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16. Abstract

The high lateral dynamic deflection of some current TxDOT portable concrete barriers renders them inappropriate for deployment in areas with restricted work space. Under this project, a new precast concrete traffic barrier system with limited deflection was developed through a program of simulation and full-scale crash testing.

Based on the results of the testing and evaluation reported herein, the new cross-bolt, F-shape, precast concrete traffic barrier is considered suitable for implementation on high-speed roadways. The low barrier deflection (19 inches (483 mm)) and ease of placement and repair make the cross-bolt F-shape barrier well suited for use as a work zone barrier.

The weight of the 30-ft (9.1 m) F-shape barrier segments was determined to be approximately 13,680 lb (6205 kg). Because this is less than the weight of the current New Jersey-shaped barriers used by TxDOT, implementation of the new barrier will not require any changes to current barrier transportation, handling, and placement procedures.

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DEVELOPMENT OF LOW-DEFLECTION PRECAST CONCRETE BARRIER

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CHAPTER 1. INTRODUCTION

INTRODUCTION

Researchers conducted a full-scale crash test on the Texas Department of Transportation (TxDOT) Type 2 precast concrete traffic barrier (PCTB(1)-90) with joint type A to assess its impact performance. [1] The type A connection consists of a prefabricated tiebar grid fabricated from three 1-inch (25 mm) diameter tiebars inserted into a slot or trough cast into the ends of the barrier segments. Although the barrier met National Cooperative Highway Research Program (NCHRP) *Report 350* evaluation criteria, separation of one of the barrier joints led to a lateral deflection of 9 ft (2.7 m) under design impact conditions. [2] A retrofit concept was developed to reduce the barrier deflection to more practical levels. [1] It was found that the addition of 4-inch (102 mm) wide by 3/16-inch (5 mm) thick steel straps bolted to the face of the barrier segments across each side of a joint limited the barrier deflection to 4 ft (1.2 m).

This retrofit connection is not without its drawbacks and limitations. Even though the straps provided marked improvement in barrier deflection, the 4-ft (1.2 m) deflection might still be too large for some restricted work zones. Although some tolerance has been provided by slotting the holes in the steel strap, barrier placement must be adequately controlled to permit the segments to be bolted together in the field. The bolting operation (which requires eight anchor bolts at each joint) is relatively labor intensive and will increase exposure of work zone personnel compared to the original drop-in connections. Finally, the walls of the barrier slots/troughs are severely damaged during impact, rendering the barriers in the impact region irreparable.

OBJECTIVES AND SCOPE

The TxDOT Type 2 PCTB (PCTB(1)-90) with joint type A is one of the most widely used precast barriers in Texas. While the barrier was found to meet *NCHRP Report 350* evaluation criteria, large deflections limit its application. Texas Transportation Institute (TTI) researchers successfully demonstrated that a retrofit connection could reduce barrier deflection. However, TxDOT desired further reduction of the maximum dynamic barrier deflection for implementation in restricted work zones. Further, the Type 2 PCTB with retrofit connection has some issues regarding cost, constructability, and reparability.

The primary objective of the research effort reported herein was to develop a precast concrete barrier (PCB) that has a maximum lateral deflection of 3 ft (0.9 m) or less when impacted under Test Level 3 (TL-3) conditions of *NCHRP Report 350*. TTI researchers conceptualized numerous connection designs. When evaluating these design options, TTI researchers and TxDOT engineers considered factors such as impact performance, deflection, cost, ease of field installation, placement on curves, etc. Various analyses were performed to help assess the ability of the selected barrier system to meet *NCHRP Report 350* impact performance criteria prior to conducting a full-scale crash test.

This report summarizes the design, testing, and evaluation of a new precast concrete traffic barrier for TxDOT. Chapter 2 describes the design and analysis process. Chapter 3 presents details of the full-scale crash test. Conclusions emanating from the research are summarized in Chapter 4, and implementation recommendations are presented in Chapter 5.

CHAPTER 2. DESIGN AND ANALYSIS

INTRODUCTION

The TxDOT Type 2 PCTB (PCTB(1)-90) with joint type A is not considered to be adequate for some site conditions from the standpoint of lateral dynamic barrier deflection. This research was conducted to develop a new portable concrete median barrier design for TxDOT that would result in lower lateral barrier deflections during vehicular impacts.

The impact performance of temporary concrete barriers is influenced by a number of variables, which include but are not limited to: barrier profile, barrier height, segment length, joint rotation slack, joint moment capacity, joint tensile strength, and barrier-roadway friction. The design of the joint connection plays a particularly critical role in the impact performance of temporary concrete barriers. The design of the joint has a direct influence on the magnitude of lateral barrier deflection and degree of barrier rotation during a vehicular impact event. A joint with inadequate strength and/or stiffness can induce instability of the vehicle, result in failure of the connection and penetration of the vehicle through the barrier, and/or produce greater than desired deflection.

Several new connection designs were conceptually developed for consideration by TxDOT engineers. When evaluating and prioritizing these design options, factors such as cost, ease of field installation, placement on curves, and aesthetics were considered.

Given that a new connection was being developed, it was considered to be an opportune time to review other aspects of the standard TxDOT precast concrete traffic barrier and consider certain changes and improvements. TxDOT engineers decided to maintain the standard 30-ft (9.1 m) segment length for the new barrier system. The reduction in the number of joints/connections associated with the long segment length helps support the primary objective of reducing dynamic barrier deflection. However, it was decided to adopt an F-shape barrier profile for the new barrier design in lieu of the New Jersey-shape profile used on current TxDOT barriers. The F-shape is widely considered to provide improved impact performance over the New Jersey-shape. Full-scale crash testing indicates that vehicles experience less climb and remain more stable during impacts with barriers having an F-shape profile compared to those with a New Jersey-shape profile.

Two of the conceptual connection designs were selected for further evaluation. These included a lapped plate connection and a cross-bolted connection. Finite element analyses were performed to help assess the ability of the selected barrier connections to meet *NCHRP Report 350* impact performance criteria and limit deflections. Preliminary LS-DYNA computer simulations results showed that the cross-bolted connection had an obvious advantage over the lapped plate connection from the standpoint of minimizing overall barrier deflections. [(3)] For this reason, TxDOT decided to pursue more detailed design, analysis, testing, and evaluation of the cross-bolted connection in conjunction with an F-shape barrier profile.

FINITE ELEMENT MODELING

The research team used numerical simulations to lead the design effort of the precast F-shape barrier with cross-bolted connection. Numerous research studies have successfully utilized simulation codes to simulate vehicle handling, vehicle impacts with roadside objects, and vehicle encroachments over roadside geometric features such as slopes, ditches, and driveways. In these studies, researchers have utilized varying levels of vehicle model sophistication ranging from simple lumped masses, springs and dampers, to detailed finite element representations using many thousands of elements. All simulation codes have their limitations, and they all incorporate different levels of assumptions or approximations. It was considered crucial that the simulation code(s) selected for use in this project be capable of accurately modeling relevant characteristics of the vehicle, the concrete median barrier, and the interactions between them. The decision to choose the explicit finite element code LS-DYNA for this project was based on several reasons including:

1. The availability of vehicle models that correspond to *NCHRP Report 350* design test vehicles -- mainly the 2000P vehicle. This vehicle model has been used for roadside safety applications for several years, and its fidelity and limitations are reasonably understood.
2. The ability to model the roadside device with a high degree of fidelity including: the barrier geometry (which affects the interaction between the vehicle and barrier), the mass and inertial properties of the barrier (which affect the kinetic behavior of the barrier), and the material properties (which affect the deformation of the device).
3. The ability to model contact-impact problems. LS-DYNA has a very extensive set of contact definitions that fit several impact-contact scenarios. Contact definitions having the option of including frictional sliding are well suited to modeling the dynamic interaction between a vehicle and roadside barrier.

In order to evaluate the cross-bolted connection design concept, a full-scale finite element model of a precast, free standing, concrete median barrier (CMB) was developed. The concrete barrier segments were modeled using an F-shape profile with the top width of the barrier maintained at 8 inches (203 mm) and the segment length maintained at 30 ft (9.1 m) (both of which are TxDOT standards). The CMB model was assigned the mass density of concrete, which makes the total mass of the CMB model equivalent to that of the actual CMB unit.

The finite element (FE) mesh for the CMB model, shown in Figure 1, was comprised of solid elements. The lowest layer of solid elements that are in contact with the ground surface were assigned elastic material properties, and the rest of the elements comprising the barrier segment were assigned rigid material properties. The lower elastic layer of solid elements was incorporated into the barrier model to provide a reliable account of friction in the contact between the CMB segments and the ground. A friction coefficient of 0.4, as determined from barrier pull tests on a concrete pavement, was used between the CMB and the ground. Rigid material representation for the remainder of the model helps speed up numerical calculations significantly.

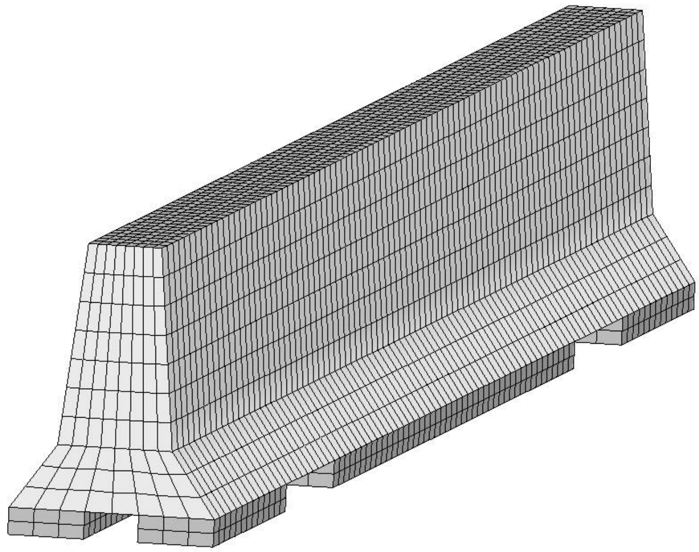


Figure 1. Finite Element Representation of F-Shape Portable Concrete Barrier.

A limitation to this type of rigid CMB model is that concrete failure is not incorporated. Modeling concrete failure requires a reliable, validated concrete material model that considers fracture. Although the Federal Highway Administration has sponsored the development of such a material model, the research effort was still in its early stages during this project and not available for use. Without incorporating concrete failure into the analysis, it should be noted that the results of the simulation represent a lower bound estimate of the overall CMB system deflection. If significant concrete fracture and spalling occurs at the ends of one or more barrier segments during an actual impact, additional joint rotation can occur and deflections can increase. Conversely, a rigid barrier representation is conservative in regard to stress and deformation of the connection bolts. Concrete fracture and spalling near the ends of the barrier segments will help relieve the loads transferred to the connection bolts. With these aspects of the model understood, valuable design and performance information can be gleaned from the predictive simulation results.

Solid elements, such as those comprising the barrier model, tend to behave less reliably compared to shell elements for contact purposes. During earlier vehicle impact simulations with precast concrete median barriers, small but significant penetrations were observed between the solid elements of adjacent barriers. In order to provide more robust contact, end faces of the CMB segment models were covered with a thin layer of finely meshed rigid shell elements. All contacts involving the barriers were defined with this shell cover.

The cross-bolted connection system utilizes two 7/8-inch (22 mm) diameter, A325 bolts or equivalent strength threaded rods to form the connection. The bolts are placed in different horizontal planes at an angle of 20 degrees with respect to the longitudinal axis of the barrier. The bolts exit one barrier segment and enter the adjacent barrier segment at the vertical center line of the barrier section. The vertical location of the connection bolts and the spacing between them were determined by parametric simulations.

The bolts pass through nominal 1-1/4-inch (32 mm) diameter, schedule 40 pipe cast into the ends of the barrier segments. Researchers selected this pipe size to provide connection tolerance for barrier fabrication and construction. The 1-1/4-inch (32 mm) diameter pipe has an inside diameter of 1.38 inches (35 mm), which provides a 1/2-inch (13 mm) tolerance between the outside diameter of the cross bolts and the inside diameter of the guide pipes. The available tolerance assists with barrier constructability and allows the barriers to be placed at a four degree angle relative to each other, which provides a minimum barrier radius of curvature of approximately 400 ft (122 m) (see Table 1). Barrier angles and radii of curvature associated with other hole diameters and tolerances are shown in Table 1. Each of the angles is based on the cross bolts having a diameter of 7/8 inch (22 mm).

Table 1. Tolerance, Barrier Angle, and Achievable Radius of Curvature for Various Cross-Bolt Hole Diameters.

Hole Diameter, inches (mm)	Tolerance, inches (mm)*	Maximum Barrier Angle, degrees	Radius of Curvature, ft (m)
1.000 (25.400)	0.125 (3.175)	1.0	1723 (525)
1.125 (28.575)	0.250 (6.350)	2.0	856 (261)
1.250 (31.750)	0.375 (9.525)	3.0	572 (174)
1.375 (34.925)	0.500 (12.700)	4.0	428 (130)
1.500 (38.100)	0.625 (15.875)	5.0	342 (104)

* Based on 7/8-inch (22 mm) diameter cross bolts

The cross-bolt connection was modeled by using shell elements to create rigid, cylindrical shafts to represent the pipe sections embedded in the concrete through which the cross bolts pass. The model of these shafts is depicted in Figure 2. These shafts were placed inside the concrete barrier segments at their appropriate locations and rigidly constrained to the concrete such that motion of the shafts relative to the barriers was prohibited (see Figure 3).

Figure 2. Finite Element Representation of Guide Pipe in Cross-Bolted Connection.

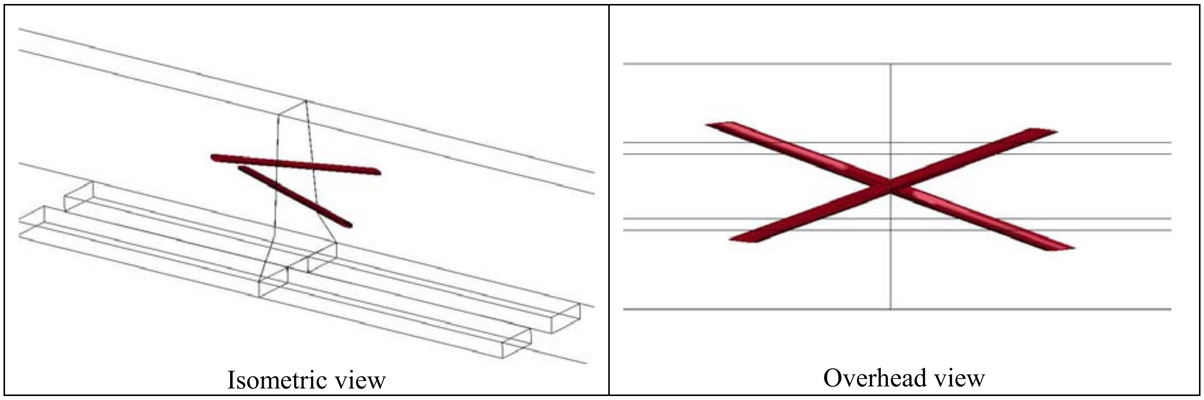


Figure 3. Cross-Bolt Connection.

The bolts were modeled using beam elements as represented in Figure 4. The bolt models were placed inside the cylindrical shafts, and contact was defined between them. The nodes on each end of the bolts were constrained to the edges of the barriers. Modeling the bolts in this manner allowed for faster computation times while realistically capturing the behavior of the bolts.

