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DEVELOPMENT OF A LOW-PROFILE BRIDGE RAIL FOR TEST LEVEL 2 APPLICATIONS

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16. Abstract (Limit: 200 words) <p>A low-profile bridge rail was developed for installations where pedestrians and/or site restrictions prevent the use of conventional bridge rails with transitions. The bridge rail design was constructed using a 22.86-m long reinforced concrete parapet. The entire system measured 508-mm high by 356-mm and 279-mm wide at the top and bottom surfaces, respectively.</p> <p>The research study included one full-scale vehicle crash test, using a ¾-ton pickup truck. The full-scale test, impacting at a speed of 70.0 km/hr and an angle of 27.1 degrees, was conducted and reported in accordance with the requirements specified in National Cooperative Highway Research Program (NCHRP) Report No. 350, <i>Recommended Procedures for the Safety Performance Evaluation of Highway Features</i>. The safety performance of the low-profile bridge rail was determined to be acceptable according to the Test Level 2 (TL-2) evaluation criteria specified in NCHRP Report No. 350.</p>			
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1 INTRODUCTION

1.1 Problem Statement

Test Level 2 (TL-2) bridge rails are often acceptable for urban applications where pedestrian traffic can be a significant concern. In this situation, it is often desirable to separate pedestrians from the vehicular traffic by placing the sidewalk behind the bridge rail. Consequently, pedestrians must be moved behind the approach guardrail far upstream of the bridge rail or the end of the bridge rail will be exposed to traffic. It is frequently impractical to place sidewalks behind an approach guardrail. Therefore, the end of the bridge rail is often treated with a costly crash cushion in this situation.

Recent testing has generated a patented TL-2 longitudinal barrier that has ends that taper to the bridge deck. While the shape of this barrier has been patented, the terminal has not. Due to prior testing of very similar barrier concepts, the patent for this shape is not believed to be viable. While it would be possible to utilize this previously accepted barrier and challenge the validity of the patent, it was decided that it would be more cost efficient to develop a barrier shape that falls outside of the boundaries of the patent and then take advantage of the sloped-end treatment testing performed to preclude additional testing of the terminal. The patent is based on a barrier traffic-side face that makes less than a 90 degree angle with the pavement to allow the top of the barrier to extend out toward traffic. Many barriers have incorporated small extensions at the top which would accomplish the same objective of localizing tire forces as this “flower pot” design does. This feature will have no effect on the performance of the tapered end treatment. Therefore, it should be possible to develop a nonproprietary TL-2 bridge rail design and gain approval for a tapered end treatment without testing the terminal again.

1.2 Objective

The objective of the research project was to design a nonproprietary, 508-mm high concrete bridge rail and evaluate its safety performance through full-scale crash testing. The bridge rail system was to be evaluated according to the TL-2 safety performance criteria set forth in the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (1).

1.3 Scope

The research objective was achieved by performing several tasks. First, a literature review was performed on previously crash tested low-profile bridge railing systems. Next, a design phase was undertaken to determine the shape of the barrier. After the final design was completed, the bridge rail system was fabricated and constructed at the Midwest Roadside Safety Facility's (MwRSF's) outdoor test site. A full-scale vehicle crash test was then performed using a ¾-ton pickup truck, weighing approximately 2,000 kg, at a target impact speed and angle of 70.0 km/hr and 25 degrees, respectively. Finally, the test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made that pertain to the safety performance of the bridge railing system.

2 LITERATURE REVIEW

Historically, very little research has been performed on the development and crash testing of low-profile barrier rails and terminals. More specifically, only two low-profile concrete bridge rails and one barrier end treatment have been evaluated by full-scale crash testing (2-4). The advantages of these systems are that they provide redirective capability for certain applications and enhanced visibility when compared to conventional 813-mm tall barriers.

2.1 Low-Profile Concrete Bridge Rails

In January 1991, the Texas Transportation Institute (TTI) and the Texas Department of Transportation developed a low-profile portable concrete barrier (PCB) (2). The low-profile PCB measures 508-mm tall and is produced in 6.10-m long segments. The low-profile PCB was developed for both temporary and permanent configurations and tested according to modified criteria found in NCHRP Report No. 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances* (5). It should be noted that a ¾-ton pickup truck test was used in lieu of the sedan test. Both the small car and the pickup truck full-scale vehicle crash tests met the NCHRP Report No. 230 criteria.

In 1993, NCHRP Report No. 350 was implemented thereby requiring the low-profile PCB, which was acceptable according to the NCHRP Report No. 230 criteria, to be re-evaluated according to the new safety performance criteria. According to NCHRP Report No. 350, a longitudinal barrier must be subjected to two full-scale vehicle crash tests, specifically an 820-kg small car impacting with a speed of 70.0 km/hr and an angle of 20 degrees and a 2,000-kg pickup truck impacting with a speed of 70.0 km/hr and an angle of 25 degrees. The first test involved a 2,043-kg pickup that impacted the low-profile PCB at a speed of 71.4 km/hr and at an angle of 26.1 degrees. These test

conditions are about the same as those specified for test designation 2-11 in NCHRP Report No. 350. The second test involved an 817-kg small car impacting with a speed of 73.5 km/hr and at an angle of 21.3 degrees. These test conditions are about the same as those specified for test designation 2-10 in NCHRP Report No. 350. For both full-scale crash tests, the vehicles were smoothly redirected and the data collected fell within the acceptable limits of the occupant and vehicle deceleration criteria found in NCHRP Report No. 350. Therefore, the previously conducted test results sufficiently demonstrated that the safety performance of the low-profile PCB successfully met the NCHRP Report No. 350 test level 2 criteria (3) and is suitable for use on most local and collector roads and many work zones as defined in NCHRP Report No. 350.

The second low-profile work-zone curb system was developed by the University of Florida's Department of Civil and Coastal Engineering (4). This low-profile work-zone barrier system measures 457-mm tall and is produced in 3.66-m segments that has a truncated slanted triangular cross section. The low-profile work-zone curb system was developed and tested according to NCHRP Report No. 350 for use in roadside work-zone situations. Both the small car and the pickup truck full-scale vehicle crash tests met the NCHRP Report No. 350 criteria. One advantage of this barrier is that its configuration does not require barrier to roadway anchorage since it utilizes inertial resistance to redirect impacting vehicles. It should be noted that end terminal testing was not undertaken in this research.

2.2 Barrier End Treatment

TTI also developed and tested a low-profile end treatment system for use with the low-profile PCB (3). The end treatment is produced in 6.10-m long segments and is 508-mm high at the connection end to match the low-profile PCB. The 508-mm height is maintained for 1.52-m from

the connection end. Along the remaining 4.57 m of length, the height is reduced linearly from 508-mm to 102-mm at the end of the terminal as the widths of the barrier top and bottom are symmetrically tapered to maintain the negative slope along the entire length.

Five crash tests, including two redirection tests, were performed on the low-profile end terminal. One crash test, test no. 1949A-2, involved an 893-kg small car impacting the end treatment at a speed of 72.6 km/hr and at an angle of 0.0 degrees. The small car in this test impacted the end treatment end-on with the centerline of the right wheel aligned with the centerline of the end terminal. The vehicle rode up the barrier and remained stable as it continued along a straight path until it exited the main body of the low-profile PCB in a controlled manner. Therefore, the results of this test proved that the system performed successfully according to the test conditions of NCHRP Report No. 350 Test Designation 2-30.

A second test, test no. 1949A-3, involved a 2,043-kg pickup impacting at a speed of 74.8 km/hr and at an angle of 0.0 degrees. In this test, the pickup impacted the end treatment end-on with the centerline of the vehicle aligned with the centerline of the end terminal. While the vehicle rode up the end treatment, the tires lost contact with the roadway surface. Shortly thereafter, the vehicle became airborne, but contacted the main body of the low-profile PCB prior to exiting the system and remained stable. Consequently, this test was successfully performed according to the test conditions of NCHRP Report No. 350 Test Designation 2-31.

Another test on the low-profile end treatment, test no. 414036-2, involved an 896-kg small car impacting the end treatment at a speed of 68.9 km/hr and at an angle of 15.1 degrees. The small car in this test impacted the nose of the end treatment with the right quarter point of the vehicle aligned with the centerline of the end treatment. The vehicle pitched upward as the left-front tire

rode up the end treatment. As the vehicle continued over the end treatment, the left-front tire dropped off of the backside of the system and the left-rear tire became airborne. Subsequently, the vehicle continued behind the system in a stable manner. Thus, the results of this test proved that the system performed successfully according to the test conditions of NCHRP Report No. 350 Test Designation 2-32.

Redirection tests were also performed on the low-profile end treatment. Due to the subjective nature of choosing the critical impact point, two different crash tests were conducted to assure that the critical impact point was accurately identified. One redirection test on the low-profile end treatment, test no. 1949A-1, involved an 893-kg small car impacting at a speed of 71.9 km/hr and at an angle of 16.3 degrees. The small car impacted the end treatment 1.98 m from the end. While the vehicle was being redirected, it became slightly airborne and remained airborne until it exited the system. Upon exiting the system, the vehicle remained upright and stable. Hence, the results of this test proved that the system performed successfully according to the test conditions of NCHRP Report No. 350 Test Designation 2-34.

Even though this system was successfully tested according to the test conditions of NCHRP Report No. 350 Test Designation 2-34, it was believed that the critical impact point chosen may not have been sufficient to fully comply with the criteria of Test Designation 2-34. Therefore, another test according to the NCHRP Report No. 350 Test Designation 2-34 criteria was performed on the low-profile end treatment. This test, test no. 414038-1, involved an 895-kg small car impacting at a speed of 70.9 km/hr and at an angle of 15.8 degrees. The vehicle impacted the end treatment 0.91 m from the end. As the vehicle began to redirect, the right-rear tire rode up on the end treatment. Shortly after the vehicle became parallel to the system with the right-rear tire on top of the end

treatment, the rear of the vehicle yawed counter-clockwise (CCW) as it became airborne. Continuing to yaw CCW, the rear tires contacted the top of the end treatment, and subsequently rolled off the barrier resulting in the stable redirection of the small car. Therefore, the results of this test show that the low-profile end treatment performed satisfactorily according to the Test Designation 2-34 criteria of NCHRP Report No. 350. Previous test results on the low-profile end treatment are summarized in Table 1.

Table 1. Previous End Treatment Terminal Tests

Test Parameter	Test 1949A-2 ³	Test 1949A-3 ³	Test 414036-2 ³	Test 1949A-1 ³	Test 414038-1 ³
NCHRP 350 Test Designation	2-30	2-31	2-32	2-34	2-34
Impact Location	end-on with centerline of right wheel aligned with centerline of end treatment	end-on with centerline of vehicle aligned with centerline of end treatment	end of terminal with vehicle's right quarter point aligned with centerline of end treatment	1.98 m downstream from end of end treatment	0.91 m downstream from end of end treatment
Test Vehicle Type	1988 Yugo GVL	1984 Chevrolet C-20 Pickup	1990 Ford Festiva	1986 Yugo	1990 Ford Festiva
Test Vehicle Gross Static Weight (kg)	893	2043	896	893	895
Impact Speed (km/hr)	72.6	74.8	68.9	71.9	70.9
Impact Angle (deg)	0.0	0.0	15.1	16.3	15.8
Exit Angle (deg)	2.0	Approximately 0	7.7	6.1	N/A
OIV (m/s)	Longitudinal	1.9	No contact	4.1	2.94
	Lateral	No contact	No contact	5.5	3.87
Ridedown Acceleration (g's)	Longitudinal	-0.6	N/A	-1.9	-2.83
	Lateral	N/A	N/A	-4.5	-3.06
Conclusion According to NCHRP Report No. 350 Criteria ¹	Meets all criteria	Meets all criteria	Meets all criteria	Meets all criteria	Meets all criteria

3 TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 Test Requirements

3.1.1 Longitudinal Barriers

Longitudinal barriers, such as low-profile bridge rails, must satisfy the requirements provided in NCHRP Report No. 350 to be accepted for use on new construction projects or as a replacement for existing systems when 3R projects are implemented where designs do not meet current safety standards. According to TL-2 of NCHRP Report No. 350, the bridge rail system must be subjected to two full-scale vehicle crash tests: (1) Test Designation 2-10: an 820-kg small car impacting at a speed of 70.0 km/hr and at an angle of 20 degrees; and (2) Test Designation 2-11: a 2,000-kg pickup truck impacting at a speed of 70.0 km/hr and at an angle of 25 degrees. However, low-height rigid barriers struck by small cars have been shown to meet safety performance standards (2-4). Therefore, the 820-kg small car crash test was deemed unnecessary for this project. The test conditions for TL-2 longitudinal barriers are summarized in Table 2.

3.1.2 Barrier End Treatments

The performance requirements in NCHRP Report No. 350 are considerably more involved for terminals, such as the end treatments for low-profile bridge rails, than for the longitudinal barrier itself. According to TL-2 of NCHRP Report No. 350, the gating end treatment must be subjected to seven different crash test conditions, which are discussed below and summarized in Table 2.

Test Designation 2-30: an 820-kg small car impacting the end treatment at a speed of 70 km/hr and at an angle of 0 degrees with the quarter point of the vehicle aligned with the centerline of the end treatment.

Test Designation 2-31: a 2,000-kg pickup truck impacting the end treatment at a speed of 70 km/hr and 0 degrees with the centerline of the vehicle aligned with the centerline of the end treatment.

Test Designation 2-32: an 820-kg small car impacting the end treatment at a speed of 70 km/hr and at an angle of 15 degrees with the centerline of the vehicle aligned with the centerline of the nose of the end treatment.

Test Designation 2-33: a 2,000-kg pickup truck impacting the end treatment at a speed of 70 km/hr and at an angle of 15 degrees with the centerline of the nose of the end treatment.

Test Designation 2-34: an 820-kg small car impacting the end treatment at a speed of 70 km/hr and at an angle of 15 degrees with the front corner of the vehicle aligned with the critical impact point of the end treatment.

Test Designation 2-35: a 2,000-kg pickup truck impacting the end treatment at a speed of 70 km/hr and at an angle of 20 degrees with the front corner of the vehicle impacting at the beginning of the length of need.

Test Designation 2-39: a 2,000-kg pickup truck impacting the end treatment at a speed of 70 km/hr and at an angle of 20 degrees from the reverse direction at the mid-length of the end treatment.

From the previous testing performed by TTI, a low-profile end treatment was tested successfully according to test designations 2-30, 2-31, 2-32, and 2-34 (3). Furthermore, these tests may be waived if the end treatment's overall sloped geometry is identical to TTI's successfully tested low-profile end treatment. In addition, test designation 2-33 is essentially a repeat of test designation 2-32, except a 2,000-kg pickup truck is used instead of an 820-kg small car. Under these test conditions, the pickup truck impact would be less severe than the small car at the same conditions. Subsequently, it is believed that test designation 2-33 can also be waived.

