W-beam splicing details. The secondary road W-Beam should have a 7.62 m (25 ft) minimum length and should be terminated with a positive anchor. Five CRT posts, spaced at 1.91 m (6.25 ft), are placed along the curved section and secondary road section. Details of the system are presented in Appendix A. On the primary road direction, the curved section is spliced to a short W-beam segment (6.25 ft) at CRT post 7. The short W-beam section has also two 200 × 200 × 1980 mm (7-7/8 × 7-7/8 × 72 inches) posts embedded 1117.6 mm (44 inches) in soil (Post Detail C).

Starting at post 8, a stiffer rail section is used to act as a transition to the bridge rail. The transition section consists of the 1905 mm (6.25 ft) short W-beam segment which is spliced to a 3810 mm (12.5 ft) W-beams guardrail. The W-beam guardrail is backed by an MC 200 x 33.9 (MC 8 × 22.8) structural steel channel which runs from post 9 to the bridge barrier. The transition has three timber posts which are 250 × 250 × 1980 mm (9-7/8 × 9-7/8 × 78 inches). They are embedded 1270 mm (50 inches) in soil (Post Detail A). The five timber posts (post 8 to post 12) have 200 × 200 × 360 mm (7-7/8 × 7-7/8 × 14 inches) wood blockouts (Blockout Detail G).

6.2. ACCEPTABLE SYSTEM CHANGES

Design changes to the aforementioned system can be made provided the impact performance is not affected. The researchers conclude the following modifications to be acceptable.

1- The T-Intersection guardrail system can be terminated on the secondary roadway using any *NCHRP Report 350* TL-2 or higher compliant terminal if the secondary roadway design requires such end termination. However, a minimum span of 7.62 m (25 ft) with a positive anchor is still required even if a crashworthy terminal is not needed.

2- The transition section on the primary road can be replaced with any *NCHRP Report 350* TL-2 or higher compliant transition.

3- The bridge barrier section can be any *NCHRP Report 350* TL-2 or higher compliant bridge rail.

4- Additional W-beam guardrail sections with standard post spacing 1.91 m (6.25 ft) may be added between the tangent point of the curved section and the beginning of the transition section as needed to provide the length of need for a given site as shown in Figure 6.2.

5- Blockout Details “E” and “G” can be replaced with other blockouts of similar size but made of different materials provided that they have been used in a successful crash test or have received FHWA acceptance under *NCHRP Report 350*.

6- A 178 mm (7 inches) diameter round wood post can be used instead of a 152 × 200 mm (6 × 8 inches) rectangular wood post. The round breakaway posts (posts 3 through 7 in Figure 6.1) should have 89 mm (3.5 inches) diameter weakening holes similar to the CRT post.

7- A standard 200 × 152 × 360 mm (7-7/8 × 5-7/8 × 14 inches) blockout can be used in the curved section. This is not expected to cause any significant change to the performance of the system since the weakened (CRT) posts are expected to break prior to any significant change of height to the system.

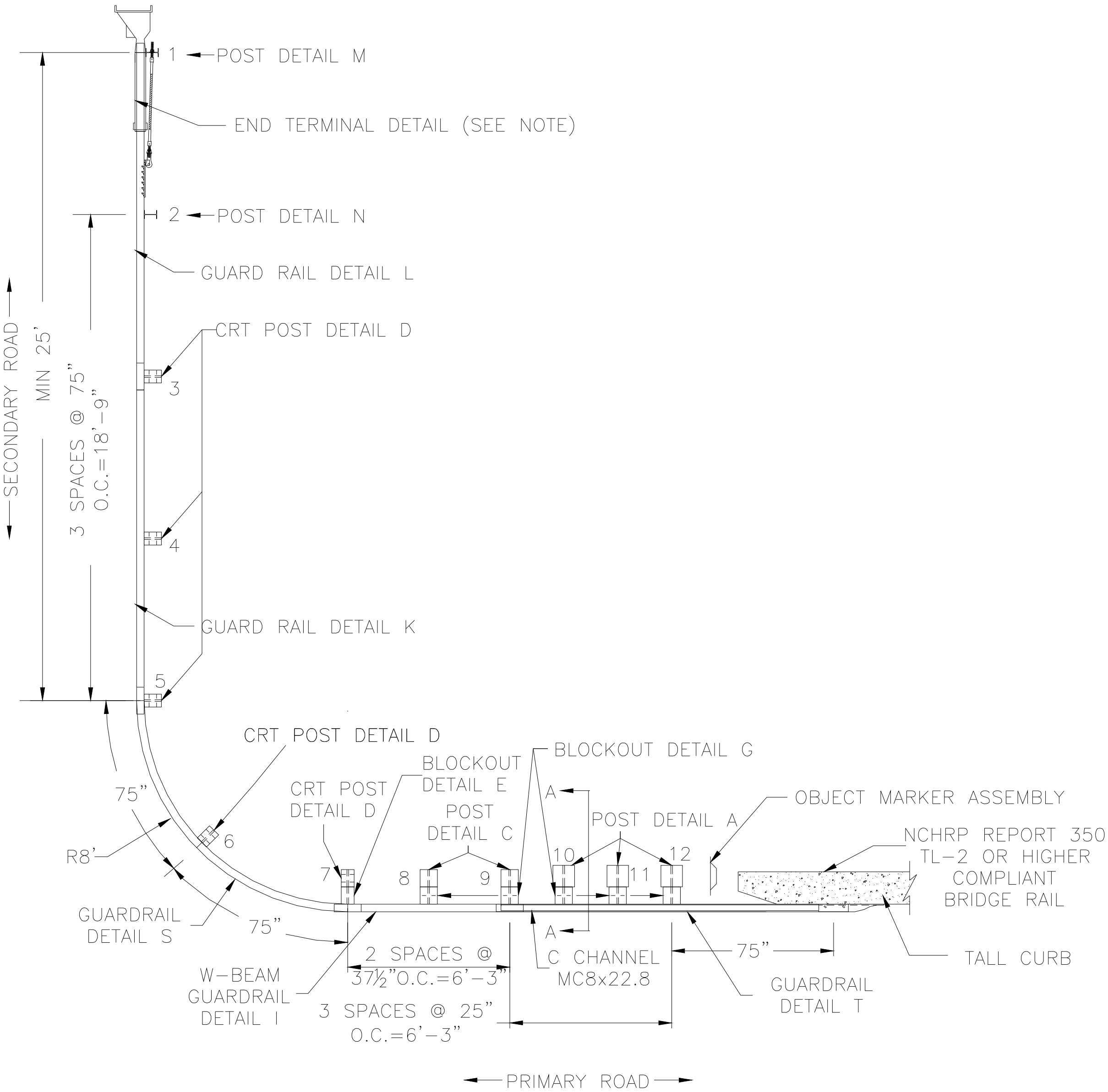


Figure 6.1 Recommended T-intersection system

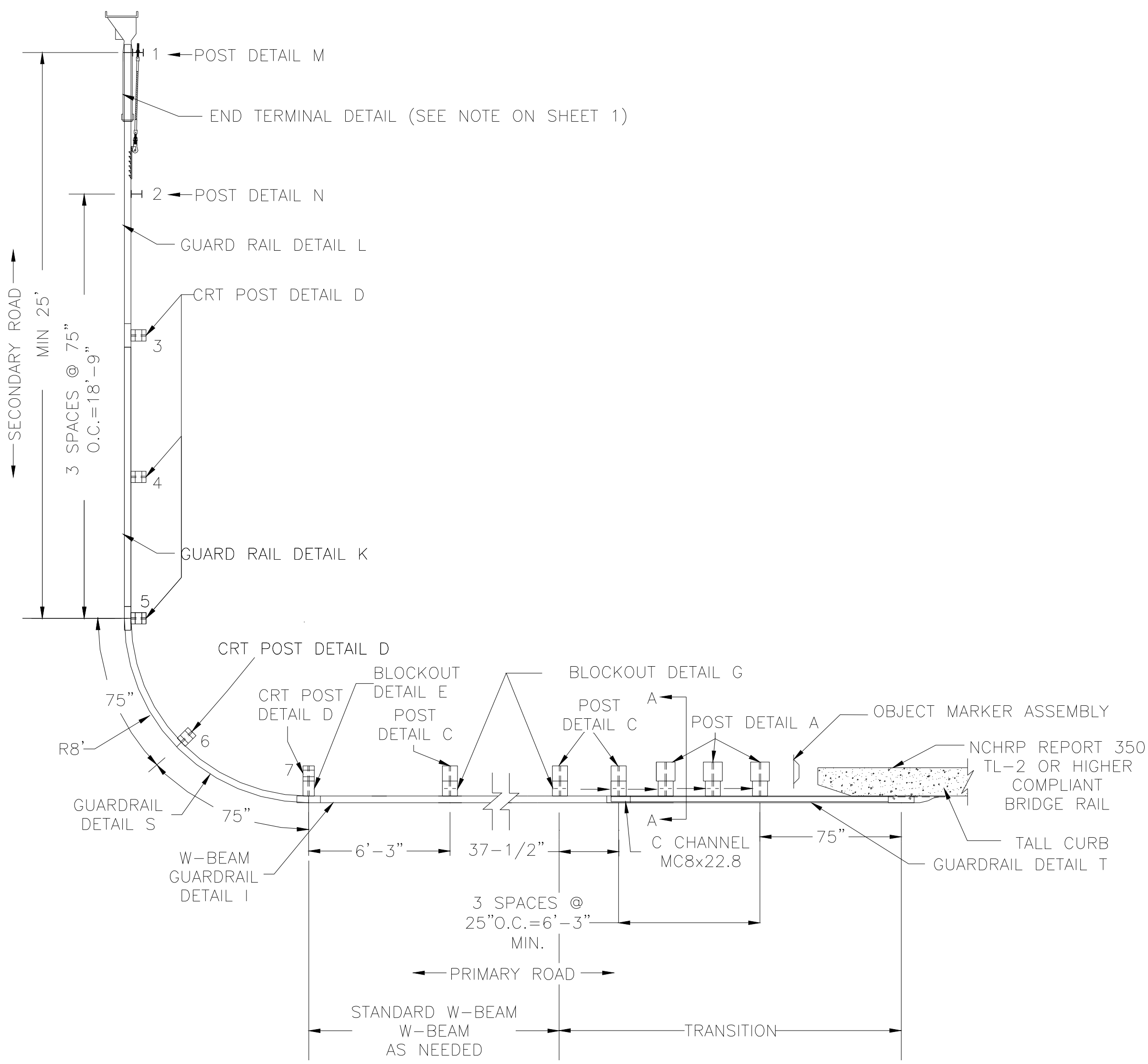


Figure 6.2 Acceptable variation of the recommended T-intersection system

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4. Ross, J., H. E., Bligh, R.P., and Parnell, C.B., *Bridge Railing End Treatments at Intersecting Streets and Drives*, Report No. FHWA-TX-91/92-1263-1F, Texas Transportation Institute, College Station, TX, 1992.

