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16. Abstract

Texas Department of Transportation (TxDOT) and Florida Department of Transportation (FDOT) frequently receive requests to provide aesthetically pleasing traffic rails for use on select bridges and roadways. TxDOT, in response to providing context sensitive design alternatives, initiated a project to develop additional aesthetically pleasing rail alternatives. Under a previous TxDOT project, the F411 bridge rail was constructed and crash tested to Test Level 3 (TL-3). The TL-3 test is a 4405-lb (2000 kg) pickup impacting the railing at 25 degrees and 62.2 mi/h (100 km/h). This test requires both containment and stability, and non-overturning. Since some breakage of the parapet is possible, potential for vehicle snagging is likely. Vehicle snagging can contribute to vehicle instabilities in the redirection sequence and potential rollover. The TxDOT F411 bridge rail contained and redirected the vehicle, which remained upright during and after the collision period. The bridge rail met the required specifications for *NCHRP Report 350* test 3-11.

The objective of this research is the full-scale crash test and evaluation of the F411 to Test Level 4 (TL-4). The most direct approach for accomplishing the objectives of this task is to perform a full-scale TL-4 crash test of this railing design. The TL-4 vehicle is a single-unit box-van truck impacting the railing at 15 degrees and 49.7 mi/h (80 km/h). While containment is required, overturning of the vehicle 90 degrees is an acceptable test outcome.

The TxDOT F411 bridge rail performed acceptably for *NCHRP Report 350* test 4-12. Based on the performance of the F411 bridge rail in the full-scale crash test to TL-4 test conditions, the F411 may be used where containment of 18,000 lb single-unit trucks is desired.

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TL-4 CRASH TESTING OF THE F411 BRIDGE RAIL

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DISCLAIMER

ACKNOWLEDGMENTS

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CHAPTER 1. INTRODUCTION

INTRODUCTION

The Florida Department of Transportation (FDOT) has identified six areas of transportation safety that require further research.

1. FDOT has extensive Jersey shaped barrier in use on highways today. A number of the designs from previous years have minimal reinforcement and when the current design procedure is used to evaluate the respective designs, the analysis indicates marginal performance may be anticipated when impacted by an errant vehicle. Therefore, FDOT has elected to full-scale crash test the most critical design currently deployed in the field.

2. The second area of research need is to evaluate one existing variant of the 32-inch Kansas Corral Railing to determine compliance status with the American Association of State Highway and Transportation Officials (*AASHTO*) *Load Resistance Factor Design* (*LRFD*) *Bridge Design Specifications* and National Cooperative Highway Research Program (*NCHRP*) *Report 350*, Test Level 4 (TL-4) criteria *(1,2)*. This task is to be accomplished by comparison to existing crash tested designs and, if warranted, a full-scale crash test to verify acceptable performance.

3. Current design procedures outlined in *AASHTO LRFD Bridge Design Specifications* specify a minimum thickness of the cantilevered portion of the bridge deck based on the strength of the bridge railing. FDOT desires to investigate failure modes of bridge railings and decks when thinner decks are used.

4. FDOT currently uses aluminum directional slip bases for small and medium size sign supports. The bases have not been full-scale tested for proper activation.

5. FDOT has a pending issue that they desire to investigate. Parapet orientation relative to the bridge deck or relative to a horizontal plane requires further evaluation. Sometimes parapets are oriented perpendicular to the deck or sometimes they are installed plumb with the earth. Investigation of other states and recommendations are desired.

6. FDOT has pending projects that require an aesthetic TL-4 bridge railing. TxDOT has previously tested the F411 bridge rail to Test Level 3 (TL-3) under a previous contract and has approved the testing of the installation under this contract *(3)*. This task is the full-scale crash test of the F411 to TL-4.

Task 6 is addressed in this report.

BACKGROUND

Texas Department of Transportation and Florida Department of Transportation frequently receive requests to provide aesthetically pleasing traffic rails for use on select bridges and roadways. TxDOT, in response to providing context sensitive design alternatives, initiated a project to develop additional aesthetically pleasing rail alternatives. The Texas T411 is an example of an aesthetic rail that has been very successful and has seen widespread implementation at both the state and national level. Aesthetic rails such as the Texas T411 are ornate, have an open architecture, and are often low in height to permit motorists to see through or over them, all features which may compromise their crashworthiness. For performance along high-speed roadways, designers avoid low-profile rails and rails with large window-type openings. Low-profile rails often do not possess the redirective capabilities necessary to contain and redirect larger automobiles traveling 62 mph (100 km/h). Additionally, openings and small rail set back distances from support posts provide an undesirable geometry and can facilitate "snagging" the vehicle and produce large occupant compartment deformations and high accelerations on the occupants.

Under a previous TxDOT project, the F411 bridge rail was constructed and crash tested to TL-3 *(3)*. The TL-3 test is a 4405-lb (2000 kg) pickup impacting the railing at 25 degrees and 62.2 mi/h (100 km/h). This test requires both containment and stability, and non-overturning. Since some breakage of the parapet is possible, potential for vehicle snagging is likely. Vehicle snagging can contribute to vehicle instabilities in the redirection sequence and potential rollover. The TxDOT F411 bridge rail contained and redirected the vehicle, which remained upright during and after the collision period. The bridge rail met the required specifications for *NCHRP Report 350* test 3-11.

OBJECTIVES/SCOPE OF RESEARCH

As stated previously, FDOT has pending projects that require an aesthetic TL-4 bridge railing. TxDOT has previously tested the F411 bridge rail to TL-3 under a previous contract and has approved the testing of the installation under this contract. The objective of this research is the full-scale crash test and evaluation of the F411 to TL-4.

The most direct approach for accomplishing the objectives of this task is to perform a full-scale TL-4 crash test of this railing design. If the railing performs satisfactorily, the railing would be acceptable by *AASHTO LRFD Specifications*. The test that is needed is the strength test for the test level of interest; in this instance, *NCHRP Report 350* test 4-12, a single-unit van-type truck weighing 17,621 lb (8000 kg).

The TL-4 vehicle is a single-unit box-van truck impacting the railing at nominally 15 degrees and 50 mi/h (80 km/h). While containment is required, overturning of the vehicle 90 degrees is an acceptable test outcome.

CHAPTER 2. CRASH TEST PROCEDURES

TEST FACILITY

The test facilities at the Texas Transportation Institute's Proving Ground consist of a 2000-acre (809 hectare) complex of research and training facilities situated 10 mi (16 km) northwest of the main campus of Texas A&M University. The site, formerly an Air Force Base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and safety evaluation of roadside safety hardware. The site selected for placing of the bridge rail is along a wide out-of-service apron. The apron/runway consists of an unreinforced jointed-concrete pavement in 12.5 ft by 15 ft (3.8 m by 4.6 m) blocks nominally 8 to 12 inches (203 to 305 mm) deep. The aprons and runways are about 50 years old, and the joints have some displacement but are otherwise flat and level.

TEST ARTICLE

The TxDOT F411 bridge rail is a 10 inch (254 mm) wide by 3 ft-6 inch (1.1 m) high parapet wall with two 6 inch (152 mm) wide concrete rails that project 6 inches (152 mm) toward the traffic side. Considering the shape and location of the two concrete rails, the cross section of the F411 closely resembles the shape of the letter "F." The height of the lower rail is 1 ft-6 inches (0.5 m) from the top of the deck. The height of the upper rail is 3 ft-6 inches (1.1 m) from the top of the deck. The total width of the rail at the top is 1 ft-4 inches (0.4 m). In addition, the rail uses square aesthetic openings located between the projecting rails. These openings were 6 inches by 11 inches (279 mm) and were spaced 1 ft-6 inches (0.5 m) apart along the entire length of the 76-ft (23.2 m) long test specimen.

The rail was constructed atop an 8 inch (203 mm) thick by 2 ft-5 inch (0.7 m) wide bridge deck cantilever. Vertical reinforcement in the rail consisted of two #5 enclosed "S" Bars spaced 6 inches (152 mm) apart in the 12 inch by 10 inch (305 mm by 254 mm) posts. These bars were approximately 3 ft-4 inches (1.0 m) long and reinforced the entire height of the rail. In addition to the "S" Bars, #3 "W" bars reinforced the 6 inch by 6 inch (152 mm by 152 mm) projecting rail, and these bars were located 6 inches (152 mm) apart along the length of the installation. Longitudinal reinforcement consisted of three #5 bars at each projecting rail location with two #5 bars located with the "S" Bars at the base of the rail. The rail was anchored to the concrete deck cantilever by #5 "U" Bars spaced 9 inches (229 mm) apart, which projected upward approximately 8 inches (203 mm) from the top of the deck cantilever into the base of the rail. Transverse reinforcement in the deck cantilever consisted of #5 bars spaced 6 inches (152 mm) apart in the top and bottom layers. Longitudinal reinforcement in the bottom layer of the deck cantilever consisted of two #5 bars spaced 3 inches (76 mm) apart near the field side edge with a third adjacent bar spaced 12 inches (305 mm) away. Longitudinal reinforcement in the top layer of the deck cantilever consisted of #4 bars spaced 9 inches (229 mm) apart. All reinforcement was bare steel (not epoxy coated) and had a minimum yield strength of 60 ksi.

Concrete compressive strength tests performed on samples taken from pours made on the deck and rail revealed compressive strengths of 5399 psi and 4341 psi, respectively.

After construction of the F411 bridge rail under the TxDOT project, a modification was made to improve performance. The rail was modified by enclosing the open space beneath the lower rail with concrete, thus making it flush. Enclosing the bottom of the rail increased the effective surface contact area of the installation. Please refer to the drawings shown in Figure 1 for additional details. Figure 2 shows photographs of the completed installation.

CRASH TEST CONDITIONS

Three tests are required to evaluate longitudinal barriers, such as the Florida Jersey safety shaped bridge rail to TL-4 according to *NCHRP Report 350*, and are described below.

> ***NCHRP Report 350* test designation 4-10**: An 1806-lb (820 kg) passenger car impacting the bridge rail at the critical impact point (CIP) of the length of need at a nominal speed and angle of 62.2 mi/h (100 km/h) and 20 degrees. The test is intended to evaluate occupant risk and post-impact trajectory.

> ***NCHRP Report 350* test designation 4-11**: A 4405-lb (2000 kg) pickup truck impacting the bridge rail at the CIP of the length of need at a nominal speed and angle of 62.2 mi/h (100 km/h) and 25 degrees. The test is intended to evaluate strength of the section in containing and redirecting the 4405-lb (2000 kg) vehicle.