For test designation 2-35, a 2,000-kg pickup truck is impacted at the beginning of the length of need. In the case of the low-profile bridge rail, the length of need was defined as the connection point between the bridge rail and the end treatment or the point where the end treatment reaches its maximum height. Since the cross section of the end treatment at the connection point and the bridge rail are the same, this test will essentially be a repeat of test designation 2-11 performed on the bridge rail with a pickup impacting at an angle of 25 degrees and consequently may be waived.

In addition to test designations 2-33 and 2-35, it is believed that test designation 2-39, a reverse-direction impact with a pickup truck at an angle of 20 degrees and at the midpoint of the end treatment, may be waived. It is believed that for the specified test conditions of height of barrier at the impact point, type of test vehicle, impact speed, and impact angle, the test results would be acceptable. Furthermore, the type of impacts simulated by these test conditions would be rare, and it is believed that test designation 2-39 may be waived. Therefore, it is believed that if the overall geometry of the low-profile end treatment is identical to that of TTI's barrier system, additional crash testing of the end treatment would be unnecessary for this project.

3.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the bridge railing to contain, redirect, or allow controlled vehicle penetration in a predictable manner. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle, including windshield damage. Vehicle trajectory after collision is a measure of the potential for the post-impact trajectory of the vehicle to cause subsequent multi-vehicle accidents, thereby subjecting occupants of other vehicles to undue hazards or to subject the occupants of the impacting vehicle to secondary collisions with other fixed objects. These three evaluation criteria are defined in Table 3. The full-scale vehicle crash tests were conducted and reported in accordance with the procedures provided in NCHRP Report No. 350.

Table 2. NCHRP Report No. 350 Test Level 2 Crash Test Conditions

Test Article	Test Designation	Test Vehicle	Impact Conditions		Evaluation Criteria ¹
			Speed (km/hr)	Angle (degrees)	
Longitudinal Barrier	2-10	820C	70	20	A,D,F,H,I,K,M
	2-11	2000P	70	25	A,D,F,K,L,M
End Treatment	2-30	820C	70	0	C,D,F,H,I,K,N
	2-31	2000P	70	0	C,D,F,H,I,K,N
	2-32	820C	70	15	C,D,F,H,I,K,N
	2-33	2000P	70	15	C,D,F,H,I,K,N
	2-34	820C	70	15	C,D,F,H,I,K,N
	2-35	2000P	70	20	A,D,F,K,L,M
	2-39	2000P	70	20	C,D,F,K,L,M,N

¹ Evaluation criteria explained in Table 3.

Table 3. NCHRP Report No. 350 Evaluation Criteria for Crash Tests (1)

Structural Adequacy	A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underide, or override the installation although controlled lateral deflection of the test article is acceptable.
	C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.
Occupant Risk	D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.
	F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.
	H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9 m/s, or at least below the maximum allowable value of 12 m/s.
	I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15 g's, or at least below the maximum allowable value of 20 g's.
Vehicle Trajectory	K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.
	L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec, and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.
	M. The exit angle from the test article preferably should be less than 60 percent of test impact angle measured at time of vehicle loss of contact with test device.
	N. Vehicle trajectory behind the test article is acceptable.

4 LOW-PROFILE BRIDGE RAIL DESIGN

4.1 Design Considerations

The development of a low-height, concrete bridge railing required the consideration of several key factors, such as design impact load, economy, minimum barrier height, front-face geometry, and barrier end termination. Each of these factors will be discussed in greater detail in the following sections.

4.1.1 Design Impact Load

The design of the low-height bridge railing required an estimate of the dynamic lateral impact force applied to the railing. Two common methods were used: (1) an approximate method to predict the lateral impact force using a mathematical model taken from NCHRP Report No. 86 (6) and the 1977 AASHTO Barrier Guide (7), and (2) an approximate method using impulse - momentum equations and the coefficient of restitution.

The first method or mathematical model (6, 7) is presented in Equations 1 and 2 by:

$$F_{\text{lat. ave.}} = \frac{W V_I^2 \sin^2 \theta}{2g [A L \sin \theta - B (1 - \cos \theta) + D]} \quad (1)$$

and

$$F_{\text{lat. peak}} = F_{\text{lat. ave}} \times DF \quad (2)$$

where

$F_{\text{lat. ave.}}$	= average lateral impact force (lbs)
$F_{\text{lat. peak}}$	= peak lateral impact force (lbs)
W	= vehicle weight (4,409 lbs)
V_I	= impact velocity (63.79 ft/sec)
θ	= impact angle (25 degrees)
g	= acceleration due to gravity (32.2 ft/sec ²)
AL	= distance from vehicle's front end to center of mass (8.66 ft)
$2B$	= vehicle width (6.5 ft)

D = lateral displacement of railing (assumed 0 ft)
 DF = dynamic factor ($\pi/2$ to 2)

The equations above estimate the average and peak forces that are applied to the vehicle from the point of initial impact until the vehicle becomes parallel to the barrier. An estimate of the duration of this phase of impact, Δt , is expressed by Equation 3 (6).

$$\Delta t = \frac{[A L \sin \theta - B (1 - \cos \theta) + D]}{\frac{1}{2} V_I \sin \theta} \quad (3)$$

For a 4,409-lb (2,000-kg) pickup impacting a bridge railing at a speed of 43.5 mph (70 km/hr) and an angle of 25 degrees, $F_{lat. ave}$ can be shown to be 14,829 lbs (65,963 N) and $F_{lat. peak}$ ranges from 23,294 lbs to 29,658 lbs (103,615 to 131,926 N). It is predicted, using Equation 3, that the vehicle will become parallel to the barrier approximately 0.249 sec after initial impact. The vehicle would be expected to move approximately 14.3 ft (4.36 m) down the rail during this time.

Impulse - momentum equations and the coefficient of restitution can also be used to estimate the lateral impact force. The coefficient of restitution, e , is the ratio between the pre-impact and post-impact velocities as shown in Equation 4. The coefficient of restitution is a measure of the energy absorbed by vehicle and barrier deformations. Higher values indicate less energy absorption and higher impulses imparted to the vehicle. Since the coefficient of restitution cannot be greater than 1, this value gives an upper bound on the impulse imparted on the vehicle and hence yields a measure of the maximum force that can be applied to the barrier.

$$e = \frac{V_{B2} - V_{A2}}{V_{A1} - V_{B1}} = \frac{|\text{relative velocity of separation}|}{|\text{relative velocity of approach}|} \quad (4)$$

where V_{A1} = velocity of auto before impact (ft/sec)

$$\begin{aligned}
V_{A2} &= \text{velocity of auto after impact (ft/sec)} \\
V_{B1} &= \text{velocity of barrier before impact (ft/sec)} \\
V_{B2} &= \text{velocity of barrier after impact (ft/sec)}
\end{aligned}$$

The impulse, or change in momentum during the impact, is estimated using equations 5 through 7.

$$I = \int_{t_1}^{t_2} F dt = M_F - M_I \quad (5)$$

$$M_I = m_A V_{A1} + m_B V_{B1} \quad (6)$$

$$M_F = m_A V_{A2} + m_B V_{B2} \quad (7)$$

where

I	= total impulse
F	= impact force function (lbs)
t_1	= initial time of impact (sec)
t_2	= final time of impact (sec)
M_I	= momentum of objects before impact (lb-sec)
M_F	= momentum of objects after impact (lb-sec)
m_A	= mass of vehicle (lb-sec ² /ft)
m_B	= mass of barrier (lb-sec ² /ft)

For an oblique impact between a vehicle and a rigid longitudinal barrier (i.e., mass of barrier infinitely large and velocity of barrier always zero, as shown in Figure 1(a)), Equation 4 can be simplified to:

$$e = \frac{-V_{A2}}{V_{A1}} \quad (8)$$

For an impact at 43.5 mph (70 km/hr) and 25 degrees, V_{A1} is as follows:

$$V_{A1} = 63.79 \text{ fps}(\sin 25^\circ \hat{i} + \cos 25^\circ \hat{j}) = 26.96 \text{ fps } \hat{i} + 57.81 \text{ fps } \hat{j} \quad (9)$$

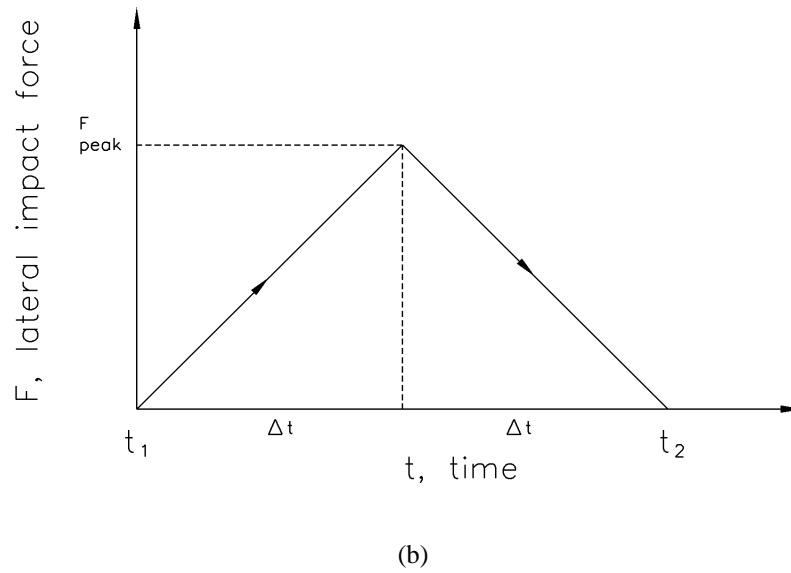
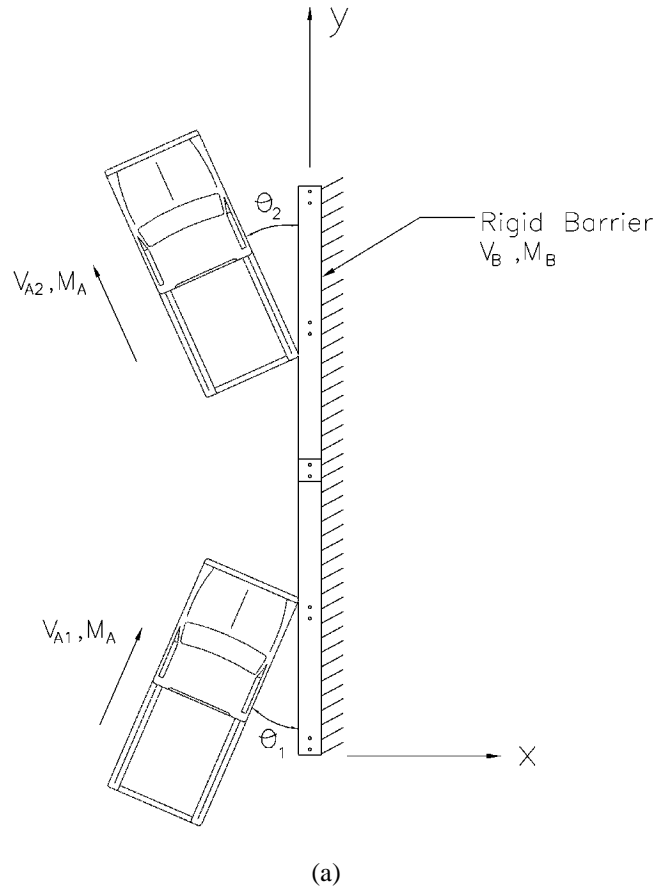


Figure 1. (a) Impact Schematic; and (b) Saw-Tooth Forcing Function

Using the coefficient of restitution, $e = 1.0$, the conservation of momentum in the x-direction, and the x-component of V_{A1} in Equation 9, the x-component of V_{A2} can be found as follows:

$$V_{A2_x} = -26.96 \text{ fps} \quad (10)$$

The momentum in the x-direction before and after impact is shown by Equations 11 and 12.

$$M_{I_x} = m_A V_{A1_x} \quad (11)$$

$$M_{F_x} = m_A V_{A2_x} \quad (12)$$

Using Equations 11 and 12 with a 4,409-lb (2,000-kg) vehicle and substituting into Equation 5, the impulse imparted to the vehicle during impact becomes:

$$\int_{t_1}^{t_2} F_x dt = M_{F_x} - M_{I_x} = \left(\frac{4,409 \text{ lbs}}{32.2 \text{ ft/sec}^2} \right) \times (-26.96 \text{ fps} - 26.96 \text{ fps}) \quad (13)$$

$$\int_{t_1}^{t_2} F_x dt = -7,383 \text{ lbs} \cdot \text{sec}$$

Assuming a single, symmetrical saw-tooth forcing function, as shown in Figure 1(b), the impulse is equal to the area under the triangle or $\frac{1}{2}(2\Delta t)F_{\text{lat. peak}}$. If the time from impact until the vehicle becomes parallel to the bridge railing is 0.249 sec, as estimated previously, the peak lateral impact force is estimated to be 29,651 lbs (131,892 N). Thus, both procedures predict that the peak lateral impact force should be approximately 30,000 lbs (133,447 N). As a result, the barrier rail was designed with sufficient capacity to withstand this estimated impact force.

4.1.2 Economy

Reinforced concrete was selected for use in the low-height, bridge railing based on ease of

construction, material availability, and overall economy. Since virtually all of the existing concrete barrier systems incorporate economical top-mounted designs, this same type of construction was utilized for this new bridge rail as well. Cast-in-place concrete construction, used in conjunction with a minimum quantity and size of longitudinal and vertical reinforcing bars, was believed to provide a viable alternative for the roadway situation. Costs for construction materials and labor were estimated to be very low for this system because the barrier: (1) was configured with widely-spaced vertical bars tied into the bridge deck; (2) utilized the smallest available bar size; and (3) used an efficient layout for the reinforcing steel.

4.1.3 Minimum Barrier Height and Front-Face Geometry

The ability of a low-height, barrier rail to adequately contain and redirect an impacting vehicle is greatly affected by its front-face geometry and top-mounting height. If the barrier height is too low and offers little vehicle containment, the vehicle may either vault or roll over the barrier system. If the barrier height is generally sufficient but its front face geometry provides increased tire interaction below or near its mid-height, then the impacting vehicle's tire may have greater propensity to climb, mount, or traverse the barrier system. These two factors were previously considered at length during the development of two low-height, timber bridge railing systems for use on timber deck bridges located low-volume roads (8-12).