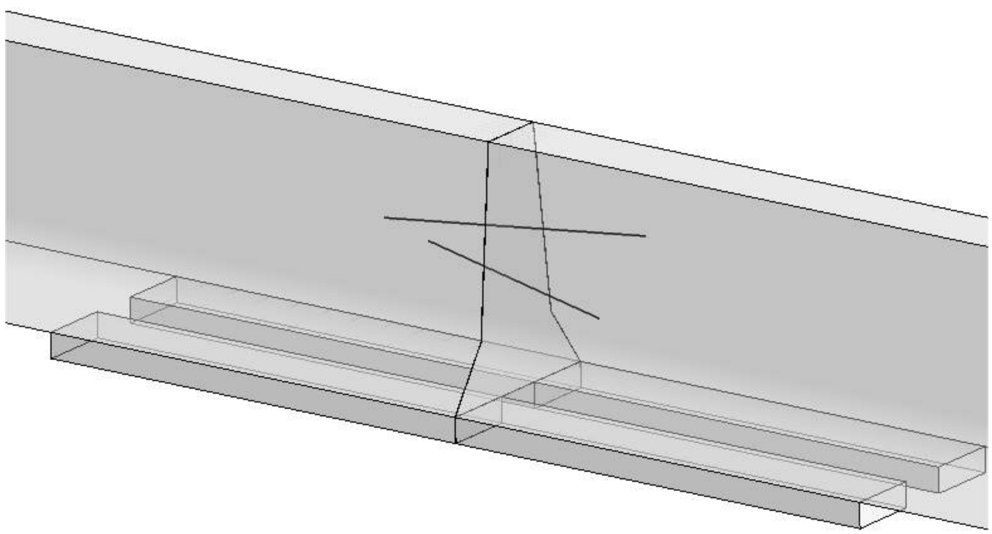


Figure 4. Beam Element Representation of Cross Bolts.

The mechanical properties of the bolts were defined using a bilinear stress strain curve representing ASTM A325 high-strength steel. A325 bolts have a yield strength of 92 ksi (634 MPa) and a tensile strength of 120 ksi (827 MPa).

The vertical spacing of the bolts dictates the torsional capacity of the cross-bolt connection. The connection must provide sufficient torsional capacity to prevent relative rotation or overturn of one barrier with respect to another. Three different vertical bolt spacings were evaluated via a parametric simulation study. The bolt spacings considered were 3 inches (76 mm), 8 inches (203 mm), and 10 inches (254 mm). In each case, the lateral deflection of the barriers and the stress in the bolts was determined.

The full-scale simulations replicated Test Designation 3-11 of *NCHRP Report 350*. This test involves a 4409 lb (2000 kg) pickup truck impacting the barrier at a speed of 62.2 mi/h (100 km/h) and an angle of 25 degrees. This test is considered to be the critical test for evaluating the structural integrity of the connection and the maximum dynamic deflection of the barrier. A total of six CMB segments were modeled to provide a barrier length of 180 ft (55 m).

Table 2 presents the primary results of the simulations. In each case, the vehicle was successfully contained and redirected in a stable manner. The predicted lateral barrier deflection of each design case is well below the 3 ft (0.9 m) design limit. As previously discussed, these predictive deflection estimates should be considered lower bound estimates. The amount that the actual dynamic barrier deflection might exceed these values is a function of the degree of concrete damage encountered in the test.

Table 2. Simulation Results for Cross-Bolted Barrier Connection.

Vertical Bolt Spacing, inches (mm)	Torsional Capacity, kip-ft (kN-m)	Lateral Barrier Deflection, ft (m)	Maximum Bolt Stress, ksi, (MPa)
3 (76)	5.3 (7.2)	1.50 (0.46)	86.9 (599)
8 (203)	12.0 (16.3)	1.34 (0.41)	86.6 (597)
10 (254)	15.0 (20.3)	1.34 (0.41)	N/A

For each design case, the stress in the bolts was below yield. The vertical spacing of the bolts appears to have little effect on the maximum bolt stress. In addition, the lateral barrier deflection showed little change with respect to the bolt spacing.

The torsional twisting or rotation of the barriers relative to one another about the longitudinal axis of the barrier was also investigated. The worst-case scenario for barrier twisting/rotation would occur at the minimum vertical bolt spacing, which offers the lowest torsional capacity for the connection. After reviewing the simulation results, barrier rotation did not appear to be a problem for the barrier system, regardless of the vertical spacing between the cross bolts. Thus, the vertical bolt spacing for the final design configuration was selected based on other considerations such as bolt length, fabrication clearances, etc.

Figure 5 shows the simulation result for the barrier system with 3-inch (76 mm) vertical spacing between cross bolts before and after impact. The pickup truck test vehicle is redirected in a stable manner with small barrier deflections.

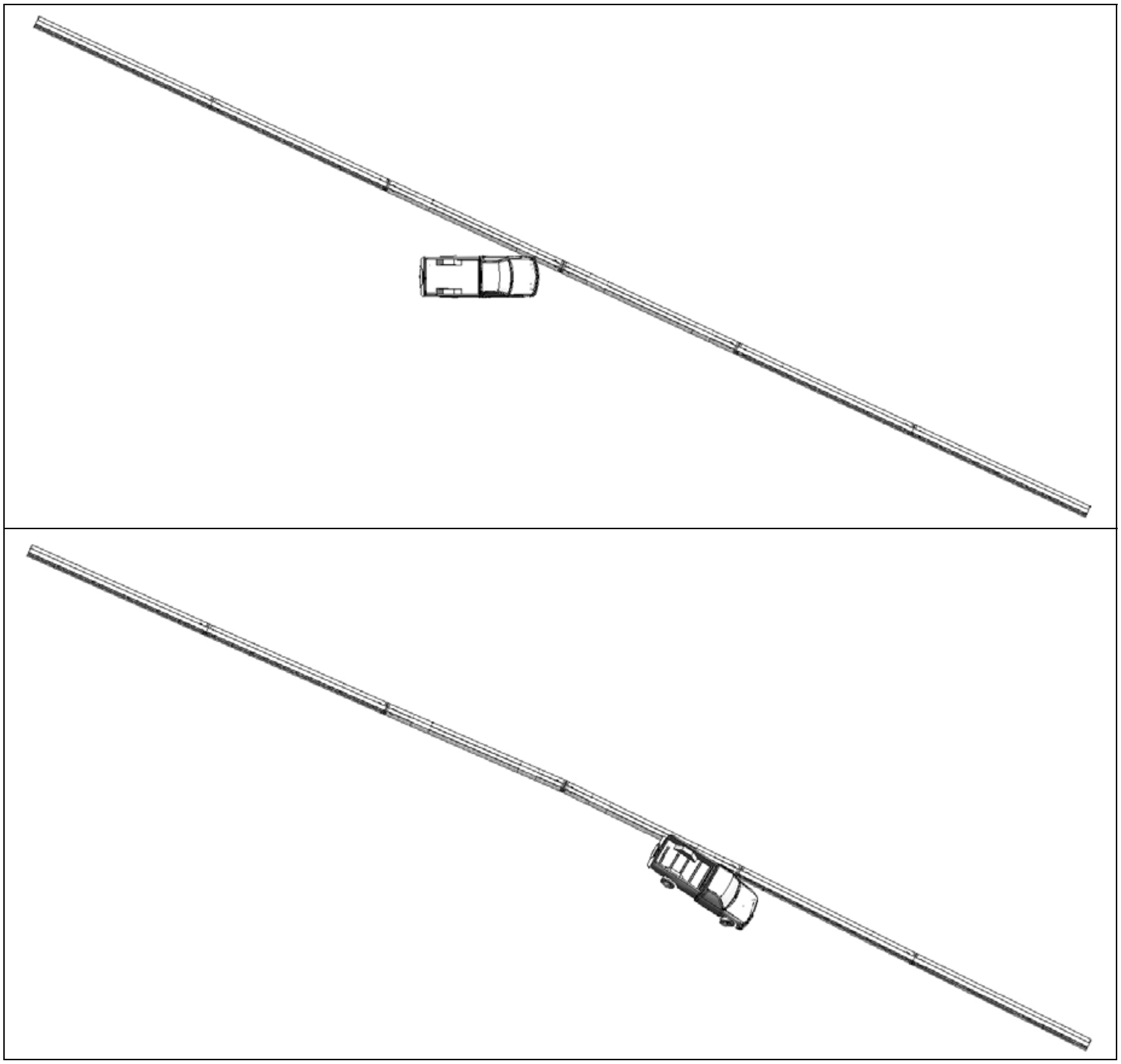


Figure 5. Finite Element Model Top View, (a) Before Impact (b) After Impact.

SUMMARY

Preliminary evaluation through simulation showed that the cross-bolted connection design had higher potential for limiting lateral barrier deflections compared to a lapped plate connection. Subsequent simulation results indicated that the cross-bolted F-shape barrier system should meet *NCHRP Report 350* evaluation criteria. The structural integrity of the connection was maintained, and the barrier successfully contained and redirected the finite element test vehicle. The simulation results estimated dynamic deflection of approximately 1.34 ft (0.41 m) under TL-3 impact conditions. This value is considered a lower-bound estimate. The actual dynamic barrier deflection was expected to exceed this value depending on the nature and degree of concrete damage obtained in the full-scale test. Based on simulation results, it was recommended that TxDOT conduct a full-scale crash test of the barrier system to verify its impact performance and dynamic deflection.

CHAPTER 3. CRASH TESTING

TEST NO. 441623-1 (*NCHRP REPORT 350* TEST NO. 3-11)

Impact Conditions

NCHRP Report 350 recommends two tests for TL-3 evaluation of longitudinal barriers:

***NCHRP Report 350* test designation 3-10:** This test involves an 1808-lb (820 kg) passenger car impacting the critical impact point (CIP) in the length of need (LON) of the longitudinal barrier at a nominal speed and angle of 62 mi/h (100 km/h) and 20 degrees, respectively. The purpose of this test is to evaluate the overall performance of the LON section in general and occupant risk in particular.

***NCHRP Report 350* test designation 3-11:** This test involves a 4409-lb (2000 kg) pickup truck impacting the CIP in the LON of the longitudinal barrier at a nominal speed and angle of 62 mi/h (100 km/h) and 25 degrees, respectively. The test is intended to evaluate the strength of the section for containing and redirecting the pickup truck.

The test reported herein corresponds to *NCHRP Report 350* test designation 3-11. The pickup truck test is considered to be the critical test in the evaluation of an existing barrier shape with a new connection type. A rigid barrier with F-shape profile has demonstrated acceptable performance when impacted by a small car under test 3-10 impact conditions. [(4)] Due to the small deflection expected for the precast F-shape CMB with cross-bolt connection when subjected to test 3-10, the behavior is expected to be similar to that obtained in the rigid barrier test.

The critical impact point for the barrier for test designation 3-11 was chosen according to guidelines contained in *NCHRP Report 350*. With reference to Figure 1, the target impact point was 3.9 ft upstream of the joint between segments 3 and 4.

The crash test and data analysis procedures were in accordance with guidelines presented in *NCHRP Report 350*. Appendix A presents brief descriptions of these procedures.

Test Article

The precast segments used to construct the test installation for the cross-bolt concrete median barrier system were 30 ft (9.1 m) in length and had a standard F-shape profile. The barrier segments were 32 inches (813 mm) in height, 23-5/8 inches (600 mm) wide at the base, and 9-1/4 inches (235 mm) wide at the top. The top width of the barrier was increased from 8 inches to 9-1/4 inches (203 to 235 mm) at the request of TxDOT to more conveniently accommodate barrier mounted lighting hardware.

Horizontal barrier reinforcement consists of eight #5 (#16) bars spaced liberally within the vertical reinforcement. Vertical barrier reinforcement in the barrier segments consists of #5 (#16) bars spaced 12 inches (305 mm) on center. These vertical bars are bent in a "hairpin" fashion to conform to the F-shape barrier profile. Within 5 ft (1.5 m) of the barrier ends, the spacing of the vertical bars is reduced to 6 inches (152 mm). A U-shaped bar is tied to the bottom of the vertical bars to provide closed stirrups in this region.

Sections of 1-1/4-inch (32 mm) diameter, schedule 40 pipe are cast into the ends of the barrier segments at an angle of 20 degrees to the barrier axis to serve as a guide shaft and reinforcement for the cross bolts. The centers of the guide pipes are vertically spaced 6 inches (152 mm) apart. A 4 × 4.5 × 3/8 inch (102 × 114 × 9.5 mm) thick, A36 steel plate is welded to one end of each pipe section. A 1-3/8-inch (35 mm) diameter hole, which matches the inside diameter of the guide pipes, is drilled through the center of the plate to permit passage of the cross-bolts. Two #6 (#19) bars are bent in an "L" shape and welded to the inside surface of each end plate. Triangular wedges are cast into the barrier to permit the exposed ends of the cross bolts to be recessed and, thus, prevent vehicle snagging. Due to space restrictions, the spacing of the vertical reinforcement is adjusted and a slightly modified vertical bar is used in the immediate vicinity of the guide pipes and triangular wedges.

The cross-bolts are fabricated from 7/8-inch (22 mm) diameter, SAE Grade 5 threaded rod. The lengths of the upper and lower cross bolts were 25-1/4 inches (641 mm) and 29 inches (737 mm), respectively. The barriers segments are placed end to end and the cross bolts are inserted through aligning guide pipes between adjacent barrier segments. A 3 × 3 × 3/8 inch (76 × 76 × 9.5 mm) thick, A36 steel plate washer is used under the nut at each end of the cross bolts.

The 1-1/4-inch (32 mm) guide pipes have an inside diameter of 1-3/8 inches (35 mm), which provides a 1/2 inch (13 mm) tolerance between the outside diameter of the cross bolts and the inside diameter of the guide pipes. The available tolerance assists with barrier constructability and permits the barriers to be placed on curves. Field trials with the barrier test sections verified they can be placed on a 400 ft (122 m) radius curve.

The completed test installation consisted of seven barrier segments connected together for a total length of approximately 210 ft (64 m). Details of the barrier and cross-bolt connection are shown in Figures 6 through 10. Figure 11 shows photographs of the completed test installation.

