NCHRP REPORT 350 TESTING OF MONTANA PORTABLE CONCRETE SAFETY SHAPE BARRIERS

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16. Abstract

The existing Montana DOT concrete median barrier sections are 3.048 m (10 ft) long New Jersey shaped barriers with a pin-and-loop connection. Two pairs of 25 mm (1 inch) diameter wire rope loops are connected using a 660 mm (26 inch) long, 25 mm (1 inch) diameter pin that is not restrained at the bottom. Since the system has a low probability of complying with the *NCHRP Report 350* guidelines, and the expected dynamic barrier deflection under design impact conditions are greater than desired by Montana DOT, two alternate barrier connection concepts were proposed and evaluated using computer simulations. These included a modified pin-and-loop connection and a newly conceived lapped splice connection.

After these two designs appeared to perform acceptably during simulation, the proposed designs were constructed for full-scale crash testing to determine whether the designs would actually meet *NCHRP Report 350* crash test criteria. This report presents the details of the simulation analysis, the details of the proposed barrier designs, the details of the full-scale crash tests, and the *NCHRP Report 350* evaluation of each of the tests. Both the modified pin-and-loop barrier and the lapped splice connection barrier performed acceptably for *NCHRP Report 350* test 3-11.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

1.0 INTRODUCTION

1.1 PROBLEM

Previous testing experience and finite element modeling has shown marginal performance on a number of portable concrete safety shapes with unrestrained pin and loop connections. Problems have been encountered with joint failures and vehicle instabilities. Joint failures have included pin failures, loop failures, under-reinforcement and/or inadequate development lengths in the concrete adjacent to the joint. Vehicle instabilities are usually introduced through rotation of the barrier and subsequent climbing by the vehicle. Increased rigidity of the joint and increased size of the barrier segments can improve vehicle stability in the crash sequence. The crash performance of the barriers is typically degraded as the segment lengths and masses are reduced.

1.2 BACKGROUND

The Federal Highway Administration (FHWA) formally adopted the performance evaluation guidelines for highway safety features set forth in National Cooperative Highway Research Program (*NCHRP) Report 350* as a "Guide or Reference document in Federal Register, Volume 58, Number 135, dated July 16, 1993, which added paragraph (a) (13) to 23 CFR, Part 625.5. (Ross, 1993) FHWA further mandated that, starting in October 1998, only Category III Work Zone Devices, such as portable concrete barriers that have successfully met the performance evaluation guidelines set forth in *NCHRP Report 350* may be used on the National Highway System (NHS) for new installations. On August 28, 1998, deadlines were revised for the use of *NCHRP Report 350* devices. (FHWA, 1998) The deadline for Category III devices was extended to October 2002 with the following statement: "Barriers with joints that fail to transfer tension and moment from one segment to another must be updated by October 1, 2000. New units purchased after October 1, 2002 shall comply with *350*. (Agencies can phase out existing devices after they complete their normal service life, except that barriers with joints that fail to transfer tension and moment from one segment to another will not be acceptable after October 1, 2000, unless demonstrated to be crashworthy.)" FHWA went on to state, "A barrier will be considered crashworthy if (a) it has been crash tested and met the acceptance requirements proposed in either *NCHRP Reports 230* or *350* or (b) it is a barrier with one of the five joints listed as "Tested and Operational Connections" starting on page 9-3 of the 1996 American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide or (c) if an Engineering Study of in-service performance demonstrates the barrier will provide the performance requirements of the site where it is to be used." (Michie, 1981; AASHTO, 1996)

1.3 OBJECTIVES/SCOPE OF RESEARCH

The existing Montana Department of Transportation (DOT) concrete median barrier sections are 3.048 m (10 ft) long New Jersey shaped barriers with a pin-and-loop connection. Two pairs of 25 mm (1 inch) diameter wire rope loops are connected using a 660 mm (26 inch) long, 25 mm (1 inch) diameter pin that is not restrained at the bottom. Since the system has a low probability of complying with the *NCHRP Report 350* guidelines, and the expected dynamic barrier deflection under design impact conditions are greater than desired by Montana DOT, two alternate barrier connection concepts were proposed and evaluated using computer simulations. These included a modified pin-and-loop connection and a newly conceived lapped splice connection.

After these two designs appeared to perform acceptably during simulation, the proposed designs were constructed for full-scale crash testing to determine whether the designs would actually meet *NCHRP Report 350* crash test criteria. This report presents the details of the simulation analysis, the details of the proposed barrier designs, the details of the full-scale crash tests, and the *NCHRP Report 350* evaluation of each of the tests.

2.0 COMPUTER SIMULATION

2.1 INTRODUCTION

Numerous research studies have successfully utilized simulation codes to simulate vehicle handling, vehicle impacts with roadside objects, and 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 a different level of assumptions. Having said that, it was considered crucial that the simulation code(s) selected for use in this study be capable of accurately modeling relevant characteristics of the vehicle, the concrete median barrier, and the interactions between them. The decision to choose the explicit finite element code (LS-DYNA) for this study was based on several reasons including:

1. The availability of vehicle models that correspond to *NCHRP Report 350* design test vehicles. The 2000P pickup truck model has been used for roadside safety applications for the last five years and its fidelity and limitations are reasonably understood.
2. The ability to model the roadside device with a high degree of fidelity. The geometry of the device (which affects the mechanics of the vehicle-barrier interaction), its mass and inertial distribution (which affects the kinetic behavior of the barrier) and the stress-strain relationship of the materials (which affects the deformation of the device) can all be reasonably represented.
3. The ability to model contact-impact problems. LS-DYNA has a very extensive set of contact definitions that fit several impact-contact scenarios. These contact definitions that have the option of including frictional sliding are well suited to model the dynamic interaction between the vehicle and the roadside barrier.

The existing Montana DOT concrete median barrier sections are 3.048 m (10 ft) long New Jersey shaped barriers with a pin-and-loop connection. Two pairs of 25 mm (1 inch) diameter wire rope loops are connected using a 660 mm (25 inch) long, 25 mm (1 inch) diameter pin that is not restrained at the bottom. Since the system has a low probability of complying with the *NCHRP Report 350* guidelines, and the expected dynamic barrier deflection under design impact conditions are greater than desired by Montana DOT, two alternate barrier connection concepts were proposed and evaluated using computer simulations. These included a modified pin-and-loop connection and a newly conceived lapped plate connection. The details of the modeling and simulation of these connections follows.

2.2 FINITE ELEMENT MODELING

In order to evaluate the alternate design concepts, full-scale finite element computer models were developed for both the modified pin-and-loop connection and the lapped plate connection. Some of the essential components of these models were the concrete barriers, pin and loops for the pin-and-loop connection, and slotted plates and bolts for the lapped plate connection.

The concrete segments were modeled using the same New Jersey profile and overall dimensions (height, width, and length) as the original Montana DOT concrete median barriers. In order to help limit dynamic deflection, it was desirable to minimize the gap between the adjacent barrier segments. To accomplish this and still provide sufficient clearance to accommodate the connection hardware, recesses or channels were cast into the ends of the barrier. The concrete median barrier (CMB) model was assigned the mass density of concrete, which makes the total mass of the CMB model equivalent to that of the actual CMB unit.

The finite element (FE) model for the CMB was meshed with solid elements that belong to two parts as shown in Figure 2.2.1. The lowest layer of solid elements which 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. Rigid material representation helps speed up numerical calculations significantly.

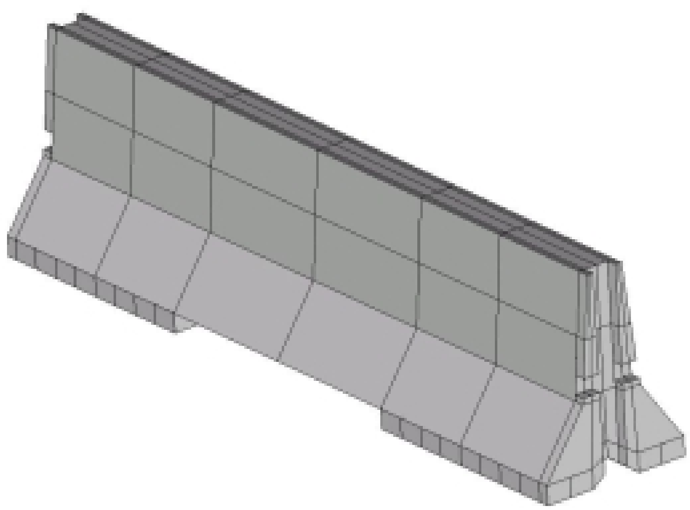


Figure 2.2.1. FE model of the CMB segment with solid elements.

A limitation to this type of rigid CMB model is that concrete failure is not captured. Modeling concrete failure requires a much higher mesh density and a reliable, validated concrete material model that considers fracture. Although the Federal Highway Administration is currently funding the development of such a material model, the research effort is still in the early stages and the results were not available for use in this project. Without the ability to incorporate concrete failure into the analysis, it should be noted that the results of the simulation will represent a lower bound estimate of the overall CMB system deflection. If significant concrete fracture and spalling occurs on the ends of one or more barrier segments during an actual impact, additional joint rotation can occur and deflections can increase.

The lower elastic layer of solid elements was incorporated into the barrier model to provide a reliable account of friction in the contact between the CMB segments and the ground. A friction coefficient of 0.4 was used between the CMB and the ground.

Solids elements tend to behave less reliably compared to shell elements for contact purposes. During earlier simulations with a vehicle impact, small but significant penetrations were observed between the solid elements of adjacent barriers. Similarly, penetrations were observed between the vehicle shell elements and the CMB solid elements. In order to have a more robust contact, the CMB segment models were covered with a layer of finely meshed rigid shell elements as shown in Figure 2.2.2. All contacts involving the barriers were defined with this shell cover.

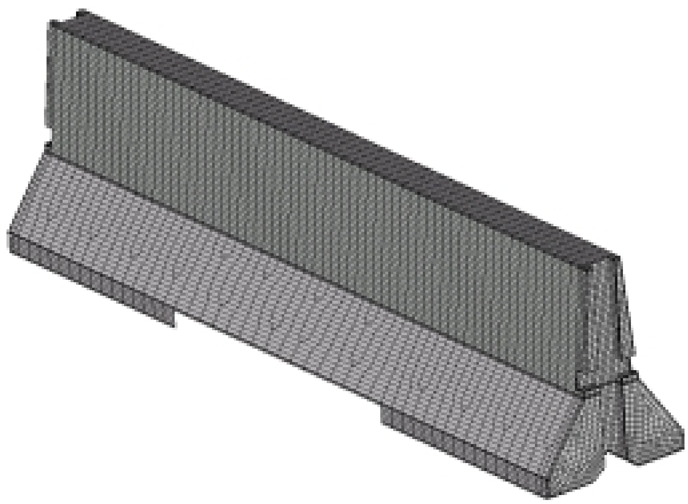


Figure 2.2.2. CMB segment covering with shell elements and a refined mesh.

Deformable loops or plates were attached to the end of the CMB segments by making the end nodes of the loops or plates a part of the CMB segment rigid body definition. This provides an efficient means of tying them to the CMB segments. However, it is noted that the stresses at the edges of the loops or plates will be overestimated in the simulation since the actual connection will generally have some relative movement due to minor cracking and/or spalling of the surrounding concrete that helps redistribute stresses.

2.2.1 Pin-and-Loop Model

The modified pin-and-loop connection is made up of an unrestrained 32-mm (1.25 inch) diameter steel pin inserted into three sets of 19-mm (0.75 inch) diameter steel bar loops. The additional intermediate set of loops changes the deformation mode of the pin and helps reduce deflections of the joint. It also adds some redundancy to the connection so that integrity of the connection is not lost if the pin pulls out of the lowest set of loops.

The pin and loops were assigned non-linear elastic-plastic properties of steel. Ideally the pin and loops would be meshed using solid elements. However due to the circular geometry and small diameter of the loop cross section, using solid elements becomes less feasible. In order to accurately model the pins and loops using solid elements, a very fine mesh would be required. This decreases the time-step for numeric calculations significantly, hence increasing the CPU time required for each simulation.