For this study, a 508-mm barrier height was chosen for the new bridge rail based on prior successful full-scale crash testing on low-height timber and concrete barriers. For the barrier's front-face geometry, MwRSF researchers believed that improved performance would result if two conditions were met. First, if the barrier's redirective force was applied to a point above the mid-height of the impacted wheel assembly, then vehicle override would be minimized. Second, if the

barrier face extended further out toward the vehicle at the top than at the lower regions, then the probability of the tire climbing the barrier's face would be reduced. As a result, a configuration was chosen which incorporated a vertical wall for the lower 55% of parapet height and a protruding step for the remaining upper parapet height. Researchers believed that acceptable vehicle performance would be obtained by having the upper protruding step blocked out 76 mm in front of the lower rail region.

4.1.4 Barrier End Termination

For all types of longitudinal barriers, it is always necessary to make consideration for proper end termination of the barrier system as it is a legitimate safety concern. As noted previously, TTI's low-profile concrete barrier system was developed with a crashworthy, sloped end terminal. For the TTI barrier system, the concrete end was sloped downward from 508 mm to 102 mm at its upstream end and over a length of 4,572 mm. In addition, the top barrier width decreased from 711 mm to 366 mm at the upstream end.

For the new low-height bridge railing system, end termination was also considered. MwRSF researchers reasoned that the new barrier's sloped geometry should replicate that of TTI's barrier system. If the overall geometry was the same, then it was believed that the same level of safety would be provided, and additional crash testing would not be required.

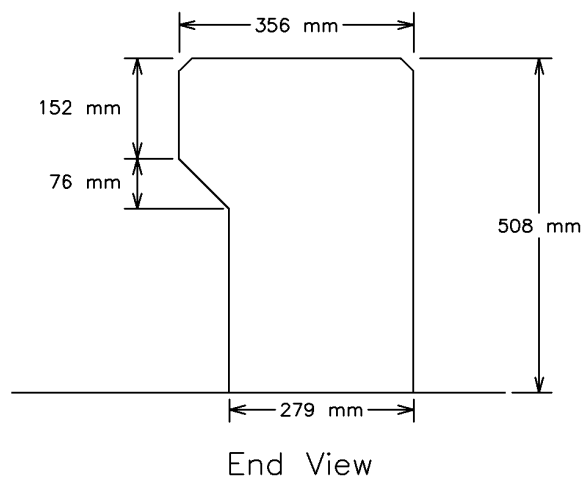
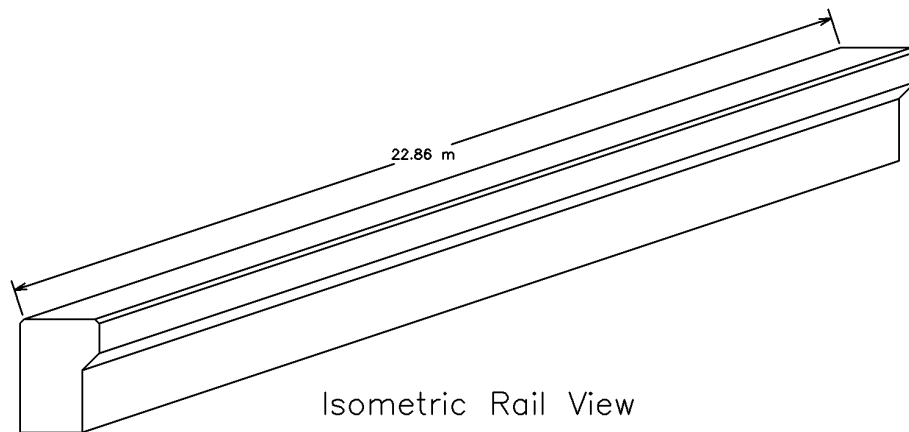
4.2 Design Details

The 22.86-m long test installation consisted of a reinforced concrete parapet, as shown in Figures 2 through 4. Photographs of the test installation are shown in Figures 5 through 6.

The entire system measured 508-mm high by 356-mm and 279-mm wide at the top and bottom surfaces, respectively, as shown in Figures 2, 5, and 6. The concrete used for the bridge rail

consisted of a Nebraska 47-BD Mix Type 3, with a minimum compressive strength of 31.03 MPa. A minimum concrete cover of 38 mm was used for all of the rebar placed within the concrete bridge rail. All of the steel reinforcement in the bridge rail was Grade 60 epoxy-coated rebar.

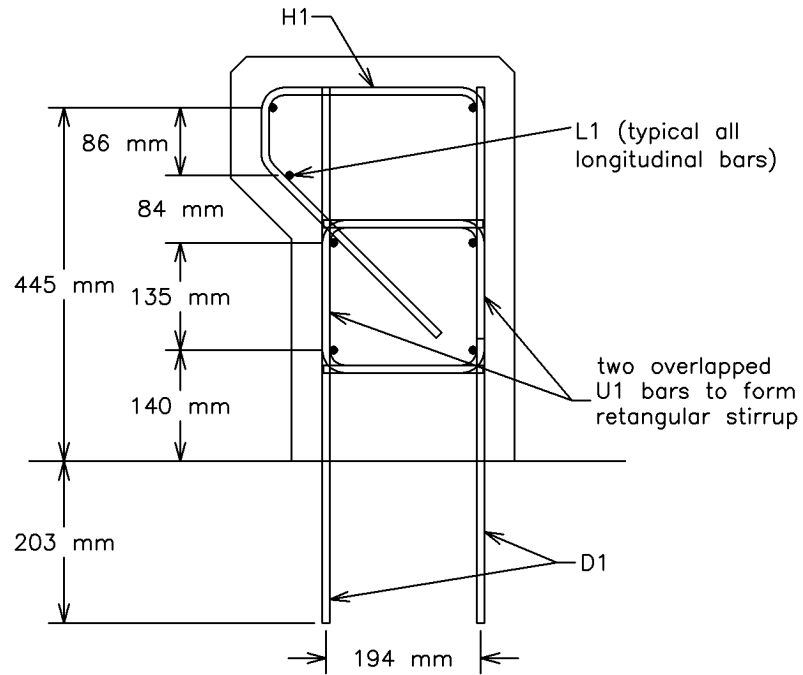
The steel reinforcement utilized No. 3 bars for the longitudinal, vertical dowel, vertical hoop, and vertical U stirrup bars, as shown in Figures 3 and 4. Each of the seven runs of longitudinal rebar was 22.78-m long. The length of the longitudinal bar can be varied as long as the minimum lap length of 229 mm is maintained. The vertical dowel bars were 673-mm long and spaced 610 mm on center. The vertical hoop bars were 956-mm long and spaced 610 mm on center, as shown in Figure 3. The vertical rectangular stirrups, formed with two overlapped 556-mm long U stirrup bars, were spaced 305 mm on center, as shown in Figure 3. The vertical dowel bars were attached to the existing concrete apron using an epoxy resin, as shown in Figure 3. For actual attachment to a reinforced concrete deck, the vertical bars would be bent into a L-shape and tied to the appropriate transverse deck bars in order to develop their structural capacity.



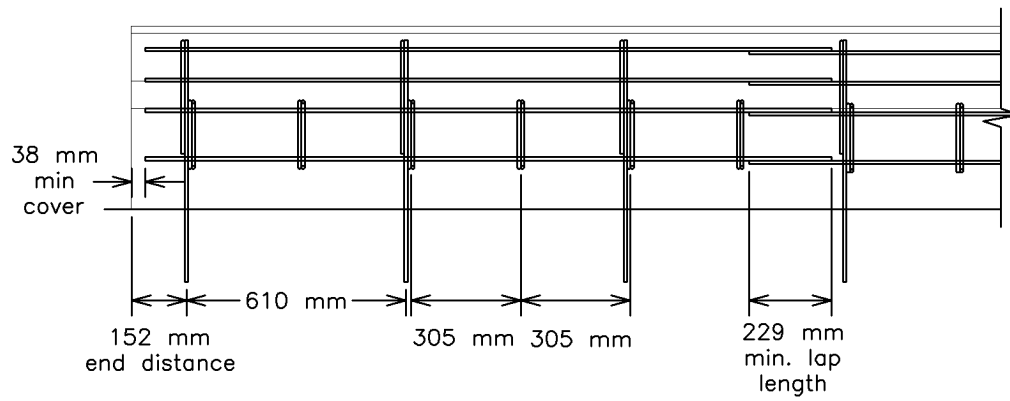
NOTES:

- (1) Use Grade 60 reinforcement.
- (2) Use minimum concrete strength of $f'_c = 31.03 \text{ MPa}$.
- (3) Use 38 mm minimum cover.
- (4) Use 19 mm chamfer on top corners.
- (5) Extra No. 3 bar place along sloped stirrup used for continuity near front face.
(Position may be altered.)
- (6) Minimum lap length for longitudinal bars is 229 mm.
- (7) Special reinforcement spacing at free ends or joints to be determined.

Figure 2. Low-Profile Bridge Rail Details



Rebar Details



Rebar Longitudinal Details

Figure 3. Low-Profile Bridge Rail Design Details

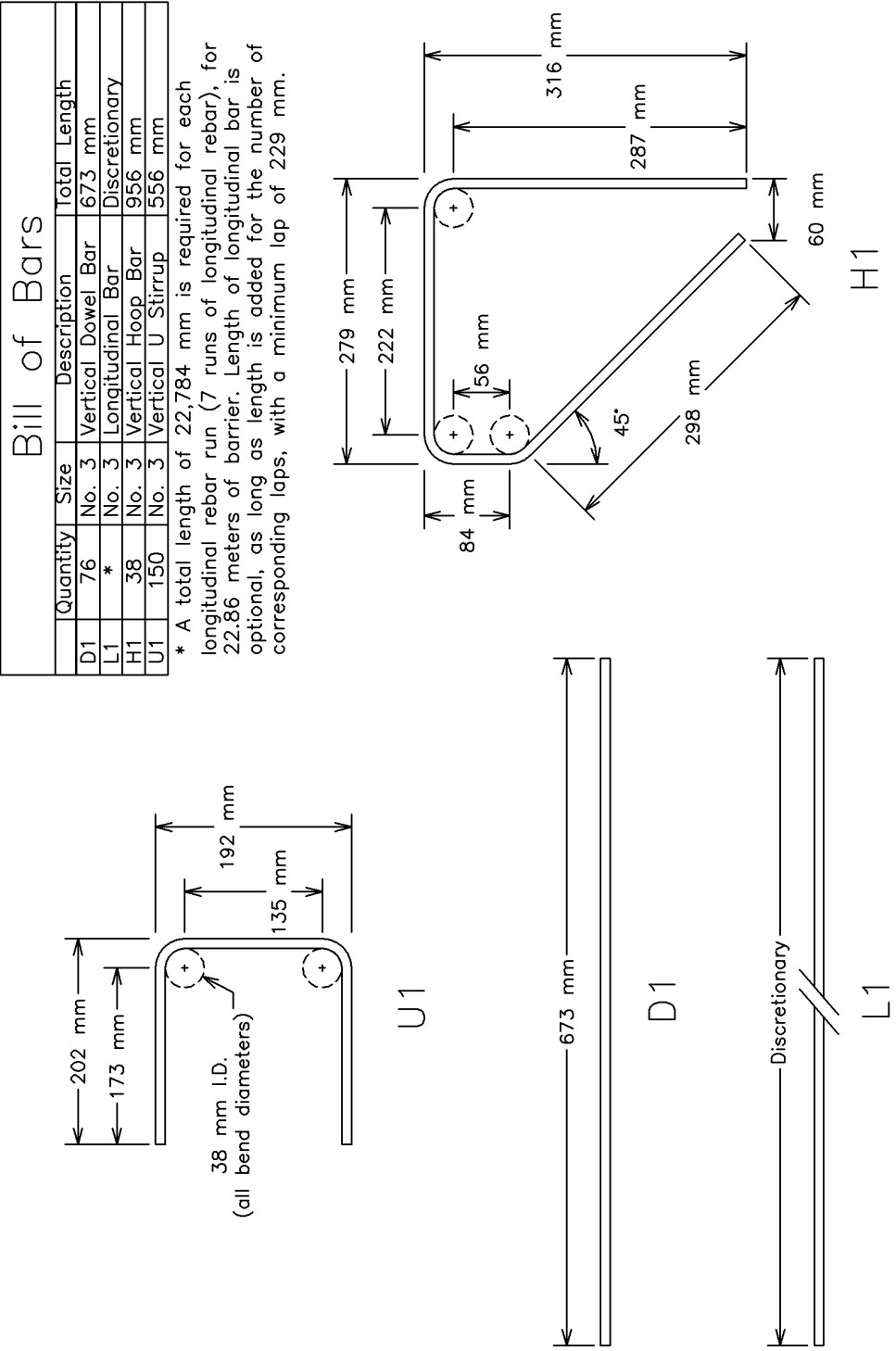


Figure 4. Low-Profile Bridge Rail Design Reinforcement Details



Figure 5. Low-Profile Bridge Rail



Figure 6. Low-Profile Bridge Rail

5 TEST CONDITIONS

5.1 Test Facility

The testing facility is located at the Lincoln Air-Park on the northwest (NW) side of the Lincoln Municipal Airport and is approximately 8.0 km NW of the University of Nebraska-Lincoln.

5.2 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the bridge rail. A digital speedometer was located on the tow vehicle to increase the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch ([13](#)) was used to steer the test vehicle. A guide-flag, attached to the front-right wheel and the guide cable, was sheared off before impact with the bridge rail. The 9.5-mm diameter guide cable was tensioned to approximately 13.3 kN, and supported laterally and vertically every 30.48 m by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide-flag struck and knocked each stanchion to the ground. The vehicle guidance system was approximately 304.8-m long.

5.3 Test Vehicles

For test LPBR-1, a 1995 GMC 2500 SL $\frac{3}{4}$ -ton pickup truck was used as the test vehicle. The test inertial and gross static weights were 2,018 kg. The test vehicle is shown in Figure 7, and vehicle dimensions are shown in Figure 8.