Test Vehicle

A 2000 Chevrolet 2500 pickup truck, shown in Figures 12 and 13, was used for the crash test. Test inertia weight of the vehicle was 4531 lb (2057 kg), and its gross static weight was 4531 lb (2057 kg). The height to the lower edge of the vehicle bumper was 16.3 inches (415 mm), and the height to the upper edge of the bumper was 25.0 inches (635 mm). Appendix B, Figure 19, gives additional dimensions and information on the vehicle. The vehicle was directed into the barrier installation using a cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

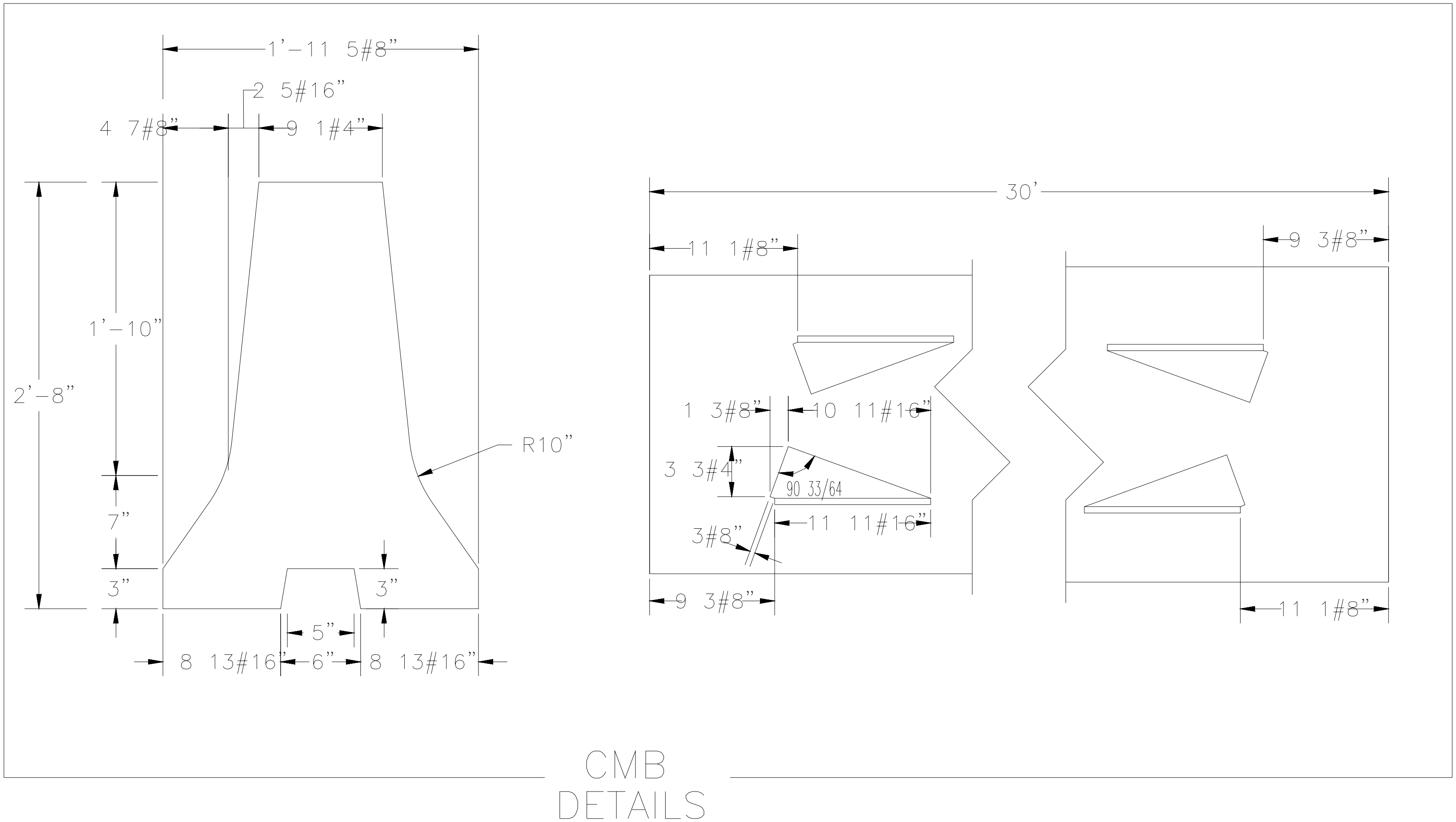


Figure 6. Details of the Cross-Bolt, F-Shape Precast Concrete Traffic Barrier.

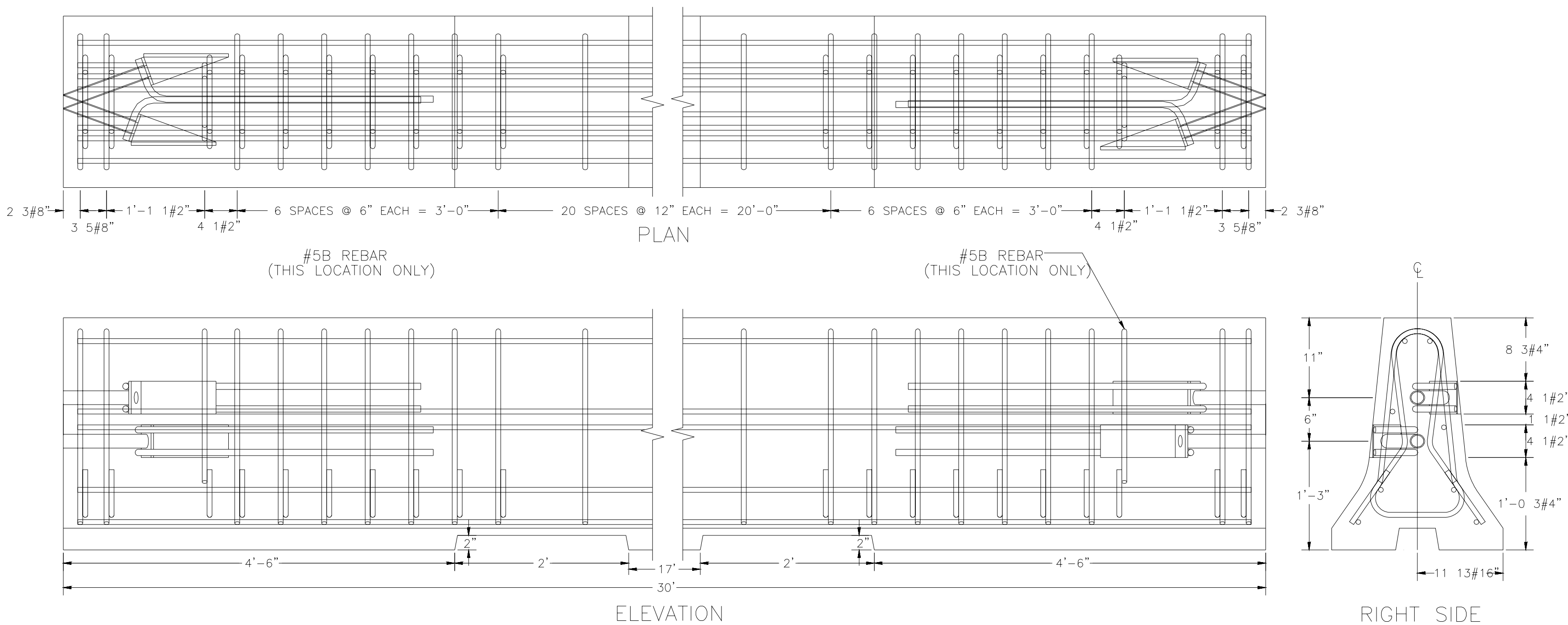
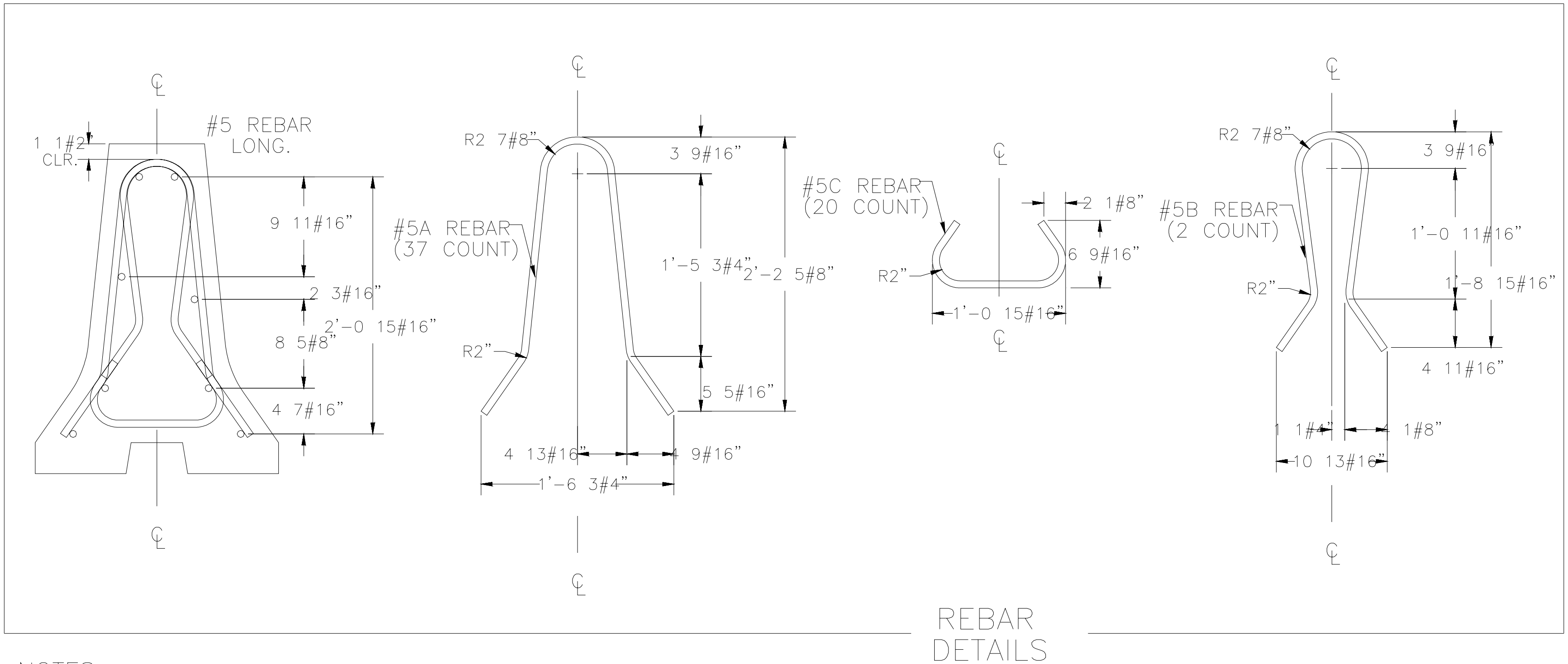


Figure 7. Layout of the Cross-Bolt, F-Shape Precast Concrete Traffic Barrier.



NOTES:
1.) ALL REINFORCING STEEL SHALL BE BARE (NOT EPOXY COATED) AND HAVE A MINIMUM YIELD STRENGTH (Fy) OF 414Mpa (60Ksi).
2.) ALL CONCRETE SHALL HAVE A MINIMUM COMPRESSIVE STRENGTH OF 21Mpa (3000psi).

Figure 8. Rebar Details of the Cross-Bolt, F-Shape Precast Concrete Traffic Barrier.

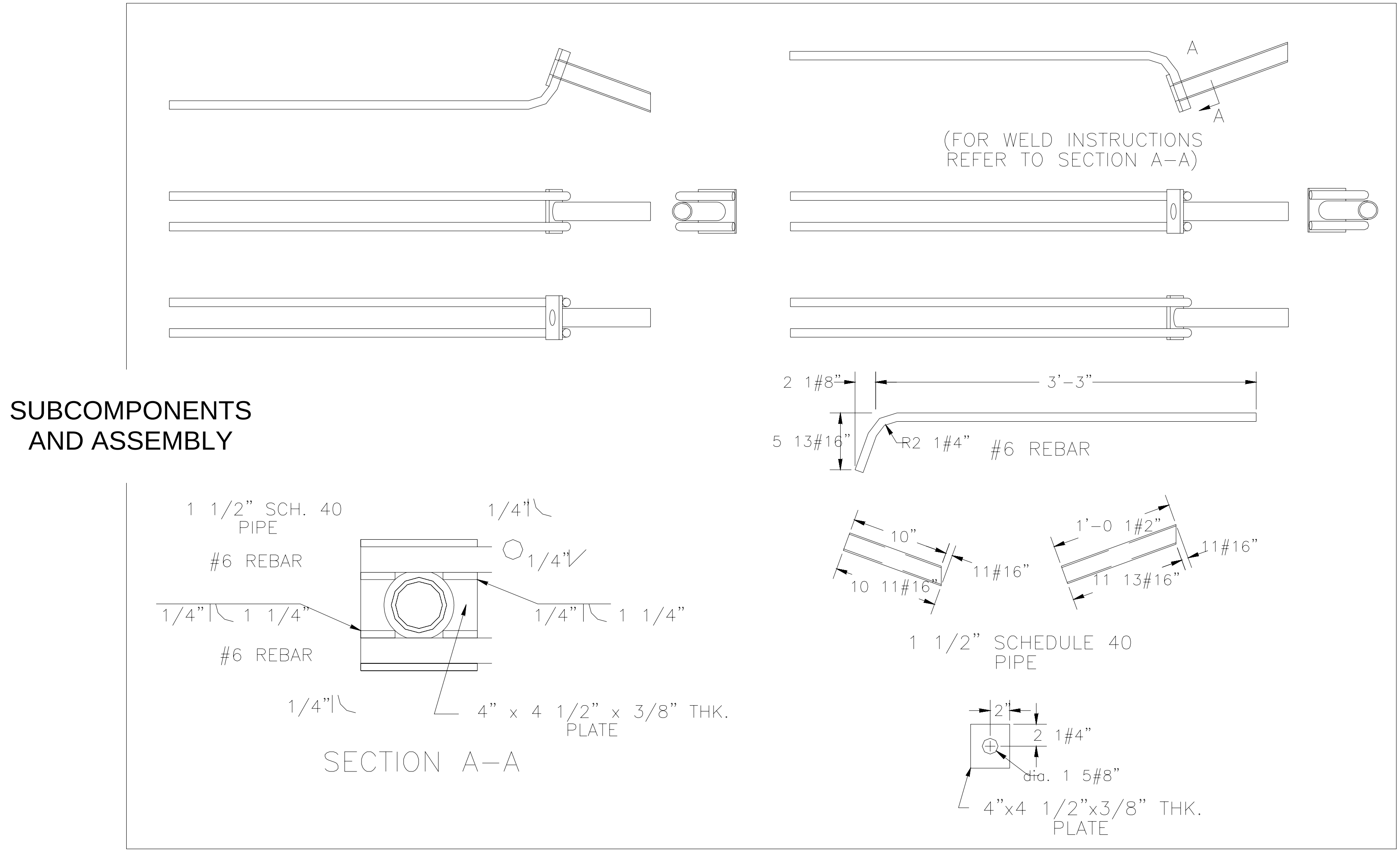


Figure 9. Subcomponents and Assembly Details of the Cross-Bolt, F-Shape Precast Concrete Traffic Barrier.

