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16. Abstract

The purpose of the research reported herein was to develop a transition barrier segment that can be used to connect the low-profile barrier (LPCB(1)-92) to the standard height, F-shape portable concrete barrier (CSB-04). The design of the new transition barrier segment is such that no new hardware is required to connect the transition barrier segment to the low-profile barrier and the F-shape barrier. Researchers used computer simulations to evaluate the proposed design and to examine the location of critical impact points that were used in specifying impact conditions for a full-scale evaluation of the new design. Results of two full-scale tests coupled with results from the computer simulations show that the new transition barrier segment is ready for immediate implementation.

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CHAPTER 1. INTRODUCTION

INTRODUCTION

A low-profile barrier system was developed more than a decade ago for use in low-speed urban work zones where it is required to have frequent cross-traffic entrances. The height of the low-profile barrier was set at 20 inches (508 mm) instead of the standard 32 inches (813 mm) that is used for traditional work zone barriers. The reduced height of the low-profile barrier greatly enhances the ability of drivers who are traversing the work zone to maintain visual contact with the local traffic situation. Since its introduction, the low-profile barrier has demonstrated that it is extremely useful in increasing safety in such situations.

The low-profile barrier system was developed for urban areas with uniformly low speed limits. However, there are a large number of situations where speed limits transition from low speeds to high speeds or vice versa. In such situations, it would be very beneficial to derive the increased visibility benefits of the low-profile barrier in the low speed areas. However, the low-profile barrier cannot now be used in such situations because there is currently no approved hardware that can be used to connect the low-profile barrier to the taller traditional barriers.

The objective of this research is to develop and test a transition barrier segment that can be used to attach the low-profile barrier to standard height, F-shape portable concrete barriers so that improved visibility can be achieved in the low speed zones and full protection can be provided in areas of higher speed. Researchers anticipate that the transition barrier segment can be utilized in both permanent and temporary applications.

BACKGROUND

The low-profile barrier was originally developed for use in low speed work zones. *(1)* Since its introduction, the low-profile barrier has gained widespread acceptance in temporary applications. The primary advantage of the low-profile barrier is that its 20-inch (508 mm) height is low enough to allow drivers to have greatly increased visibility when compared with traditional 32-inch (813 mm) high barriers. This visibility is particularly important in urban areas where it is often necessary to have frequent openings in the barriers that allow cross-traffic vehicles to enter the main traffic stream and vehicles in the main traffic stream to exit.

The low-profile barrier system consists of two different types of barrier segments: the primary low-profile segment and the end-treatment segment. The primary low-profile barrier segment is 20 inches (508 mm) high prismatic concrete barrier section. *(1)* The low-profile end-treatment segment is a sloped-end segment that tapers the 20-inch (508 mm) height of the primary low-profile barrier linearly down to a height of about 4 inches (102 mm). *(2)* The efficacy of the low-profile barrier system has been demonstrated through numerous crash tests. The low-profile barrier system has been successfully tested and approved for Test Level 2 (TL-2) of the *National Cooperative Highway Research Program (NCHRP) Report 350*. *(3)* This system permits its use on roadways with speeds up to and including 43 mi/h (70 km/h). The 20-inch

(508 mm) tall low-profile barrier system was originally intended for use in low-speed urban work zones where sight distance problems at intersections and barrier openings are common. *(2)* In such applications, the low-profile barrier system has been shown to perform well.

In many applications, the posted speed limits are not constant. In such cases, the posted speed may transition from a low-speed situation where speeds are less than or equal to 43 mi/h (70 km/h) to high-speed transitions where speeds are greater than 43 mi/h (70 km/h) over a specified zone, or vice versa. These transitional speed situations can occur in permanent applications where speed limits are increased or decreased based on local conditions. In addition, transitional speed situations can occur in temporary work zones where the normal high speed limits are temporarily reduced in the immediate area of the work zone. In a temporary work zone with a transitional speed situation, a vehicle will move from a posted speed limit that is greater than 43 mi/h (70 km/h) into the area of the work zone where the temporary speed limit has been reduced to 43 mi/h (70 km/h) or less, and then back into an area where the posted speed limit returns to its original higher value. In permanent applications, it will more likely be a one-way transition where the speeds either increase or decrease in a single direction. While it may be of great benefit to increase driver visibility in the reduced speed areas in both permanent applications and temporary work zone applications, there currently is no approved hardware that will allow the direct integration of standard 32-inch (813 mm) high temporary barriers with 20-inch (508 mm) low-profile barriers.

OBJECTIVES/SCOPE OF RESEARCH

The purpose of the research reported herein was to develop a transition barrier segment that can be used to connect the low-profile barrier (LPCB(1)-92) to the standard height, F-shape portable concrete barrier (CSB-04). The proposed transition barrier segment will have to be positioned at a point where the local posted speed limit is 43 mi/h (70 km/h) or less as required for the use of the low-profile barrier. Therefore, it seems logical to develop a transition barrier segment that can perform under the same TL-2 low-speed impact conditions as used for the low-profile barrier itself. Once the transition has been made to a standard barrier height, then the speed limits can be returned to those that are consistent with the TL-3 performance levels of the traditional height barrier.

The transition barrier segment developed is a reinforced concrete element that has a standard 32-inch (813 mm) height concrete barrier cross-section at one end and a 20-inch (508 mm) high low-profile barrier cross-section at the other end. The transition barrier segment was designed so that it is compatible with the standard low-profile connection system on the low end and with the F-shape barrier system on the high end. Therefore, the complete transition between F-shape barriers and the low-profile system is accomplished through the length of a single transition barrier segment and the use of traditional connection hardware. The transition barrier segment has an overall length of 10 ft (3 m).

It was necessary to design the transition barrier segment so that it could safely redirect a vehicle impacting from either direction within the constraints presented in *NCHRP Report 350* guidelines. The precise impact conditions and vehicles selected to examine the performance of the transition barrier segment were based on engineering judgment and results of simulation efforts performed during the research. Researchers performed two full-scale crash tests to demonstrate that the transition barrier segment is compatible with TL-2 criteria as presented in *NCHRP Report 350*.

CHAPTER 2. DESIGN AND SIMULATION

The research team used numerical simulations to lead the design effort for developing a transition barrier segment that will allow a standard height, F-shape portable concrete barrier to be connected to a low-profile concrete barrier. Numerous research studies have successfully utilized simulation codes to simulate vehicle handling, vehicle impacts with roadside objects, and vehicle encroachments over roadside geometric features such as slopes, ditches, and driveways. In these studies, researchers have utilized varying levels of vehicle model sophistication ranging from simple lumped masses, springs and dampers, to detailed finite element representations using many thousands of elements. All simulation codes have their limitations, and they all incorporate different levels of assumptions or approximations. Researchers considered it crucial that the simulation code(s) selected for use in this project be capable of accurately modeling relevant characteristics of the vehicle, the concrete barriers, and the interactions between them. After due consideration, the research team chose the explicit finite element code LS-DYNA for this project based on several reasons including:

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

Based upon numerous crash tests and computer studies, it is well established that both the low-profile barrier and the F-shape barrier result in very stable and well controlled vehicle redirections at the TL-2 level. Based upon interactions with engineers at Texas Department of Transportation (TxDOT) and discussions within the research team at Texas Transportation Institute (TTI), it was determined that the transition barrier section should be as short as practical while still maintaining the ability for the segment to be able to connect directly to the two standard TxDOT barrier sections. After considerable deliberation, researchers decided that the simplest shape that could be developed for the transition barrier segment would be to simply morph the low-profile shape into the F-shape using straight lines and planar surfaces at a rate that would allow the traditional barrier connections to be maintained at either end of the transition barrier segment. Based primarily upon engineering judgment and crash test experience, a proposed transition barrier segment was designed to provide a smooth transition between the two different standard barrier profiles.

The proposed transition barrier segment design selected for development is a 10 ft (3 m) segment that transitions from the F-shape barrier shape on one end to the low-profile barrier shape on the other end. On the F-shape barrier end, the transition barrier connects using the standard cross-blot connections for the F-shape barrier system. Connection to the low-profile barrier system is made using the standard bolted connections used in the low-profile system. Use of standard connections on each end of the transition segment, eliminates the need for inventorying additional hardware. Figure 1 presents an isometric sketch of the proposed transition barrier segment.

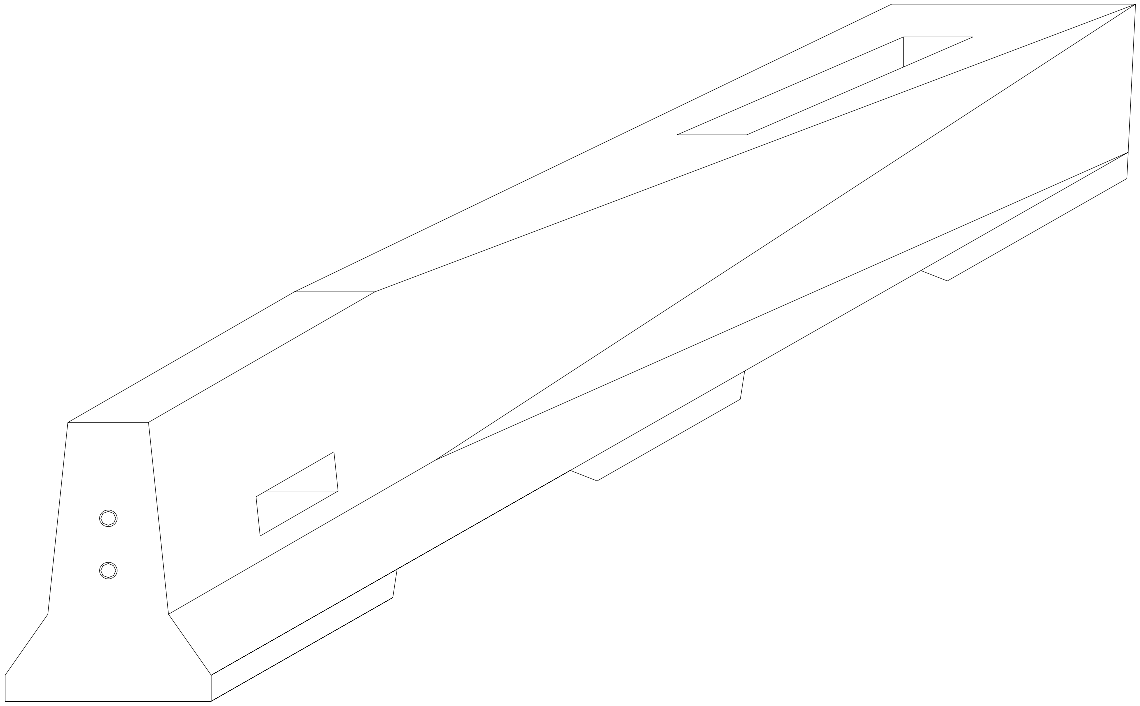


Figure 1. Isometric Sketch of Proposed Transition Barrier Segment.

Both the low-profile barrier and the F-shape barrier segments are structurally capable of redirecting TL-3 impacts. Therefore, the only question with regard to the design of the new transition barrier segment, which is only required to resist a TL-2 impact, is whether the new shape will destabilize an errant vehicle. To investigate this effect, researchers performed initial vehicular impact simulations with a rigid barrier model that was assumed to be fixed to the ground. Using a fixed, rigid barrier model reduces the size of the finite element model and thus allows a large number of design iterations to be performed in a relatively short period of time. These initial rigid barrier system simulations were also used to evaluate critical points for vehicular impact. Four different impact points were investigated, as shown in Figure 2.

Vehicles used in the more detailed simulations were a 4409-lb (2000 kg) pickup truck and an 1808-lb (820 kg) small car. The pickup truck model used was the reduced version originally developed by the National Crash Analysis Center (NCAC) and modified by TTI to include a deformable suspension system. The small car Geo Metro model used was also originally developed by NCAC and modified later at Politecnico di Milano, Italy.

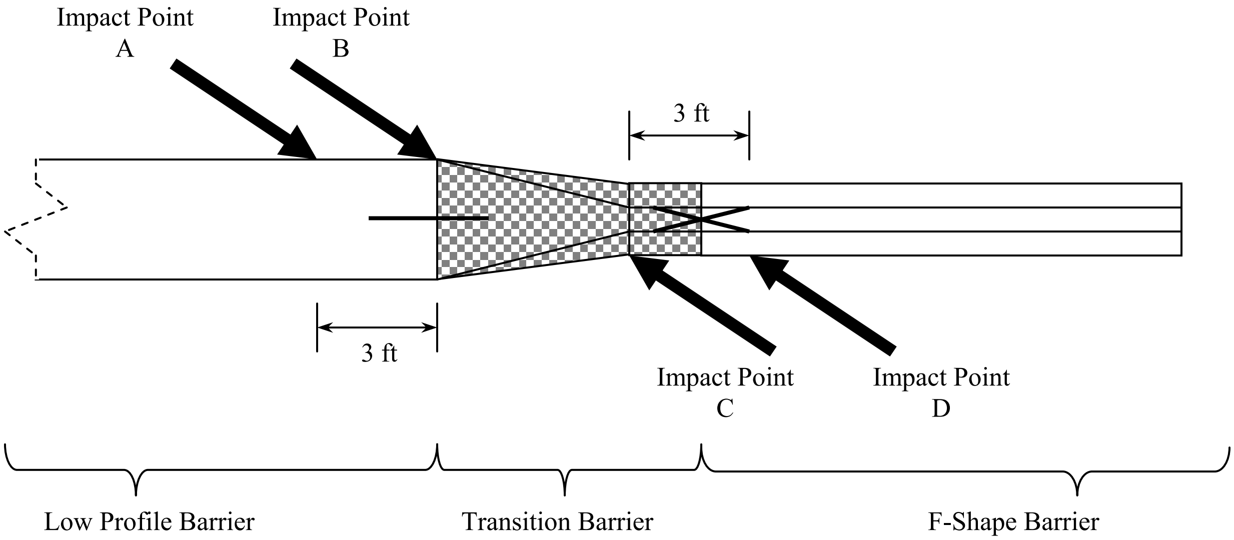


Figure 2. Impact Point Locations.

Pickup truck impact simulations with the rigidly fixed barrier were performed for all four impact points shown in Figure 2. In the case of impact points A and B, the vehicle traveled from the low-profile barrier to the F-shape barrier. For impact points C and D, the vehicle traveled from the F-shape barrier to the low-profile barrier. Impact points B and C were at the locations of slope change on the transition barrier segment. Impact points A and D were located 3 ft (1 m) upstream of these slope initiation points. The objective of conducting impact simulations 3 ft (1 m) upstream of the slope change points was to determine if the lateral slope changes (transition in barrier width), coupled with the vertical slope changes (transition in barrier height), would have a greater effect on vehicle stability once the vehicle had undergone some initial deformation and was fully engaged with the barrier in the impact region.

Figure 3 shows simulation results for the pickup truck impact transitioning from the low-profile barrier to the F-shape barrier, 3 ft (1 m) upstream of the slope change point (impact point A). Figure 4 shows simulation results for the pickup truck impact transitioning from the low-profile barrier to the F-shape barrier, at the slope change point (impact point B). Figure 5 shows simulation results for the pickup truck impact transitioning from the F-shape barrier to the low-profile barrier, 3 ft (1 m) upstream of the slope change point (impact point D). Figure 6 shows simulation results for the pickup truck impact transitioning from the F-shape barrier to the low-profile barrier, at the slope change point (impact point C). It can be seen from the simulation results presented in Figures 3 through 6 that the pickup truck was successfully redirected with no concerns regarding vehicular stability. As expected, impacts A and B, while the pickup was transitioning from the low-profile barrier to the F-shape barrier, resulted in a slightly higher vehicle climb. However, this increase in climb did not lead to any vehicular instability concerns.

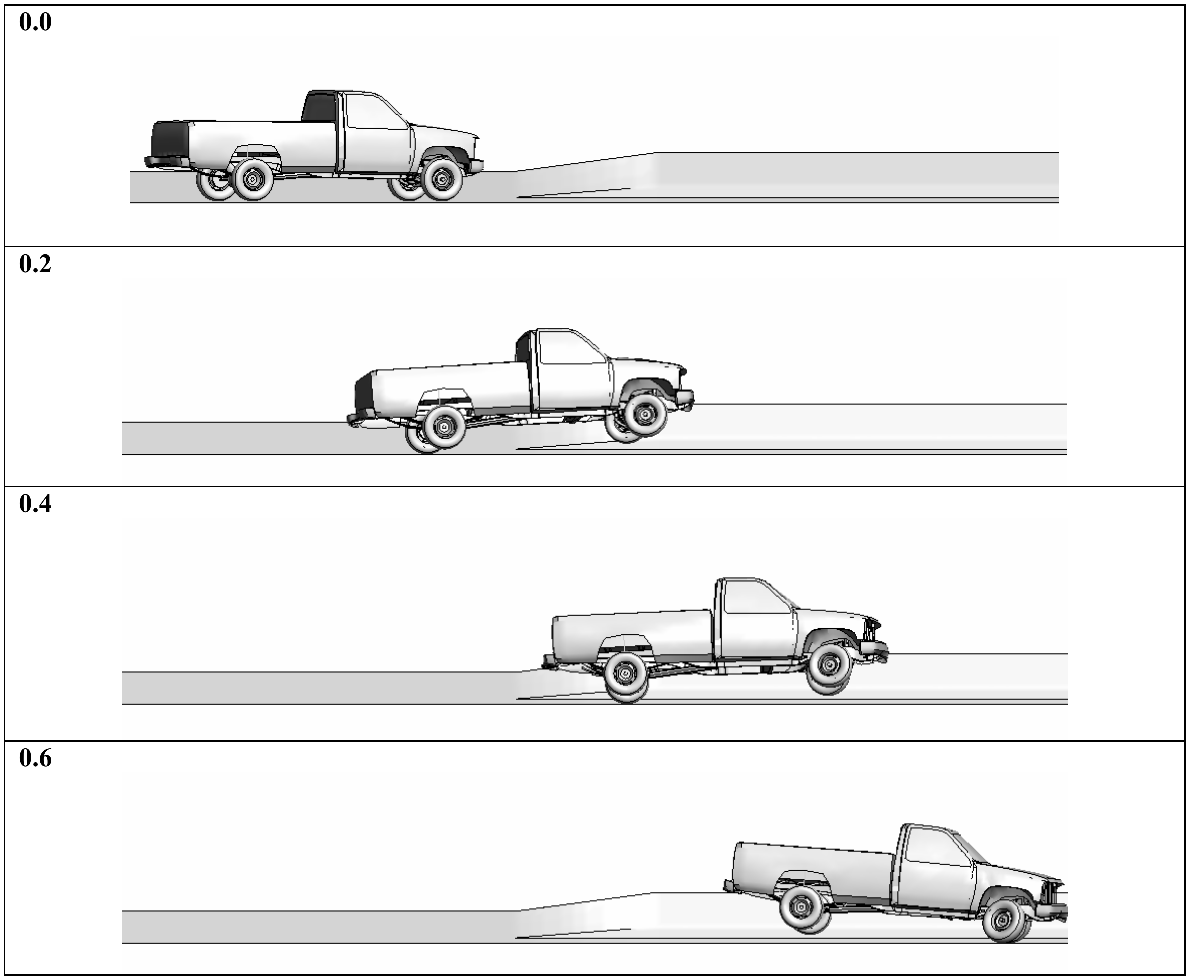


Figure 3. Pickup Truck Impact from Low-Profile Barrier to F-Shape Barrier, 3 ft (1 m) Upstream of the Slope Change Point (Impact Point A).

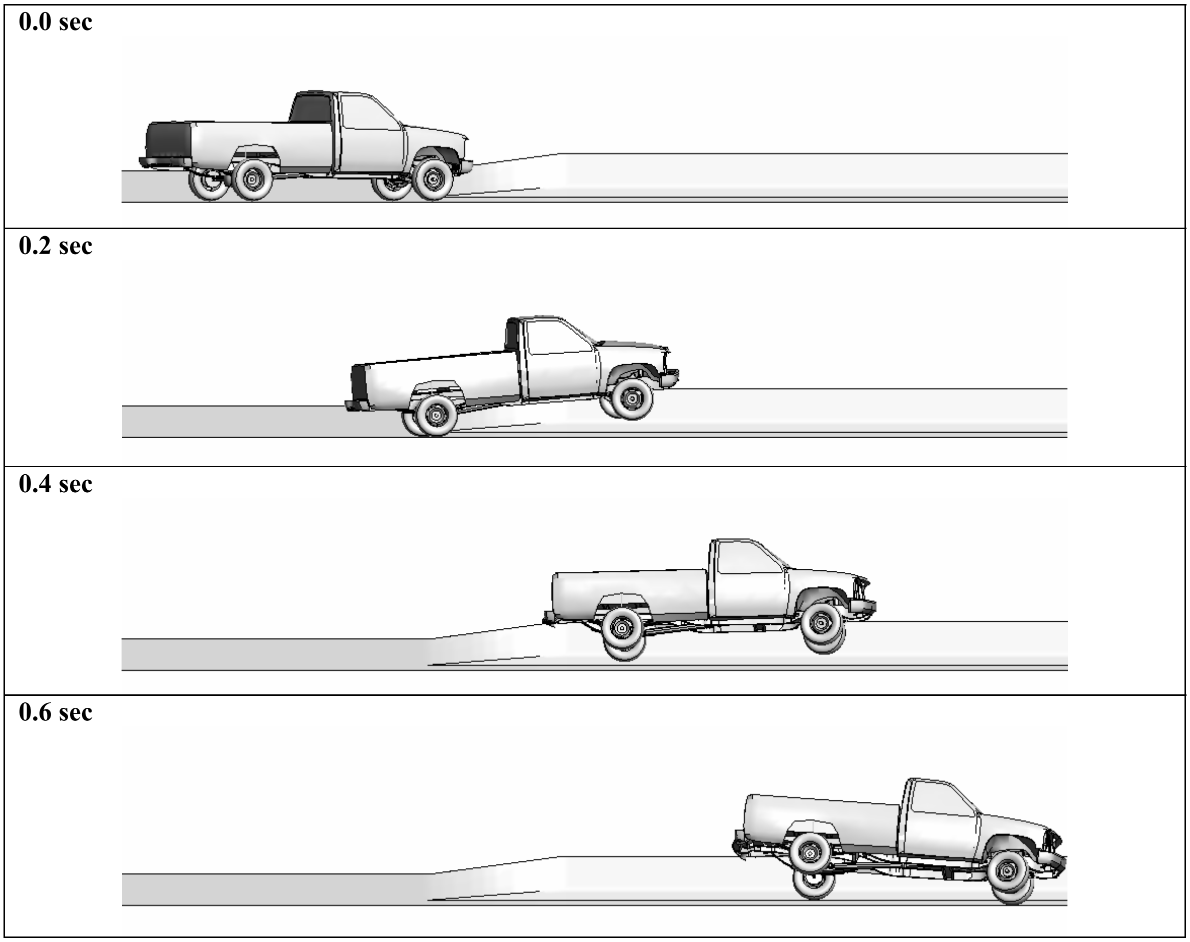


Figure 4. Pickup Truck Impact Transitioning from Low-Profile Barrier to F-Shape Barrier, at the Slope Change Point (Impact Point B).

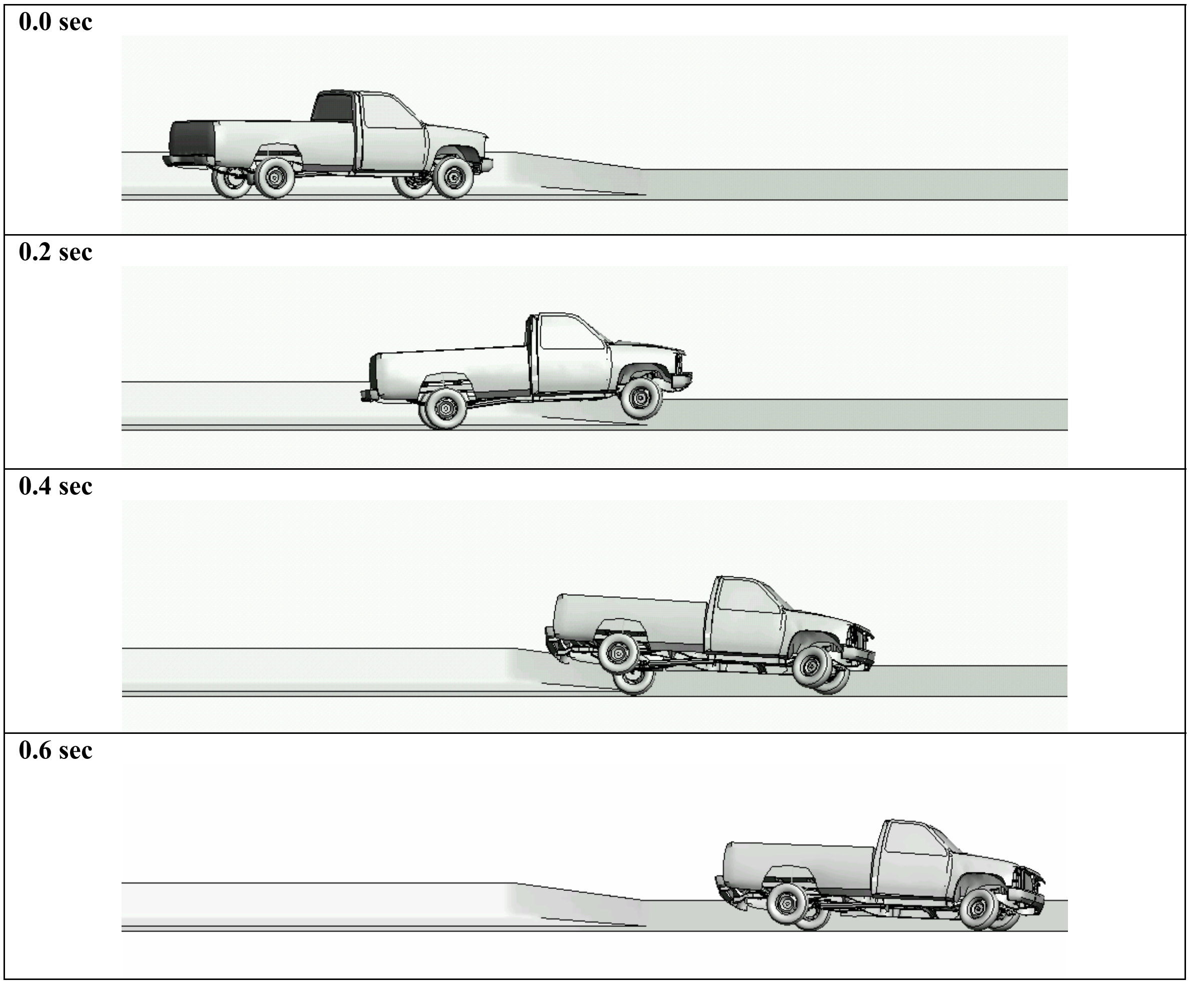


Figure 5. Pickup Truck Impact Transitioning from F-Shape Barrier to Low-Profile Barrier, 3 ft (1 m) Upstream of the Slope Change Point (Impact Point D).