5. Bligh, Roger P., Hayes E. Ross, Jr., and Dean C. Alberson, *Short-Radius Thrie Beam Treatment for Intersecting Streets and Drives*, Report No. FHWA/TX-95/1442-1F, Texas Transportation Institute, College Station, Texas, November 1994.

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8. *1989 Guide Specifications for Bridge Railings*, American Association of State Highway and Transportation Officials, Washington, D.C., 1989.

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11. Arens S. W., Faller R. K., Rohde J. R., Polivka K. A., *DYNAMIC IMPACT TESTING OF CRT WOOD POSTS IN A RIGID SLEEVE*, Performed by Midwest Roadside Safety Facility, Sponsored by Minnesota Department of Transportation, April, 2008

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APPENDIX A: DETAILS OF RECOMMENDED T-INTERSECTION SYSTEM

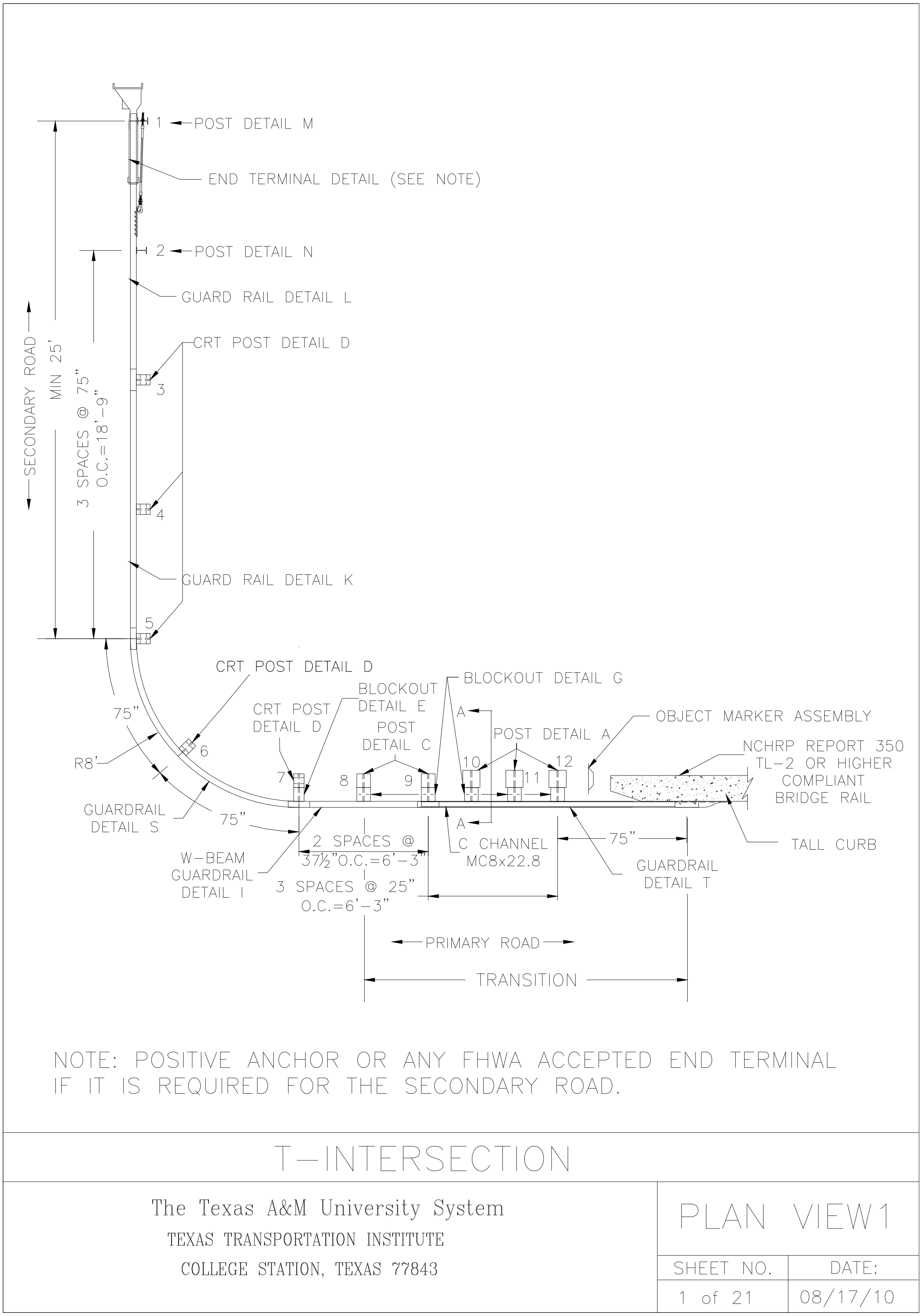


Figure A 1 T-intersection recommended system (plan view)

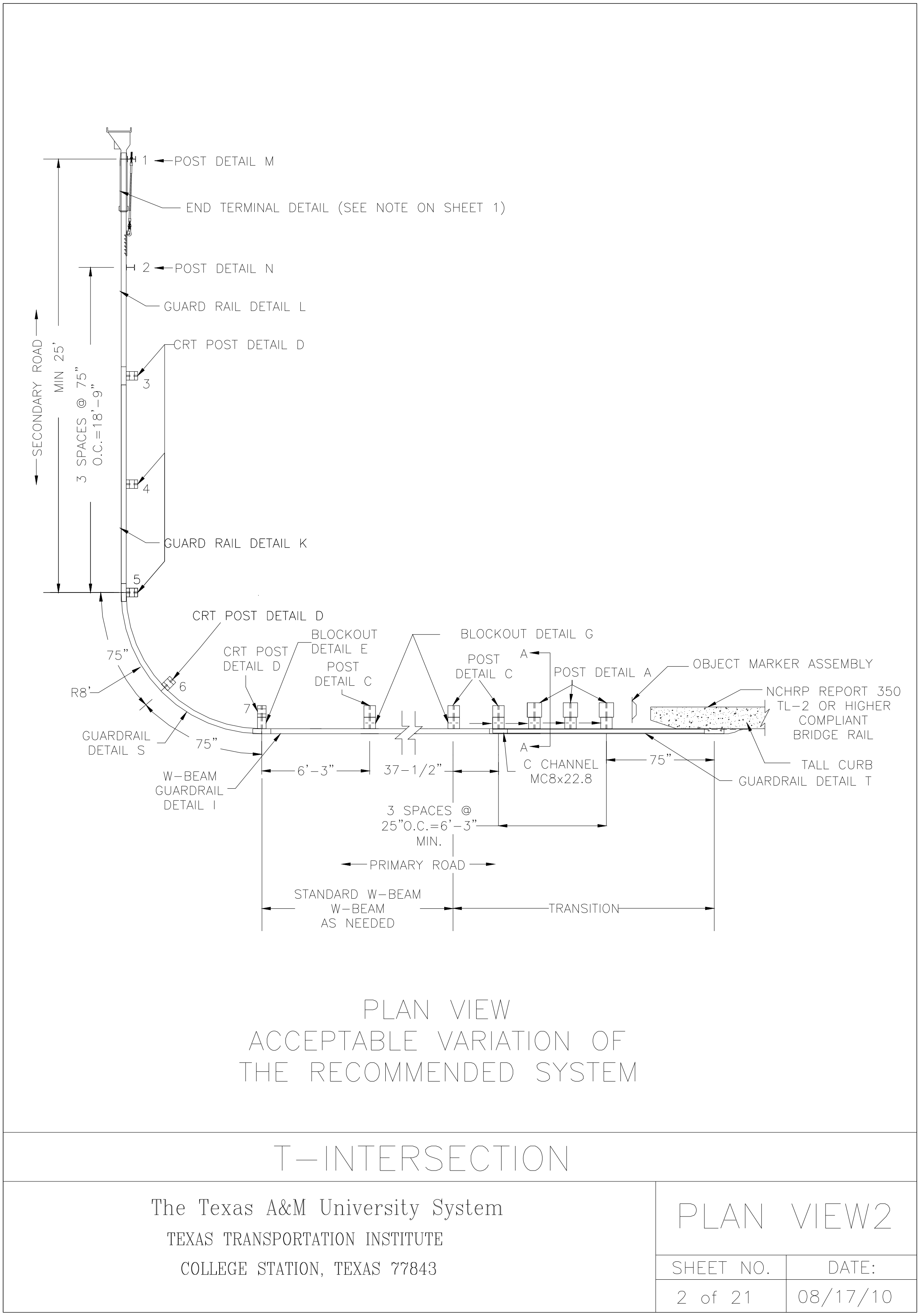
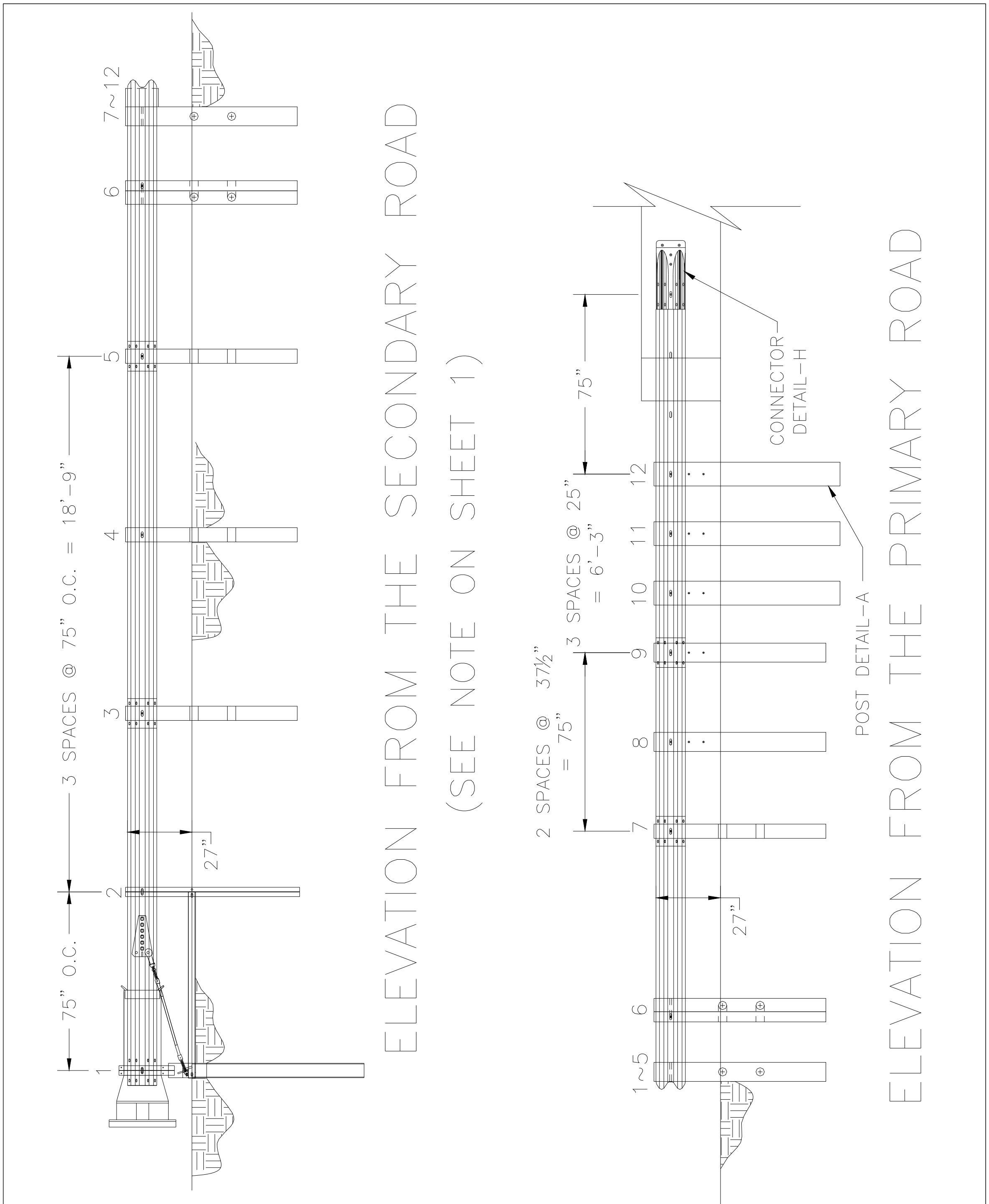