> ***NCHRP Report 350* test designation 4-12**: A 17,621-lb (8000 kg) single-unit truck impacting the bridge rail at the CIP of the length of need at a nominal speed and angle of 49.7 mi/h (80 km/h) and 15 degrees. The test is intended to evaluate strength of the section in containing and redirecting the 17,621-lb (8000 kg) vehicle.

The test reported herein corresponds to *NCHRP Report 350* test designation 4-12. The objective of this particular test was to evaluate the strength of the concrete parapet. According to *NCHRP Report 350* guidelines, the target impact point for this test was 4.9 ft (1.5 m) upstream of an opening in the F411.

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.

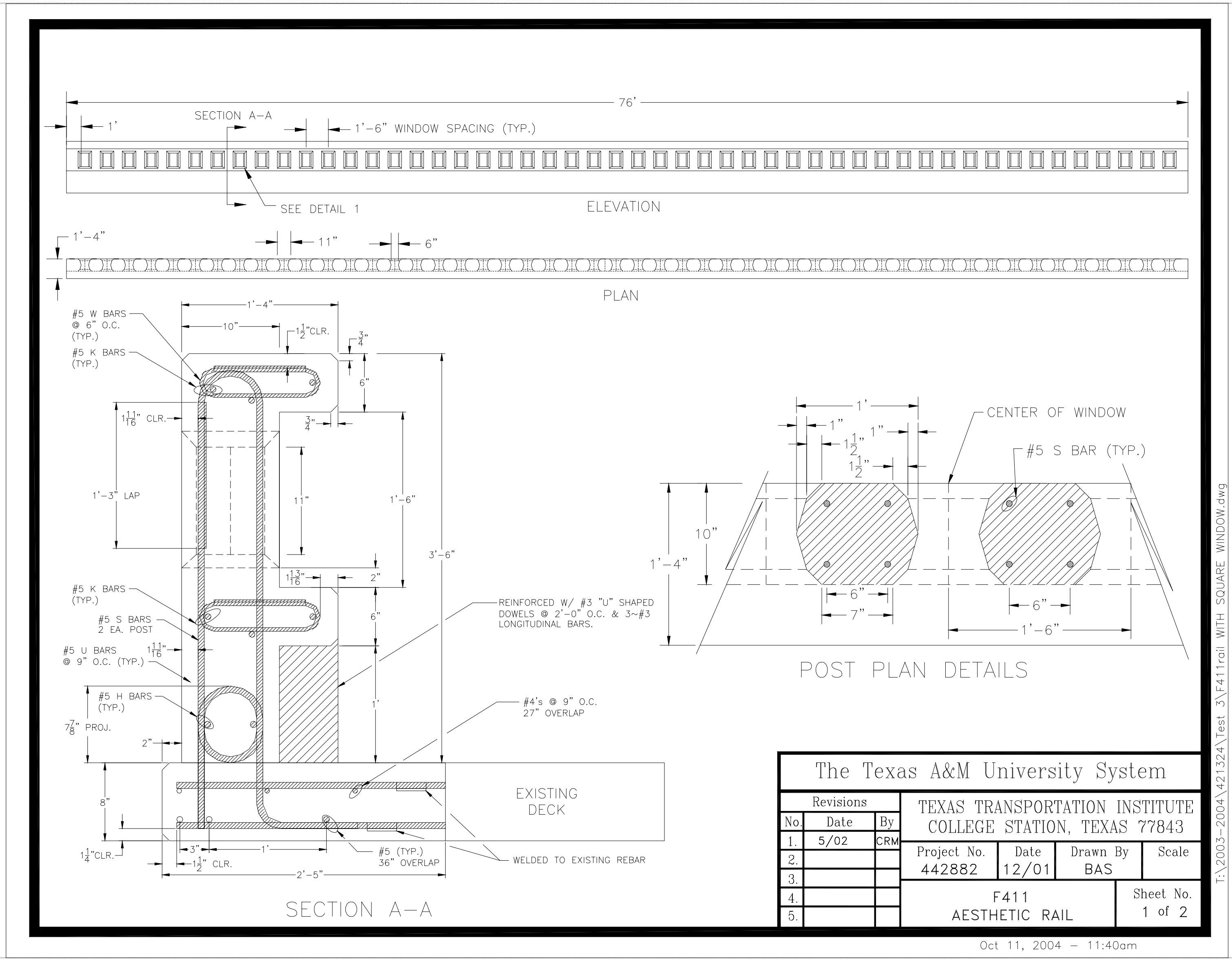


Figure 1. Details of the TxDOT F411 Bridge Rail.

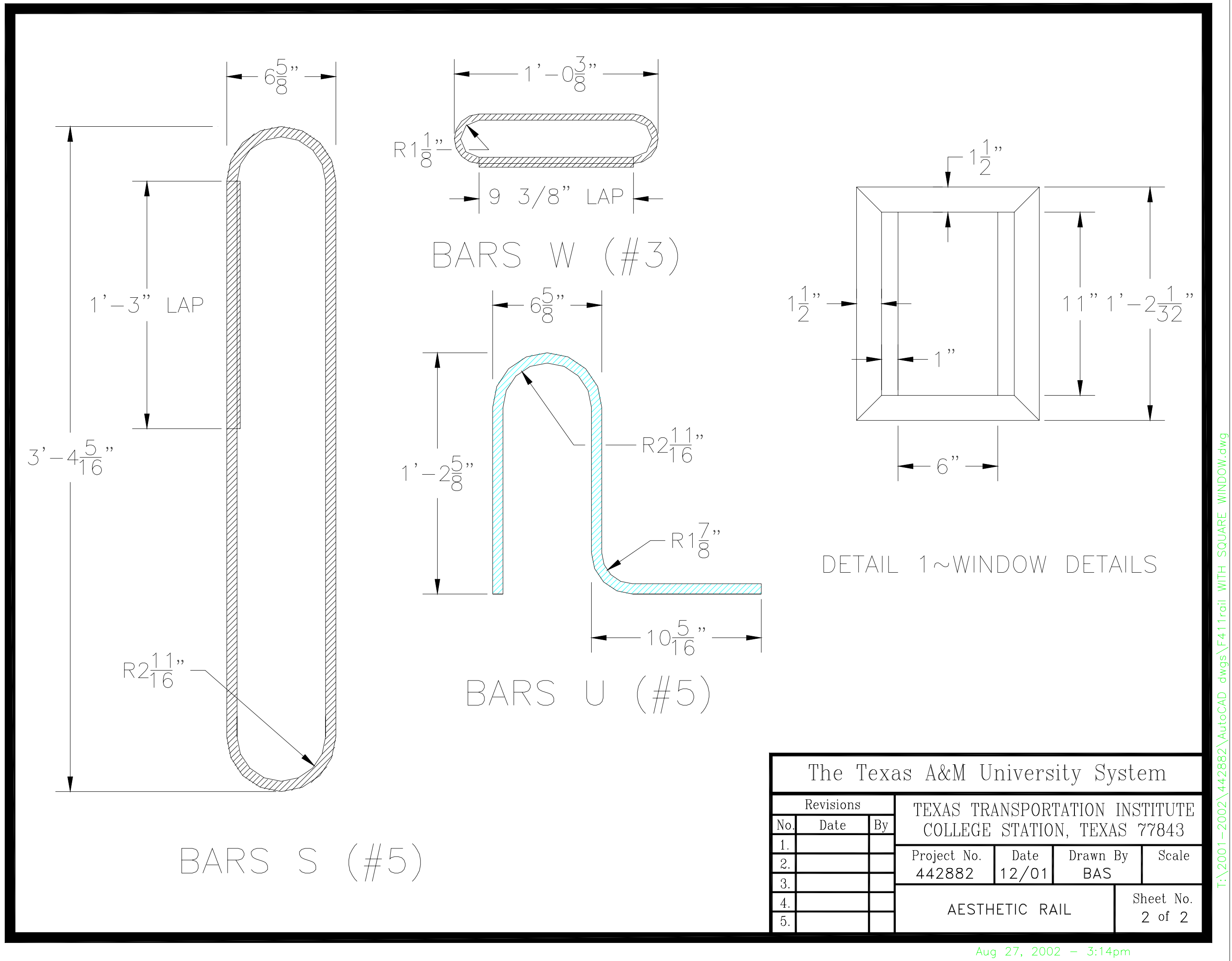
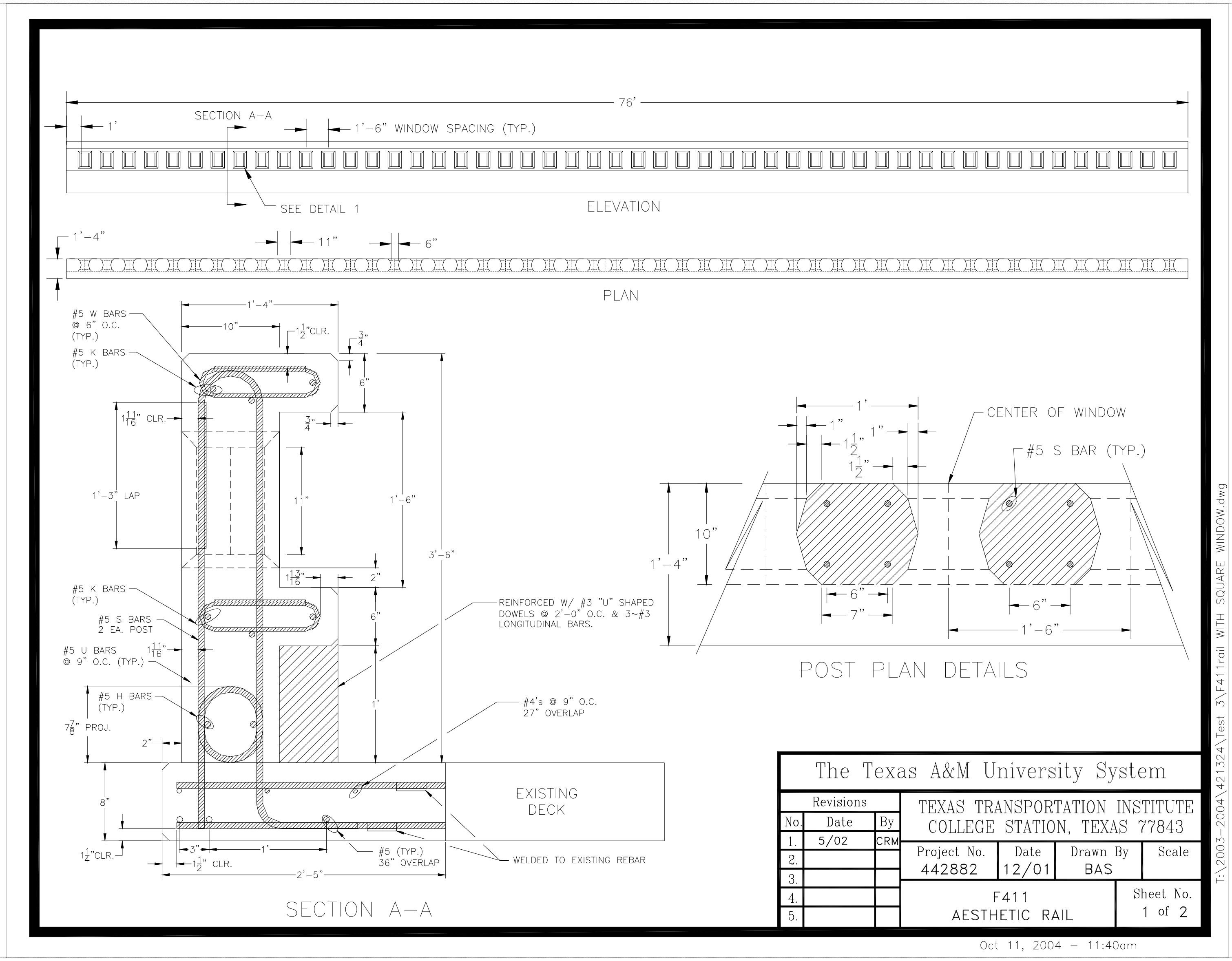


Figure 1. Details of the TxDOT F411 Bridge Rail (continued).