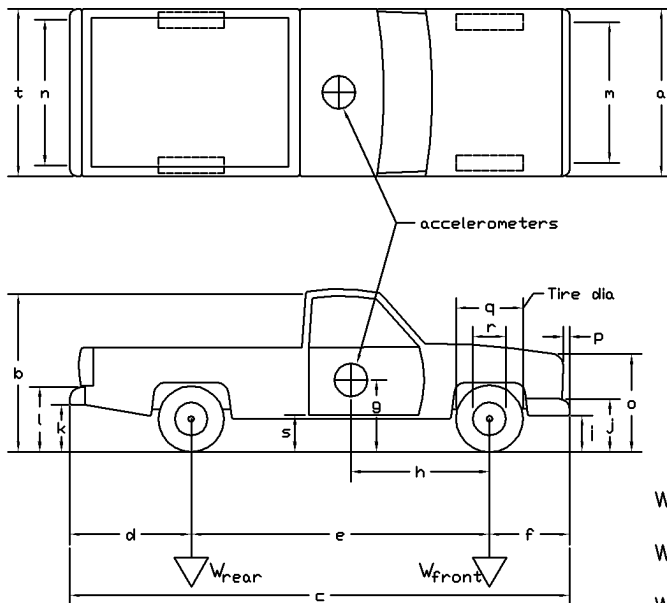
The longitudinal component of the center of gravity was determined using the measured axle



Figure 7. Test Vehicle, Test LPBR-1

Date: 4/9/01 Test Number: LPBR-1 Model: 2500
 Make: GMC Vehicle I.D.#: 1GDGC24K85799769
 Tire Size: 245/75 R16 Year: 1995 Odometer: 231268

*(All Measurements Refer to Impacting Side)



Vehicle Geometry – mm

a 1861 b 1842
 c 5537 d 1295
 e 3327 f 914
 g 667 h 1384
 i 445 j 673
 k 578 l 781
 m 1613 n 1625
 o 1041 p 108
 q 765 r 445
 s 476 t 1842

Wheel Center Height Front 375
 Wheel Center Height Rear 371
 Wheel Well Clearance (FR) 914
 Wheel Well Clearance (RR) 959

Weights – kg	Curb	Test Inertial	Gross Static
W_{front}	<u>1169</u>	<u>1178</u>	<u>1178</u>
W_{rear}	<u>856</u>	<u>842</u>	<u>842</u>
W_{total}	<u>2025</u>	<u>2020</u>	<u>2020</u>

Engine Type 8 CYL. GAS
 Engine Size 5.7 L 350 CID

Transmission Type:
☒ Automatic or Manual
 FWD or ☒ RWD or 4WD

Note any damage prior to test: PASS. SIDE FENDER AND DOOR DENTS
BOX SIDE DENTS

Figure 8. Vehicle Dimensions, Test LPBR-1

weights. The location of the final centers of gravity are shown in Figure 7.

Square, black and white-checked targets were placed on the vehicle to aid in the analysis of the high-speed film and E/cam video, as shown in Figure 9. Round, checkered targets were placed on the center of gravity on the driver's side door, the passenger's side door, and on the roof of the vehicle. The remaining targets were located for reference so that they could be viewed from the high-speed cameras for film analysis.

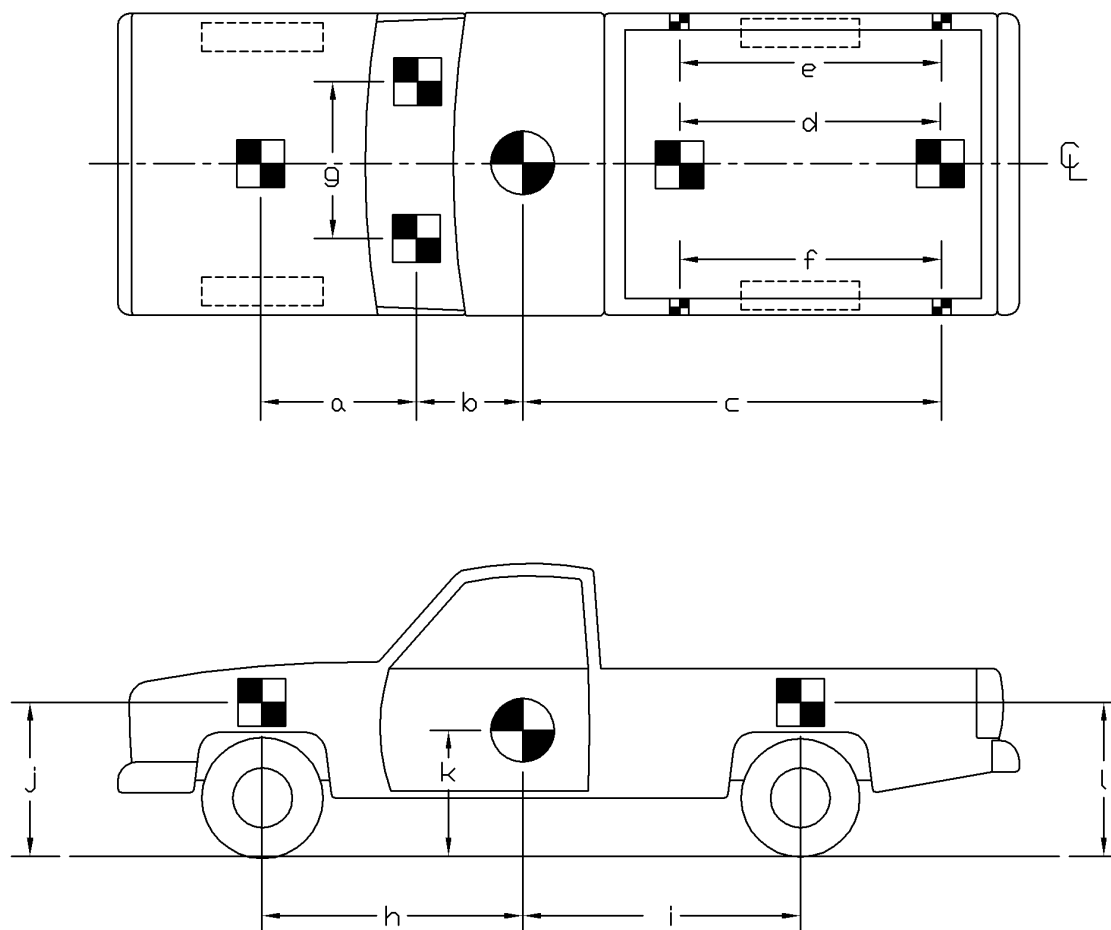
The front wheels of the test vehicle were aligned for camber, caster, and toe-in values of zero so that the vehicle would track properly along the guide cable. Two 5B flash bulbs were mounted on both the hood and roof of the vehicle to pinpoint the time of impact with the bridge rail on the high-speed film and E/cam video. The flash bulbs were fired by a pressure tape switch mounted on the front face of the bumper. A remote controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

5.4 Data Acquisition Systems

5.4.1 Accelerometers

One triaxial piezoresistive accelerometer system with a range of ± 200 G's was used to measure the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 10,000 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-4M6, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan and includes three differential channels as well as three single-ended channels. The EDR-4 was configured with 6 Mb of RAM memory and a 1,500 Hz lowpass filter. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to analyze and plot the accelerometer data.

A backup triaxial piezoresistive accelerometer system with a range of ± 200 G's was also



TEST #: LPBR-1			
TARGET GEOMETRY (mm)			
a 914	d 1873	g 1121	j 1013
b 692	e 2146	h 1384	k 667
c 2743	f 2143	i 1943	l 1067

Figure 9. Vehicle Target Locations, Test LPBR-1

used to measure the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 3,200 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-3, was developed by Instrumental Sensor Technology (IST) of Okemos, Michigan. The EDR-3 was configured with 256 Kb of RAM memory and a 1,120 Hz lowpass filter. Computer software, “DynaMax 1 (DM-1)” and “DADiSP” were used to analyze and plot the accelerometer data.

5.4.2 Rate Transducers

A Humphrey 3-axis rate transducer with a range of 360 deg/sec in each of the three directions (pitch, roll, and yaw) was used to measure the rates of motion of the test vehicle. The rate transducer was rigidly attached to the vehicle near the center of gravity of the test vehicle. Rate transducer signals, excited by a 28 volt DC power source, were received through the three single-ended channels located externally on the EDR-4M6 and stored in the internal memory. The raw data measurements were then downloaded for analysis and plotted. Computer software, “DynaMax 1 (DM-1)” and “DADiSP” were used to analyze and plot the rate transducer data.

5.4.3 High-Speed Photography

For test LPBR-1, two high-speed 16-mm Red Lake Locam cameras, with operating speeds of approximately 500 frames/sec, were used to film the crash test. Three high-speed Red Lake E/cam video cameras, with operating speeds of 500 frames/sec, were also used to film the crash test. Three Canon digital video cameras, with a standard operating speed of 29.97 frames/sec, were also used to film the crash test. A Locam, with a wide-angle 12.5-mm lens, a high-speed E/cam video camera, and a Canon digital video camera were placed above the test installation to provide a field of view perpendicular to the ground. A high-speed E/cam video camera and a Canon digital video camera were placed downstream from the impact point and had a field of view parallel to the barrier.

A high-speed E/cam video camera and an SVHS video camera were placed upstream from the impact point and had a field of view parallel to the barrier. A Locam and a Canon digital video camera were placed on the traffic side of the barrier and had a field of view perpendicular to the barrier. A schematic of all nine camera locations for test LPBR-1 is shown in Figure 10. The Locam film and E/cam video were analyzed using the Vanguard Motion Analyzer and the Redlake Motion Scope software, respectively. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed film.

5.4.4 Pressure Tape Switches

For test LPBR-1, five pressure-activated tape switches, spaced at 2-m intervals, were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the left-front tire of the test vehicle passed over it. Test vehicle speed was determined from electronic timing mark data recorded using the "Test Point" software. Strobe lights and high-speed film analysis are used only as a backup in the event that vehicle speed cannot be determined from the electronic data.

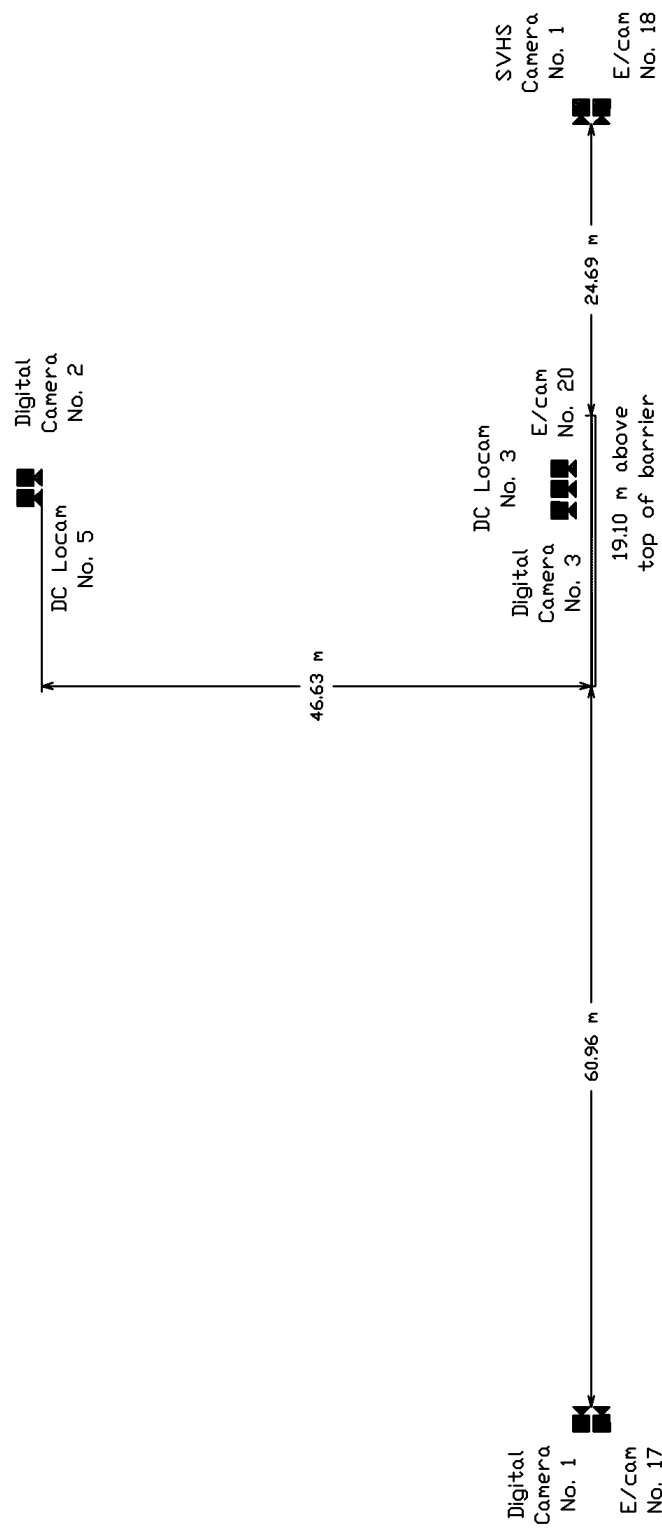


Figure 10. Location of High-Speed Cameras, Test LPBR-1

6 CRASH TEST NO. 1

6.1 Test LPBR-1

The 2,018-kg pickup truck impacted the low-profile bridge rail at a speed of 70.0 km/hr and at an angle of 27.1 degrees. A summary of the test results and the sequential photographs are shown in Figure 11. Additional sequential photographs are shown in Figures 12 and 13. Documentary photographs of the crash test are shown in Figures 14 and 15.

6.2 Test Description

Initial impact occurred 5.79-m downstream from the upstream end of the system, as shown in Figure 16. At 0.036 sec after impact, the left-front corner of the vehicle was located 0.76-m downstream from the impact point and protruding across the rail. At 0.070 sec, the left-rear corner of the vehicle's cab contacted the rail. At this same time, the gap at the top of the left-side door began to widen. At 0.100 sec, the left-front tire became airborne as the front of the vehicle pitched upward. At 0.106 sec, the right-front tire became airborne. At 0.108 sec, half of the left-side door was in contact with the rail. At 0.114 sec, the truck began to redirect. At 0.120 sec, the left-front corner of the vehicle reached its maximum intrusion of 457 mm over the rail. At 0.132 sec, the left-rear tire became airborne. At 0.150 sec, the front of the vehicle was 3.05-m downstream from the impact point. At 0.164 sec, the left side of the vehicle's cab was in contact with the rail. At 0.174 sec, the right-rear tire became airborne as the front bumper continued to slide along the top of the rail. At 0.211 sec, the vehicle began to roll counter-clockwise (CCW) toward the rail. At 0.247 sec, the left-front corner of the truck box contacted the wall. At 0.293 sec, one half of the left side of the truck box was in contact with the wall. At 0.352 sec, the front end of the truck reached its maximum height above the ground. At 0.359 sec, the front of the vehicle was 6.10-m downstream from the

impact point. The vehicle became parallel to the bridge rail at 0.378 sec after impact with a resultant velocity of 49.9 km/hr. At 0.406 sec, the vehicle was completely airborne. At 0.417 sec, the left side of the truck box began to slide along the top of the rail. At 0.479 sec, the right-side tires were airborne. At 0.500 sec, the left side of the truck box continued to slide along the top of the bridge rail as the vehicle continued to roll CCW toward the rail. At 0.584 sec, the front of the vehicle was 9.14-m downstream from the impact point. At 0.559 sec, the truck box reached its maximum intrusion of 442 mm over the rail. At 0.600 sec, the vehicle's rear end reached its maximum height above the ground as the front end of the vehicle pitched downward into the ground. At 0.612 sec, the vehicle reached its maximum roll angle of 36 degrees toward the rail. At this same time, the left side of the vehicle's box and cab remained in contact with the bridge rail. At 0.650 sec, the left-front corner of the vehicle contacted the ground. Shortly after this time, the vehicle began to roll clockwise (CW). At 0.756 sec, the rear of the vehicle remained in contact with the rail at 6.10-m downstream from the impact point. At 0.794 sec, the vehicle exited the bridge rail at an estimated trajectory angle of 5 to 7 degrees and at a resultant velocity of 46.1 km/hr. At 0.905 sec, the rear of the vehicle was 7.62-m downstream from the impact point and no longer in contact with the system. At 1.003 sec, the right-rear tire remained airborne. At 1.118 sec, the right-front tire contacted the ground. At 1.306 sec, the rear of the vehicle contacted the ground. The vehicle came to rest 39.62-m downstream from impact and 2.43-m laterally away from the traffic-side face of the rail, as shown in Figures 11 and 17.