Figure A 2 Acceptable variation of the recommended system (plan view)



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ELEVATION

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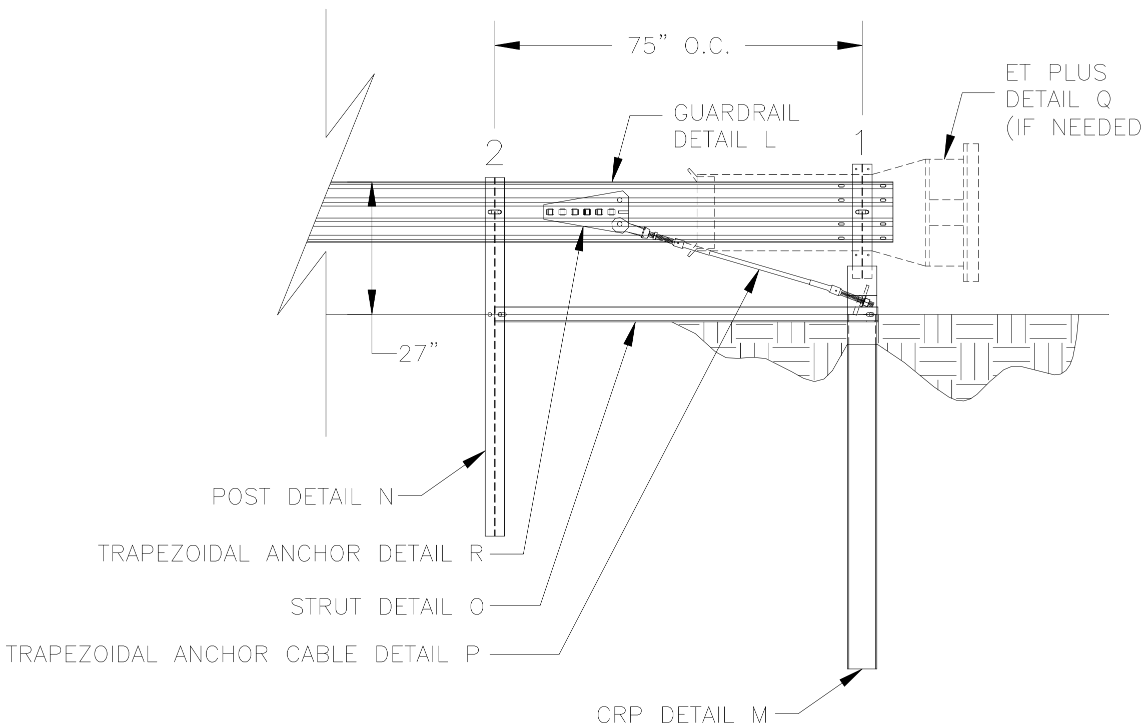
Figure A 3 T-intersection recommended system (elevation view)



SINGLE SPAN WITH POSITIVE ANCHOR
DETAILS ELEVATION VIEW

NOTE: AT MINIMUM, A SINGLE SPAN WITH POSITIVE ANCHOR IS REQUIRED. HOWEVER AN NCHRP REPORT 350 COMPLIANT TERMINAL IS NEEDED IF THE SECONDARY ROADWAY DESIGN REQUIRES A COMPLIANT END TERMINAL

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Figure A 4 End terminal detail