Shell elements were used as an alternative modeling option for the solid pin and loop parts. The diameter and thickness of shell elements were selected such that the resulting models of the steel loops and pins had 96% of the area and 99% of the second moment of area (i.e., moment of inertia) of the solid section. A steel loop model comprised of shell elements is depicted in Figure 2.2.3. Similarly, the pin and washer were modeled using shell elements as shown in Figure 2.2.4.

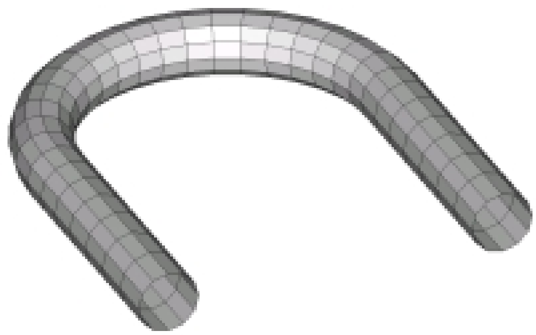


Figure 2.2.3. Steel loop model using shell elements.

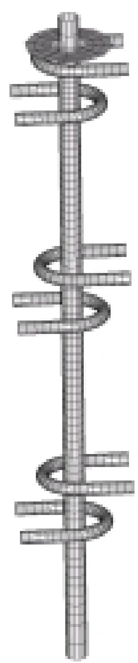


Figure 2.2.4. Steel pin, loops and washer model.

The full-scale simulation replicated Test Designation 3-11 of *NCHRP Report 350*, which involves a 2000-kg (4405 lb) pickup truck impacting the barrier at a speed of 100 km/h (62 mi/h) and an angle of 25 degrees. The initial simulation setup prior to impact is shown in Figure 2.2.5. A total of 14 CMB segments were used in the simulation with the truck impacting the 7th segment 1200 mm (48 inches) upstream from the joint.

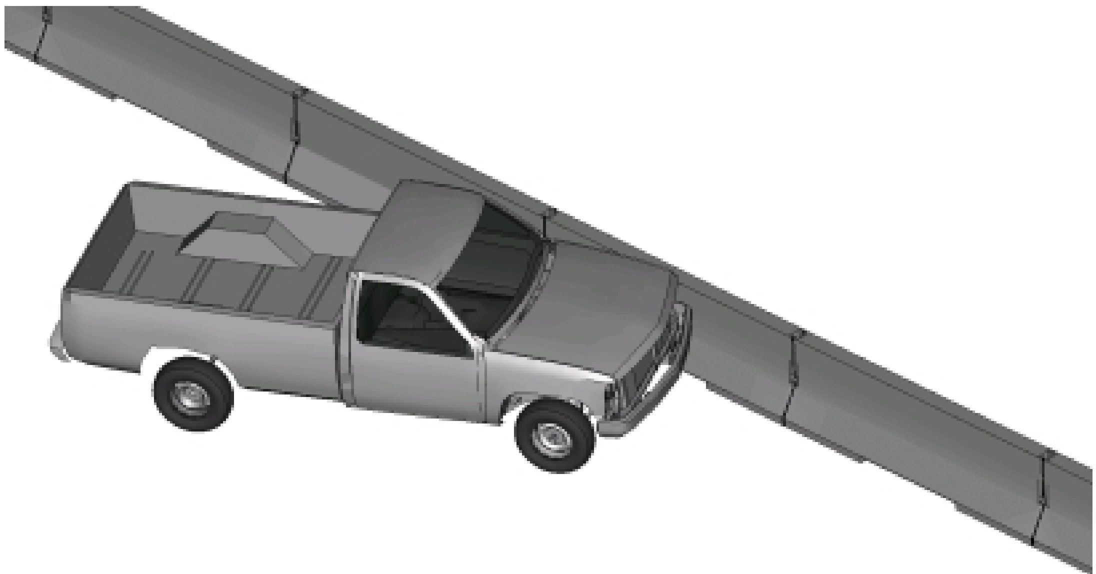


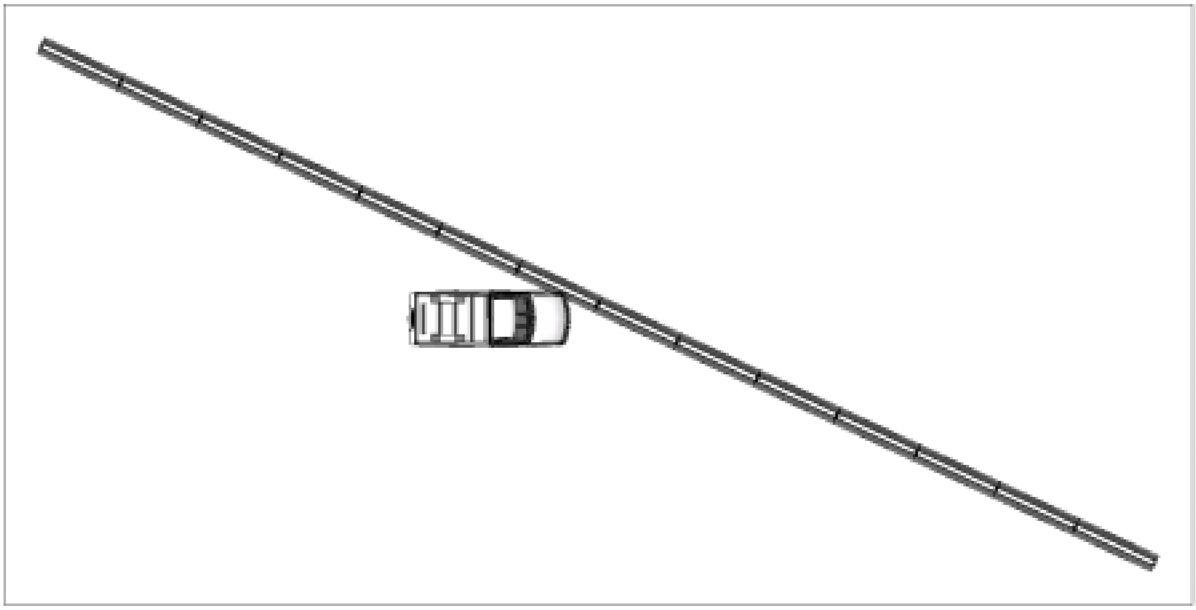
Figure 2.2.5. Simulation setup for the modified pin-and-loop model.

AUTOMATIC_SINGLE_SURFACE contact type with EDGE = 1 and SOFT = 2 was used to define contact between the pins, loops and washer. NODES_TO_SURFACE contact was defined between the shell covers of adjacent barrier segments. Contacts were individually defined for each joint in the CMB system.

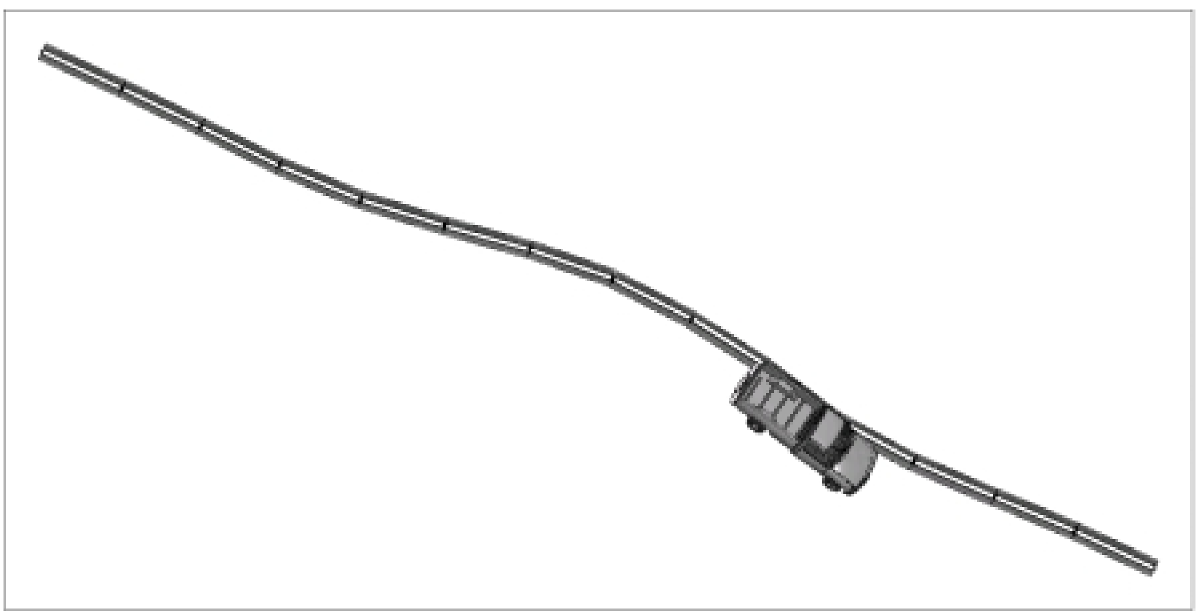
2.2.2 Pin-and-Loop Simulation Results

The vehicle was successfully contained and redirected by the modified barrier system. The results from the simulation showed an overall dynamic deflection of 1.2 m (4 ft). As previously discussed, this was considered to be a lower bound estimate. The amount that the actual dynamic barrier deflection might exceed this value is a function of the degree of concrete damage encountered in the test.

Figure 2.2.6 shows the overhead view of the full-scale simulation of the modified pin-and-loop barrier before and after impact. Figure 2.2.7 shows a rear view of the simulation. Figure 2.2.8 shows the field side of the barrier joint at which maximum deflection occurred at time of contact and as the vehicle is exiting the barrier system.



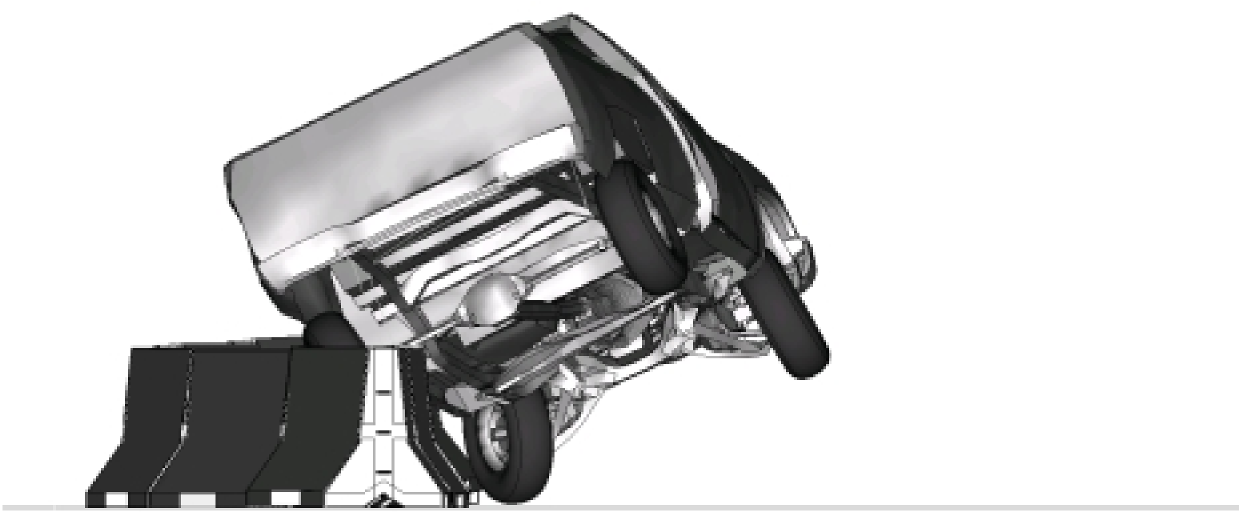
(a) Initial impact.



(b) Vehicle exiting barrier installation.

