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16. Abstract <p>The crash performance of the TxDOT Type 2 precast concrete traffic barrier (PCTB(1)-90) with joint type A is unproven with respect to the <i>National Cooperative Highway Research Program (NCHRP) Report 350</i> guidelines. Under this project, TTI researchers and TxDOT engineers worked together to evaluate the crash performance of this barrier system and determine if cost effective modifications can be made to the barrier to meet <i>NCHRP Report 350</i> criteria and limit dynamic deflections to practical levels.</p> <p>The research team performed various analyses to help assess the ability of the selected barrier systems to meet <i>NCHRP Report 350</i> impact performance criteria prior to conducting the full-scale crash testing. Computer simulation techniques were used to support the analysis efforts. The simulation provided a more detailed understanding of the three-dimensional impact response of the barrier design. The program utilized in the computer modeling efforts was LS-DYNA. LS-DYNA is a general-purpose, explicit finite element code used to analyze the nonlinear dynamic response of three-dimensional inelastic structures. This code is capable of capturing many of the complex interactions that occur when a vehicle impacts a roadside safety structure. Limitations in the ability of existing material models to accurately capture concrete fracture and failure led to some simplifying assumptions regarding the model of the grid-slot connection. Nonetheless, the simulations assisted in the impact performance evaluation of the existing and modified designs.</p> <p>During the project, several retrofit connection designs were conceptualized for the objective of reducing dynamic barrier deflections. TxDOT engineers and TTI researchers developed these design modifications jointly. When developing these retrofit design options, factors such as impact performance, cost, ease of field installation, and aesthetics were considered.</p> <p>Three full-scale crash tests were performed to evaluate the safety performance of the selected barrier systems. The purpose of the testing was to assess compliance of the "grid-slot" portable concrete barrier (PCB) with <i>NCHRP Report 350</i> and examine alternatives for reducing dynamic deflection. The tests were performed in the order of the cost effectiveness of the barrier modifications to investigate the relative improvement in crash performance.</p> <p>All three crash tests satisfied <i>NCHRP Report 350</i> evaluation criteria. Although each barrier configuration met <i>NCHRP Report 350</i> guidelines, researchers observed variations in performance associated with the different connection details.</p>					
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EVALUATION OF TEXAS GRID-SLOT PORTABLE CONCRETE BARRIER SYSTEM

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CHAPTER 1. INTRODUCTION

BACKGROUND

On July 16, 1993, the Federal Highway Administration formally adopted the new performance evaluation guidelines for highway safety features set forth in National Cooperative Highway Research Program (*NCHRP Report 350*).⁽¹⁾ The ruling requires that highway safety appurtenance used on new construction projects on the National Highway System (NHS) meet these new guidelines. Among the changes adopted by *NCHRP Report 350* was the selection of a pickup truck as a new design test vehicle. The pickup is intended to represent the increasing population of light trucks (e.g., pickups, vans, sport utility vehicles (SUVs)) in the vehicle fleet, which now equal passenger cars in percentage of new vehicle sales. Consequently, to demonstrate compliance with *NCHRP Report 350*, the impact performance of many roadside safety features has had to be re-evaluated.

Under this research project, various barrier performance and placement issues are being investigated. This report summarizes the testing and evaluation of TxDOT's Type 2 precast concrete traffic barrier (PCTB(1)-90) with joint type A. This portable barrier system is constructed using precast segments that are 30 ft in length and have a standard New Jersey safety shape profile. The barrier segments are 2 ft-8 in. in height, 2 ft-3 ¼ in. wide at the base, and 8 in. wide at the top. The joint connection involves placing a prefabricated tiebar grid into a slot formed into the ends of adjacent concrete barrier segments. The slots are 2-in. wide, 9-in. long, and extend to a depth of approximately 22 in. from the top of the barrier. The segments are connected by aligning the slots on adjoining barrier ends and inserting an 18-in. square steel bar grid (Slotted Design) fabricated from three 1-in. diameter steel tiebars in the horizontal direction and two ½-in. diameter tiebars in the vertical direction. The tiebars can be fabricated from smooth round bar stock or deformed reinforcing steel. The vertical and horizontal tiebars are welded together at all points of contact. For ease of installation of the steel grid, the barriers are located such that a ½-in. gap is present between the adjoining barriers. TxDOT standard drawings PCTB(1)-90 and PCTB(2)-85 entitled "Precast Concrete Traffic Barrier Type 2" provide additional information on the barrier segments and steel bar connection grid.

OBJECTIVES/SCOPE OF RESEARCH

The impact performance of temporary concrete barriers is influenced by a number of variables that 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 and/or result in failure of the connection and penetration of the vehicle through the barrier.

The crash performance of the TxDOT Type 2 PCTB(1)-90 with joint type A is unproven with respect to the *NCHRP Report 350* guidelines. Under this project, TTI researchers and TxDOT engineers worked together to evaluate the crash performance of this barrier system and determine if cost effective modifications can be made to the barrier to meet *NCHRP Report 350* criteria and limit dynamic deflections to practical levels.

The research team performed various analyses to help assess the ability of the selected barrier systems to meet *NCHRP Report 350* impact performance criteria prior to conducting the full-scale crash testing. Computer simulation techniques were used to support the analysis efforts. The simulation provided a more detailed understanding of the three-dimensional impact response of the barrier design. The program utilized in the computer modeling efforts was LS-DYNA. LS-DYNA is a general-purpose, explicit finite element code used to analyze the nonlinear dynamic response of three-dimensional inelastic structures. This code is capable of capturing many of the complex interactions that occur when a vehicle impacts a roadside safety structure. Limitations in the ability of existing material models to accurately capture concrete fracture and failure led to some simplifying assumptions regarding the model of the grid slot connection. Nonetheless, the simulations assisted in the impact performance evaluation of the existing and modified designs.

During the project, several retrofit connection designs were conceptualized for the objective of reducing dynamic barrier deflections. TxDOT engineers and TTI researchers developed these design modifications jointly. When developing these retrofit design options, factors such as impact performance, cost, ease of field installation, and aesthetics were considered.

Three full-scale crash tests evaluated the safety performance of the selected barrier systems. The purpose of the testing was to assess compliance of the “grid-slot” portable concrete barrier (PCB) with *NCHRP Report 350* and examine alternatives for reducing dynamic deflection. The tests were performed in the order of the cost effectiveness of the barrier modifications to investigate the relative improvement in crash performance.

CHAPTER 2. CRASH TEST PROCEDURES

TEST FACILITY

The test facilities at the Texas Transportation Institute's Proving Ground consist of an 809-hectare complex of research and training facilities situated 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 the installation of the temporary concrete barrier is along an out-of-service runway apron. The runway apron consists of an unreinforced jointed concrete pavement cast in 12.5 ft by 15 ft blocks that are nominally 8 to 12 in. deep. The aprons and runways are about 50 years old and the joints have some displacement, but are otherwise flat and level. [Figure 1](#) shows the general layout of the temporary concrete barrier.

CRASH TEST CONDITIONS

NCHRP Report 350 typically requires two tests for test level 3 (TL-3) evaluation of longitudinal barriers:

NCHRP Report 350 test designation 3-10: This test involves an 820-kg passenger vehicle (820C) impacting the length-of-need (LON) of the barrier at a nominal speed and angle of 100 km/h and 20 degrees. 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: The test involves a 2000-kg pickup truck (2000P) impacting the LON of the barrier at a nominal speed and angle of 100 km/h and 25 degrees. The test is intended to evaluate strength of the section in containing and redirecting the 2000P vehicle.

All three tests reported herein correspond to *NCHRP Report 350* test designation 3-11. This pickup truck test is considered to be the critical test in the recertification of an existing barrier under *NCHRP Report 350*. The critical impact point for the barrier was chosen according to guidelines contained in *NCHRP Report 350*. The target impact point for each test was 3.9 ft upstream of the joint nearest the one-third point of the test installation, which with reference to [Figure 1](#), is the joint between segments 4 and 5.

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.

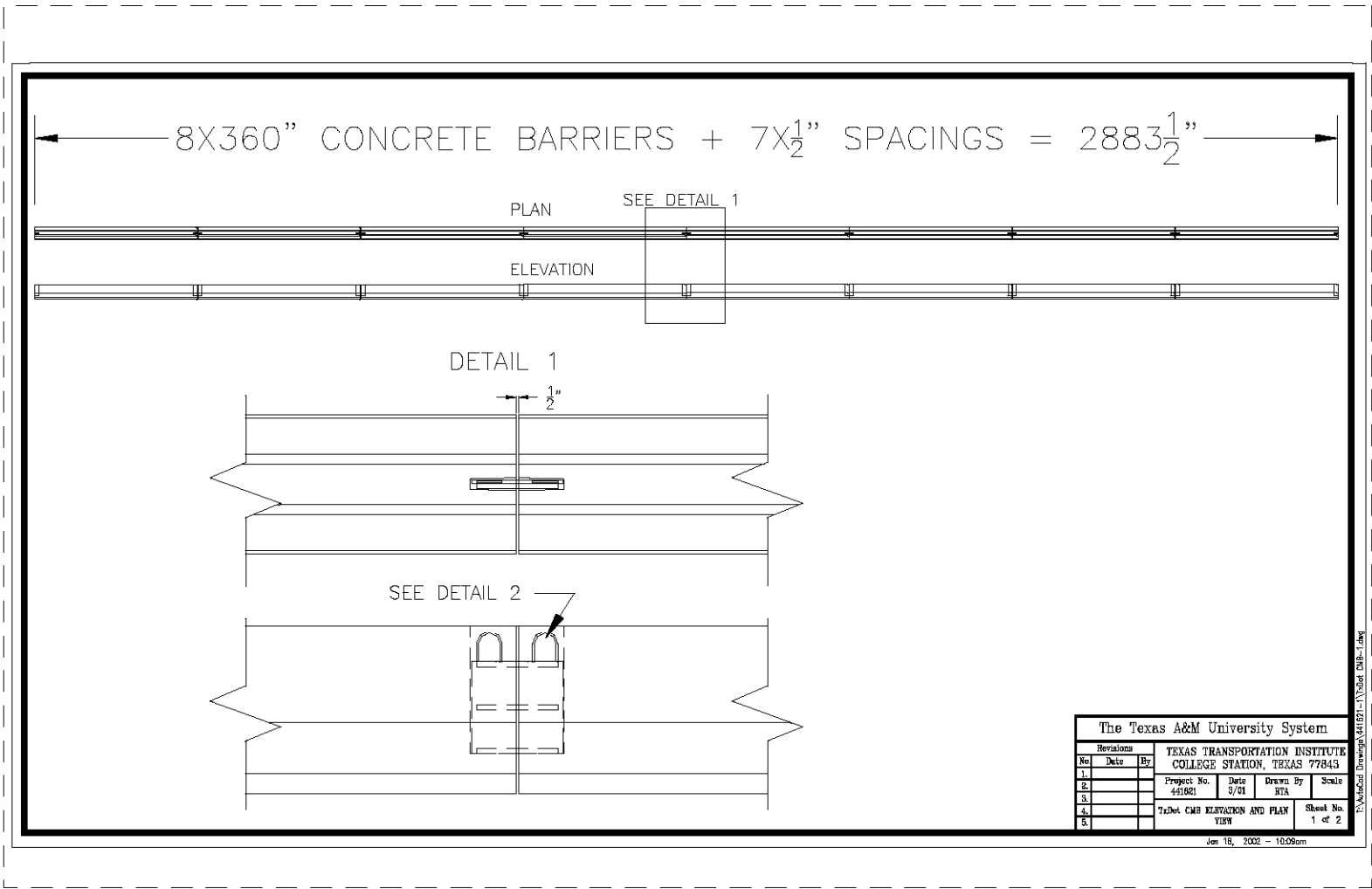


Figure 1. Details of the Test Article/Installation.

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. 441621-1 (NCHRP Report 350 TEST NO. 3-11)

Test Article

The test article for this crash test consisted of standard, unmodified precast concrete barrier segments as detailed in TxDOT standard drawing PCTB(2)-85. However, the standard steel bar grid used to connect the segments was replaced with an 18 in. × 18 in. × 0.75 in. thick steel plate. Three pieces of #6 reinforcing steel were welded to the plate longitudinally to reduce play in the precast slots in the barrier segments. The plate and reinforcing bars provided an overall thickness equivalent to that of the standard steel bar grid. The pieces of reinforcing steel were 16 in. in length and equally spaced. Two 6-in. tall loops were fabricated from #3 reinforcing steel and welded to the top of the plate. These loops served as handles to facilitate the installation and extraction of the connection plate. The total weight of the plate was approximately 81 lb. The intent of substituting the steel plate for the steel bar grid was to ensure the full strength of the concrete was utilized at the joints. Figure 2 shows details of the barrier segments and connection plate.

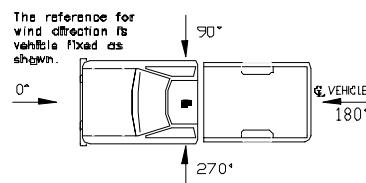
The test installation was comprised of eight barrier segments connected together for a total test installation length of approximately 240 ft-3½ in. This total length includes a 0.5-in. gap between each segment. Figure 3 shows photographs of the completed test installation.

Test Vehicle

A 1996 Chevrolet 2500 pickup truck, shown in Figures 4 and 5, was used for the crash test. Test inertia weight of the vehicle was 4405 lb, and its gross static weight was 4405 lb. The height to the upper and lower edges of the vehicle bumper was 25.8 in. and 17.1 in, respectively. Additional dimensions and information on the vehicle are given in Appendix B, Figure 29. 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 the morning of February 28, 2001. No rainfall was recorded during the 10 days prior to the test. Weather conditions at the time of testing were as follows: wind speed: 5 mph; wind direction: 0 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); temperature: 47 °F; relative humidity: 100 percent.



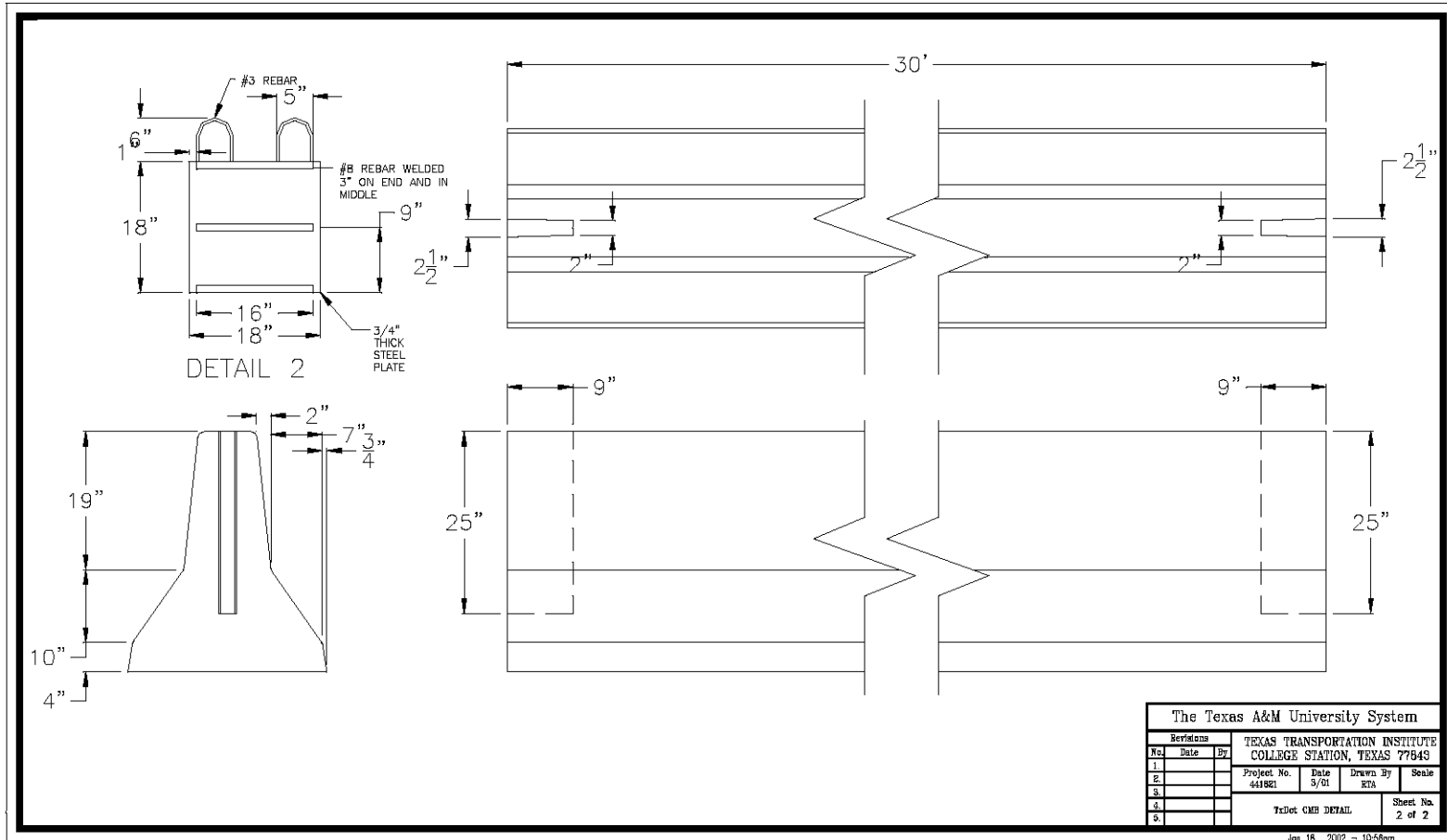


Figure 2. Details of Test Installation for Test 441621-1.



Figure 3. Test Article/Installation before Test 441621-1.



Figure 4. Vehicle/Installation Geometrics for Test 441621-1.



Figure 5. Vehicle before Test 441621-1.

Test Description

The 2000P vehicle, traveling at 63.0 mi/h, impacted the temporary concrete barrier installation 3.87 ft upstream of joint 4-5 at an impact angle of 25.2 degrees. At 0.012 s after impact, the left front tire began to ride up the face of the barrier, and segment 4 began to deflect toward the field side. The left front tire deflated at 0.019 s and segment 5 began to deflect toward the field side at 0.031 s. The vehicle began to redirect at 0.038 s, and the front of the vehicle became airborne at 0.137 s. At 0.215 s, the rear of the vehicle contacted the barrier installation and the left rear tire deflated. The vehicle was parallel with the installation at 0.226 s, traveling at a speed of 51.5 mi/h. At 0.470 s, the left front tire contacted the rear side of the barrier. The vehicle lost contact with the barrier at 0.858 s. The vehicle re-contacted the barriers at 1.170 s and lost contact a second time at 1.818 s. Brakes on the vehicle were applied at 1.7 s, and the vehicle subsequently came to rest 250 ft downstream of the point of impact and in line with the traffic face of the barrier. Sequential photographs of the test period are presented in Appendix C, Figures 32 and 33.

Damage to Test Installation

As shown in Figures 6 and 7, the barrier separated at the joint between segments 4 and 5. The edges of the barriers at joint 4-5 were fractured and spalled, but no large fragments were present. The barrier had a maximum rearward deflection of 9.0 ft.

Vehicle Damage

Damage to the vehicle is shown in Figure 8. Structural damage was imparted to the left upper and lower A-arms, left side rod ends, stabilizer bar, left front frame, floor pan, and fire wall. Also damaged were the front bumper, hood, fan, radiator, left front quarter panel, left door, and the left front and rear tires and wheel rims. Maximum exterior crush to the front plane of the vehicle at the left front corner was 18.5 in. Maximum exterior crush to the side plane of the vehicle at the left front corner was 13.8 in. Maximum occupant compartment deformation was 3.2 in. in the left fire wall area. Photographs of the interior of the vehicle are shown in Figure 9. Exterior crush measurements and occupant compartment measurements are detailed in Appendix B, Tables 4 and 5.

Occupant Risk Factors

Data from the tri-axial accelerometer, located at the vehicle center of gravity, were digitized to compute occupant impact velocity and ridedown accelerations. Only the longitudinal occupant impact velocity and ridedown accelerations are required for evaluation of criterion L of *NCHRP Report 350*. In the longitudinal direction, the occupant impact velocity was 13.8 ft/s (4.2 m/s) at 0.103 s, the highest 0.010-s occupant ridedown acceleration was -2.5 g's from 1.302 s to 1.312 s, and the maximum 0.050-s average acceleration was -6.1 g's between 0.012



Figure 6. After Impact Trajectory for Test 441621-1.



Figure 7. Installation after Test 441621-1.

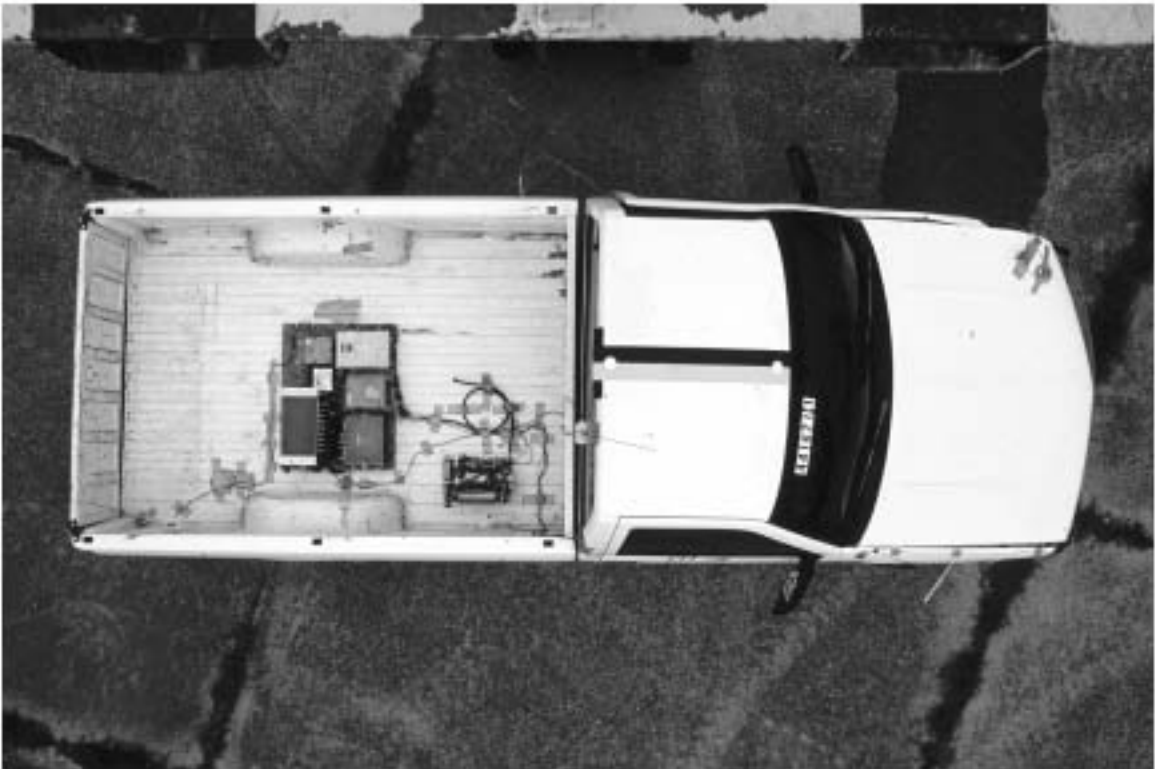


Figure 8. Vehicle after Test 441621-1.