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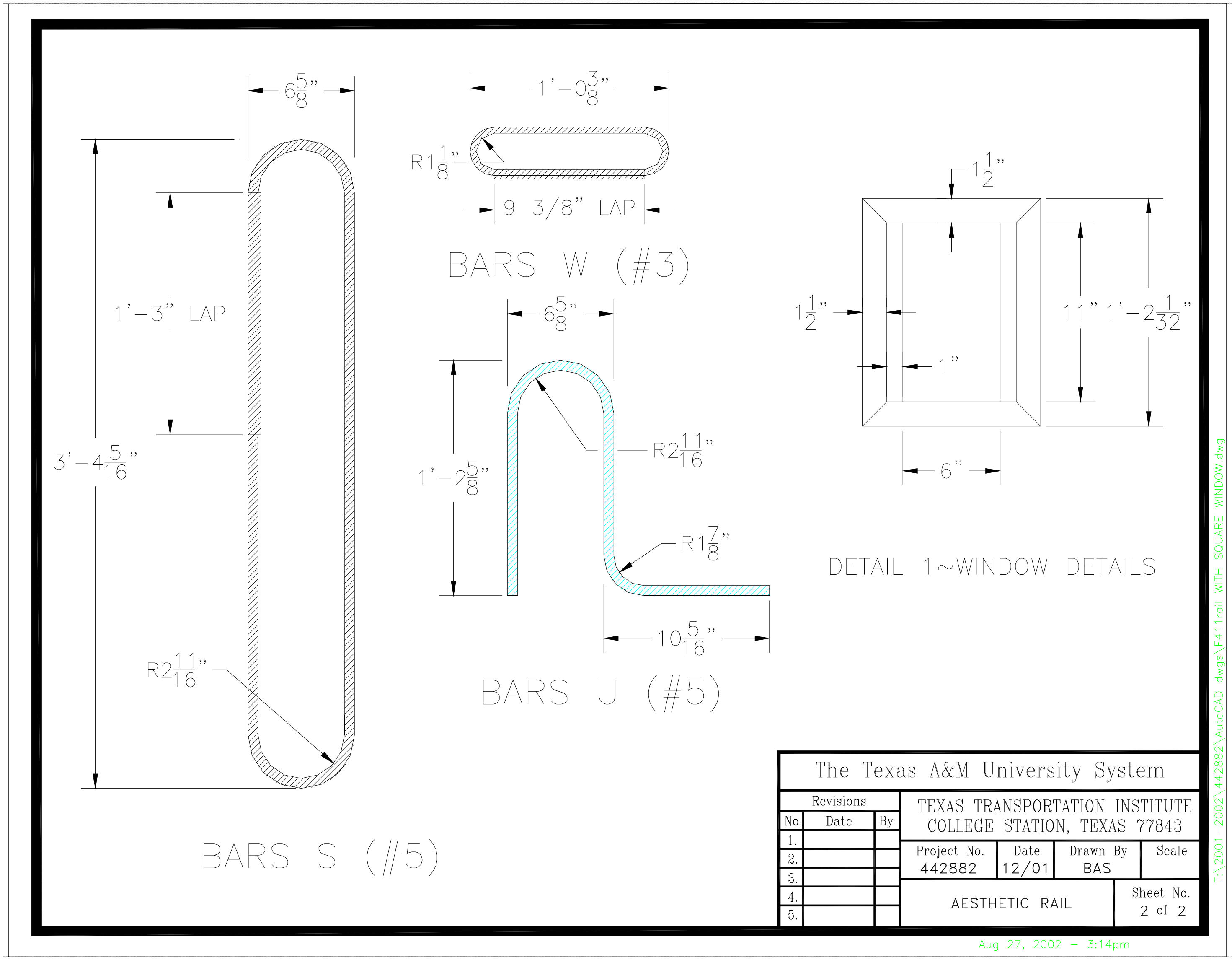


Figure 1. Details of the TxDOT F411 Bridge Rail (continued).

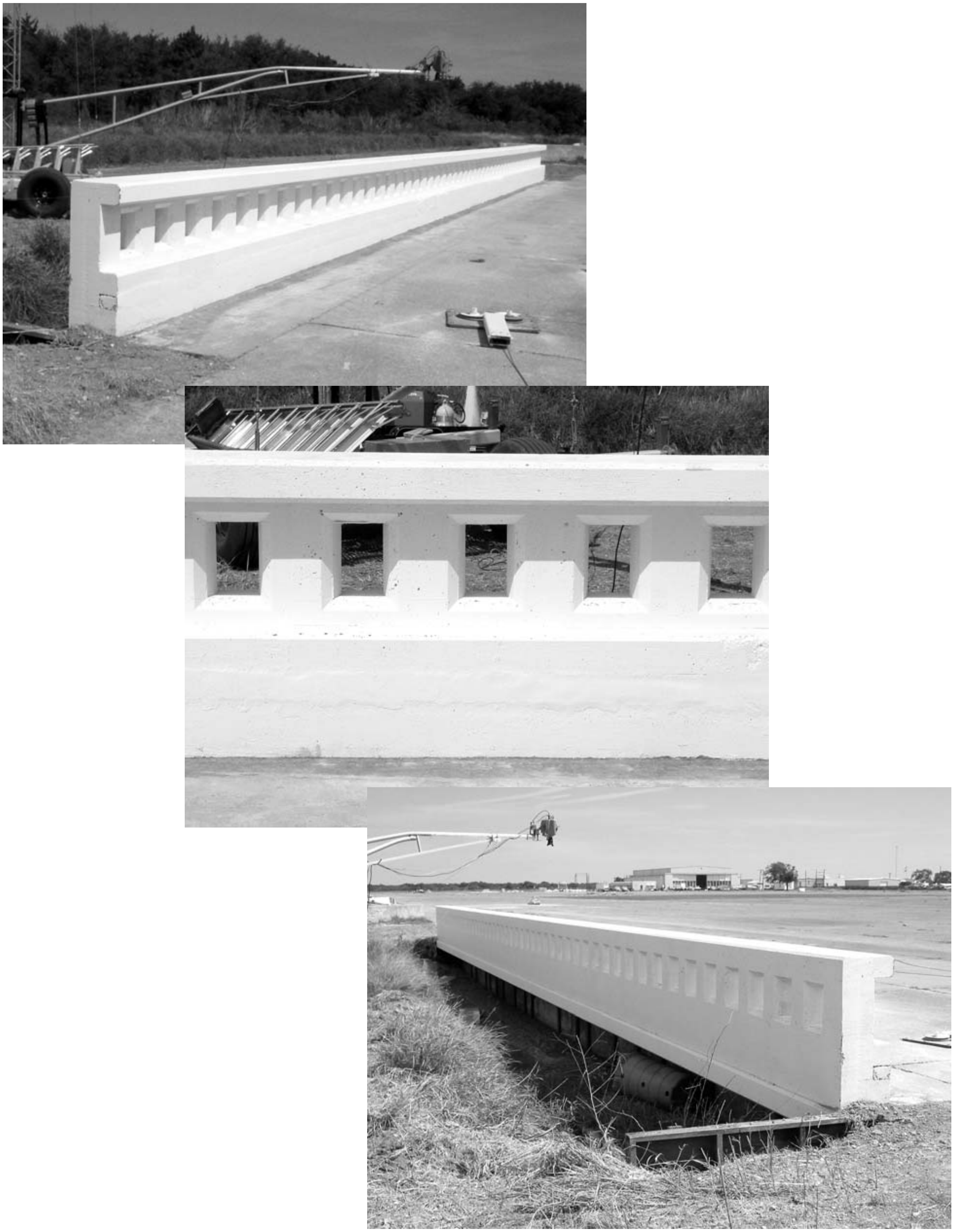


Figure 2. TxDOT F411 Bridge Rail before Test No. 421324-3.

EVALUATION CRITERIA

The crash tests performed were evaluated in accordance with *NCHRP Report 350*. As stated in *NCHRP Report 350*, "Safety performance of a highway appurtenance cannot be measured directly but can be judged on the basis of three factors: structural adequacy, occupant risk, and vehicle trajectory after collision." Accordingly, researchers used the safety evaluation criteria from Table 5.1 of *NCHRP Report 350* to evaluate the crash tests reported herein.

CHAPTER 3. CRASH TEST RESULTS

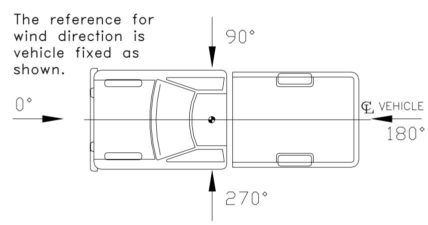
TEST NO. 421324-3 (*NCHRP REPORT 350* TEST DESIGNATION 4-12)

Test Vehicle

A 1984 Chevrolet C-60 single-unit box van, shown in Figures 3 and 4, was used for the crash test. Test inertia weight of the vehicle was 17,770 lb (8068 kg), and its gross static weight was 17,770 lb (8068 kg). The height to the lower edge of the vehicle bumper was 19.75 inches (502 mm), and it was 32.0 inches (813 mm) to the upper edge of the bumper. Figure 9 in Appendix B gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

Soil and Weather Conditions

The test was performed on the afternoon of August 13, 2004. Rainfall of 0.1 inch was recorded three days prior to the test. Weather conditions at the time of testing were as follows: Wind speed: 8 mi/h (13 km/h); Wind direction: 195 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); Temperature: 86°F (30°C), Relative humidity: 45 percent.