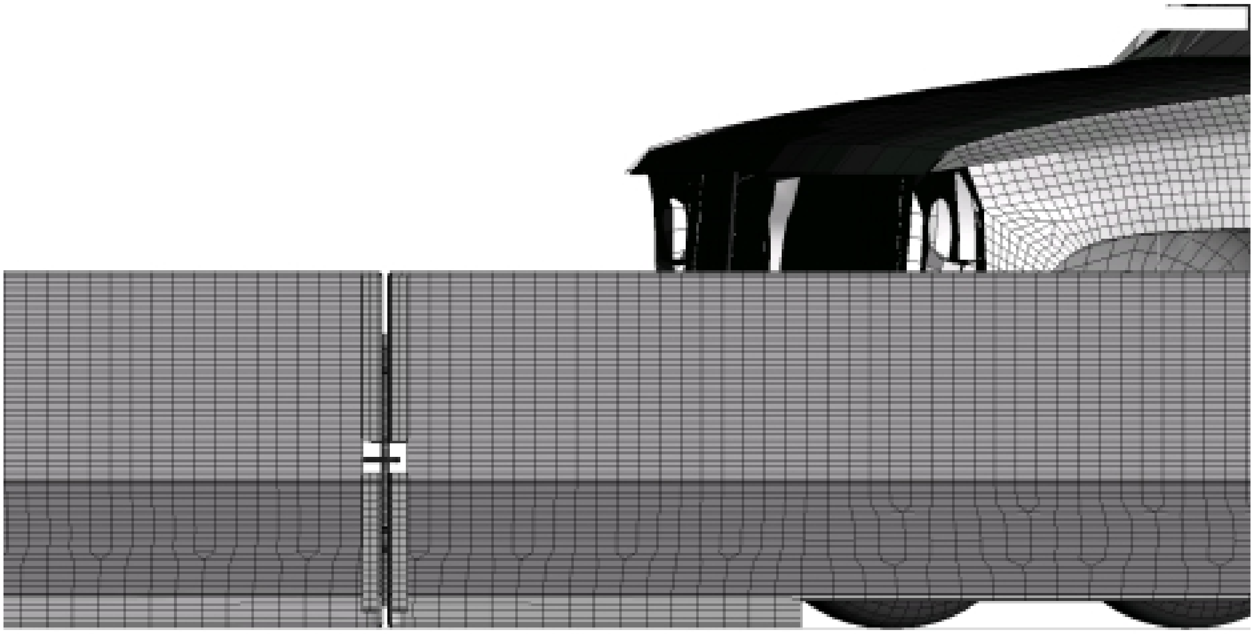
Figure 2.2.6. Overhead view of simulation of modified pin-and-loop barrier connection.

(a) Initial impact.

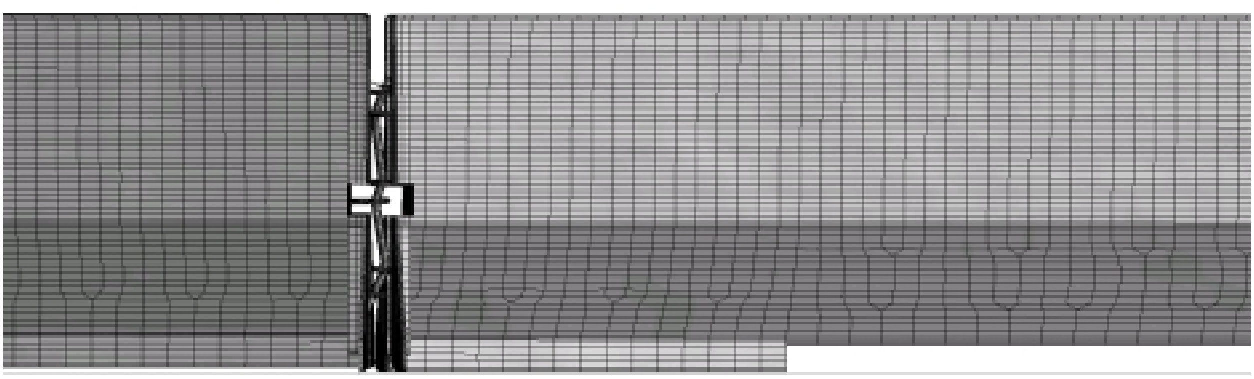


(b) Vehicle exiting barrier installation.

Figure 2.2.7. Rear view of simulation of modified pin-and-loop barrier connection.



(a) Initial impact.



(b) Vehicle exiting barrier installation.

Figure 2.2.8. Rear view of barrier joint with maximum deflection.

2.2.3 Lapped Plate Model

This design incorporates two sets of vertical plates that are lapped and bolted through recesses cast horizontally across the ends of the concrete barrier. The steel connection plates are 102 mm (4 inch) wide and 25 mm (1 inch) thick. The plates are joined using 25-mm (1 inch) diameter A325 or equivalent high-strength bolts. Slots are provided in the plates rather than round holes in order to provide connection tolerance for placement of the barriers on horizontal or vertical curves.

The plates were assigned non-linear elastic-plastic properties of steel. Initially, elastic-plastic bolt shafts were explicitly modeled using shell elements following the same approach previously described for the steel pins and loops. Several different LS-DYNA contact types were investigated to incorporate the contact between the bolt shaft surface and the interior edges of the slotted plates. However a robust edge-to-surface contact could not be established and some penetrations were observed. The rotation of the barrier segments, and hence the overall deflection of the system is very sensitive to the amount of slack in the joint. With the slot edges penetrating the bolt shaft, the slack in joint increased thereby resulting in an over prediction of the maximum dynamic deflection of the system.

To resolve this contact problem, bolts were removed from the model and the nodes along the edges of slots at which the bolt shaft would bear were coupled in all degrees of freedom using the CONSTRAINED_SPOTWELD option. During testing, the barriers are typically installed with all slack removed from the connection. Thus, the bolt shafts would be in direct bearing contact with the outside edge of each slot in the lapped plates. Further, it was analytically determined that the bolted connection was strong enough to prevent opening or separation of the lapped plates during impact. Therefore, the simplifying assumption of using spot weld constraints in lieu of bolts was considered to provide valid response.

The full-scale simulation replicated Test Designation 3-11 of *NCHRP Report 350*, which involves a 2000-kg (4405-lb) pickup truck impacting the barrier at a speed of 100 km/h (62 mi/h) and an angle of 25 degrees. The initial simulation setup prior to impact is shown in Figure 2.2.9. A total of 14 CMB segments were used in the simulation with the truck impacting the 7^{th} segment 1200 mm (4 ft) upstream from the joint between the 7^{th} and 8^{th} segments.

AUTOMATIC_GENERAL contact type was used to define contact between the plate surfaces. NODES_TO_SURFACE contact was defined between the shells covers of adjacent barrier segments. Contacts were individually defined for each joint in the CMB system.

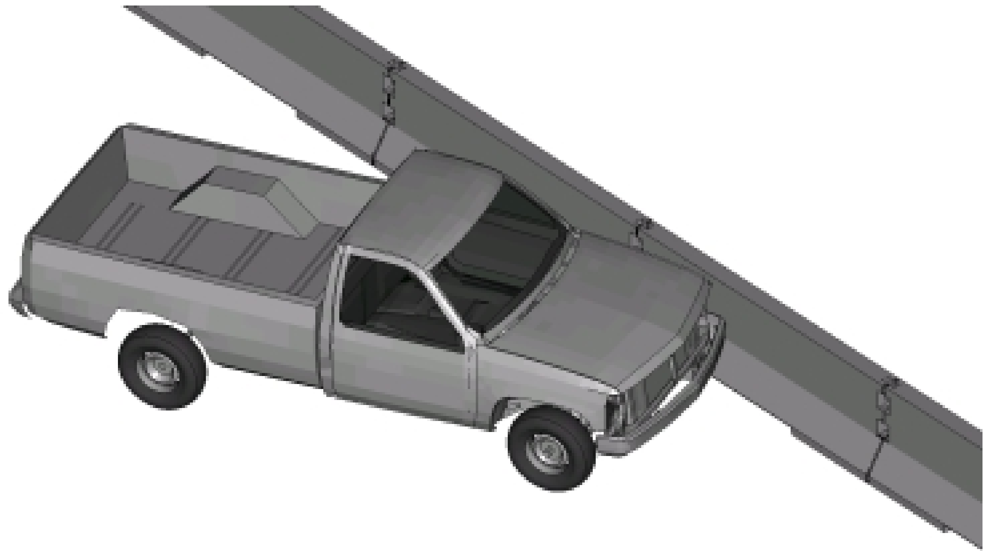


Figure 2.2.9. Simulation setup for the lapped plate model.

2.2.4 Lapped Plate Simulation Results

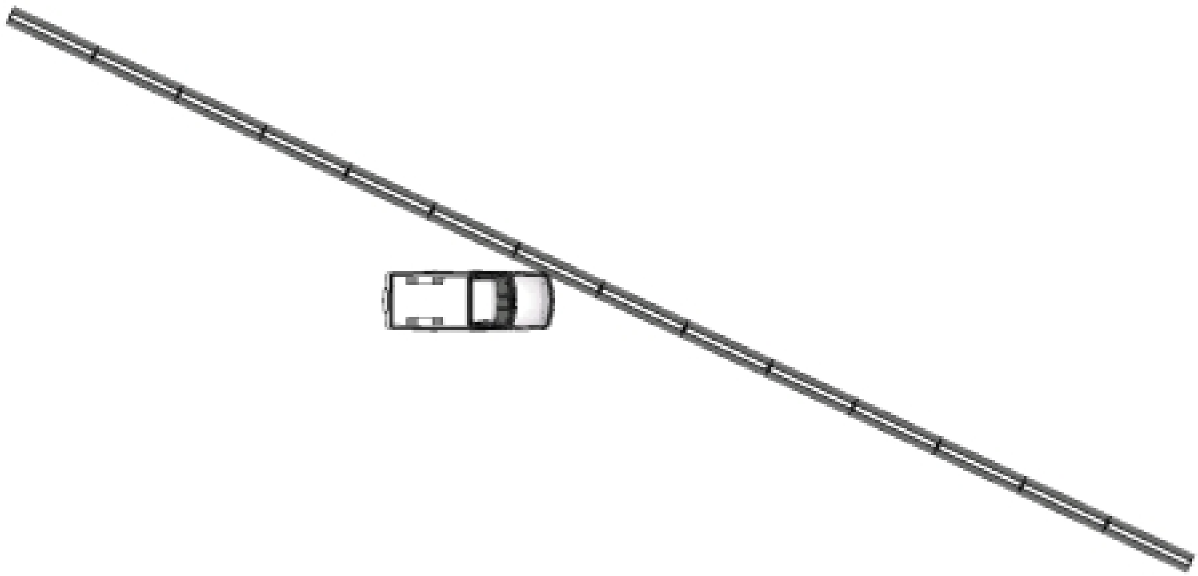
The vehicle was successfully contained and redirected by the modified barrier system. The simulation results indicated a dynamic lateral barrier deflection of 0.82 m (2.75 ft). As previously discussed, this was considered to be a lower-bound estimate. The amount that the actual dynamic barrier deflection might exceed this value is a function of the degree of concrete damage encountered in the test.

Figure 2.2.10 shows the overhead view of the simulation of the barrier with lapped plate connection before and after impact. Figure 2.2.11 shows a rear view of the simulation. Figure 2.2.12 shows the field side of the barrier joint at which maximum deflection occurred at time of contact and as the vehicle is exiting the barrier system.

2.3 SUMMARY

Montana DOT did not consider their existing portable concrete median barrier design to be adequate from the standpoint of impact performance or lateral dynamic barrier deflection. Two alternate barrier connection concepts were proposed and evaluated using computer simulations. These included a modified pin-and-loop connection and a lapped plate connection.

In order to evaluate these alternate design concepts, full-scale finite element computer models were developed for both barrier systems. The full-scale simulations replicated Test Designation 3-11 of *NCHRP Report 350*, which involves a 2000-kg pickup truck impacting the barrier at a speed of 100 km/h and an angle of 25 degrees.