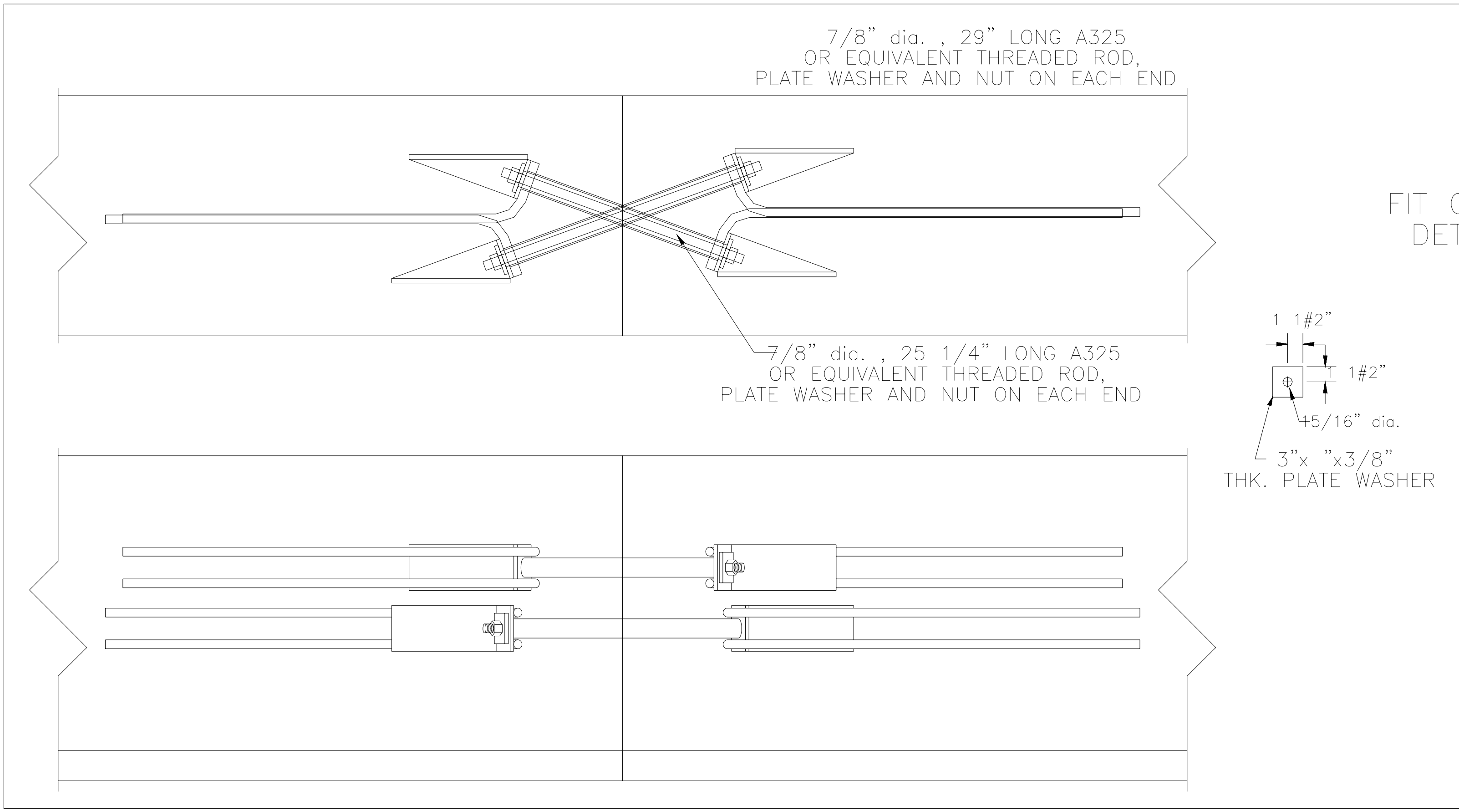


Figure 10. Fit Check Details of the Cross-Bolt, F-Shape Precast Concrete Traffic Barrier.

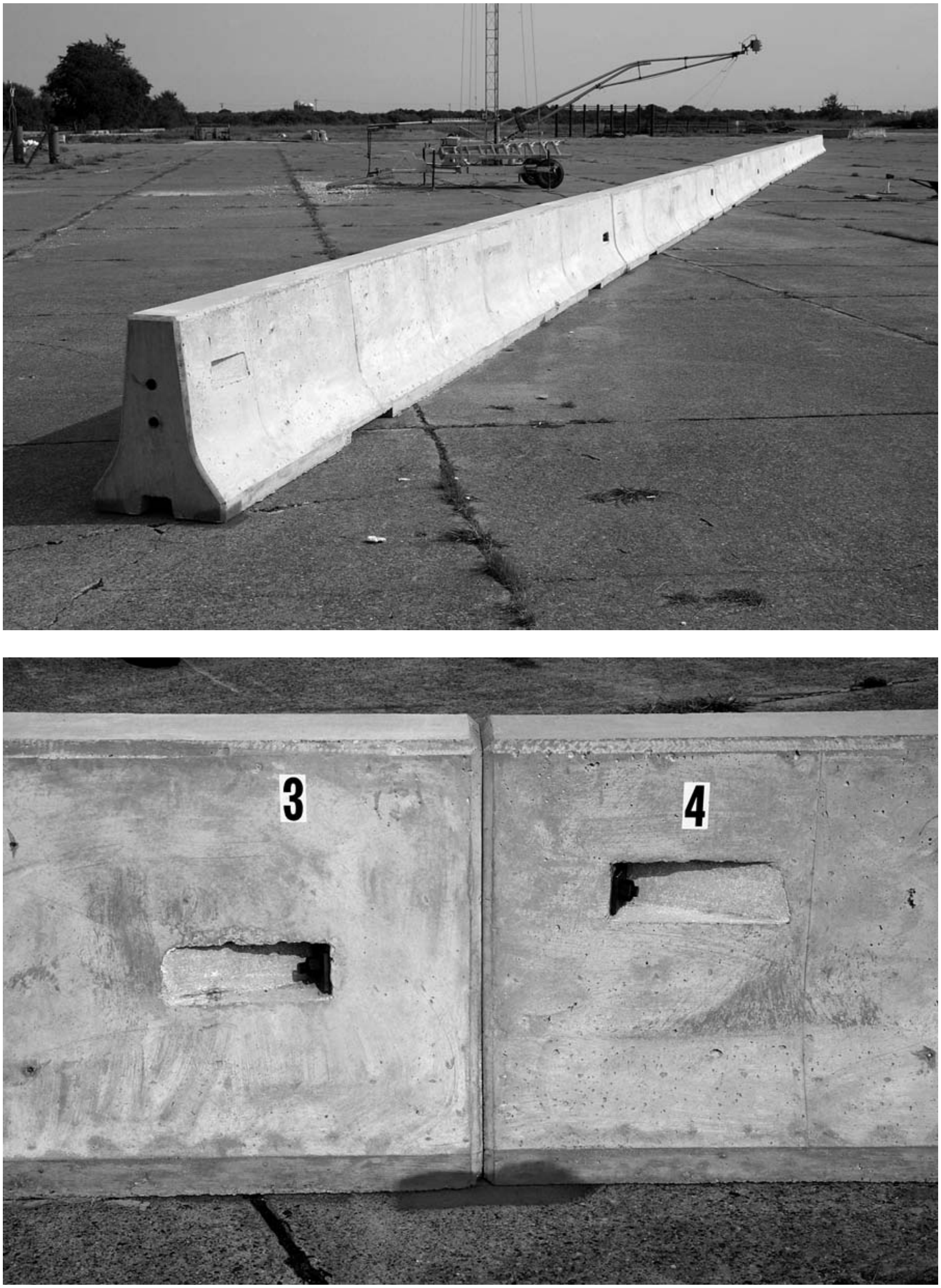


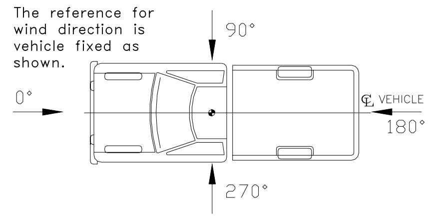
Figure 11. Cross-Bolt, F-Shape Precast Concrete Traffic Barrier before Test 441623-1.

Figure 12. Vehicle/Installation Geometrics for Test 441623-1.

Figure 13. Vehicle before Test 441623-1.

Weather Conditions

The test was performed on the morning of August 22, 2003. Rainfall of 0.6 inches was recorded one day prior to the test. No other rainfall was recorded for the remaining 10 days before the test. Weather conditions at the time of testing were as follows: Wind speed: 4 mi/h (7 km/h); Wind direction: 170 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); Temperature: 85 ºF (29 ºC), Relative humidity: 65 percent.



Test Description

The pickup truck, traveling at a speed of 62.3 mi/h (100.3 km/h), impacted the concrete barrier installation 4.2 ft (1.27 m) upstream of joint 3-4 at an impact angle of 25.7 degrees. At 0.010 s after impact, the left front tire of the vehicle began to ride up the face of the barrier, and by 0.032 s, the left front corner of the vehicle reached joint 3-4. The vehicle began to redirect at 0.064 s, and the right front tire lost contact with the ground surface at 0.087 s. At 0.219 s, the vehicle was traveling parallel with the barrier at a speed of 54.1 mi/h (87.0 km/h). The rear of the vehicle contacted the barrier at 0.226 s. At 0.404 s, the vehicle lost contact with the barrier while traveling at a speed of 51.6 mi/h (83.1 km/h) and an exit angle of 5.1 degrees. As the vehicle continued traveling along the barrier, there was a secondary impact with the installation 4.3 ft (1.3 m) upstream of joint 6-7 at 1.414 s. The vehicle slid off the end of segment 7, yawed counterclockwise, and came to rest with the front of the vehicle facing toward the barrier installation, 247.5 ft (75.4 m) downstream of impact and 27.5 ft (8.4 m) behind the traffic face of the barrier. Sequential photographs of the test are presented in Appendix C, Figure 20.

Damage to Test Installation

The free end of segment 1 was pushed toward the field side 0.6 in (15 mm), and the joint between segment 1 and 2 was pushed toward the traffic lanes 0.4 in (10 mm) with no damage at the joint. The joint between segment 2 and 3 was separated 0.2 in (5 mm) and was pushed toward the field side 2.0 in (50 mm). Both segment 2 and 3 had some spalling of concrete on the field side of the joint, and the bolts were very slightly deformed but reusable. The joint between segments 3 and 4 was separated 0.47 in (12 mm) and pushed toward the field side 18.1 in (460 mm). Segment 3 was cracked at 8.1 in (205 mm) from the end nearest joint 4 near the top and radiating into the field side. The end of segment 4 was cracked at its base near its joint with segment 3. The bolts at joint 3-4 were deformed, and the threads were stretched. The joint between segments 4 and 5 was pushed toward the field side 4.9 in (125 mm). Both segments had cracks near the top and at the base on both the traffic side and the field side. The joint between segments 5 and 6 was pushed toward the field side 1.4 in (35 mm). The base of segment 6 was cracked on the traffic side and the field side. The joint between segments 6 and 7 was pushed toward the field side 0.6 in (15 mm), and there was no damage. The free end of segment 7 did not move. During initial impact, the vehicle was in contact with the installation 20.2 ft (6.2 m). The vehicle contacted the installation again 4.3 ft (1.3 m) upstream of joint 6-7 and slid off the end of the barrier for a total secondary contact of 34.3 ft (10.5 m). Maximum dynamic deflection during the test was 19.0 in (483 mm), and maximum permanent deflection was 18.1 in (460 mm). Damage to the concrete barriers is shown in Figures 14 and 15.

After the test, the nuts on the cross bolts in the impact region were removed with an impact wrench. After the nuts were removed, the bolts could be readily removed by hand without having to move or reposition the barrier segments in any way. The two bolts at the joint directly downstream from impact (i.e., the joint between segments 3 and 4) required replacement. The other bolts were reusable. Of the four barrier segments damaged in the impact, two could be readily repaired and reused while two would likely need to be replaced.

Vehicle Damage

Damage to the pickup is shown in Figure 16. Structural damage was imparted to the left upper and lower A-arm, left frame rail, and the floor pan. The inner and outer rim of the left front tire separated at the welds, and the tire was deflated. Also damaged were the front bumper, hood, grill, radiator, fan, left door, left front quarter panel, and left exterior bed. The tailgate separated from the pickup, the left rear wheel rim was deformed, and the tire was deflated. Maximum exterior crush to the vehicle was 17.7 in (450 mm) in the side plane at the left front corner of the vehicle near bumper height. Maximum occupant compartment deformation was 2.6 in (65 mm) just to the left of the center of the floor pan, near the transmission tunnel. Photographs of the interior of the vehicle are shown in Figure 17. Exterior vehicle crush and occupant compartment measurements are shown in Appendix B, Tables 4 and 5.

Occupant Risk Factors

Data from the triaxial accelerometer located at the vehicle center of gravity were digitized to compute occupant impact velocity and ridedown accelerations. Note that only the occupant impact velocity and ridedown acceleration in the longitudinal axis are required from these data for evaluation of criterion L of *NCHRP Report 350*. In the longitudinal direction, occupant impact velocity was 16.1 ft/s (4.9 m/s) at 0.094 s, maximum 0.010-s ridedown acceleration was -3.7 g's from 0.514 to 0.524 s, and the maximum 0.050-s average was -7.6 g's between 0.026 and 0.076 s. These data and other information pertinent to the test are presented in Figure 18. Vehicle angular displacements and accelerations versus time traces are shown in Appendix D, Figures 21 through 27.

Figure 14. After Impact Trajectory for Test 441623-1.

Figure 15. Installation after Test 441623-1.

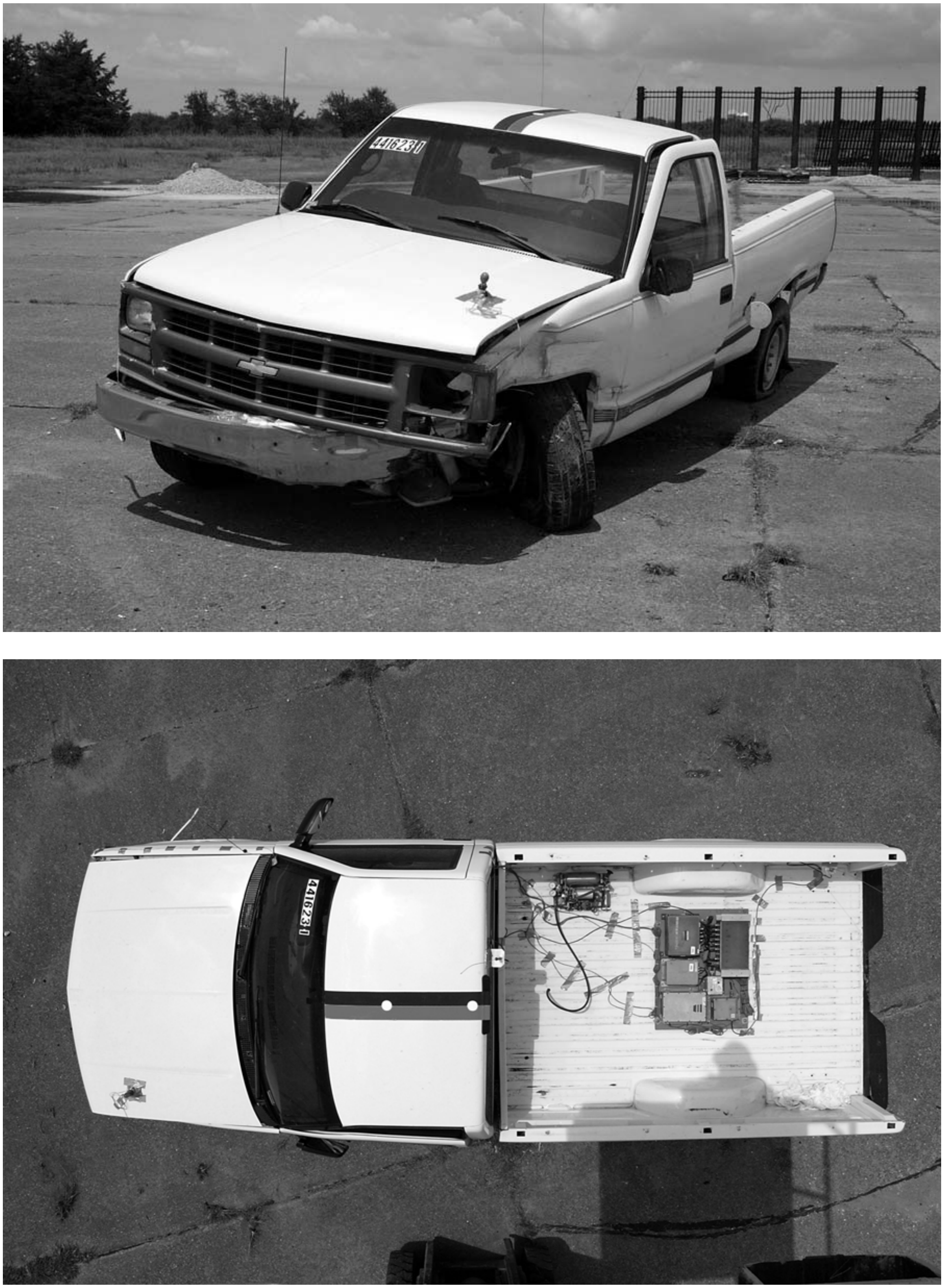


Figure 16. Vehicle after Test 441623-1.