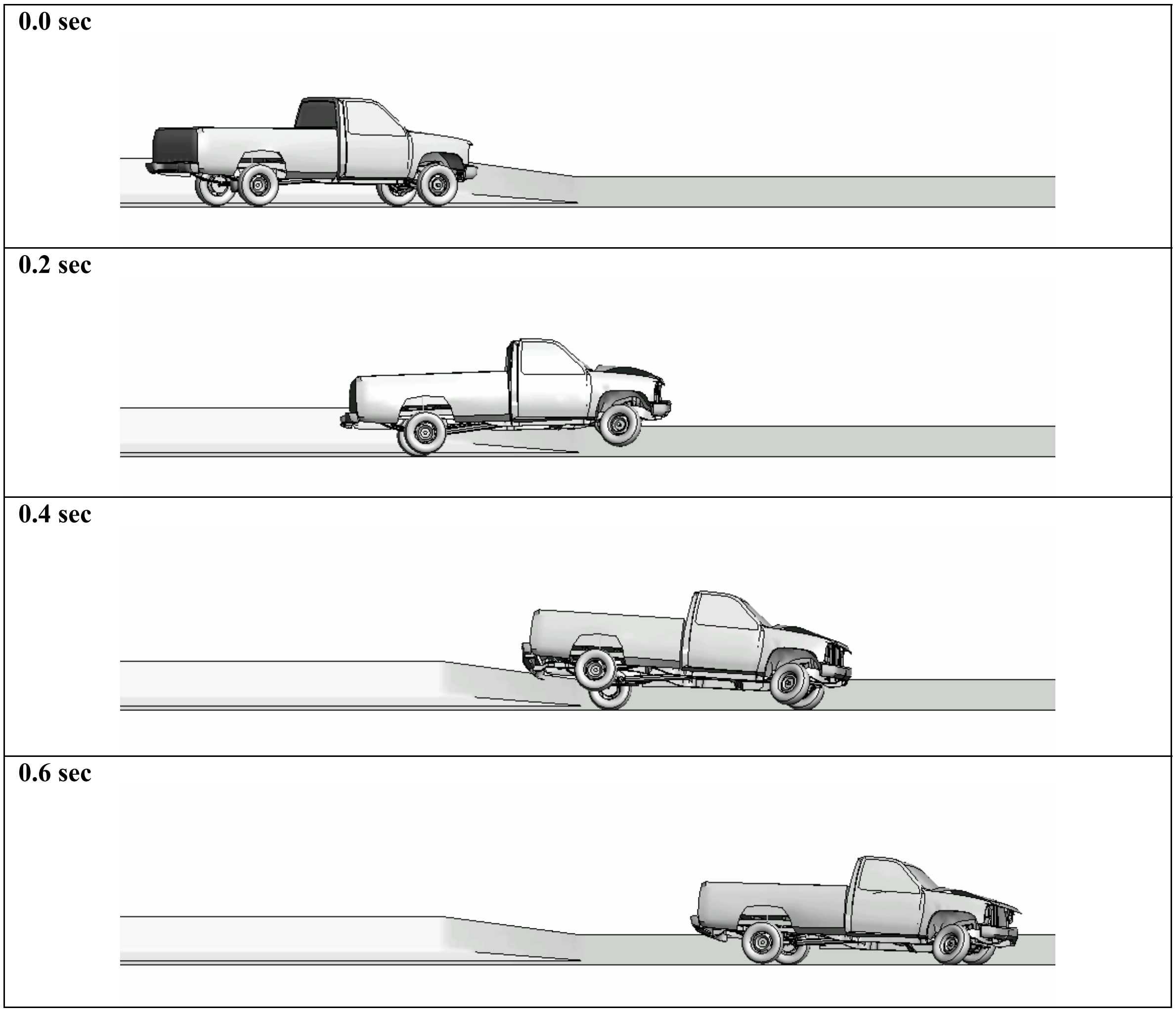


Figure 6. Pickup Truck Impact Transitioning from F-Shape Barrier to Low-Profile Barrier, at the Slope Change Point (Impact Point C).

Examination of the pickup truck results presented in Figures 3 through 6 shows that there is very little difference in the vehicle stabilities between impacts and A and B, and C and D. Thus, it is shown that whether the transition section was impacted at the point of slope change or 3 ft (1 m) upstream of the slope change, there was little difference in the simulation outcome. In the case of a TL-2 small car impact, the vehicle is lighter and the impact angle is less. Thus, it is to be expected that the differences between impacts at points A and B, and C and D would be even less pronounced than was the case for the pickup truck simulations. Therefore, researchers performed small car simulations for the rigidly fixed barrier only for impact points B and C as shown in Figure 2.

Figure 7 shows simulation results for the small car impact transitioning from the F-shape to low-profile barrier, at the slope change point (impact point C). Figure 8 shows simulation results for the small car impact transitioning from the low-profile barrier to F-shape barrier, at the slope change point (impact point B). As shown in Figures 7 and 8, the small car was successfully redirected, and there were no concerns regarding vehicular stability.

From the initial vehicular impact simulations, researchers determined that the proposed transition barrier segment had good potential of meeting vehicle redirection and stability criteria for TL-2 applications. It was also determined that the points of slope change (i.e., impact points B and C) were sufficient to evaluate the barrier transition. Finally, it was determined that while the stabilities of both the pickup and the small car seem to both be very good, it would appear that the pickup impacts were slightly less stable than the small car impacts. Therefore, the pickup impacts were selected for full-scale testing.

Once the design of the transition barrier was finalized using the rigid barrier system simulations, and the critical impact conditions were identified, further details were added to the finite element barrier model to allow a more rigorous evaluation of the proposed transition barrier segment. In these more detailed simulations, deformable barrier connections were added, and the barriers were assumed be free-standing with no positive connection to the ground. The purpose of these more detailed simulations was to evaluate the effect of barrier deflection on vehicle stability and redirection.

The finite element models of the different concrete segments are shown in Figure 9. The lowest layer of solid elements that are in contact with the ground surface were assigned elastic material properties, and the rest of the elements comprising the barrier segment were assigned rigid material properties. The lower elastic layer of solid elements was incorporated into the barrier model to provide a reliable account of friction in the contact between the concrete barrier segments and the ground. A friction coefficient of 0.4, as determined from barrier pull tests on a concrete pavement, was used between the concrete barriers and the ground. Rigid material representation for the remainder of the model helps speed up numerical calculations significantly.

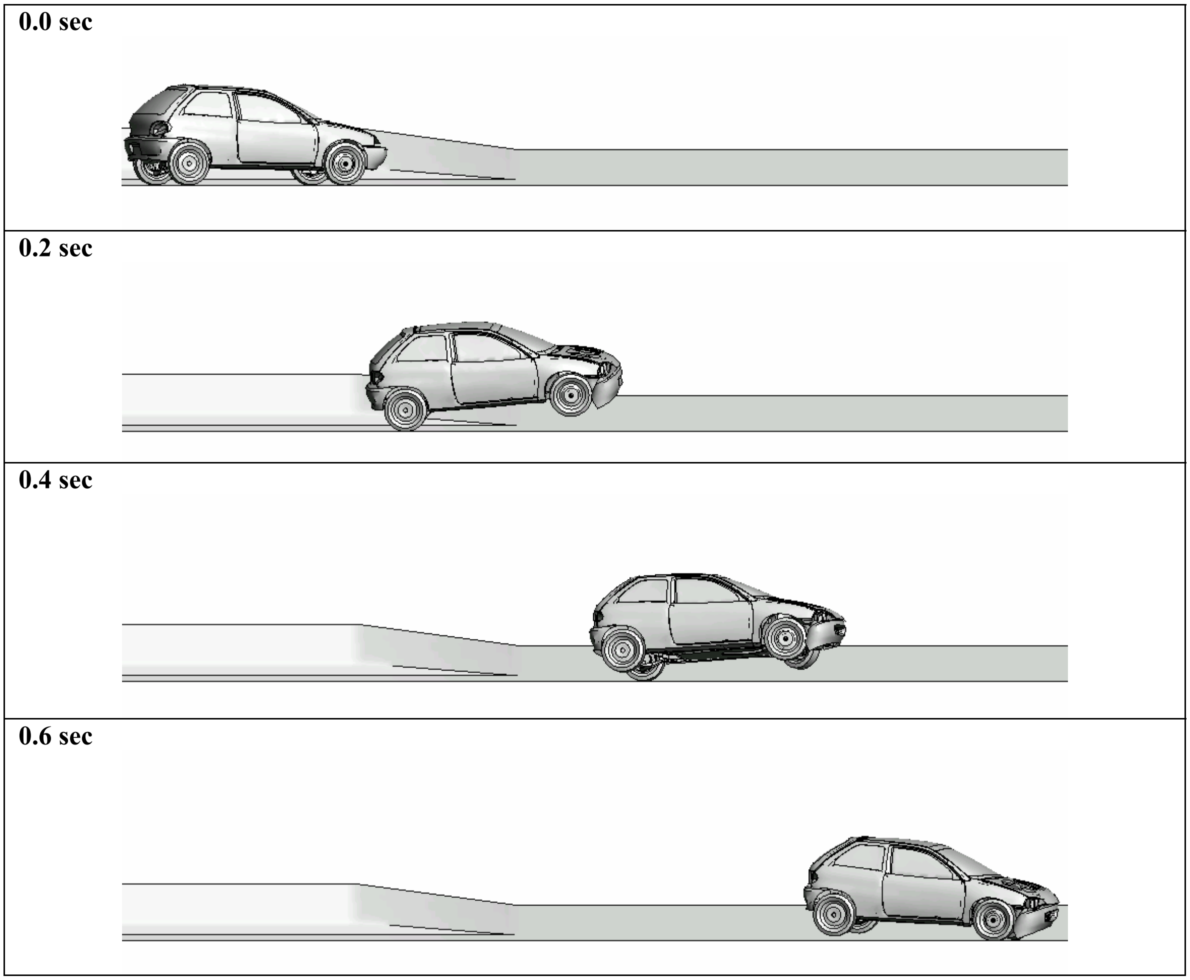


Figure 7. Small Car Impact Transitioning from F-Shape to Low-Profile Barrier, at the Slope Change Point (Impact Point C).

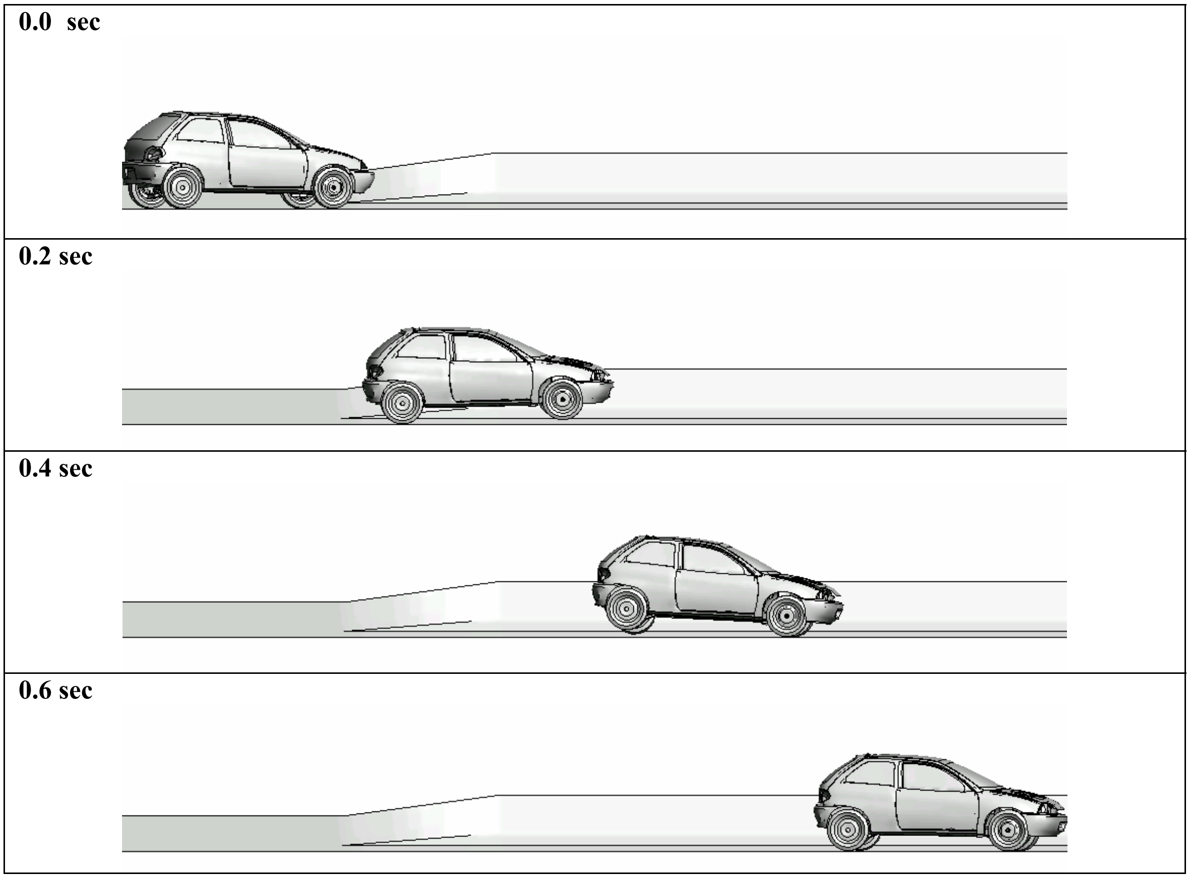
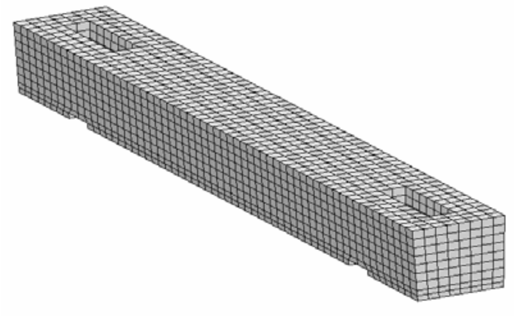
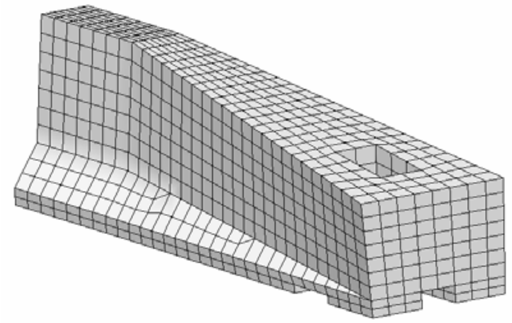


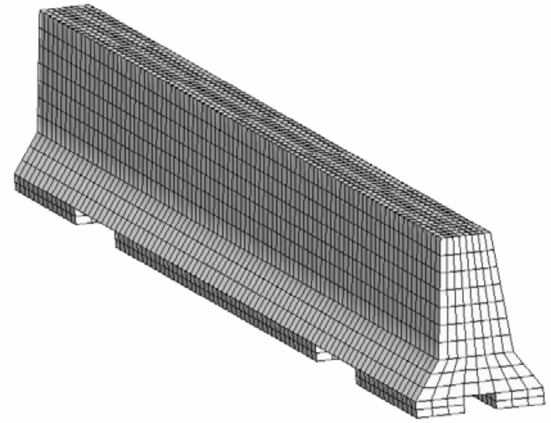
Figure 8. Small Car Impact Transitioning from Low-Profile Barrier to F-Shape Barrier, at the Slope Change Point (Impact Point B).



(a) Low-profile barrier model



(b) Transition barrier model

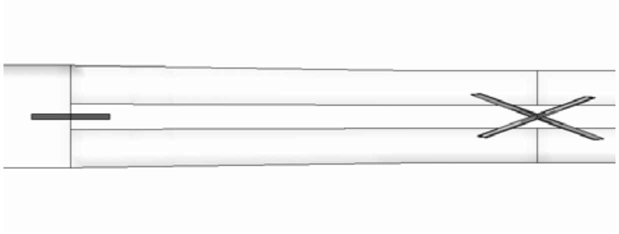


(c) F-shape barrier model

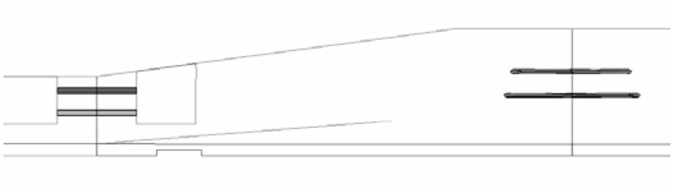
Figure 9. Finite Element Barrier Model Details.

A limitation to this type of rigid concrete barrier model is that it does not incorporate concrete failure. Without incorporating concrete failure into the analysis, it should be noted that the results of the simulation represent a lower bound estimate of the overall barrier system deflection. If significant concrete fracture and spalling occurs at the ends of one or more barrier segments during an actual impact, additional joint rotation can occur and deflections can increase. However, results of previous testing on both the low-profile and the F-shape barriers showed that concrete fracture and spalling is minimal under TL-2 conditions. Since the proposed design of the transition barrier segment incorporates standard bolted connection details, researchers expect that the performance of the transition barrier segment will be at least as good as the documented performances of the F-shape and low-profile barriers.

The cross-bolt connection between the transition barrier segment and the F-shape barrier and the connection between the transition barrier segment and the low-profile barrier were modeled by creating rigid, cylindrical sleeves with shell elements to represent the pipe sections embedded in the concrete through which the connection bolts pass. These sleeves were placed in the concrete barrier segments at their appropriate locations and rigidly constrained to the concrete such that the motion of the sleeves relative to the barriers was prohibited. The connection bolts inside the sleeves were modeled using beam elements. The mechanical properties of the connection bolts were defined using a bilinear stress-strain curve representing the actual material of the bolts. This model is shown in Figure 10.



(a) Top view



(b) Side view

Figure 10. Transition Barrier Segment Connection Modeling.

Researchers performed impact simulations with the detailed model for impact points B and C. Figure 11 shows simulation results for the pickup truck impact transitioning from the F-shape barrier to the low-profile barrier, at the slope change point (impact point C). It can be seen from these results that the vehicle was successfully contained and redirected. The added flexibility of the barrier did not appear to significantly affect the stability of the impacting vehicle. The maximum lateral deflection of the barrier system during this simulation was about 9 inches (230 mm). Figure 12 shows simulation results for the pickup truck impact transitioning from the low-profile barrier to the F-shape barrier, at the slope change point (impact point B). The vehicle was successfully contained and redirected. The vehicle remained stable and upright throughout the impact. The maximum lateral deflection of the barrier system was about 6 inches (155 mm). As discussed previously, these predictive deflection estimates should be considered lower bound estimates because the computer model does not account for concrete cracking and spalling. However, based on previous experience, researchers believe that the additional lateral deflection resulting from concrete damage should be minimal.

SUMMARY

A new concrete transition barrier segment was developed that will allow traditional F-shape portable barrier segments to be connected to low-profile barrier segments. The new transition barrier segment is designed so that it connects directly to both the F-shape and low-profile barrier segments without the introduction of new connection hardware. Complete construction fabrication details are presented in Appendix A.

Simulation results discussed above show that the proposed 10-ft (3 m) long transition barrier segment is able to contain and redirect both the pickup and small car impacts associated with TL-2 impact conditions. Further, the results show that the structural integrities of the barrier connections were maintained under TL-2 impact conditions. Therefore, researchers concluded that the proposed transition barrier segment design should meet *NCHRP Report 350* evaluation criteria. In addition, the simulation results show an estimated maximum dynamic deflection of approximately 9 inches (230 mm) when the proposed transition barrier segment was impacted with the pickup under TL-2 impact conditions, with the pickup transitioning from the F-shape to low-profile barrier. Finally, the simulation results show an estimated maximum dynamic deflection of approximately 6 inches (155 mm) when the transition barrier segment was impacted with the pickup under TL-2 impact conditions, with the pickup transitioning from the low-profile to F-shape barrier. These maximum estimated dynamic deflections values are considered lower-bound estimates. The actual dynamic barrier deflections are expected to exceed these values slightly depending on the nature and degree of concrete damage obtained in the full-scale tests.

Based on these simulation results, researchers recommended that the impact performance of the transition barrier segment should be evaluated using two full-scale crash tests involving the TL-2 pickup conditions. It was recommended that one full-scale impact should involve a TL-2 pickup impacting at the slope change point with the vehicle traveling from the F-shape to low-profile barrier and the other impact at the slope change point with the vehicle traveling from the low-profile to F-shape barrier.

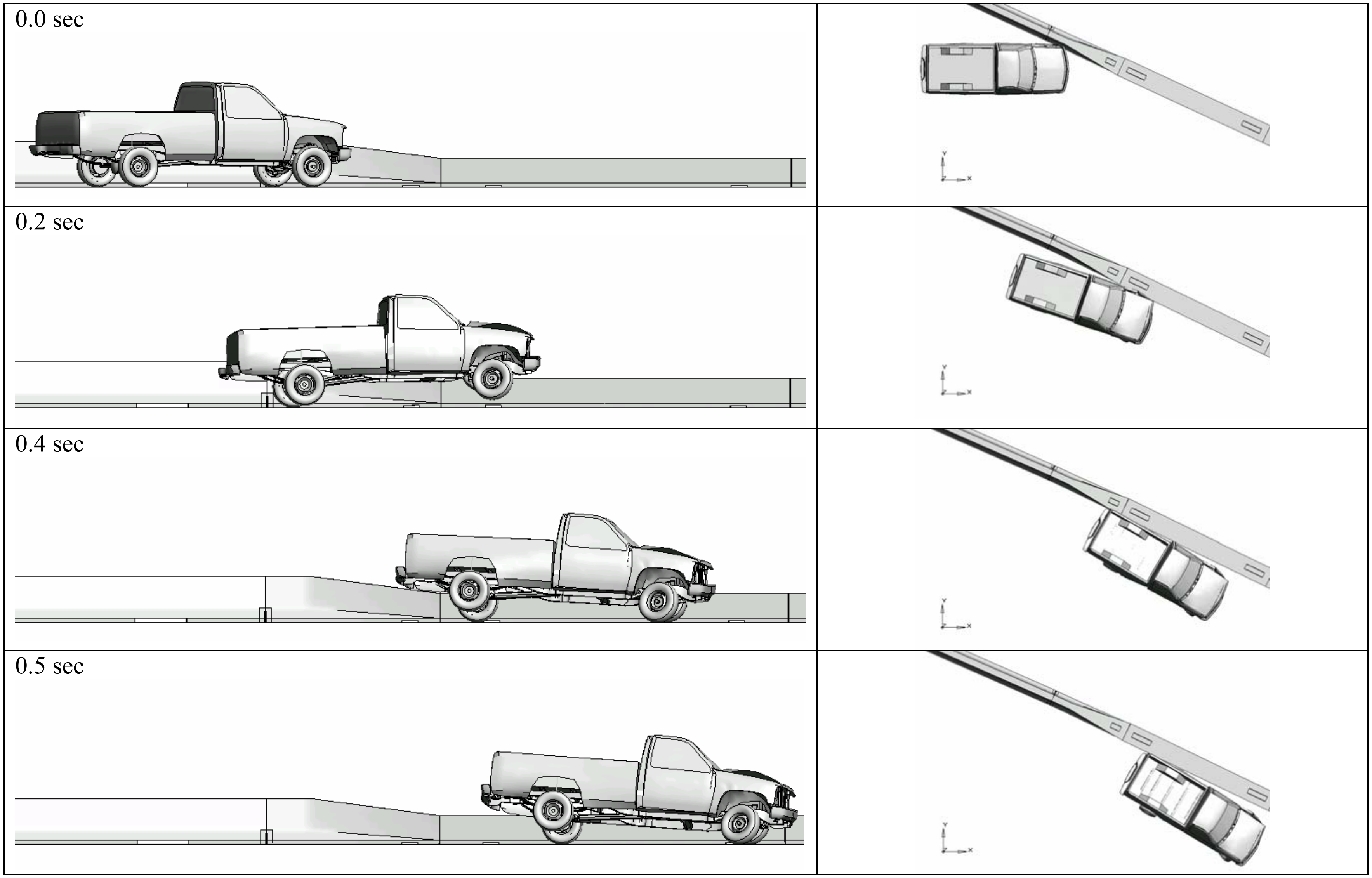


Figure 11. Pickup Truck Impact Transitioning from F-Shape Barrier to Low-Profile Barrier, at the Slope Change Point (Impact Point C).