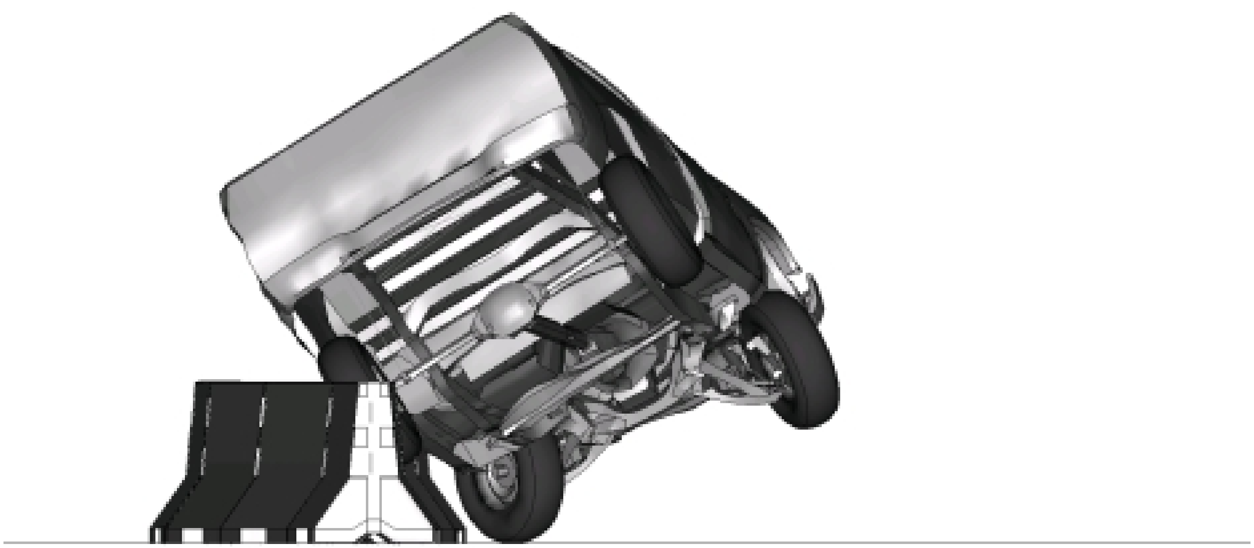


(a) Initial impact.

(b) Vehicle exiting barrier installation.

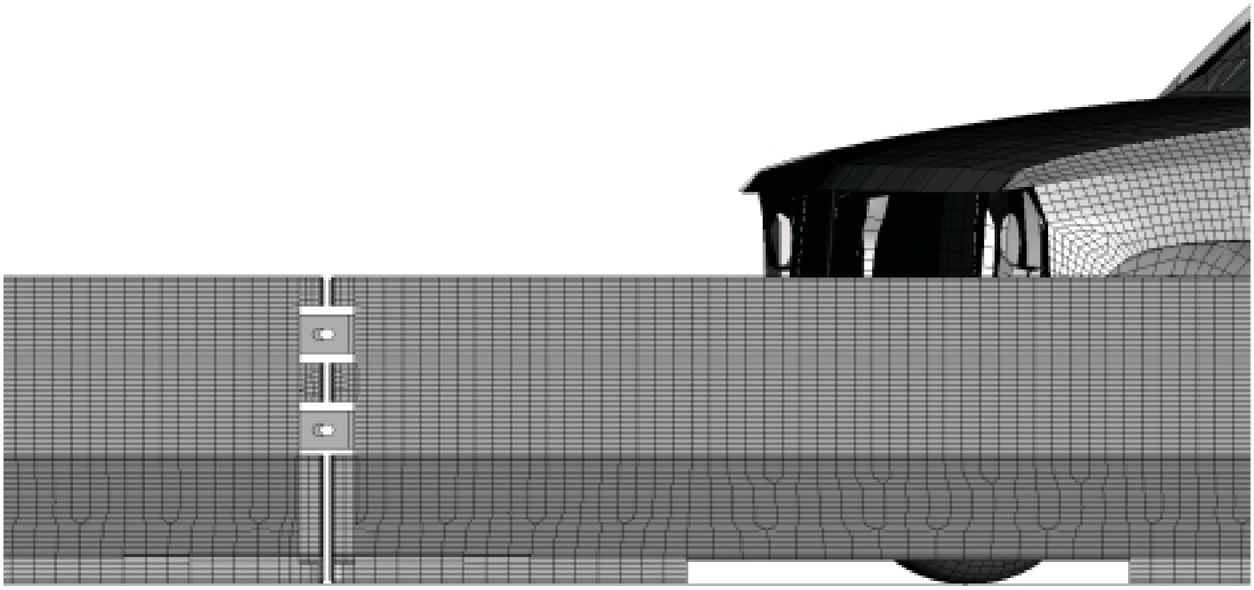
Figure 2.2.10. Overhead view of simulation of lapped plate barrier connection.

(a) Initial impact.

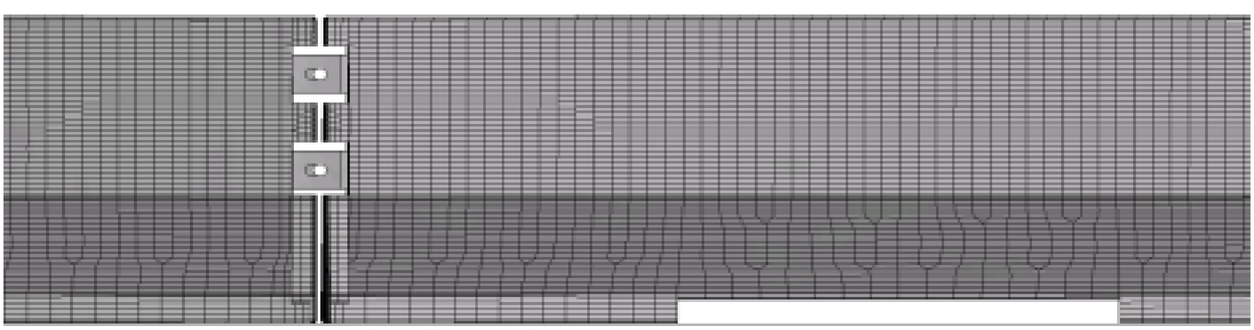


(b) Vehicle exiting barrier installation.

Figure 2.2.11. Rear view of simulation of lapped plate barrier connection.



(a) Initial impact.



(b) Vehicle exiting barrier installation

Figure 2.2.12. Field side view of barrier joint with maximum deflection.

The simulation results indicated that both barriers should meet *NCHRP Report 350* evaluation criteria. In each case, structural integrity of the connections was maintained and the modified barriers successfully contained and redirected the finite element test vehicle. The simulation results estimated dynamic deflections of 1.2 m (4 ft) and 0.82 m (2.75 ft) for the modified pin-and-loop and lapped plate connections, respectively. These values were considered lower-bound estimates. The actual dynamic barrier deflections could exceed these values depending on the nature and degree of concrete damage obtained in the full-scale tests.

3.0 CRASH TEST PARAMETERS

3.1 TEST FACILITY

The test facilities at the Texas Transportation Institute's Proving Ground consist of a 809-hectare (2,000 acre) complex of research and training facilities situated 16 km (10 mi) northwest of the main campus of Texas A&M University. The site, formerly an Air Force Base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and safety evaluation of roadside safety hardware. The site selected for placing of the portable concrete median barriers is along a wide out-of-service apron/runway. The apron/runway consists of an unreinforced jointed concrete pavement in 3.8 m by 4.6 m (12 ft x 15 ft) blocks, nominally 203-305 mm (8-12 inches) deep. The aprons and runways are about 50 years old and the joints have some displacement, but are otherwise flat and level.

3.2 TEST ARTICLES – DESIGN AND CONSTRUCTION

Texas Transportation Institute (TTI) designed, constructed, and crash tested two New Jersey Shaped Concrete Median Barrier designs for Montana Department of Transportation. Both designs were identical except for the connections details on the ends of the barrier segments. The barrier segments were 813 mm (32 inches) in height and were 3050 mm (120 inches) in length. The segments were 152 mm (6 inches) wide at the top and 610 mm (24 inches) wide at the base. Vertical reinforcement in the barrier segments consisted of #16 "V" shaped bars spaced 280 mm (11 inches) apart. Horizontal reinforcement consisted of seven #16 bars spaced liberally within the vertical reinforcement.

3.2.1 Modified Pin-and-Loop Barrier Used in Test 474550-1

The first barrier tested for this project (Test 474550-1) consisted of a pin and loop connection design consisting of three loops on each end of the barrier segment. The loops were constructed from 19 mm diameter round bar material. The inside radii of each loop was 22 mm (7/8 inch). The loops projected 88 mm (3.5 inch) from a 102 mm (4 inch) wide by 44 mm (1.75 inch) deep recess located at the end of each barrier segment. The loops were anchored with two #19 reinforcing bars, 1035 mm long and welded to the loops. These #19 bars were embedded in the barrier concrete. The loops were spaced 190 mm (7.5 inch) apart. The loops on one end of the barrier were vertically offset 24 mm (0.9 inch) from the loops on the opposite end of the barrier segment. This offset distance was necessary for alignment of the loops for insertion of a 32 mm (1.25 inch) diameter by 597 mm (23.5 inch) long pin, which was used to connect the barrier segments together.

The test installation for this test consisted of 20 barrier segments for a total installation length of approximately 61.0 m (200 ft). The three exterior barriers on each end were bolted together using the connections details as described for the following test (Test 474550-2). The compressive strength of the concrete at the time the test was performed averaged 36.1 MPa (5234 psi). All reinforcement used to construct the barrier segments was specified to have a minimum yield strength of 414 MPa (60 ksi). For additional information, please refer to the drawings as shown as Figure 3.2.1 and photographs in Figure 3.2.2.

3.2.2 Lapped Splice Connection Barrier Used in Test 474550-2

The second barrier design tested under this project was identical to Test 474550-1 with the exception of the barrier connection. Instead of three loops on each end, the barrier design for this test incorporated two 102 mm x 297 mm x 25 mm (4 inch x 11.7 inch x 1 inch) thick plates anchored within the barrier concrete with the #19 reinforcing steel similar to the design above. The lower plate was located 407 mm (16 inch) from bottom of the barrier segment with the upper plate located 254 mm (10 inch) above the lower plate. The plates were located within a 152 mm (6 inch) wide by 63 mm (2.5 inches) deep horizontal recess constructed on the ends of the segment. The plates projected 50 mm (2 inch) from the ends of the barrier segments and were offset 25 mm (1 inch) relative to the plates on the opposite end of the barrier segment. The connection of the barrier segments was achieved by aligning each barrier segment with the adjacent segment and bolting the overlapping connection plates together with 25 mm (1 inch) diameter A325 bolts through slots in the connecting plates.

The test installation for this test consisted of 21 barrier segments for a total installation length of approximately 64.0 m (210 ft). The first three barrier segments and the last four barrier segments used in the installations were of the pin and loop design as described above. Please refer to Figures 3.2.3 and 3.2.4 for further details of the lapped plate barrier connection.

3.3 TEST CONDITIONS

According to *NCHRP Report 350*, two crash tests are required for evaluation of longitudinal barriers, such as the Montana DOT portable barriers, to test level three (TL-3):

> ***NCHRP Report 350* test designation 3-10**: An 820-kg (1806-lb) passenger car impacting the critical impact point (CIP) in the length of need (LON) of the longitudinal barrier at a nominal speed and angle of 100 km/h (62 mi/h) and 20 degrees. The purpose of this test is to evaluate the overall performance of the LON section in general, and occupant risk in particular.