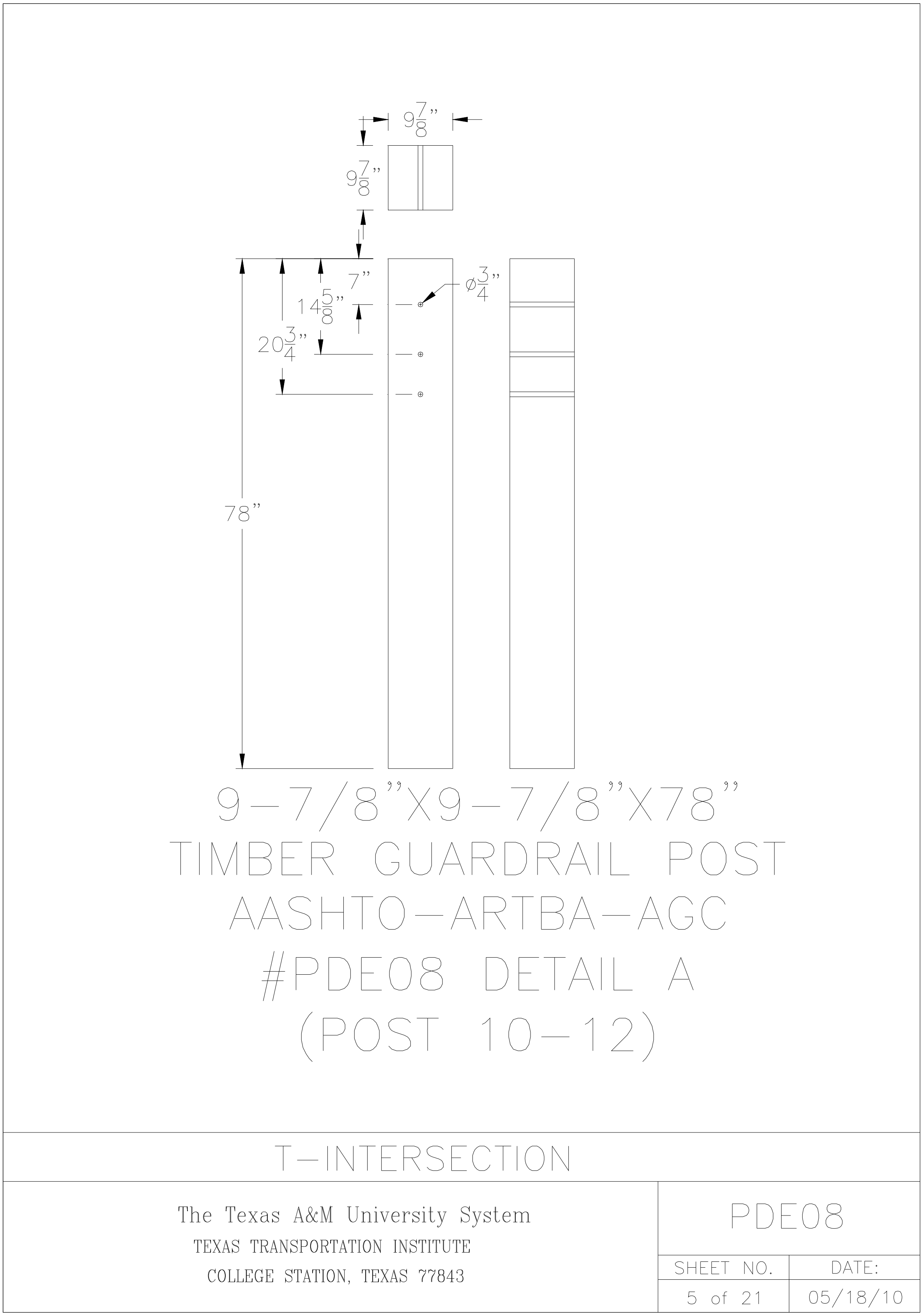
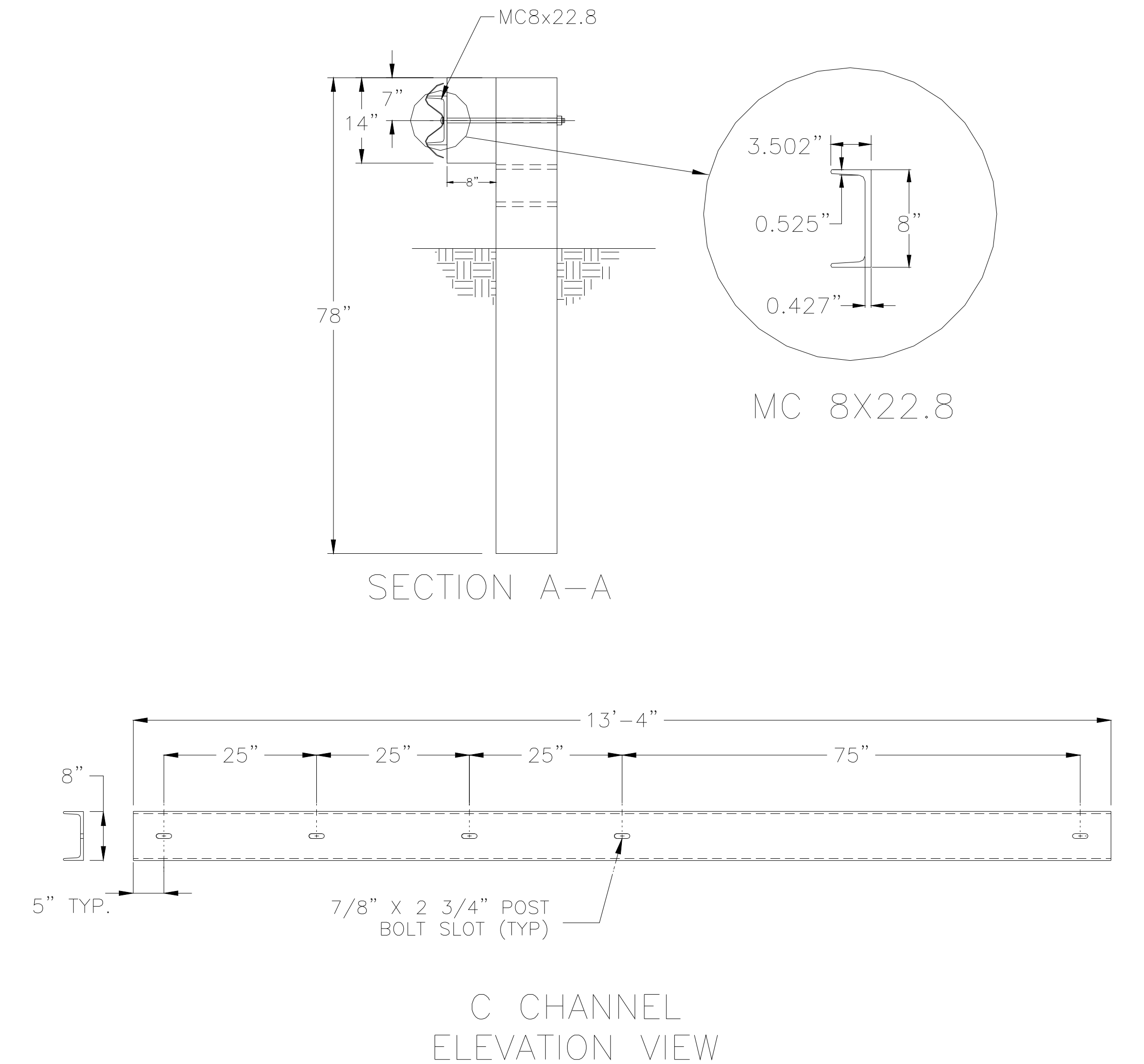


Figure A 5 Post A (PDE 08)



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SECTION A-A

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Figure A 6 Section A-A

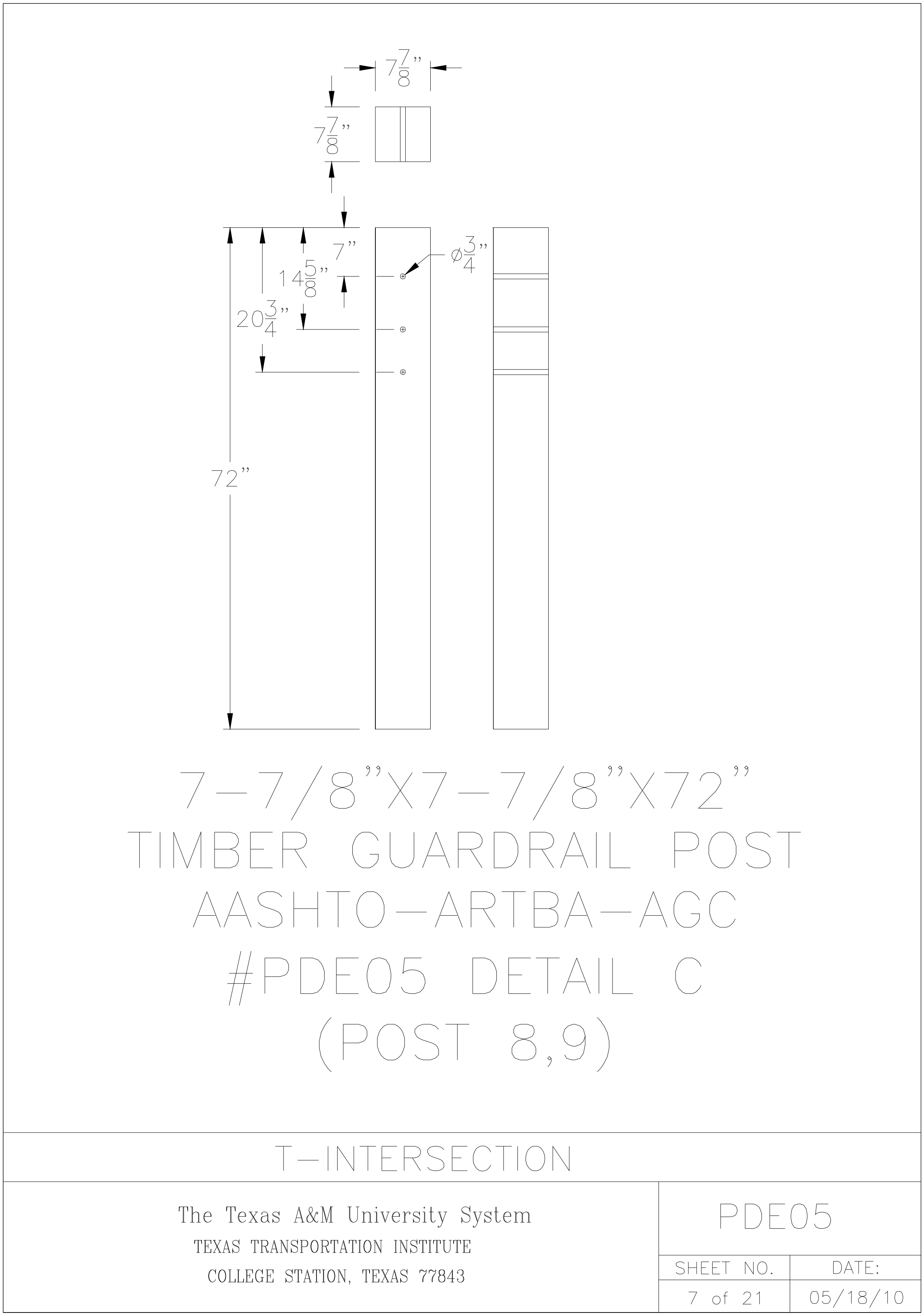
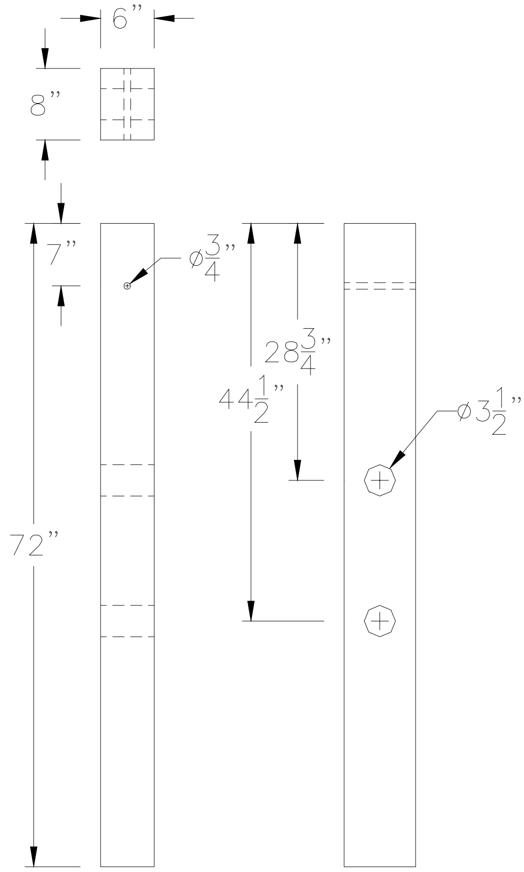