Before Test



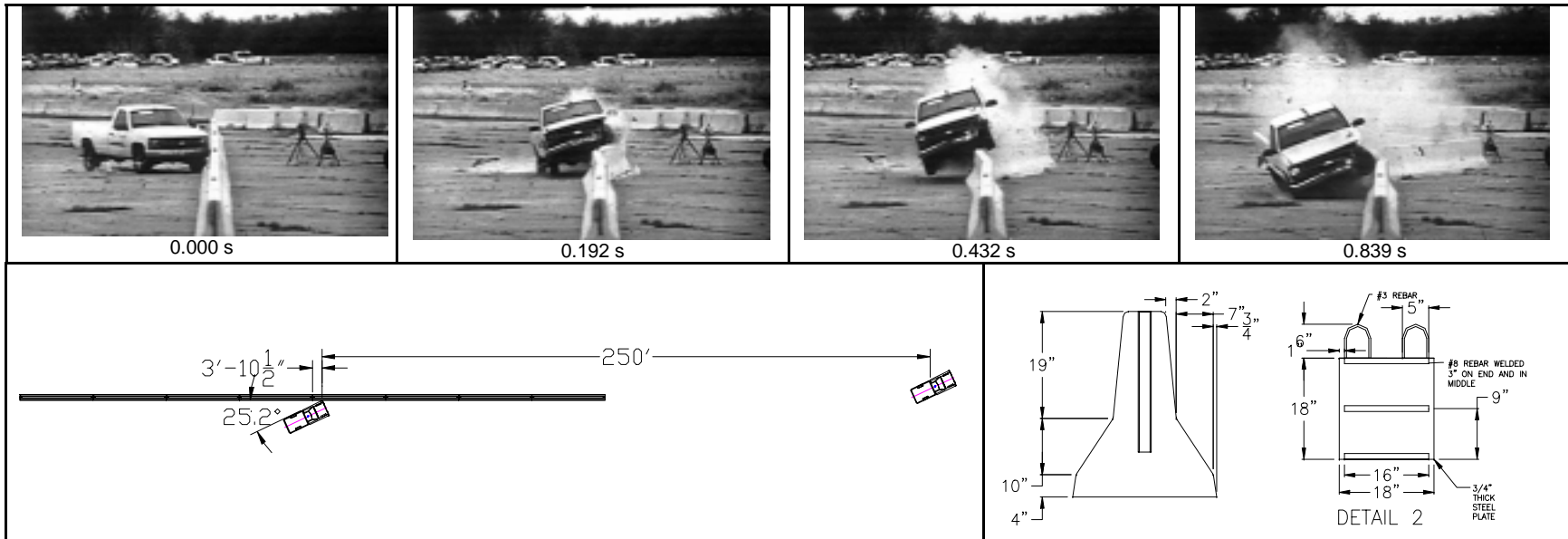
After Test

Figure 9. Interior of Vehicle for Test 441621-1.

and 0.062 s. In the lateral direction, the occupant impact velocity was 20.3 ft/s (6.2 m/s) at 0.103 s, the highest 0.010-s occupant ridedown acceleration was 8.7 g's from 0.270 s to 0.280 s, and the maximum 0.050-s average was 10.3 g's between 0.041 and 0.091 s. These data and other information pertinent to the test are presented in [Figure 10](#). Vehicle angular displacements and acceleration versus time traces are shown in Appendix D, Figures [38](#) and [41](#) through [46](#), respectively.

Assessment of Results for Test 441621-1

[Table 1](#) provides an assessment of the test based on the applicable *NCHRP Report 350* safety evaluation criteria. In summary, the modified Texas grid-slot portable concrete barrier with steel connector plate met *NCHRP Report 350* evaluation criteria. Although one of the barrier joints separated, the test vehicle was contained and redirected. The maximum lateral barrier movement experienced in the test (9 ft) should be given due consideration if this system is implemented in the field.



General Information		Impact Conditions		Test Article Deflections (m)	
Test Agency	Texas Transportation Institute	Speed (km/h).....	101.3	Dynamic	2.74
Test No.....	441621-1	Angle (deg)	25.2	Permanent	2.72
Date.....	02/28/01	Exit Conditions		Working Width	2.95
Test Article		Speed (km/h).....	N/A	Vehicle Damage	
Type	Temporary Concrete Barrier	Angle (deg)	N/A	Exterior	
Name.....	TxDOT Grid Slot	Occupant Risk Values		VDS	11LFQ4
Installation Length (m)	45.7	Impact Velocity (m/s)		CDC	11FLEK3
Material or Key Elements.....		x-direction	4.2	Maximum Exterior	
Soil Type and Condition.....		y-direction	6.2	Vehicle Crush (mm).....	470
Test Vehicle		THIV (km/h)	26.2	Interior	
Type	Production	Ridedown Accelerations (g's)		OCDI.....	LF0011000
Designation	2000P	x-direction	-2.5	Max. Occ. Compart.	
Model	1996 Chevrolet 2500 Pickup Truck	y-direction	8.7	Deformation (mm)	81
Mass (kg)		PHD (g's)	8.9	Post-Impact Behavior	
Curb	2105	ASI	1.32	(during 1.0 s after impact)	
Test Inertial.....	2000	Max. 0.050-s Average (g's)		Max. Yaw Angle (deg)	22
Dummy.....	No dummy	x-direction	-6.1	Max. Pitch Angle (deg)	7
Gross Static.....	2000	y-direction	10.3	Max. Roll Angle (deg).....	28
		z-direction	-5.4		

Figure 10. Summary of Results for Test 441621-1, NCHRP Report 350 Test 3-11.

Table 1. Performance Evaluation Summary for Test 441621-1, NCHRP Report 350 Test 3-11.

Test Agency: Texas Transportation Institute		Test No.: 441621-1	Test Date: 02/28/2001
NCHRP Report 350 Evaluation Criteria		Test Results	Assessment
<u>Structural Adequacy</u>			
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 temporary concrete barrier contained and redirected the vehicle. Maximum lateral movement of the barrier was 9.0 ft.	Pass
<u>Occupant Risk</u>			
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.	Some small fragments of the barriers were present, but did not penetrate the occupant compartment nor show potential for penetrating the occupant compartment, nor did they present undue hazard to others in the area. Maximum occupant compartment deformation was 3.2 in. in the firewall area.	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
<u>Vehicle Trajectory</u>			
K.	After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	The vehicle subsequently came to rest 250 ft downstream of impact and inline with 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 impact velocity was 4.2 m/s and longitudinal ridedown acceleration was -2.5 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.	Exit angle was not attainable.	N/A*

*Criteria K and M are preferable, not required.

TEST NO. 441621-2 (NCHRP Report 350 TEST NO. 3-11)

Test Article

Although the barrier evaluated in the first crash test met *NCHRP Report 350* evaluation criteria, the researchers desired further reduction of the maximum dynamic barrier deflection. As evidenced by the failure of the walls of the slotted barrier ends in the first crash test, the barrier segments did not possess any additional moment capacity at the joint that could be utilized to reduce deflections. Therefore, various retrofit concepts were explored to introduce tensile capacity across the joints.

The concept that TxDOT elected to test involved using a “U-shaped” bar across the joints to connect the barrier segments. A 1¾-in. diameter hole was drilled vertically into each barrier segment near the inside end of the precast slot. No other modifications were made to the barrier segments. A U-bar was bent from 1½-in. diameter steel bar stock. The 6-in. legs of the U-bar were inserted into the predrilled holes in adjacent ends of two barrier segments. The square steel connector plate used in the first crash test was replaced with a modified steel bar grid. The modified steel bar grid was fabricated from six #8 reinforcing bars in the horizontal direction and two #4 reinforcing bars in the vertical direction. The vertical and horizontal reinforcing bars were welded together at all points of contact. The bottom horizontal bar was then welded to the top of the U-bar to assist with installation and extraction. The total weight of the steel bar grid and U-bar was approximately 39 lb. The modified steel bar grid was more economical and easier to handle than the steel connector plate, but still possessed sufficient flexural strength to utilize the full moment capacity of the barrier walls.

Due to the lack of reinforcement in and around the walls of the concrete barrier sections, it was recognized that the tensile capacity of the U-bar alternative was limited by the shear strength of the concrete beneath the precast slot. Although it was believed that the barrier segments lacked the strength to maintain the integrity of the U-bar connection, this retrofit option was much more cost effective than the other proposed designs. Therefore, a crash test with the U-bar connector was conducted to see if the available concrete strength was sufficient to reduce dynamic barrier deflections. Details of the barrier and U-bar connector are shown in [Figure 11](#).

The test installation consisted of six barrier segments connected together for a total test installation length of approximately 180 ft-2½ in. This total length includes a 0.5-in. gap between each segment. Photographs of the completed test installation are shown in [Figure 12](#).

Test Vehicle

The crash test used a 1997 Chevrolet 2500 pickup truck, shown in [Figures 13 and 14](#). Test inertia weight of the vehicle was 4405 lb, and its gross static weight was 4405 lb. The height to the upper and lower edges of the vehicle bumper was 25.8 in. and 17.1 in., respectively. Additional dimensions and information on the vehicle are given in [Appendix B, Figure 30](#). 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.

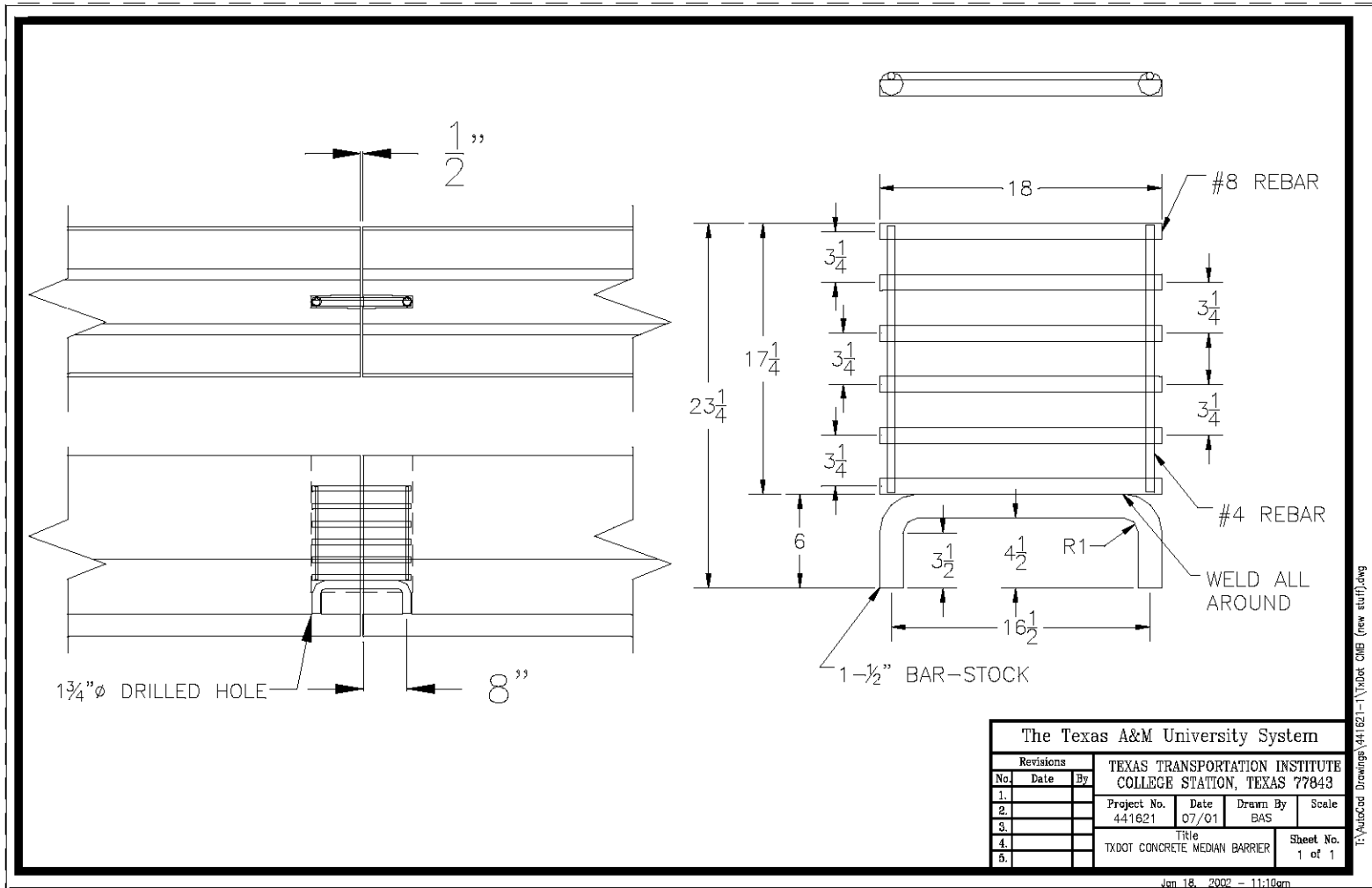


Figure 11. Details of the Barrier and U-bar Connector used in Test 441621-2.



Figure 12. Test Article/Installation before Test 441621-2.



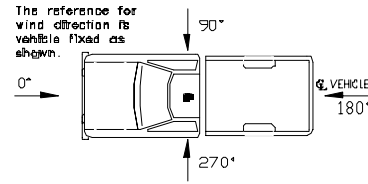
Figure 13. Vehicle/Installation Geometrics for Test 441621-2.



Figure 14. Vehicle before Test 441621-2.

Soil and Weather Conditions

Researchers performed the test the morning of August 10, 2001. No rainfall was recorded for the 10 days prior to the test. Weather conditions at the time of testing were as follows: wind speed: 6 mi/h; wind direction: 225 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); temperature: 97 °F; relative humidity: 39 percent.



Test Description

The 2000 kg (4404 lb) pickup truck, traveling at a speed of 63.5 mi/h, impacted the portable concrete barrier 4.0 ft upstream of the joint between segments 3 and 4. Shortly after impact, the left front tire rode up on the face of the barrier and segment 3 began to deflect toward the field side. At 0.020 s, the left front tire deflated and at 0.030 s segment 4 began to deflect. The vehicle began to redirect at 0.032 s and the ends of the concrete barrier segments began to fracture at the joint between segments 3 and 4 at 0.054 s. At 0.081 s, segment 5 began to deflect toward the field side and at 0.229 s the vehicle was traveling parallel with the barrier at a speed of 50.2 mi/h. The rear of the vehicle contacted the barrier at 0.252 s, and the left rear tire deflated at 0.262 s. At 0.437 s, the vehicle lost contact with the barrier while traveling at a speed of 46.7 mi/h and an exit angle of 3.8 degrees. The left rear of the vehicle came down on top of the barrier segments at 1.153 s. The vehicle lost contact with the barrier again at 1.553 s and brakes on the vehicle were applied at 2.4 s. The vehicle subsequently came to rest 205 ft downstream of the point of impact and 20 ft toward adjacent traffic lanes. Sequential photographs of the test period are shown in Appendix C, Figures 34 and 35.

Damage to Test Installation

Damage to the test installation is shown in Figures 15 and 16. The ends of several barrier segments were damaged and the barrier separated at the connections of segments 3 to 4 and 4 to 5. The maximum barrier deflection toward the field side was 12.4 ft and occurred at the end of segment 4, which had been attached to segment 3. The downstream end of segment 4, which was attached to segment 5, was displaced toward adjacent traffic lanes 4.3 ft.



Figure 15. After Impact Trajectory for Test 441621-2.



Figure 16. Installation after Test 441621-2.

Vehicle Damage

Damage to the vehicle is shown in [Figure 17](#). Structural damage was imparted to the stabilizer bar, left upper and lower A-arms, left side tie rod ends, the left front frame and the left front tire and wheel. Also damaged were the front bumper, fan, radiator, left front quarter panel, left door, and left rear bed. The right side door was jammed. Maximum exterior crush to the vehicle was 15.75 in. at the left front corner at bumper height. The left side of the floor pan and firewall were deformed. Maximum occupant compartment deformation was 0.6 in. at the left side instrument panel area. Photographs of the interior of the vehicle are shown in [Figure 18](#). Exterior crush and occupant compartment measurements are shown in Appendix B, Tables [6](#) and [7](#).

Occupant Risk Factors

Data from the tri-axial accelerometer, located at the vehicle center of gravity, were digitized to compute occupant impact velocity and ridedown accelerations. Only the longitudinal occupant impact velocity and ridedown accelerations are required for evaluation of criterion L of *NCHRP Report 350*. In the longitudinal direction, occupant impact velocity was 16.4 ft/s (5.0 m/s) at 0.105 s, maximum 0.010-s ridedown acceleration was -5.2 g's from 0.239 to 0.249 s, and the maximum 0.050-s average was 7.4 g's between 0.037 and 0.087 s. In the lateral direction, occupant impact velocity was 19.0 ft/s (5.8 m/s) at 0.105 s, maximum 0.010-s ridedown acceleration was 9.7 g's from 0.240 to 0.250 s, and the maximum 0.050-s average was 9.8 g's between 0.040 and 0.090 s. These data and other information pertinent to the test are presented in [Figure 19](#). Vehicle angular displacements and accelerations versus time traces are shown in Appendix D, Figures [39](#) and [47](#) through [52](#), respectively.

Assessment of Results for Test 441621-2

An assessment of the test based on the applicable *NCHRP Report 350* safety evaluation criteria is provided in [Table 2](#). In summary, the modified Texas grid-slot portable concrete barrier with U-bar connector and rebar grid met all required *NCHRP Report 350* evaluation criteria. Although barrier separation occurred at two of the joints, the test vehicle was contained and redirected. The maximum lateral barrier movement experienced in the test (12.4 ft) should be given due consideration if this system is implemented in the field.



Figure 17. Vehicle after Test 441621-2.

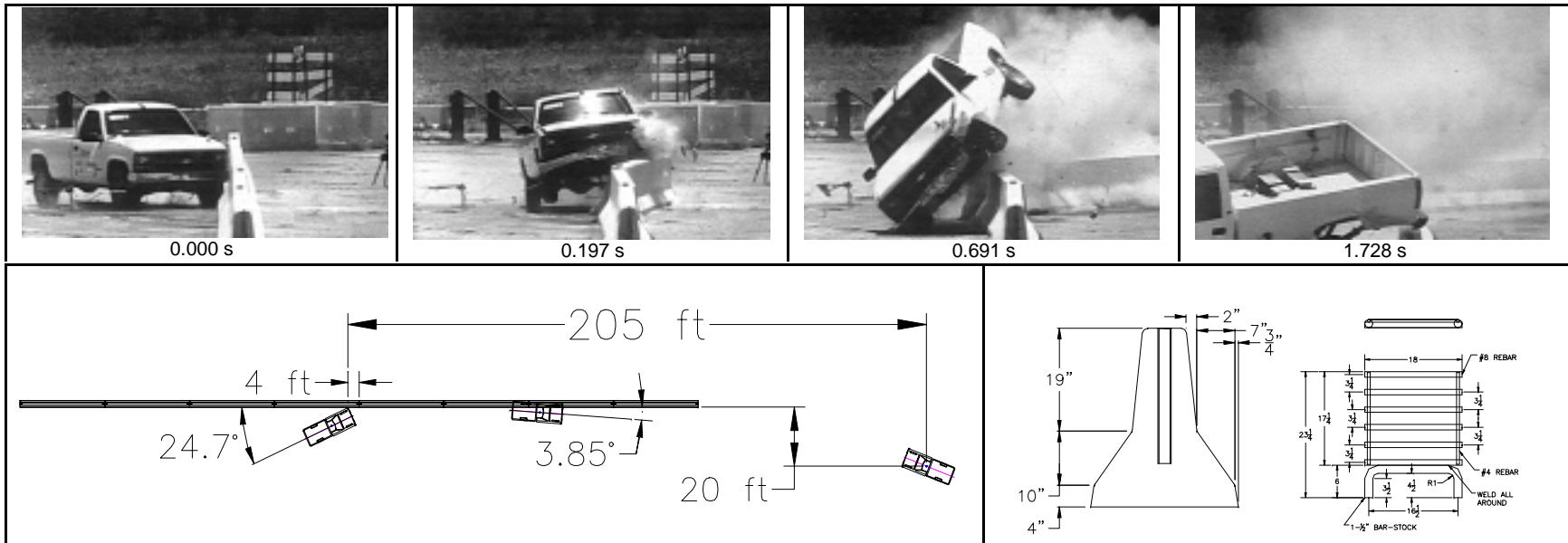


Before Test



After Test

Figure 18. Interior of Vehicle for Test 441621-2.



General Information		Impact Conditions		Test Article Deflections (m)		
Test Agency	Texas Transportation Institute	Speed (km/h).....	101.5	Dynamic.....	3.78	
Test No.....	441621-2	Angle (deg)	24.7	Permanent	1.32	
Date.....	08/10/01	Exit Conditions		Working Width	4.35	
Test Article		Speed (km/h).....	75.2	Vehicle Damage		
Type	Temporary Concrete Barrier	Angle (deg)	3.85	Exterior		
Name.....	TxDOT Grid Slot	Occupant Risk Values		VDS	11FL2	
Installation Length (m)	54.9	Impact Velocity (m/s)		CDC	11FLEW2	
Material or Key Elements.....		x-direction	5.0	Maximum Exterior		
Soil Type and Condition		y-direction	5.8	Vehicle Crush (mm).....		400
Concrete Pavement, Dry		THIV (km/h)	26.9	Interior		
Test Vehicle		Ridedown Accelerations (g's)		OCDI.....		LF0000000
Type	Production	x-direction	-5.2	Max. Occ. Compart.		
Designation	2000P	y-direction	9.7	Deformation (mm)		22
Model	1997 Chevrolet 2500 Pickup Truck	PHD (g's)	11.0	Post-Impact Behavior		
Mass (kg)		ASI	1.26	(during 1.0 s after impact)		
Curb	2153	Max. 0.050-s Average (g's)		Max. Yaw Angle (deg).....	81.9	
Test Inertial.....	2000	x-direction	-7.4	Max. Pitch Angle (deg)	-17.8	
Dummy.....	No dummy	y-direction	9.8	Max. Roll Angle (deg).....	-53.4	
Gross Static.....	2000	z-direction	-5.0			

Figure 19. Summary of Results for Test 441621-2, NCHRP Report 350 Test 3-11.