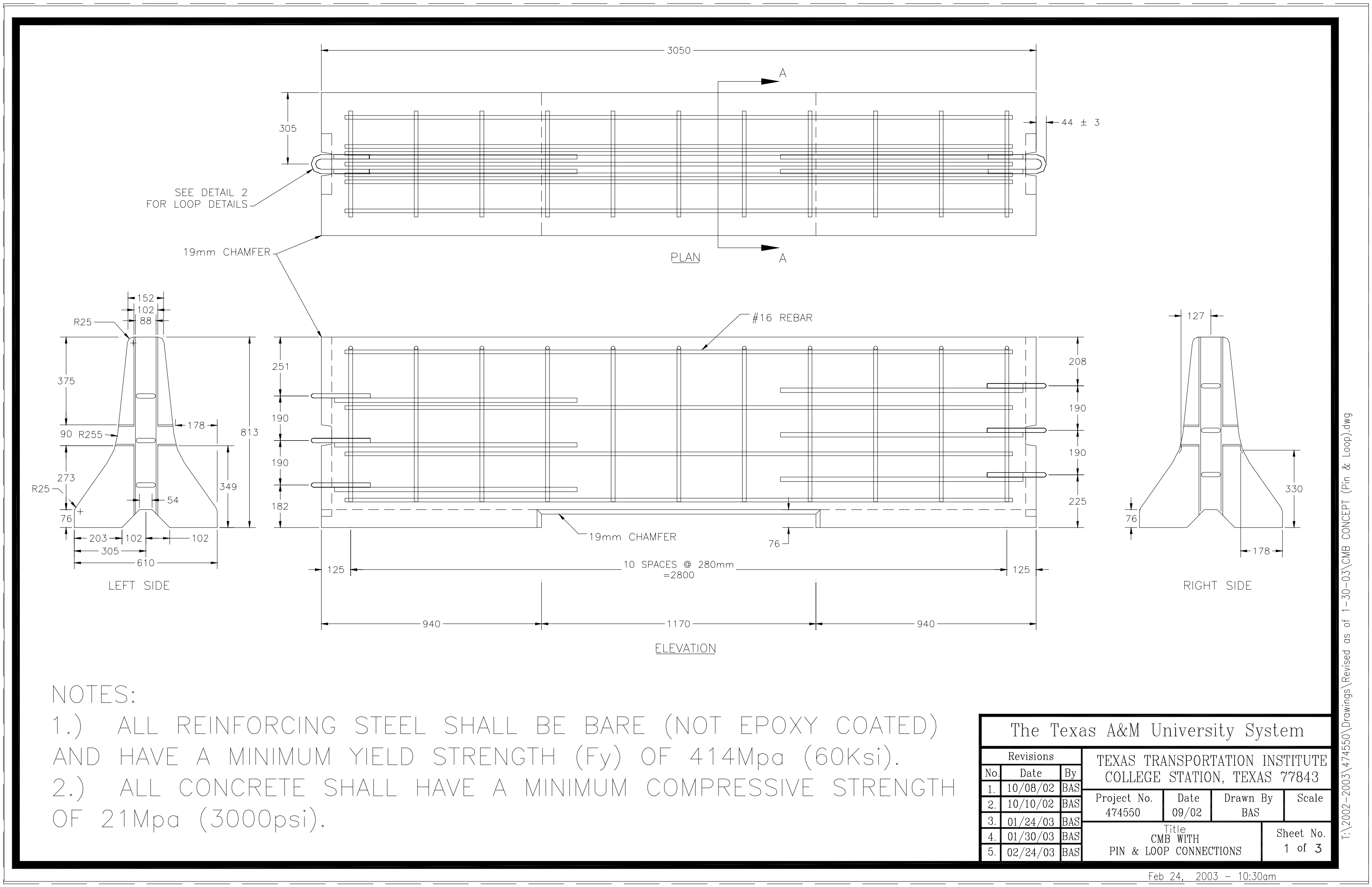


Figure 3.2.1. Details of modified pin-and-loop safety shape barriers used in test 474550-1.

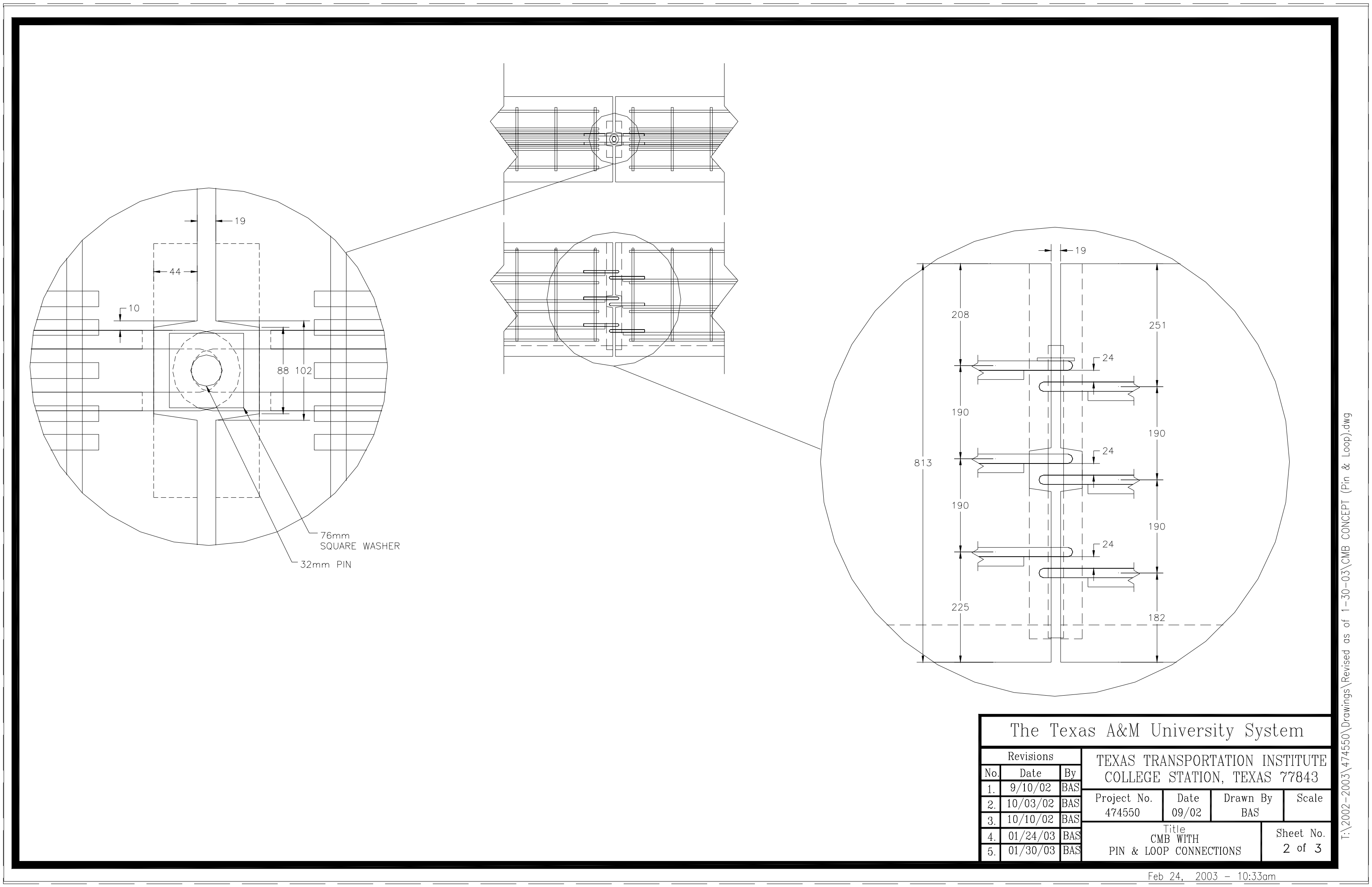


Figure 3.2.1. Details of modified pin-and-loop safety shape barriers used in test 474550-1 (continued).

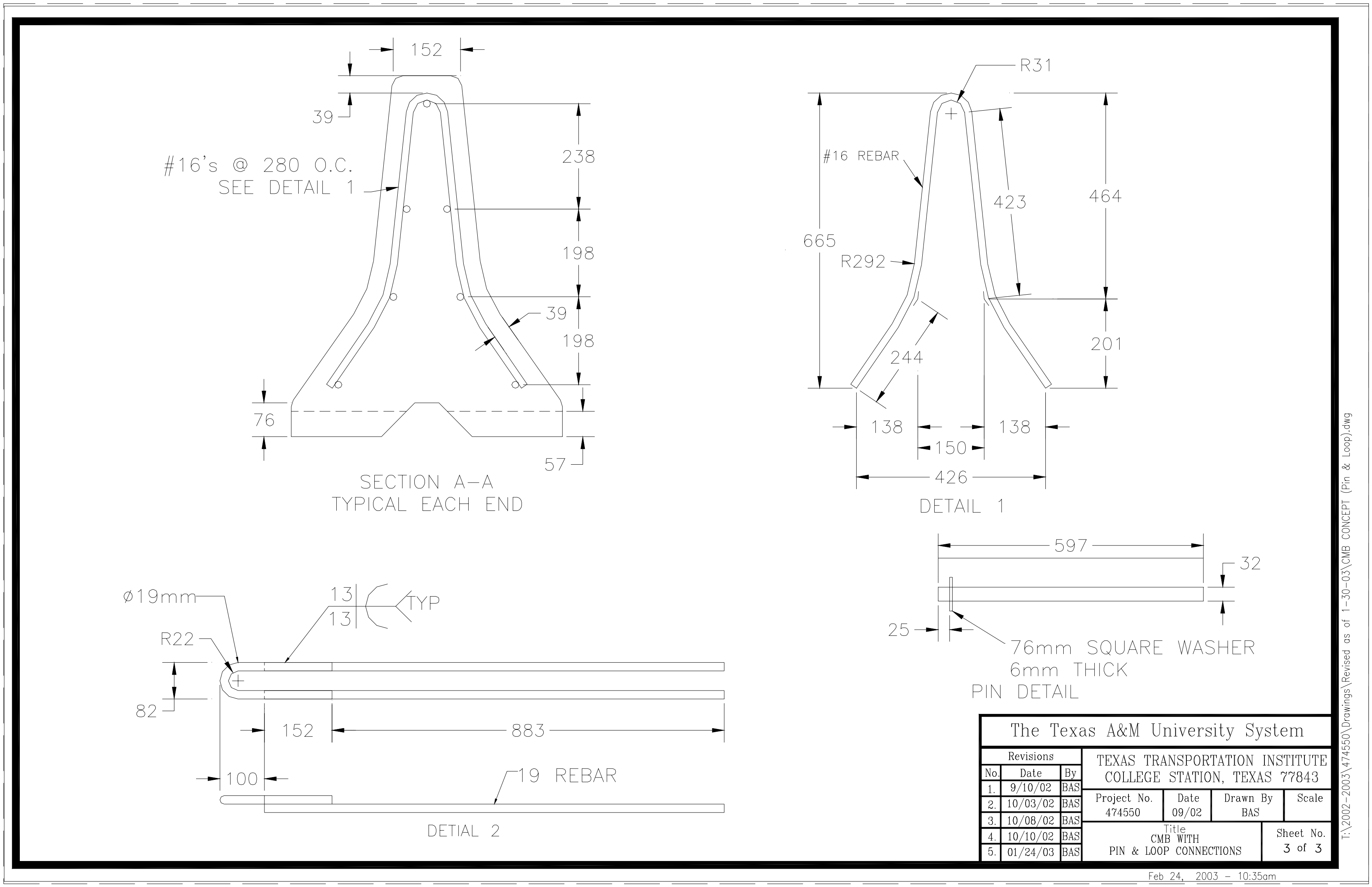


Figure 3.2.1. Details of modified pin-and-loop safety shape barriers used in test 474550-1 (continued).

Figure 3.2.2. Modified pin-and-loop barriers prior to test 474550-1.