6.3 Barrier Damage

Damage to the barrier was minimal, as shown in Figures 17 through 19. Cracking of the bridge rail did not occur. Barrier damage consisted mostly of contact marks on the concrete face

and minor spalling of the concrete. The length of vehicle contact along the concrete bridge rail was approximately 2.74 m. Minor spalling and black contact marks were found on the front face of the bridge rail. The lower front face of the bridge rail encountered 457 mm of contact marks originating at the impact point. Black contact marks and minor scrape mark were found on the concrete deck 7.62-m downstream from impact and 0.91-m laterally away from the traffic-side face of the rail.

6.4 Vehicle Damage

Exterior vehicle damage was moderate, as shown in Figures 20 through 22. The left-front side of the bumper was twisted in toward the engine compartment. The left-front fender was dented and deformed. Scrape marks and slight deformations were found on the lower portion of the box and the rear bumper. The box was also slightly twisted thereby increasing the gap between the cab and the box. Small scrape marks were found on the left-rear steel rim. Two 152-mm long scrape marks from the concrete rail were found on the left-rear wheel side wall. The left-front tire was almost pulled completely off of the steel rim. The left-front wheel disengaged from the upper A-frame control arm. The lower A-frame control arm was bent downward. The left-front tie rod disengaged. The sway bar was stretched but remained attached to the lower control arm. The left-front frame member encountered major deformations. The left side of the interior floorboard was deformed near the left toe pan and under the brake pedal, as shown in Figure 22. The roof, the hood, the right-side and left-side doors, and all the window glass remained undamaged.

6.5 Occupant Risk Values

The longitudinal and lateral occupant impact velocities were determined to be 6.61 m/sec and 4.78 m/sec, respectively. The maximum 0.010-sec average occupant ridedown decelerations in the longitudinal and lateral directions were 7.87 g's and 8.10 g's, respectively. It is noted that the

occupant impact velocities (OIV's) and occupant ridedown decelerations (ORD's) were within the suggested limits provided in NCHRP Report No. 350. The results of the occupant risk, determined from the accelerometer data, are summarized in Figure 11. Results are shown graphically in Appendix A. The results from the rate transducer are shown graphically in Appendix B.

6.6 Discussion

The analysis of the test results for test LPBR-1 showed that the low-profile bridge rail system adequately contained and redirected the vehicle with controlled lateral displacements of the bridge rail. There were no detached elements or fragments which showed potential for penetrating the occupant compartment or presented undue hazard to other traffic. Deformations of, or intrusion into, the occupant compartment that could have caused serious injury did not occur. The test vehicle did not penetrate or ride over the bridge rail and remained upright during and after the collision. Vehicle roll, pitch, and yaw angular displacements were noted, but they were deemed acceptable because they did not adversely influence occupant risk safety criteria nor cause rollover. After collision, the vehicle's trajectory revealed minimum intrusion into adjacent traffic lanes. In addition, the vehicle's exit angle was less than 60 percent of the impact angle. Therefore, test LPBR-1 conducted on the bridge railing was determined to be acceptable according to the NCHRP Report No. 350 safety performance criteria.

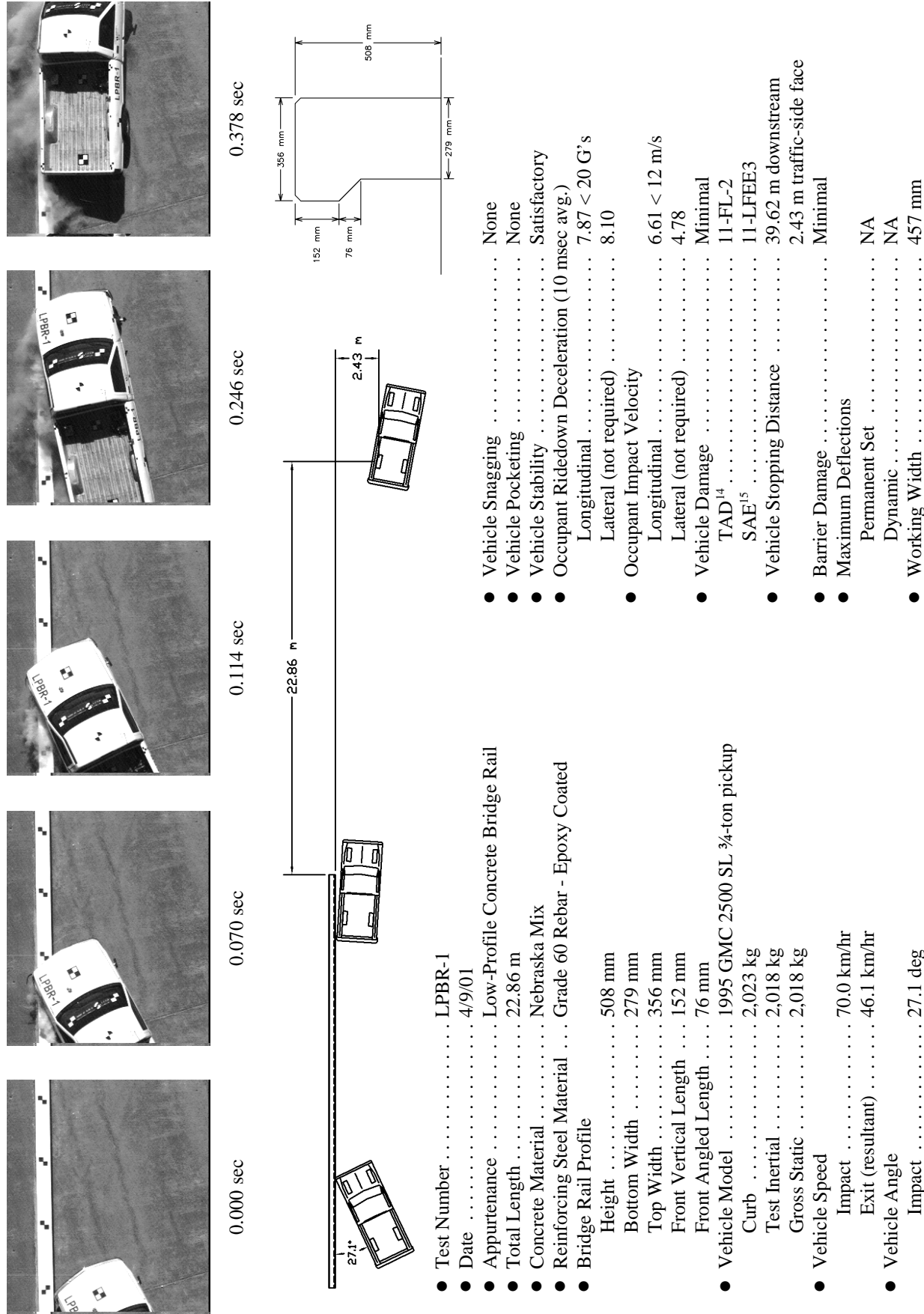


Figure 11. Summary of Test Results and Sequential Photographs, Test LPBR-1



0.000 sec



0.106 sec



0.384 sec



0.650 sec



1.118 sec



0.000 sec



0.070 sec



0.154 sec



0.338 sec



0.640 sec

Figure 12. Additional Sequential Photographs, Test LPBR-1



0.000 sec



0.172 sec



0.414 sec



0.724 sec



1.310 sec

Figure 13. Additional Sequential Photographs, Test LPBR-1



Figure 14. Documentary Photographs, Test LPBR-1



Figure 15. Documentary Photographs, Test LPBR-1



Figure 16. Impact Location, Test LPBR-1



Figure 17. Overall Damage and Final Positions, Test LPBR-1



Figure 18. Low-Profile Bridge Rail Damage, Test LPBR-1



Figure 19. Low-Profile Bridge Rail Damage, Test LPBR-1



Figure 20. Vehicle Damage, Test LPBR-1



Figure 21. Vehicle Damage, Test LPBR-1



Figure 22. Occupant Compartment Deformations, Test LPBR-1

7 SUMMARY AND CONCLUSIONS

A low-profile bridge railing was constructed and full-scale vehicle crash tested. The bridge rail was configured as a minimally-reinforced, low-height concrete parapet. A full-scale vehicle crash test was performed with a $\frac{3}{4}$ -ton pickup truck on the bridge rail system and was determined to be acceptable according to the TL-2 safety performance criteria presented in NCHRP Report No. 350. A summary of the safety performance evaluation is provided in Table 4.

Table 4. Summary of Safety Performance Evaluation Results

Evaluation Factors	Evaluation Criteria	Test LPBR-1
Structural Adequacy	A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	S
Occupant Risk	D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	S
	F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.	S
Vehicle Trajectory	K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	S
	L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec, and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.	S
	M. The exit angle from the test article preferably should be less than 60 percent of test impact angle measured at time of vehicle loss of contact with test device.	S

S - Satisfactory
 M - Marginal
 U - Unsatisfactory
 NA - Not Available

8 RECOMMENDATIONS

A low-profile bridge railing system designed for use in urban areas, as described in this report, was successfully crash tested according to the criteria found in NCHRP Report No. 350. The results of this test indicate that this design is a suitable design for use on Federal-aid highways where pedestrians and/or site restrictions prevent the use of conventional bridge rails with transitions. However, any design modifications made to the low-profile bridge railing system can only be verified through the use of full-scale crash testing.

Furthermore, a low-profile end treatment system for use with the low-profile bridge railing system has also been designed. This design, as shown in Figures 23 through 27, is based on the successful full-scale vehicle crash testing on a NCHRP Report No. 350 TL-2 low-profile end treatment previously developed by TTI. Based on similarities between TTI's crash-tested TL-2 end treatment and the proposed end treatment system, the researchers believe that the proposed end treatment would meet the TL-2 criteria of NCHRP Report No. 350.