Before Test

After Test

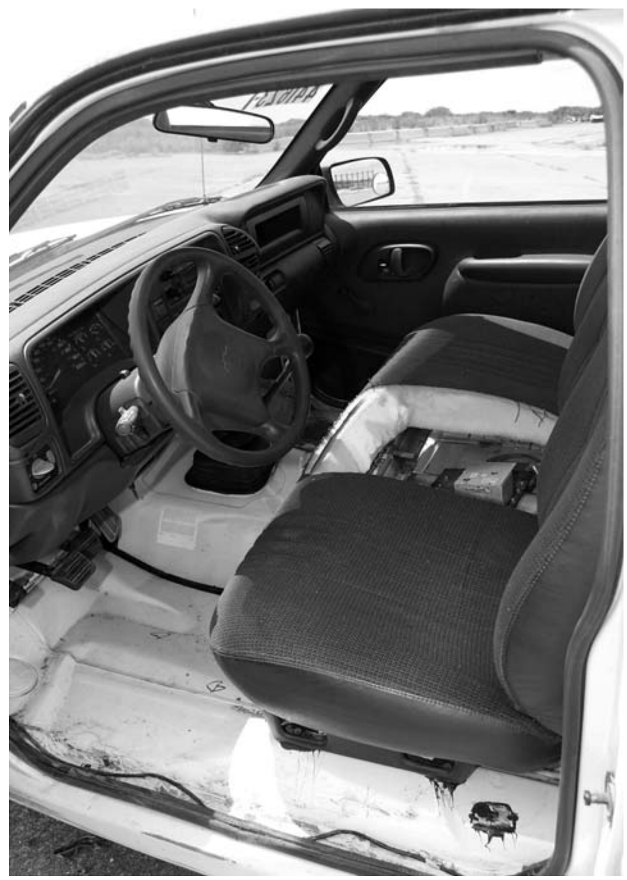
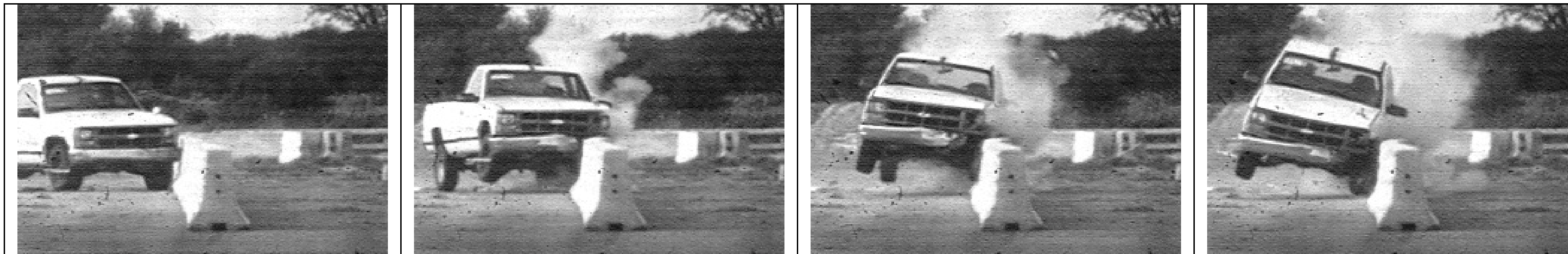
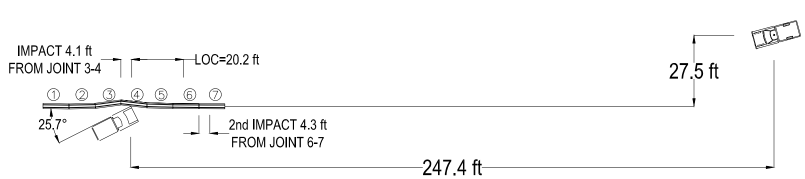
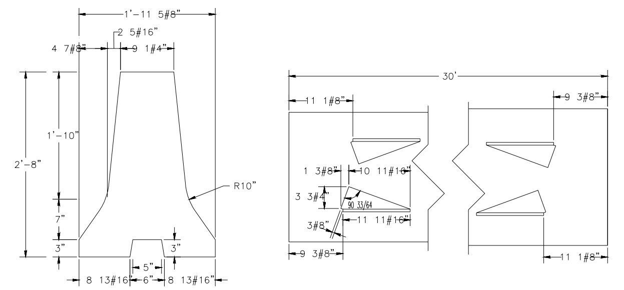


Figure 17. Interior of Vehicle for Test 441623-1.



0.000 s | 0.133 s | 0.266 s | 0.404 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	441623-1
Date	08-22-2003
Test Article	
Type	Median Barrier
Name	TxDOT Precast Concrete Barrier
Installation Length (ft)	30.0
Material or Key Elements	Precast Concrete Barrier With Cross-Bolted Barrier Connection
Soil Type and Condition	Concrete Apron
Test Vehicle	
Type	Production
Designation	2000P
Model	2000 Chevrolet Cheyenne 2500 Pickup
Mass (kg)	
Curb	2075
Test Inertial	2057
Dummy	N/A
Gross Static	2057

Impact Conditions	
Speed (mi/h)	62.3
Angle (deg)	25.7
Exit Conditions	
Speed (mi/h)	51.6
Angle (deg)	5.1
Occupant Risk Values	
Impact Velocity (ft/s)	
Longitudinal	16.1
Lateral	25.3
THIV (mi/h)	19.9
Ridedown Accelerations (g's)	
Longitudinal	-3.7
Lateral	10.0
PHD (g's)	10.0
ASI	1.69
Max. 0.050-s Average (g's)	
Longitudinal	-7.6
Lateral	12.5
Vertical	-8.1

Test Article Deflections (in)	
Dynamic	19.0
Permanent	18.1
Working Width	18.8
Vehicle Damage	
Exterior	
VDS	11FL3
CDC	11FLEW3
Maximum Exterior Vehicle Crush (in)	17.7
Interior	
OCDI	LF0111000
Maximum Occupant Cmpt. Deformation (in)	2.6
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle (deg)	32.6
Max. Pitch Angle (deg)	-18.0
Max. Roll Angle (deg)	-23.3

Figure 18. Summary of Results for *NCHRP Report 350* Test 3-11 on the Cross-Bolt, F-Shape PCTB.

Assessment of Test Results

An assessment of the test based on the applicable *NCHRP Report 350* evaluation criteria is provided below.

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.*

Results: The cross-bolt, F-shape precast concrete traffic barrier contained and redirected the vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection was 19.0 inches (483 mm). (PASS)

Occupant Risk

D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*

Results: No detached elements, fragments, or other debris was present. Maximum occupant compartment deformation was 2.6 inches (65 mm) near the center of the floor pan adjacent to the transmission tunnel. (PASS)

F. *The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.*

Results: The vehicle remained upright during and after the collision event. (PASS)

Vehicle Trajectory

K. *After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*

Results: The vehicle came to rest 247.5 ft (75.4 m) downstream of impact and 27.5 ft (8.4 m) toward the field side of the traffic face of the barrier. (PASS)

L. *The occupant impact velocity in the longitudinal direction should not exceed 12 m/s, and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 g's.*

Results: Longitudinal occupant impact velocity was 16.1 ft/s (4.9 m/s), and longitudinal occupant ridedown acceleration was -3.7 g's. (PASS)

M. *The exit angle from the test article preferably should be less than 60 percent of the test impact angle, measured at time of vehicle loss of contact with the test device.*

Results: The exit angle at loss of contact with the barrier was 5.1 degrees, which was 20 percent of the impact angle. (PASS)

The following supplemental evaluation factors and terminology, as presented in the FHWA memo entitled "Action: Identifying Acceptable Highway Safety Features," were used for visual assessment of test results:

Passenger Compartment Intrusion

1. *Windshield Intrusion*
   - *a. No windshield contact*
   - *b. Windshield contact, no damage*
   - *c. Windshield contact, no intrusion*
   - *d. Device embedded in windshield, no significant intrusion*
   - *e. Complete intrusion into passenger compartment*
   - *f. Partial intrusion into passenger compartment*
2. *Body Panel Intrusion* *yes* *or* *no*

Loss of Vehicle Control

1. *Physical loss of control*
2. *Loss of windshield visibility*
3. *Perceived threat to other vehicles*
4. *Debris on pavement*

Physical Threat to Workers or Other Vehicles

1. *Harmful debris that could injure workers or others in the area*
2. *Harmful debris that could injure occupants in other vehicles*

   No debris was present.

Vehicle and Device Condition

1. *Vehicle Damage*
   - *a. None*
   - *b. Minor scrapes, scratches, or dents*
   - *c. Significant cosmetic dents*
   - *d. Major dents to grill and body panels*
   - *e. Major structural damage*
2. *Windshield Damage*
   - *a. None*
   - *b. Minor chip or crack*
   - *c. Broken, no interference with visibility*
   - *d. Broken or shattered, visibility restricted but remained intact*
   - *e. Shattered, remained intact but partially dislodged*
   - *f. Large portion removed*
   - *g. Completely removed*
3. *Device Damage*
   - *a. None*
   - *b. Superficial*
   - *c. Substantial, but can be straightened*
   - *d. Substantial, replacement parts needed for repair*
   - *e. Cannot be repaired*

CHAPTER 4. CONCLUSIONS

TxDOT does not consider some of its existing portable concrete median barrier designs to be adequate for some site conditions from the standpoint of lateral dynamic barrier deflection. The objective of this project was to develop a new precast, concrete traffic barrier system with a design deflection of 3 ft (0.9 m) or less.

The design of the joint has a direct influence on the magnitude of lateral barrier deflection during a vehicular impact event. Several joint concepts were considered for the new TxDOT barrier system. Preliminary evaluation indicated that a cross-bolted connection design had a high potential for limiting lateral barrier deflections. Predictive LS-DYNA computer simulations were performed to help design the barrier, quantify its deflection characteristics, and assess its ability to meet *NCHRP Report 350* impact performance criteria. The simulation effort provided TTI researchers and TxDOT engineers a more detailed understanding of the three-dimensional impact response of the barrier prior to conducting full-scale crash testing.

In consultation with TTI researchers, TxDOT decided to adopt an F-shape barrier profile for the new barrier design in lieu of the New Jersey-shape profile used on current TxDOT barriers. The F-shape is widely considered to provide improved impact performance over the New Jersey-shape. Full-scale crash testing indicates that vehicles experience less climb and remain more stable during impacts with barriers having an F-shape profile compared to those with a New Jersey-shape profile.

Subsequent to its design and simulation, a full-scale crash test was conducted to assess impact performance and quantify the design deflection of the cross-bolted F-shape barrier. The test involved a 4409-lb (2000 kg) pickup truck impacting the barrier at a speed of 62.2 mi/h (100 km/h) and an angle of 25 degrees. As summarized in Table 3, the new TxDOT concrete barrier satisfied *NCHRP Report 350* evaluation criteria for test designation 3-11. The structural integrity of the barrier and its connections was maintained, and the barrier successfully contained and redirected the test vehicle in an upright manner. The F-shape profile reduced the amount of vehicle climb and kept the vehicle more stable during redirection.

The occupant risk factors were within the preferred limits specified in *NCHRP Report 350*. Although the barrier sustained some damage that would require repair, there were no detached elements, fragments, or other debris that showed potential for penetrating the occupant compartment, or presented a hazard to workers or others in the area. The dynamic barrier deflection was 19 inches (483 mm). This deflection is well below the 3 ft (0.9 m) deflection constraint imposed by TxDOT at the onset of the project and is the lowest deflection of any free-standing, portable concrete barrier approved to *NCHRP Report 350* requirements. It is worthwhile noting that this deflection resulted from a relatively severe design impact condition. Even less deflection and barrier damage would be expected for the majority of in-service impacts.

After impact, the cross-bolt barrier connections were readily disassembled without having to move or reposition any of the barrier segments. The two bolts at the joint directly downstream from impact were damaged to an extent that they would need to be replaced, but all the other bolts were reusable.

The weight of the 30-ft (9.1 m) F-shape barrier segments was determined to be approximately 13,680 lb (6205 kg). This is less than the weight of the current New Jersey-shape barriers used by TxDOT. Therefore, implementation of the new barrier system should not require any changes to current barrier transportation, handling, and placement procedures.

Table 3. Performance Evaluation Summary for *NCHRP Report 350* Test 3-11 on the Cross-Bolt, F-Shape PCTB.

Test Agency: Texas Transportation Institute | Test No.: 441623-1 | Test Date: 08/22/03

***NCHRP Report 350* Test 3-11 Evaluation Criteria**	**Test Results**	**Assessment**
Structural Adequacy A. *Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.*	The cross-bolt, F-shape PCTB contained and redirected the vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection was 19.0 inches (483 mm).	Pass
Occupant Risk D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*	No detached elements, fragments, or other debris was present to penetrate or to show potential for penetrating the occupant compartment, or to present hazard to others in the area. Maximum occupant compartment deformation was 2.6 inches (65 mm) near the center of the floor pan adjacent to the transmission tunnel.	Pass
F. *The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.*	The vehicle remained upright during and after the collision event.	Pass
Vehicle Trajectory K. *After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*	The vehicle came to rest 247.5 ft (75.4 m) downstream of impact and 27.5 ft (8.4 m) toward the field side of the traffic face of the barrier.	Pass
L. *The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 g's.*	Longitudinal occupant impact velocity was 16.1 ft/s (4.9 m/s), and longitudinal occupant ridedown acceleration was -3.7 g's.	Pass
M. *The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.*	The exit angle at loss of contact with the barrier was 5.1 degrees, which was 20 percent of the impact angle.	Pass

CHAPTER 5. IMPLEMENTATION STATEMENT

The high lateral dynamic deflection of some current TxDOT portable concrete barriers renders them inappropriate for deployment in areas with restricted work space. Under this project, a new precast concrete traffic barrier system with limited deflection was developed through a program of simulation and full-scale crash testing.

Based on the results of the testing and evaluation reported herein, the new cross-bolt, F-shape precast concrete traffic barrier is considered suitable for implementation on high-speed roadways. The low barrier deflection (19 inches (483 mm)) and ease of placement and repair make the cross-bolt F-shape barrier well suited for use as a work zone barrier.

The weight of the 30-ft (9.1 m) F-shape barrier segments was determined to be approximately 13,680 lb (6205 kg). Because the weight of the F-shape barriers is less than the weight of the current New Jersey-shaped barriers used by TxDOT, implementation of the new barrier will not require any changes to current barrier transportation, handling, and placement procedures.

The F-shape barrier profile should provide improved safety in comparison with the current New Jersey-profile barriers by reducing the frequency of rollover crashes. Full-scale crash testing indicates that vehicles impacting barriers with an F-shape profile experience less climb and remain more stable compared to those that impact barriers with a New Jersey-profile.

Finally, the increased top width (9-1/4 inches versus 8 inches (235 mm versus 203 mm) for current barriers) and improved strength of the new barrier should provide improved accommodation of barrier-mounted lighting standards. Current practice requires casting recesses into the top of the barrier to provide the needed width to accommodate barrier mounted lighting, and barrier cracking is commonly seen in the corners of these cutouts/recesses.

Statewide implementation of the new cross-bolt F-shape barrier can be achieved by TxDOT's Design Division through the development and issuance of a new standard detail sheet. The barrier details provided in Figures 6 through 10 can be used for this purpose.