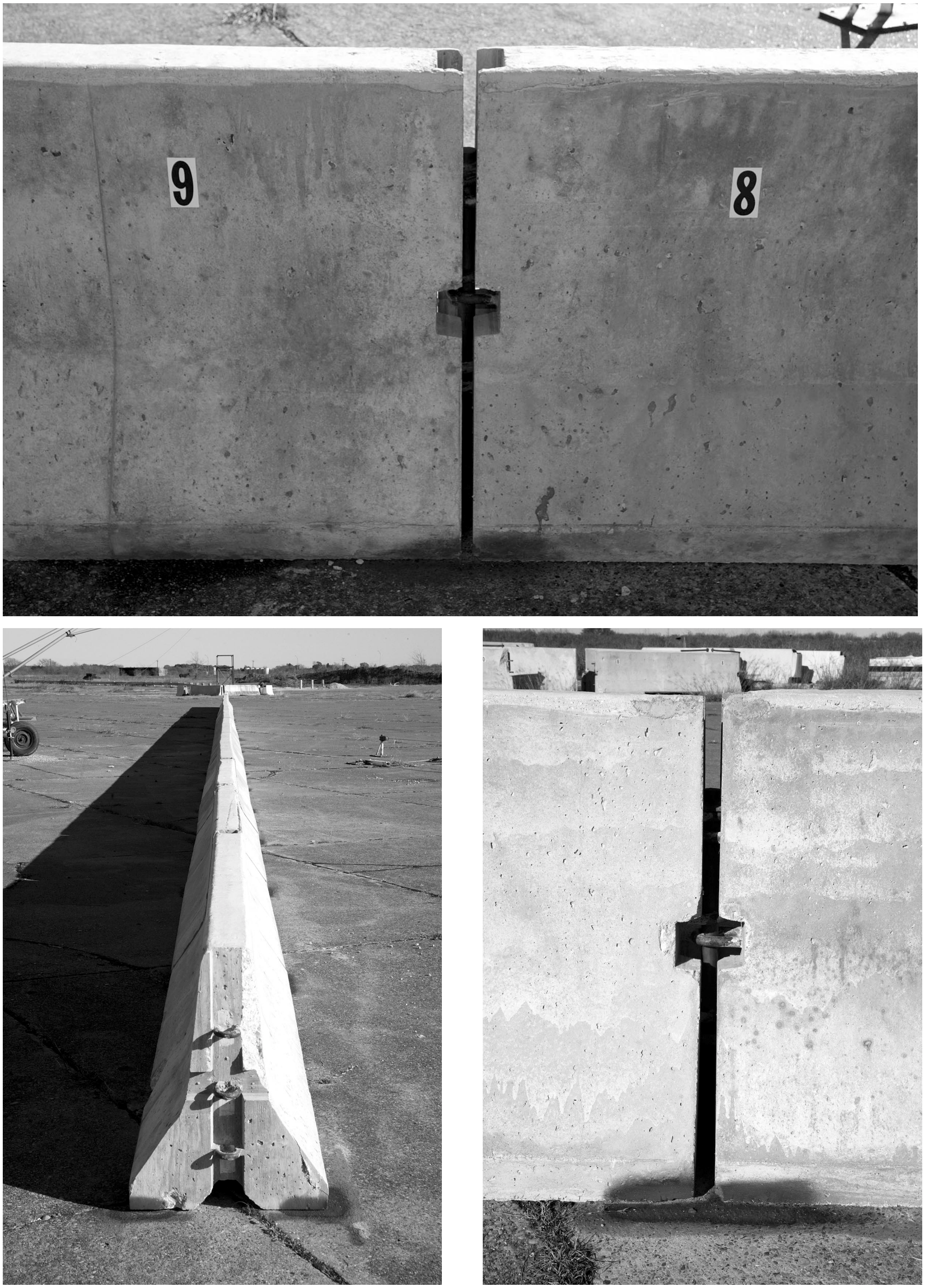


Figure 3.2.2. Modified pin-and-loop barriers prior to test 474550-1 (continued).

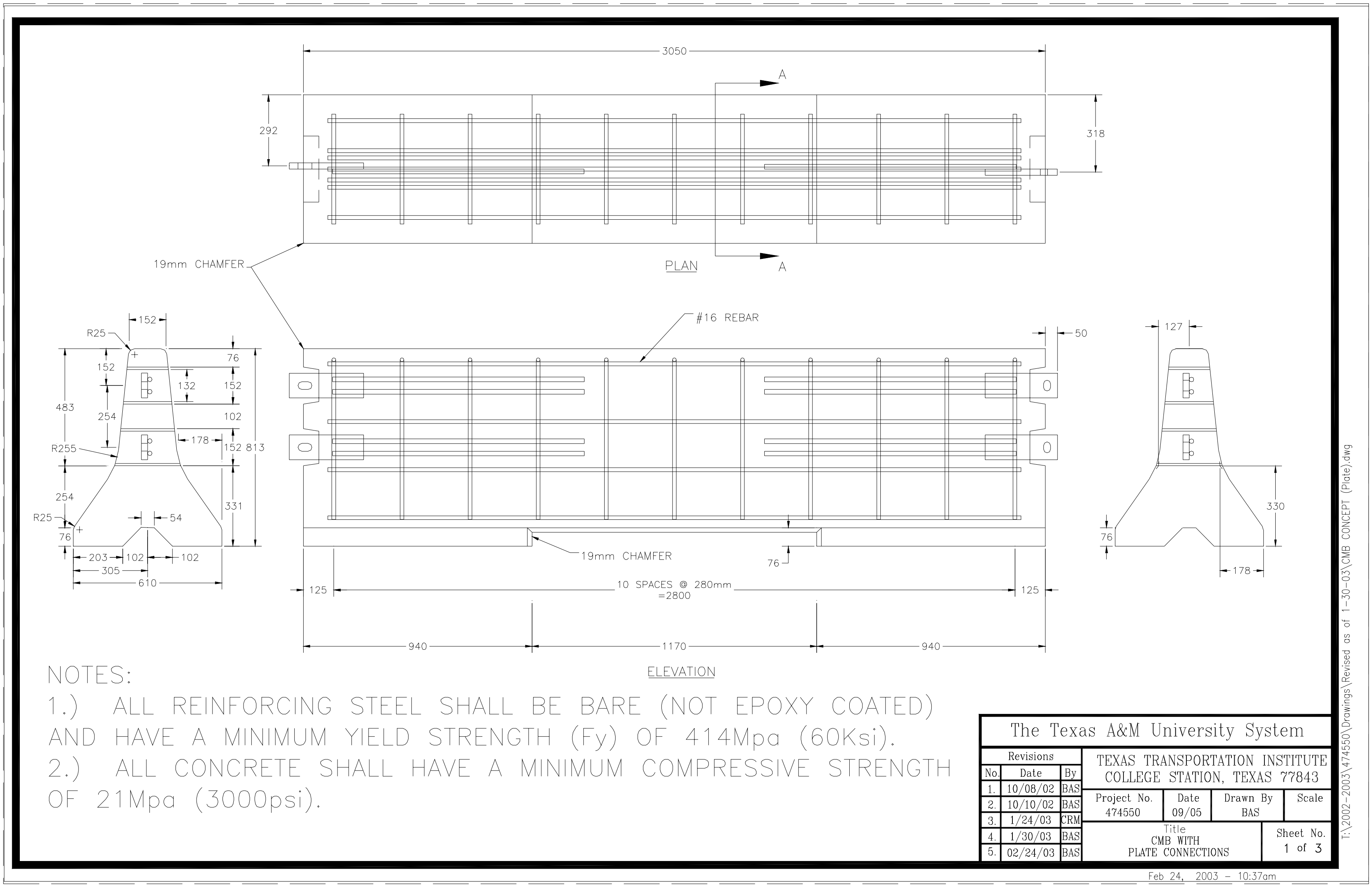


Figure 3.2.3. Details of lapped splice connection safety shape barriers used in test 474550-2.

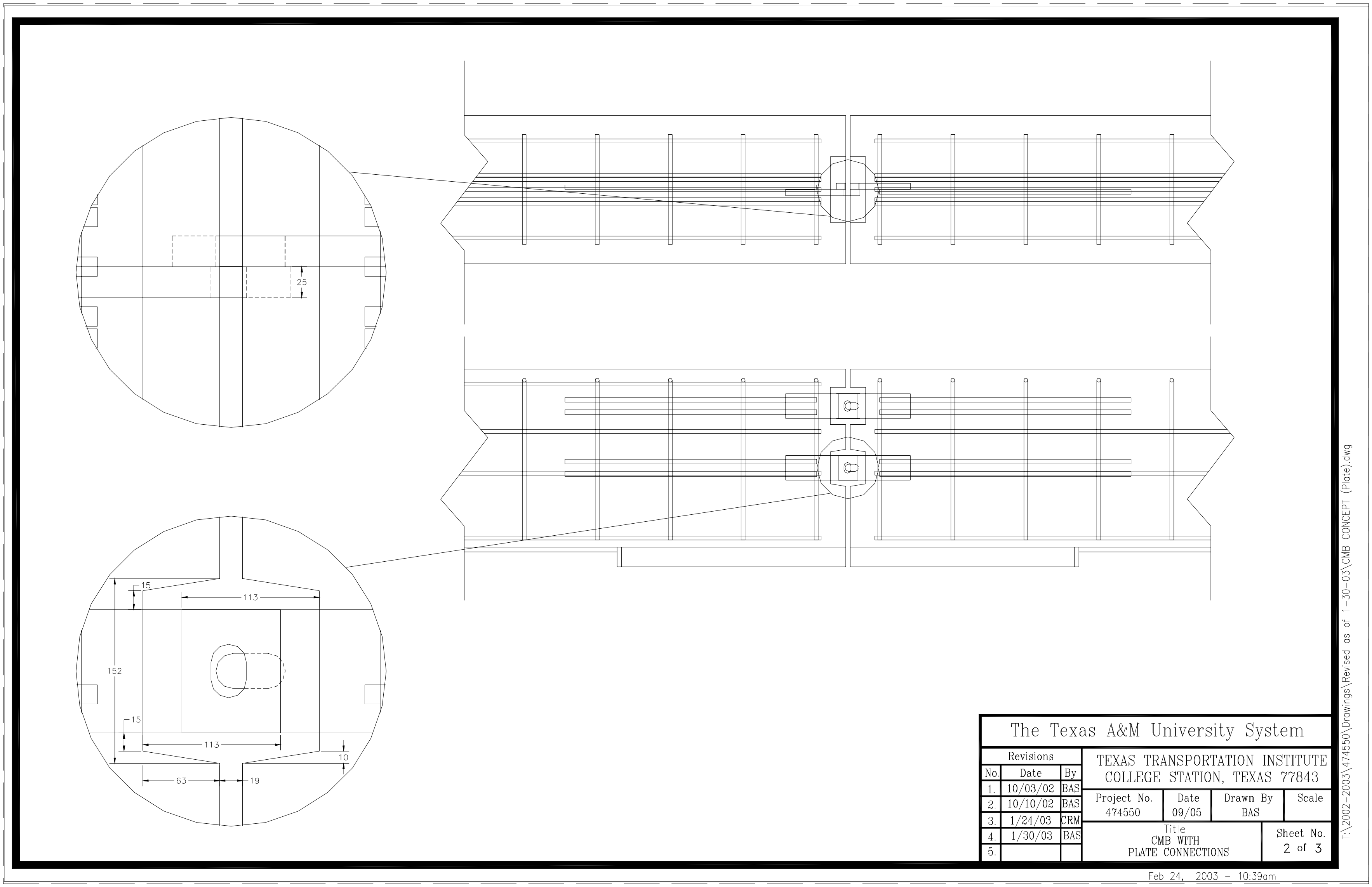


Figure 3.2.3. Details of lapped splice connection safety shape barriers used in test 474550-2 (continued).