Table 2. Performance Evaluation Summary for Test 441621-2, NCHRP Report 350 Test 3-11.

Test Agency: Texas Transportation Institute		Test No.: 441621-2	Test Date: 08/10/2001
NCHRP Report 350 Evaluation Criteria		Test Results	Assessment
<u>Structural Adequacy</u>			
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 temporary concrete barrier contained and redirected the vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum lateral movement of the barrier was 12.4 ft.	Pass
<u>Occupant Risk</u>			
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.	None of the detached elements penetrated the occupant compartment nor showed potential for penetrating the occupant compartment, nor did they present undue hazard to others in the area. Maximum occupant compartment deformation was 0.6 in. at the left side instrument panel area.	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 period.	Pass
<u>Vehicle Trajectory</u>			
K.	After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	The vehicle subsequently came to rest 205 ft downstream of impact and 20 ft forward of the traffic face of the barrier.	Fail*
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 impact velocity was 16.4 ft/s (5.0 m/s) and longitudinal ridedown acceleration was -5.2 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.	Exit angle was 3.9 degrees which was 16 percent of the impact angle.	Pass*

*Criteria K and M are preferable, not required.

TEST NO. 441621-3 (NCHRP REPORT 350 TEST NO. 3-11)

Test Article

Since the limited concrete capacity rendered the U-bar treatment ineffective in terms of reducing dynamic barrier deflection, a third crash test was conducted on another retrofit concept. The treatment consisted of bolting 4-in. wide, $\frac{3}{16}$ -in. thick steel straps across the joint on both the front and back sides of the barrier. Two 1 $\frac{1}{4}$ in. x 2 $\frac{1}{2}$ in. slotted holes were fabricated into each end of the 48-in. long straps. The straps were anchored to the sloped face of the toe of each barrier using two M20/30 Hilti HSL Heavy Duty sleeve anchors embedded approximately 7 in. A $\frac{7}{8}$ -in. A Grade 8 flat washer was used beneath the head of each anchor bolt to span the slotted hole. The anchors were vertically located approximately 8 $\frac{1}{4}$ in. from the base of the barrier and were spaced 9 in. apart. Computer simulation indicated that the tensile capacity provided by the steel straps should significantly reduce dynamic barrier deflections.

The same modified steel bar grid previously described for Test 441621-2 was used in this test installation. The U-bar was not included. The total weight of the modified steel grid without the U-bar was approximately 26 lb. Details of the steel strap connection are shown in [Figure 20](#).

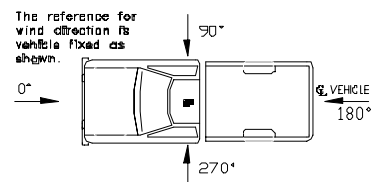
The completed test installation consisted of eight barrier segments connected together for a total test installation length of approximately 240 ft-3 $\frac{1}{2}$ in. This total length includes a 0.5-in. gap between each segment. Photographs of the completed test installation are shown in [Figure 21](#).

Test Vehicle

A 1997 Chevrolet 2500 pickup truck, shown in [Figures 22](#) and [23](#), was used for the crash test. Test inertia weight of the vehicle was 4496 lb, and its gross static weight was 4496 lb. The height to the upper and lower edges of the vehicle bumper was 28.5 in. and 17.1 in., respectively. Additional dimensions and information on the vehicle are given in Appendix B, [Figure 31](#). 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 the morning of August 24, 2001. No rainfall was recorded for the 10 days prior to the test. Weather conditions at the time of testing were as follows: wind speed: 2 mi/h; wind direction: 225 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); temperature: 90 °F; relative humidity: 50 percent.



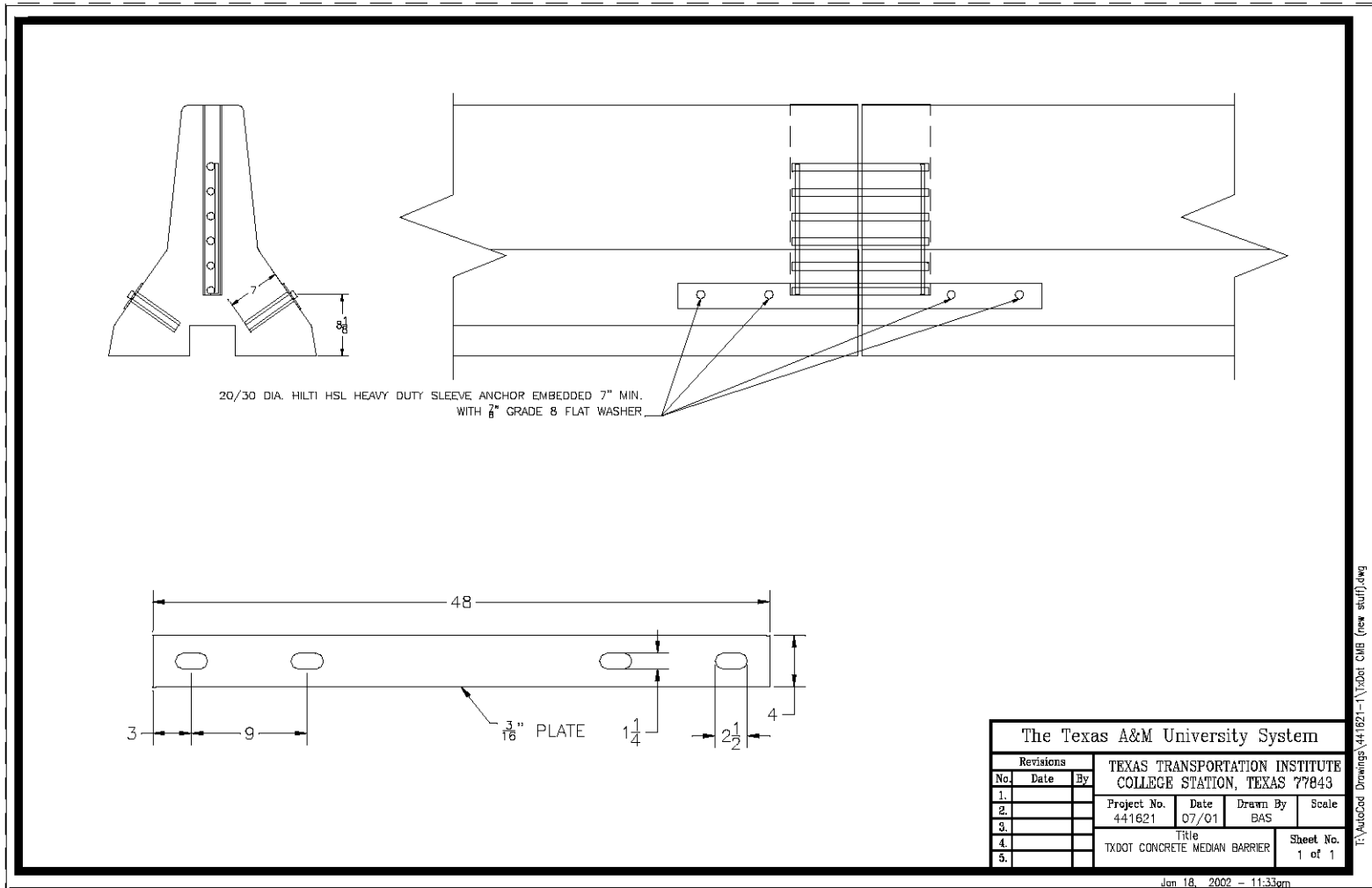


Figure 20. Details of Steel Strap Connection for Test 441621-3.

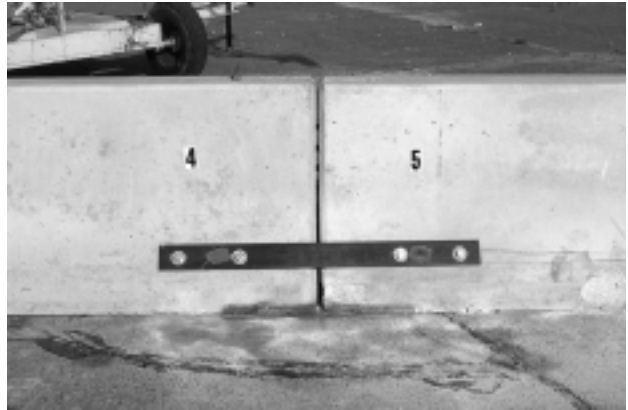


Figure 21. Test Article/Installation before Test 441621-3.



Figure 22. Vehicle/Installation Geometrics for Test 441621-3.



Figure 23. Vehicle before Test 441621-3.

Test Description

The vehicle, traveling at a speed of 62.5 mi/h, impacted the concrete median barriers (CMBs) 3.75 ft upstream of the joint between segments 4 and 5. Shortly after impact, segment 4 began to displace toward the field side and at 0.019 s the left front tire began to ride up the face of the CMB. The left front tire deflated at 0.024 s and the vehicle began to redirect at 0.032 s. At 0.037 s, segment 5 began to deflect toward the field side, and at 0.234 s the vehicle was traveling parallel to the barrier at a speed of 50.3 mi/h. The rear of the vehicle contacted the barriers at 0.244 s and began to ride up on the barriers at 0.253 s. At 0.710 s, the vehicle lost contact with the barriers while traveling at a speed of 50.5 mi/h and an exit angle of 2.6 degrees. The left rear tire separated from the vehicle at 0.817 s, and brakes on the vehicle were applied at 2.5 s. The vehicle yawed counterclockwise and came to rest 145 ft downstream of the point of impact and 15 ft toward adjacent traffic lanes. Sequential photographs of the test period are shown in Appendix C, Figures 36 and 37.

Damage to Test Installation

Damage to the test installation is shown in Figures 24 and 25. All the barrier segments remained attached to one another. However, the strap on the field side of the joint between segments 4 and 5 failed in tension through a bolt hole on segment 4. The straps on the traffic side and field side of joints 3-4, 5-6, and 6-7 were buckled but not separated. Length of contact of the vehicle with the barriers was 47.9 ft. Maximum displacement of the barriers was 4.0 ft at joint 4-5.

Vehicle Damage

Damage to the vehicle is shown in Figure 26. Structural damage included deformation of the stabilizer bar, upper and lower A-arms, left ball joints and tie rod ends, and the left front of the frame. Also damaged were the front bumper, hood, fan, radiator, left front quarter panel, left door, right front quarter panel and the left front and rear wheel rims and tires. Maximum exterior crush to the vehicle was 17.3 in at the left front corner at bumper height. Maximum occupant compartment deformation was 6.3 in. at the lower left firewall near the floor pan. Photographs of the interior of the vehicle are shown in Figure 27. Exterior crush and occupant compartment measurements are shown in Appendix B, Tables 8 and 9.

Occupant Risk Factors

Data from the tri-axial accelerometer, located at the vehicle center of gravity, were digitized to compute occupant impact velocity and ridedown accelerations. Only the longitudinal occupant impact velocity and ridedown accelerations are required for evaluation of criterion L of *NCHRP Report 350*. In the longitudinal direction, occupant impact velocity was 15.1 ft/s (4.6 m/s) at 0.112 s, maximum 0.010-s ridedown acceleration was -3.8 g's from 0.118 to 0.128 s, and the maximum 0.050-s average was -7.2 g's between 0.022 and 0.072 s. In the lateral



Figure 24. After Impact Trajectory for Test 441621-3.

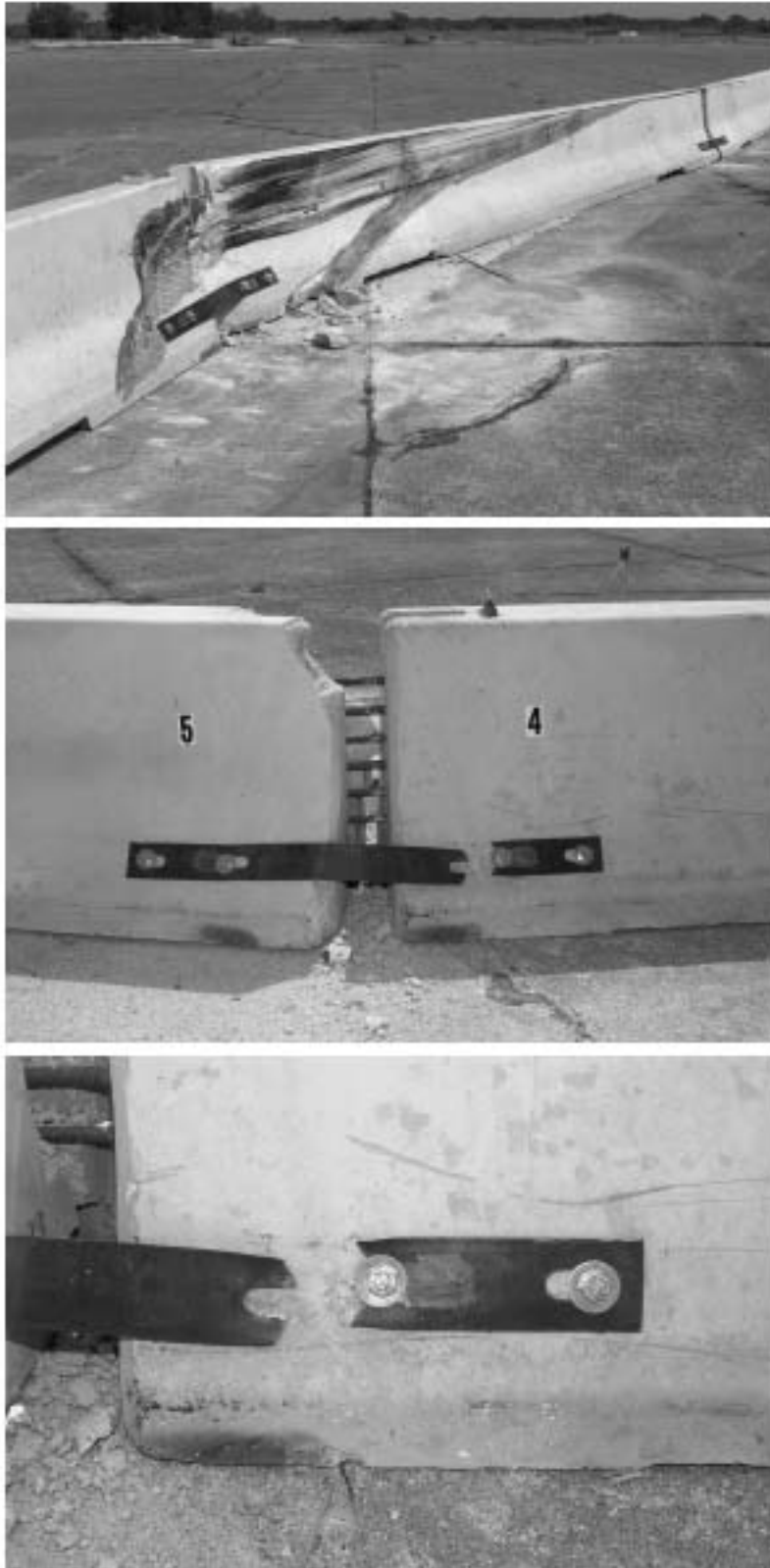


Figure 25. Installation after Test 441621-3.



Figure 26. Vehicle after Test 441621-3.



Before Test



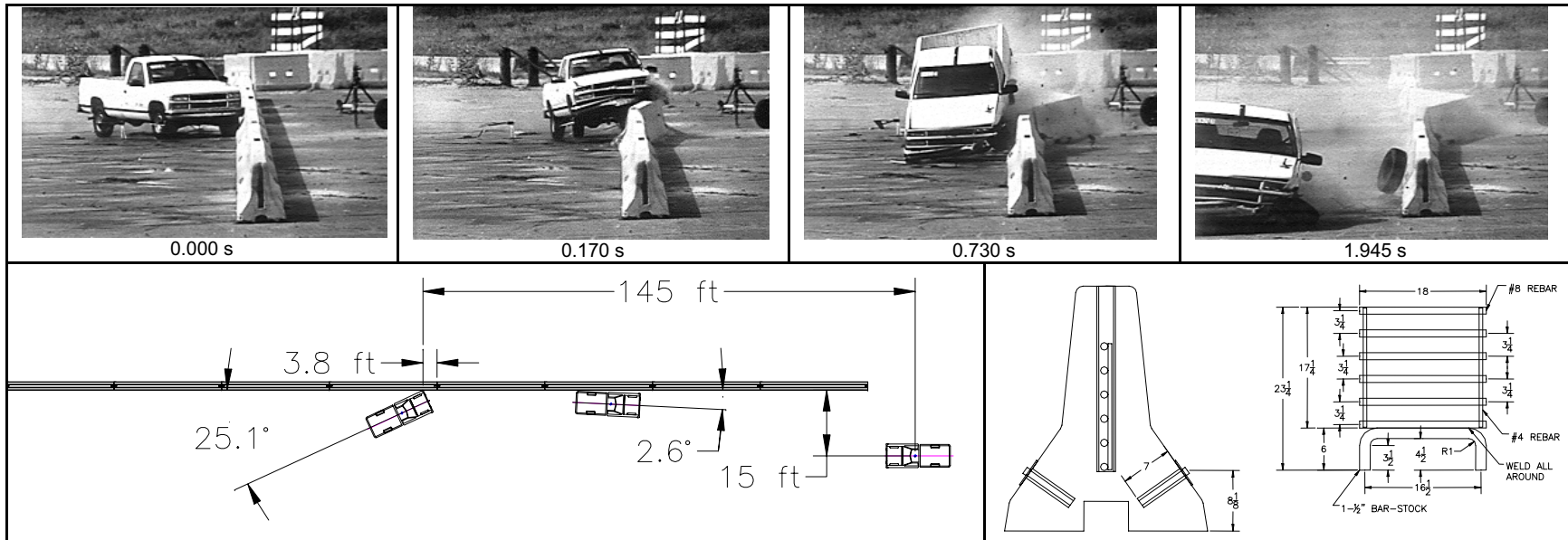
After Test

Figure 27. Interior of Vehicle for Test 441621-3.

direction, occupant impact velocity was 19.0 ft/s (5.8 m/s) at 0.112 s, maximum 0.010-s ridedown acceleration was 8.7 g's from 0.225 to 0.235 s, and the maximum 0.050-s average was 8.8 g's between 0.043 and 0.093 s. These data and other information pertinent to the test are presented in [Figure 28](#). Vehicle angular displacements and accelerations versus time traces are shown in Appendix D, Figures [40](#) and [53](#) through [58](#).

Assessment of Results for Test 441621-3

An assessment of the test based on the applicable *NCHRP Report 350* safety evaluation criteria is provided in [Table 3](#). In summary, the modified Texas grid-slot portable concrete barrier with plate connector and rebar grid met *NCHRP Report 350* evaluation criteria. The plate connector substantially reduced the maximum dynamic deflection of the barrier. The maximum lateral barrier movement experienced in the test (4 ft) should be given consideration if this system is implemented in the field.



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General Information		Impact Conditions		Test Article Deflections (m)	
Test Agency	Texas Transportation Institute	Speed (km/h).....	101.9	Dynamic	1.10
Test No.	441621-3	Angle (deg).....	25.1	Permanent	1.24
Date	08/24/01	Exit Conditions		Working Width	1.71
Test Article		Speed (km/h).....	81.3	Vehicle Damage	
Type	Temporary Concrete Barrier	Angle (deg).....	2.6	Exterior	
Name	TxDOT Grid Slot	Occupant Risk Values		VDS.....	11FL2
Installation Length (m)	73.2	Impact Velocity (m/s)		CDC	11FLEW2
Material or Key Elements.....		x-direction	4.6	Maximum Exterior	
Soil Type and Condition		y-direction	5.8	Vehicle Crush (mm)	440
Concrete Pavement, Dry		THIV (km/h)	26.2	Interior	
Test Vehicle		Ridedown Accelerations (g's)		OCDI	LF0020000
Type	Production	x-direction	-3.8	Max. Occ. Compart.	
Designation	2000P	y-direction	8.7	Deformation (mm).....	160
Model	1997 Chevrolet 2500 Pickup Truck	PHD (g's).....	9.0	Post-Impact Behavior	
Mass (kg)		ASI	1.19	(during 1.0 s after impact)	
Curb	2113	Max. 0.050-s Average (g's)		Max. Yaw Angle (deg).....	29.4
Test Inertial	2041	x-direction	-7.2	Max. Pitch Angle (deg).....	-17.3
Dummy.....	No dummy	y-direction	8.8	Max. Roll Angle (deg)	-35.9
Gross Static	2041	z-direction.....	-5.9		

Figure 28. Summary of Results for Test 441621-3, NCHRP Report 350 Test 3-11.

Table 3. Performance Evaluation Summary for Test 441621-3, NCHRP Report 350 Test 3-11.

Test Agency: Texas Transportation Institute		Test No.: 441621-3	Test Date: 08/24/2001
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 temporary concrete barrier contained and redirected the vehicle. The vehicle did not underride or override the barrier. Maximum lateral movement of the barrier was 4.0 ft.	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.	Some small fragments of the barriers were present but did not penetrate the occupant compartment nor show potential for penetrating the occupant compartment, nor did they present undue hazard to others in the area. Maximum occupant compartment deformation was 6.3 in. at the lower left firewall area.	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 period.	Pass
Vehicle Trajectory			
K.	After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	The vehicle subsequently came to rest 145 ft downstream of impact and 15 ft into adjacent traffic lanes.	Fail*
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 impact velocity was 15.1 ft/s (4.6 m/s) and longitudinal ridedown acceleration was -3.8 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.	Exit angle at loss of contact was 2.6 degrees, which was 10 percent of the impact angle.	Pass*

*Criterion K and M are preferable, not required.

CHAPTER 4. SUMMARY AND CONCLUSIONS

The crash performance of the TxDOT Type 2 precast concrete traffic barrier (PCTB(1)-90) with joint type A is unproven with respect to the *NCHRP Report 350* guidelines. Under this project, TTI researchers and TxDOT engineers worked together to evaluate the crash performance of this barrier system and determine if cost effective modifications can be made to the barrier to meet *NCHRP Report 350* criteria and limit dynamic deflections to practical levels.