Test Description

The C-60 single-unit truck, traveling at a speed of 50.0 mi/h (80.5 km/h), impacted the TxDOT F411 bridge rail 19.5 ft downstream of the upstream end of the bridge rail at an impact angle of 16.8 degrees. At approximately 0.014 s after impact, the left front quarter panel of the vehicle began to deform. The vehicle began to redirect at 0.020 s. At 0.050 s, the left front wheel rim began to gouge into the rail, and at 0.117 s, the left front corner of the van box began to deform. At 0.314 s, the left rear of the van box contacted the rail, and the vehicle began traveling parallel to the rail at a speed of 43.5 mi/h (70.1 km/h). As the vehicle exited the view of the cameras at 0.594 s, the vehicle was traveling at a speed of 45.3 mi/h (72.9 km/h) and an exit angle of 1.6 degrees. The vehicle subsequently contacted a second barrier 135 ft (41 m) downstream of impact at 1.876 s after impact, where the vehicle came to rest. Figures 10 and 11 in Appendix C show sequential photographs of the test period.

Figure 3. Vehicle/Installation Geometrics for Test No. 421324-3.

Figure 4. Vehicle before Test No. 421324-3.

Damage to Test Installation

The TxDOT F411 bridge rail sustained cosmetic damage from contact with the vehicle. Figures 5 and 6 show damage to the bridge rail. There was spalling of concrete on the curb and upper rail from point of impact and extending for 39 inches (991 mm) downstream. The vehicle was in contact with the rail from point of impact until the end of the bridge rail. No measurable deflection of the rail was noted, and working width was 30.6 inches (777 mm).

Vehicle Damage

Much of the damage to the vehicle was due to the contact with the second barrier downstream of impact. Figure 7 shows the vehicle after impact.

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. These factors are not required for evaluation of this test and are provided for information purposes only. In the longitudinal direction, occupant impact velocity was 15.1 ft/s (4.6 m/s) at 0.244 s, maximum 0.010-s ridedown acceleration was -4.2 g's from 0.973 to 0.983 s, and the maximum 0.050-s average was -2.8 g's between 0.082 and 0.132 s. In the lateral direction, the occupant impact velocity was 9.2 ft/s (2.8 m/s) at 0.244 s, the highest 0.010-s occupant ridedown acceleration was 21.5 g's from 0.285 to 0.295 s, and the maximum 0.050-s average was -5.3 g's between 0.296 and 0.346 s. Figure 8 presents these data and other pertinent information from the test. Figures 12 through 19 in Appendix D present vehicle angular displacements and accelerations versus time traces.

Figure 5. After Impact Trajectory Path for Test No. 421324-3.

Figure 6. Installation after Test No. 421324-3.

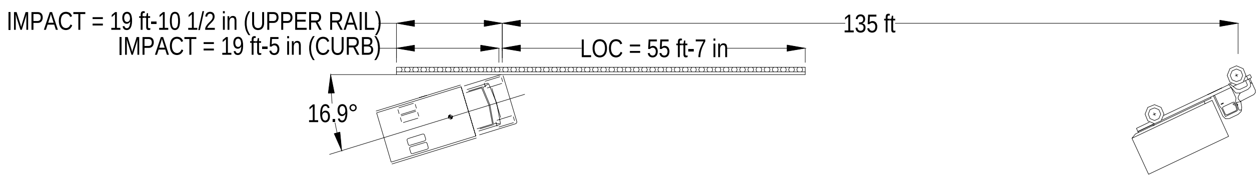
Figure 7. Vehicle after Test No. 421324-3.

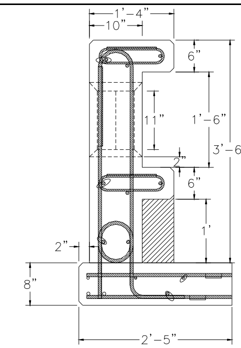
0.000 s

0.159 s

0.479 s

0.801 s





General Information
- Test Agency.............................. Texas Transportation Institute
- Test No. 421324-3
- Date 08-13-2004

Test Article
- Type.. Bridge Rail
- Name .... TxDOT F411 Bridge Rail
- Installation Length (ft (m)).......... 76.0 (23.2)
- Material or Key Elements .... Concrete Parapet Bridge Rail With Aesthetic Windows

Soil Type and Condition............ Concrete Footing

Test Vehicle
- Type.. Production
- Designation............................... 8000S
- Model.. 1984 Chevrolet C-60 Box Van
- Mass (lb (kg))
  - Curb....................................... 10450 (4744)
  - Test Inertial............................ 17770 (8068)
  - Dummy .... N/A
  - Gross Static............................ 17770 (8068)

Impact Conditions
- Speed (mi/h (km/h))..................50.0 (80.5)
- Angle (deg) 16.8

Exit Conditions
- Speed (mi/h (km/h))..................45.3 (72.9)
- Angle (deg) 1.6

Occupant Risk Values
- Impact Velocity (ft/s (m/s))
  - Longitudinal........................... 9.2 (2.8)
  - Lateral ....-3.6 (11.8)
- THIV (mi/h (km/h))....................9.0 (14.5)
- Ridedown Accelerations (g's)
  - Longitudinal...........................-3.6
  - Lateral 24.2
- PHD (g's).................................24.2
- ASI 0.69
- Max. 0.050-s Average (g's)
  - Longitudinal...........................-2.2
  - Lateral 6.1
  - Vertical 2.2

Test Article Deflections (in (mm))
- Dynamic .... None
- Permanent..................................... None
- Working Width 30.6 (777)

Vehicle Damage
- Exterior
  - VDS.. Not obtainable
  - CDC .... Not obtainable
  - Maximum Exterior Vehicle Crush (in (mm)) .... Not obtainable
- Interior
  - OCDI .... Not obtainable
  - Maximum Occupant Cmpt. Deformation (in (mm)) ... Not obtainable

Post-Impact Behavior
- (during 1.0 s after impact)
  - Max. Yaw Angle (deg)................ 1.1
  - Max. Pitch Angle (deg)................ -3.8
  - Max. Roll Angle (deg) 18.4

Figure 8. Summary of Results for *NCHRP Report 350* Test 4-12 on the TxDOT F411 Bridge Rail.

CHAPTER 4. SUMMARY AND CONCLUSIONS

ASSESSMENT OF TEST RESULTS

An assessment of the test based on the applicable *NCHRP Report 350* safety 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 TxDOT F411 bridge rail contained and redirected the single-unit truck. The vehicle did not penetrate, underride, or override the installation. No measurable deflection was noted. (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 to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Occupant compartment measurements were not obtainable, but it was determined that they were minimal, if any. (PASS)

G. It is preferable, although not essential, that the vehicle remain upright during and after the collision.

Results: The vehicle remained upright during the collision event. However, the vehicle rolled 90 degrees after exiting the test site. (PASS)

Vehicle Trajectory

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

Results: The vehicle did not intrude into adjacent traffic lanes. (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: Exit angle at loss of contact was 1.6 degrees, which was 9 percent of the impact angle. (PASS)

The following supplemental evaluation factors and terminology, as presented in the Federal Highway Administration (FHWA) memo entitled "ACTION: Identifying Acceptable Highway Safety Features," were used for visual assessment of test results (4). Factors underlined below pertain to the results of the crash test reported herein.

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*

CONCLUSIONS

The TxDOT F411 bridge rail performed acceptably for *NCHRP Report 350* test 4-12, as shown in Table 1.

Table 1. Performance Evaluation Summary for *NCHRP Report 350* Test 4-12 on the TxDOT F411 Bridge Rail.

Test Agency: Texas Transportation Institute | Test No.: 421324-3 | Test Date: 08-13-2004

***NCHRP Report 350* 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 TxDOT F411 bridge rail contained and redirected the single-unit truck. The vehicle did not penetrate, underride, or override the installation. No measurable deflection was noted.	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 undue hazard to others in the area. Occupant compartment measurements were not obtainable, but it was determined that they were minimal, if any.	Pass
G. It is preferable, although not essential, that the vehicle remain upright during and after collision.	The vehicle remained upright during the collision event. However, the vehicle rolled after exiting the test site.	Pass*
Vehicle Trajectory		
K. After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	The vehicle did not intrude into adjacent traffic lanes.	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.	Exit angle at loss of contact was 1.6 degrees, which was 9 percent of the impact angle.	Pass*

* Criteria G, K, and M are preferable, but not required.

CHAPTER 5. IMPLEMENTATION STATEMENT

Based on the performance of the F411 bridge rail in the full-scale crash test to TL-4 test conditions, the F411 may be used where containment of 18,000 lb single-unit trucks is desired. Working drawings of this bridge rail have been developed by the Bridge Division of TxDOT.

REFERENCES

1. American Association of State Highway and Transportation Officials, *AASHTO LRFD Bridge Design Specifications*, AASHTO Subcommittee on Bridges and Structures, Washington, D.C., May 2001.

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. D. L. Bullard, W. F. Williams, W. L. Menges, and R. R. Haug. *Design and Evaluation of the TxDOT F411 and T77 Aesthetic Bridge Rails*, Texas Department of Transportation, Texas Transportation Institute, the Texas A&M University System, College Station, Texas, October 2002.

4. Federal Highway Administration Memorandum from the Director, Office of Engineering, entitled: "ACTION: Identifying Acceptable Highway Safety Features," dated July 25, 1997.

APPENDIX A. CRASH TEST AND DATA ANALYSIS PROCEDURES

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 ±100 g 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 resistive 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 Society of Automotive Engineers (SAE) J211 class 180 phaseless digital filtering and vehicle impact velocity.

All accelerometers are calibrated annually according to the SAE J211 *4.6.1* by means of an 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 are 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 millisecond (ms) average ridedown acceleration. WinDigit calculates change in vehicle velocity at the end of a given impulse period. In addition, WinDigit computes maximum average accelerations over 50 ms intervals in each of the three directions. 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 system being initial impact.

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 were used to record and document 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 the vehicle’s brakes were activated to bring it to a safe and controlled stop.