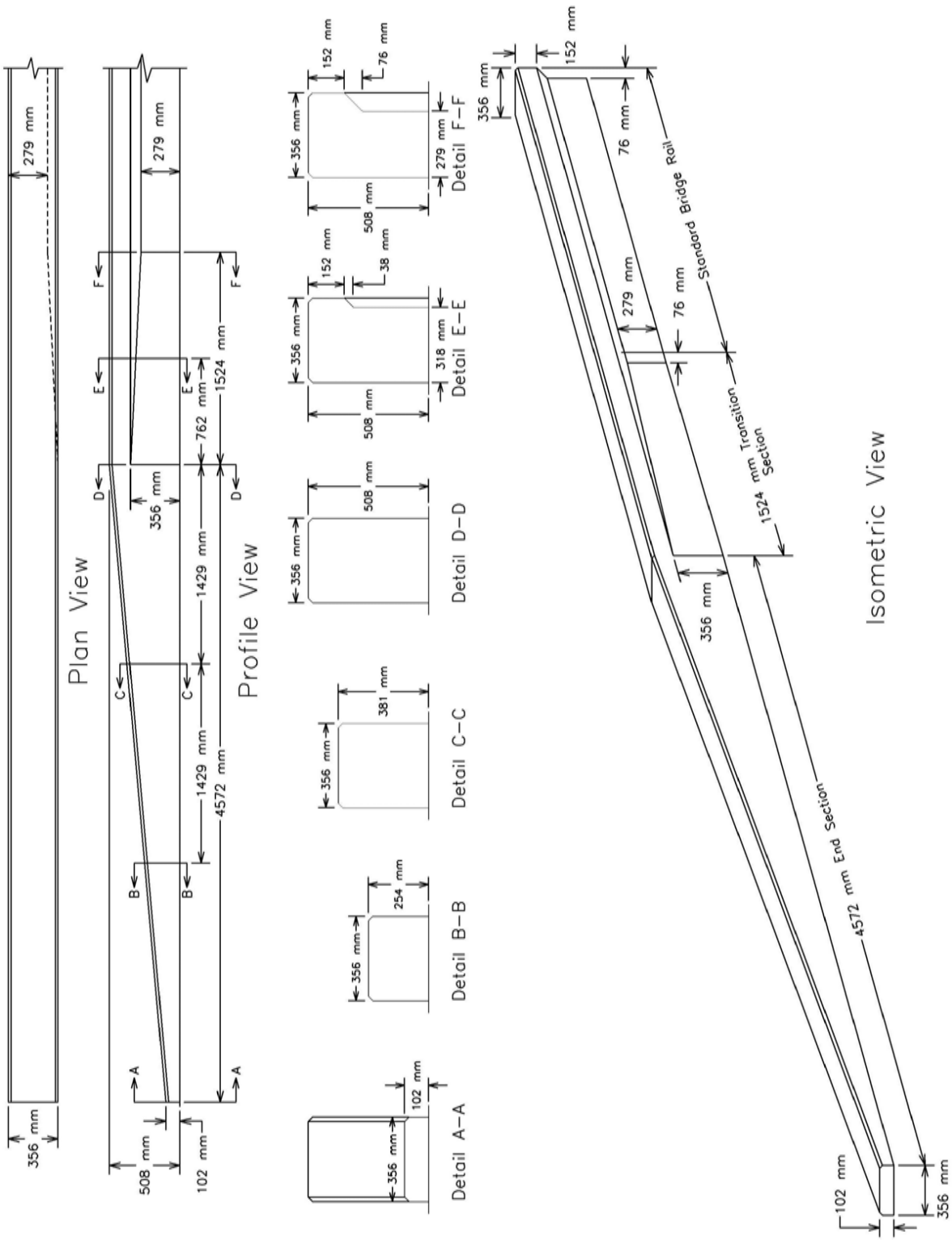


Figure 23. Low-Profile Bridge Rail End Treatment Design Details

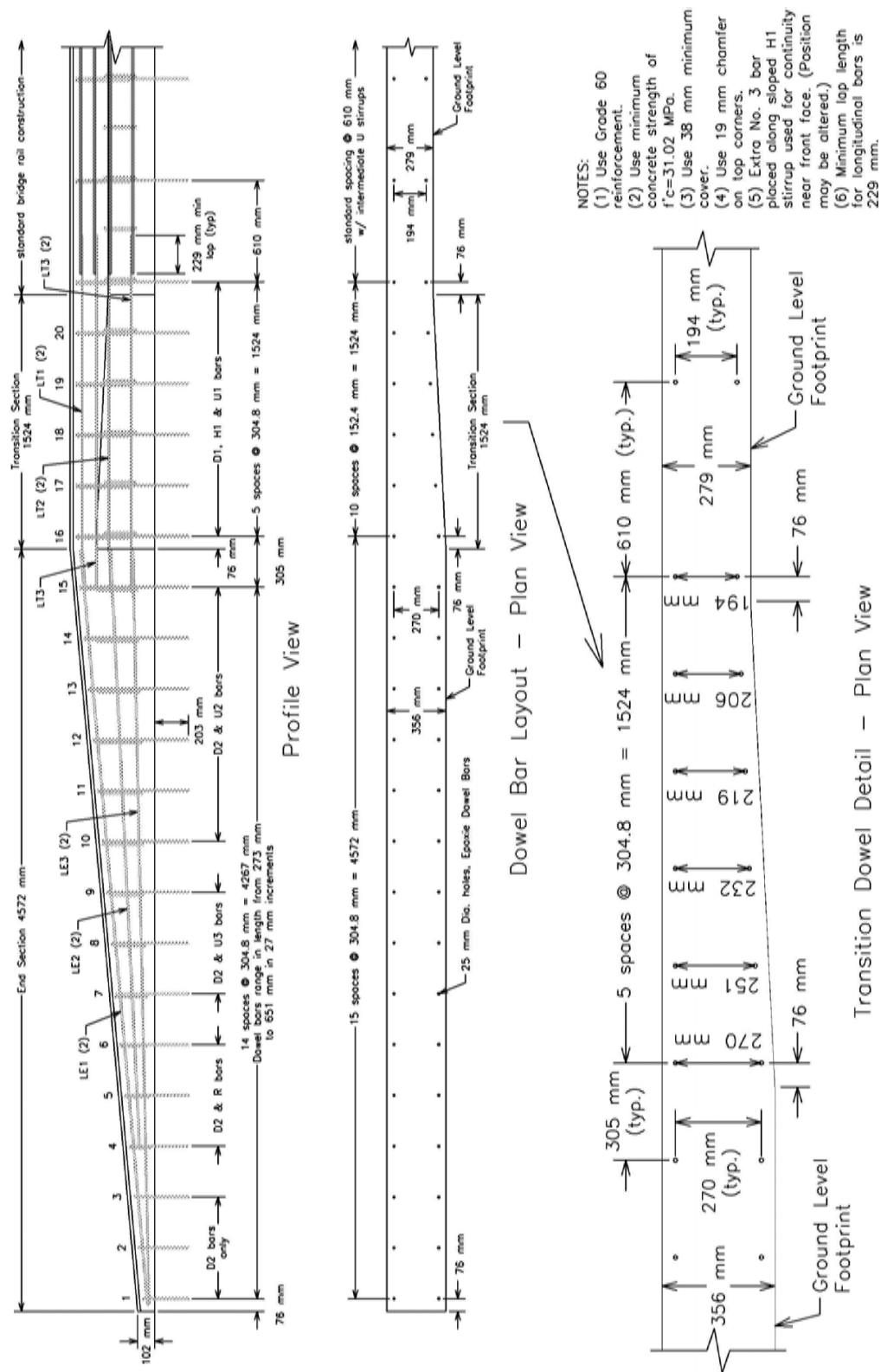
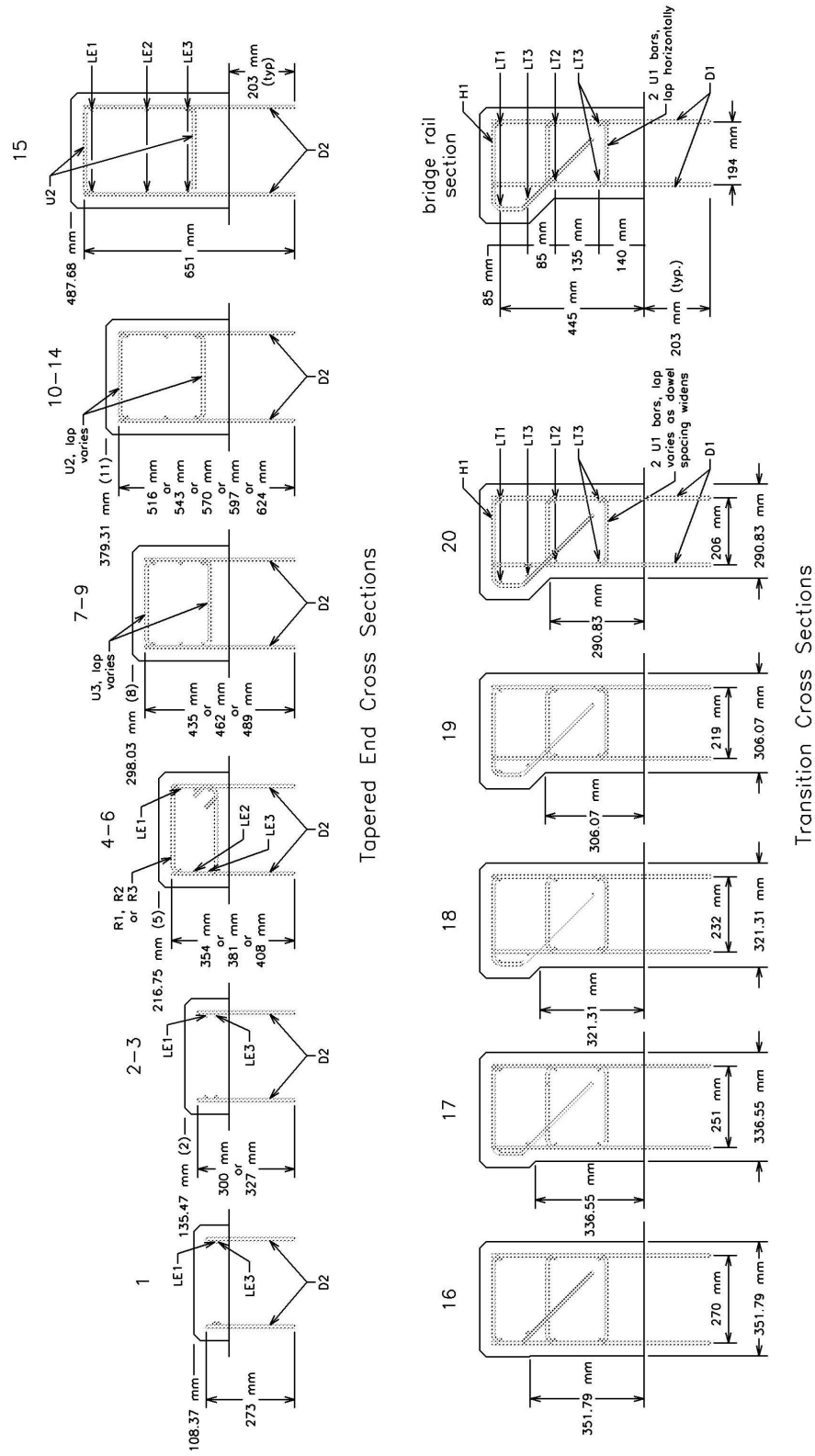


Figure 24. Low-Profile Bridge Rail End Treatment Design Details



Bill of Bars				
Quantity	Size	Description	Total Length	
D1	20	Vert. Trans. Dowel	673 mm	
D2	30	Vert. End Dowel (see dimension)		
H1	10	Vertical Hoop Bar	956 mm	
U1	20	Vertical Trans. U	556 mm	
U2	12	Vertical End U	743 mm	
U3	6	Vertical End U	622 mm	
R1	1	Vert. End Rectangular	962 mm	
R2	1	Vert. End Rectangular	918 mm	
R3	1	Vert. End Rectangular	879 mm	