REFERENCES

1. R.P. Bligh, D.L. Bullard, Jr., W.L. Menges, and B.G. Butler, *Evaluation of Texas Grid-Slot Portable Concrete Barrier System*, TxDOT Research Report 4162-1, Texas Transportation Institute, College Station, Tx, April 2002.

2. H.E. Ross, Jr., D.L. Sicking, R.A. Zimmer, and J.D. Michie, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program Report 350, Transportation Research Board, National Research Council, Washington, D.C., 1993.

3. J. O. Hallquist, *LS-DYNA*, Livermore Software Technology Corporation, 2002.

4. C.E. Buth, T.J. Hirsch, and W.L. Menges, *Testing of New Bridge Rail and Transition Designs, Volume VII: Appendix F, 32-inch (813 mm) F-Shape Bridge Railing*, FHWA Report FHWA-RD-93-064, Federal Highway Administration, McLean, Va, June 1997.

APPENDIX A. CRASH TEST PROCEDURES AND DATA ANALYSIS

The crash test and data analysis procedures were in accordance with guidelines presented in *NCHRP Report 350*. Brief descriptions of these procedures are presented as follows.

ELECTRONIC INSTRUMENTATION AND DATA PROCESSING

The test vehicle was instrumented with three solid-state angular rate transducers to measure roll, pitch, and yaw rates; a triaxial accelerometer near the vehicle center of gravity (c.g.) to measure longitudinal, lateral, and vertical acceleration levels; and a backup biaxial accelerometer in the rear of the vehicle to measure longitudinal and lateral acceleration levels. These accelerometers were ENDEVCO Model 2262CA, piezoresistive accelerometers with a ±100g range.

The accelerometers are strain gage type with a linear millivolt output proportional to acceleration. Angular rate transducers are solid state, gas flow units designed for high-"g" service. Signal conditioners and amplifiers in the test vehicle increase the low-level signals to a ±2.5 volt maximum level. The signal conditioners also provide the capability of a resistance calibration (R-cal) or shunt calibration for the accelerometers and a precision voltage calibration for the rate transducers. The electronic signals from the accelerometers and rate transducers are transmitted to a base station by means of a 15-channel, constant bandwidth, Inter-Range Instrumentation Group (I.R.I.G.), FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Calibration signals, from the test vehicle, are recorded before the test and immediately afterwards. A crystal-controlled time reference signal is simultaneously recorded with the data. Wooden dowels actuate pressure-sensitive switches on the bumper of the impacting vehicle prior to impact by wooden dowels to indicate the elapsed time over a known distance to provide a measurement of impact velocity. The initial contact also produces an "event" mark on the data record to establish the instant of contact with the installation.

The multiplex of data channels, transmitted on one radio frequency, is received and demultiplexed onto separate tracks of a 28-track, (I.R.I.G.) tape recorder. After the test, the data are played back from the tape machine and digitized. A proprietary software program (WinDigit) converts the analog data from each transducer into engineering units using the R-cal and pre-zero values at 10,000 samples per second, per channel. WinDigit also provides SAE J211 class 180 phaseless digital filtering and vehicle impact velocity.

All accelerometers are calibrated annually according to SAE J211 *4.6.1* by means of a ENDEVCO 2901, precision primary vibration standard. This device and its support instruments are returned to the factory annually for a National Institute of Standards Technology (NIST) traceable calibration. The subsystems of each data channel are also evaluated annually, using instruments with current NIST traceability, and the results are factored into the accuracy of the total data channel, per SAE J211. Calibrations and evaluations are made any time data is suspect.

The Test Risk Assessment Program (TRAP) uses the data from WinDigit to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 10 ms average ridedown acceleration. WinDigit calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50 ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with a 60-Hz digital filter, and acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted using TRAP.

TRAP uses the data from the yaw, pitch, and roll rate transducers to compute angular displacement in degrees at 0.0001-s intervals and then plots yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate systems being initial impact.

ANTHROPOMORPHIC DUMMY INSTRUMENTATION

Use of a dummy in the 2000P vehicle is optional according to *NCHRP Report 350*, and there was no dummy used in this test.

PHOTOGRAPHIC INSTRUMENTATION AND DATA PROCESSING

Photographic coverage of the test included three high-speed cameras: one overhead with a field of view perpendicular to the ground and directly over the impact point; one placed behind the installation at an angle; and a third placed to have a field of view parallel to and aligned with the installation at the downstream end. A flash bulb activated by pressure sensitive tape switches was positioned on the impacting vehicle to indicate the instant of contact with the installation and was visible from each camera. The films from these high-speed cameras were analyzed on a computer-linked Motion Analyzer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A 16-mm movie cine, a BetaCam, a VHS-format video camera and recorder, and still cameras recorded and documented conditions of the test vehicle and installation before and after the test.

TEST VEHICLE PROPULSION AND GUIDANCE

The test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point, through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A 2 to 1 speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released to be free-wheeling and unrestrained. The vehicle remained free-wheeling, i.e., no steering or braking inputs, until the vehicle cleared the immediate area of the test site, at which time brakes on the vehicle were activated to bring it to a safe and controlled stop.

APPENDIX B. TEST VEHICLE PROPERTIES AND INFORMATION

Date: 8-22-2003 Test No.: 441623-1 VIN No.: 1GCGC24RXYR158928

Year: 2000 Make: Chevrolet Model: Cheyenne 2500 Pickup

Tire Inflation Pressure: 60 psi Odometer: 160874 Tire Size: 245 75 R15

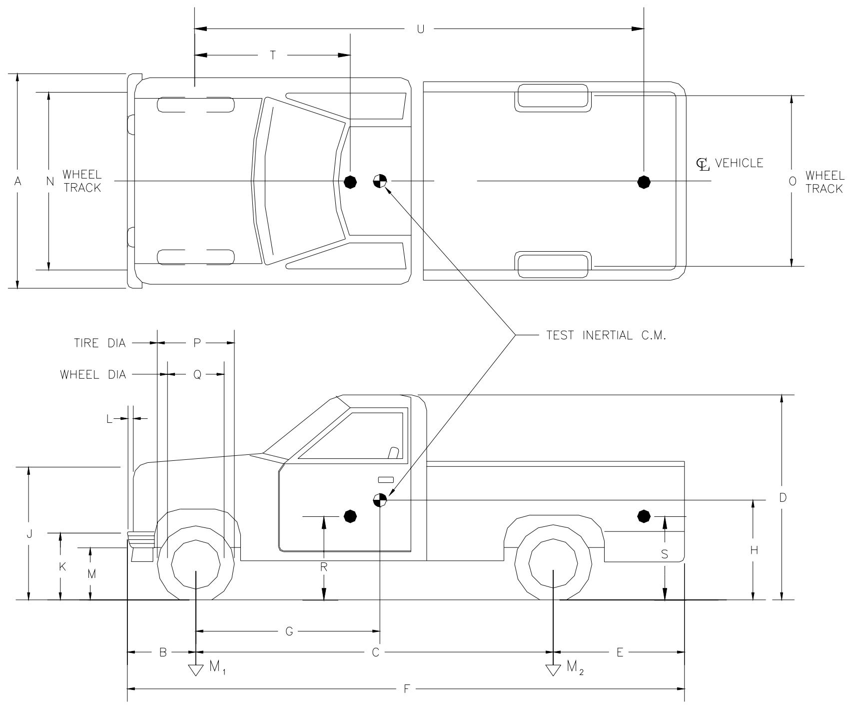
Describe any damage to the vehicle prior to test: ______

● Denotes accelerometer location.

NOTES: ______

Engine Type: V-8
Engine CID: 5.8 L
Transmission Type:
___ Auto
X Manual
Optional Equipment:
8 LUGS

Dummy Data:
Type: None
Mass: ______
Seat Position: ______



Geometry (mm)

A	1880	E	1310	J	1038	N	1590	R	750
B	810	F	5470	K	635	O	1610	S	900
C	3350	G	1423.4	L	70	P	725	T	1460
D	1820	H		M	415	Q	440	U	3360

Mass (kg)	Curb	Test Inertial	Gross Static
M_1	1213	1183	
M_2	862	874	
M_{Total}	2075	2057	

Mass Distribution (kg): LF: 593 RF: 590 LR: 423 RR: 451

Figure 19. Vehicle Properties for Test 441623-1.

Table 4. Exterior Crush Measurements for Test 441623-1.

VEHICLE CRUSH MEASUREMENT SHEET[1]

Complete When Applicable	
End Damage	Side Damage
Undeformed end width ________	Bowing: B1 _____ X1 _____
Corner shift: A1 ________	B2 _____ X2 _____
A2 ________	
End shift at frame (CDC)	Bowing constant
(check one)	$\frac{X1+X2}{2}$ = _______
< 4 inches ________	
≥ 4 inches ________	

Note: Measure C_1 to C_6 from Driver to Passenger side in Front or Rear impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	At front bumper	820	430	650	430	350	250	200	95	0	-325
2	At front bumper	820	450	1230	0	80	N/A		330	450	+1640

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

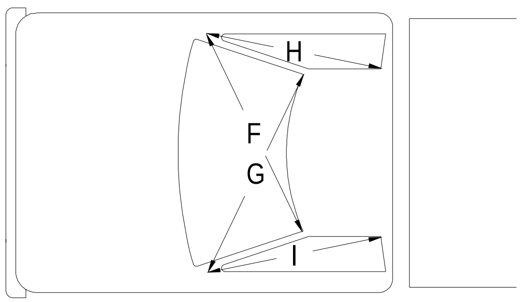
***Measure and document on the vehicle diagram the location of the maximum crush.

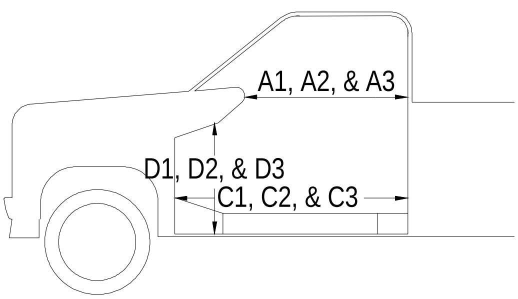
Note: Use as many lines/columns as necessary to describe each damage profile.

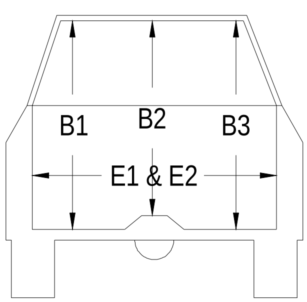
Table 5. Occupant Compartment Measurements for Test 441623-1.

T R U C K

Occupant Compartment Deformation







	BEFORE (mm)	AFTER (mm)
A1	870	860
A2	930	925
A3	934	937
B1	1083	1061
B2	985	940
B3	1072	1080
C1	1365	1300
C2		
C3	1370	1370
D1	327	313
D2	160	145
D3	310	312
E1	1590	1596
E2	1592	1605
F	1465	1465
G	1465	1458
H	1260	1252
I	1247	1247
J*	1520	1500

*Lateral area across the cab from
driver’s side kickpanel to passenger’s side kickpanel.

APPENDIX C. SEQUENTIAL PHOTOGRAPHS

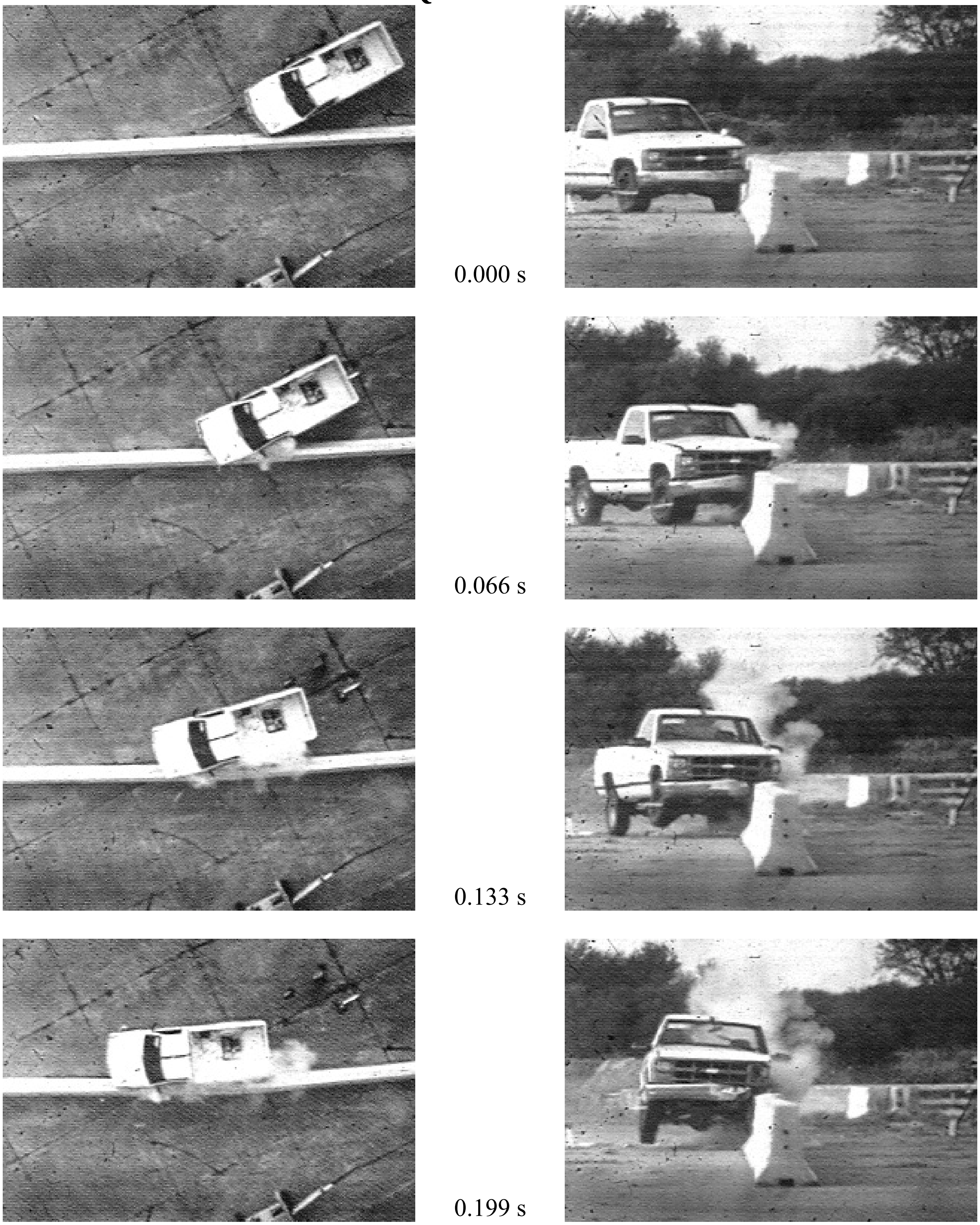


Figure 20. Sequential Photographs for Test 441623-1 (Overhead and Frontal Views).