APPENDIX B. TEST VEHICLE PROPERTIES AND INFORMATION

Date: 8-13-2004 Test No.: 421324-3 VIN No.: 1GBG6D1A4EV101410

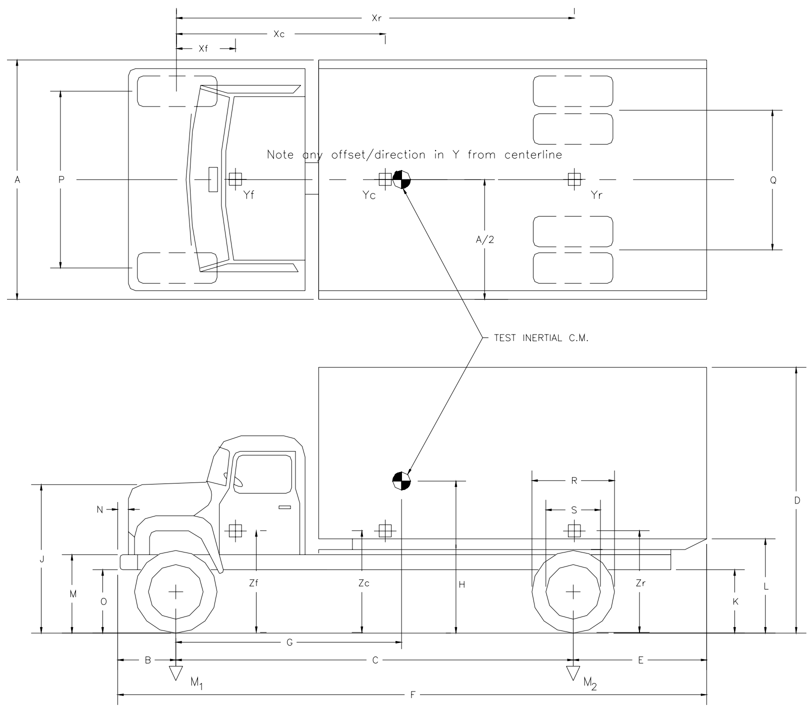
Year: 1984 Make: Chevrolet Model: C-60 Box Van

Tire Inflation Pressure: ________ Odometer: 156228 Tire Size: 11 R 22.5

Describe any damage to the vehicle prior to test: ________

Denotes accelerometer location.

NOTES: ________



Accelerometer Locations (mm):

	x	y	z
f			
c			
r			

Geometry (in)

A	96	E	87.5	J	61	N	3	R	41.5
B	30	F	320.5	K	29.9	O	19.75	S	23.25
C	203	G	123.6	L	46.5	P	75.5		
D	144	H		M	32	Q	71		

Mass (lb)	Curb	Test Inertial	Gross Static
M_1	4320	6950	
M_2	6130	10820	
M_{Total}	10450	17770	

Mass Distribution (lb): LF: 3480 RF: 3470 LR: 5810 RR: 5010

Figure 9. Vehicle Properties for Test No. 421324-3.

APPENDIX C. SEQUENTIAL PHOTOGRAPHS

0.000 s

0.040 s

0.159 s

0.323 s

Figure 10. Sequential Photographs for Test No. 421324-3 (Overhead and Frontal Views).

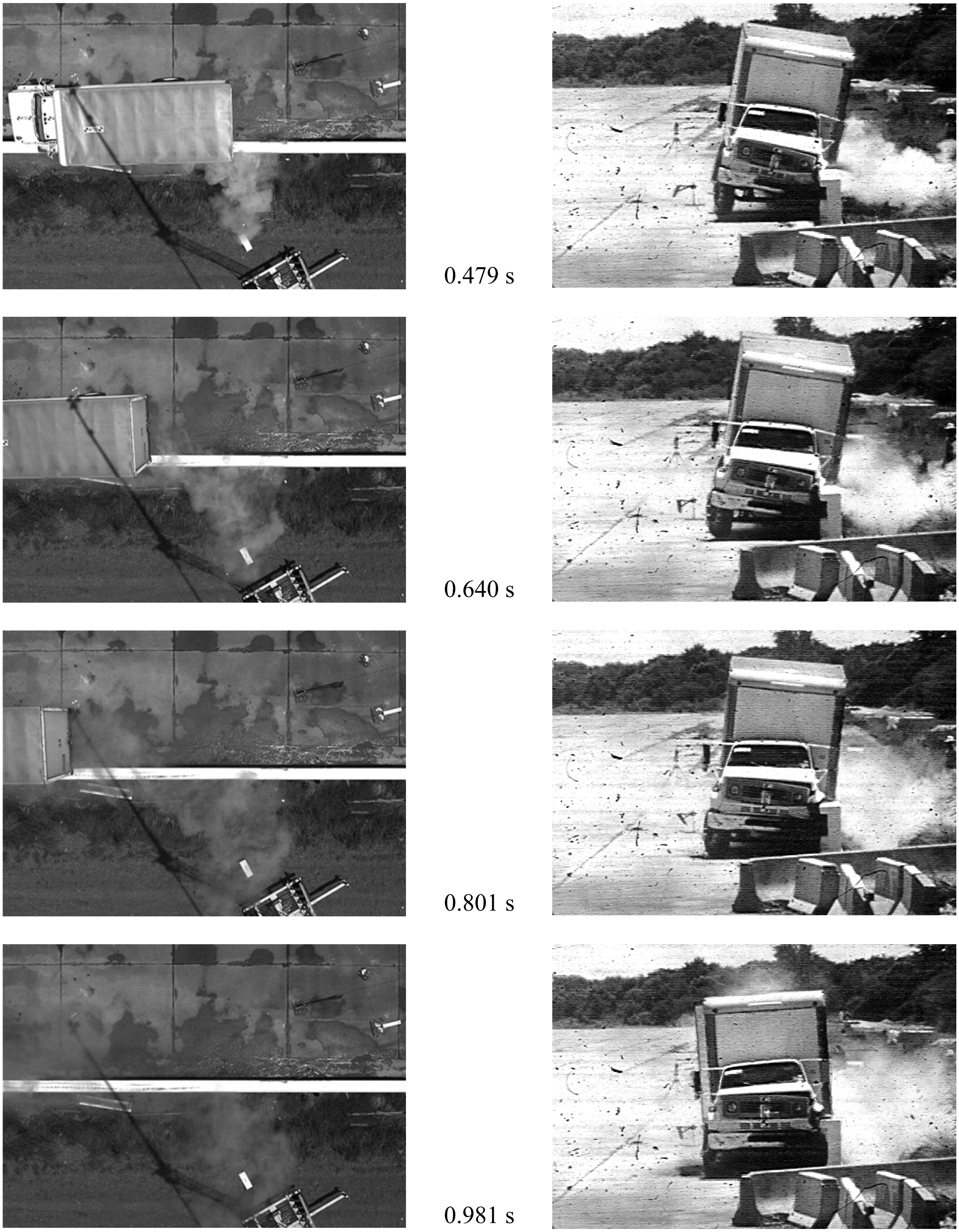
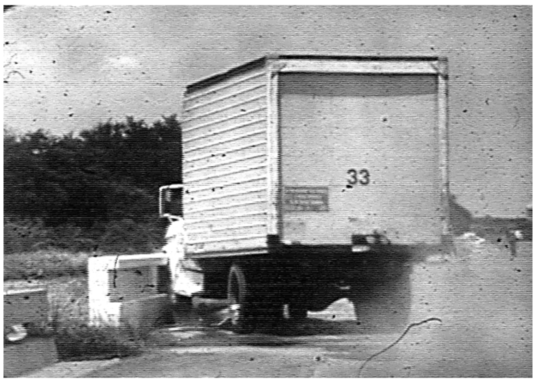


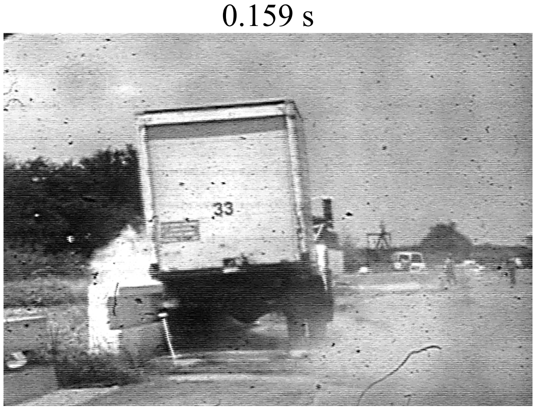
Figure 10. Sequential Photographs for Test No. 421324-3 (Overhead and Frontal Views) (Continued).

0.000 s



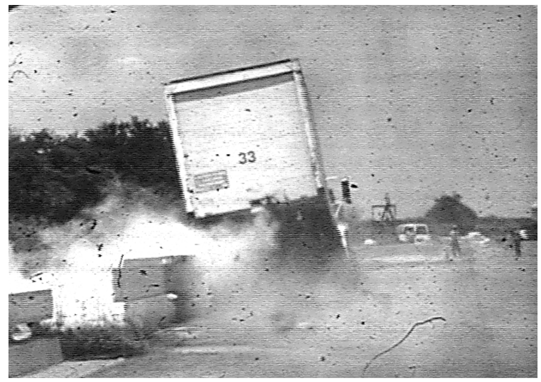
0.040 s

0.159 s

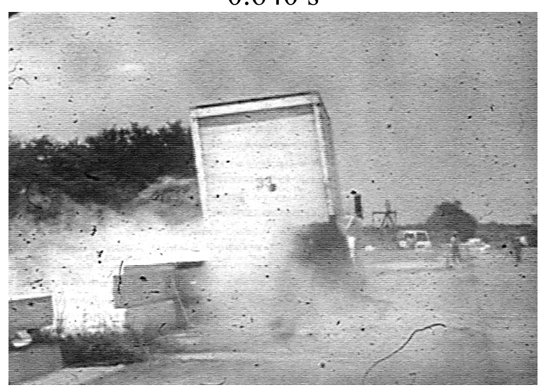


0.323 s

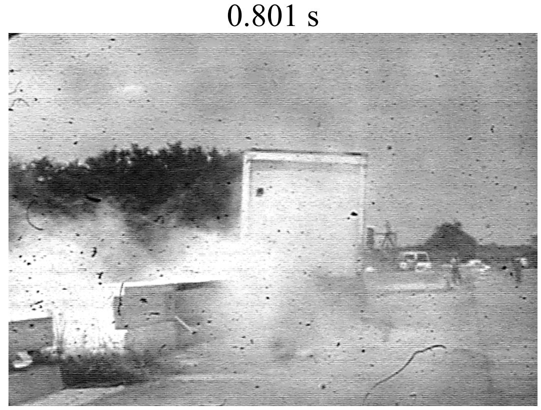
0.479 s



0.640 s



0.801 s



0.981 s

Figure 11. Sequential Photographs for Test No. 421324-3 (Rear View).