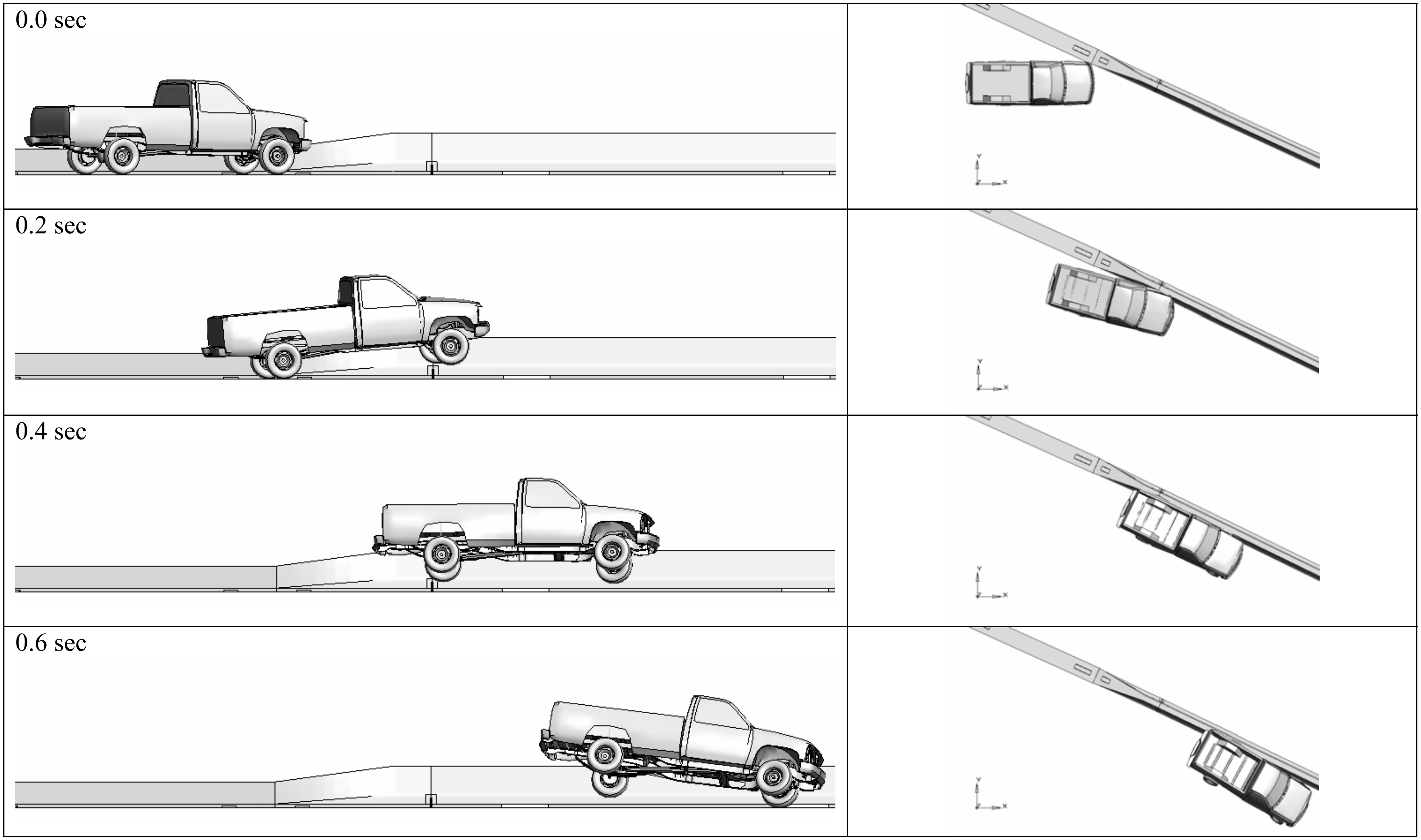


Figure 12. Pickup Truck Impact Transitioning from Low-Profile Barrier to F-Shape Barrier, at the Slope Change Point (Impact Point B).

CHAPTER 3. CRASH TEST PARAMETERS

CRASH TEST CONDITIONS

According to *NCHRP Report 350*, two tests are recommended to evaluate transitions, such as the proposed transition barrier segment, at the desired level as described below.

> ***NCHRP Report 350* test designation 2-20**: An 1808-lb (820 kg) passenger car impacting the critical impact point (CIP) of the transition at a nominal speed and angle of 43 mi/h (70 km/h) and 20 degrees. The purpose of this test is to evaluate the overall performance of the transition section in general, and the occupant risk in particular.
>
> ***NCHRP Report 350* test designation 2-21**: A 4409-lb (2000 kg) pickup truck impacting the CIP of the transition at a nominal speed and angle of 43 mi/h (70 km/h) and 25 degrees. The test is intended to evaluate the strength of the transition section in containing and redirecting the pickup truck.

In addition, *NCHRP Report 350* provides complete guidance for evaluation of the crash test results. 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.

Based on discussions presented in the previous chapter researchers recommended that test designation 2-20 be waived based on detailed computer simulation results. Based on the same computer simulation results it was recommended that test designation 2-21 be conducted for two different potential critical impact points to assure that the critical impact conditions were fully evaluated. These impact locations are referred to as locations B and C, as shown in Figure 2. Thus, the new transition article was subjected to two full-scale crash tests.

Test no. 455276-1 involved a 4409-lb (2000 kg) pickup impacting the test article at point C (reference Figure 2) as the vehicle progressed in the direction from the low-profile barrier to the F-shape barrier. Test no 455276-2 involved a 4409-lb (2000 kg) pickup impacting the test article at point B (reference Figure 2) in the previous section as the vehicle progressed in the direction of the F-shape barrier to the low-profile barrier. In both cases, the impact speed was 43 mi/h (70 km/h) with an impact angle of 25 degrees.

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

TEST FACILITY

All testing discussed in this report was conducted at the TTI Proving Ground. This facility is a 2000-acre (809 hectare) complex of research and training facilities located 10 miles (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 construction and testing of the barrier transition segment evaluated under this project is along an out-of-service runway. The runway consists of an un-reinforced jointed-concrete pavement in 12.5 ft × 15 ft (3.8 m × 4.6 m) blocks nominally 8-12 inches (203-305 mm) deep. The aprons and runways are over 50 years old, and the joints have some displacement, but are otherwise flat and level.

TEST INSTALLATION

The new transition barrier segment is designed so that it connects directly to both the F-shape and low-profile barrier segments without the introduction of new connection hardware. Overall details of the transition barrier segment are shown in Figure 13, and complete construction fabrication details are presented in Appendix A. As shown in Figure 13, the F-shape profile is maintained for distance of 30 inches (762 mm) from the high end of the transition barrier segment. This was done so that the standard F-shape cross-bolt connection could be cast into the high end of the transition barrier segment. It was possible to make the low end of the transition barrier segment compatible with the low-profile barrier while starting the geometry changes at the very end of the transition barrier segment. To minimize the length of the transition barrier segment, a shorter bolt trough was cast into the low end of the transition barrier segment than is the case with the ends of a standard low-profile barrier. As a result, it is necessary to install the connecting bolts from the traditional low-profile barrier segment instead of the transition barrier segment. The internal reinforcement for the transition barrier segment consists of eight #5 longitudinal reinforcing bars and 21 specially shaped stirrups fabricated with #4 reinforcing bars. In addition, slightly modified versions of the connection reinforcement for both the F-shape and the low-profile barriers are incorporated in the ends of the transition barrier segment. Appendix A presents full details of the internal steel reinforcement.

The full-scale crash tests were conducted using three 30 ft (9.14 m) long, traditional full-size F-shape barrier segments that were connected to five 20 ft (6.1 m) long, low-profile barrier segments with the new 10 ft (3 m) long, prototype barrier transition segment. The result is a longitudinal barrier system that is 200 ft (61 m) in total length. Figure 14 presents a photograph of the crash test article prior to testing.

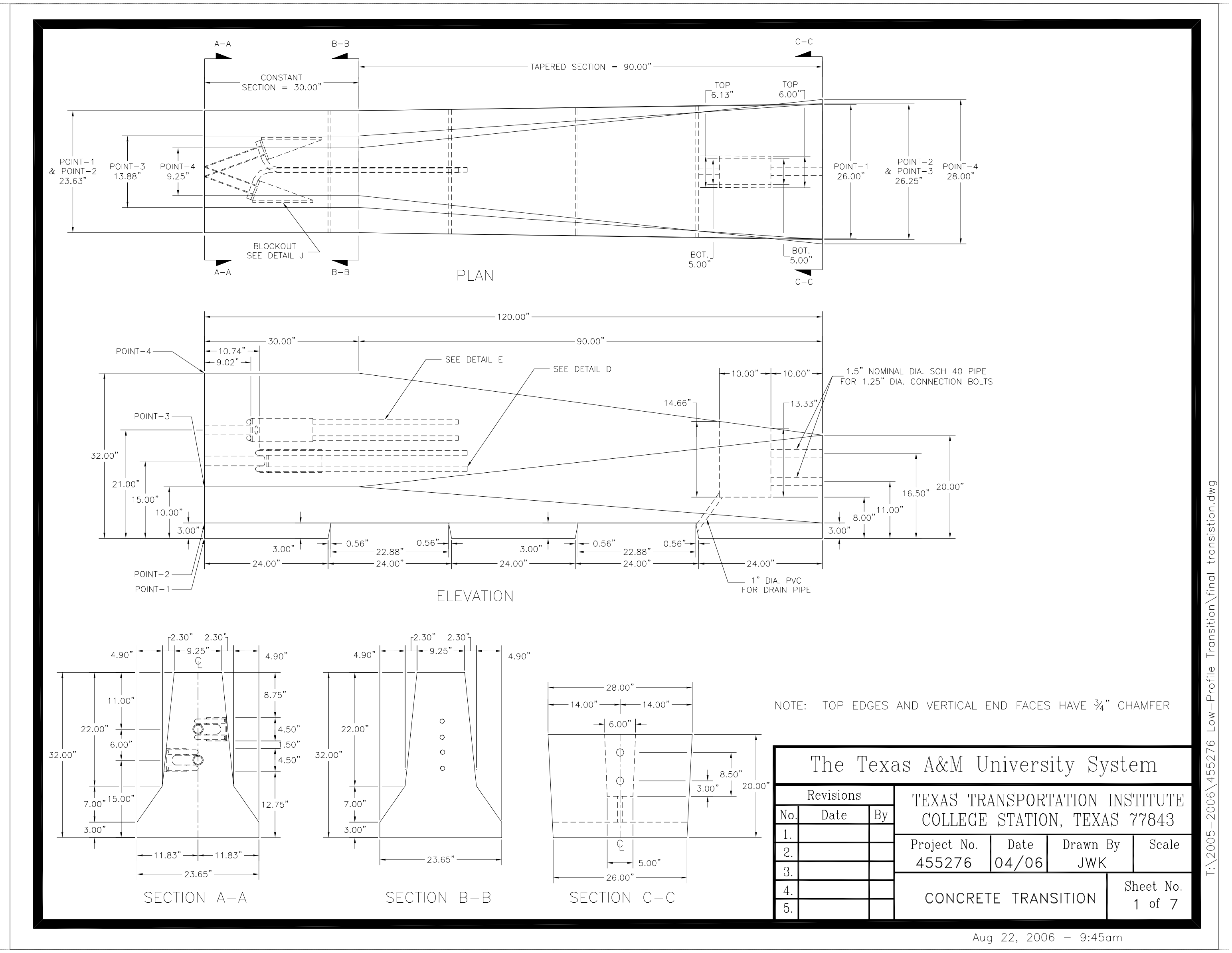


Figure 13. Details of the Low-Profile Transition to Standard Concrete Barrier – Overall Layout.

Figure 14. Low-Profile Transition Installation before Testing.

CHAPTER 4. CRASH TEST RESULTS

TEST NO. 455276-1 (*NCHRP REPORT 350* TEST DESIGNATION 2-21) ON THE F-SHAPE TRANSITION END

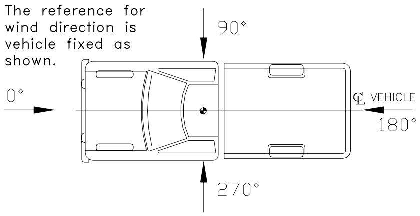
Researchers performed this test on the transition barrier segment at the F-shape barrier end. The target impact point was 29 inches (740 mm) downstream of the joint between the F-shape barrier segment and the transition segment.

Test Vehicle

A 2001 Chevrolet C2500 pickup truck, shown in Figures 15 and 16, was used for the crash test. Test inertia weight of the vehicle was 4725 lb (2143 kg), and its gross static weight was 4725 lb (2143 kg). The height to the lower edge of the vehicle bumper was 14.6 inches (370 mm), and it was 25.6 inches (650 mm) to the upper edge of the bumper. Figure 35 in Appendix C 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.

Weather Conditions

The test was performed on the morning of June 1, 2006. On May 29, 0.11 inches of rain was recorded, and on May 31, 0.15 inches of rain. Weather conditions at the time of testing were as follows: wind speed: 7 mi/h (12 km/h); wind direction: 25 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); temperature: 90°F (32°C).



Test Description

The 2001 Chevrolet C2500 pickup truck, traveling at an impact speed of 44.0 mi/h (70.8 km/h), impacted the transition barrier segment 25.6 inches (650 mm) downstream of the joint between the F-shape barrier segment and the transition barrier segment at an impact angle of 25.1 degrees. At approximately 0.034 s after impact, the left front tire blew out. The vehicle began to redirect at 0.081 s, and the transition began to deflect toward the field side at 0.088 s. At 0.318 s, the vehicle was traveling parallel with the installation and was traveling at a speed of 33.9 mi/h (54.5 km/h). The rear of the vehicle contacted the installation at 0.367 s. At 0.543 s, the rear of the vehicle lost contact with the installation while the front of the vehicle was still in contact. Speed of the vehicle at this time was 28.5 mi/h (45.9 km/h), and heading angle was 0.8 degrees. The vehicle remained in contact with the low-profile barriers and came to rest adjacent to the fourth low-profile barrier segment downstream of impact, approximately 83 ft (25.3 m). Figure 37 in Appendix D shows sequential photographs of the test period.

Figure 15. Vehicle/Installation Geometrics for Test No. 455276-1.

Figure 16. Vehicle before Test No. 455276-1.

Damage to Test Installation

Figures 17 and 18 show damage to the barrier system. The F-shape barrier moved toward the traffic side 2.6 inches (65 mm) at the joint between segments 2 and 3, and moved toward the field side 8.1 inches (205 mm) at the joint between segments 3 and the transition barrier segment. The transition barrier segment was moved toward field side 10.2 inches (260 mm) at the joint between the transition barrier segment and the low-profile segment 5. The low-profile barrier was also pushed toward field side 2.0 inches (50 mm) at the joint between segment 5 and 6. The concrete was spalled off segment 3 at the joint between segments 2 and 3 of the F-shape barrier. A piece of concrete also broke off the top of the transition barrier segment at the joint between the transition barrier segment and the low-profile barrier, and another piece broke off near ground level near the middle of the same segment of low-profile barrier. Length of contact of the vehicle with the barrier was 83 ft (25.3 m), and working width was 38.2 inches (971 mm). Maximum dynamic deflection of the barrier was 10.2 inches (260 mm), and maximum permanent deflection of the barrier was 10.2 inches (260 mm).

Vehicle Damage

Damage to the vehicle is shown in Figure 19. Structurally, the left upper and lower A-arm were deformed; the left upper ball joint pulled out of the socket; the left outer ball joint broke at the steering knuckle, and the left outer tie rod end broke. Also damaged were the front bumper, radiator and fan, left front quarter panel, left front tire and rim, left door, and left rear wheel rim (but no loss of air from the tire). Maximum exterior crush to the vehicle was 19.7 inches (500 mm) in the left side plane at the front corner at bumper height. Maximum occupant compartment deformation was 2.8 inches (70 mm) in the firewall area on the left side. Photographs of the interior of the vehicle are shown in Figure 20. Exterior crush measurements and occupant compartment deformation are shown in Appendix C, Tables 3 and 4, respectively.

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. Only the occupant impact velocity and ridedown accelerations in the longitudinal axis are required from these data for evaluation of criterion L in *NCHRP Report 350*. In the longitudinal direction, occupant impact velocity was 17.7 ft/s (5.4 m/s) at 0.121 s, maximum 0.010-s ridedown acceleration was 16.1 g's from 0.172 to 0.182 s, and the maximum 0.050-s average was -6.6 g's between 0.053 and 0.103 s. In the lateral direction, the occupant impact velocity was 17.1 ft/s (5.2 m/s) at 0.121 s, the highest 0.010-s occupant ridedown acceleration was 6.0 g's from 0.162 to 0.172 s, and the maximum 0.050-s average was 7.8 g's between 0.054 and 0.104 s. Figure 21 presents these data and other pertinent information from the test. Figures 39 through 45 in Appendix E present vehicle angular displacements and accelerations versus time traces.

Figure 17. After Impact Trajectory Path for Test No. 455276-1.

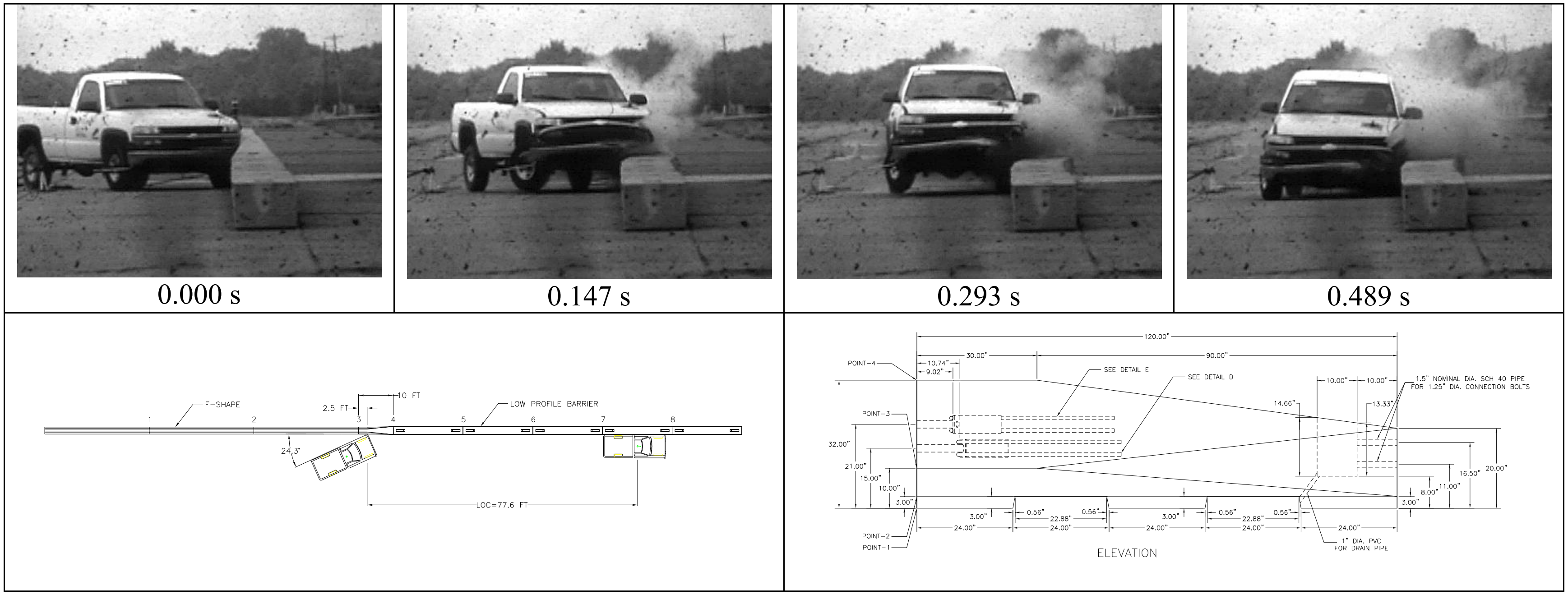
Figure 18. Installation after Test No. 455276-1.

Figure 19. Vehicle after Test No. 455276-1.

Before test

After test

Figure 20. Interior of Vehicle for Test No. 455276-1.



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0.293 s

0.489 s

General Information	
Test Agency	Texas Transportation Institute
Test No.	455276-1
Date	06-01-2006
Test Article	
Type	Transition
Name	F-Shape to Low-Profile
Installation Length (ft (m))	200 (61 m)
Material or Key Elements	Reinforced Concrete Barrier Segment Transitions from F-Shape to Low-Profile
Soil Type and Condition	Concrete Pavement, Dry
Test Vehicle	
Type	Production
Designation	2000P
Model	2001 Chevrolet C2500 Pickup Truck
Mass (lb (kg))	
Curb	4936 (2239)
Test Inertial	4725 (2143
Dummy	No dummy
Gross Static	4725 (2143)

Impact Conditions	
Speed (mi/h (km/h))	44.0 (70.8)
Angle (deg)	25.1
Exit Conditions	
Speed (mi/h (km/h))	28.5 (45.9)
Angle (deg)	0.8
Occupant Risk Values	
Impact Velocity (ft/s (m/s))	
Longitudinal	17.7 (5.4)
Lateral	17.1 (5.2)
THIV (km/h)	26.2
Ridedown Accelerations (g's)	
Longitudinal	16.1
Lateral	6.0
PHD (g's)	16.6
ASI	1.02
Max. 0.050-s Average (g's)	
Longitudinal	-6.6
Lateral	7.8
Vertical	-2.5

Test Article Deflections (inches (mm))	
Dynamic	10.2 (260)
Permanent	10.2 (260)
Working Width	38.2 (971)
Vehicle Damage	
Exterior	
VDS	11LFQ4
CDC	11LFEW4
Maximum Exterior Vehicle Crush (inch (mm))	19.7 (500)
Interior	
OCDI	LS0010000
Maximum Occupant Compartment Deformation (inch (mm))	2.8 (70)
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle (deg)	26
Max. Pitch Angle (deg)	4
Max. Roll Angle (deg)	6

Figure 21. Summary of Results for *NCHRP Report 350* Test 2-21 on the F-Shape Transition End.

Assessment of Results

Below is an assessment of the test based on the applicable *NCHRP Report 350* safety evaluation criteria.

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.*

Result: The F-shape to low-profile transition barrier segment contained and redirected the pickup truck. The pickup did not penetrate, underride, or override the installation. Maximum dynamic deflection of the barrier was 10.2 inches (260 mm). (PASS)

Occupant Risk

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

Result: No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 2.8 inches (70 mm) in the firewall area on the left side. (PASS)

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

Result: The pickup truck remained upright during and after the collision event. (PASS)

Vehicle Trajectory

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

Result: The vehicle came to rest 83 ft (25.3 m) downstream of impact and adjacent to the traffic face of the barrier, and did not intrude into adjacent traffic lanes. (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.*

Result: Longitudinal occupant impact velocity was 17.7 ft/s (5.4 m/s), and longitudinal ridedown acceleration was 16.1 g's. (PASS)

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

Result: Exit angle at loss of contact was 0.8 degrees, which was 3 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*

TEST NO. 455276-2 (*NCHRP REPORT 350* TEST DESIGNATION 2-21) ON THE LOW-PROFILE TRANSITION END

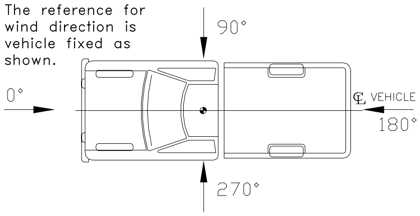
Researchers performed this test on the transition barrier segment at the low-profile transition end. Target impact point was at the joint between the low-profile barrier segment and the transition barrier segment.

Test Vehicle

A 2001 Chevrolet C2500 pickup truck, shown in Figures 22 and 23, was used for the crash test. Test inertia weight of the vehicle was 4744 lb (2152 kg), and its gross static weight was 4744 lb (2152 kg). The height to the lower edge of the vehicle bumper was 14.6 inches (370 mm), and it was 25.6 inches (650 mm) to the upper edge of the bumper. Figure 36 in Appendix C 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.

Weather Conditions

The test was performed on the morning of June 5, 2006. On May 29, 0.11 inches of rain was recorded; May 31, 0.15 inches of rain; June 1, 0.21 inches of rain; and June 2, 0.01 inches of rain. Weather conditions at the time of testing were as follows: wind speed: 7 mi/h (12 km/h); wind direction: 335 degrees with respect to the vehicle (vehicle was traveling in a southwesterly direction); temperature: 87°F (31°C).



Test Description

The 2001 Chevrolet C2500 pickup truck, traveling at an impact speed of 44.7 mi/h (71.9 km/h), impacted the transition barrier segment at the joint between the low-profile barrier segment and the transition barrier segment at an impact angle of 25.9 degrees. At approximately 0.047 s after impact, the right front tire blew out. The transition barrier segment began to deflect toward the field side at 0.056 s, and the vehicle began to redirect at 0.059 s. At 0.382 s, the vehicle was traveling parallel with the installation, and the vehicle was traveling at a speed of 34.0 mi/h (54.8 km/h). The vehicle became totally airborne at 0.399 s, and the front tires touched the ground at 0.734 s. At 0.788 s, the vehicle lost contact with the installation and was traveling at an exit speed of 31.6 mi/h (50.8 m/h) and an exit angle of 4.2 degrees toward the installation. Brakes on the vehicle were applied at 1.7 s, and the vehicle subsequently came to rest 245 ft (74.7 m) downstream of impact and 28 ft (8.5 m) forward of the face of the barrier. Figure 38 in Appendix D show sequential photographs of the test period.

Figure 22. Vehicle/Installation Geometrics for Test No. 455276-2.

Figure 22. Vehicle/Installation Geometrics for Test No. 455276-2.

Figure 23. Vehicle before Test No. 455276-2.

Damage to Test Installation

Figures 24 and 25 show damage to the barrier installation. The top corner of the barrier transition segment at the joint with the low-profile barrier segment spalled off. The low-profile barrier moved toward field side 0.4 inches (10 mm) at the joint between low-profile segments 4 and 5, and 6.7 inches (170) mm at the joint between low-profile segment 5 and the barrier transition segment. The F-shape barrier moved toward field side 5.5 inches (140 mm) at the joint between the transition barrier segment and the F-shape barrier segment 7, while the barrier moved forward 4.7 inches (120 mm) at the joint between F-shape barrier segments 7 and 8. Length of contact of the vehicle with the barrier was 32.5 ft (9.9 m), and working width was 2.9 ft (0.89 m). Maximum dynamic deflection during the test was 7.0 inches (177 mm), and maximum permanent deflection was 6.7 inches (170 mm).

Vehicle Damage

Damage to the vehicle is shown in Figure 26. Structurally, the right upper and lower A-arms and right side frame rail were deformed. Also damaged were the front bumper, radiator, right front quarter panel, and right door. Both wheel rims on the right side were deformed, but there was no loss of air in the tires. There was also a scuff mark on the lower forward edge of the exterior bed. Maximum exterior crush to the vehicle was 13.8 inches (350 mm) in the side plane on the right side at the front corner at bumper height. No occupant compartment deformation occurred. Photographs of the interior of the vehicle are shown in Figure 27. Exterior crush measurements and occupant compartment measurements are shown in Appendix C, Tables 5 and 6, respectively.

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. Only the occupant impact velocity and ridedown accelerations in the longitudinal axis are required from these data for evaluation of criterion L in *NCHRP Report 350*. In the longitudinal direction, occupant impact velocity was 16.1 ft/s (4.9 m/s) at 0.133 s, maximum 0.010-s ridedown acceleration was -2..9 g's from 0.359 to 0.369 s, and the maximum 0.050-s average was -6.1 g's between 0.052 and 0.102 s. In the lateral direction, the occupant impact velocity was 14.4 ft/s (4.4 m/s) at 0.133 s, the highest 0.010-s occupant ridedown acceleration was -6.6 g's from 0.359 to 0.369 s, and the maximum 0.050-s average was -5.7 g's between 0.039 and 0.089 s. Figure 28 presents these data and other pertinent information from the test. Figures 46 through 52 in Appendix E present vehicle angular displacements and accelerations versus time traces.