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. During the project, the research team considered several retrofit connection designs for the objective of reducing dynamic barrier deflections. TxDOT engineers and TTI researchers developed these design modifications jointly. When developing these retrofit design options, factors such as impact performance, cost, ease of field installation, and aesthetics were considered. Various analyses were performed to help assess the ability of the selected barrier modifications to meet *NCHRP Report 350* impact performance criteria and limit deflections prior to conducting the full-scale crash testing. LS-DYNA computer simulations were used to support the analysis efforts.

Three full-scale crash tests were performed to evaluate the safety performance of the selected barrier connections, assess compliance with *NCHRP Report 350*, and quantify maximum dynamic deflection. The tests were performed in the order of the cost effectiveness of the barrier modifications to investigate their relative improvement in crash performance.

As previously summarized in Tables 1, 2, and 3, all three crash tests conducted on the “grid-slot” portable concrete barrier systems satisfied *NCHRP Report 350* evaluation criteria. In each test, the 2000P test vehicle was successfully contained and redirected in an upright manner without penetrating through or vaulting over the barrier. The occupant risk factors were within the preferred limits specified in *NCHRP Report 350*. Damage to the ends of the barrier segments generated some small fragments and debris. However, these fragments did not penetrate the occupant compartment or show potential for penetrating the occupant compartment, and were not considered to present undue hazard to others in the area.

Although each barrier configuration met *NCHRP Report 350* guidelines, variations in performance associated with the different connection details were observed. From a barrier deflection standpoint, the steel strap bolted to the toe of the barrier segments across the joints offer the best alternative from among the three connection details investigated. The drop-in plate connector and U-bar connector with rebar grid both permitted large barrier deflections after the integrity of the connection immediately downstream of the point of impact was lost. The capacity of the plate connection was controlled by the strength moment capacity of the lightly reinforced walls of the slotted barrier ends, which was not sufficient to develop the moment capacity of the plate. Failure of the barrier walls permitted the barrier ends at that joint to deflect 9 ft. Although the U-bar connector provided tensile capacity across the joints, this tensile capacity was limited by the shear strength of an unreinforced section of concrete beneath the

precast slot. After failure of this concrete block and the walls forming the slot, the barrier ends deflected 12.4 ft. Comparatively, the steel strap limited the barrier deflection to 4 ft. Although one of the straps ruptured in tension on the field side of the barrier, the failure did not occur until after the vehicle had passed the joint and a considerable reduction in deflection was realized.

In terms of cost and ease of installation, the plate connector or modified rebar grid has an advantage over the other connection details. This modified connector plate can be used without modification to the concrete barrier segments. Further, the drop-in nature of the connector permits rapid field placement, which minimizes exposure of work zone personnel.

The U-bar connector also provides a drop-in type connection. However, use of the U-bar connector requires drilling a 1 3/4-in. diameter hole into the bottom of the slot at each end of the barrier segments, and more precise barrier spacing. There are no perceived advantages in using the U-bar connector since both barrier deflections and installation costs are greater than for the plate connector.

The steel strap connection is the most expensive and labor intensive of the three connections evaluated. This alternative requires four holes to be drilled into each end of the barrier segments to accommodate the anchor bolts that secure the steel strap to the toe of the barrier segment. Although slotting the holes in the steel strap has provided some tolerance, 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) will increase exposure of work zone personnel compared to the drop-in connections.

CHAPTER 5. IMPLEMENTATION STATEMENT

Under this project, the impact performance of TxDOT's Type 2 precast concrete traffic barrier (PCTB(1)-90) with joint type A was investigated through full-scale crash testing. Crash tests were conducted to evaluate the performance of three different connection details: steel plate connector, U-bar connector with rebar grid, and steel strap in combination with rebar grid. In all three tests, the portable concrete barrier system satisfied *NCHRP Report 350* evaluation criteria. However, some variations in performance associated with the different connection details were observed.

From a functional standpoint, the steel strap offers the best alternative from among the three connections investigated. This connection limited the barrier deflection to only 4 ft compared to the steel plate connector and U-bar connector, which had deflections of 9 ft and 12.4 ft, respectively.

In terms of cost and ease of installation, the plate connector or modified rebar grid has an advantage over the other connection details. This modified connector plate can be used without modification to the concrete barrier segments. Further, the drop-in nature of the connector permits rapid field placement, which minimizes exposure of work zone personnel during barrier installation.

In summary, based on the results of the testing and evaluation reported herein, the TxDOT Type 2 precast concrete traffic barrier (PCTB(1)-90) with joint type A is considered suitable for continued implementation as a temporary work zone barrier. However, the existing drop-in rebar grid or modified steel plate connector permit barrier separation when the strength of the barrier ends is exceeded. As mentioned above, this joint separation leads to barrier deflections of 9 ft or more under design impact conditions. It should be noted that these design impact conditions are considered to be difficult to achieve due to the restricted roadway widths that exist at many work zone sites. The barrier deflection range and the ability to achieve the design impact conditions should be appropriately considered when developing a site implementation plan for this barrier system with drop-in connection grid or plate.

The addition of 4-in. wide by $\frac{3}{16}$ -in. thick steel straps bolted to the face of the barrier segments across the joints limits the barrier deflection to 4 ft under design impact conditions. Use of the steel strap connection will, therefore, permit the barrier to be used in more restricted work zone areas.

It was observed in the crash test of this connection detail that one of the steel straps failed in tension on the field side of the barrier. It is logical to conclude that if the strength of the connection can be further increased to avoid failure of the strap without inducing failure of the anchor bolts that the barrier deflection can be further decreased. A series of computer simulations were conducted to investigate this issue. It was determined that if the size of the steel strap is increased to 6-in. wide by $\frac{1}{4}$ -in., tensile failure of the strap can be avoided and barrier deflections will be reduced to approximately 3.25 ft. Besides than the change in plate dimensions, all other details of the connection, including anchor bolt size and location, remain

the same as those used in the test installation (see [Figure 20](#)). Since this reduction in deflection can be achieved with only a small increase in material cost, it is recommended that the 6-in. wide by 1/4-in. thick steel straps be implemented when site conditions cannot accommodate the larger deflections associated with the drop-in plate or grid connectors.

REFERENCES

1. 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.

RELATED RESEARCH

1. T. R. Guidry and W. L. Beason, "Development of a Low-Profile Concrete Barrier," Research Report 990-4F, Texas Transportation Institute, Texas A&M University, November 1991.
2. W. L. Beason, H. E. Ross, Jr., H. S. Perera, and W. L. Campise, "Development of a Single Slope Concrete Median Barrier," Research Report 9429C-1, Texas Transportation Institute, Texas A&M University, February, 1989.
3. W. L. Beason and D. L. Bullard, "Development of a Limited Slip Portable Concrete Barrier Connection," Research Report No. 1959-1, Texas Transportation Institute, Texas A&M University, November 1993.

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 back-up 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 an 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 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 is suspect.

The Test Risk Assessment Program (TRAP) uses the data from WinDigit to compute occupant/compartiment impact velocities, time of occupant/compartiment 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 system being initial impact.

ANTHROPOMORPHIC DUMMY INSTRUMENTATION

An Alderson Research Laboratories Hybrid II, 50th percentile male anthropomorphic dummy, restrained with lap and shoulder belts, was placed in the driver's position of the 820C vehicle. The dummy was uninstrumented. Use of a dummy in the 2000P vehicle is optional according to *NCHRP Report 350* and there was no dummy used in the tests with the 2000P vehicle.

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 two-to-one 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: <u>02-28-01</u>	TEST NO.: <u>441621-1</u>	VIN NO.: <u>1GCGC24R1TE172524</u>		
YEAR: <u>1996</u>	MAKE: <u>Chevrolet</u>	MODEL: <u>2500 Pickup Truck</u>		
TIRE INFLATION PRESSURE: _____	ODOMETER: <u>102681</u>	TIRE SIZE: <u>LT 245 75R16</u>		
MASS DISTRIBUTION (kg)	LF <u>585</u>	RF <u>557</u>	LR <u>420</u>	RR <u>438</u>
DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:		All units in mm 1 mm=0.039 in.		
		● Denotes accelerometer location. NOTES: _____ _____ _____ ENGINE TYPE: <u>8 CYL</u> ENGINE CID: <u>5.7L</u> TRANSMISSION TYPE: _____ AUTO _____ <input checked="" type="checkbox"/> MANUAL OPTIONAL EQUIPMENT: <u>8 LUGS</u> _____ _____ DUMMY DATA: TYPE: _____ MASS: _____ SEAT POSITION: _____		
GEOMETRY - (mm)				
A <u>1870</u>	E <u>1300</u>	J <u>1090</u>	N <u>1600</u>	R <u>740</u>
B <u>830</u>	F <u>5480</u>	K <u>655</u>	O <u>1615</u>	S <u>910</u>
C <u>3350</u>	G <u>1437.2</u>	L <u>70</u>	P <u>760</u>	T <u>1450</u>
D <u>1060</u>	H _____	M <u>435</u>	Q <u>445</u>	U <u>3350</u>
MASS - (kg)			TEST INERTIAL	GROSS STATIC
M ₁	<u>1210</u>	<u>1142</u>	_____	
M ₂	<u>895</u>	<u>858</u>	_____	
M _T	<u>2105</u>	<u>2000</u>	_____	

Figure 29. Vehicle Properties for Test 441621-1.

Table 4. Exterior Crush Measurements For Test 441621-1.

VEHICLE CRUSH MEASUREMENT SHEET¹

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

Note: Measure C₁ to C₆ 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	Front bumper	720	470	650	470	380	320	200	120	0	-325
2	740 mm above ground	800	380	880	0	120	Wheel Well			380	+1480
					All units in mm						
					1 mm.= 0.039 in.						

¹Table 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).

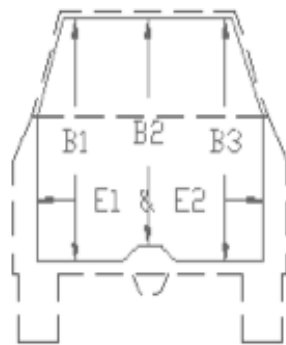
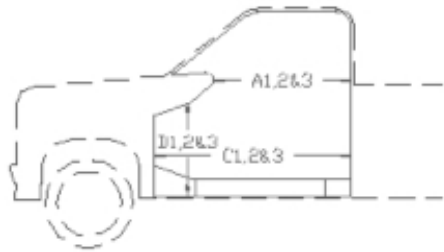
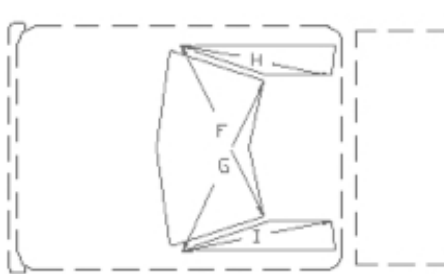
***Measure and document on the vehicle diagram the location of the maximum crush.

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

Table 5. Occupant Compartment Measurements For Test 441621-1.

T r u c k

O c c u p a n t C o m p a r t m e n t D e f o r m a t i o n



	BEFORE	AFTER
A1	940	928
A2	935	927
A3	963	963
B1	1072	1073
B2	1063	1063
B3	1071	1071
C1	1400	1319
C2	1257	1251
C3	1372	1372
D1	322	297
D2	167	160
D3	316	316
E1	1588	1595
E2	1595	1605
F	1465	1465
G	1465	1465
H	1000	1000
I	1000	1000

All units in mm
1 mm=0.039 in.

DATE: 08-10-01 TEST NO.: 441621-2 VIN NO.: 1GCGC24R8VZ238739
 YEAR: 1997 MAKE: Chevrolet MODEL: 2500 Pickup Truck
 TIRE INFLATION PRESSURE: _____ ODOMETER: 129936 TIRE SIZE: LT 245 75R16

MASS DISTRIBUTION (kg) LF 1275 RF 1250 LR 960 RR 1015

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST: _____

All units in mm
1 mm=0.039 in.

● Denotes accelerometer location.

NOTES: _____

ENGINE TYPE: 8 CYL
 ENGINE CID: 5.7L
 TRANSMISSION TYPE:
 AUTO
 MANUAL

OPTIONAL EQUIPMENT: _____

DUMMY DATA:
 TYPE: _____
 MASS: _____
 SEAT POSITION: _____

GEOMETRY - (mm)

A	<u>1870</u>	E	<u>1320</u>	J	<u>1090</u>	N	<u>1595</u>	R	<u>720</u>
B	<u>820</u>	F	<u>5490</u>	K	<u>655</u>	O	<u>1615</u>	S	<u>920</u>
C	<u>3350</u>	G	<u>1449.1</u>	L	<u>70</u>	P	<u>760</u>	T	<u>1450</u>
D	<u>1860</u>	H	_____	M	<u>435</u>	Q	<u>445</u>	U	<u>3400</u>

MASS - (kg)	CURB	TEST INERTIAL	GROSS STATIC
M ₁	<u>1228</u>	<u>1145</u>	_____
M ₂	<u>925</u>	<u>895</u>	_____
M _T	<u>2153</u>	<u>2000</u>	_____

Figure 30. Vehicle Properties for Test 441621-2.

Table 6. Exterior Crush Measurements For Test 441621-2.

VEHICLE CRUSH MEASUREMENT SHEET¹

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

Note: Measure C₁ to C₆ 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	Front bumper	700	400	800	400	270	40	90	30	0	-200
2	750 mm above ground	700	330	1300	0	10	90	N/A	N/A		+1230

¹Table 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).

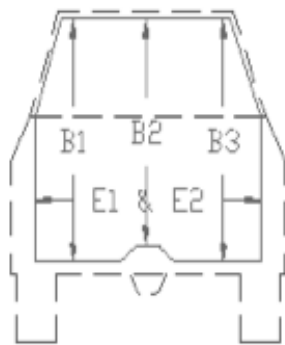
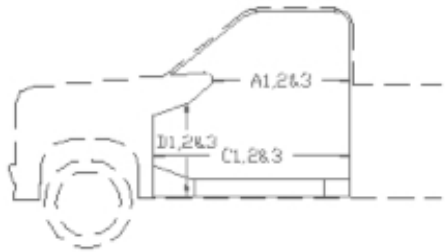
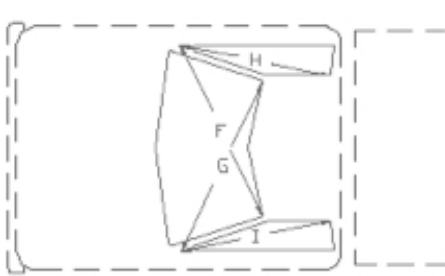
***Measure and document on the vehicle diagram the location of the maximum crush.

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

Table 7. Occupant Compartment Measurements For Test 441621-2.

T r u c k

O c c u p a n t C o m p a r t m e n t D e f o r m a t i o n



	BEFORE	AFTER
A1	868	862
A2	930	922
A3	911	906
B1	1077	1071
B2	1037	1068
B3	1072	1072
C1	1375	1353
C2	328	319
C3	1373	1373
D1	320	339
D2	160	162
D3	311	311
E1	1586	1590
E2	1597	1613
F	1460	1460
G	1460	1460
H	900	900
I	900	900
J	1518	1505

All units in mm
1 mm=0.039 in.

DATE: 08-24-01 TEST NO.: 441621-3 VIN NO.: 1GCGC24R2VZ112697
 YEAR: 1997 MAKE: Chevrolet MODEL: 2500 Pickup
 TIRE INFLATION PRESSURE: _____ ODOMETER: 130635 TIRE SIZE: LT24575R16

MASS DISTRIBUTION (kg) LF 578 RF 565 LR 435 RR 463

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST: _____

All units in mm
1 mm=0.039 in.

● Denotes accelerometer location.

NOTES: _____

ENGINE TYPE: 8 CYL
 ENGINE CID: 5.7 L

TRANSMISSION TYPE:
 AUTO
 MANUAL

OPTIONAL EQUIPMENT:
8 LUGS

DUMMY DATA:
 TYPE: _____
 MASS: _____
 SEAT POSITION: _____

GEOMETRY - (mm)

A	<u>1870</u>	E	<u>1320</u>	J	<u>1090</u>	N	<u>1600</u>	R	<u>730</u>
B	<u>820</u>	F	<u>5490</u>	K	<u>655</u>	O	<u>1620</u>	S	<u>920</u>
C	<u>3350</u>	G	<u>1473.9</u>	L	<u>70</u>	P	<u>760</u>	T	<u>1450</u>
D	<u>1860</u>	H	_____	M	<u>435</u>	Q	<u>445</u>	U	<u>3420</u>

MASS - (kg)	CURB	TEST INERTIAL	GROSS STATIC
M ₁	<u>1231</u>	<u>1143</u>	_____
M ₂	<u>882</u>	<u>898</u>	_____
M _T	<u>2113</u>	<u>2041</u>	_____

Figure 31. Vehicle Properties for Test 441621-3.

Table 8. Exterior Crush Measurements For Test 441621-3.

VEHICLE CRUSH MEASUREMENT SHEET¹

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

Note: Measure C₁ to C₆ 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	Front bumper	800	440	700	440	300	210	80	40	30	-350
2	670 mm above ground	800	360	9000	0	100	Wheel Well			360	+1520

¹Table 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).

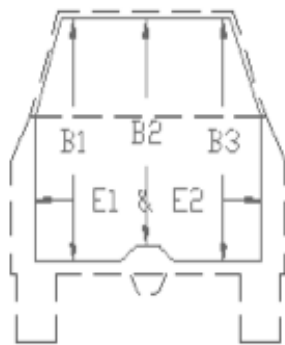
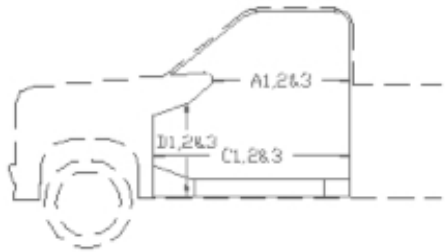
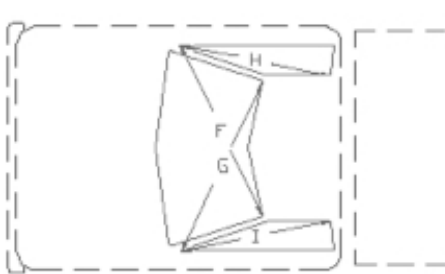
***Measure and document on the vehicle diagram the location of the maximum crush.

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

Table 9. Occupant Compartment Measurements For Test 441621-3.

T r u c k

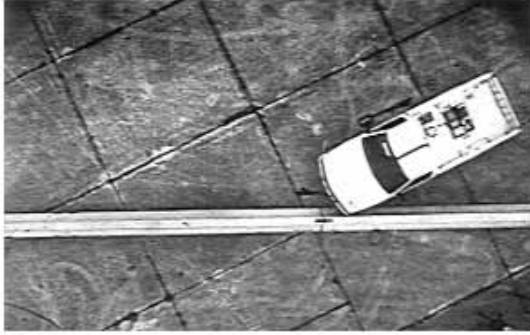
O c c u p a n t C o m p a r t m e n t D e f o r m a t i o n



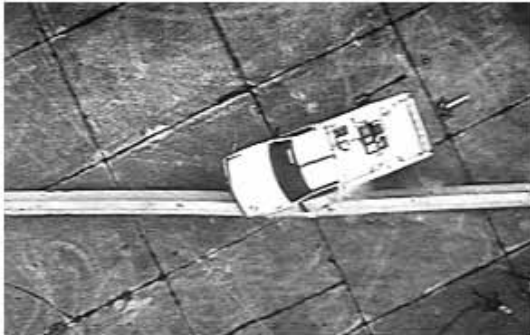
	BEFORE	AFTER
A1	870	862
A2	933	925
A3	910	910
B1	1075	1086
B2	1045	1035
B3	1072	1072
C1	1420	1260
C2	530	530
C3	1372	1372
D1	323	342
D2	157	162
D3	315	315
E1	1587	1598
E2	1595	1612
F	1460	1460
G	1460	1460
H	900	900
I	900	900
J	1524	1498

All units in mm
1 mm=0.039 in.

APPENDIX C. SEQUENTIAL PHOTOGRAPHS



0.000 s



0.096 s



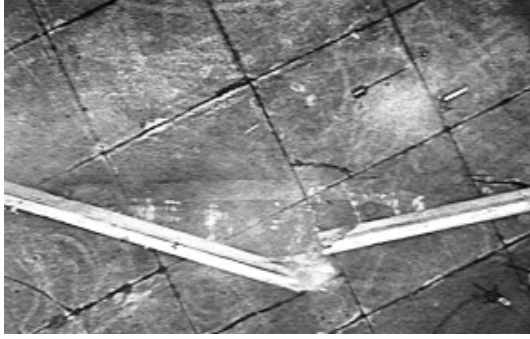
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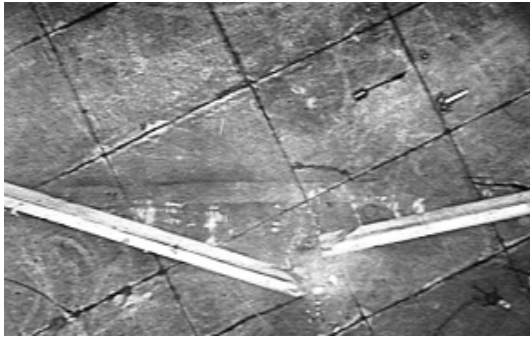
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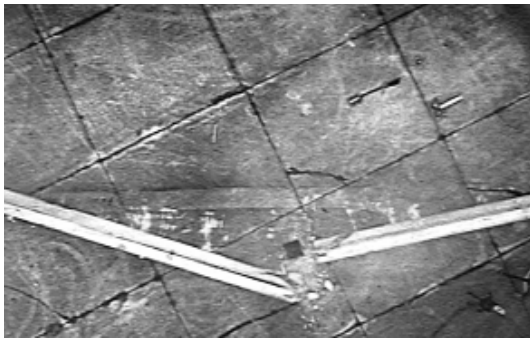
Figure 32. Sequential Photographs for Test 441621-1 (Overhead and Frontal Views).