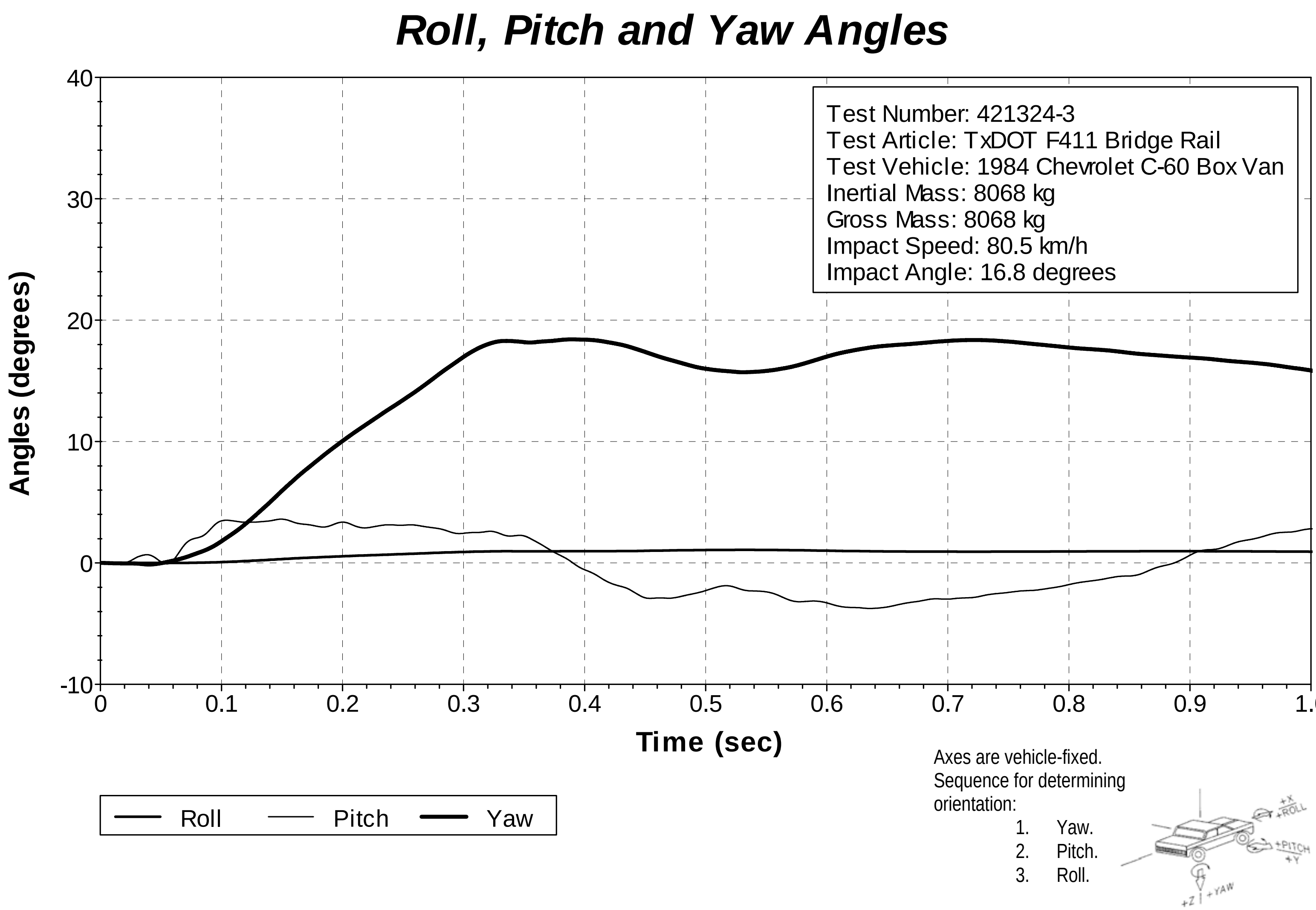


Figure 12. Vehicle Angular Displacements for Test No. 421324-3.

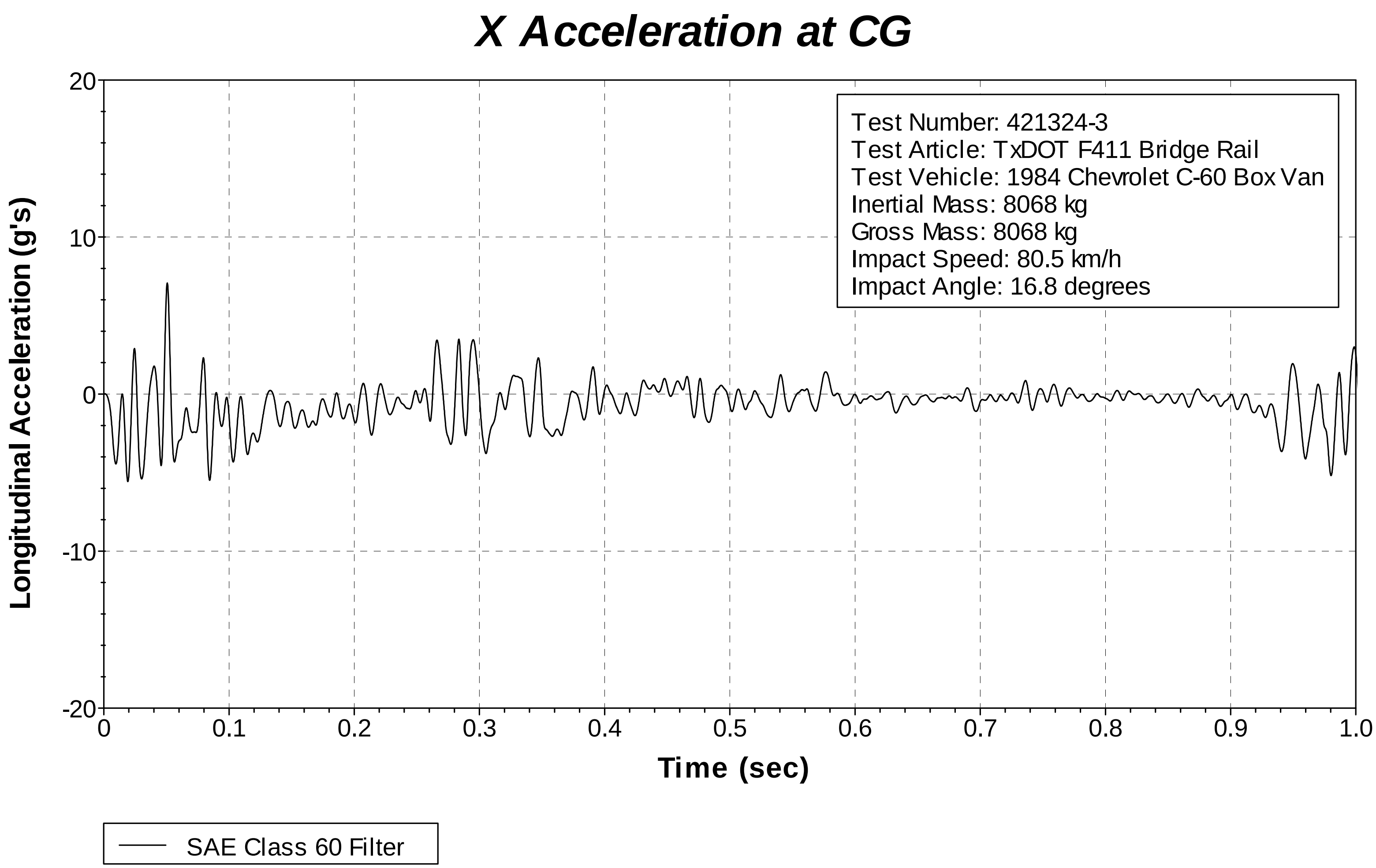


Figure 13. Vehicle Longitudinal Accelerometer Trace for Test No. 421324-3 (Accelerometer Located at Center of Gravity).

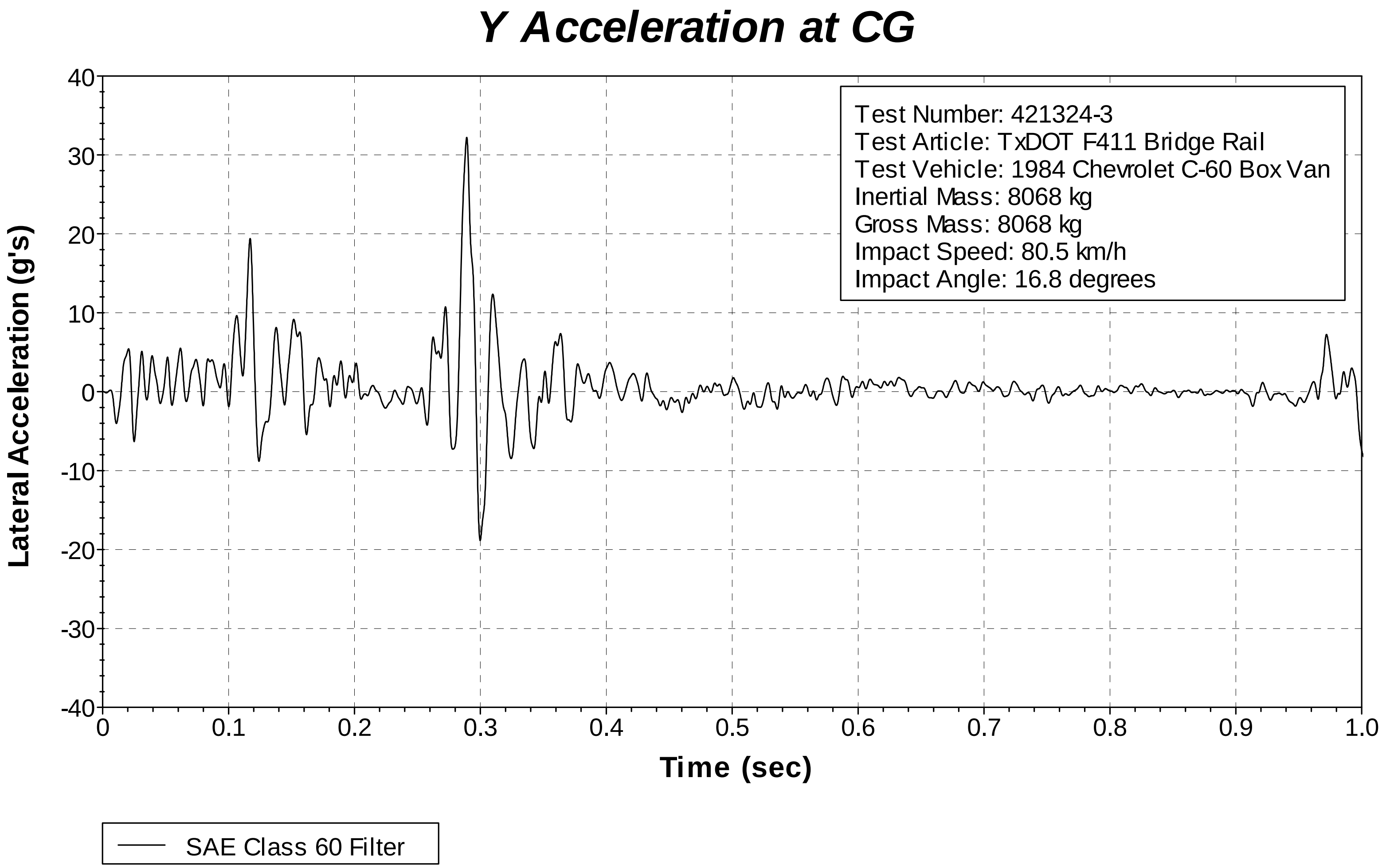


Figure 14. Vehicle Lateral Accelerometer Trace for Test No. 421324-3 (Accelerometer Located at Center of Gravity).