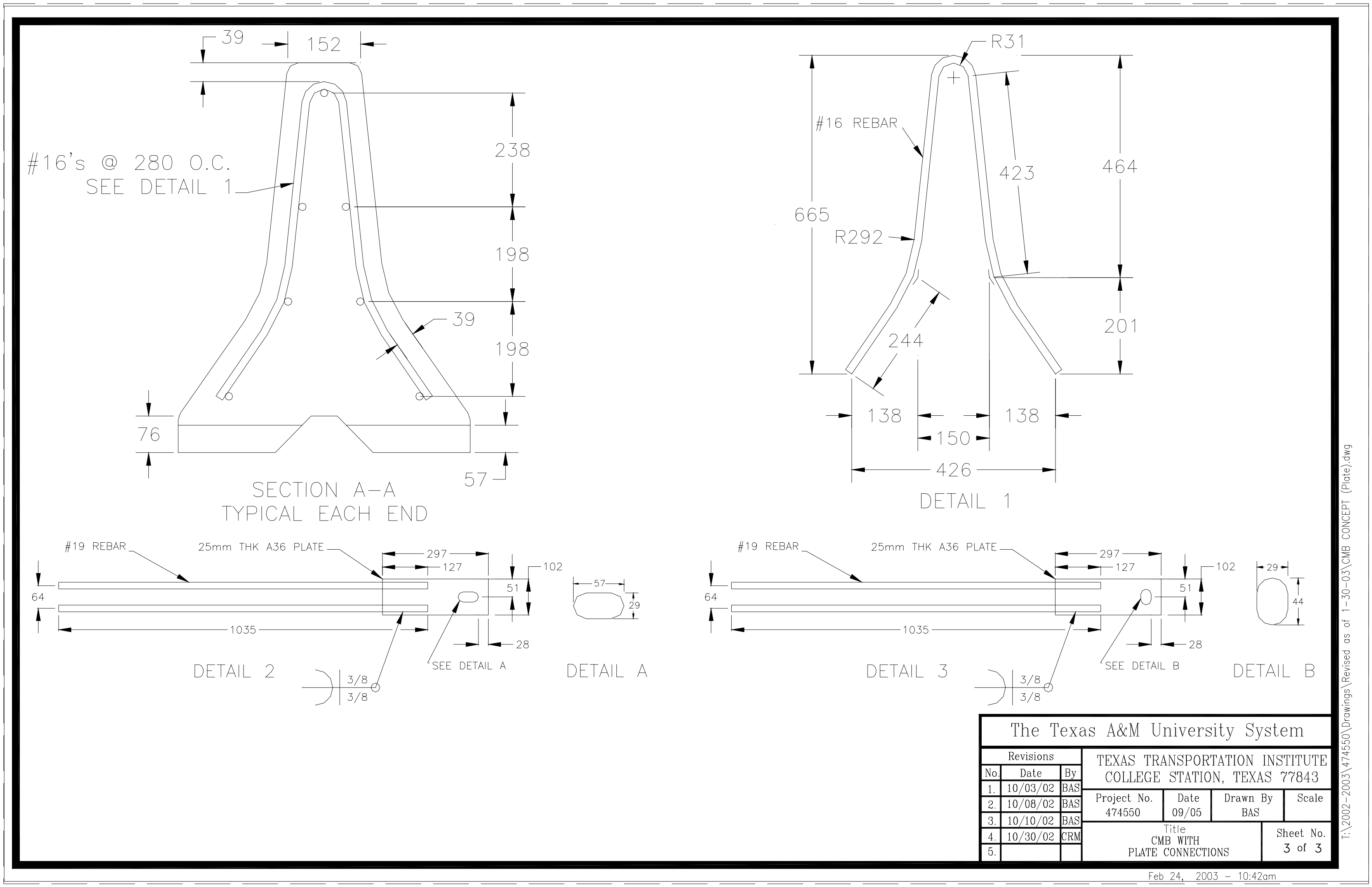


Figure 3.2.3. Details of lapped splice connection safety shape barriers used in test 474550-2 (continued).

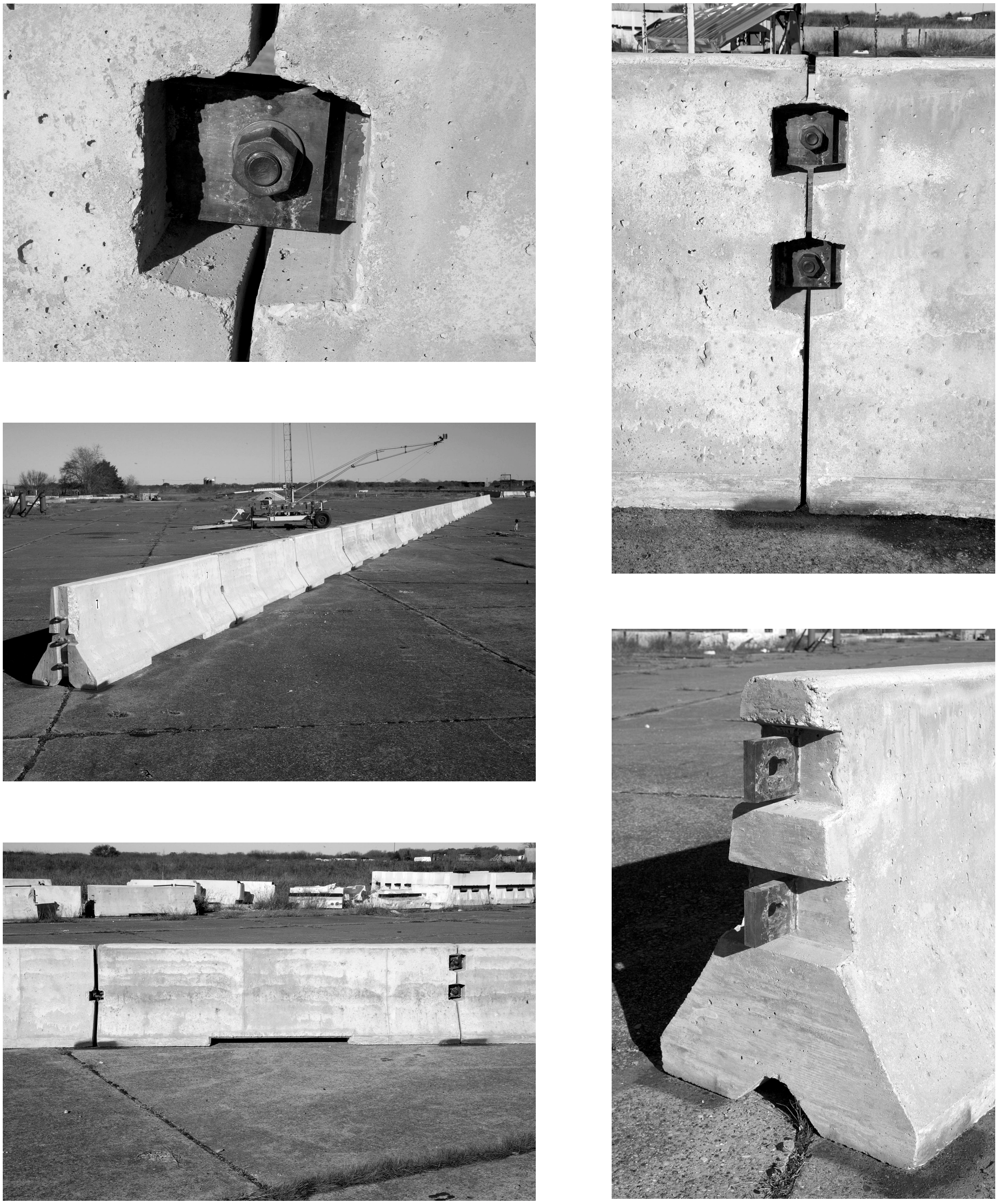


Figure 3.2.4. Lapped splice connection barriers prior to test 474550-2.

***NCHRP Report 350* test designation 3-11**: A 2000-kg (4405-lb) pickup truck impacting the CIP in the LON of the longitudinal barrier at a nominal speed and angle of 100 km/h (62 mi/h) and 25 degrees. The test is intended to evaluate the strength of the section for containing and redirecting the pickup truck.

The tests reported herein correspond to *NCHRP Report 350* test designation 3-11. The CIP for the Montana DOT portable barrier installations was determined using information contained *NCHRP Report 350*. This distance was determined to be 1.2 m (4 ft) upstream of a joint. Since a significant amount of deflection was anticipated, therefore the impact point was chosen to be 1.2 m (4 ft) upstream of the joint between barrier segments 8 and 9.

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

3.4 EVALUATION CRITERIA

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

4.0 MODIFIED PIN-AND-LOOP BARRIER (TEST NO. 474550-1)

4.1 TEST VEHICLE

A 2000 Chevrolet Silverado 2500 pickup truck, shown in Figures 4.1.1 and 4.1.2, was used for the crash test. Test inertia weight of the vehicle was 2080 kg (4582 lb), and its gross static weight was 2080 kg (4582 lb). The height to the lower edge of the vehicle front bumper was 370 mm (14.6 inches), and the height to the upper edge of the front bumper was 650 mm (15.6 inches). Additional dimensions and information on the vehicle are given in Appendix B, Figure B.1.1. 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.

4.2 SOIL AND WEATHER CONDITIONS

The crash test was performed the morning of December 13, 2002. Rainfall of 29 mm, 31 mm, and 66 mm was recorded one, four, and nine days prior to the test, respectively. Weather conditions at the time of testing were as follows: wind speed: 13 km/h (8 mi/h); wind direction: 345 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); temperature: 14 °C (83 °F; relative humidity: 58 percent.

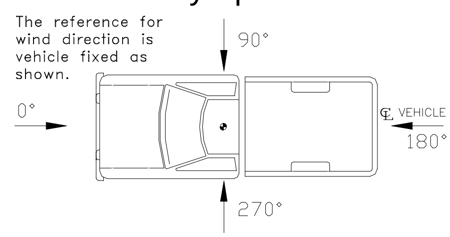


Figure 4.2.1. Wind direction diagram.

4.3 IMPACT DESCRIPTION

The 2080-kg (4582 lb) pickup truck, traveling at a speed of 100.1 km/h (62.2 mi/h), impacted the modified pin-and-loop barrier 1.22 m (4.0 ft) upstream of the joint between 8 and 9, at an impact angle of 26.5 degrees.

Shortly after impact, segment 8 began to move toward the field side, and at 0.022 s after impact segment 9 moved toward the field side. The right front tire and wheel began to ride up the face of the barrier at 0.031 s and the vehicle began to redirect at 0.042 s. At 0.049 s the base of segment 9 adjacent to segment 10 cracked, and at 0.084 s segment 10 began to move toward the field side. Segment 11 began to move toward the field side at 0.202 s. At 0.235 s, the vehicle became parallel with the barriers and was traveling at a speed of 75.1 km/h (46.7 mi/h). The rear of the vehicle impacted the barrier at 0.279 s. At 0.532 s, the vehicle first lost contact with the barriers as it was airborne above the top of the barriers. The undercarriage of the vehicle contacted the top of the barriers at 0.735 s. At 0.921 s the left front tire contacted the top, field side of the barrier, and at 1.422 s the left rear tire contact the top, field side of the barrier. The vehicle traveled along most of the remaining length of the installation with the left tires along the top of the barrier. Just prior to reaching the end of the installation, the vehicle dropped off the barriers traveling at a speed of 74.6 km/h (46.4 mi/h) and an exit angle of 4.4 degrees.

Figure 4.1.1. Vehicle/installation geometrics for test 474550-1.

Figure 4.1.2. Vehicle before test 474550-1.

Brakes on the vehicle were applied at 2.2 s after impact. The vehicle subsequently came to rest 61.8 m (202.8 ft) downstream of impact and 3.8 m (12.5 ft) behind the traffic face of the barriers. Sequential photographs of the test period are shown in Appendix C, Figures C.1.1 and C.1.2.

4.4 DAMAGE TO TEST ARTICLE

Damage to the barriers is shown in Figures 4.4.1 and 4.4.2. The connection pins were deformed between segments 8 and 9, and 9 and 10; and slightly bent between segments 7 and 8, 10 and 11, and 11 and 12. The upstream end of the installation was pulled longitudinally 135 mm (5.3 inches) and the downstream end 5 mm (0.2 inch). The vehicle was in contact with the installation from 1.22 m (4.0 ft) upstream of joint 8-9, and various places along the top of the barrier before it came off the barrier 0.23 m (0.75 ft) from the end of the last barrier (segment 20). Maximum dynamic movement of the barriers toward the field side was 1.27 m (4.2 ft), at which the barriers remained for a permanent deformation of 1.27 m (4.2 ft).

4.5 VEHICLE DAMAGE

Most of the damage to the vehicle was to the left front quarter, as shown in Figure 4.5.1. Structural damage was imparted to the front left of the frame rail and left side firewall and floor pan area. Also damaged were the front bumper, hood, grill, radiator, fan, left front quarter panel, and left front tire and wheel rim. The left rear wheel rim was also deformed but the tire had no loss of air. Maximum exterior crush of the vehicle was 420 mm (16.5 inches) in the side plane at the left front corner near bumper height. Maximum occupant compartment deformation was 20 mm (0.8 inch) in the left floor pan area near the toe pan, and there was very slight separation of the seam between the floor pan and firewall. Photographs of the interior of the vehicle are shown in Figure 4.5.2. Exterior vehicle crush and occupant compartment measurements are shown in Appendix B, Tables B.1.1 and B.1.2.

4.6 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 of *NCHRP Report 350*.

In the longitudinal direction, occupant impact velocity was 4.8 m/s (15.7 ft/s) at 0.111 s, maximum 0.010-s ridedown acceleration was -3.3 g's from 0.114 to 0.124 s, and the maximum 0.050-s average was -6.1 g's between 0.012 and 0.062 s. In the lateral direction, the occupant impact velocity was 6.4 m/s (21.0 ft/s) at 0.111 s, the highest 0.010-s occupant ridedown acceleration was 5.3 g's from 0.293 to 0.303 s, and the maximum 0.050-s average was 8.4 g's between 0.050 and 0.100 s.

Figure 4.4.1. Vehicle trajectory after test 474550-1.