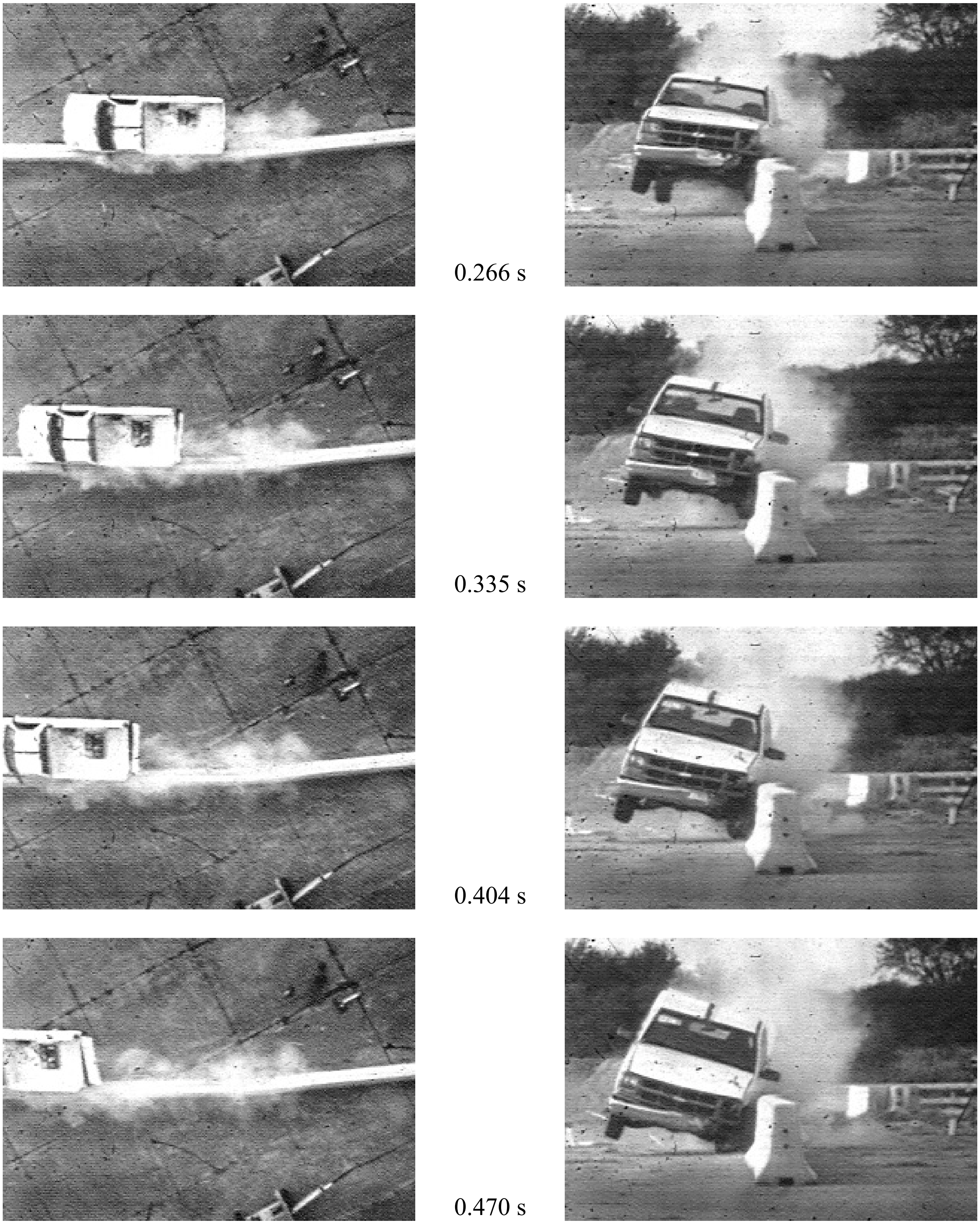


Figure 20. Sequential Photographs for Test 441623-1
(Overhead and Frontal Views) (Continued).

APPENDIX D. VEHICLE ANGULAR DISPLACEMENTS AND ACCELERATIONS

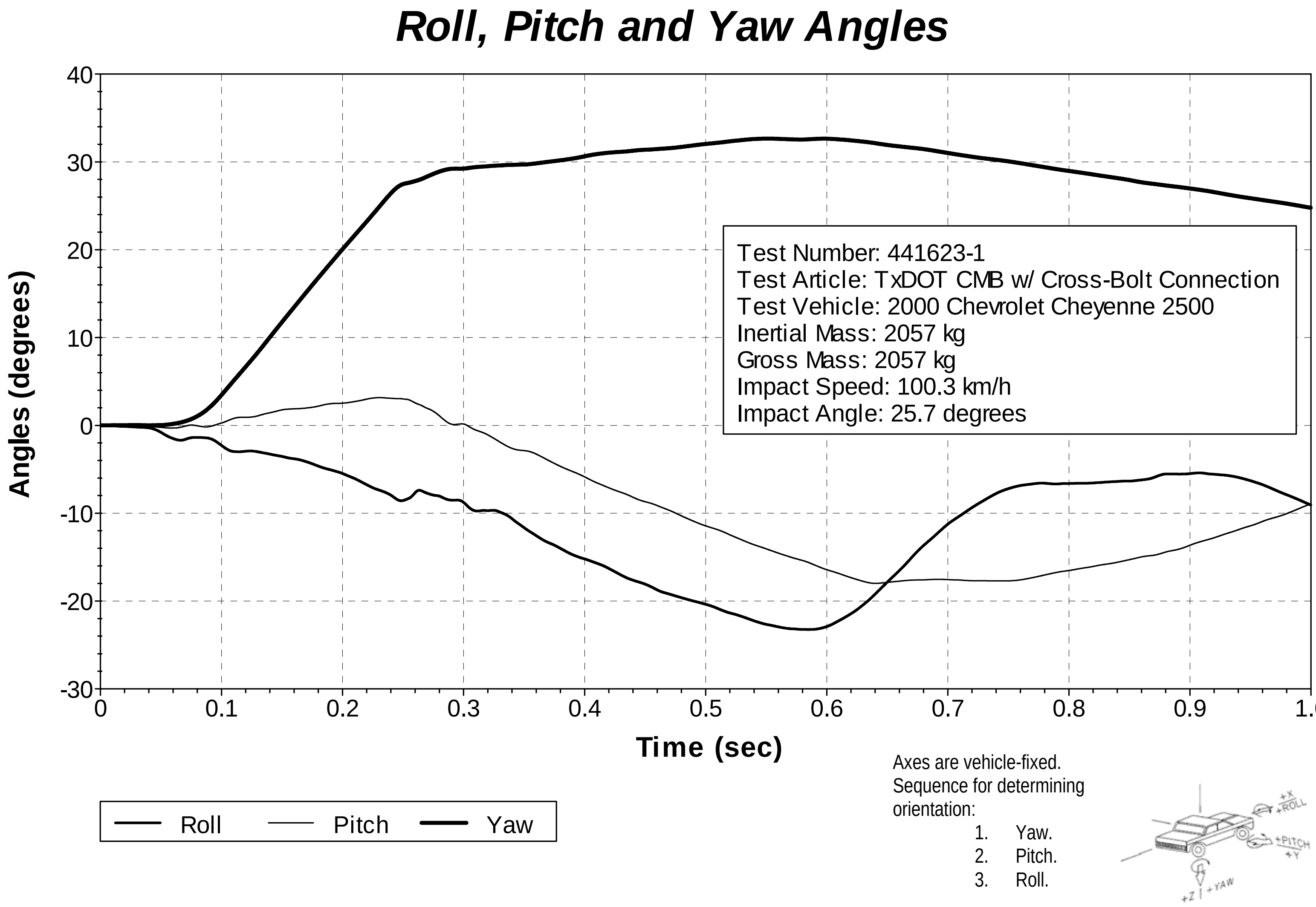


Figure 21. Vehicular Angular Displacements for Test 441623-1.

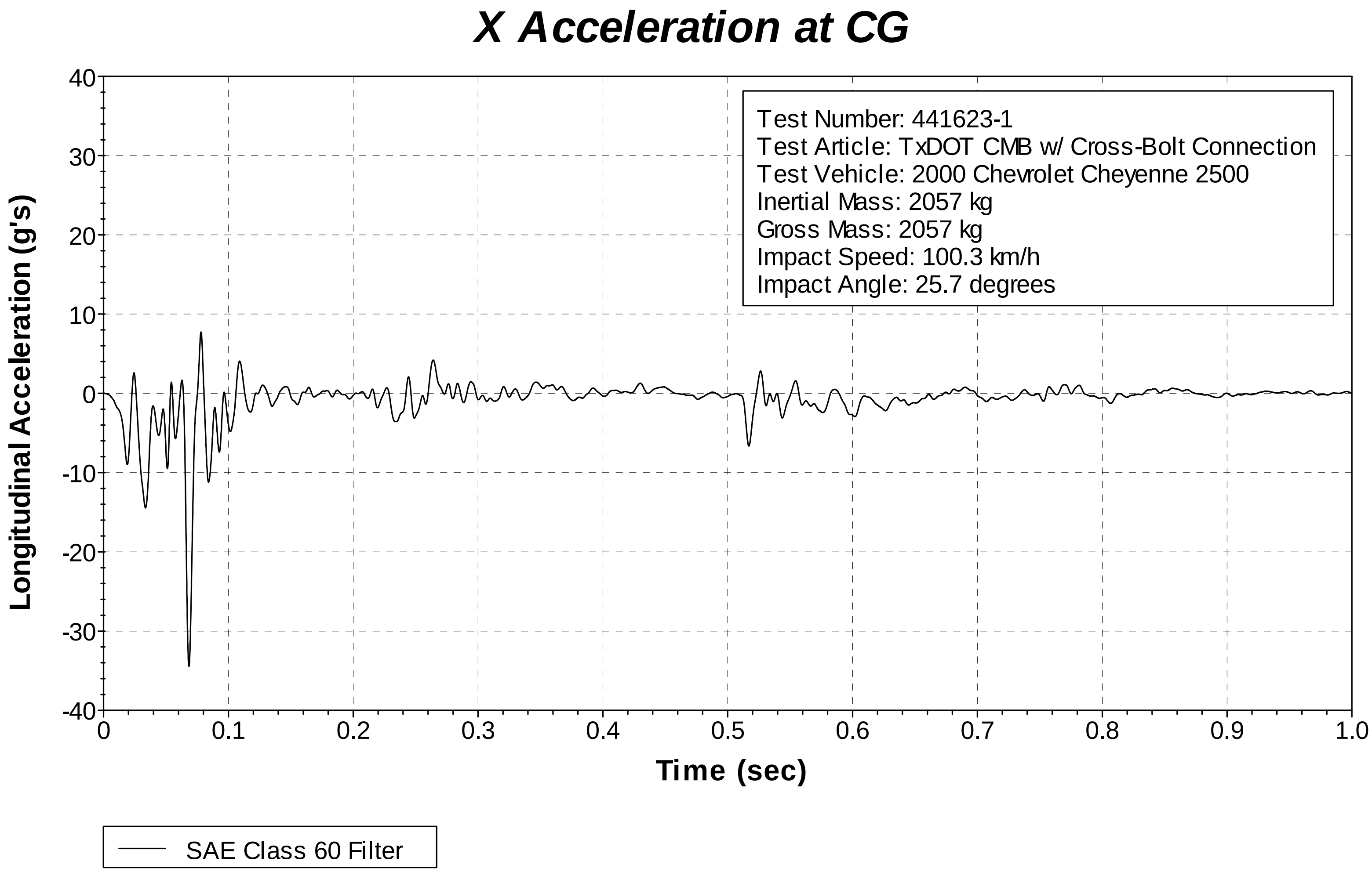


Figure 22. Vehicle Longitudinal Accelerometer Trace for Test 441623-1 (Accelerometer Located at Center of Gravity).

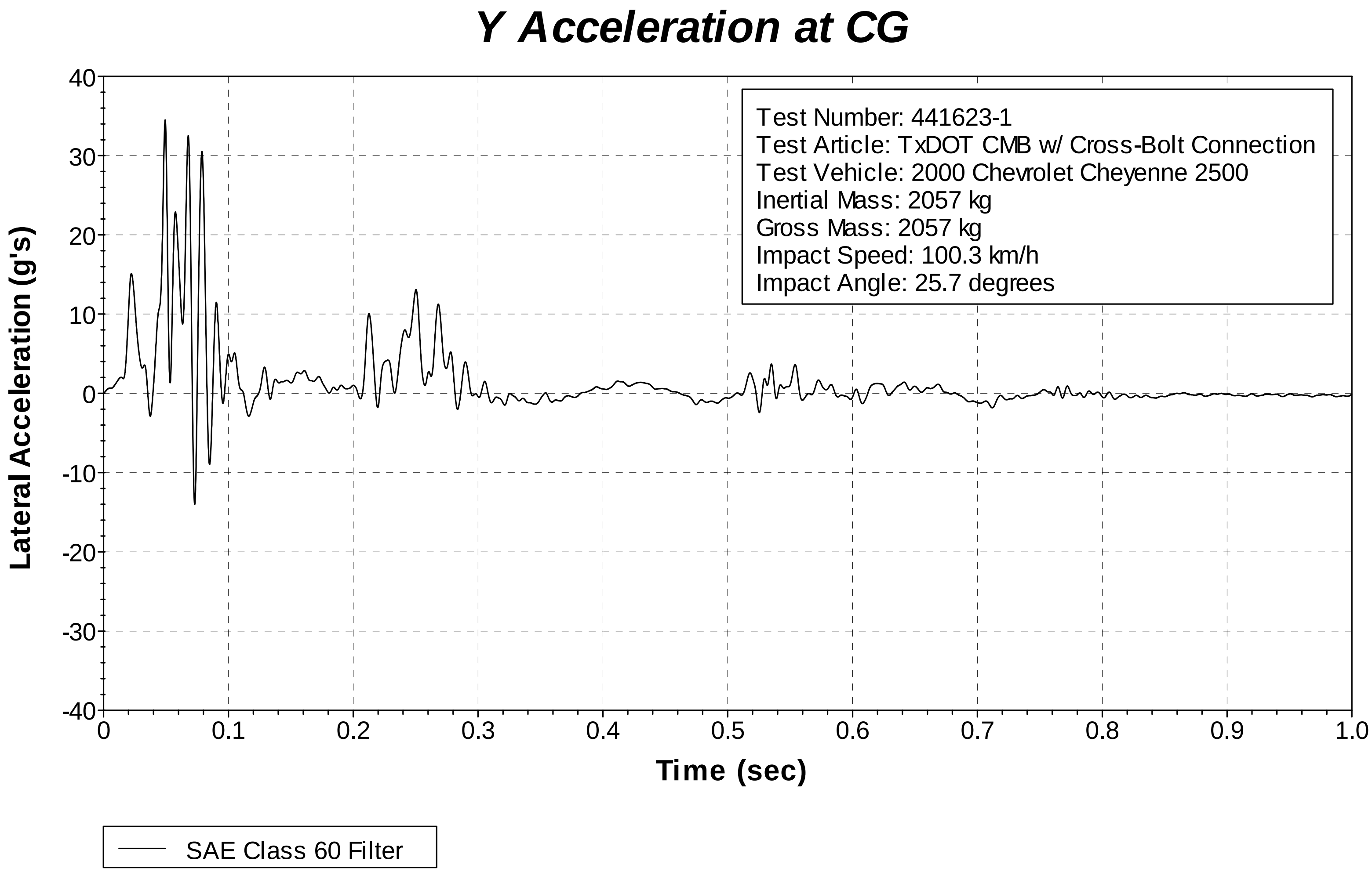


Figure 23. Vehicle Lateral Accelerometer Trace for Test 441623-1 (Accelerometer Located at Center of Gravity).