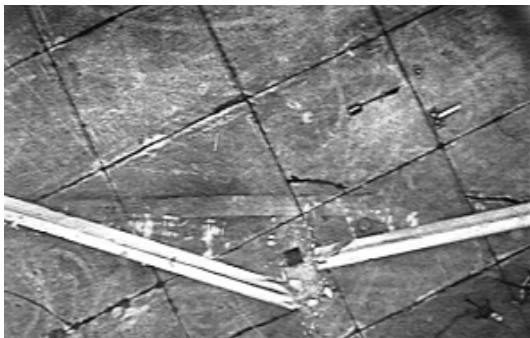
0.839 s



1.439 s



2.398 s



4.795 s



**Figure 32. Sequential Photographs for Test 441621-1
(Overhead and Frontal Views) (Continued).**



0.000 s



0.839 s



0.096 s



1.439 s



0.192 s



2.398 s



0.432 s



4.795 s

**Figure 33. Sequential Photographs for Test 441621-1
(Rear View).**



0.000 s



0.099 s



0.197 s



0.395 s



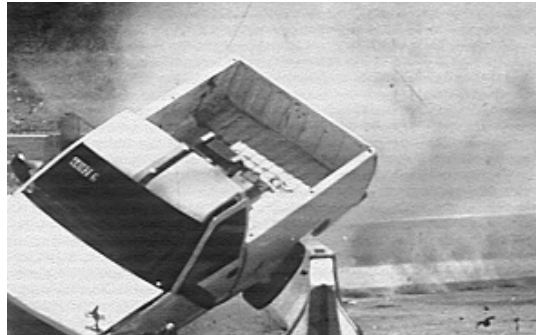
Figure 34. Sequential Photographs for Test 441621-2 (Overhead and Frontal Views).



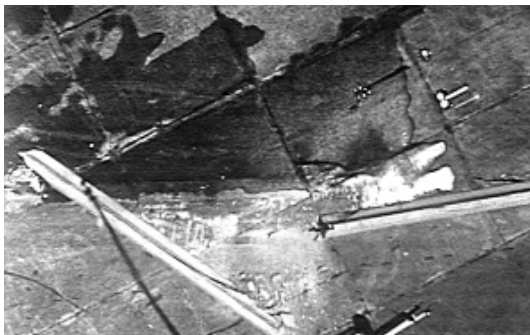
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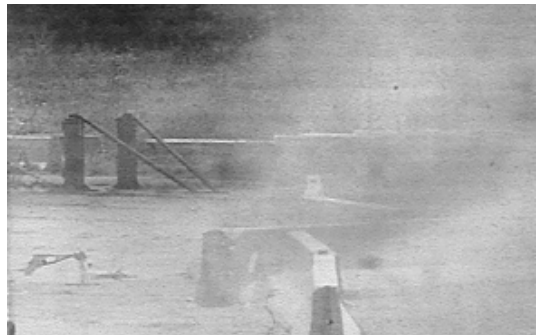
1.111 s



1.728 s



2.962 s



**Figure 34. Sequential Photographs for Test 441621-2
(Overhead and Frontal Views) (Continued).**



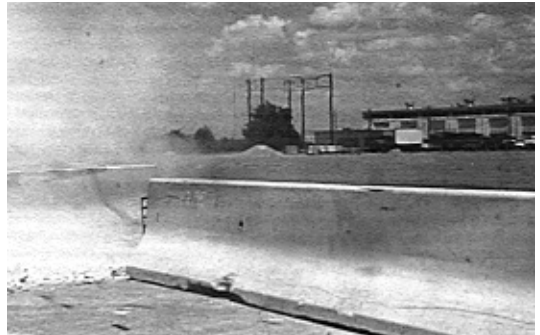
0.000 s



0.691 s



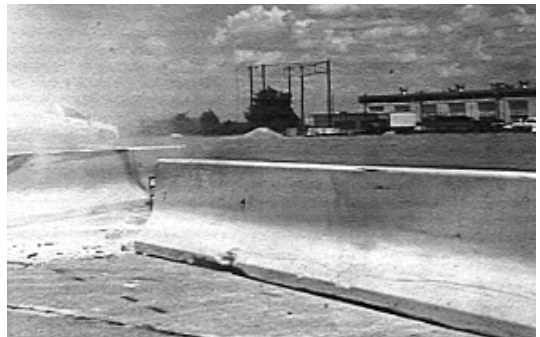
0.099 s



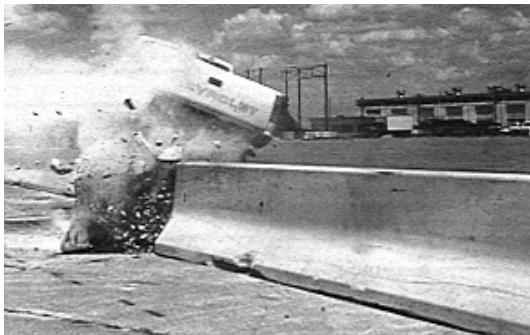
1.111 s



0.197 s



1.728 s

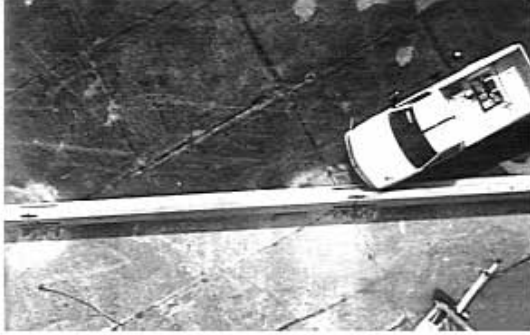


0.395 s

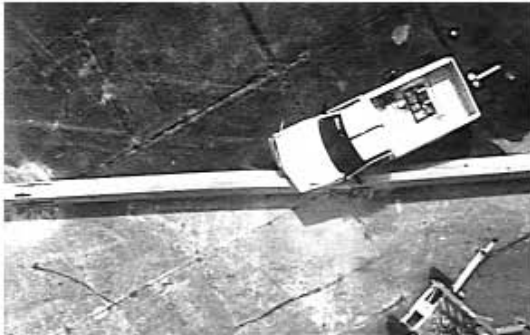


2.962 s

**Figure 35. Sequential Photographs for Test 441621-2
(Rear View).**



0.000 s



0.073 s



0.170 s



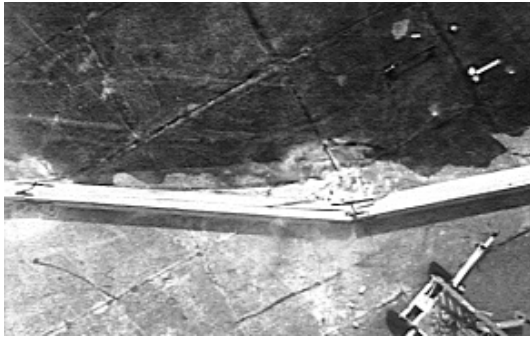
0.365 s



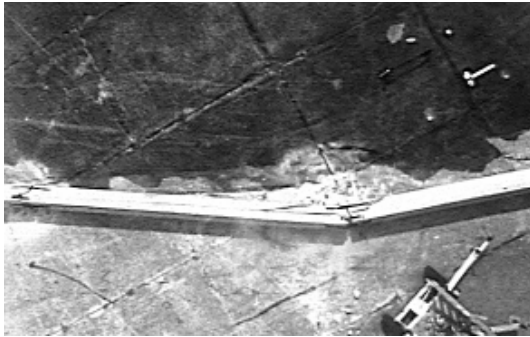
Figure 36. Sequential Photographs for Test 441621-3 (Overhead and Frontal Views).



0.730 s



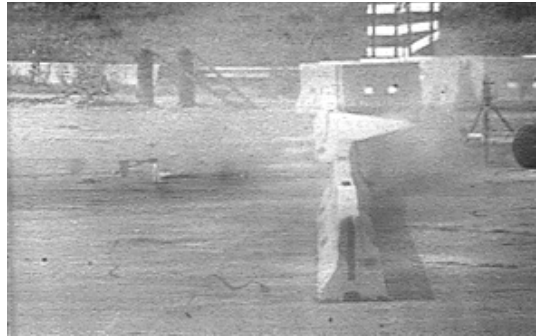
1.216 s



1.945 s



4.620 s



**Figure 36. Sequential Photographs for Test 441621-3
(Overhead and Frontal Views) (Continued).**



0.000 s



0.730 s



0.073 s



1.216 s



0.170 s



1.945 s



0.365 s



4.620 s

**Figure 37. Sequential Photographs for Test 441621-3
(Rear View).**

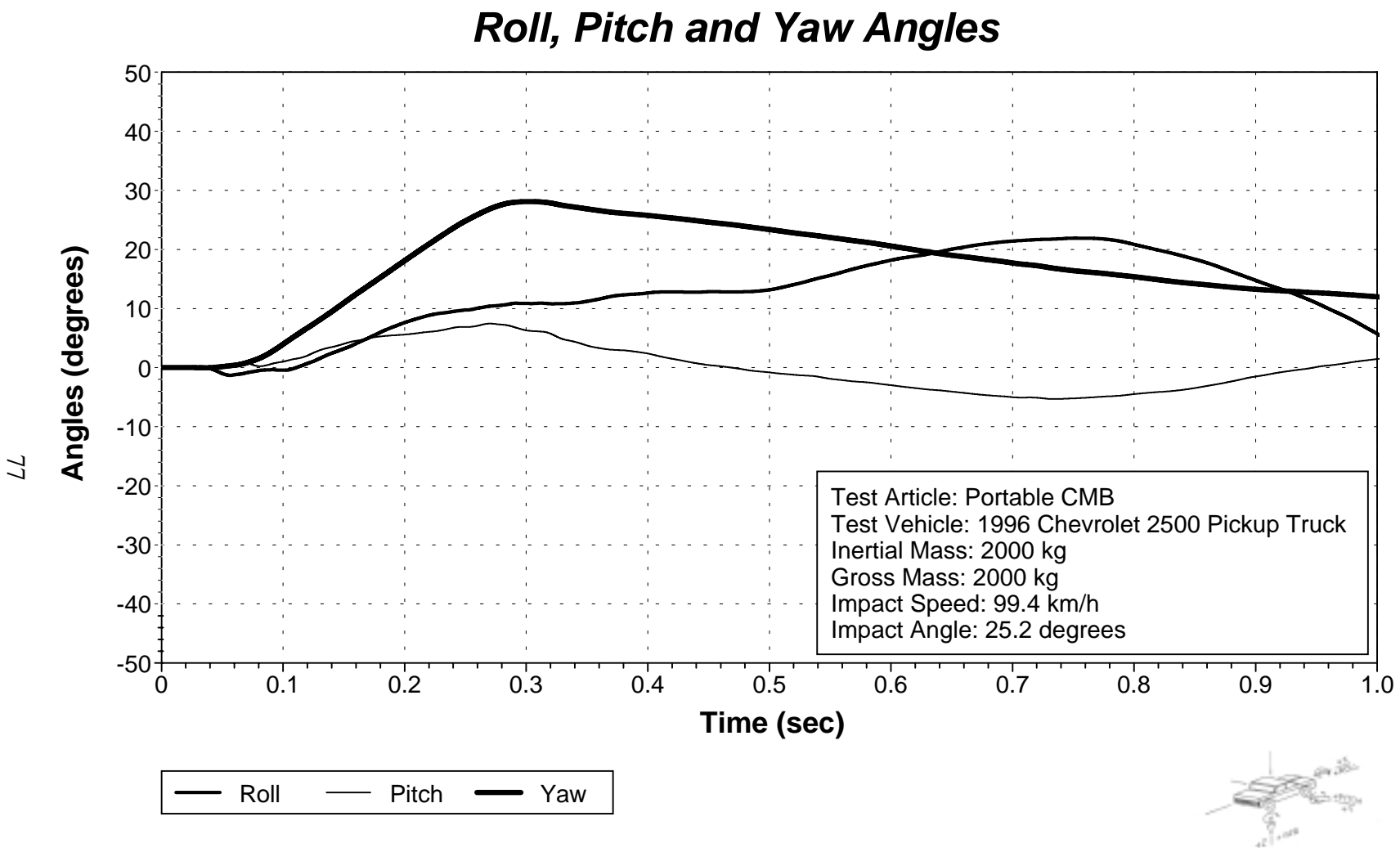


Figure 38. Vehicular Angular Displacements for Test 441621-1.

Roll, Pitch and Yaw Angles

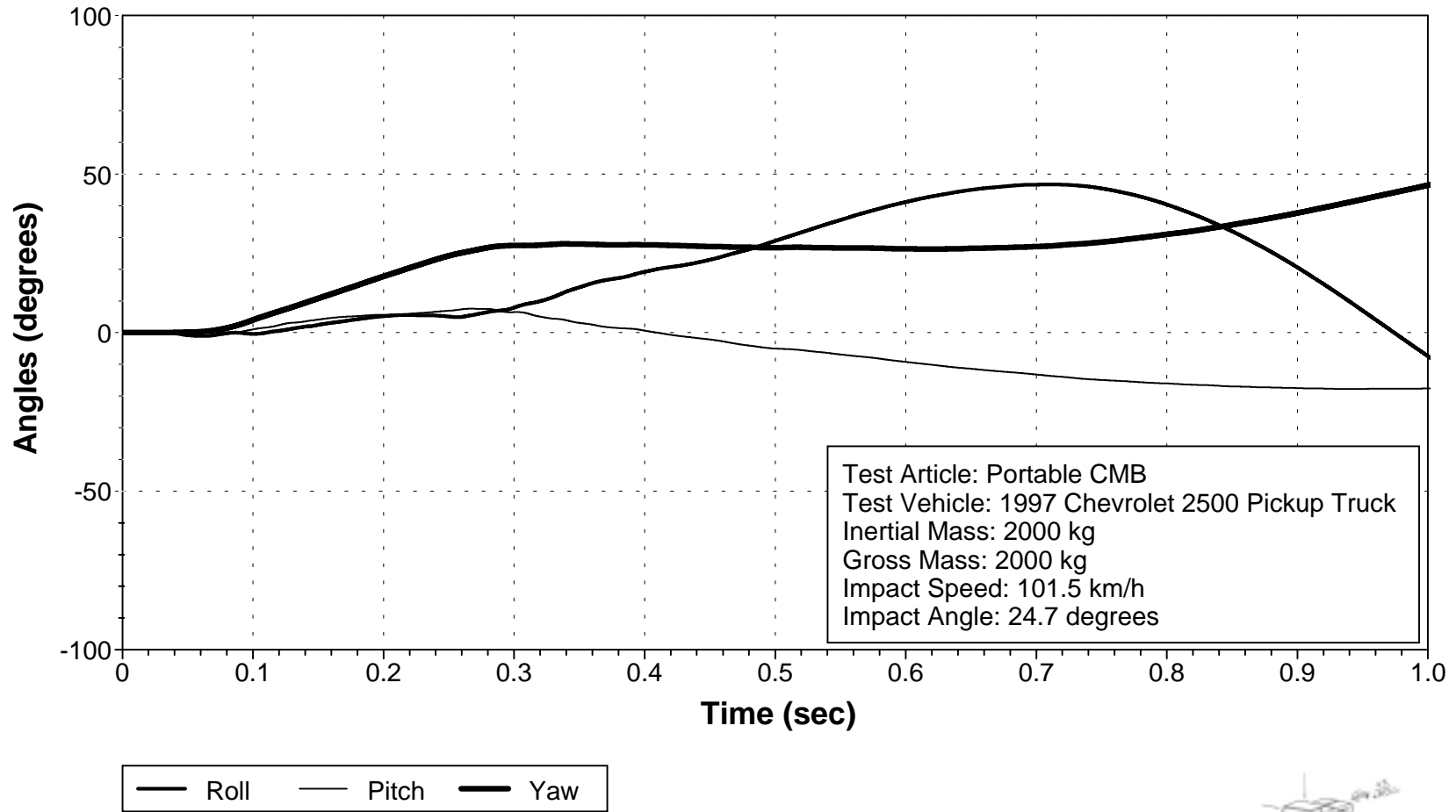


Figure 39. Vehicular Angular Displacements for Test 441621-2.

Roll, Pitch and Yaw Angles

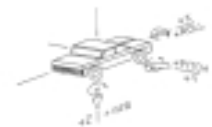
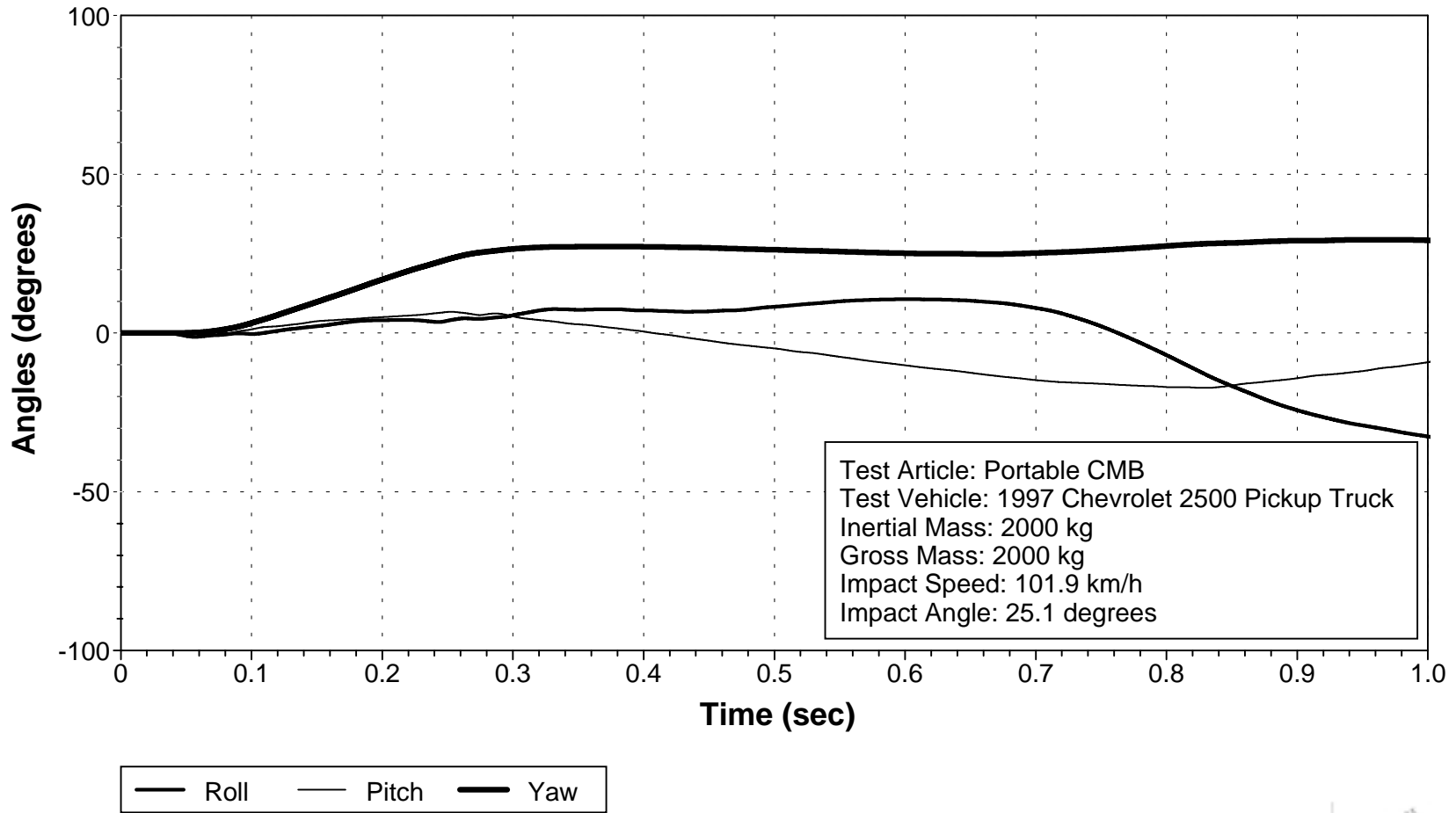


Figure 40. Vehicular Angular Displacements for Test 441621-3.

X Acceleration at CG

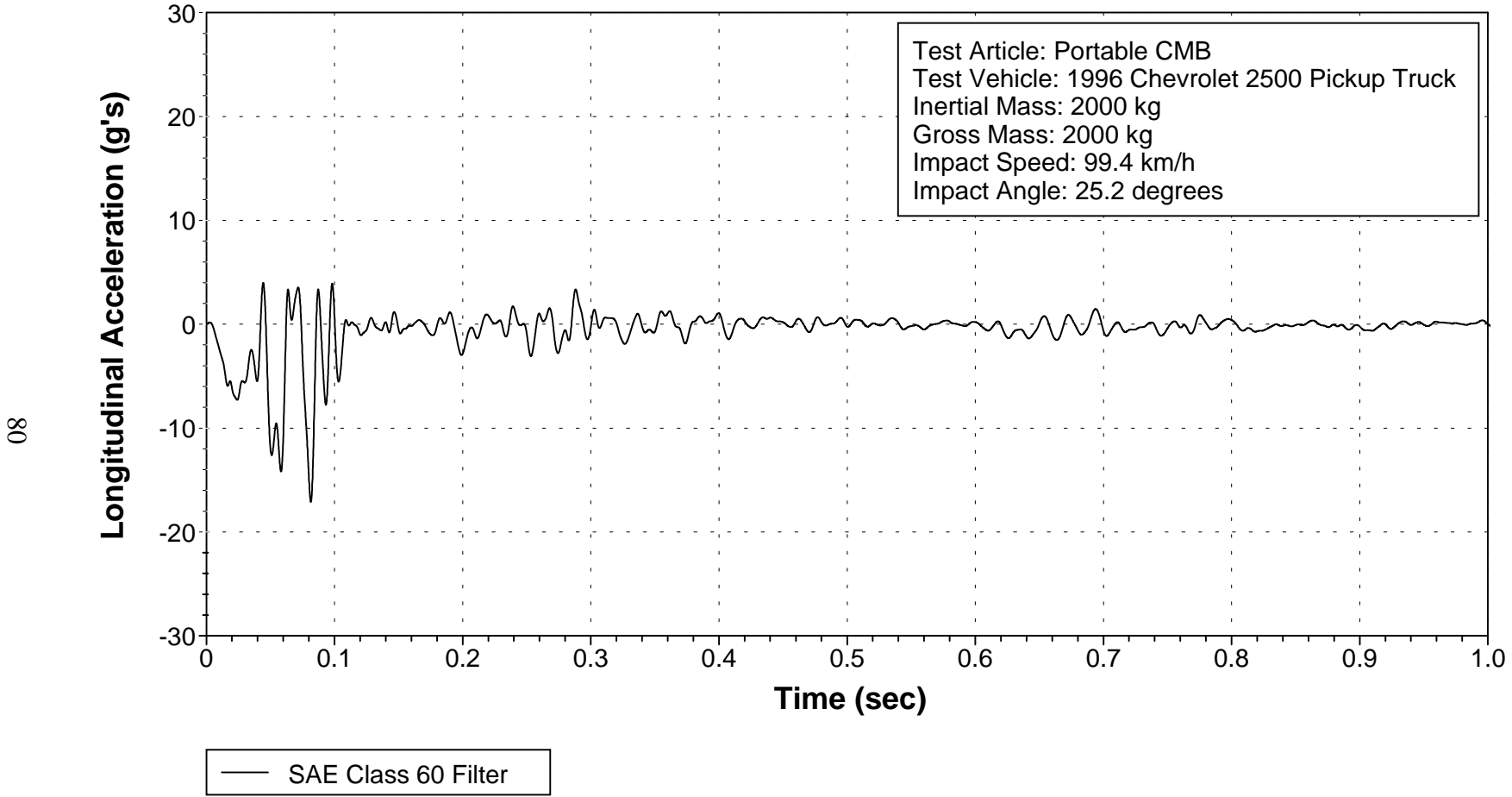


Figure 41. Vehicle Longitudinal Accelerometer Trace for Test 441621-1 (Accelerometer Located at Center of Gravity).