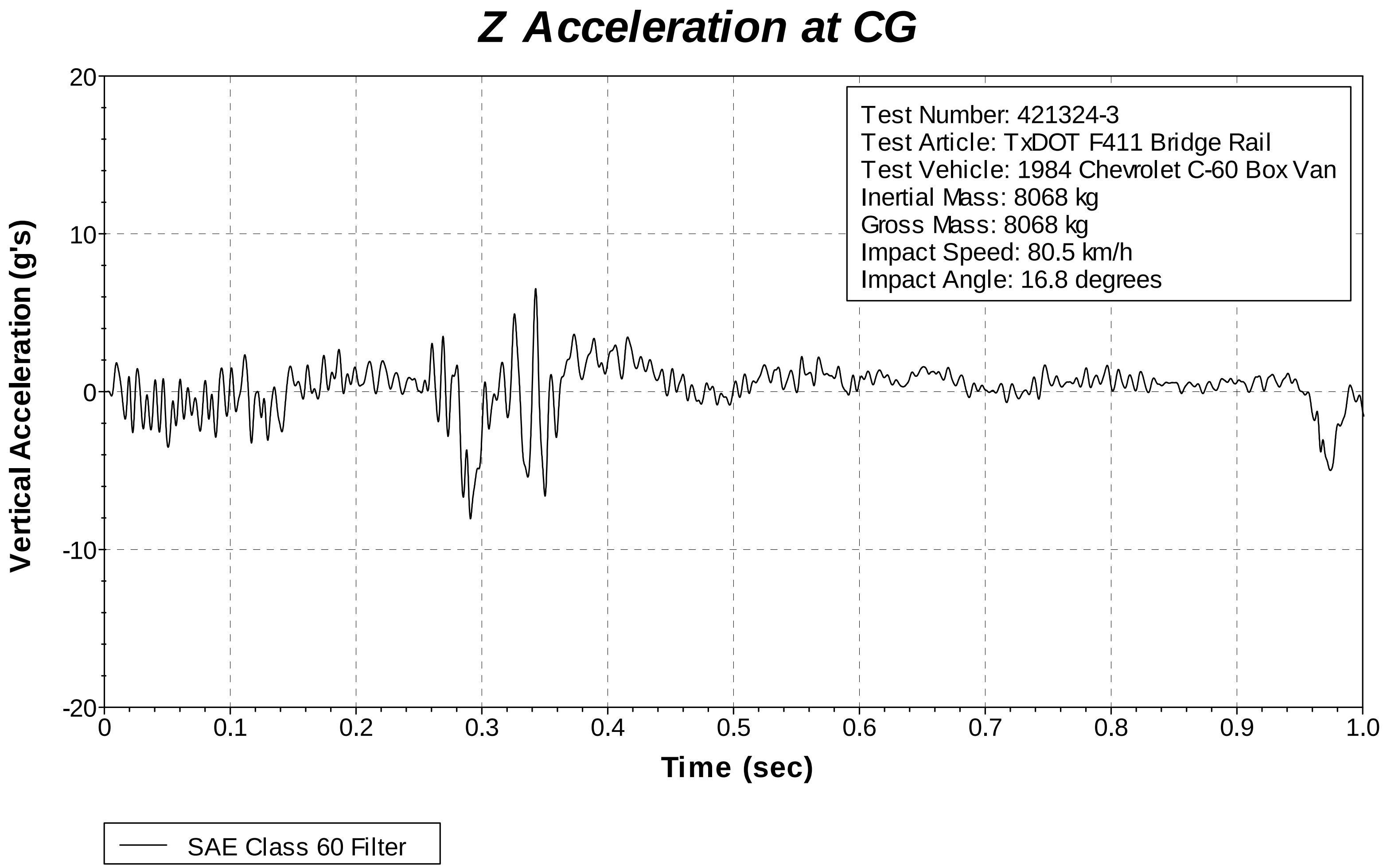


Figure 15. Vehicle Vertical Accelerometer Trace for Test No. 421324-3 (Accelerometer Located at Center of Gravity).

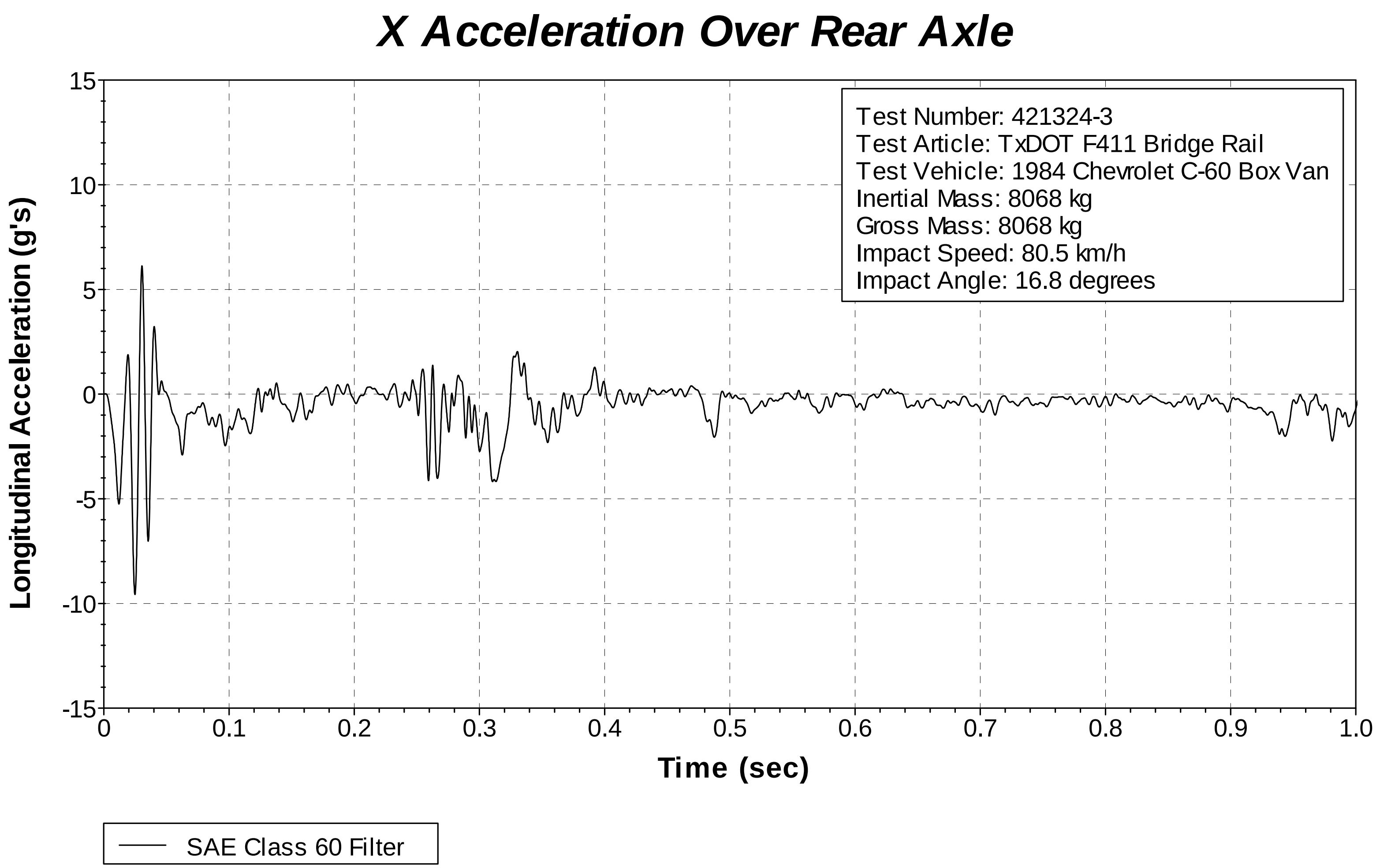


Figure 16. Vehicle Longitudinal Accelerometer Trace for Test No. 421324-3 (Accelerometer Located Over Rear Axle).