Figure A 7 Post C (PDE05)



CRT TIMBER POST
DETAIL D
(POST 3-7)

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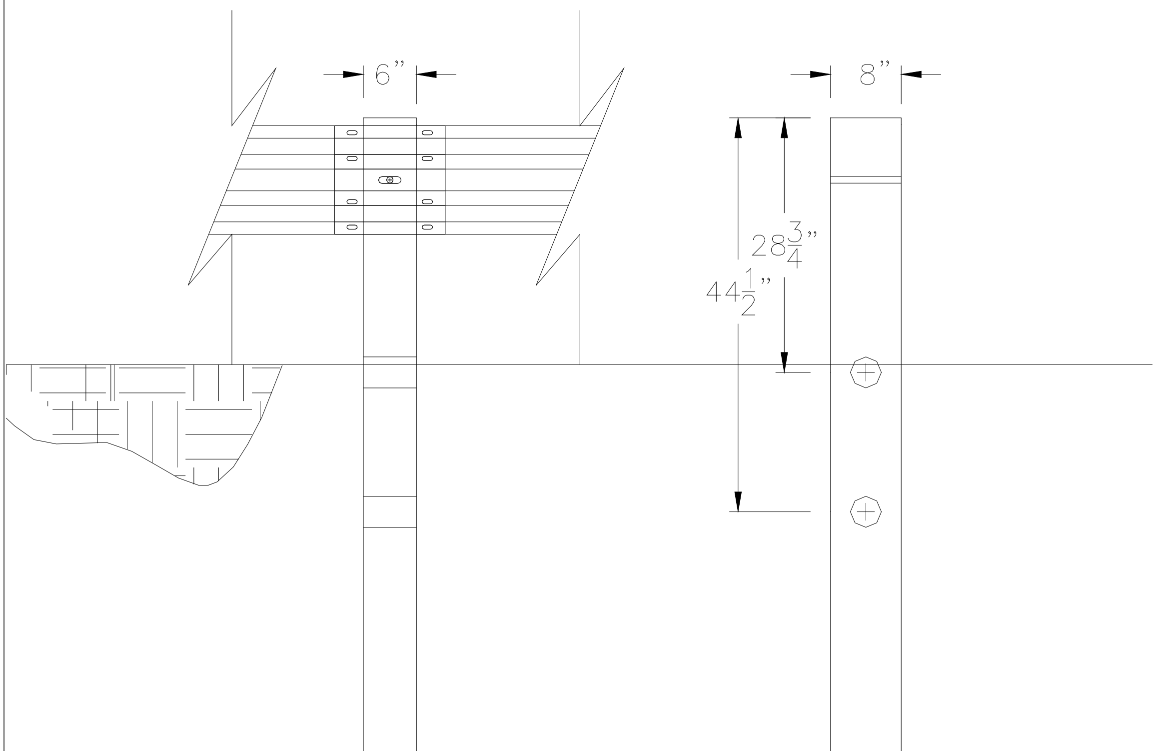
Figure A 8 CRT Post D



CRT TIMBER POST ORIENTATION
WITH RESPECT TO RAIL

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Figure A 9 CRT Post orientation

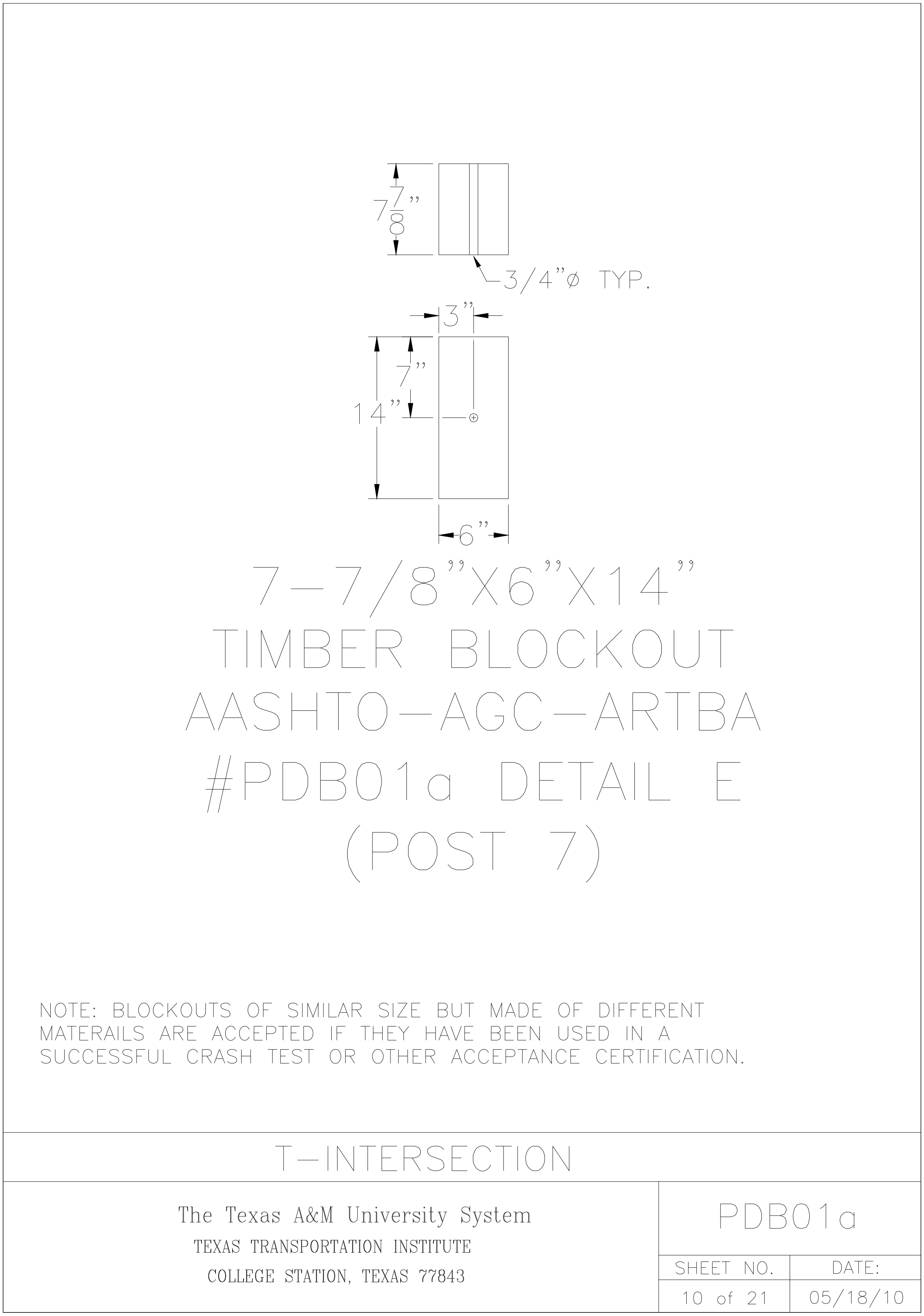
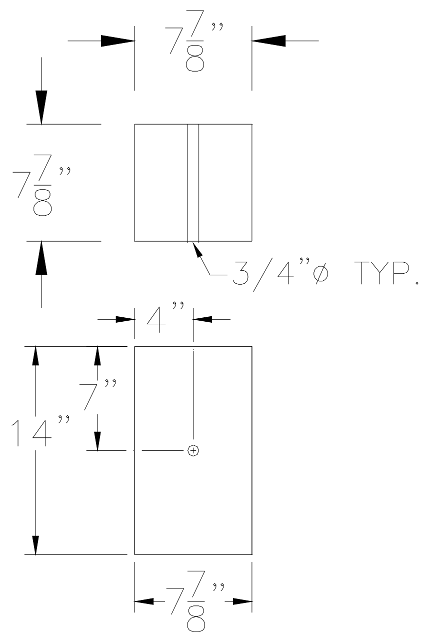


Figure A 10 Blockout E (PDB01a)



7-7/8"X7-7/8"X14"
W-BEAM
TIMBER BLOCKOUT
DETAIL G
(POST 8-12)

NOTE: BLOCKOUTS OF SIMILAR SIZE BUT MADE OF DIFFERENT MATERAILS ARE ACCEPTED IF THEY HAVE BEEN USED IN A SUCCESSFUL CRASH TEST OR OTHER ACCEPTANCE CERTIFICATION.