Figure 24. After Impact Trajectory Path for Test No. 455276-2.

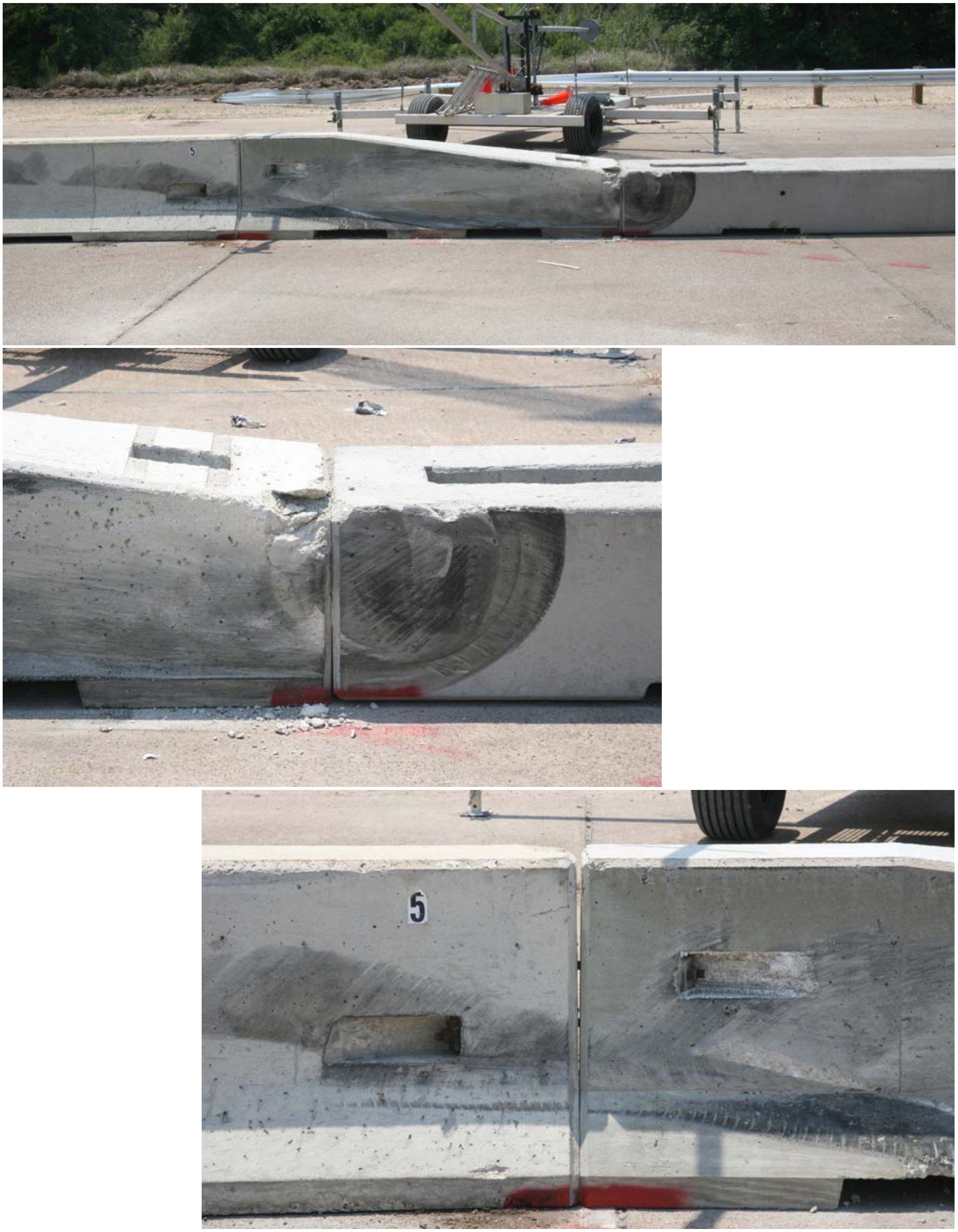


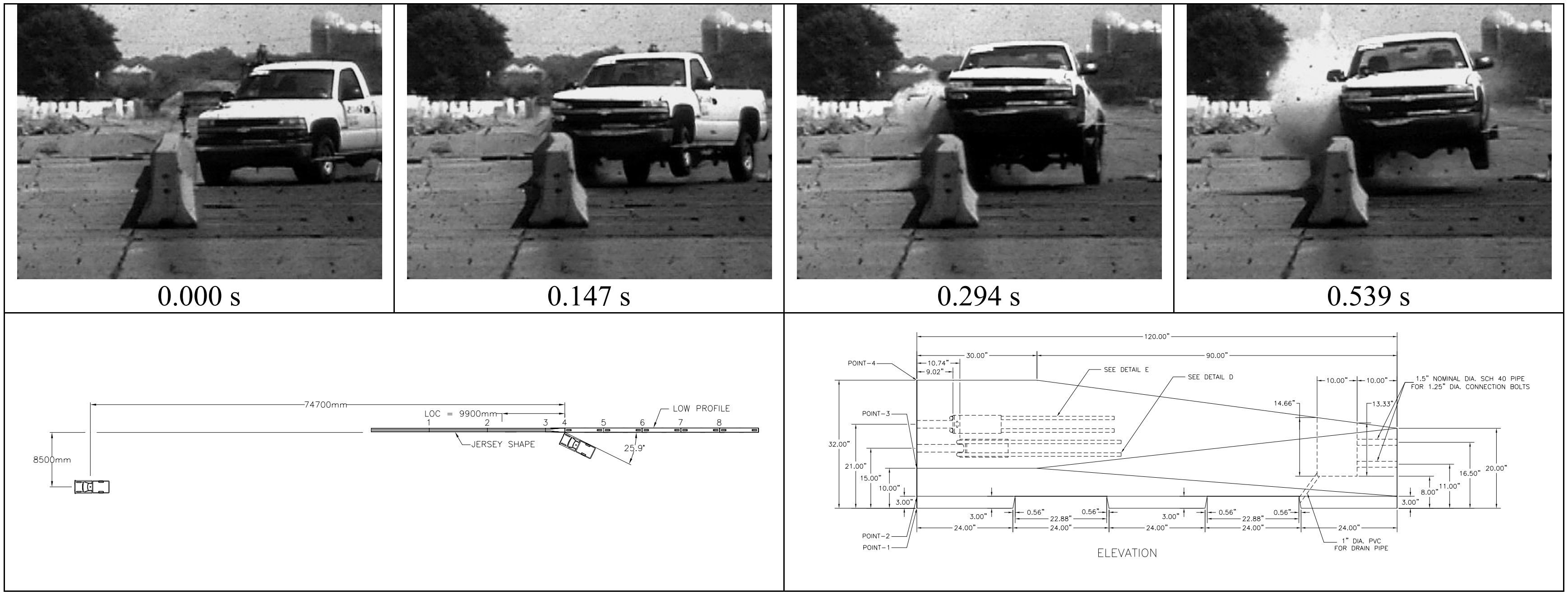
Figure 25. Installation after Test No. 455276-2.

Figure 26. Vehicle after Test No. 455276-2.

Before test

After test

Figure 27. Interior of Vehicle for Test No. 455276-2.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General Information	
Test Agency	Texas Transportation Institute
Test No.	455276-2
Date	06-05-2006
Test Article	
Type	Transition
Name	Low-Profile to Traditional
Installation Length (ft)	200 (61 m)
Material or Key Elements	Reinforced Concrete Barrier Segment Transitions from F-Shape to Low-Profile
Soil Type and Condition	Concrete Pavement, Dry
Test Vehicle	
Type	Production
Designation	2000P
Model	2001 Chevrolet C2500 Pickup Truck
Mass (lb (kg))	
Curb	4762 (2160)
Test Inertial	4744 (2152)
Dummy	No dummy
Gross Static	4744 (2152)

Impact Conditions	
Speed (mi/h (km/h))	44.7 (71.9)
Angle (deg)	25.9
Exit Conditions	
Speed (mi/h (km/h))	31.6 (50.8)
Angle (deg)	-4.2
Occupant Risk Values	
Impact Velocity (ft/s (m/s))	
Longitudinal	16.1 (4.9)
Lateral	14.4 (4.4)
THIV (km/h)	22.7
Ridedown Accelerations (g's)	
Longitudinal	-2.9
Lateral	-6.6
PHD (g's)	7.2
ASI	0.81
Max. 0.050-s Average (g's)	
Longitudinal	-6.1
Lateral	-5.7
Vertical	-2.8

Test Article Deflections (inches (mm))	
Dynamic	7.0 (177)
Permanent	6.7 (170)
Working Width	35.0 (888)
Vehicle Damage	
Exterior	
VDS	01RFQ3
CDC	01LFEW3
Maximum Exterior Vehicle Crush (inch (mm))	13.8 (350)
Interior	
OCDI	RS0000000
Maximum Occupant Compartment Deformation (inch (mm))	0
Post-Impact Behavior	
(during 1.0 sec after impact)	
Max. Yaw Angle (deg)	-25
Max. Pitch Angle (deg)	9
Max. Roll Angle (deg)	-7

Figure 28. Summary of Results for *NCHRP Report 350* Test 2-21 on the Low-Profile Transition End.

Assessment of Results

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

Structural Adequacy

B. 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.

Result: The low-profile to F-shape transition barrier segment contained and redirected the pickup truck. The pickup did not penetrate, underride, or override the installation. Maximum dynamic deflection of the barrier was 7.0 inches (177 mm). (PASS)

Occupant Risk

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

Result: No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. No occupant compartment deformation occurred. (PASS)

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

Result: The pickup truck remained upright during and after the collision event. (PASS)

Vehicle Trajectory

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

Result: The vehicle came to rest 245 ft (74.7 m) downstream of impact and 28 ft (8.5 m) forward of the face of the barrier, and may intrude 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.

Result: Longitudinal occupant impact velocity was 16.1 ft/s (4.9 m/s), and longitudinal ridedown acceleration was -2.9 g's. (PASS)

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

Result: Exit angle at loss of contact was 4.2 degrees toward the installation, which was 16 percent of the impact angle. (PASS/FAIL)

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

CHAPTER 5. SIGHT-DISTANCE GUIDELINES FOR USE OF TRANSITION BARRIER SEGMENT

The original purpose for the development and use of the low-profile barrier system was to improve work zone visibility within low-speed work zones. Figure 29 shows the typical geometry of the sight-distance problem in an urban situation where a cross-traffic vehicle is attempting to enter the traffic stream while avoiding oncoming traffic. If the cross-traffic vehicle fails to observe the oncoming traffic, it is necessary for the distance, d, between the cross-traffic vehicle and the oncoming vehicle to be sufficient to allow the driver of the oncoming vehicle time to come to a safe stop without impacting the errant cross-traffic vehicle.

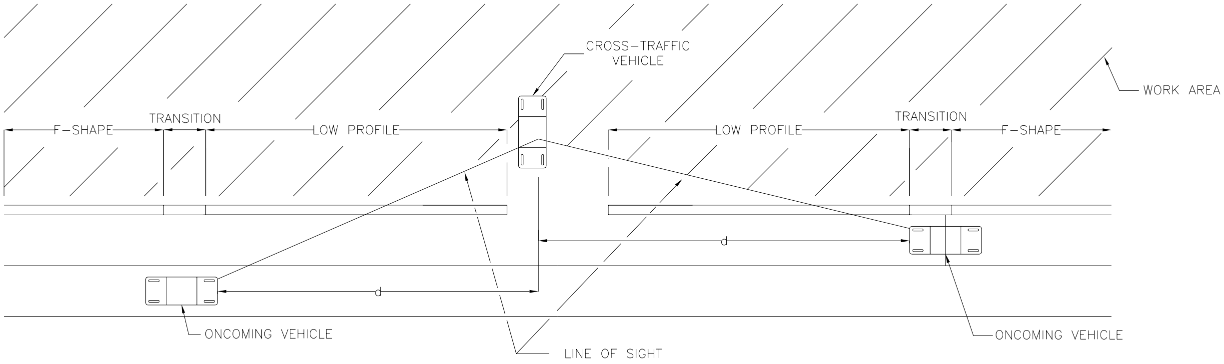


Figure 29. Geometry of Sight-Distance Problem.

If the roadside barrier is made up of only low-profile barriers, then the sight distance is not a problem. However, if the barrier is made up of a combination of low-profile and F-shape barriers as is now possible with the introduction of the new transition barrier segment, it is important to note that a certain minimum distance, d, of low-profile barrier is required before the transition barrier segment is used to connect the low-profile barrier to the F-shape barrier.

This sight-distance situation was first addressed more than a decade ago when TTI researchers suggested the use of a similar barrier transition segment. *(5)* In this effort, it was determined that the minimum required length of low-profile barrier, d, on a level roadway or upgrade is 400 ft (122 m). If the system is used on a downgrade that does not exceed 9 percent, the minimum required length of low-profile barrier can be conservatively estimated with the following relationship:

$$d = 400 + 10g \qquad (1)$$

where d is expressed in ft, and g is the level of downgrade expressed in percent. In development of this relationship, researchers assumed that the driver reaction time is 2.5 seconds, that the oncoming vehicle is traveling at 45 mph (73 km/hr), and that the coefficient of friction between the pavement and the tires is 0.31. *(5)*

Practical application of the above recommendations suggests that there should be a minimum of twenty 20 ft (6.1 m) low-profile barrier segments in use before the transition barrier segment is used to connect the low-profile barriers to F-shape barriers. In addition, if the longitudinal barrier is installed on a downgrade, one additional 20 ft (6.1 m) low-profile barrier segment should be added for each 2 percent of down grade.

In addition to assuring adequate sight distance, a minimum length of 400 ft (121.9 m) of low-profile barrier should provide for adequate ride-down distance if an errant vehicle straddles the low-profile barrier.

CHAPTER 6. SUMMARY AND CONCLUSIONS

A new transition barrier segment has been developed that will allow a standard height, F-shape portable concrete barrier to be connected to a low-profile barrier. The new transition barrier segment is 10 ft (3 m) in length and is fabricated with a connection that is compatible with the F-shape barrier on one end and a connection that is compatible with a low-profile barrier on the other end. In both cases, the transition barrier segment is fabricated so that all connection hardware is standard.

The shape of the new transition barrier segment was developed based on engineering judgment, crash-test experience, and refined through the use of computer simulation. The final geometry selected for development was further studied through a series of computer simulations involving multiple impact points and two different vehicles: a 4409-lb (2000 kg) pickup truck and an 1808-lb (820 kg) small car. At the conclusion of this effort, researchers determined that impacts involving the 4409-lb (2000 kg) pickup truck present a more critical situation than impacts with the 1808-lb (820 kg) small car. In addition, two specific impact points were identified as potentially critical impact points for the 4409-lb (2000 kg) pickup truck. Then, more detailed computer simulations that take into account the flexibility of the barrier connections and the lateral movement of the barrier across the supporting pavement were conducted to develop a realistic computer simulation prediction of the new transition barrier segment. On the basis of these simulation results, a recommendation was made for the development and testing of a full-scale transition barrier segment prototype.

Based on the information generated in the computer simulations, researchers determined to conduct two full-scale crash tests to evaluate the performance of the new transition barrier segment. One test was conducted with a 4409-lb (2000 kg) pickup truck impacting at the critical point as the vehicle progressed in the direction of the low-profile barrier to the F-shape barrier; the other test was conducted at the critical impact point with the vehicle traveling in the opposite direction. As shown in Tables 1 and 2, all results for both tests were within the performance limits as described in *NCHRP Report 350* test for TL-2 conditions. As such, the new transition barrier segment is recommended for immediate use.

Table 1. Performance Evaluation Summary for *NCHRP Report 350* Test 2-21 on the F-Shape Transition End.

Test Agency: Texas Transportation Institute — Test No.: 455276-1 — Test Date: 06-01-2006

NCHRP Report 350 Test 2-21 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 low-profile to traditional transition contained and redirected the pickup truck. The pickup did not penetrate, underride, or override the installation. Maximum dynamic deflection of the barrier during the test was 10.2 inches (260 mm).	Pass
Occupant Risk		
D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*	No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to cause undue hazard to others in the area. Maximum occupant compartment deformation was 2.8 inches (70 mm).	Pass
F. *The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.*	The pickup truck remained upright during and after the collision event.	Pass
Vehicle Trajectory		
K. *After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*	The vehicle came to rest 83 ft (25.3 m) downstream of impact and adjacent to the traffic face of the barrier, and did not intrude into adjacent traffic lanes.	Pass*
L. *The occupant impact velocity in the longitudinal direction should not exceed 12 m/s, and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 g's.*	Longitudinal occupant impact velocity was 17.7 ft/s (5.4 m/s), and longitudinal ridedown acceleration was 16.1 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 0.8 degrees, which was 3 percent of the impact angle.	Pass*

* Criterion K and M are desired, not required.

Table 2. Performance Evaluation Summary for *NCHRP Report 350* Test 2-21 on the Low-Profile Transition End.

Test Agency: Texas Transportation Institute Test No.: 455276-2 Test Date: 06-05-2006

***NCHRP Report 350* Test 2-21 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 low-profile to traditional transition contained and redirected the pickup truck. The pickup did not penetrate, underride, or override the installation. Maximum dynamic deflection of the barrier was 7.0 inches (177 mm).	Pass
Occupant Risk D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*	No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. No occupant compartment deformation occurred.	Pass
F. *The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.*	The pickup truck remained upright during and after the collision event.	Pass
Vehicle Trajectory K. *After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*	The vehicle came to rest 245 ft (74.7 m) downstream of impact and 28 ft (8.5 m) forward of the face of the barrier, and may intrude 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 occupant impact velocity was 16.1 ft/s (4.9 m/s), and longitudinal ridedown acceleration was -2.9 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 4.2 degrees towards the installation, which was 16 percent of the impact angle.	Pass *

* Criterion K and M are desired, not required.

CHAPTER 7. IMPLEMENTATION STATEMENT

A new transition barrier segment has been developed and tested that allows a low-profile barrier (LCPB(1)-92) to be connected to a standard height, F-shape portable concrete barrier (CSB-04). This new transition barrier segment will allow increased visibility where it is necessary to deploy concrete barriers in zones that involve both low and high speed areas.

The performance of the new transition barrier segment has been demonstrated through the use of computer simulations. In addition, researchers performed two full-scale tests were conducted to verify the performance of the new transition barrier segment for Test Level 2 conditions as defined in the *NCHRP Report 350* *(3)*. This level of performance permits the use of the new transition barrier segment on roadways with speeds up to and including 43 mi/h (70 km/h).

In addition to providing guidance on the redirective capabilities of the new transition barrier segment, recommendations are presented in this report for the minimum length of low-profile barrier segments that should be used in conjunction with a transition barrier segment. If the full sight distance benefits of the low-profile barrier are to be maintained on level roadways or roadways with an upward slope, it is recommended that a minimum of twenty, 20 ft (6.1 m) low-profile barrier segments (total distance of 400 ft [122m]) should be incorporated before the transition barrier segment is used to connect the low-profile barriers to F-shape barriers. If the longitudinal barrier is installed on a downgrade, one additional 20 ft (6.1 m) low-profile barrier segment should be added for each 2 percent of down grade up to a total down grade of 9 percent.

In addition to preserving the sight-distance benefits of the low profile barrier, the use of the above recommended minimum low-profile barrier lengths should assure that the frictional forces between the top of the concrete barrier and the under side of the errant vehicle are sufficient to assure that an errant vehicle that straddles the low-profile barrier system will have adequate run down length before it engages the transition barrier segment and becomes unstable on top of the F-shape barriers.

Finally, this report presents sufficient information for the development of a new standard detail sheet that will allow general fabrication of the new transition barrier segment. Once the new standard detail sheet is completed by TxDOT, the new transition barrier segment will be ready for implementation.

REFERENCES

1. T. R. Guidry and W. L. Beason. *Development of a Low-Profile Portable Concrete Barrier*, Research Report 990-4F, Texas Transportation Institute, College Station, TX, November 1991.

2. W. L. Beason, W. L. Menges, and D. L. Ivey. *Compliance Testing of an End Treatment for the Low-Profile Concrete Barrier*, Research Report 1403-S, Texas Transportation Institute, College Station, TX, April 1998.

3. 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.

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

5. W. L. Beason and D. L. Ivey. *Development of Low-Profile to Safety-Shape Transition Sections*, Research Report 1992-1, Texas Transportation Institute, College Station, TX, November 1994.

APPENDIX A. FABRICATION DETAILS FOR TRANSITION BARRIER SEGMENT

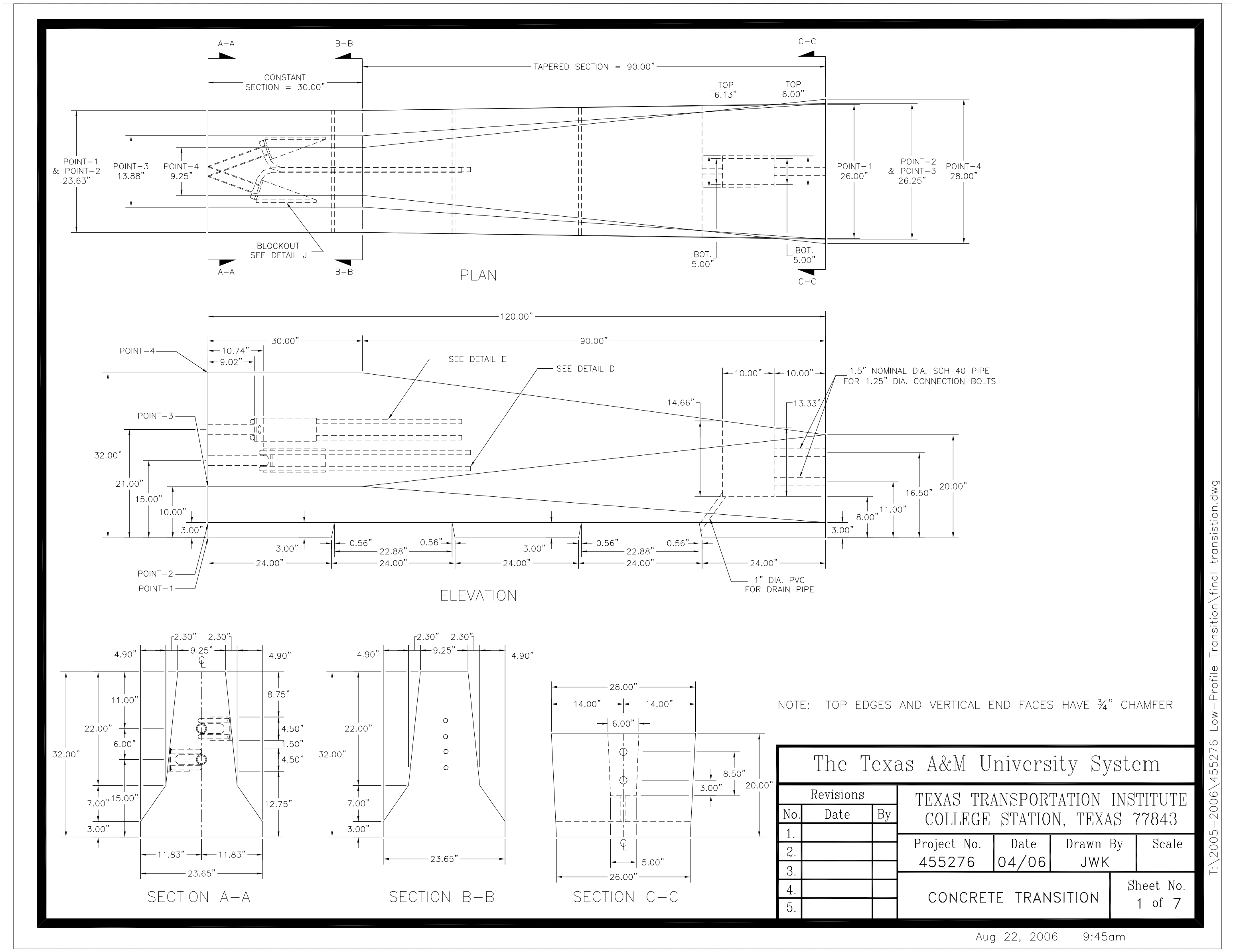


Figure 30. Details of the Low-Profile Transition to Standard Concrete Barrier – Overall Layout.

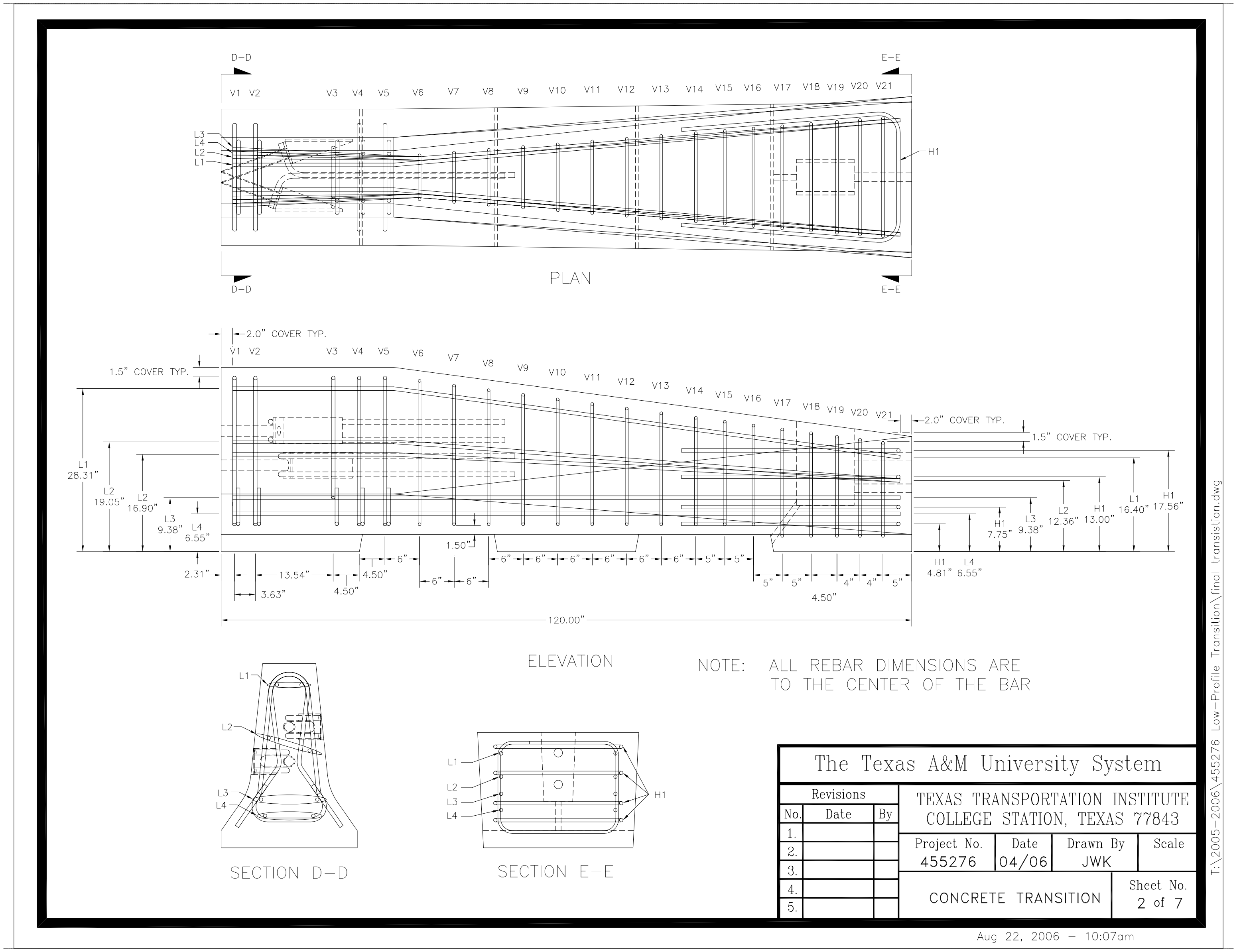


Figure 31. Details of the Low-Profile Transition to Standard Concrete Barrier – Rebar Placement Details.