Y Acceleration at CG

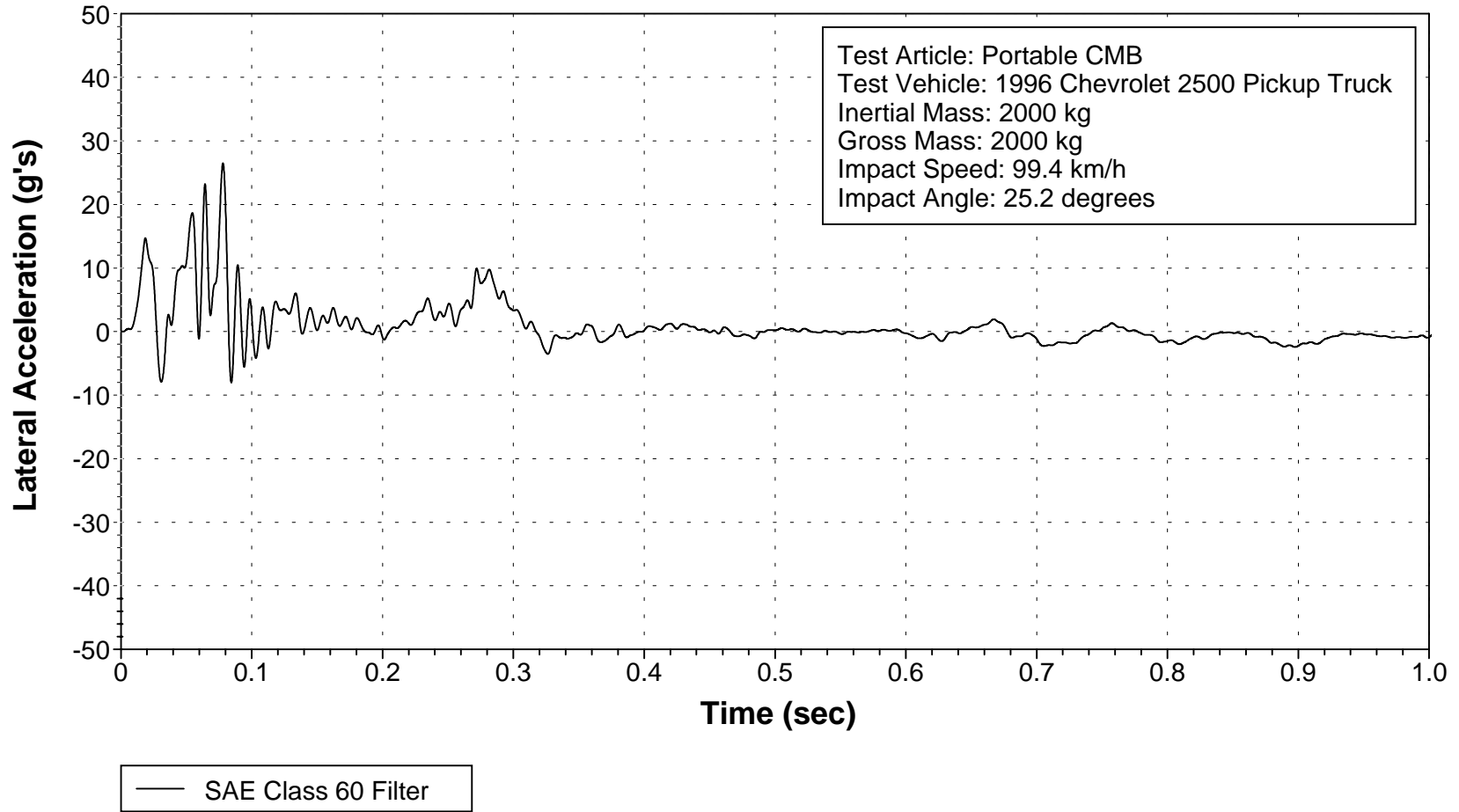


Figure 42. Vehicle Lateral Accelerometer Trace for Test 441621-1 (Accelerometer Located at Center of Gravity).

Z Acceleration at CG

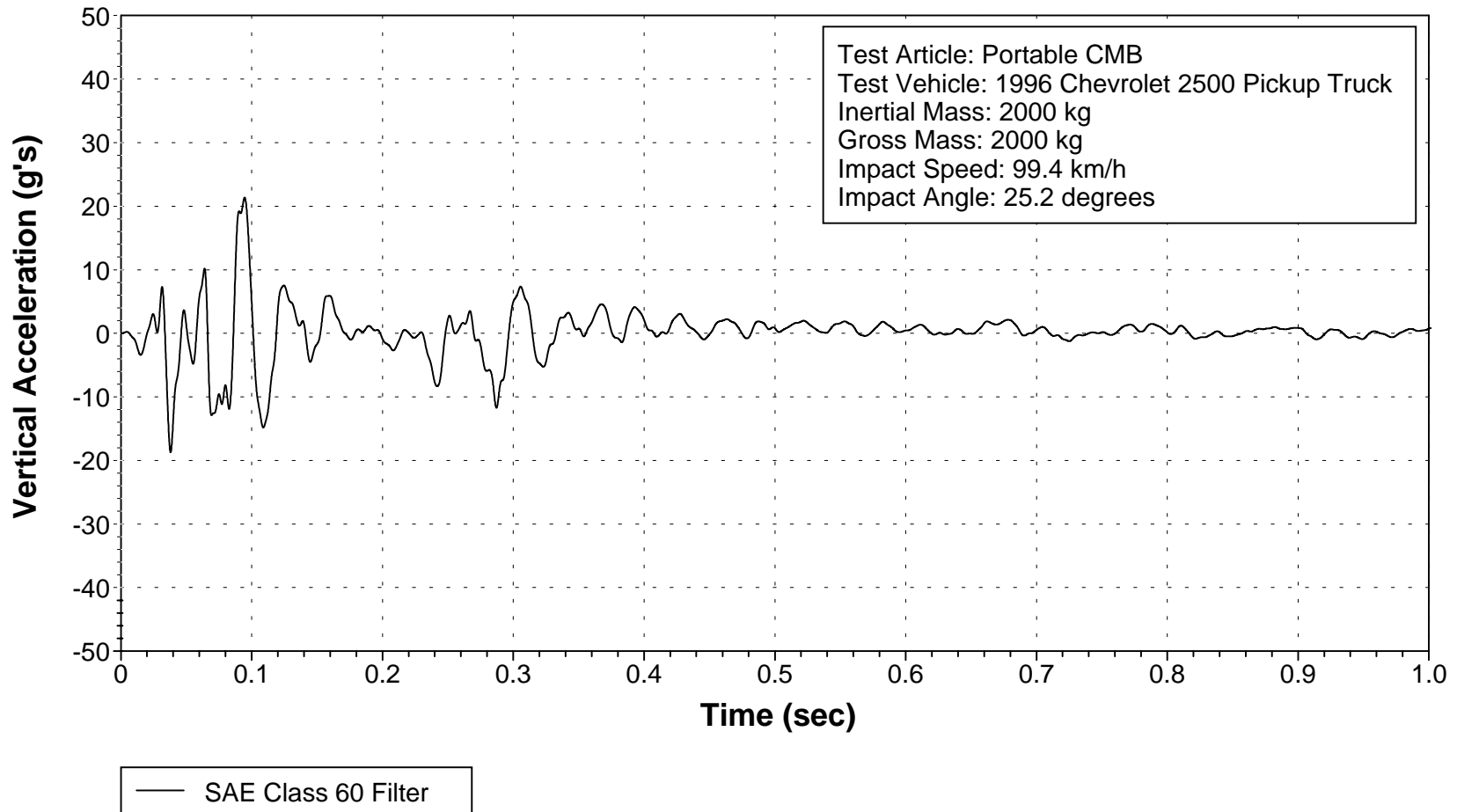
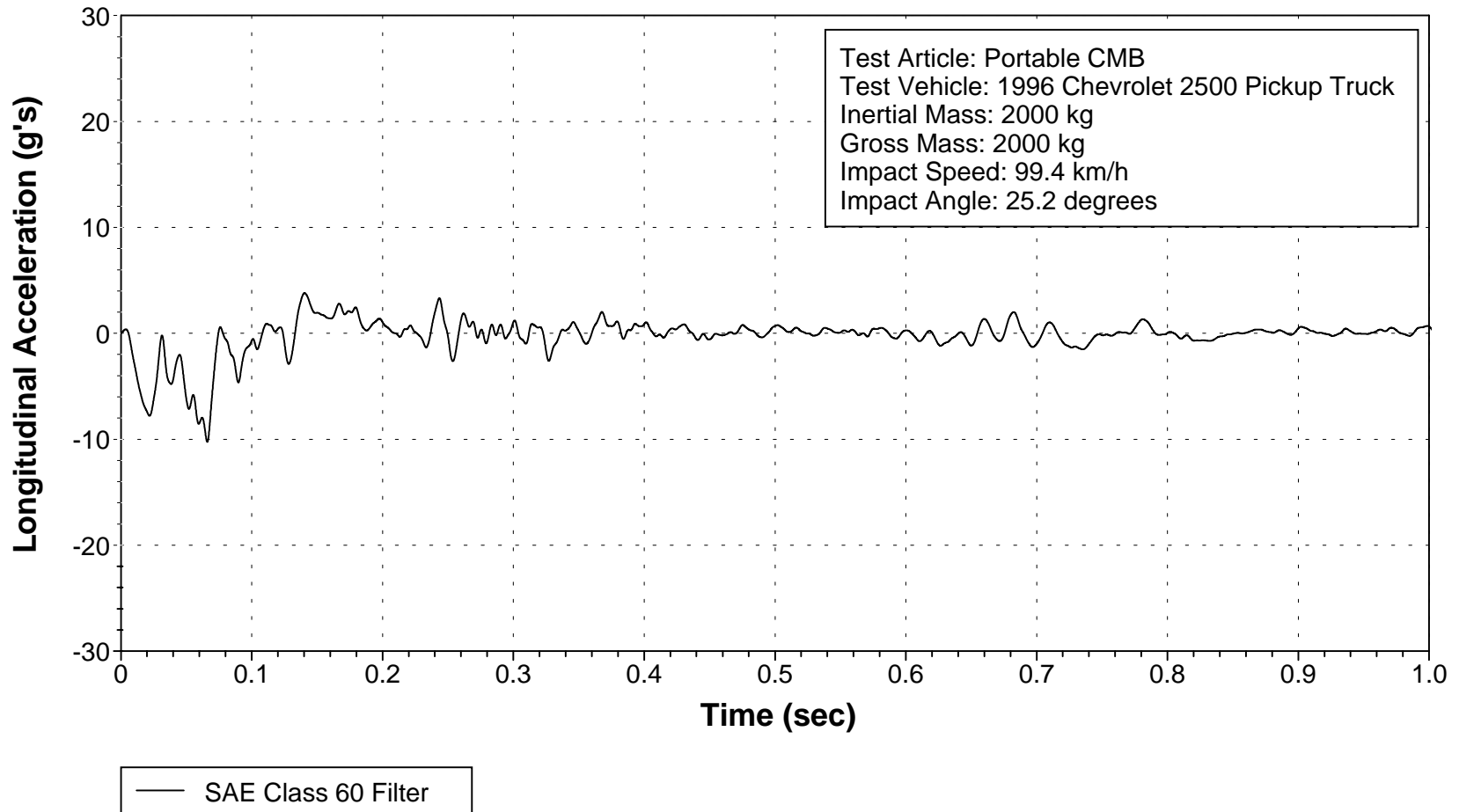


Figure 43. Vehicle Vertical Accelerometer Trace for Test 441621-1 (Accelerometer Located at Center of Gravity).

X Acceleration Over Rear Axle

83



**Figure 44. Vehicle Longitudinal Accelerometer Trace for Test 441621-1
(Accelerometer Located Over Rear Axle).**

Y Acceleration Over Rear Axle

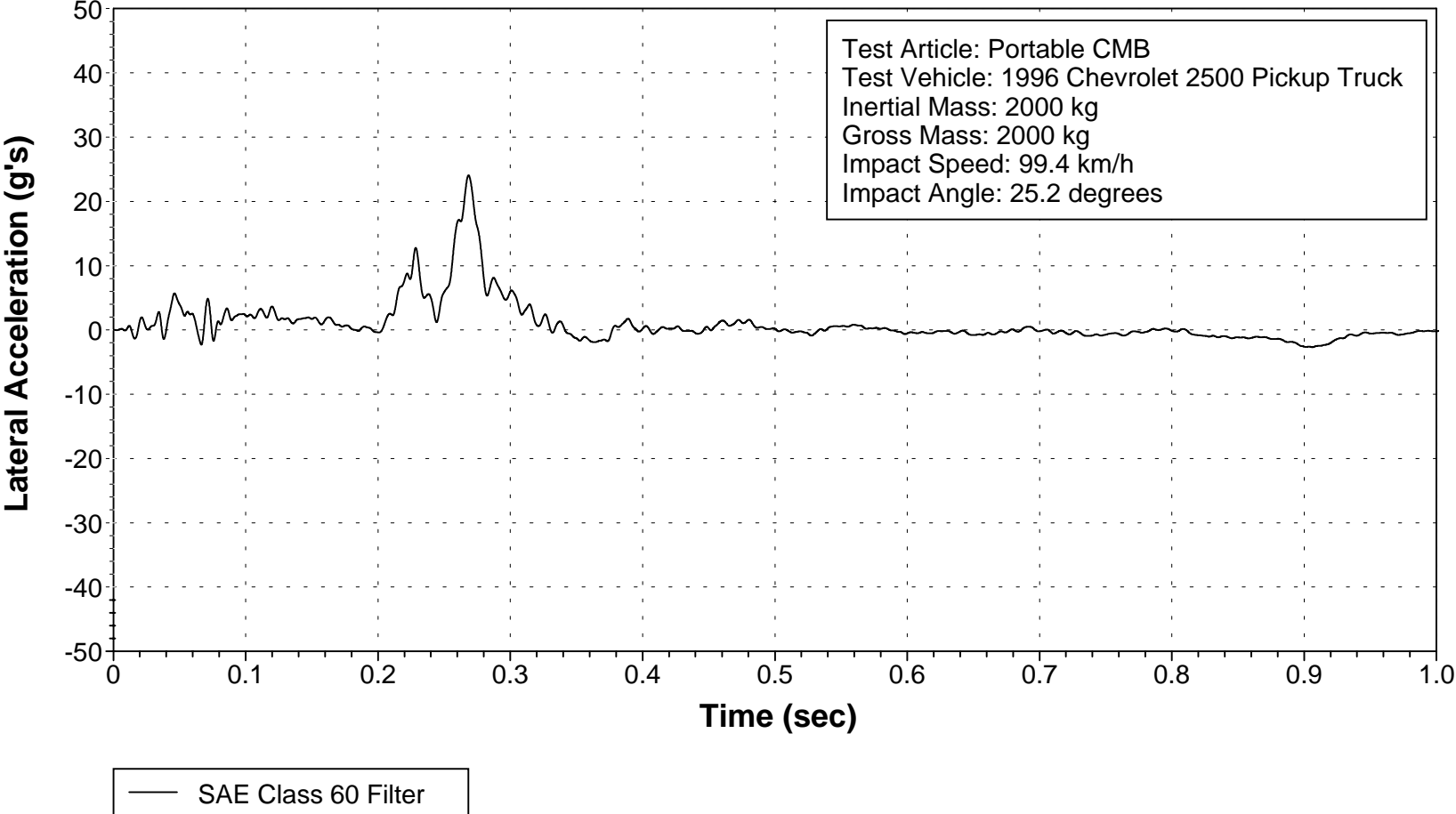
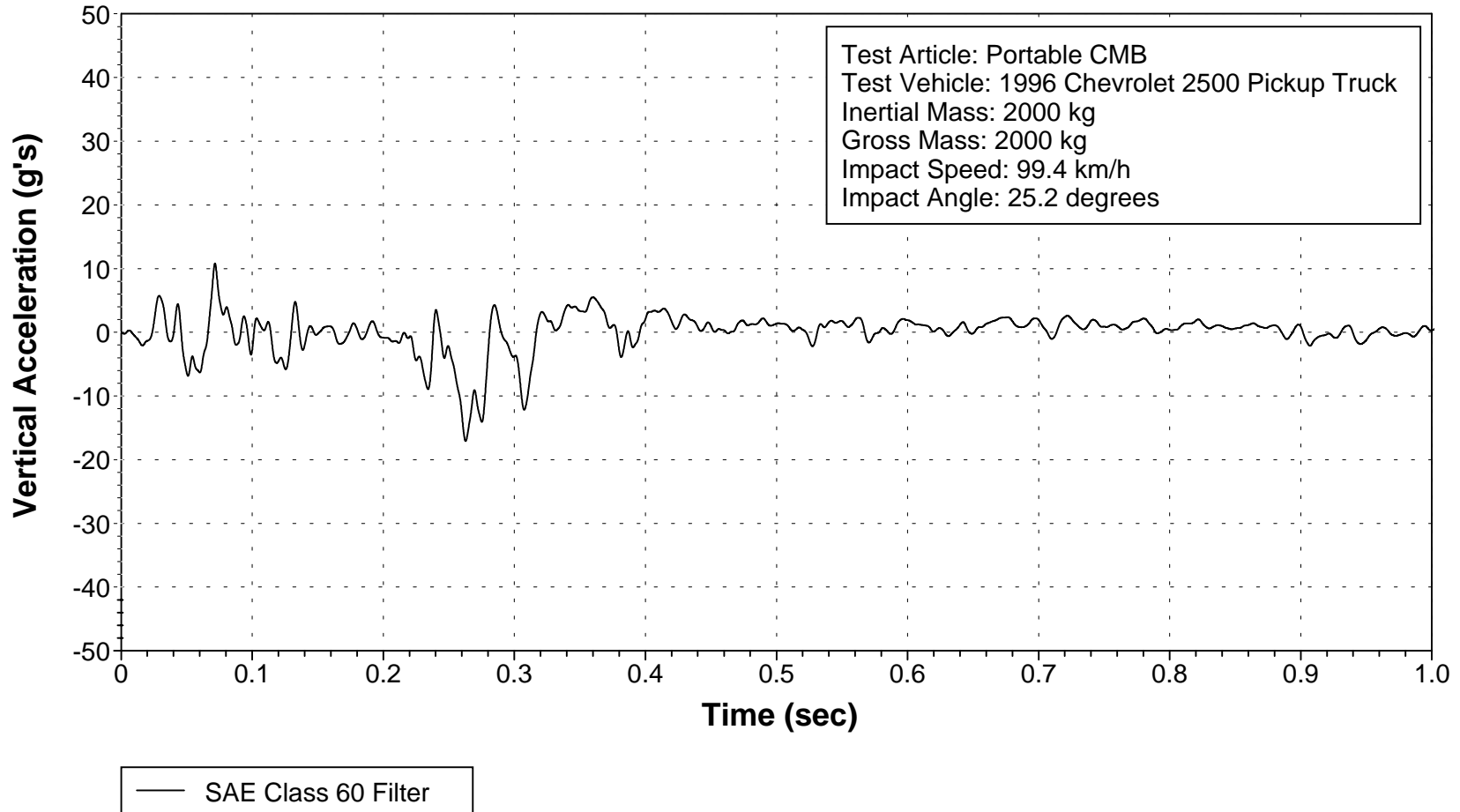


Figure 45. Vehicle Lateral Accelerometer Trace for Test 441621-1 (Accelerometer Located Over Rear Axle).

Z Acceleration Over Rear Axle

85



**Figure 46. Vehicle Vertical Accelerometer Trace for Test 441621-1
(Accelerometer Located Over Rear Axle).**

X Acceleration at CG

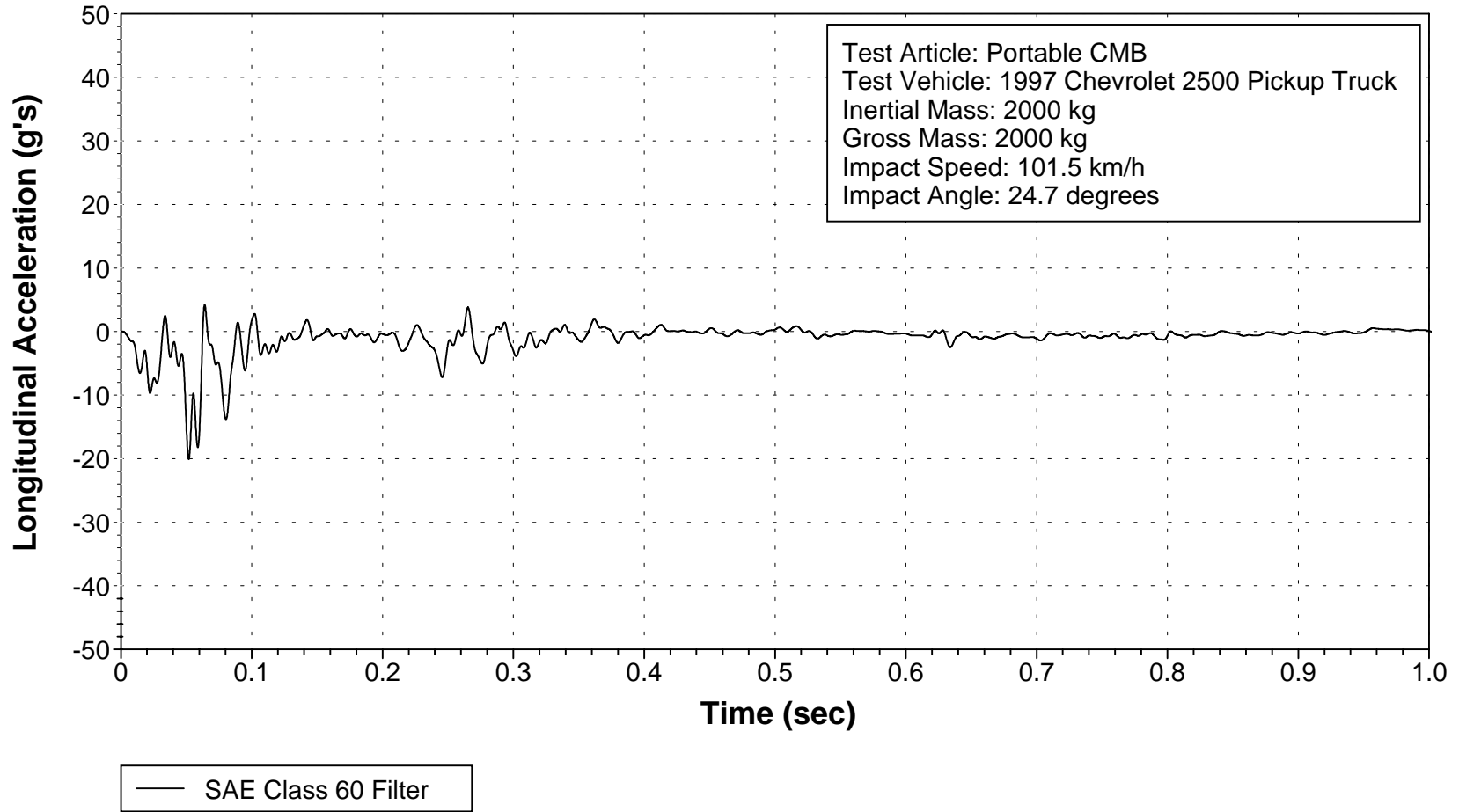


Figure 47. Vehicle Longitudinal Accelerometer Trace for Test 441621-2 (Accelerometer Located at Center of Gravity).