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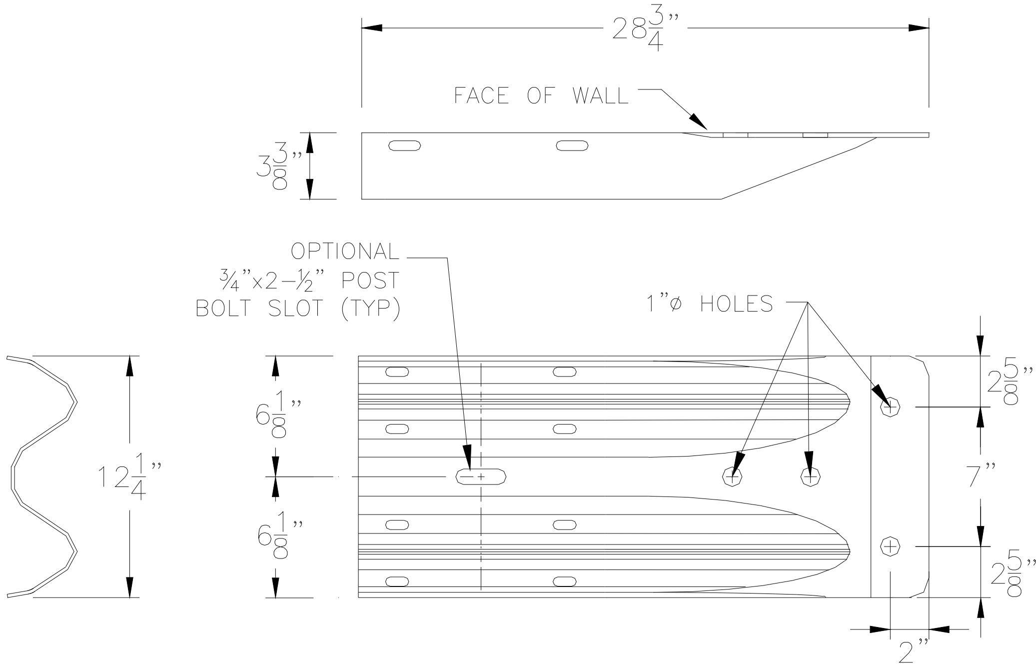
Figure A 11 Blockout G



W–BEAM TERMINAL CONNECTOR
(AASHTO–AGC–ARTBA# RWE02a)
DETAIL H

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RWE02a	
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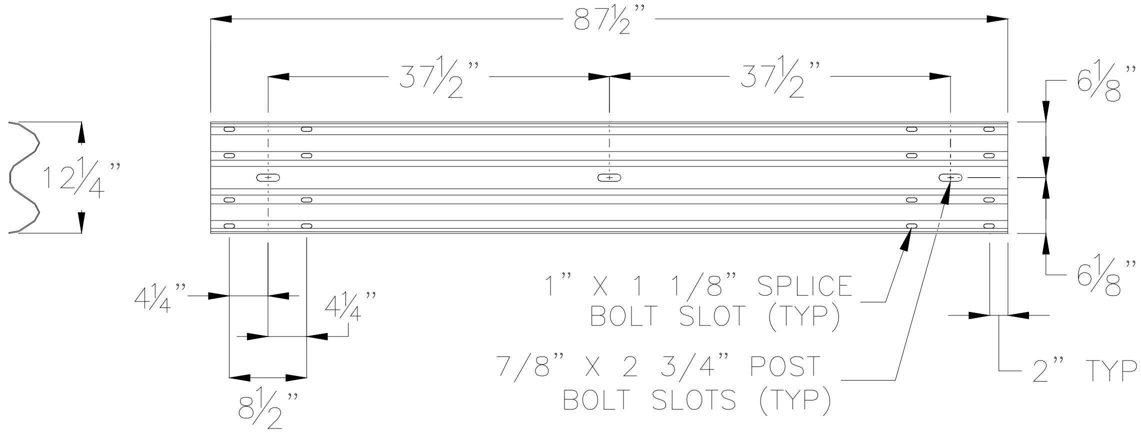
Figure A 12 W-beam terminal connector (RWE02a)



W-BEAM GUARDRAIL
DETAIL I

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W-BEAM-I

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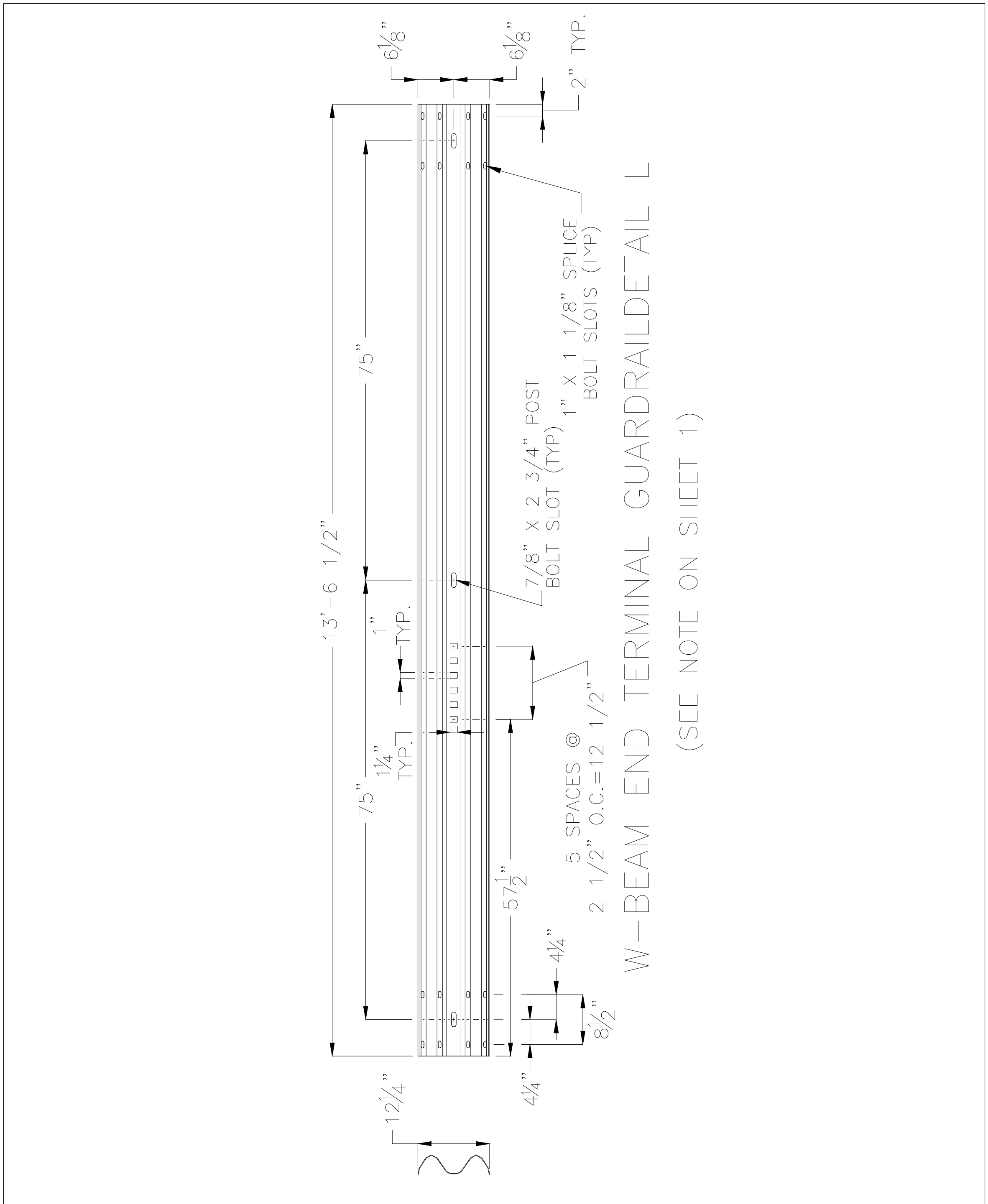
Figure A 13 W-beam guardrail I



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W-BEAM-L

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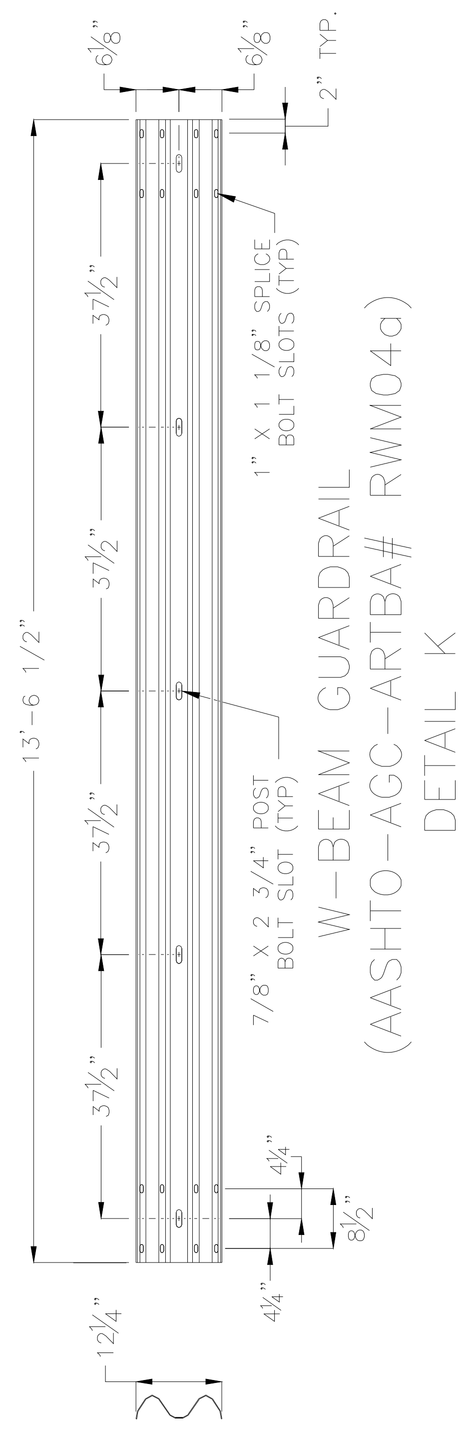
Figure A 14 W-beam terminal guardrail L



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The Texas A&M University System TEXAS TRANSPORTATION INSTITUTE COLLEGE STATION, TEXAS 77843	RWM04a	
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Figure A 15 W-beam guardrail K