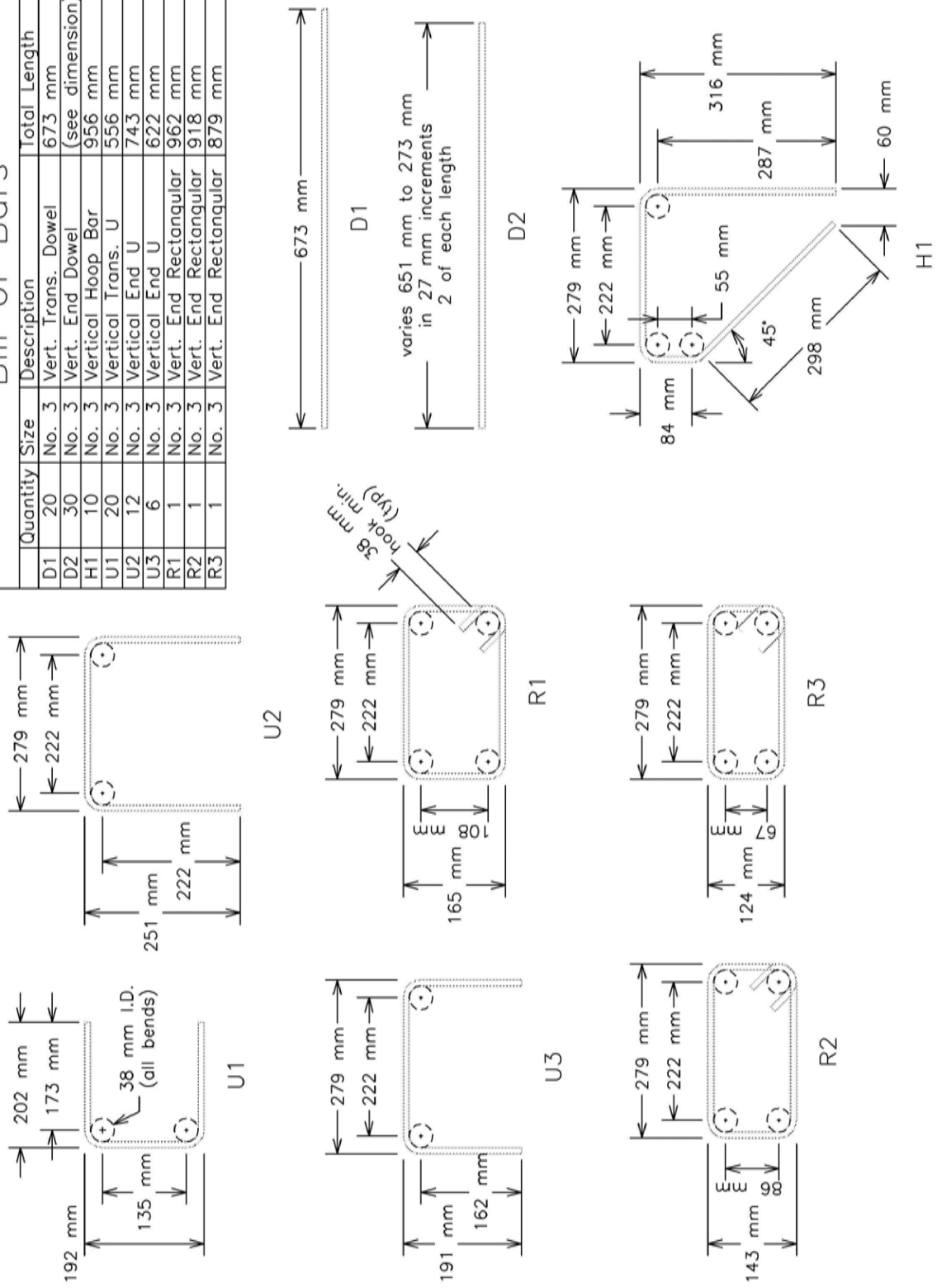


Figure 26. Low-Profile Bridge Rail End Treatment Reinforcement Details

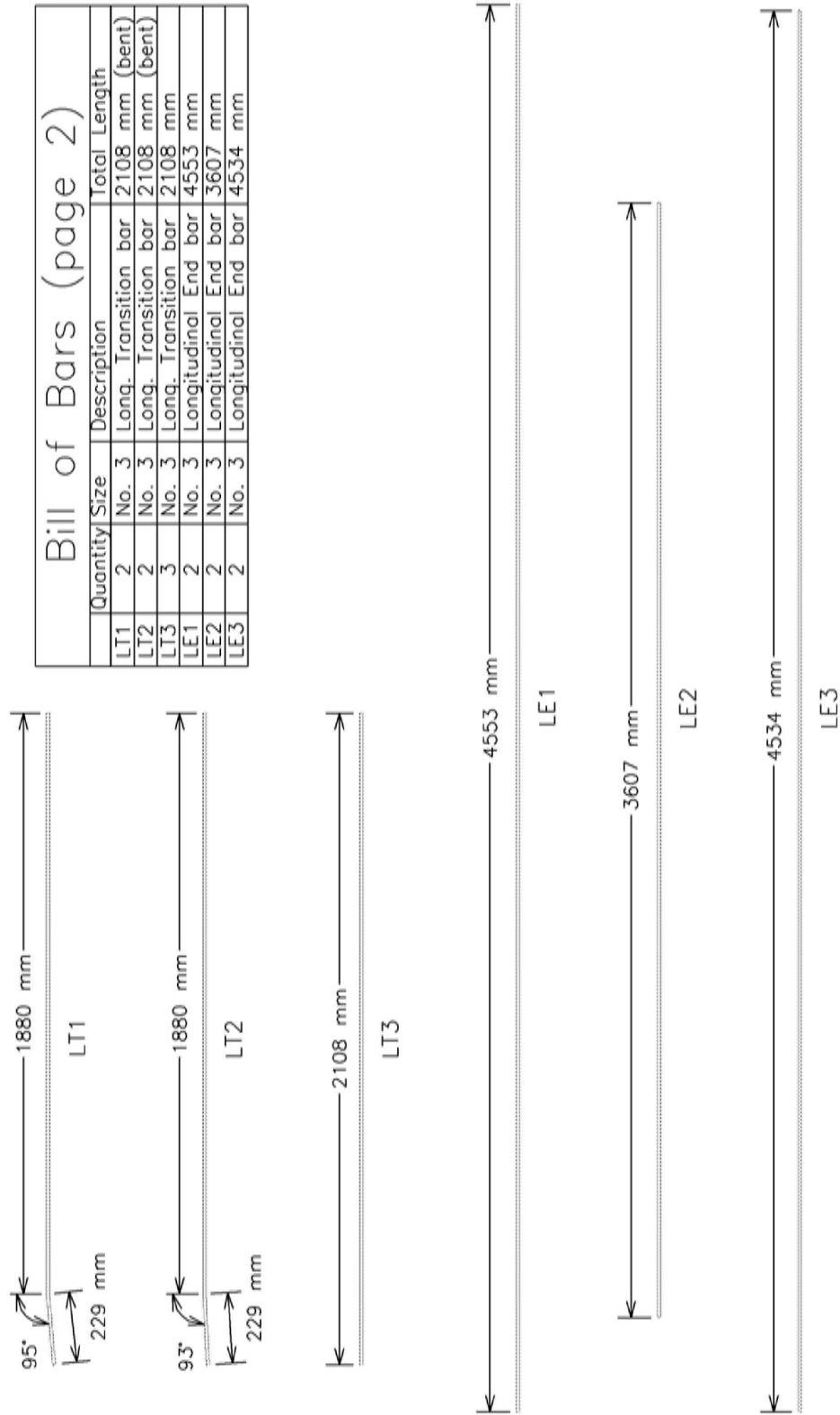


Figure 27. Low-Profile Bridge Rail End Treatment Reinforcement Details

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10 APPENDICES

APPENDIX A

Accelerometer Data Analysis, Test LPBR-1

Figure A-1. Graph of Longitudinal Deceleration, Test LPBR-1

Figure A-2. Graph of Longitudinal Occupant Impact Velocity, Test LPBR-1

Figure A-3. Graph of Longitudinal Occupant Displacement, Test LPBR-1

Figure A-4. Graph of Lateral Deceleration, Test LPBR-1

Figure A-5. Graph of Lateral Occupant Impact Velocity, Test LPBR-1

Figure A-6. Graph of Lateral Occupant Displacement, Test LPBR-1

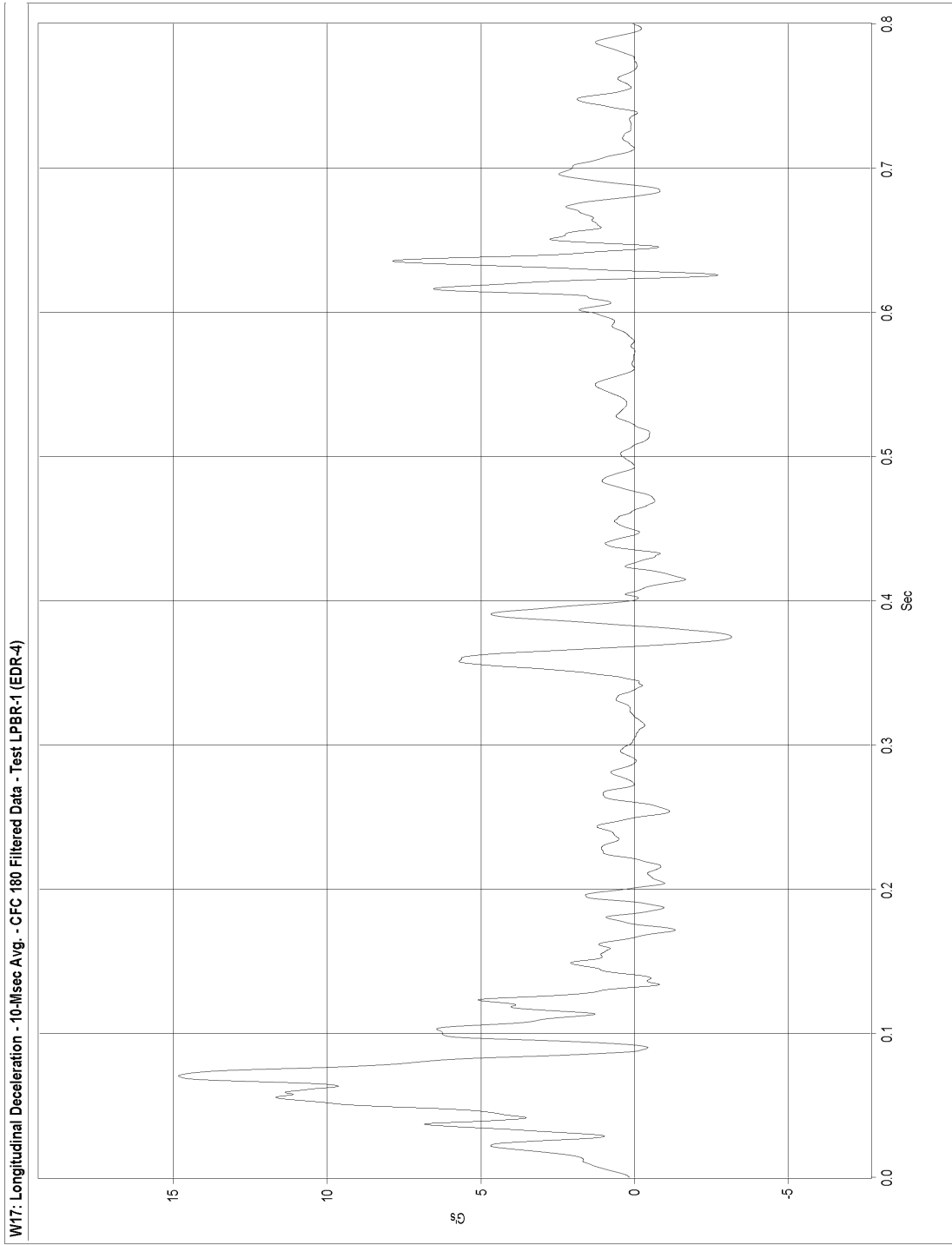


Figure A-1. Graph of Longitudinal Deceleration, Test LPBR-1