Y Acceleration at CG

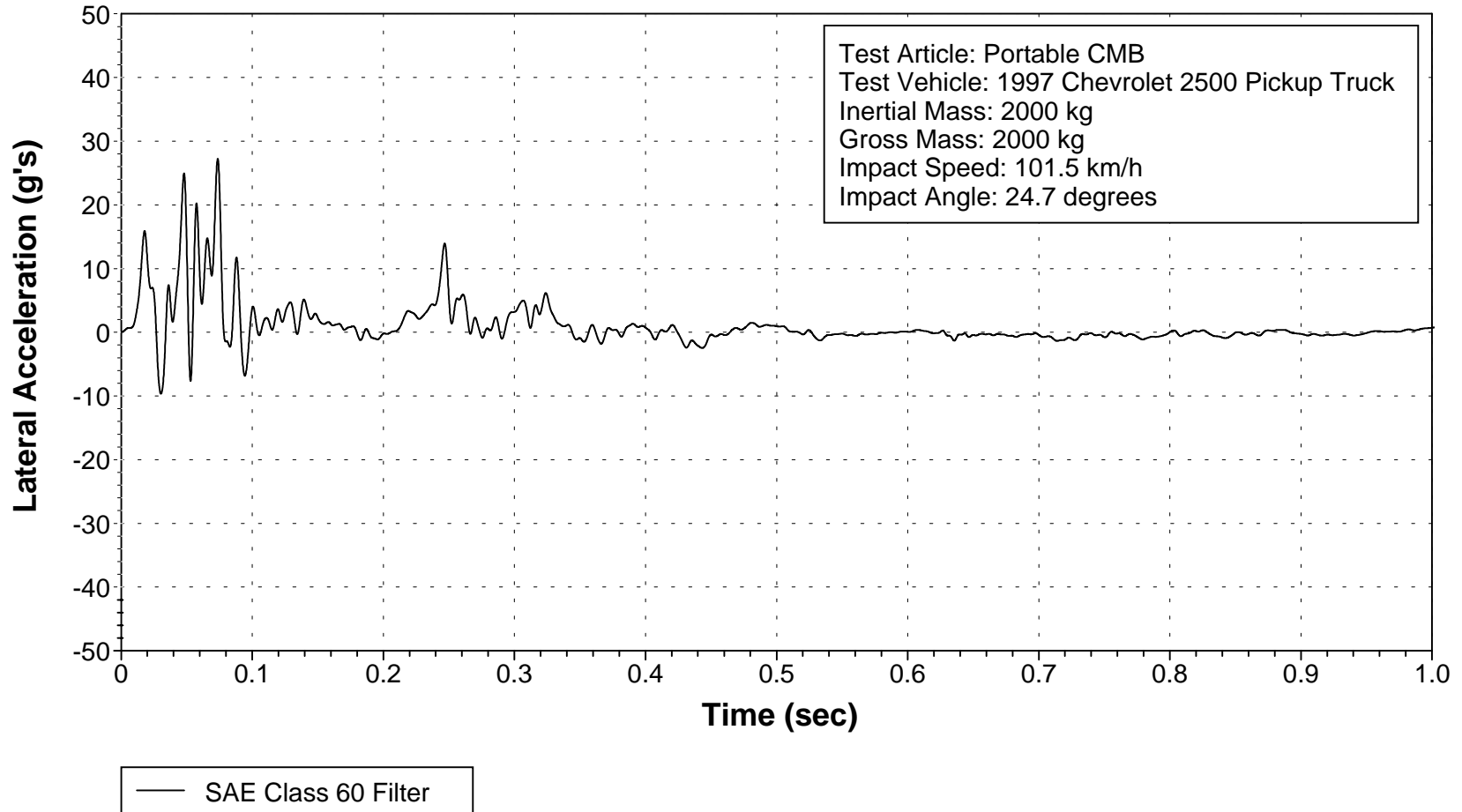


Figure 48. Vehicle Lateral Accelerometer Trace for Test 441621-2 (Accelerometer Located at Center of Gravity).

Z Acceleration at CG

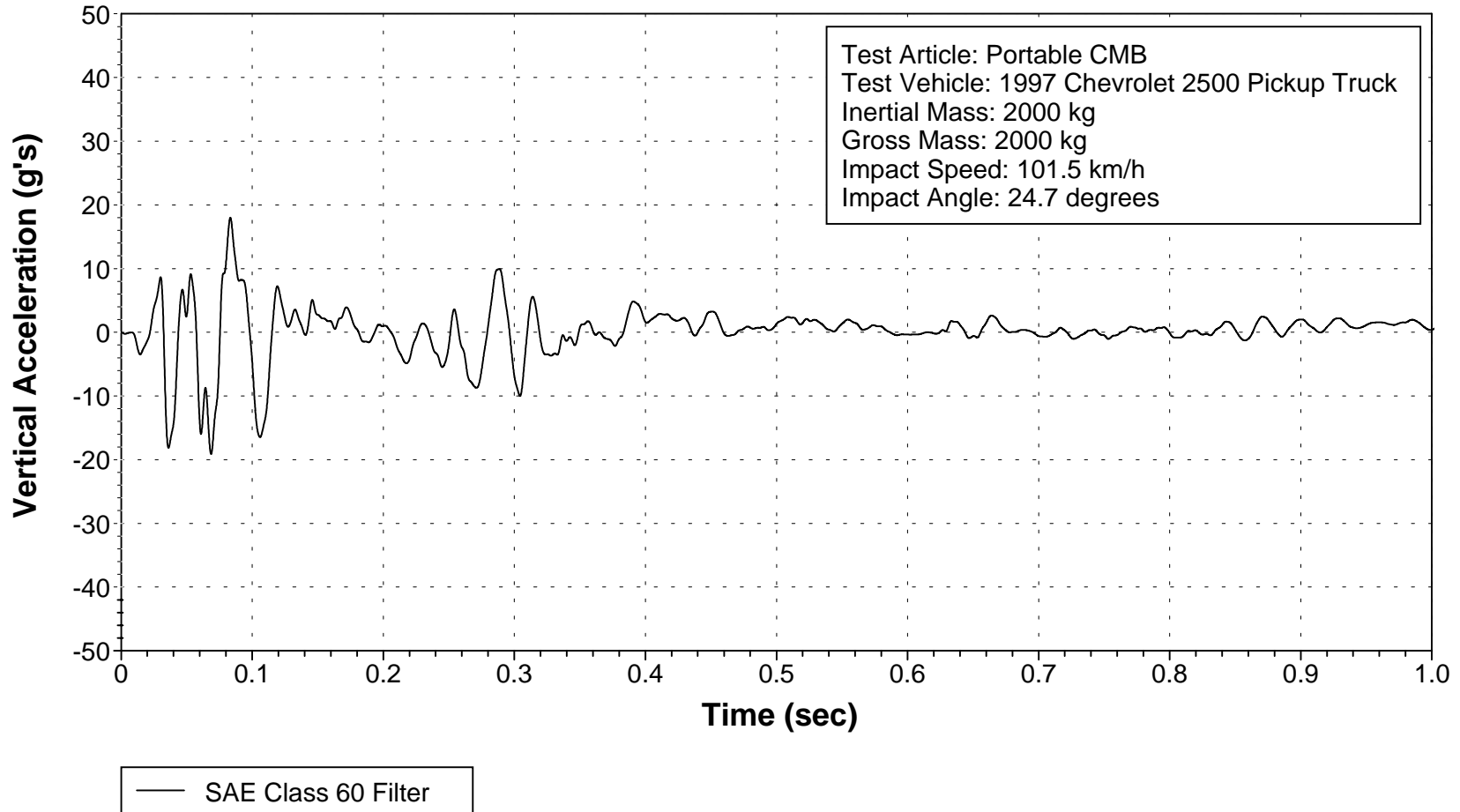
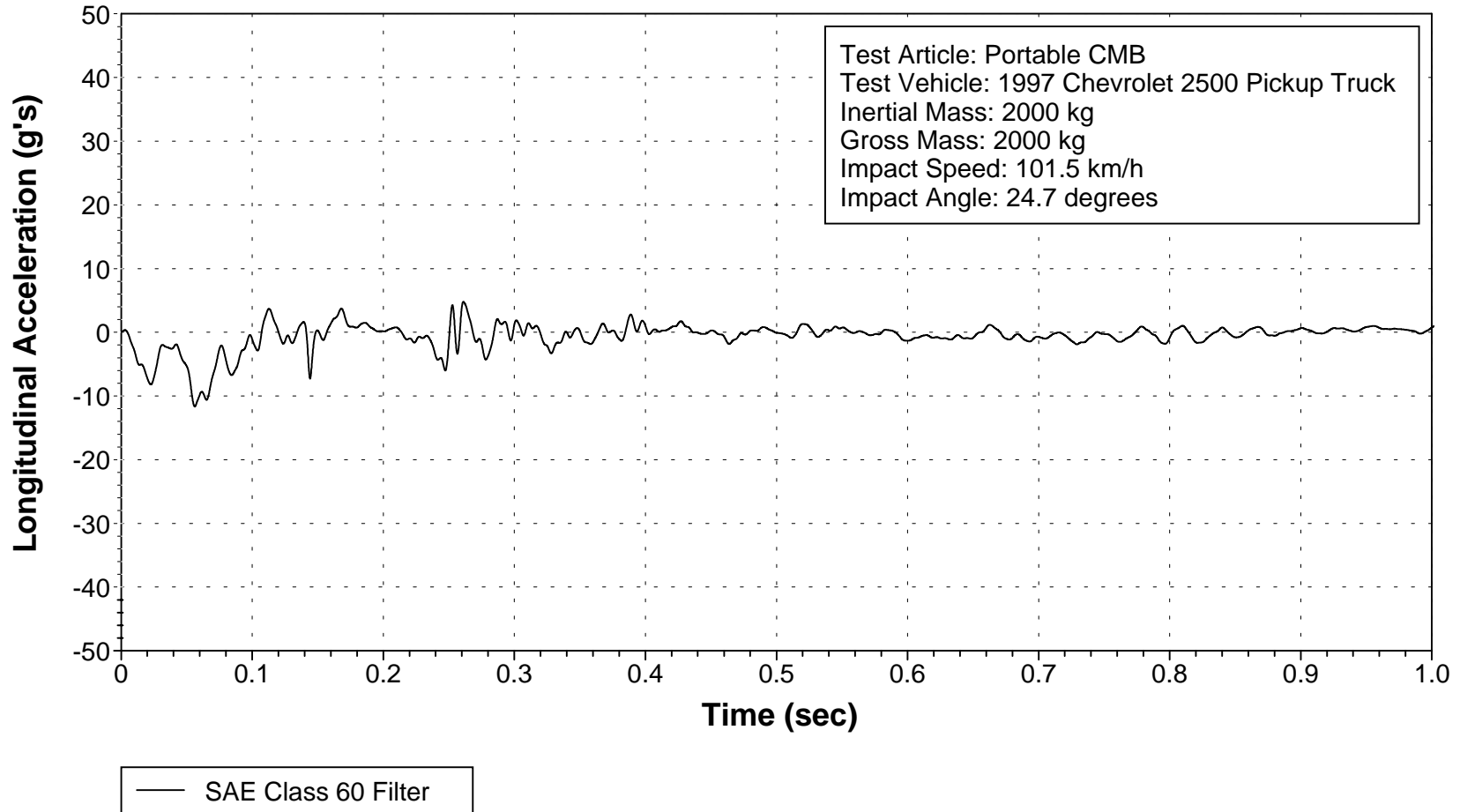


Figure 49. Vehicle Vertical Accelerometer Trace for Test 441621-2 (Accelerometer Located at Center of Gravity).

X Acceleration Over Rear Axle



**Figure 50. Vehicle Longitudinal Accelerometer Trace for Test 441621-2
(Accelerometer Located Over Rear Axle).**

Y Acceleration Over Rear Axle

06

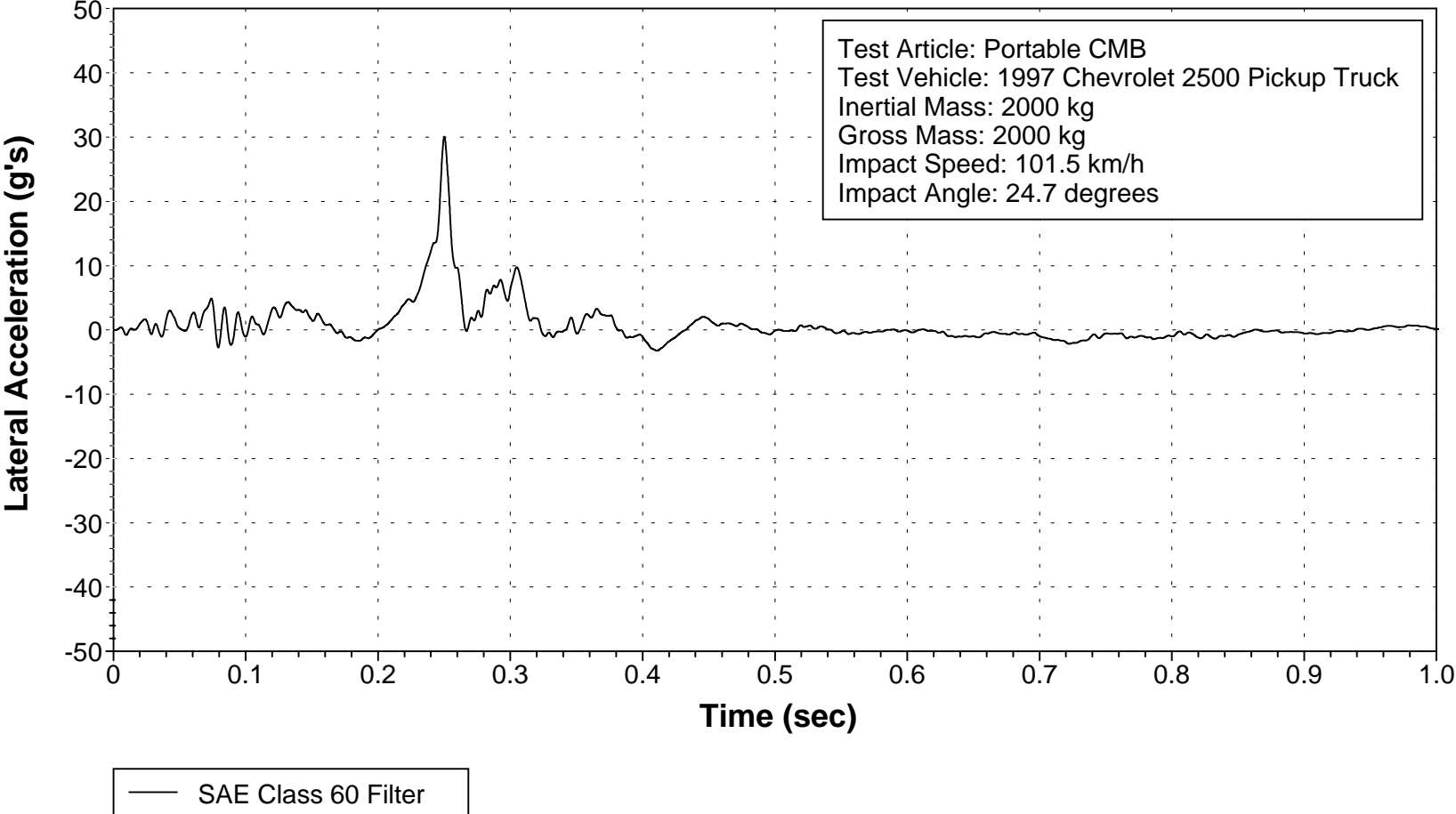
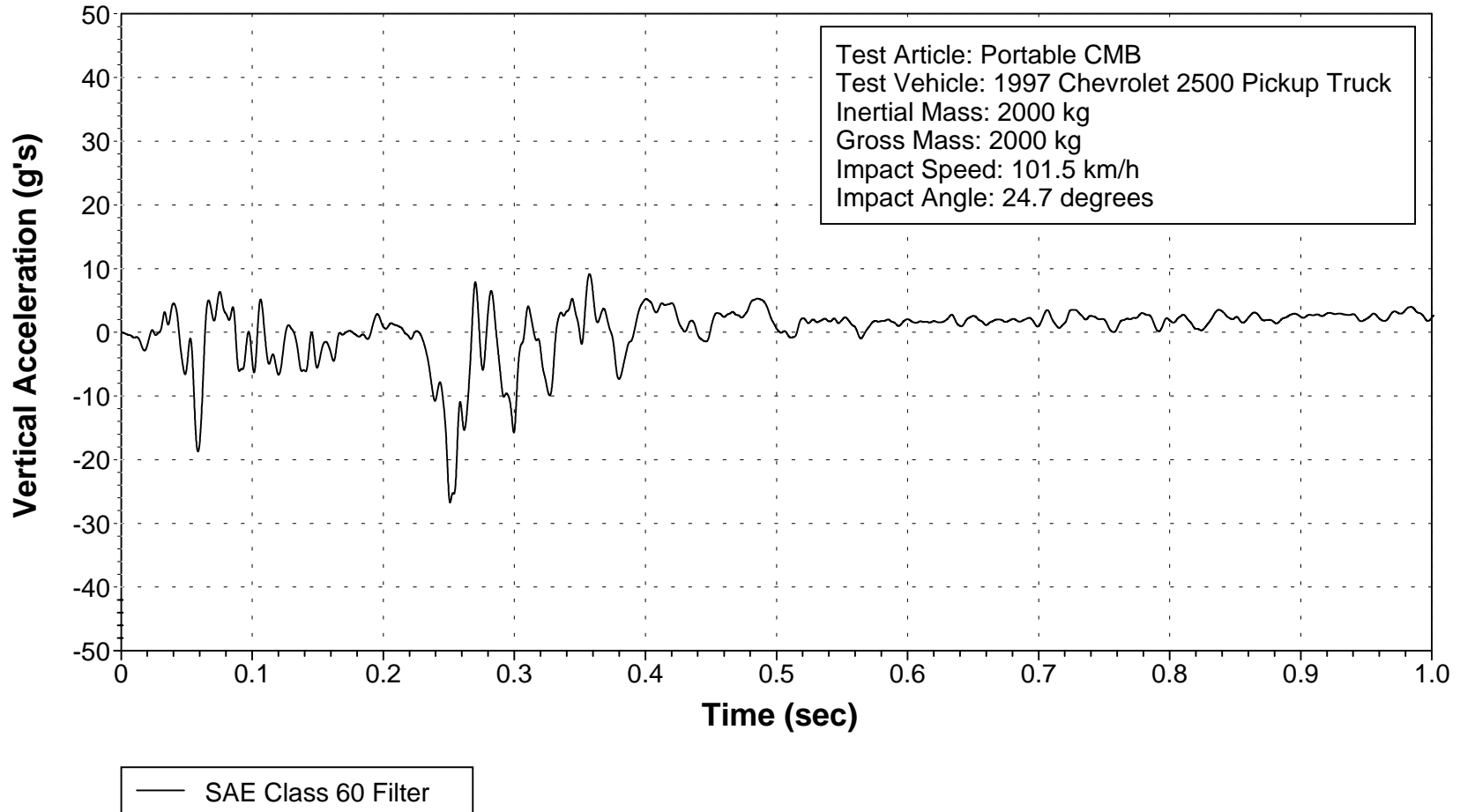


Figure 51. Vehicle Lateral Accelerometer Trace for Test 441621-2 (Accelerometer Located Over Rear Axle).