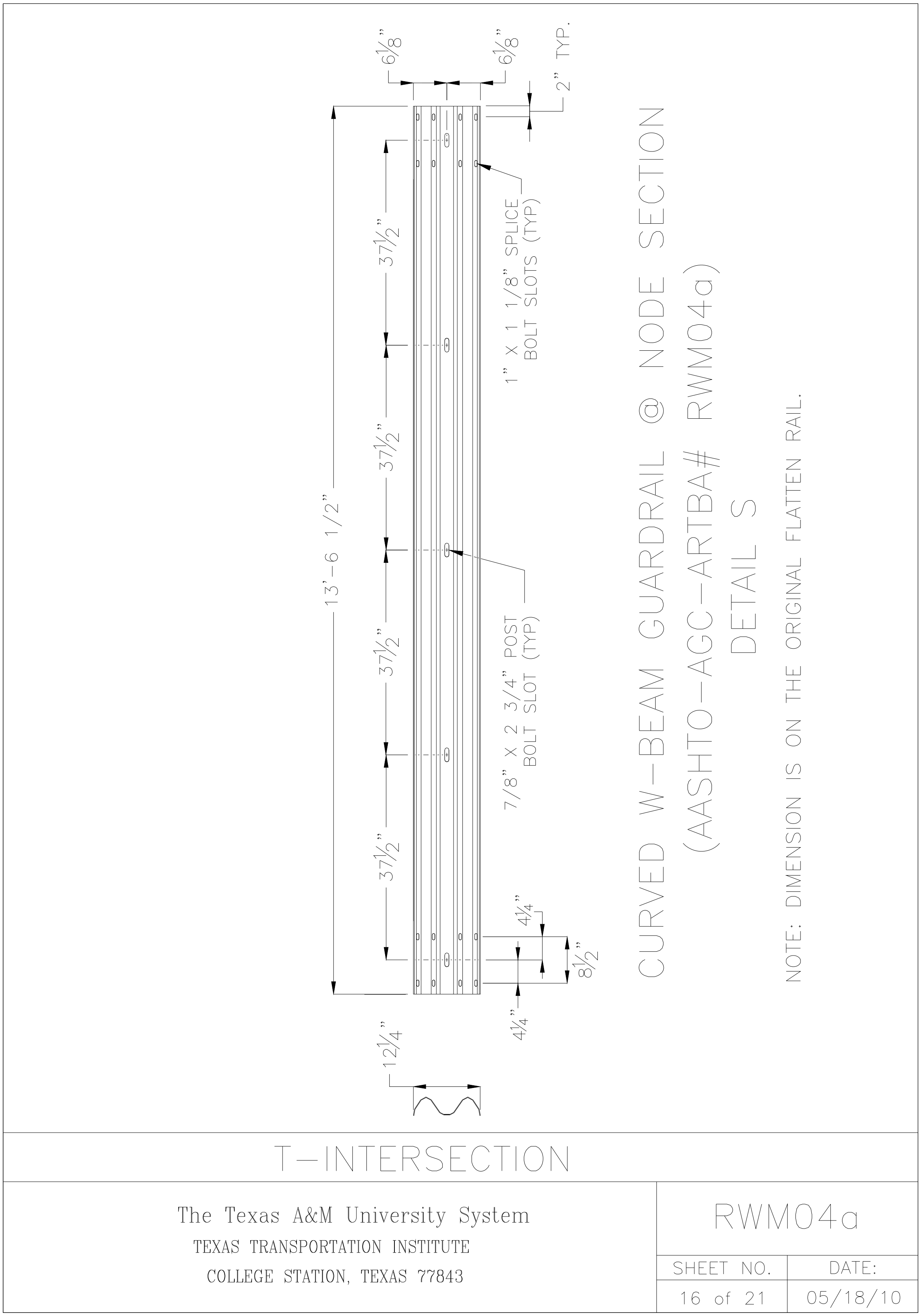


Figure A 16 Curved W-beam guardrail S (RWM04a)

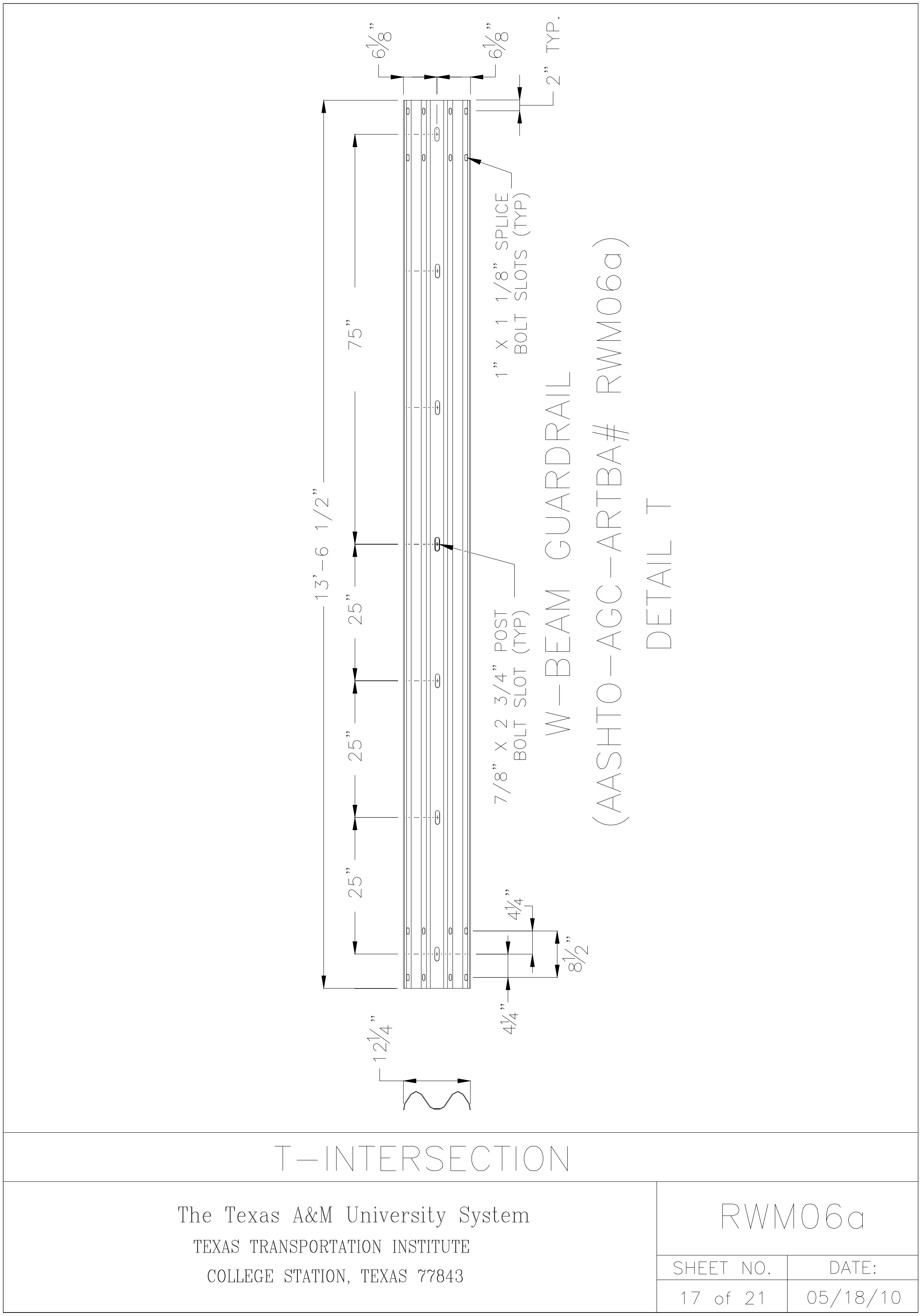
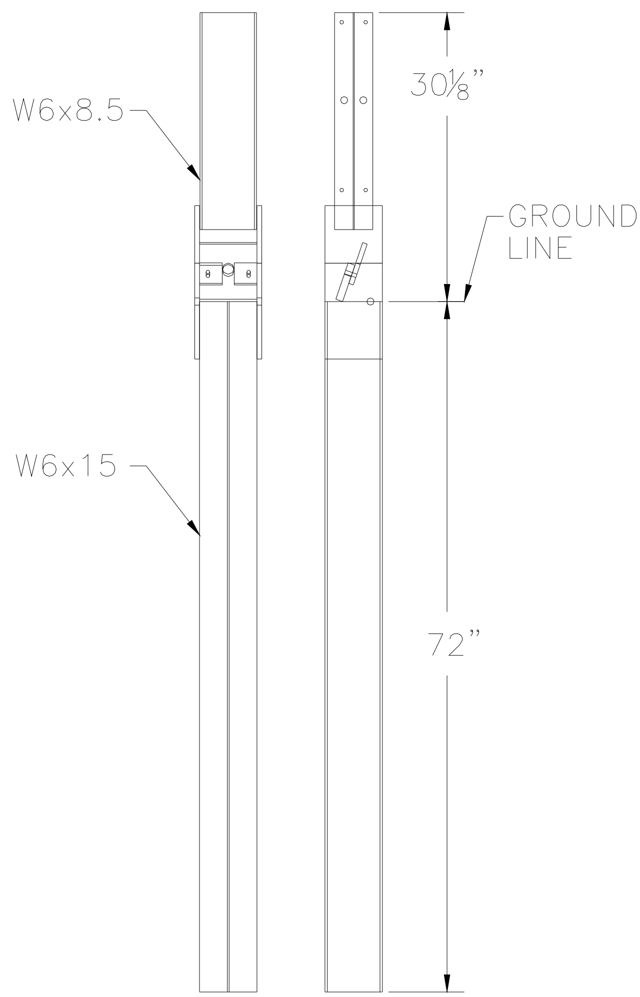


Figure A 17 W-beam guardrail T (RWM06a)



STANDARD CRP
WITH 20° OFFSET
DETAIL M
(SEE NOTE ON SHEET 1)