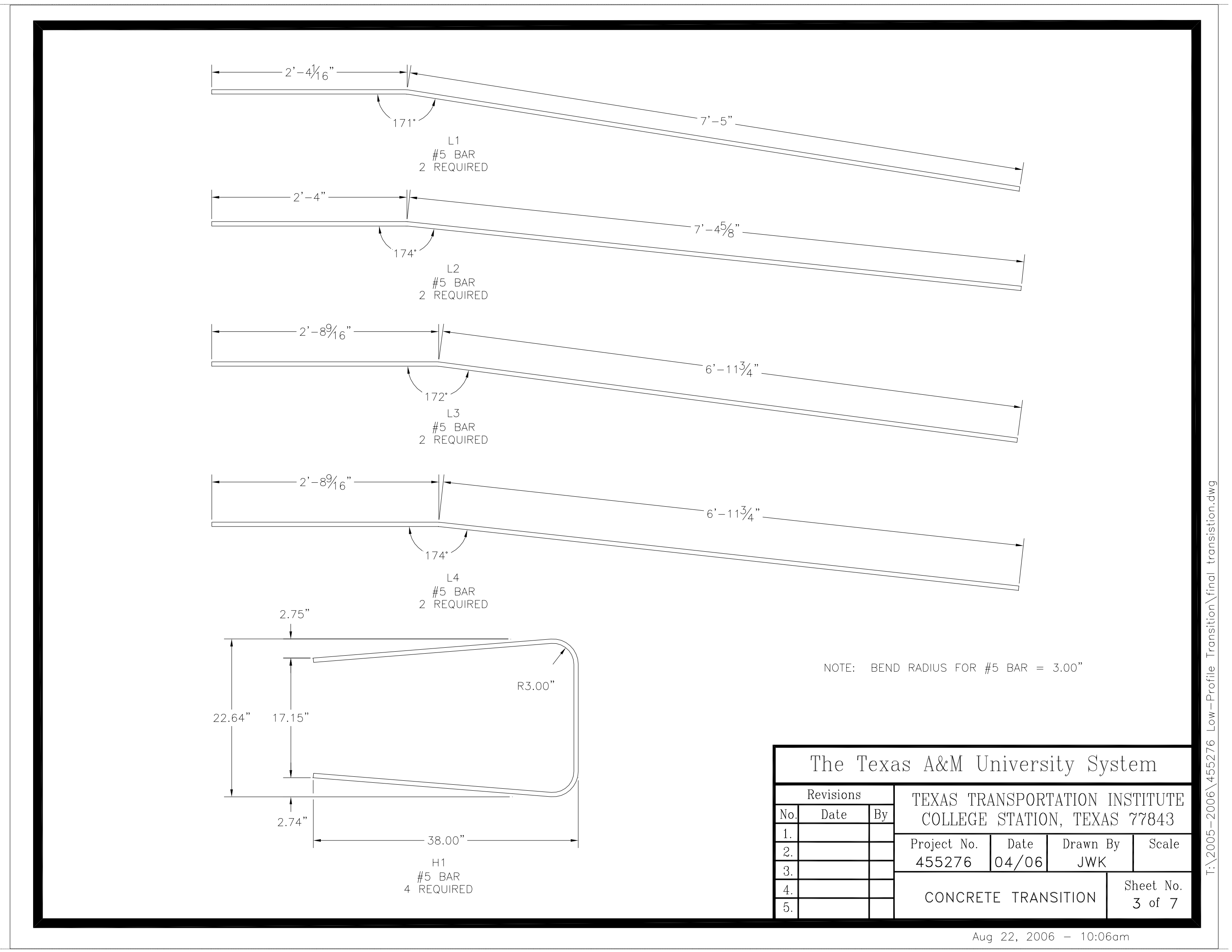


Figure 32. Details of the Low-Profile Transition to Standard Concrete Barrier – Longitudinal Rebar Details.

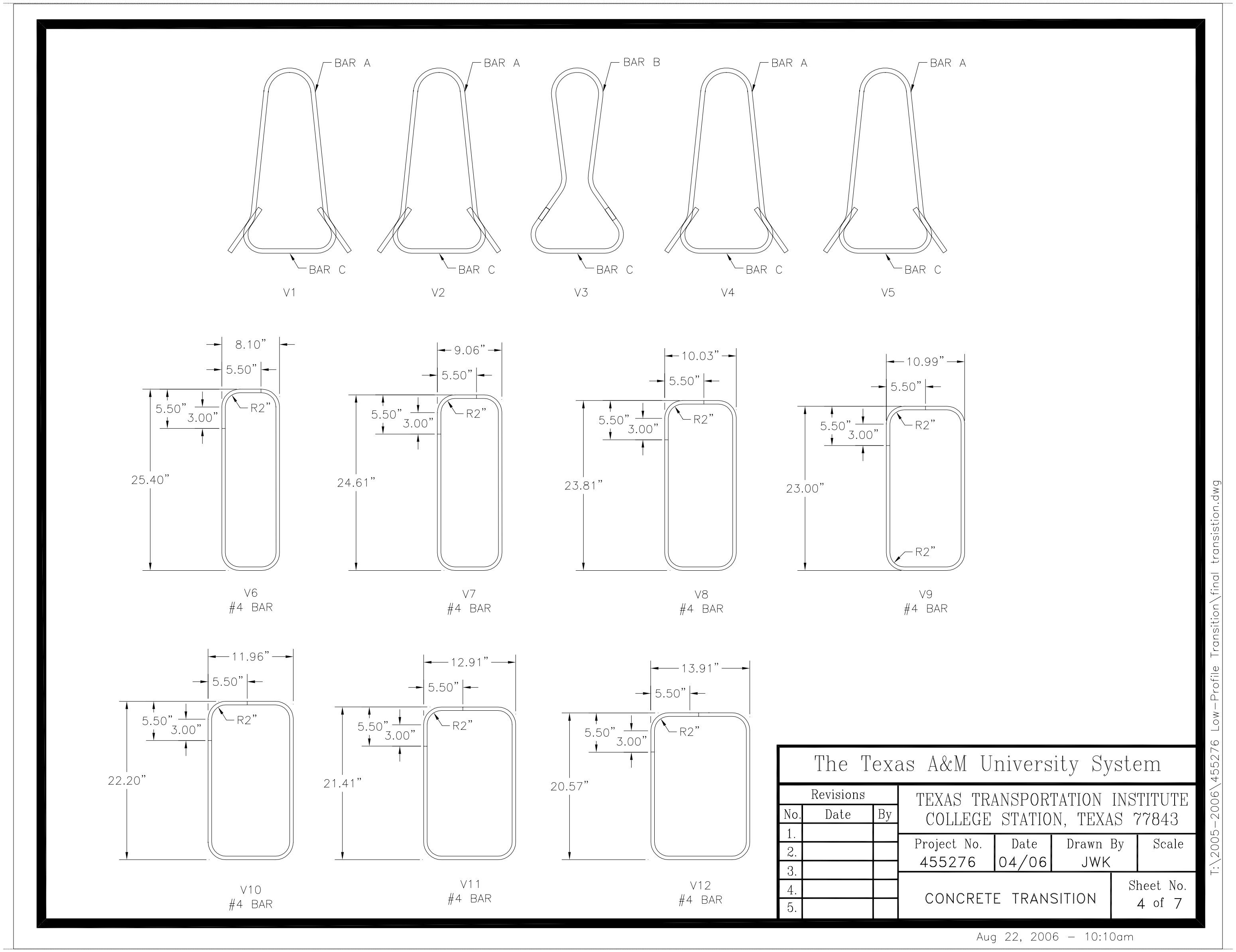


Figure 33. Details of the Low-Profile Transition to Standard Concrete Barrier – Vertical Rebar Details.

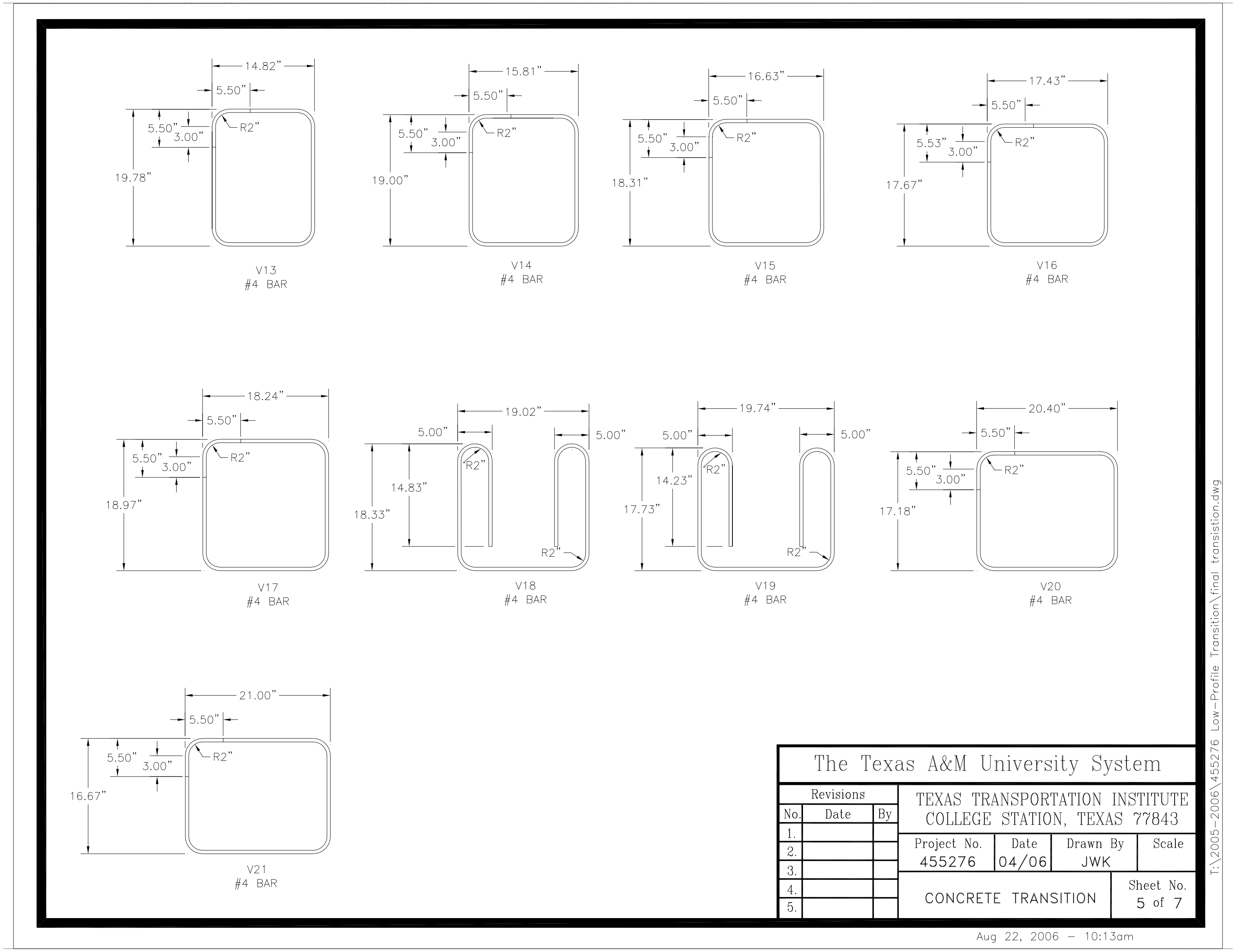


Figure 33. Details of the Low-Profile Transition to Standard Concrete Barrier – Vertical Rebar Details (Continued).

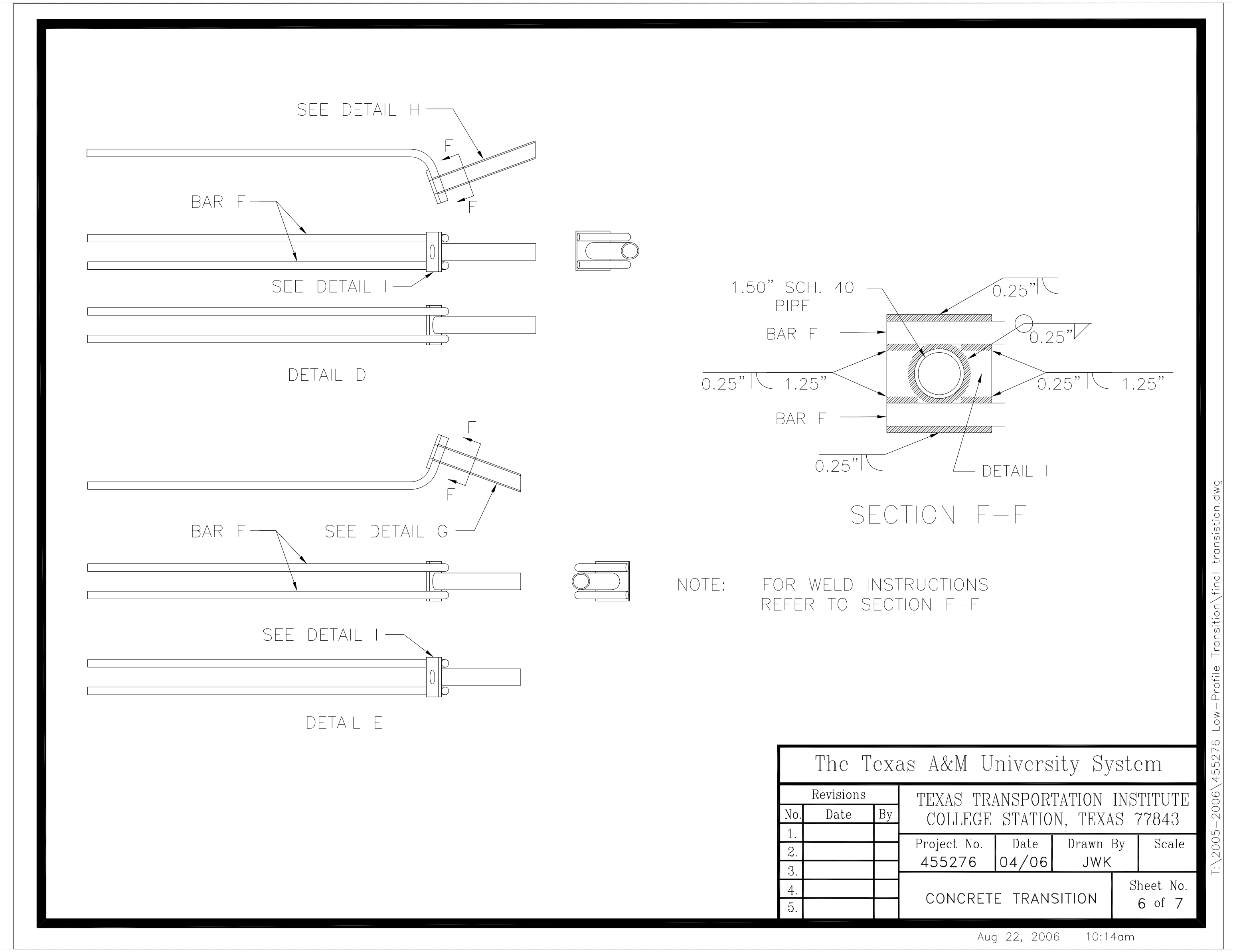


Figure 34. Details of the Low-Profile Transition to Standard Concrete Barrier – X-Bolt Rebar Details.

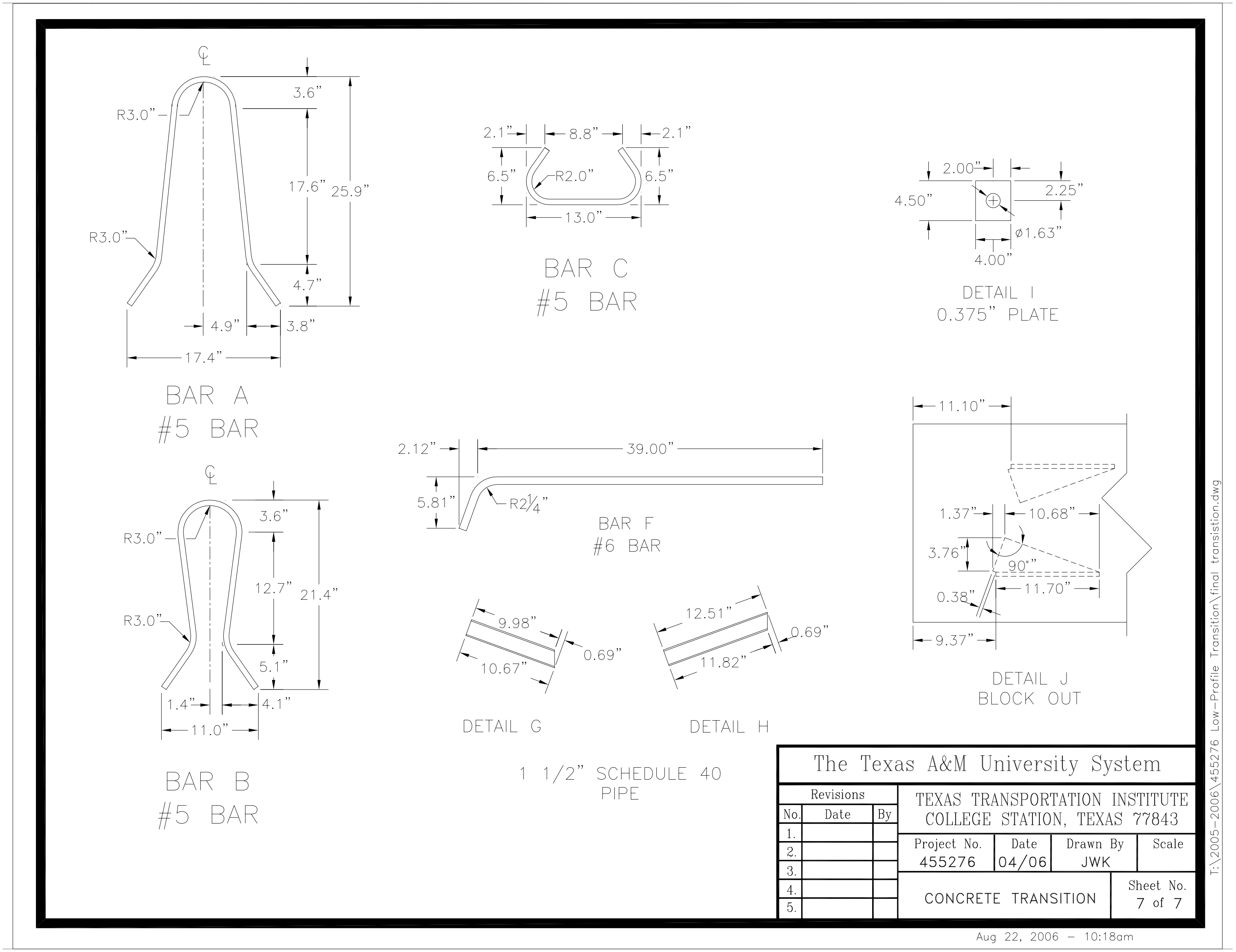


Figure 34. Details of the Low-Profile Transition to Standard Concrete Barrier – X-Bolt Rebar Details (Continued).

APPENDIX B. 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 and for display. 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 a TEAC® instrumentation data recorder. After the test, the data are played back from the TEAC® recorder 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 systems being initial impact.

ANTHROPOMORPHIC DUMMY INSTRUMENTATION

Use of a dummy in the 2000P vehicle is optional according to *NCHRP Report 350*, and there was no dummy used in 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 mini-DV camera 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 C. TEST VEHICLE PROPERTIES AND INFORMATION

Date: 05-31-2006 Test No.: 455276-1 VIN No.: 1GCGC24U31Z285207

Year: 2001 Make: Chevrolet Model: C2500

Tire Inflation Pressure: 60 psi Odometer: 141376 Tire Size: 245/75R16

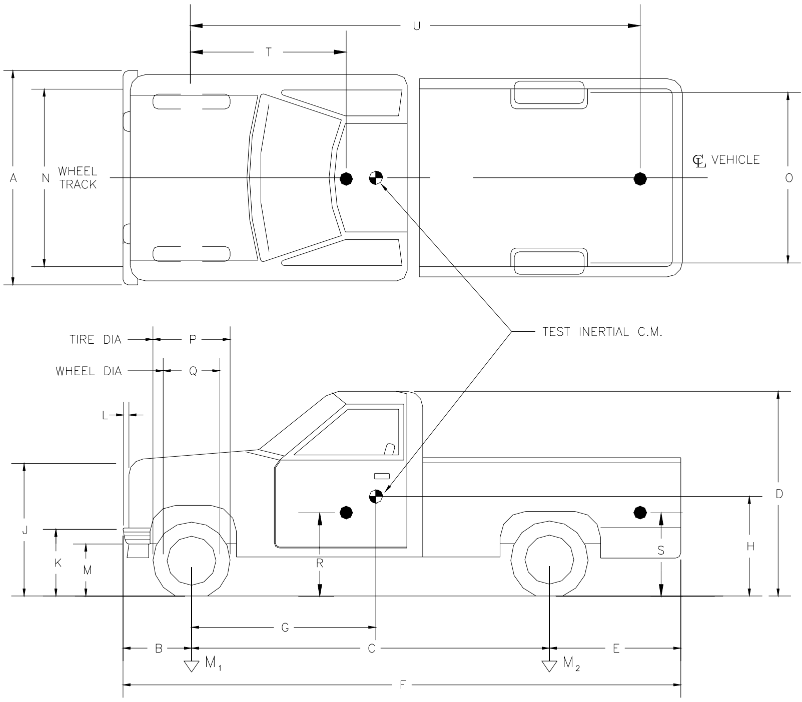
Describe any damage to the vehicle prior to test: ____________________

● Denotes accelerometer location.

NOTES: ____________________

Engine Type: V-8
Engine CID: 5.3 liter
Transmission Type:
x Auto
___ Manual
Optional Equipment:

Dummy Data:
Type: No dummy
Mass: ____________
Seat Position: ____________



Geometry (mm)

A	1820	E	1340	J	1090	N	1670	R	730
B	840	F	5560	K	650	O	1680	S	890
C	3380	G	1375.34	L	90	P	740	T	1440
D	1865	H		M	370	Q	440	U	3330

Mass (kg)	Curb	Test Inertial	Gross Static
M_1	1337	1271	
M_2	902	872	
M_{Total}	2239	2143	

Mass Distribution (kg): LF: 635 RF: 636 LR: 445 RR: 427

Figure 35. Vehicle Properties for Test No. 455276-1.

Table 3. Exterior Crush Measurements for Test No. 455276-1.

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	Front at bumper height	900	400	800	400	300	265	155	105	50	-400
2	Side at bumper height	900	500	1200	N/A	N/A	N/A	380	430	500	1800

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

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

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

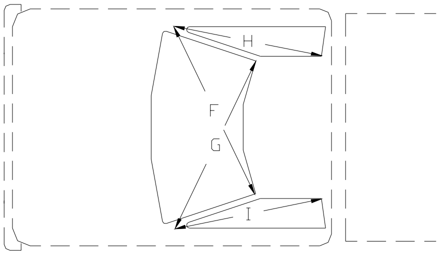
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

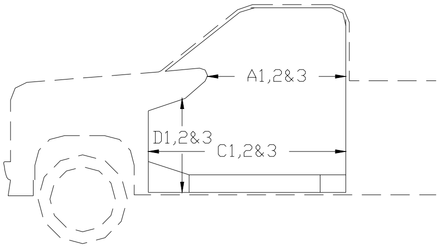
***Measure and document on the vehicle diagram the location of the maximum crush.

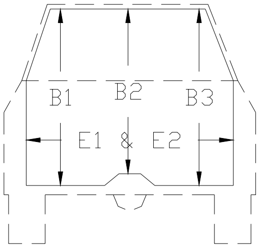
Note: Use as many lines/columns as necessary to describe each damage profile.

Table 4. Occupant Compartment Measurements for Test No. 455276-1.