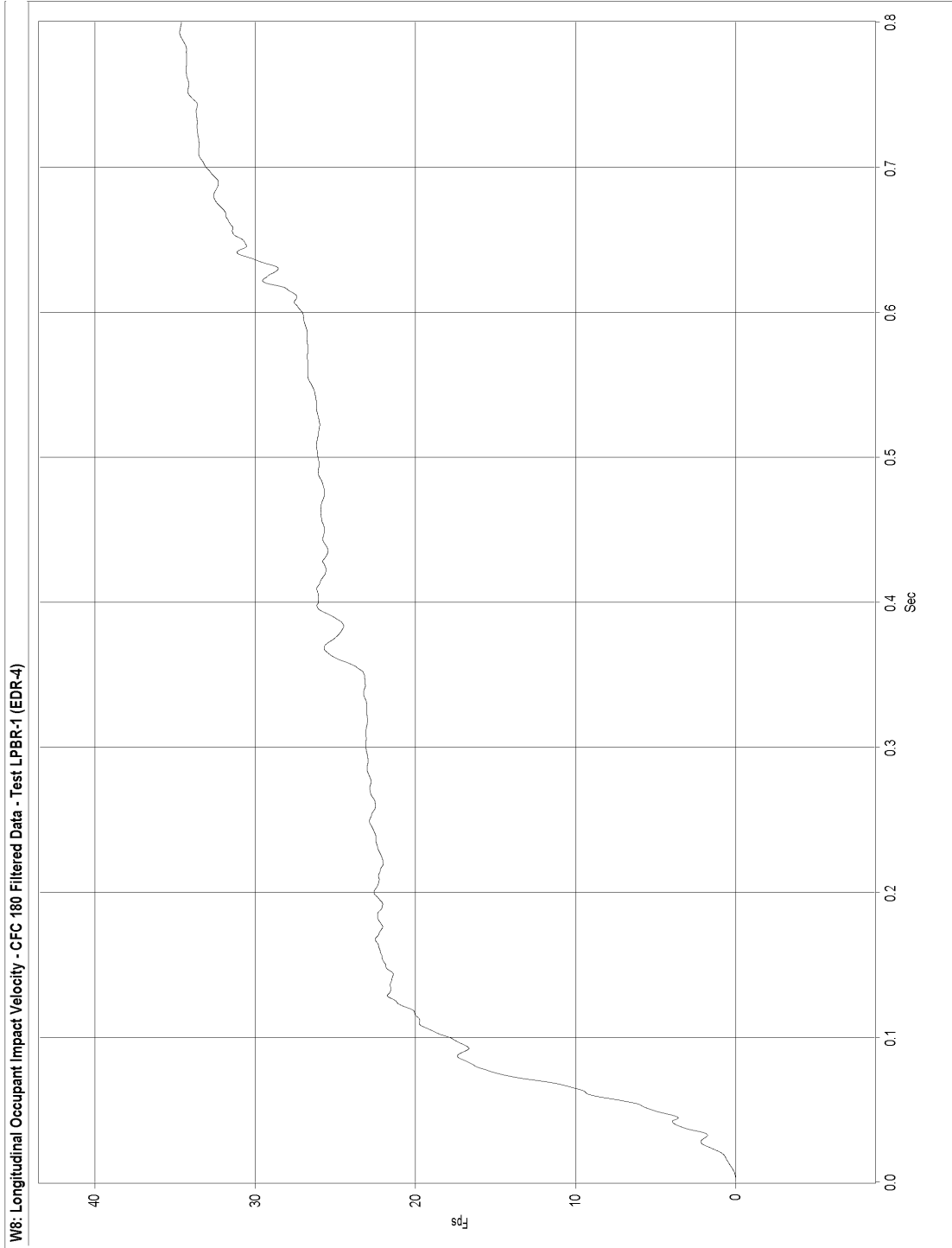


Figure A-2. Graph of Longitudinal Occupant Impact Velocity, Test LPBR-1

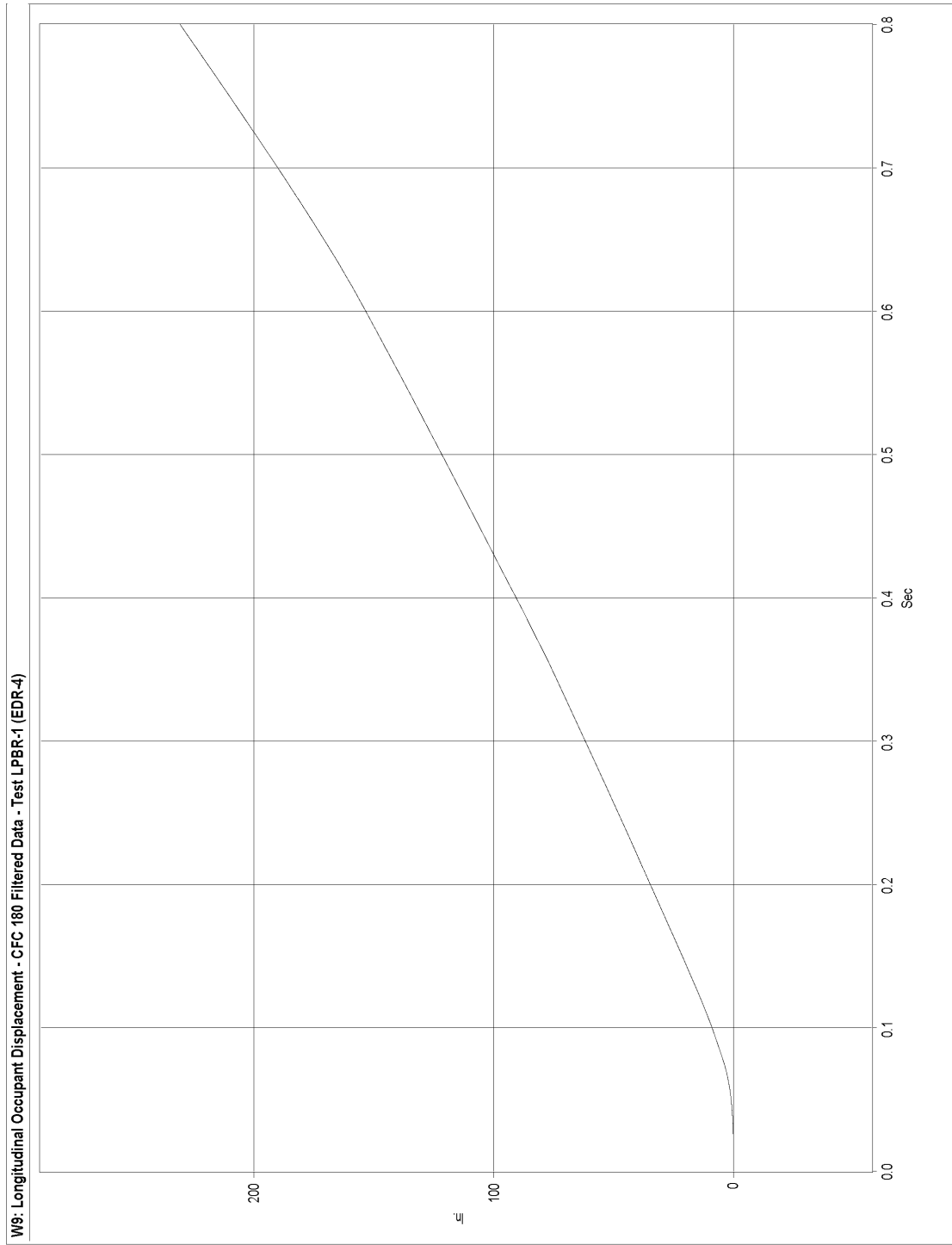


Figure A-3. Graph of Longitudinal Occupant Displacement, Test LPBR-1

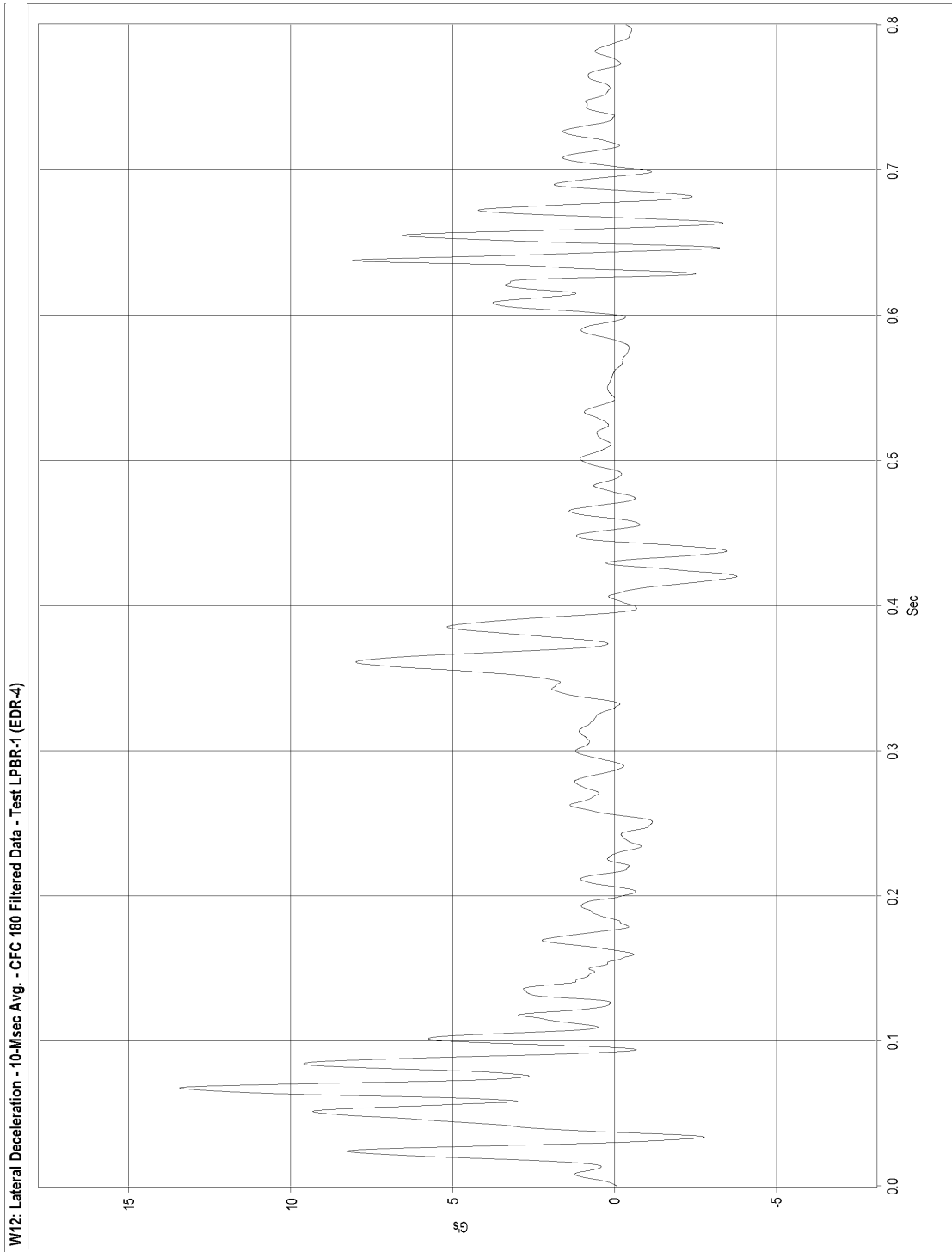


Figure A-4. Graph of Lateral Deceleration, Test LPBR-1

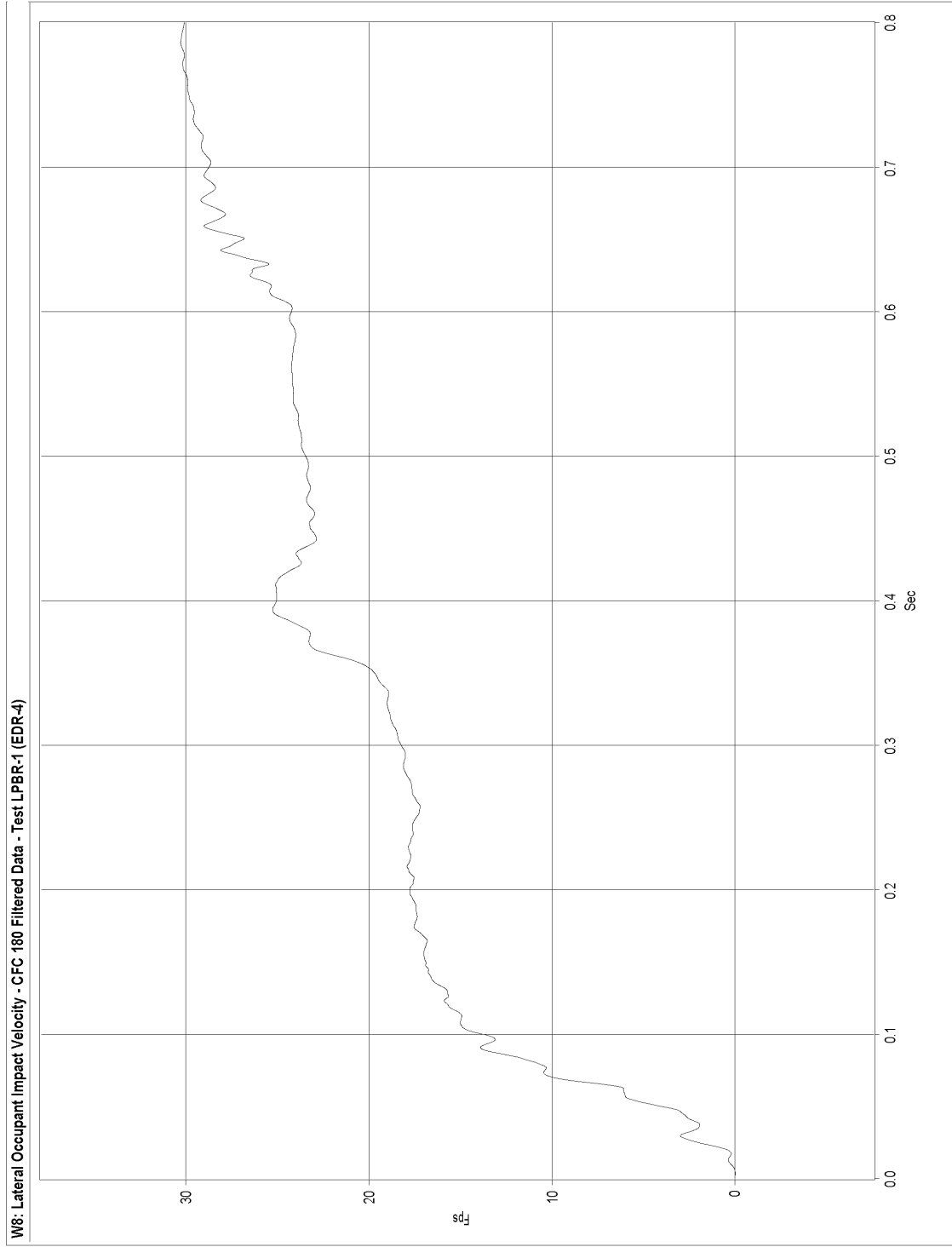


Figure A-5. Graph of Lateral Occupant Impact Velocity, Test LPBR-1

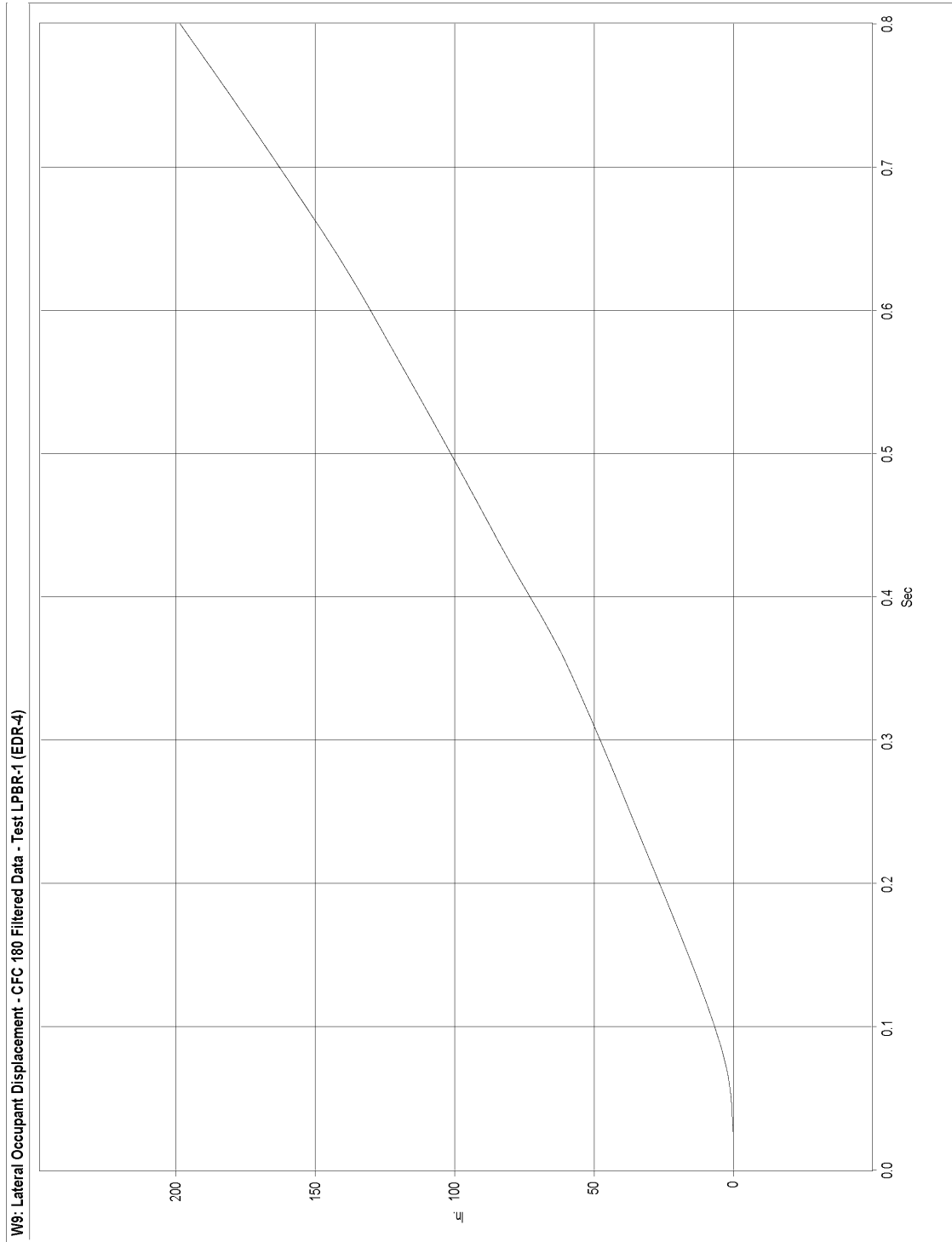


Figure A-6. Graph of Lateral Occupant Displacement, Test LPBR-1

APPENDIX B

Rate Transducer Data Analysis, Test LPBR-1

Figure B-1. Graph of Roll, Pitch, and Yaw Angular Displacements, Test LPBR-1

TEST LPBR-1, UNCOUPLED ANGULAR DISPLACEMENTS

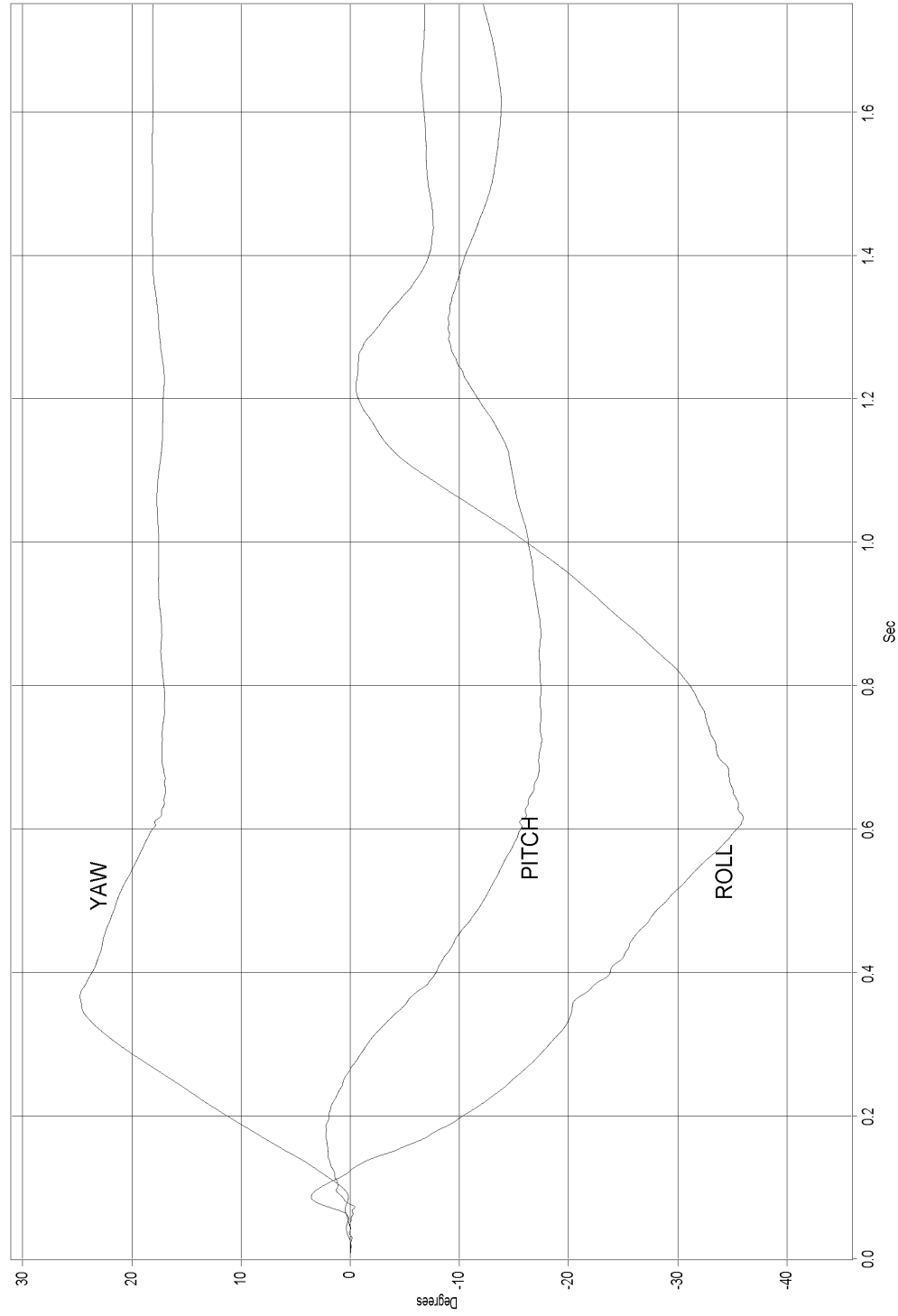


Figure B-1. Graph of Roll, Pitch, and Yaw Angular Displacements, Test LPBR-1