Z Acceleration Over Rear Axle



**Figure 52. Vehicle Vertical Accelerometer Trace for Test 441621-2
(Accelerometer Located Over Rear Axle).**

X Acceleration at CG

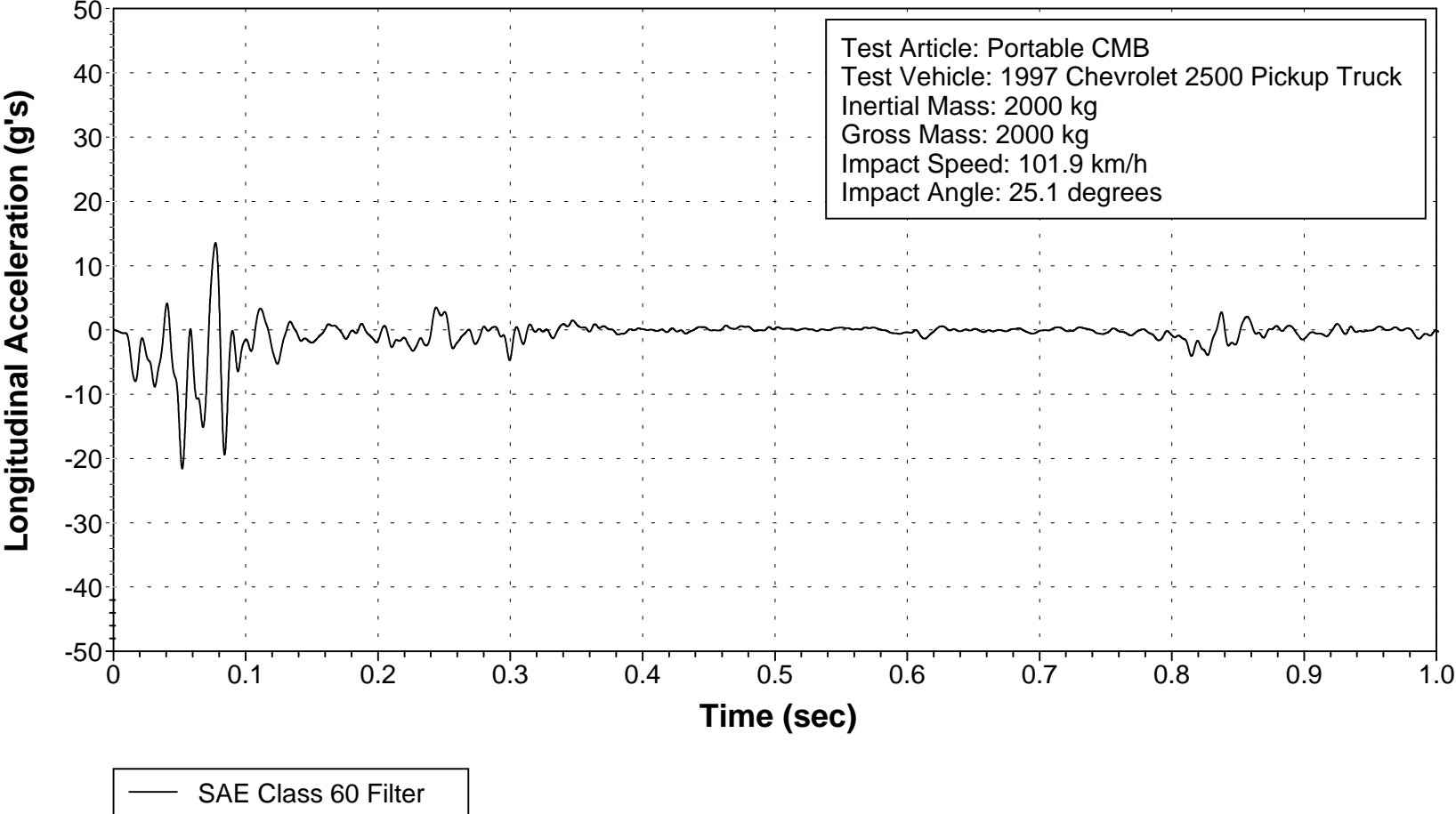
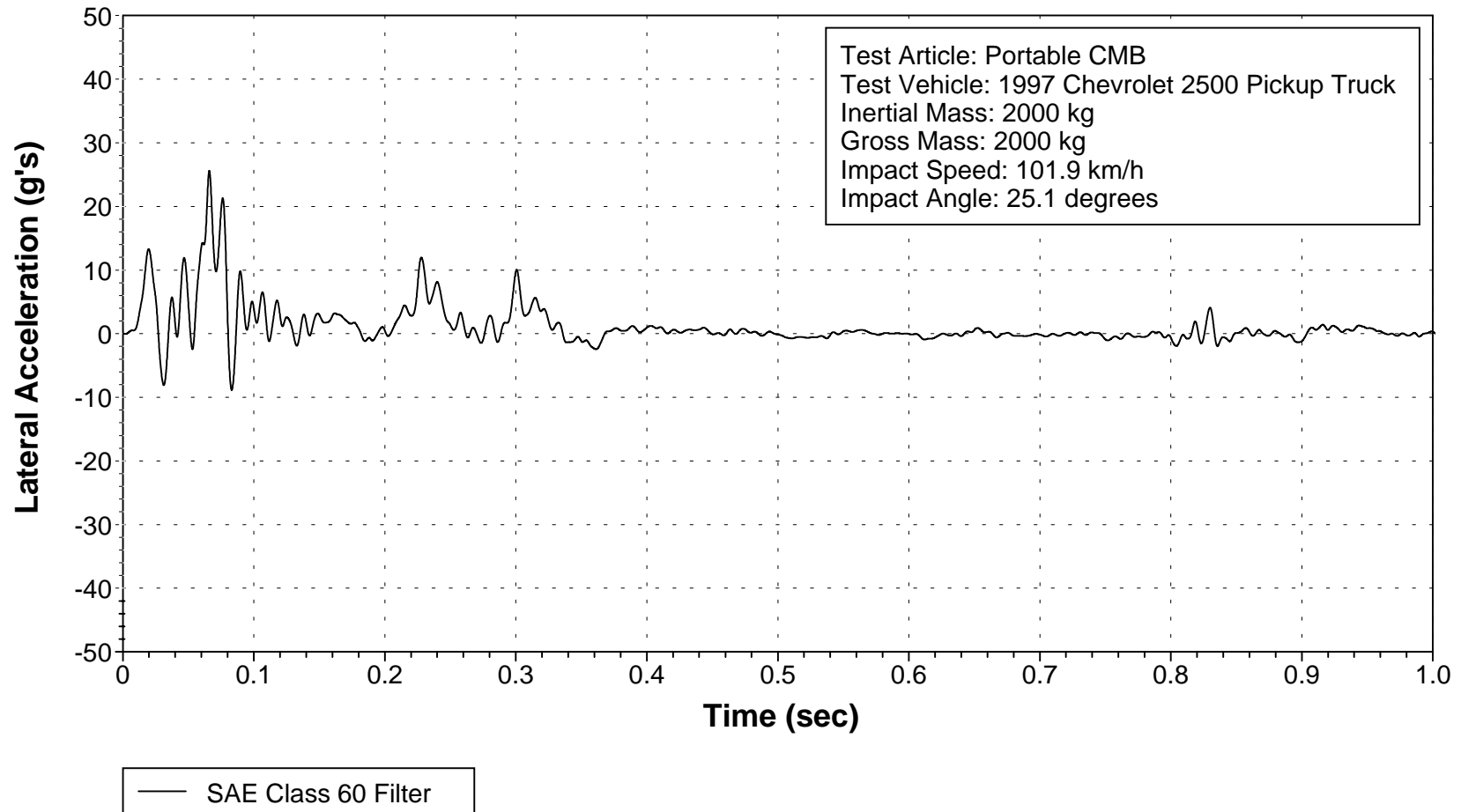


Figure 53. Vehicle Longitudinal Accelerometer Trace for Test 441621-3 (Accelerometer Located at Center of Gravity).

Y Acceleration at CG



**Figure 54. Vehicle Lateral Accelerometer Trace for Test 441621-3
(Accelerometer Located at Center of Gravity).**

Z Acceleration at CG

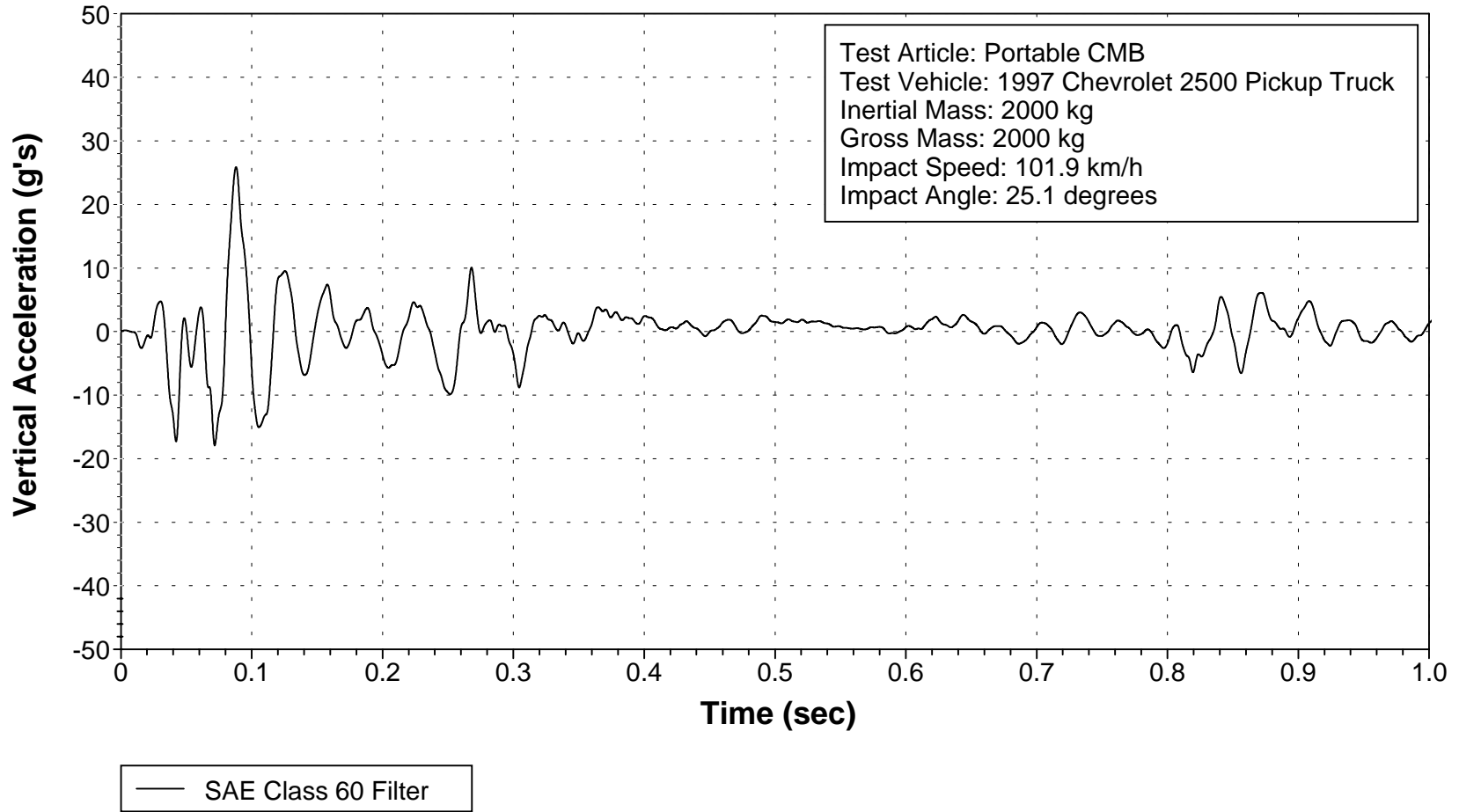
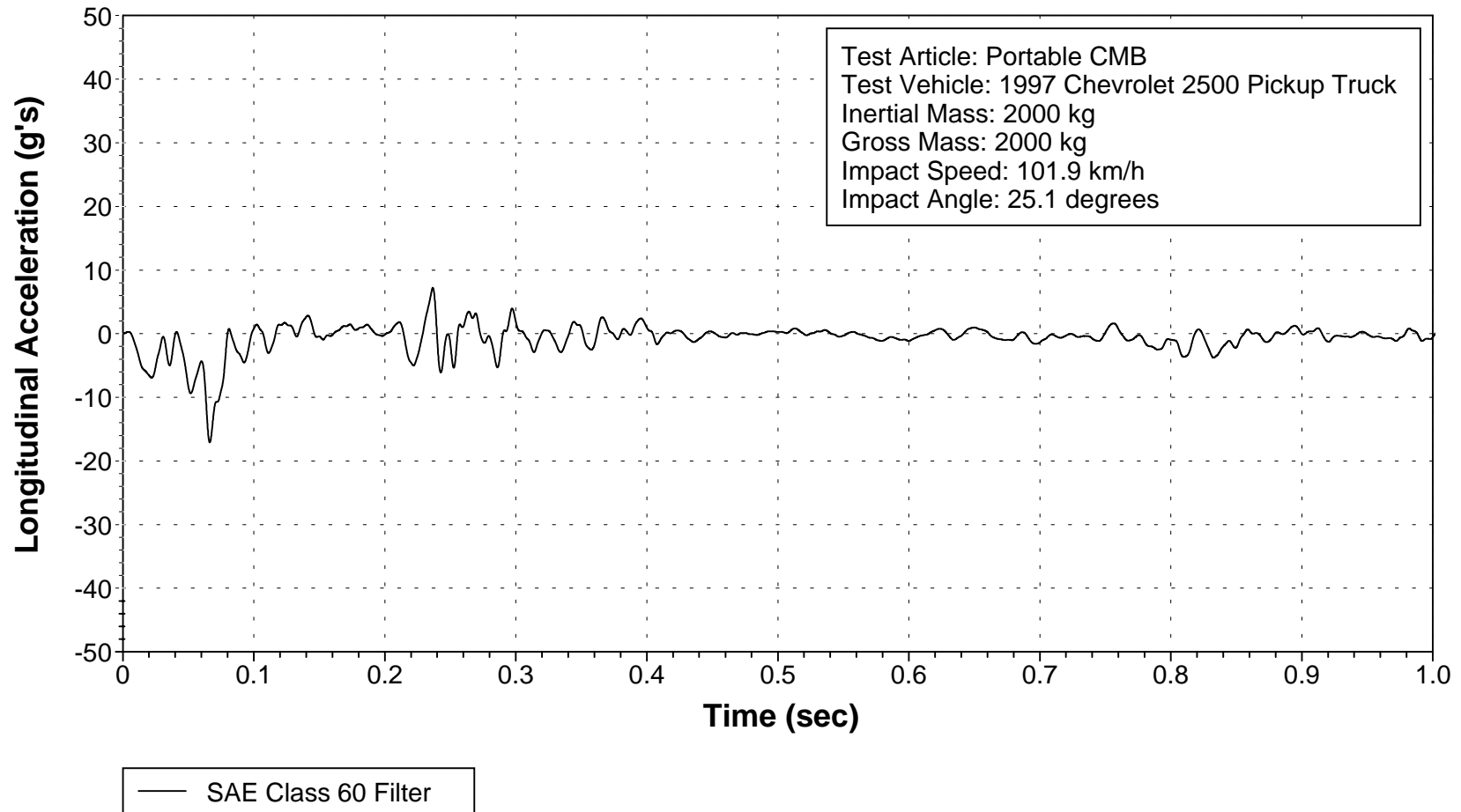


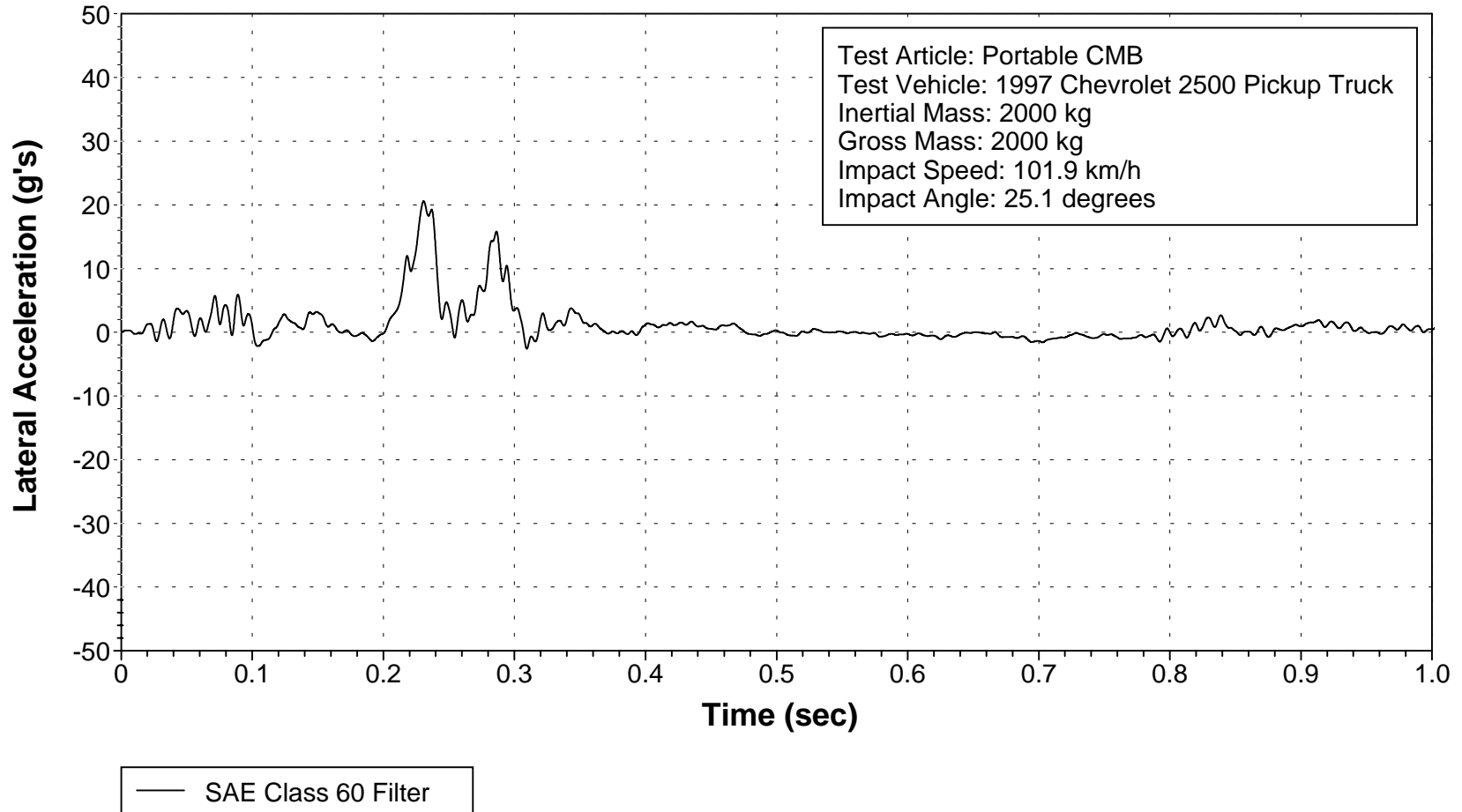
Figure 55. Vehicle Vertical Accelerometer Trace for Test 441621-3 (Accelerometer Located at Center of Gravity).

X Acceleration Over Rear Axle



**Figure 56. Vehicle Longitudinal Accelerometer Trace for Test 441621-3
(Accelerometer Located Over Rear Axle).**

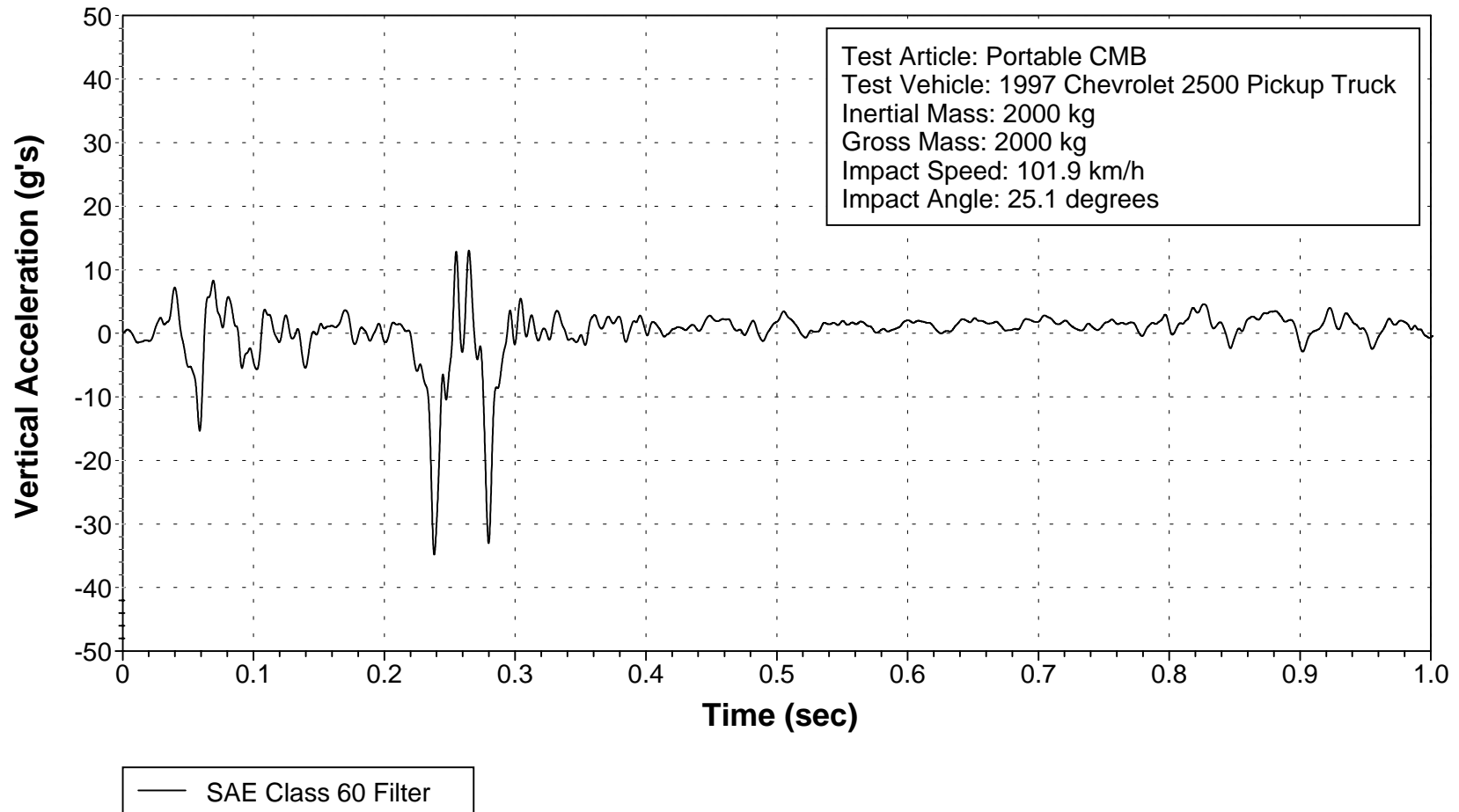
Y Acceleration Over Rear Axle



**Figure 57. Vehicle Lateral Accelerometer Trace for Test 441621-3
(Accelerometer Located Over Rear Axle).**

Z Acceleration Over Rear Axle

96



**Figure 58. Vehicle Vertical Accelerometer Trace for Test 441621-3
(Accelerometer Located Over Rear Axle).**