TRUCK







Occupant Compartment Deformation

	BEFORE (mm)	AFTER (mm)
A1	934	
A2	948	948
A3	935	935
B1	1106	1100
B2	950	950
B3	1096	1096
C1	1420	1350
C2	1353	1353
C3	1399	1399
D1	316	297
D2	145	145
D3	326	326
E1	1595	1595
E2	1590	1590
F	1464	1464
G	1464	1464
H	880	880
I	950	950
J*	1542	1535

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

Date: 06-01-2006 Test No.: 455276-2 VIN No.: 1GCGC24U112283309

Year: 2001 Make: Chevrolet Model: C2500

Tire Inflation Pressure: 60 psi Odometer: (not working) Tire Size: 245-75R16

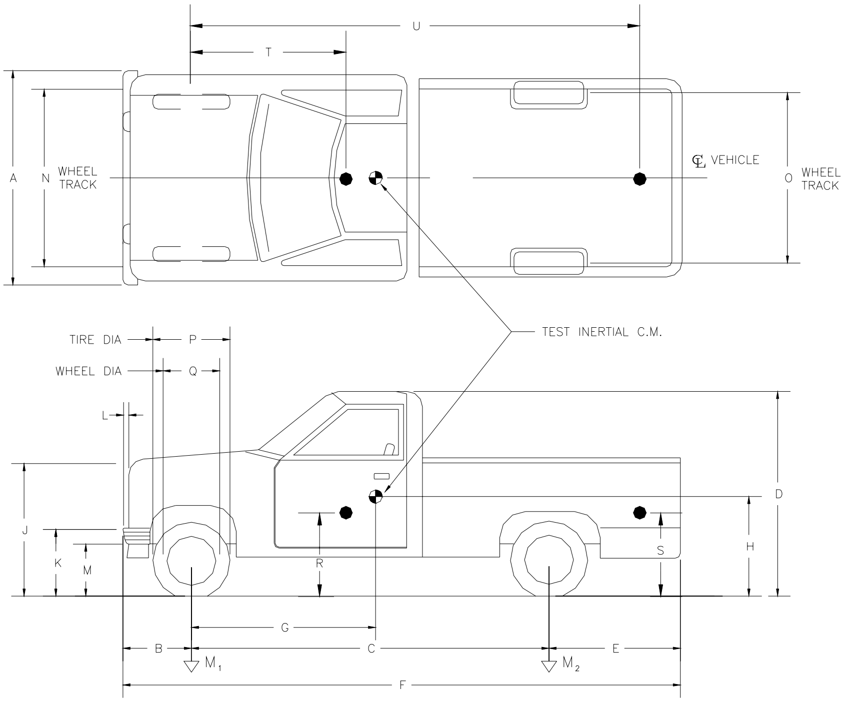
Describe any damage to the vehicle prior to test:

● Denotes accelerometer location.

NOTES:

Engine Type: V-8
Engine CID: 5.3 liter
Transmission Type:
x Auto
Manual
Optional Equipment:

Dummy Data:
Type: No dummy
Mass:
Seat Position:



Geometry (mm)

A	1820	E	1340	J	1090	N	1670	R	730
B	840	F	5560	K	650	O	1680	S	890
C	3380	G	1361.7	L	90	P	740	T	1440
D	1865	H		M	370	Q	440	U	3330

Mass (kg)	Curb	Test Inertial	Gross Static
M_1	1315	1285	
M_2	845	867	
M_{Total}	2160	2152	

Mass Distribution (kg): LF: 646 RF: 639 LR: 442 RR: 425

Figure 36. Vehicle Properties for Test No. 455276-2.

Table 5. Exterior Crush Measurements for Test No. 455276-2.

VEHICLE CRUSH MEASUREMENT SHEET[1]

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 $\frac{X1 + X2}{2} =$ _______

Note: Measure C_1 to C_6 from driver to passenger side in front or rear impacts – rear to front in side impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	Front at bumper ht	800	300	700	20	40	110	200	220	300	+500
2	Right side at bumper ht	800	350	1000	0	N/A	N/A	270	300	350	+1670

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

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

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

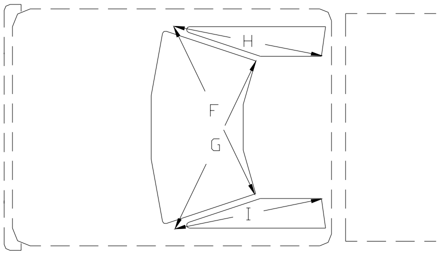
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

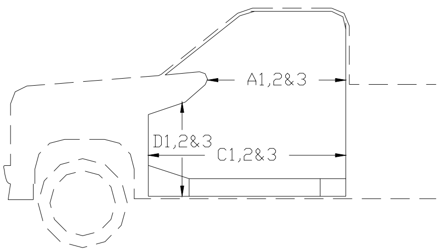
***Measure and document on the vehicle diagram the location of the maximum crush.

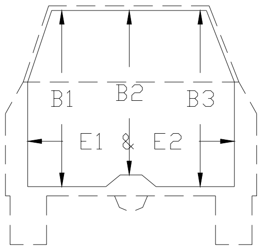
Note: Use as many lines/columns as necessary to describe each damage profile.

Table 6. Occupant Compartment Measurements for Test No. 455276-2.

TRUCK





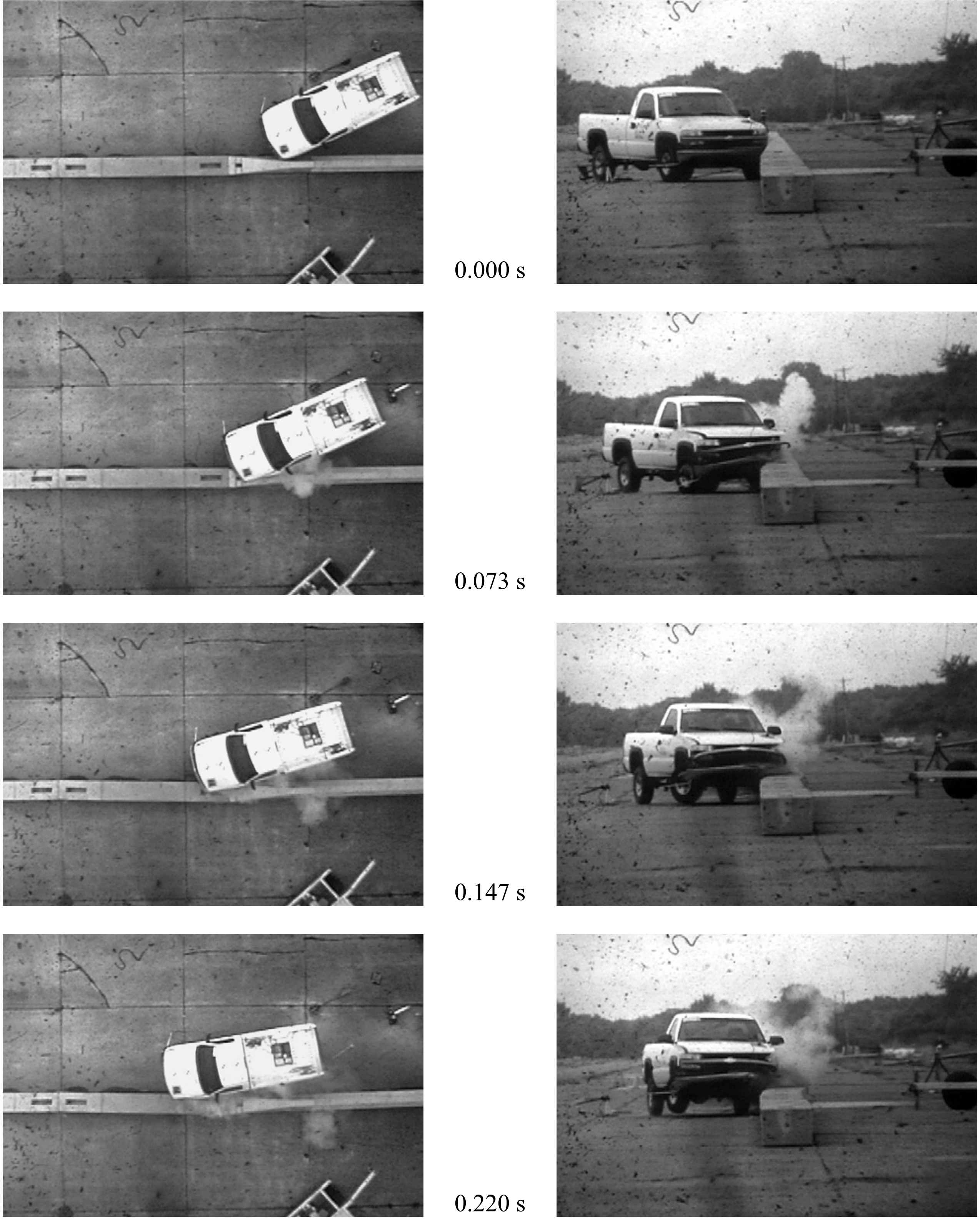


Occupant Compartment Deformation

	BEFORE (mm)	AFTER (mm)
A1	931	931
A2	945	945
A3	945	945
B1	1114	1114
B2	947	947
B3	1105	1105
C1	1409	1409
C2	1362	1362
C3	1395	1395
D1	316	316
D2	145	145
D3	299	299
E1	1586	1586
E2	1588	1588
F	1475	1475
G	1475	1475
H	880	880
I	942	942
J*	1544	1544

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

APPENDIX D. SEQUENTIAL PHOTOGRAPHS



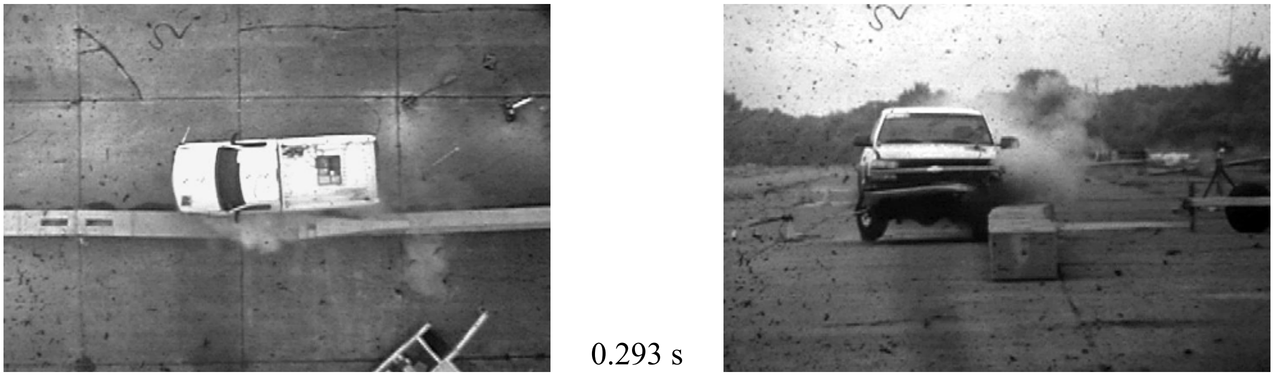
0.000 s

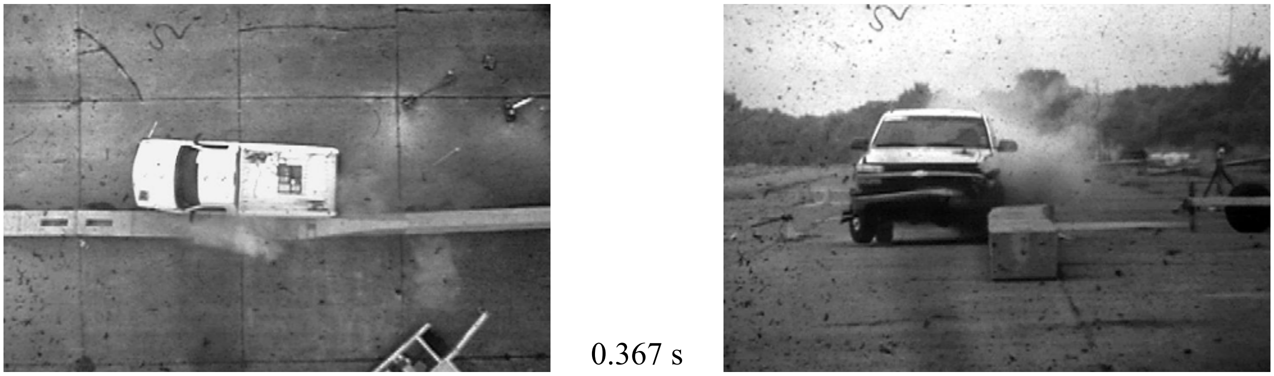
0.073 s

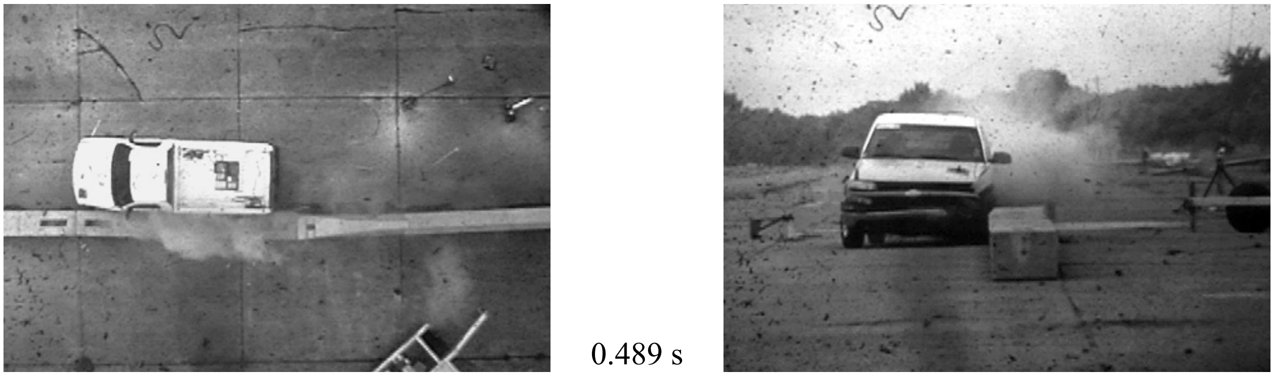
0.147 s

0.220 s

Figure 37. Sequential Photographs for Test No. 455276-1 (Overhead and Frontal Views).


0.293 s


0.367 s


0.489 s

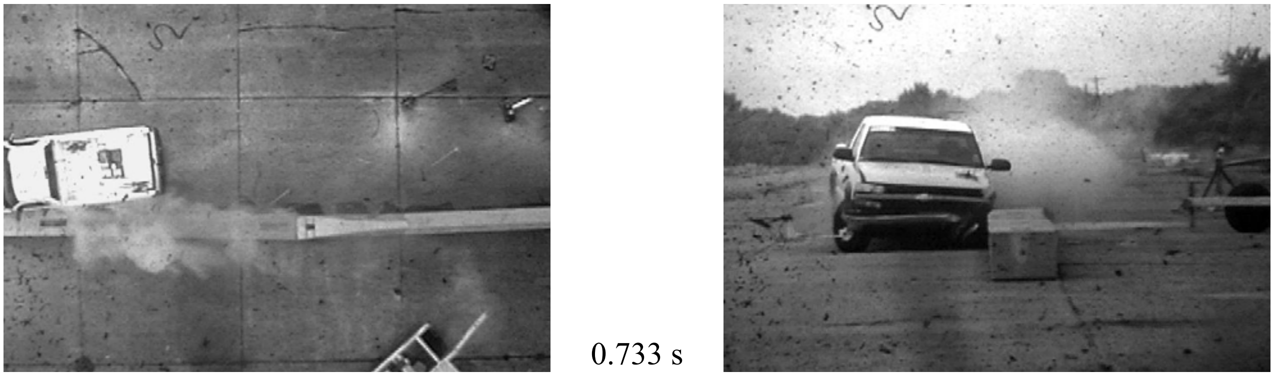
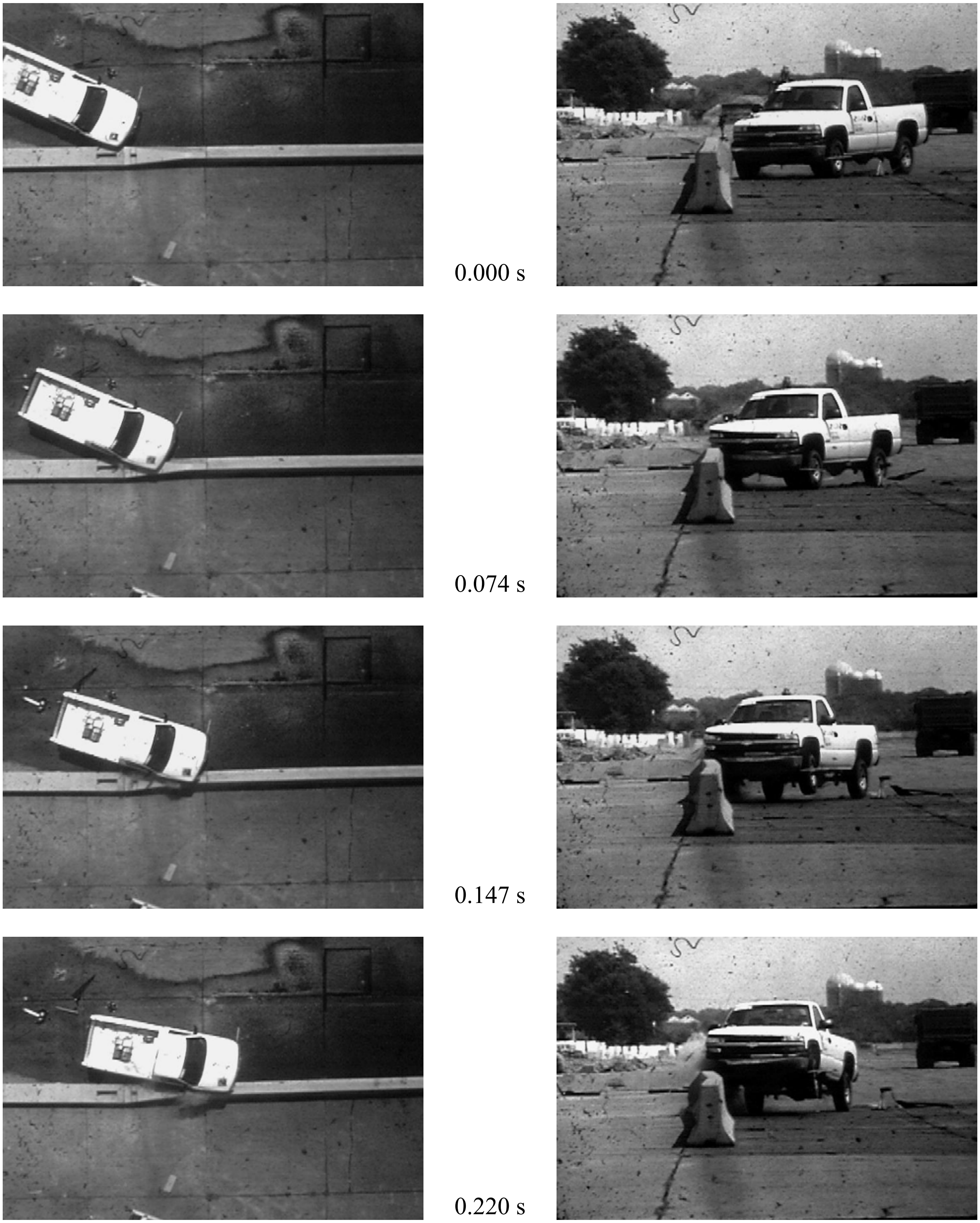

0.733 s

Figure 37. Sequential Photographs for Test No. 455276-1 (Overhead and Frontal Views) (Continued).



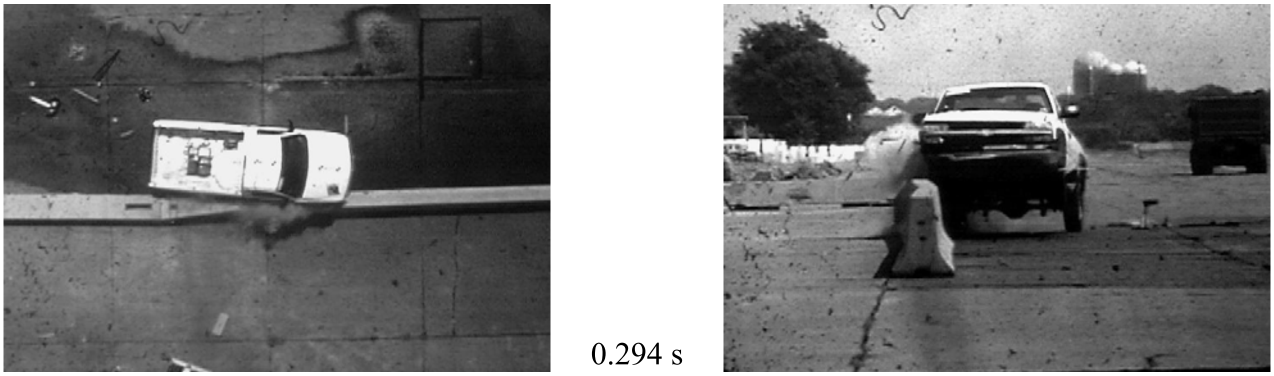
0.000 s

0.074 s

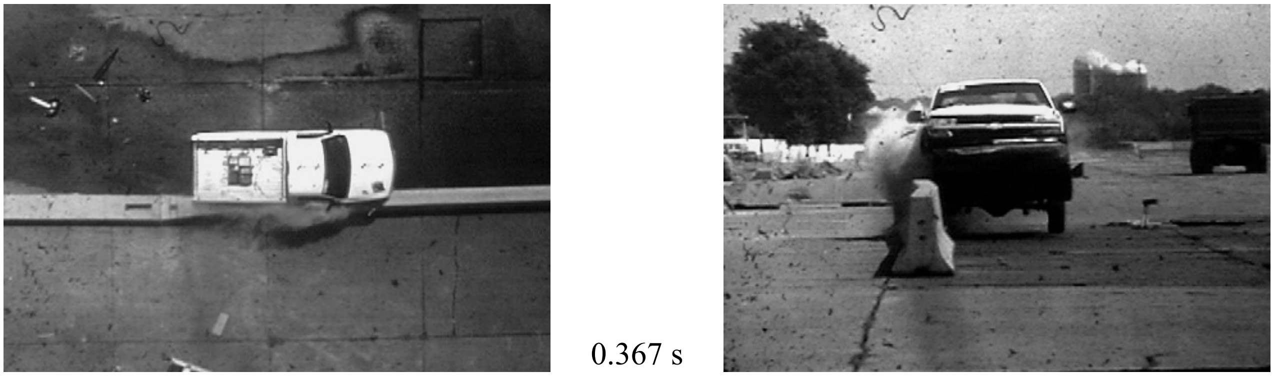
0.147 s

0.220 s

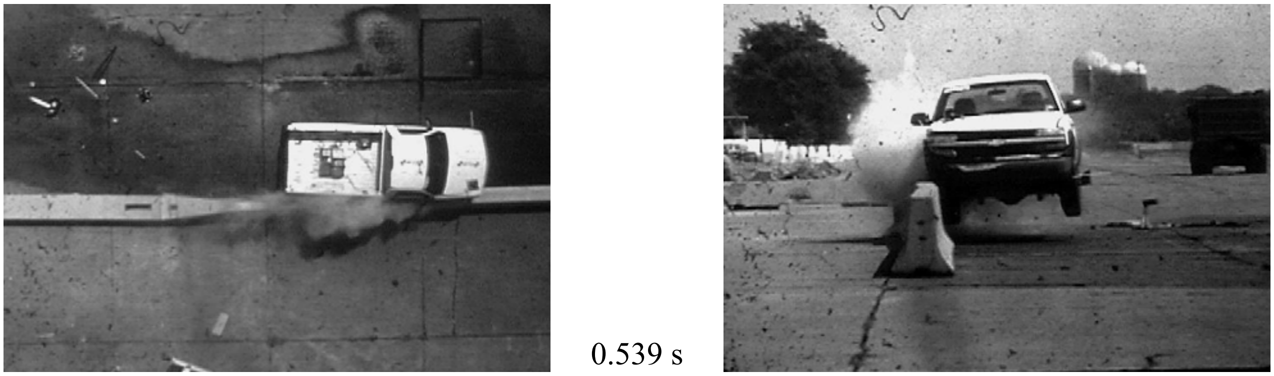
Figure 38. Sequential Photographs for Test No. 455276-2 (Overhead and Frontal Views).



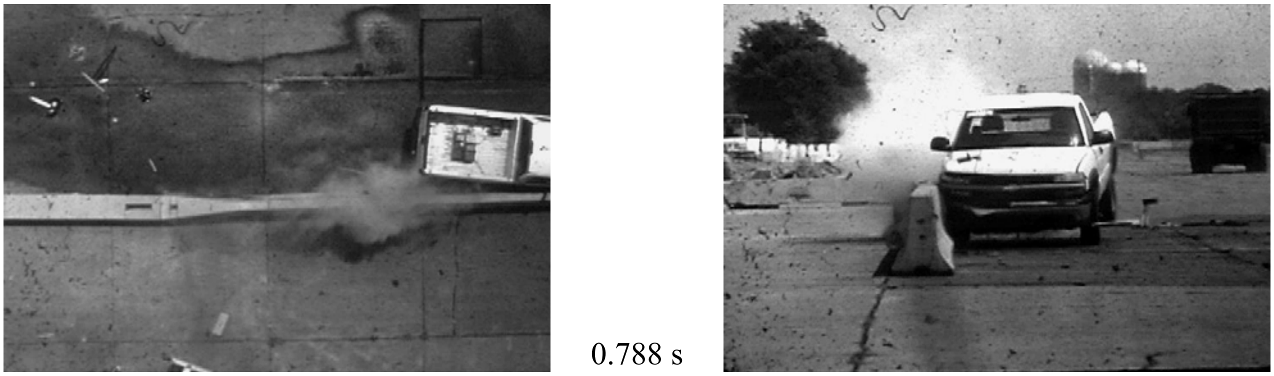
0.294 s



0.367 s



0.539 s



0.788 s

Figure 38. Sequential Photographs for Test No. 455276-2 (Overhead and Frontal Views) (Continued).