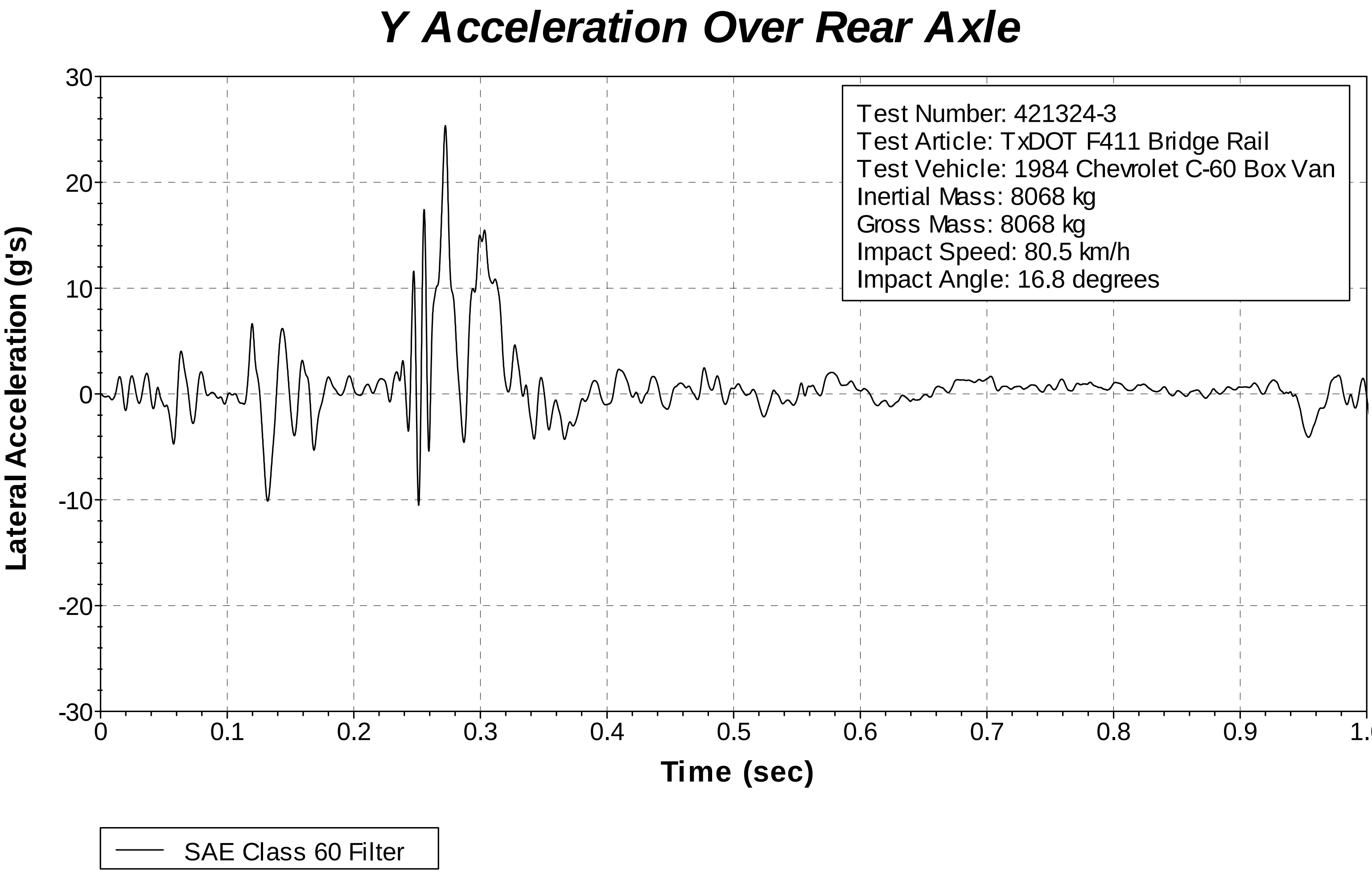


Figure 17. Vehicle Lateral Accelerometer Trace for Test No. 421324-3 (Accelerometer Located Over Rear Axle).

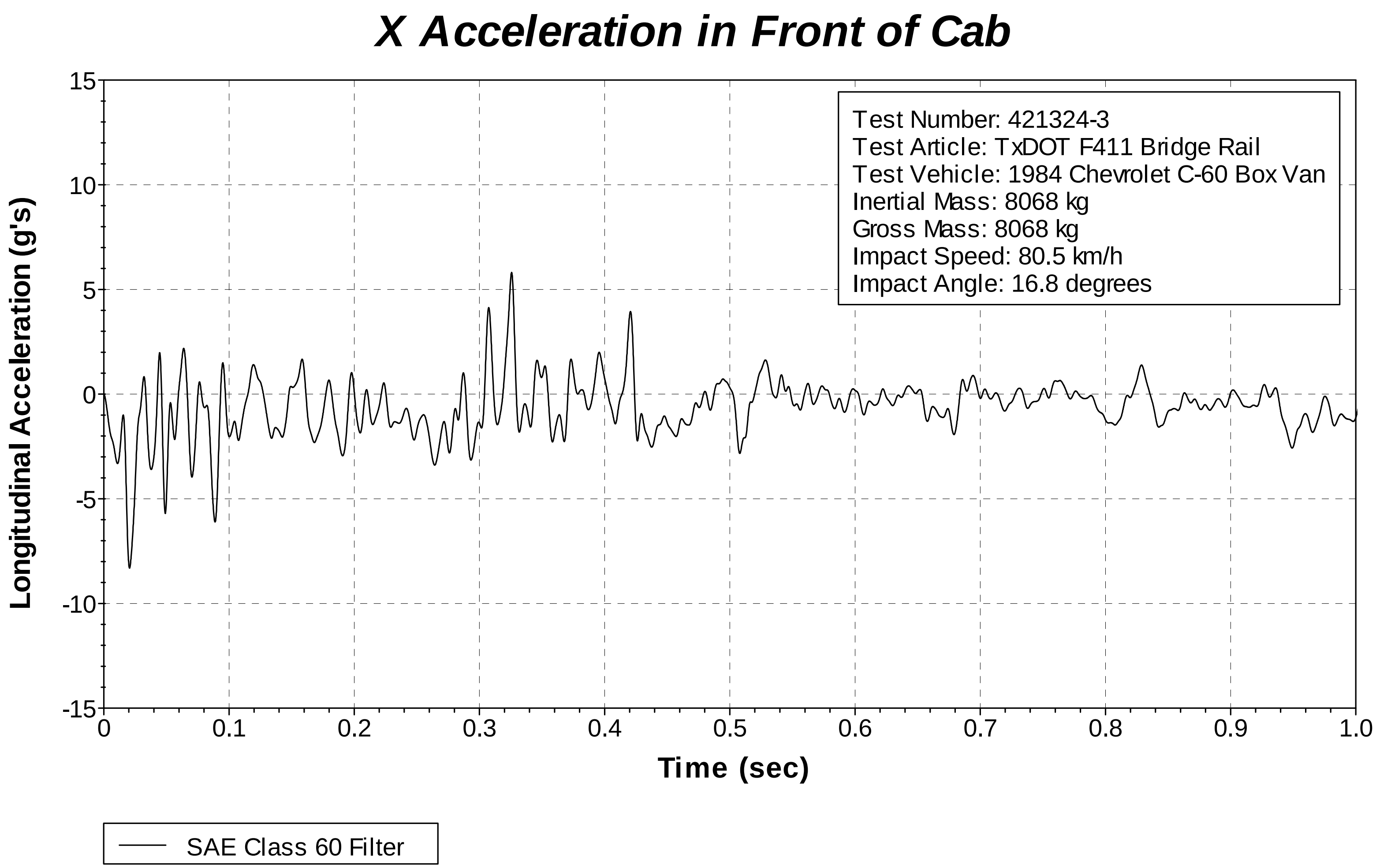


Figure 18. Vehicle Longitudinal Accelerometer Trace for Test No. 421324-3 (Accelerometer Located in Front of Cab).

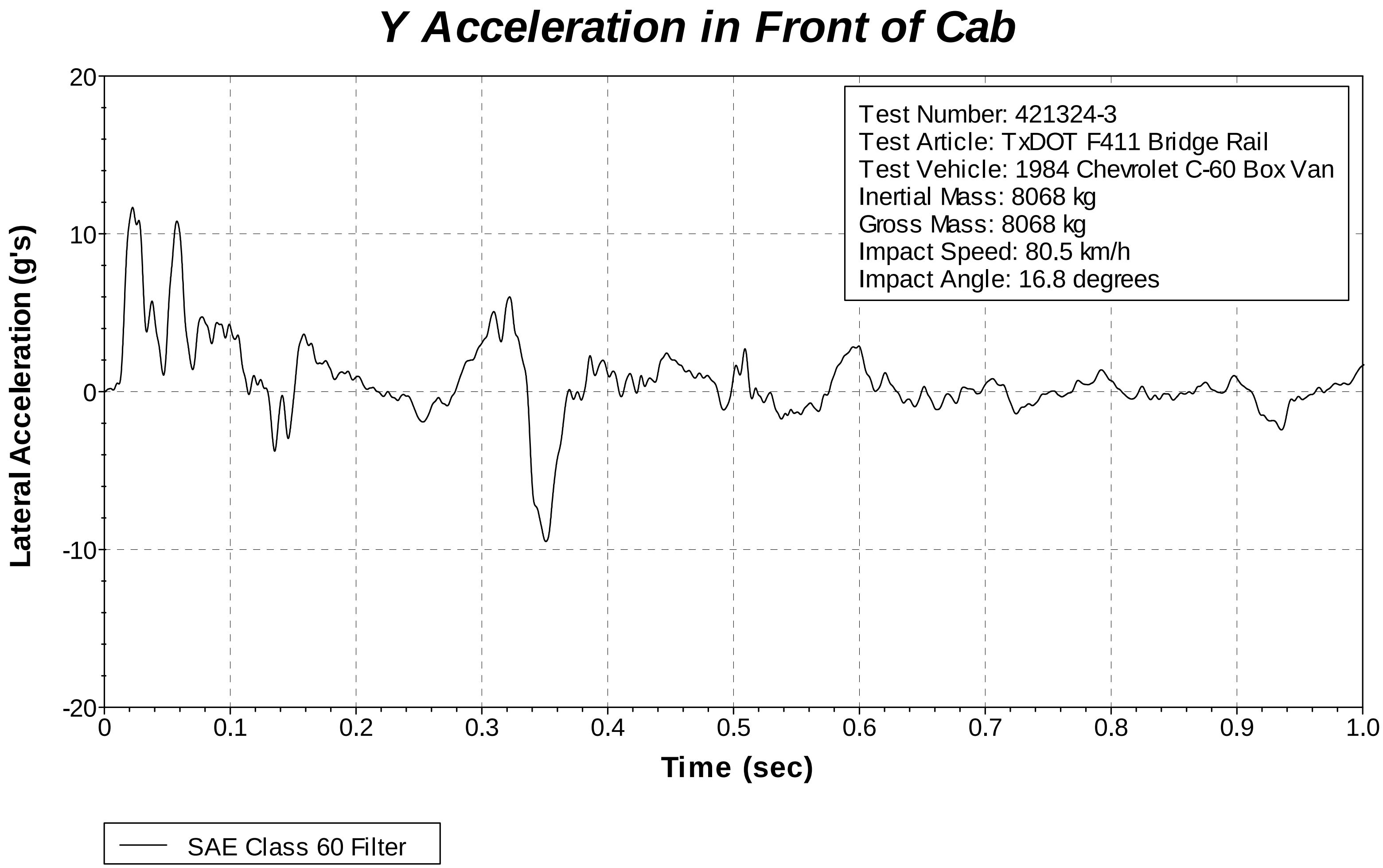


Figure 19. Vehicle Lateral Accelerometer Trace for Test No. 421324-3 (Accelerometer Located in Front of Cab).