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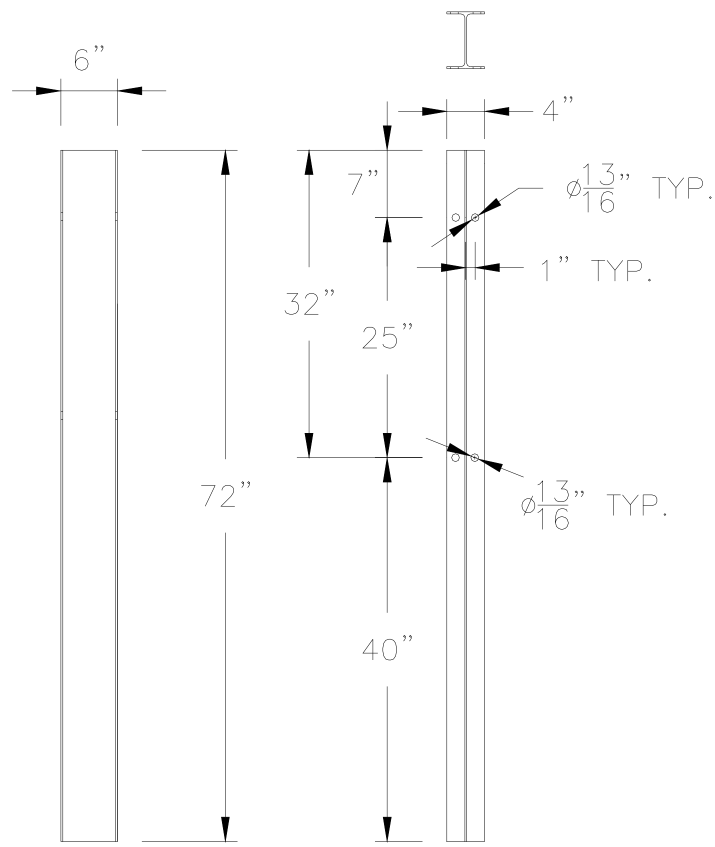
Figure A 18 CRP post M



SYTP–W6X8.5
POST DETAIL N
(SEE NOTE ON SHEET 1)

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POST N

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Figure A 19 SYTP post N

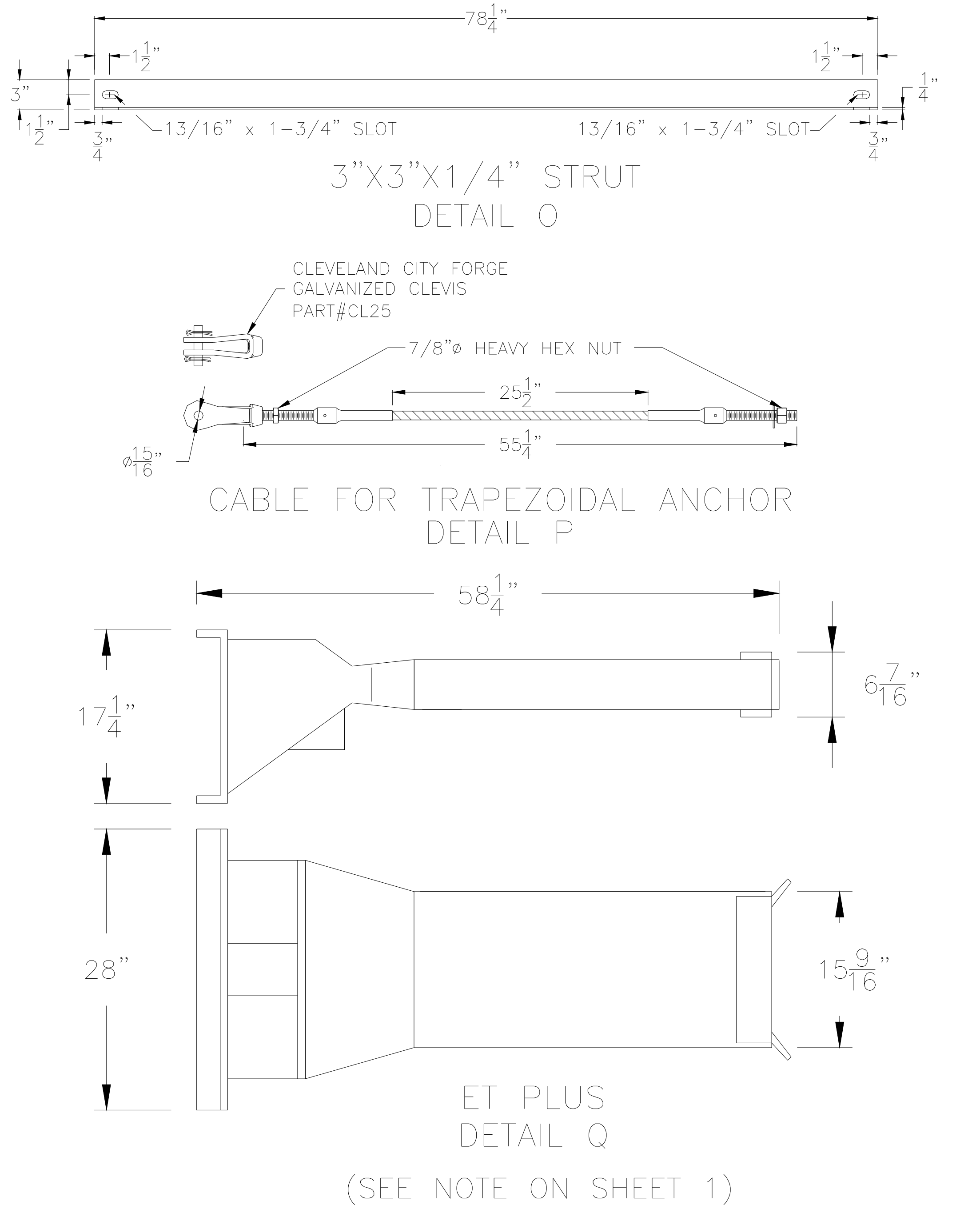

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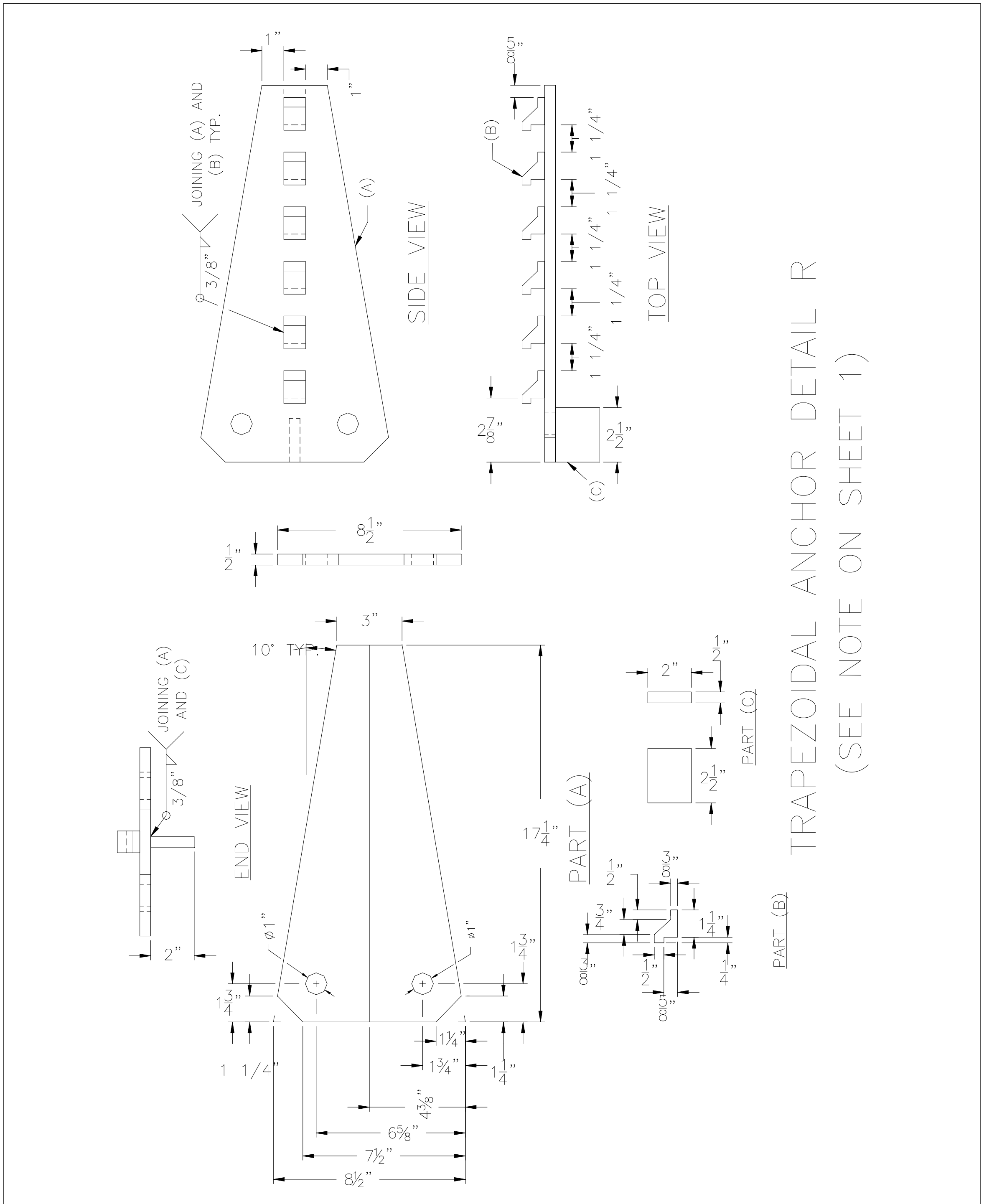
Figure A 20 End Terminal part I



T-INTERSECTION

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Figure A 21 End Terminal part II