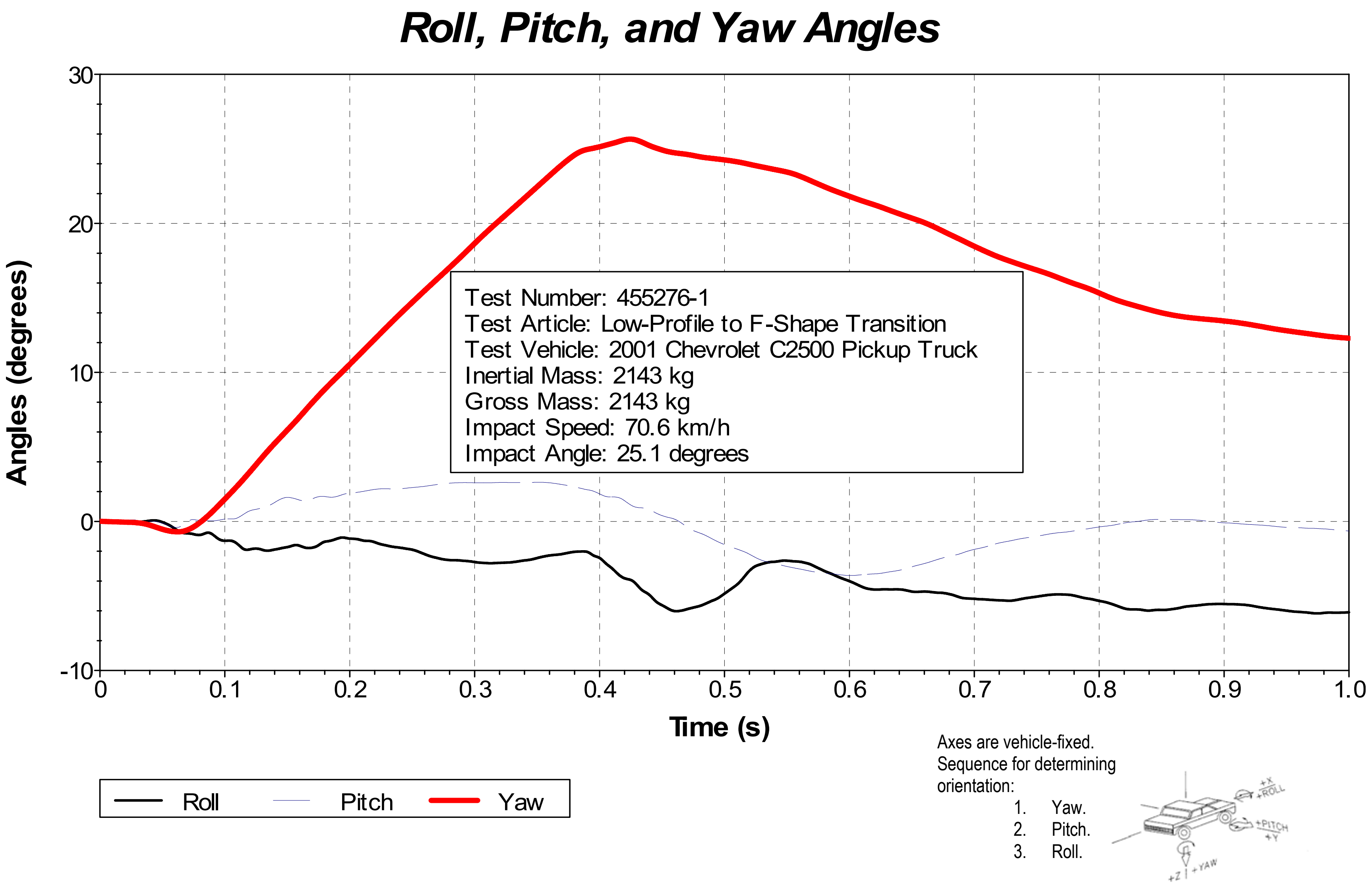


Figure 39. Vehicle Angular Displacements for Test No. 455276-1.

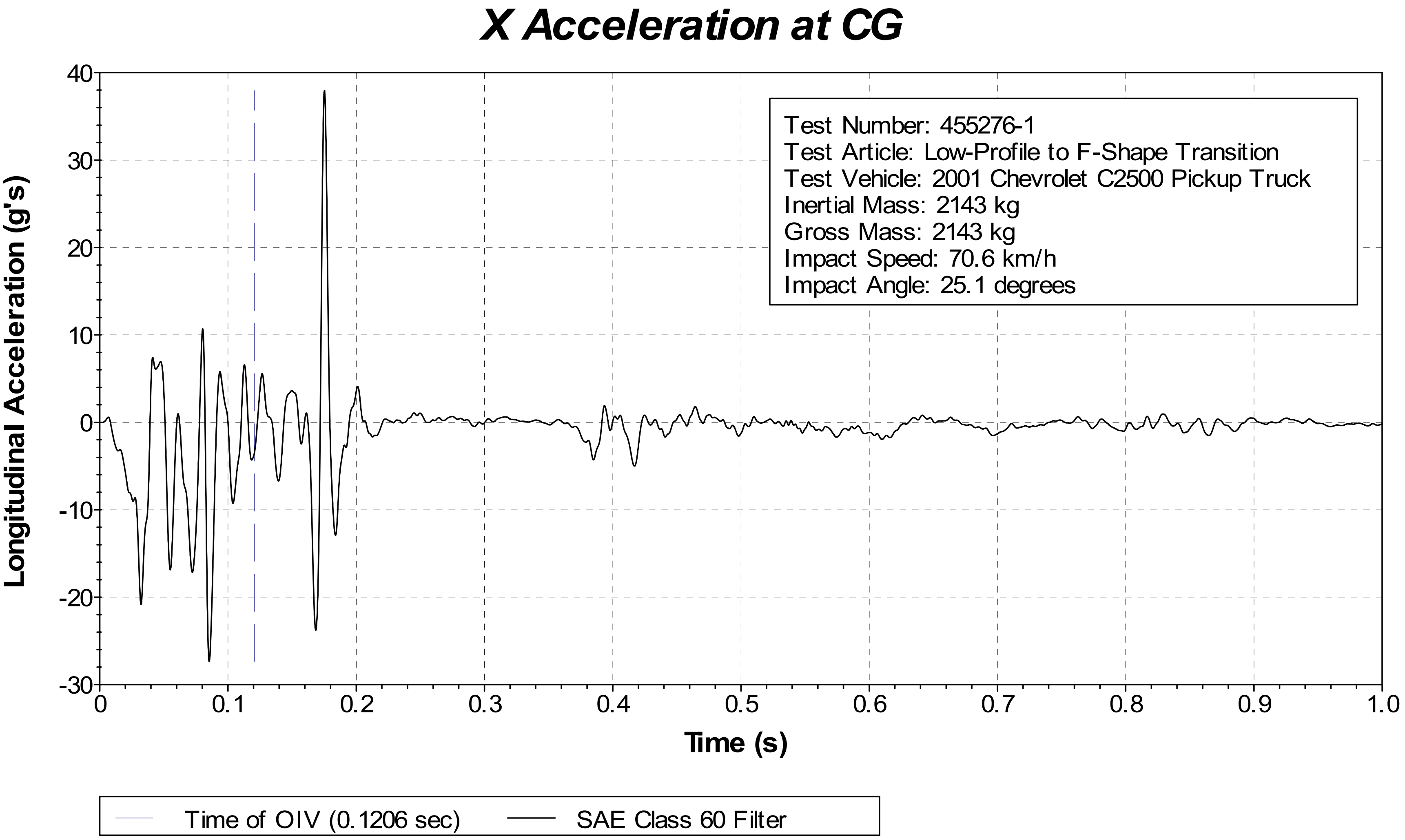


Figure 40. Vehicle Longitudinal Accelerometer Trace for Test No. 455276-1 (Accelerometer Located at Center of Gravity).

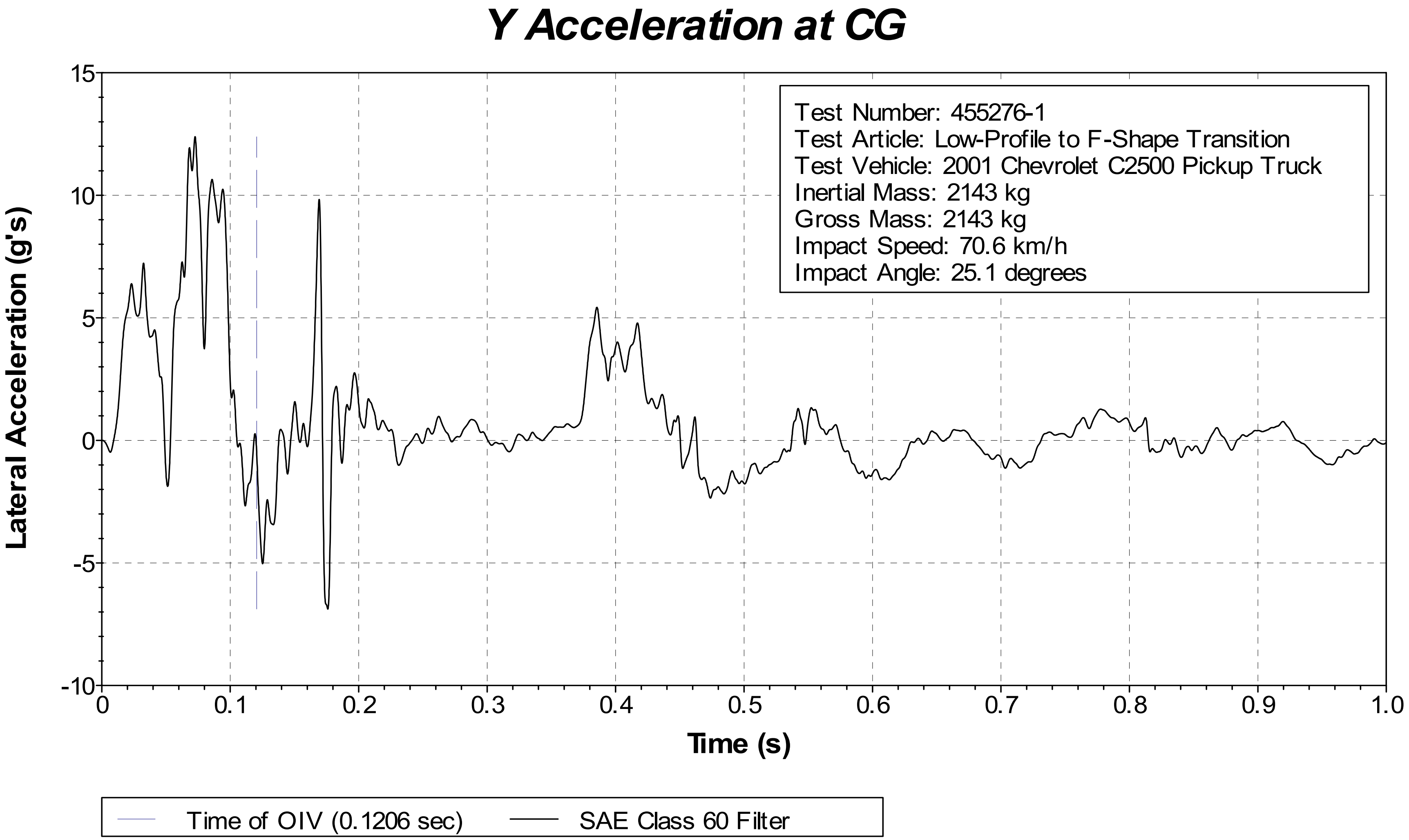
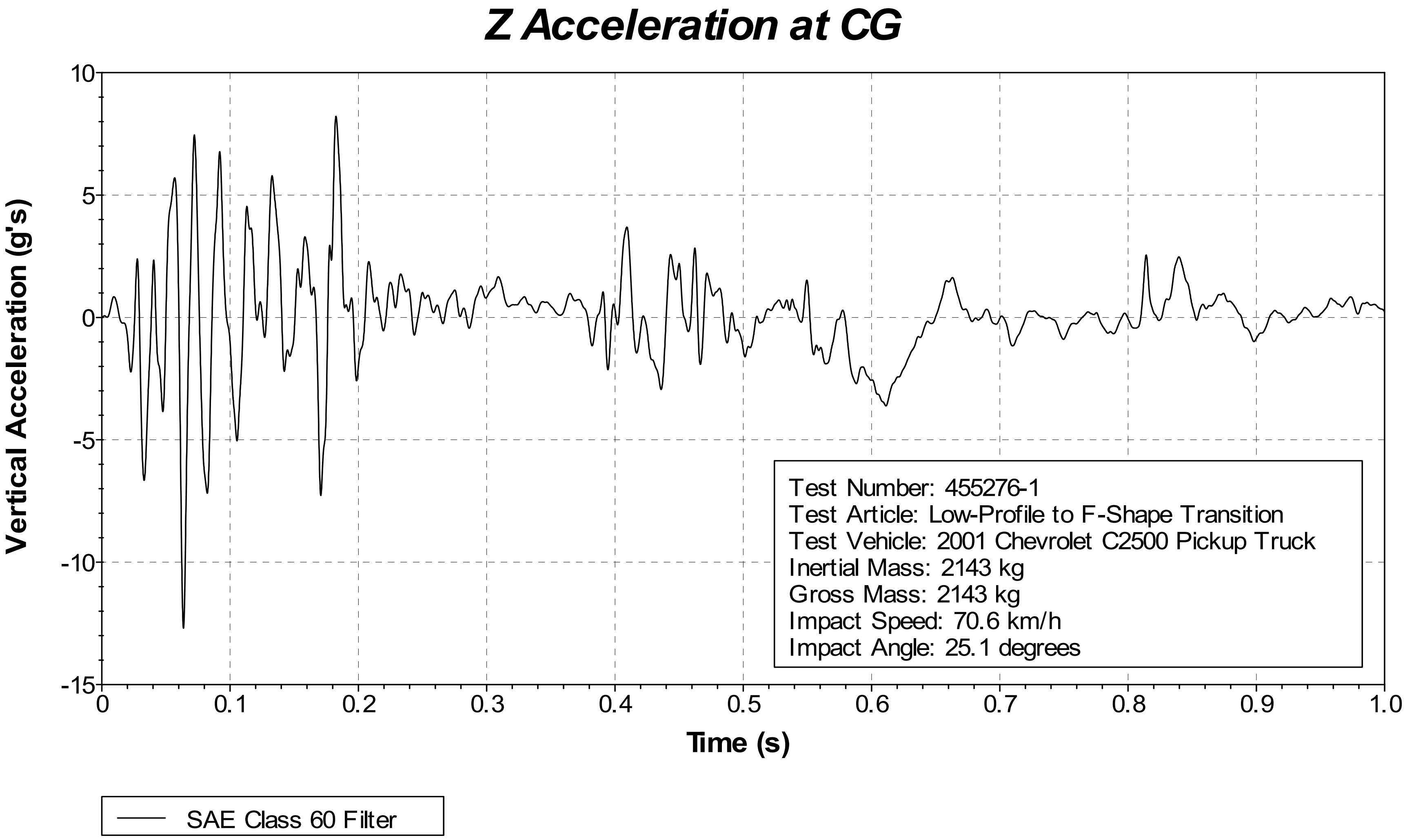


Figure 41. Vehicle Lateral Accelerometer Trace for Test No. 455276-1 (Accelerometer Located at Center of Gravity).



Test Number: 455276-1
Test Article: Low-Profile to F-Shape Transition
Test Vehicle: 2001 Chevrolet C2500 Pickup Truck
Inertial Mass: 2143 kg
Gross Mass: 2143 kg
Impact Speed: 70.6 km/h
Impact Angle: 25.1 degrees

Figure 42. Vehicle Vertical Accelerometer Trace for Test No. 455276-1 (Accelerometer Located at Center of Gravity).

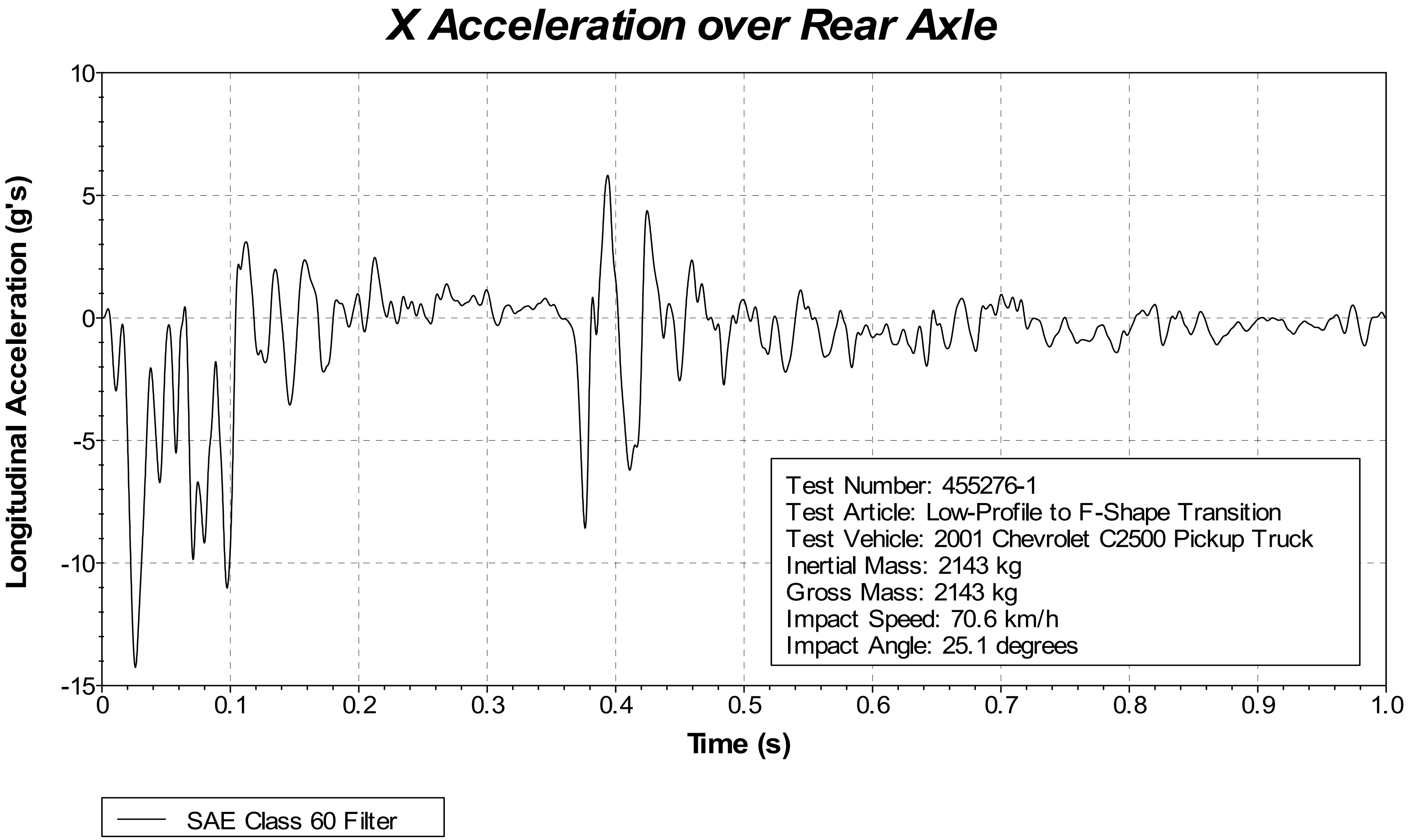


Figure 43. Vehicle Longitudinal Accelerometer Trace for Test No. 455276-1 (Accelerometer Located over Rear Axle).

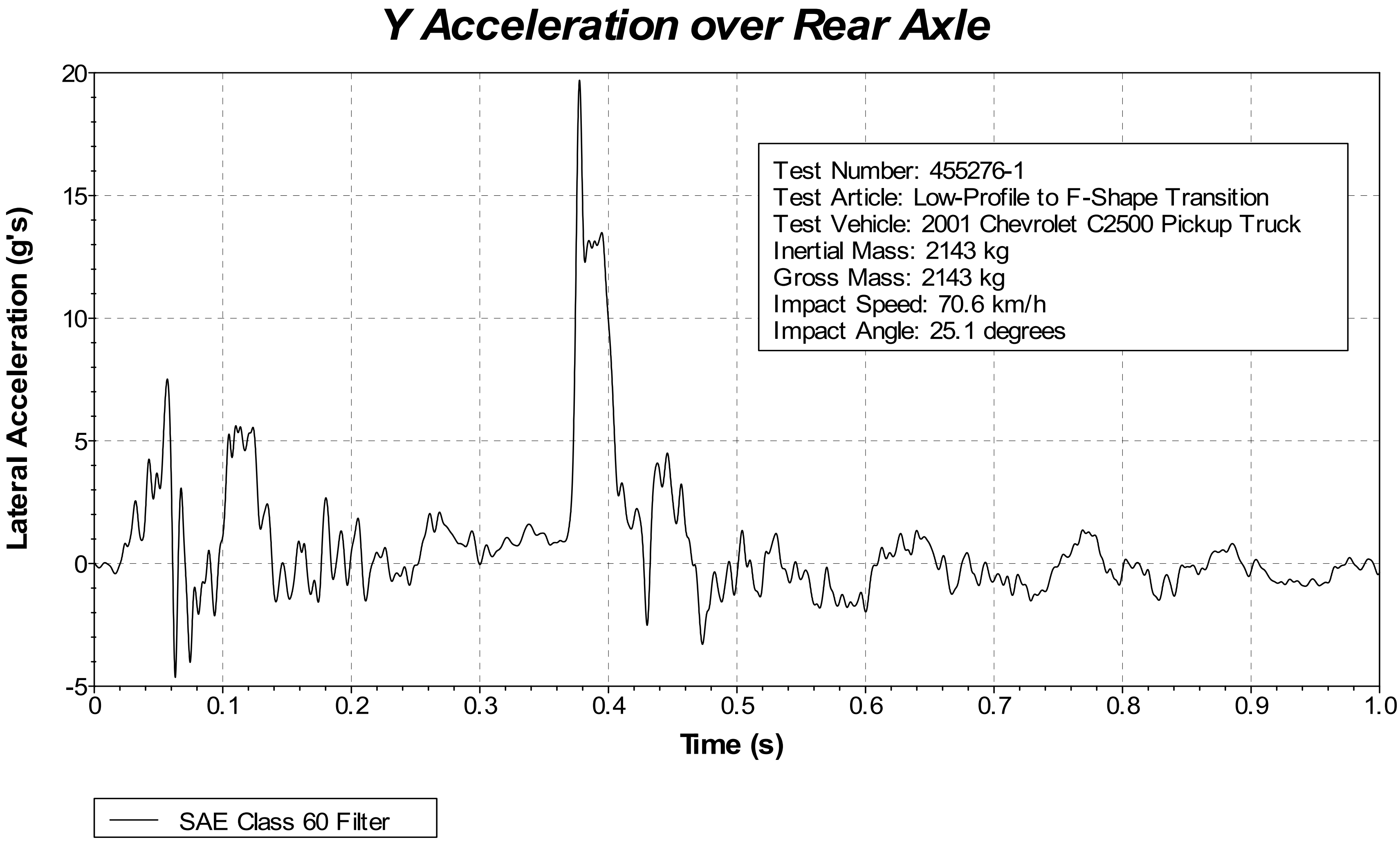


Figure 44. Vehicle Lateral Accelerometer Trace for Test No. 455276-1 (Accelerometer Located over Rear Axle).

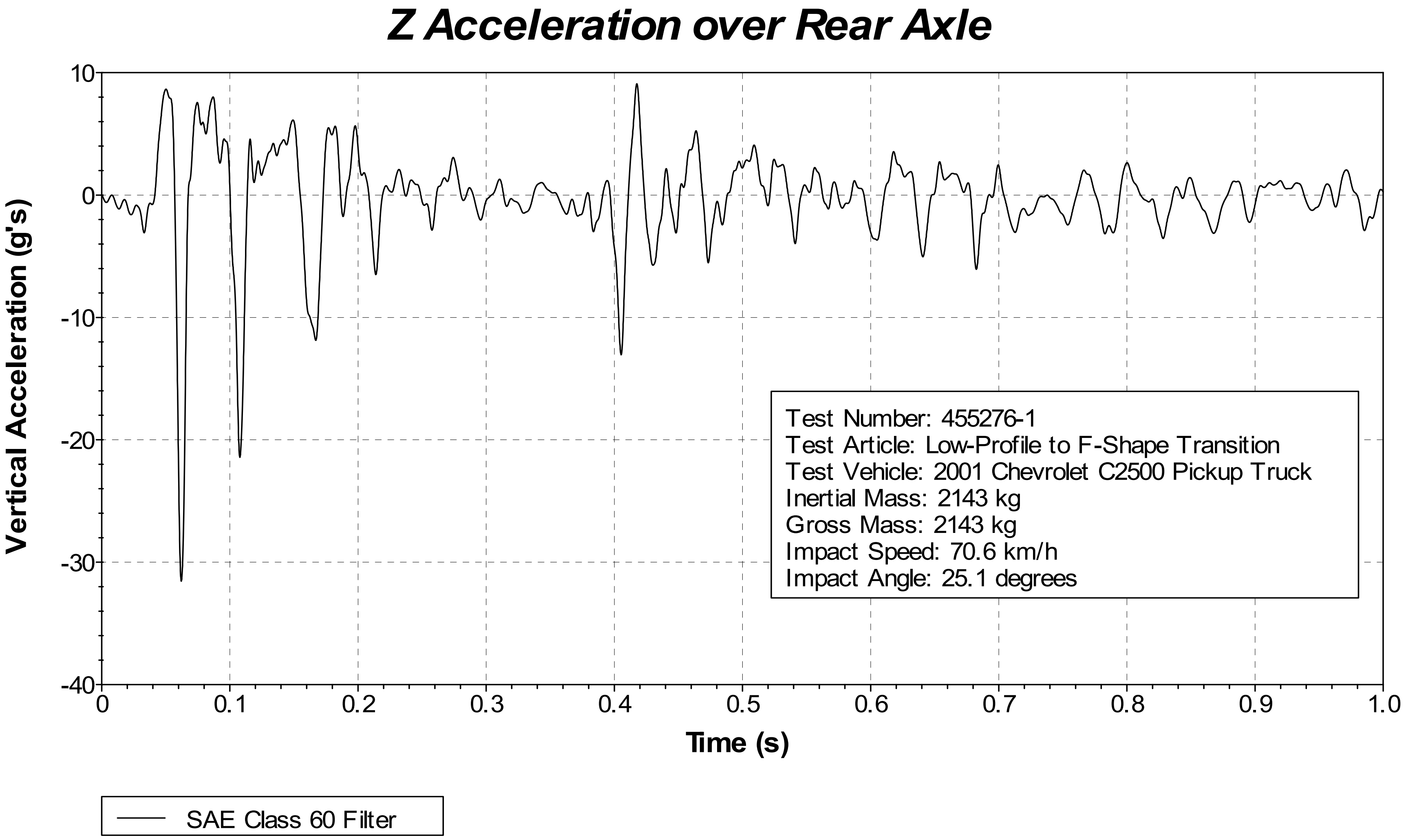


Figure 45. Vehicle Vertical Accelerometer Trace for Test No. 455276-1 (Accelerometer Located over Rear Axle).