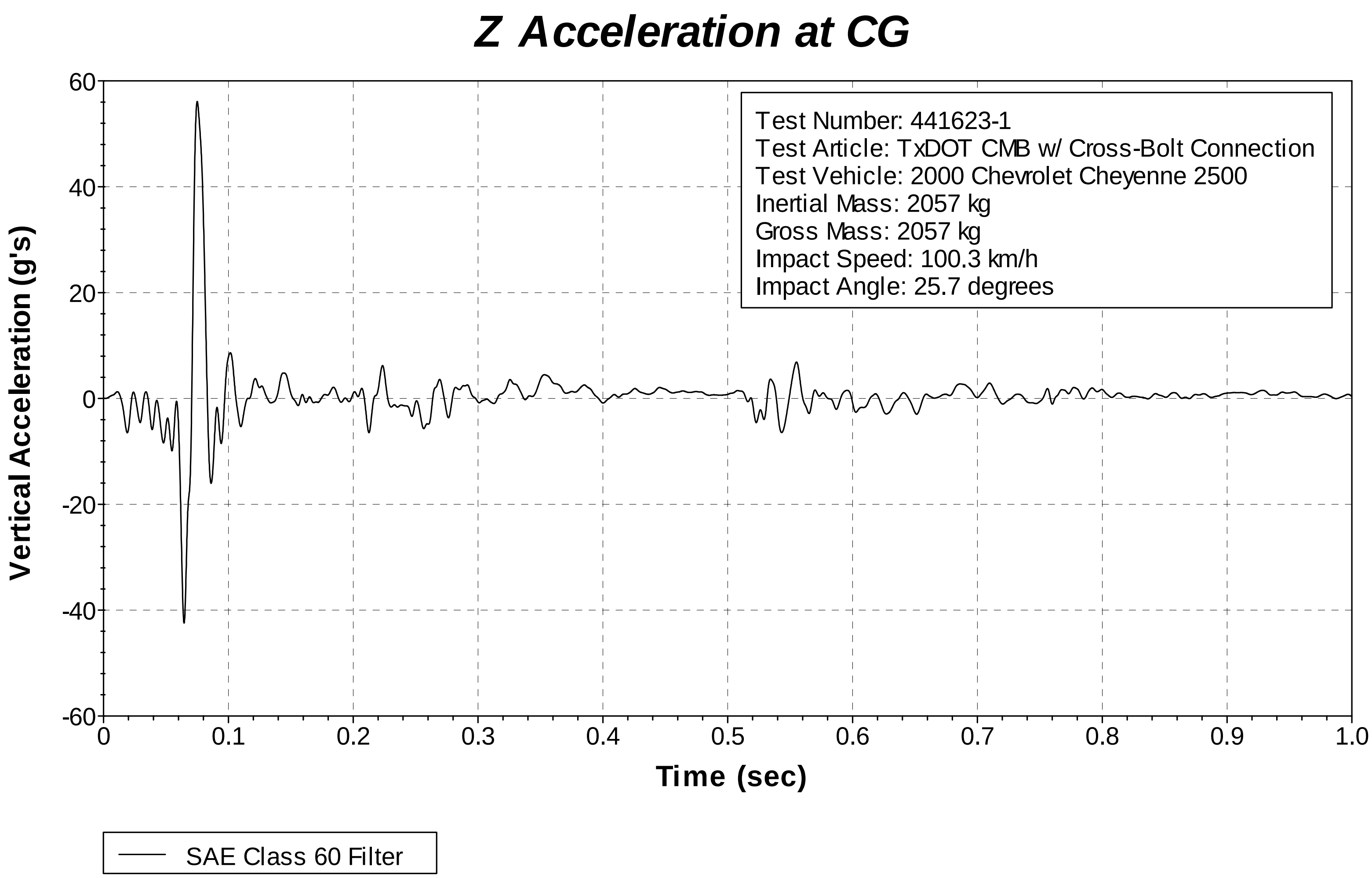


Figure 24. Vehicle Vertical Accelerometer Trace for Test 441623-1 (Accelerometer Located at Center of Gravity).

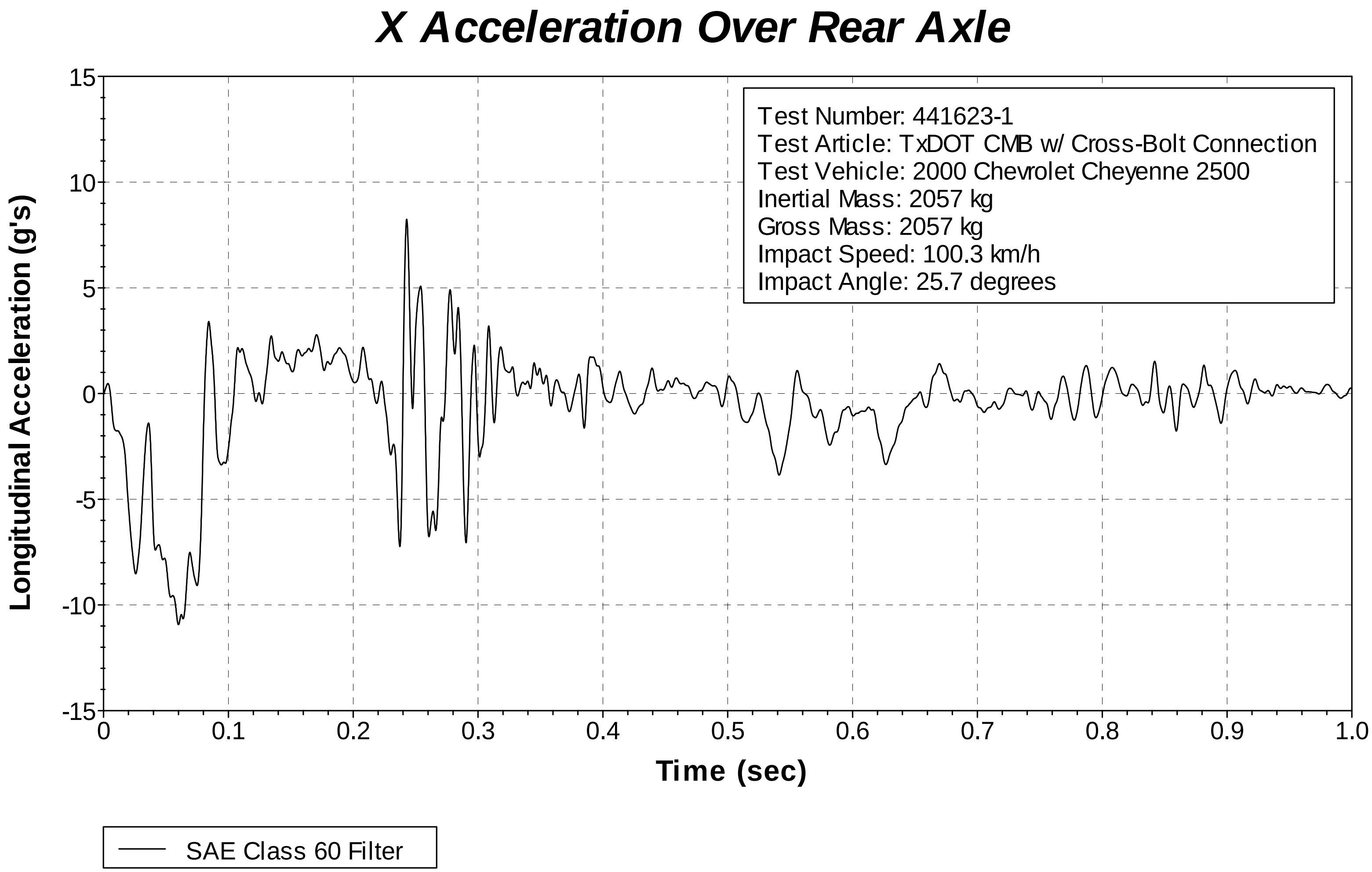


Figure 25. Vehicle Longitudinal Accelerometer Trace for Test 441623-1 (Accelerometer Located over Rear Axle).

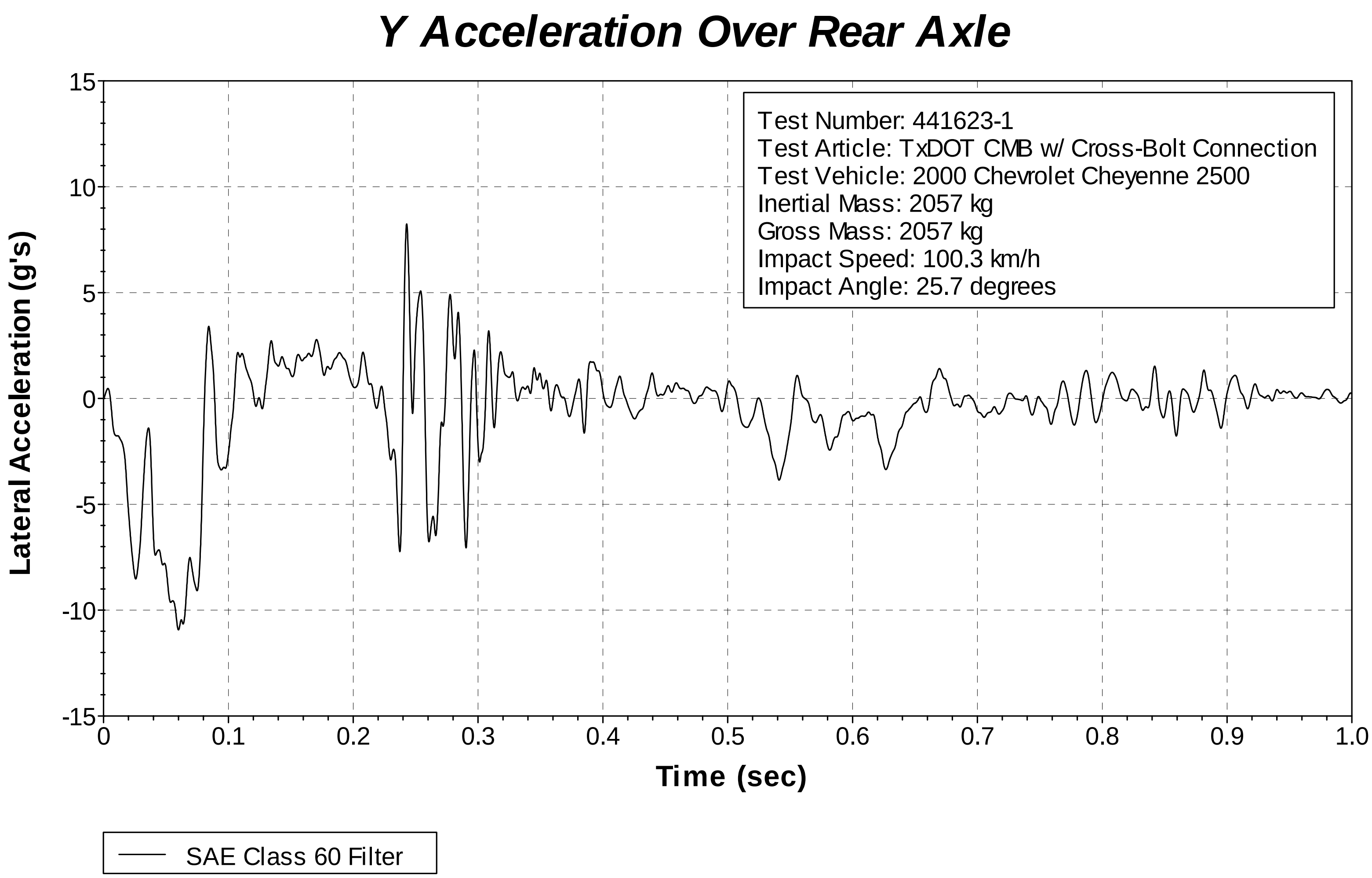


Figure 26. Vehicle Lateral Accelerometer Trace for Test 441623-1 (Accelerometer Located over Rear Axle).

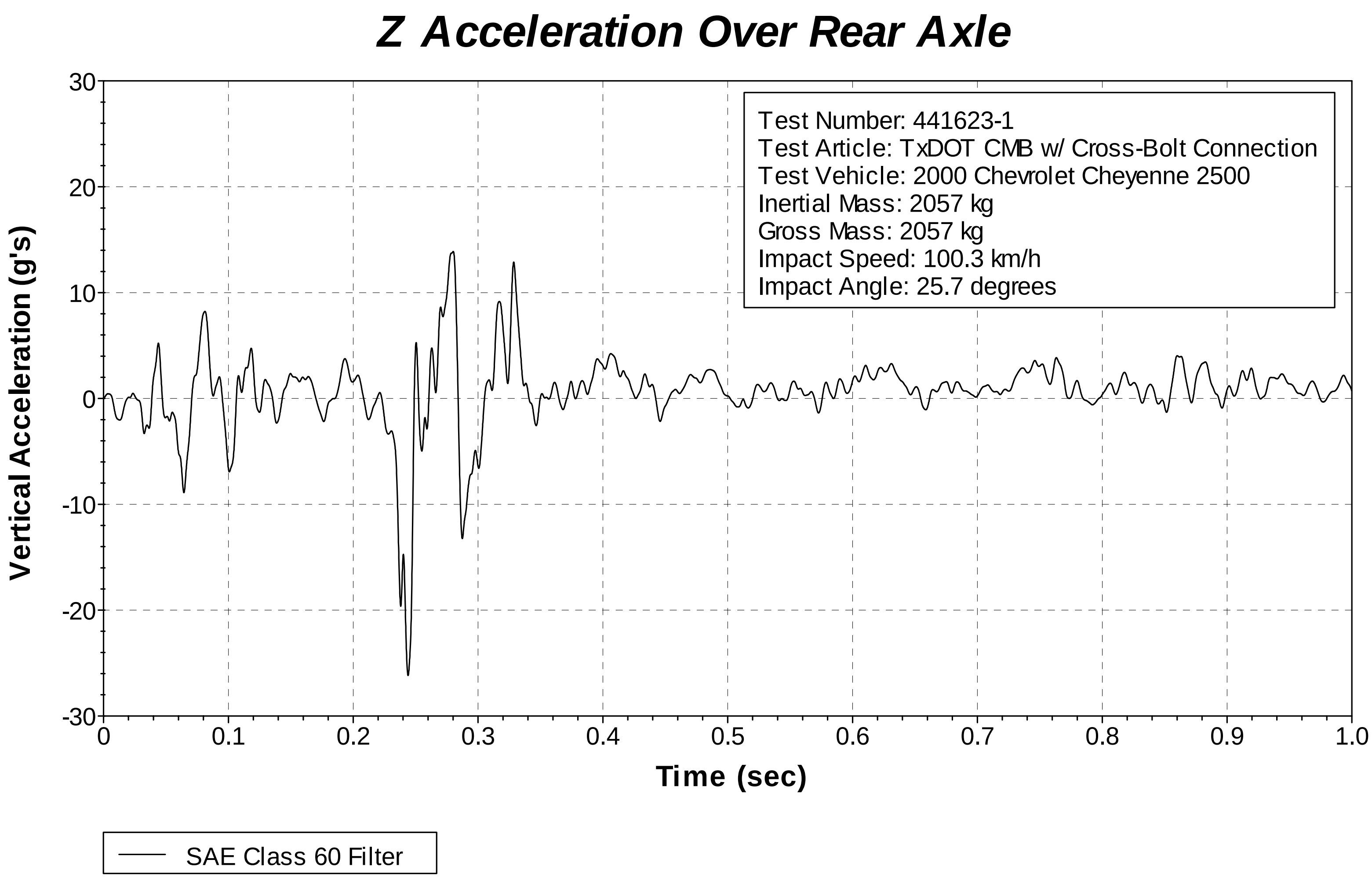


Figure 27. Vehicle Vertical Accelerometer Trace for Test 441623-1 (Accelerometer Located over Rear Axle).