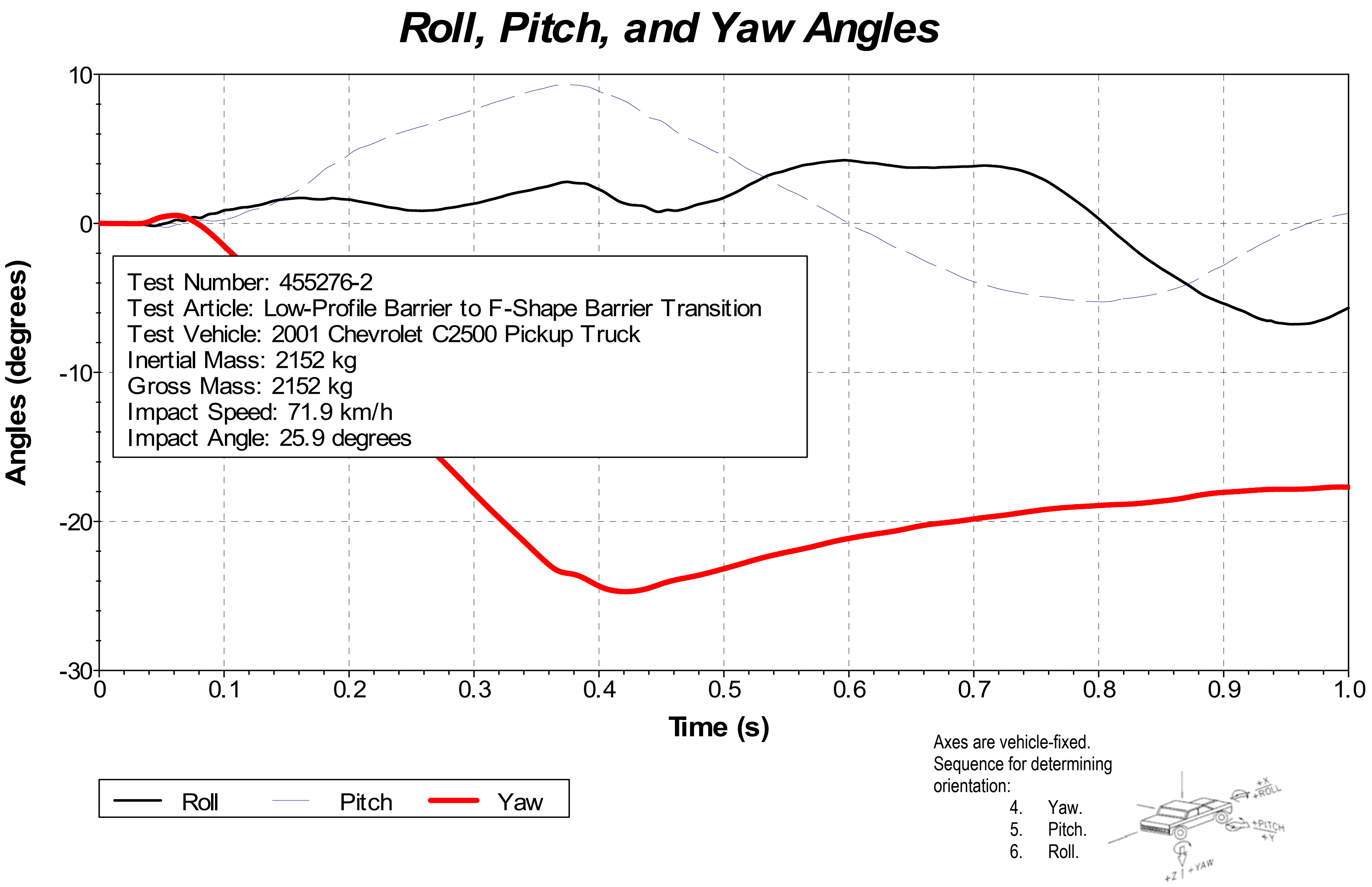


Figure 46. Vehicle Angular Displacements for Test 455276-2.

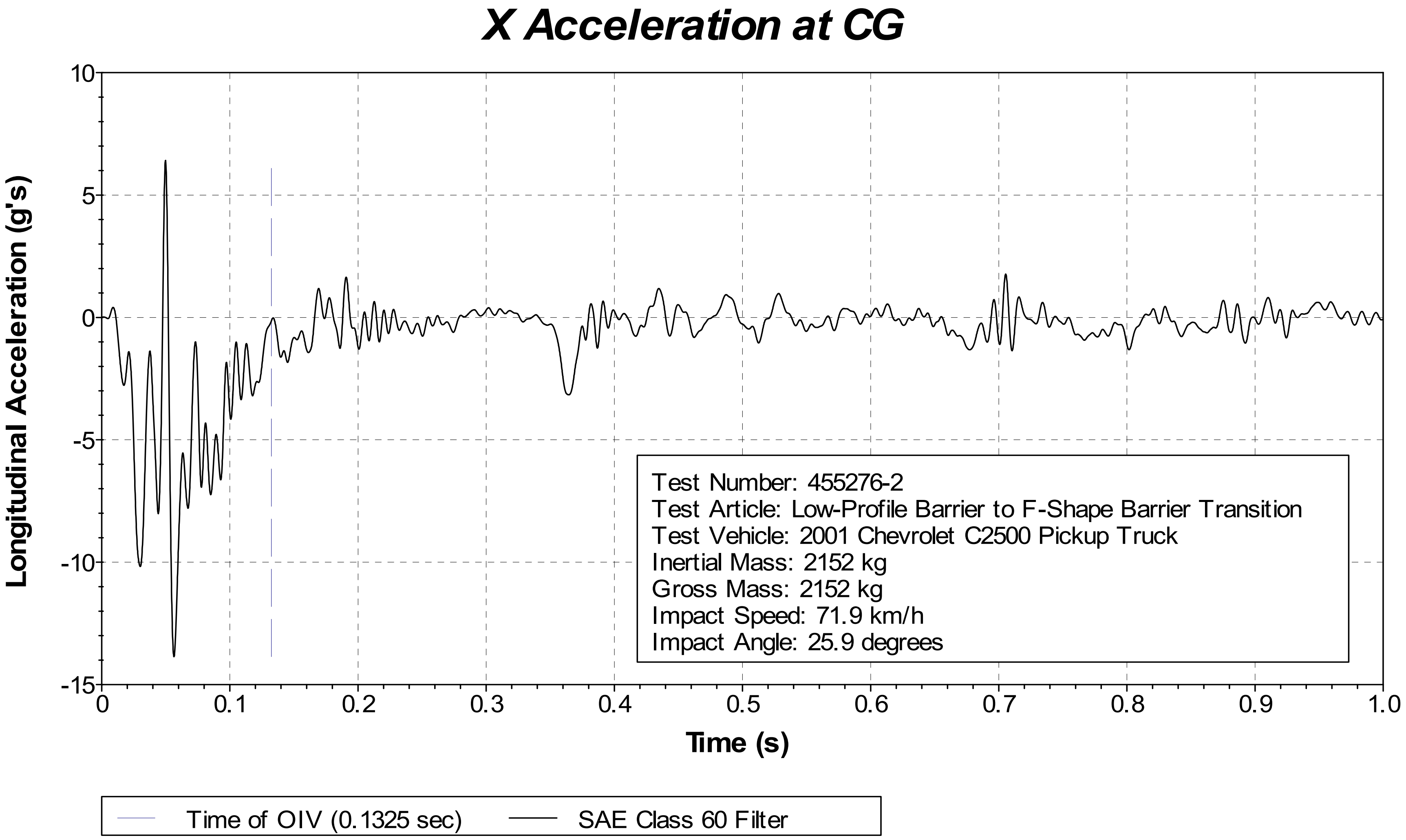


Figure 47. Vehicle Longitudinal Accelerometer Trace for Test 455276-2 (Accelerometer Located at Center of Gravity).

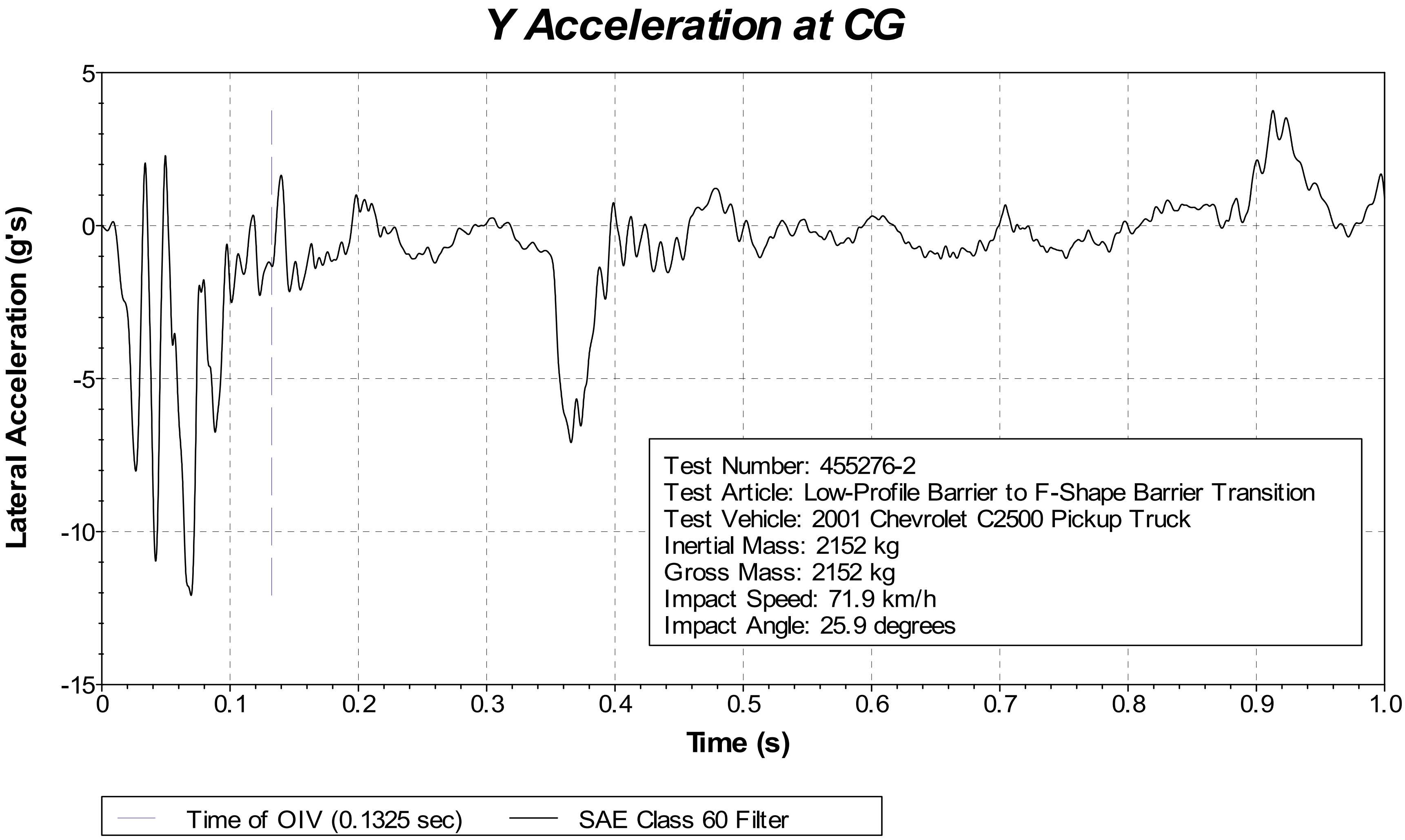


Figure 48. Vehicle Lateral Accelerometer Trace for Test 455276-2 (Accelerometer Located at Center of Gravity).

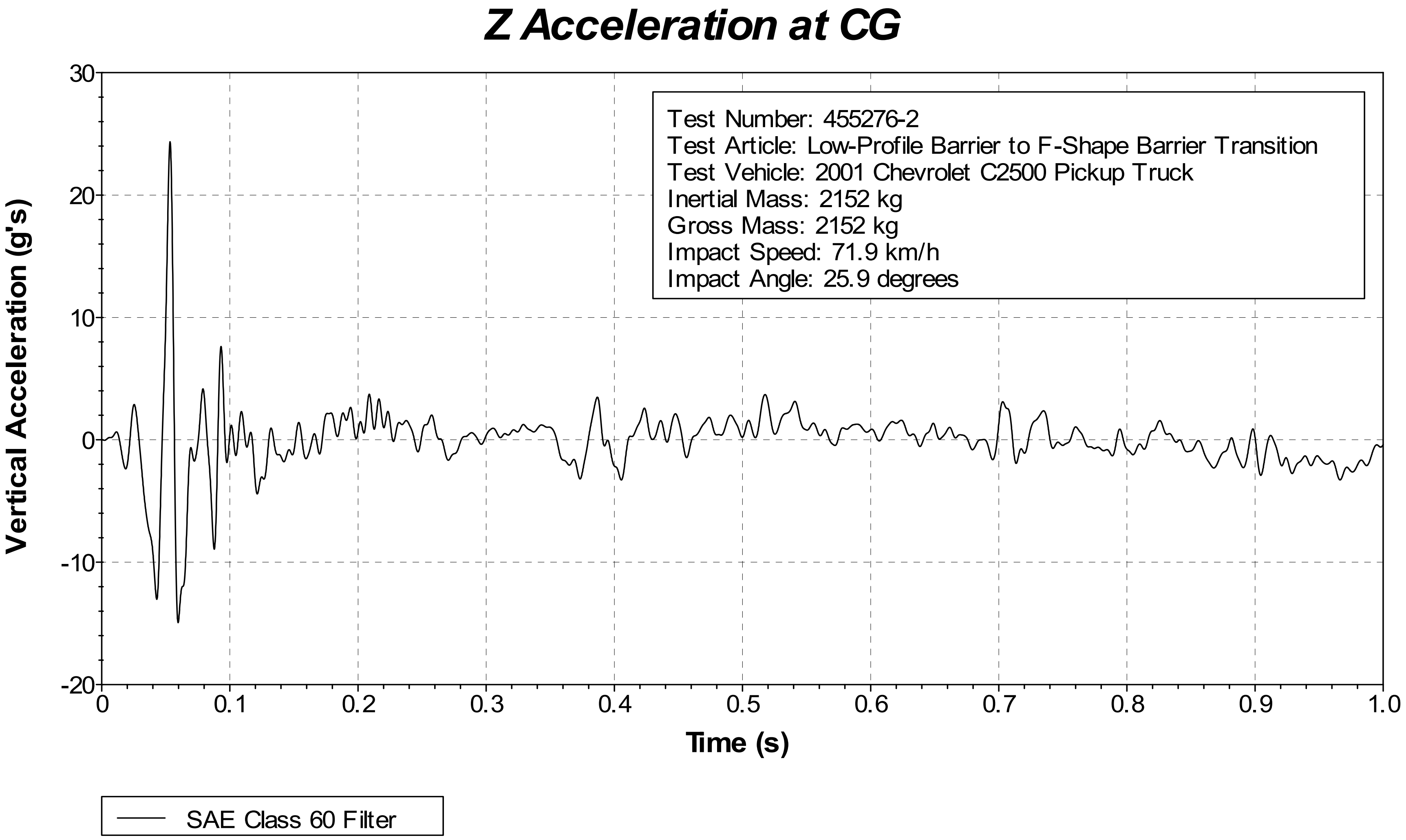


Figure 49. Vehicle Vertical Accelerometer Trace for Test 455276-2 (Accelerometer Located at Center of Gravity).

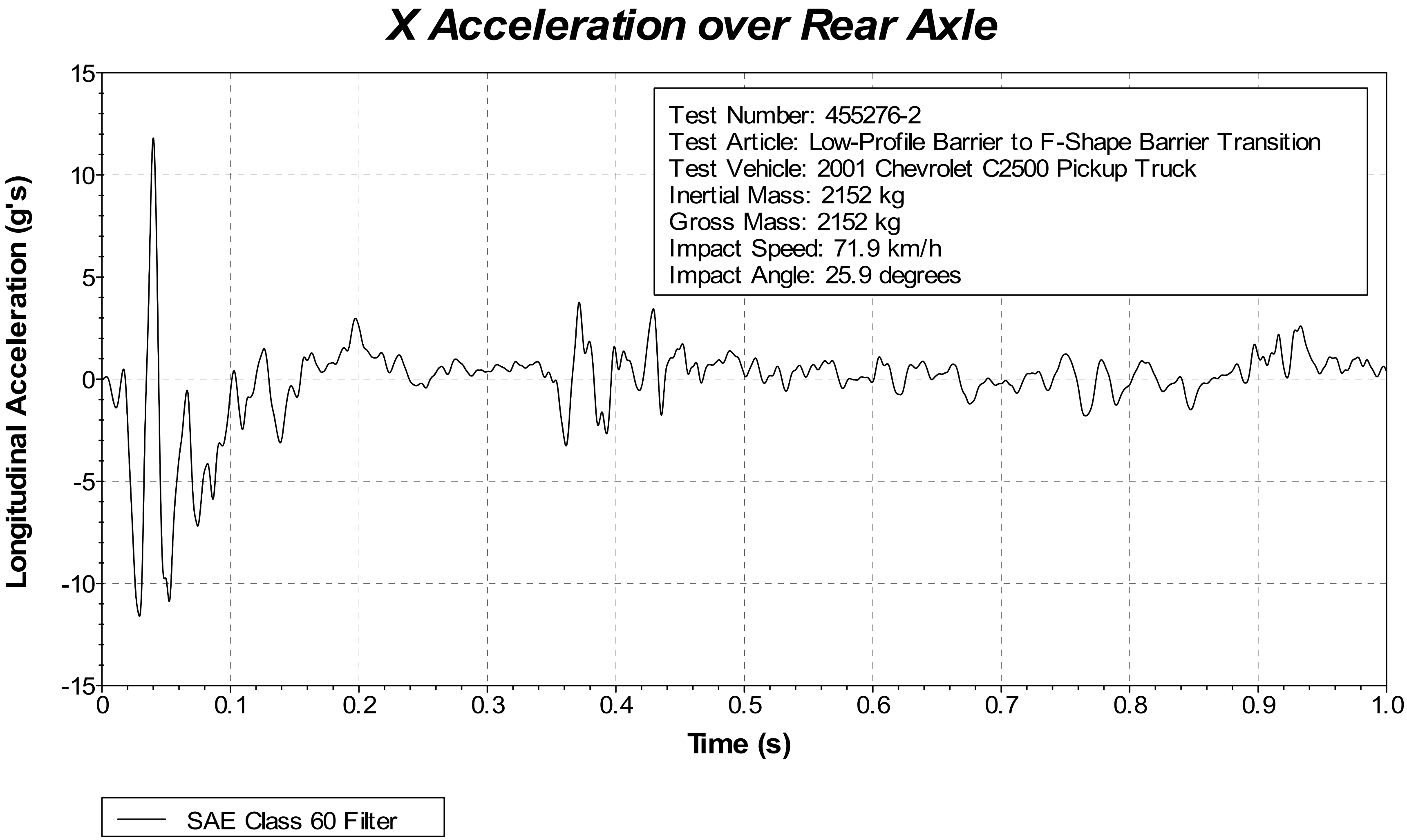


Figure 50. Vehicle Longitudinal Accelerometer Trace for Test 455276-2 (Accelerometer Located over Rear Axle).

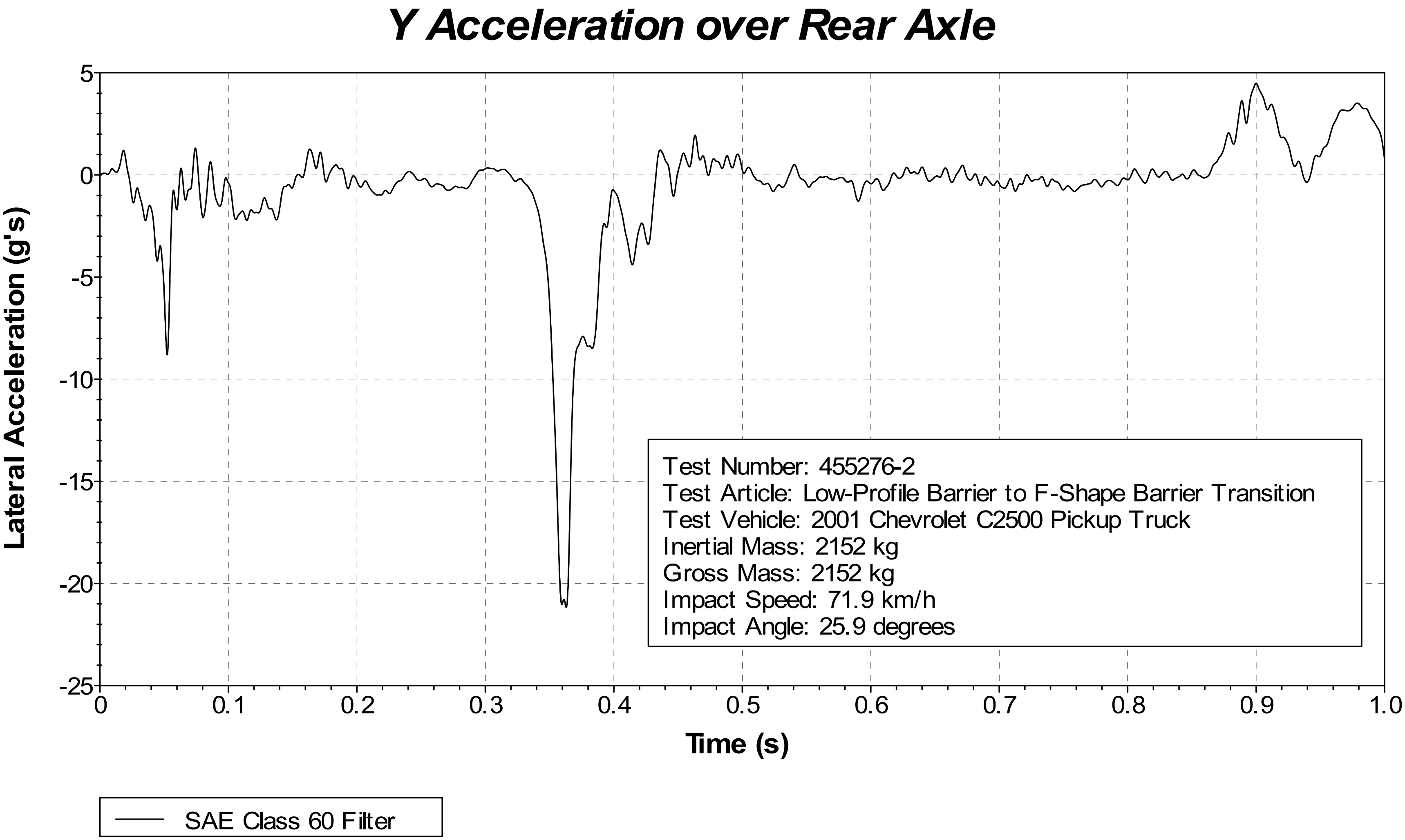


Figure 51. Vehicle Lateral Accelerometer Trace for Test 455276-2 (Accelerometer Located over Rear Axle).

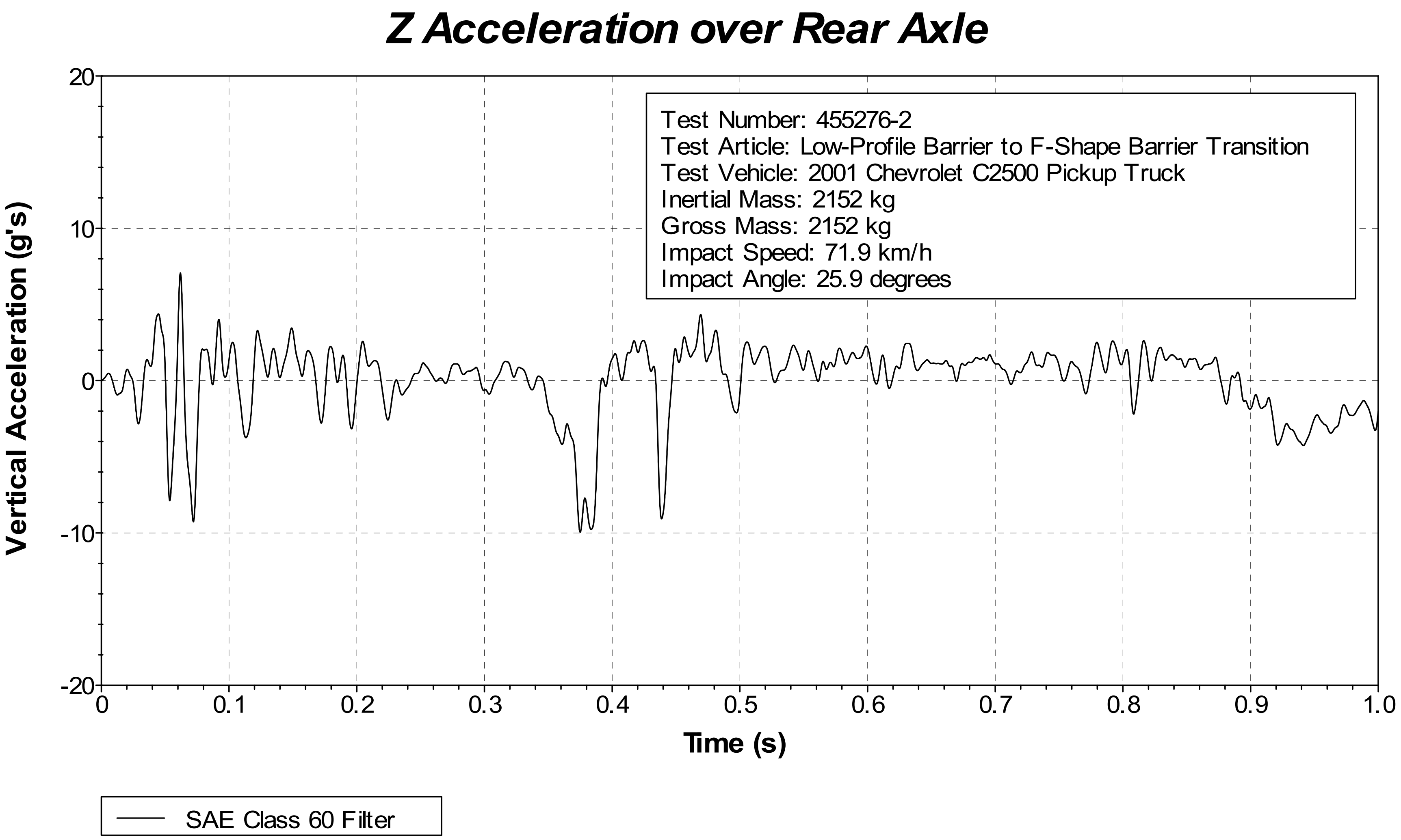


Figure 52. Vehicle Vertical Accelerometer Trace for Test 455276-2 (Accelerometer Located over Rear Axle).