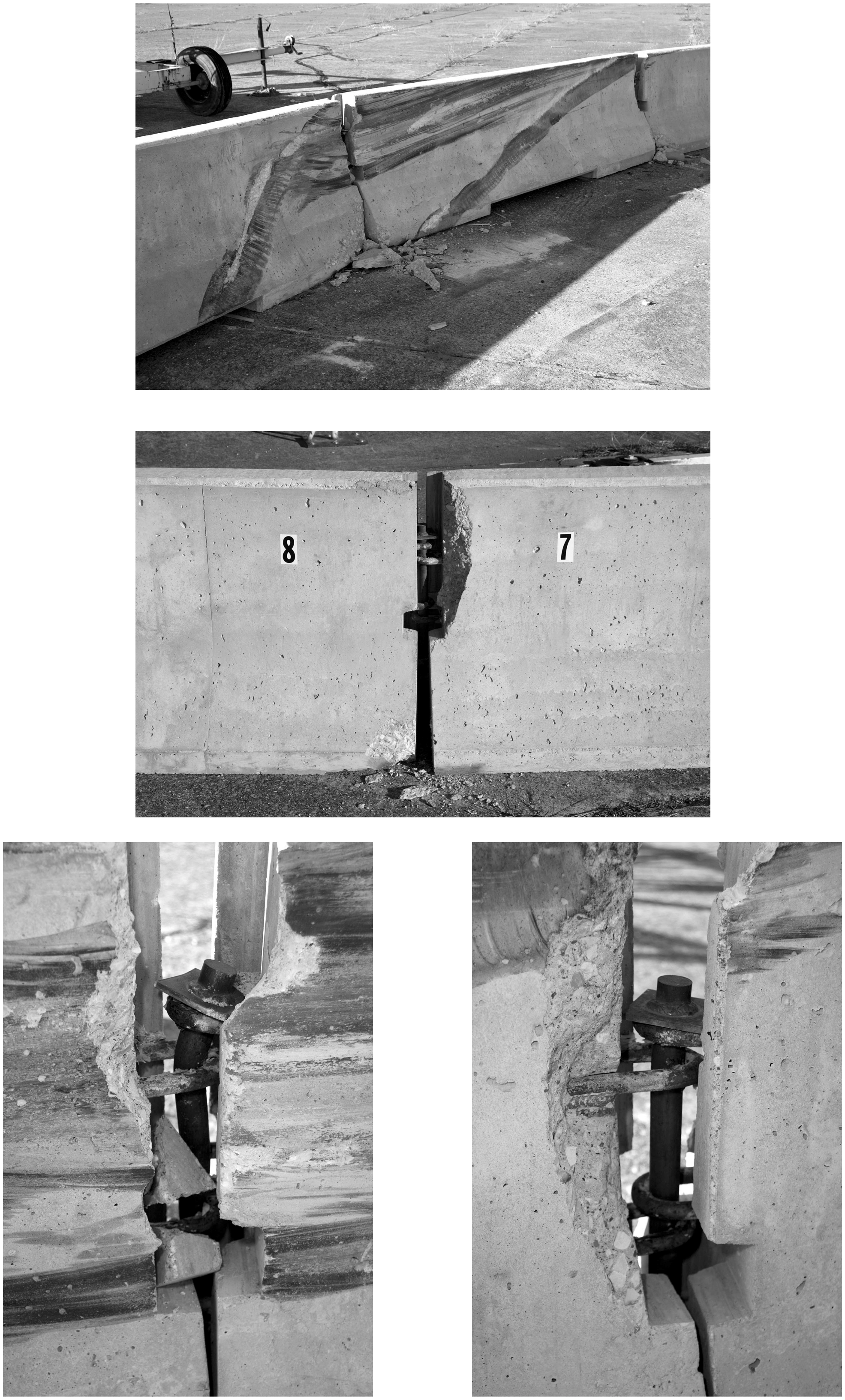


Figure 4.4.2. Modified pin-and-loop barrier installation after test 474550-1.

Figure 4.5.1. Vehicle after test 474550-1.

Before Test

After Test

Figure 4.5.2. Interior of vehicle for test 474550-1.

These data and other information pertinent to the test are presented in Figure 4.6.1. Vehicle angular displacements are presented in Appendix D, Figure D.1.1, and vehicle accelerations versus time traces are shown in Appendix E, Figures E.1.1 through E.1.6.

4.7 ASSESSMENT OF TEST RESULTS

An assessment of the test based on the applicable *NCHRP Report 350* safety evaluation criteria for *NCHRP Report 350* test 3-11 is provided below.

Structural Adequacy

A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.

Result: The modified pin-and-loop barrier contained and redirected the vehicle. The vehicle did not penetrate or underride the barrier, and although the vehicle straddled the barrier it did not go over the installation. Maximum movement of the barriers was 1.27 m (4.2 ft).

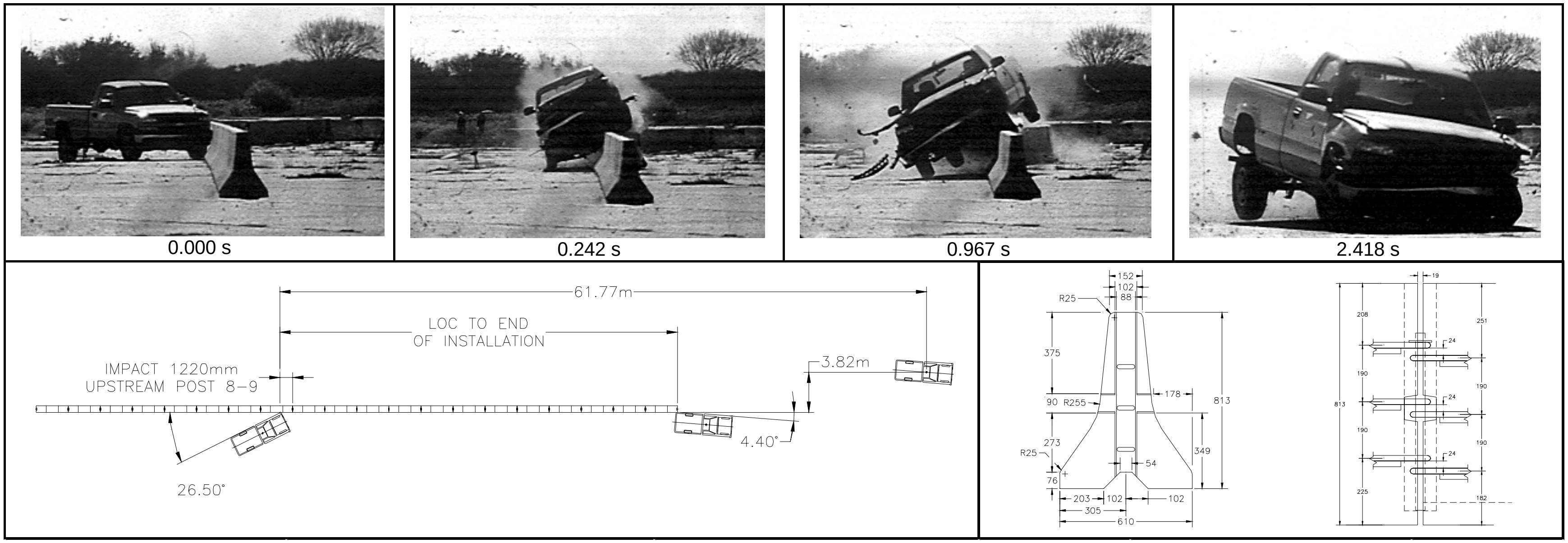
Occupant Risk

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 was 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 20 mm (0.8 inch) in the left side floor pan near the toe pan.

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

Result: The vehicle remained upright during and after the collision period.



General Information

Test Agency	Texas Transportation Institute
Test No.	474550-1
Date	12/13/02
Test Article	
Type	Median Barrier
Name	Montana Modified Pin-And-Loop CMB
Installation Length (m)	61.0
Material or Key Elements	New Jersey Shaped Concrete Median Barriers With Pin-And-Loop Connection
Soil Type and Condition	Concrete Surface, Dry
Test Vehicle	
Type	Production
Designation	2000P
Model	2000 Chevrolet 2500 Pickup
Mass (kg)	
Curb	2121
Test Inertial	2080
Dummy	N/A
Gross Static	2080

Impact Conditions

Speed (km/h)	100.1
Angle (deg)	26.5
Exit Conditions	
Speed (km/h)	74.6
Angle (deg)	4.4
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	4.8
y-direction	6.4
THIV (km/h)	27.8
Ridedown Accelerations (g's)	
x-direction	-3.3
y-direction	5.3
PHD (g's)	5.9
ASI	1.03
Max. 0.050-s Average (g's)	
x-direction	-6.1
y-direction	8.4
z-direction	-3.2

Test Article Deflections (m)

Dynamic	1.27
Permanent	1.27
Working Width	1.70
Vehicle Damage	
Exterior	
VDS	11FL2
CDC	11FLEW2
Maximum Exterior Vehicle Crush (mm)	420
Interior	
OCDI	LF0001000
Max. Occ. Compart. Deformation (mm)	20
Post-Impact Behavior (during 1.0 s after impact)	
Max. Yaw Angle (deg)	34.4
Max. Pitch Angle (deg)	9.9
Max. Roll Angle (deg)	37.5

Figure 4.6.1. Summary of results for modified pin-and-loop barrier (test 474550-1).

Vehicle Trajectory

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

Result: The vehicle did not intrude into adjacent traffic lanes as it came to rest 61.8 m (202.8 ft) downstream of impact and 3.8 m (12.5 ft) toward the field side of the face of the barriers.

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 4.8 m/s (15.7 ft/s) and longitudinal ridedown acceleration was -3.3 g's.

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 with the barriers was 4.4 degrees, which was 17 percent of the impact angle.

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: (FHWA, 1998)

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
   <u>d. Major dents to grill and body panels</u>
   e. Major structural damage
2. Windshield Damage
   <u>a. None</u>
   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
   <u>d. Substantial, replacement parts needed for repair</u>
   e. Cannot be repaired

5.0 LAPPED SPLICE CONNECTION BARRIER (TEST NO. 474550-2)

5.1 TEST VEHICLE

A 1999 Chevrolet LS 2500 pickup truck, shown in Figures 5.1.1 and 5.1.2, was used for the crash test. Test inertia weight of the vehicle was 2163 kg (4764 lb), and its gross static weight was 2163 kg (4764 lb). The height to the lower edge of the vehicle front bumper was 390 mm (15.4 inches), and the height to the upper edge of the front bumper was 670 mm (26.4 inches). Additional dimensions and information on the vehicle are given in Appendix B, Figure B.2.1. 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.

5.2 SOIL AND WEATHER CONDITIONS

The crash test was performed the morning of December 19, 2002. Rainfall of 29 mm and 28 mm was recorded seven and ten days prior to the test, respectively. Weather conditions at the time of testing were as follows: wind speed: 17 km/h (11 mi/h); wind direction: 340 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); temperature: 17 °C (88 °F); relative humidity: 38 percent.

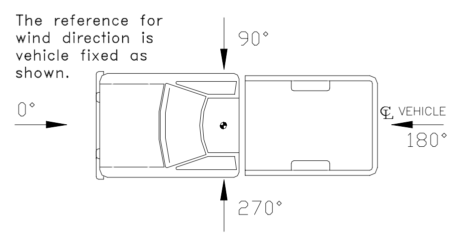


Figure 5.2.1. Wind direction diagram.

5.3 IMPACT DESCRIPTION

The 2163-kg (4764-lb) pickup truck, traveling at a speed of 99.3 km/h (61.7 mi/h), impacted the lapped splice connection barriers 1.36 m (4.4 ft) upstream of the joint between segments 8 and 9, at an impact angle of 25.6 degrees.

At 0.015 s after impact, the left front tire began to climb the face of the barrier, and at 0.017 s segments 8 and 9 began to move toward the field side. The left front tire deflated at 0.029 s, and the right front tire began to turn toward the barriers at 0.032 s. At 0.035 s, segments 7 and 10 began to move toward the field side, and at 0.036 s the vehicle began to redirect. At 0.234 s, the vehicle became parallel with the barriers. The rear of the vehicle contacted the barriers at 0.265 s, and the vehicle first lost contact with the barriers at 0.391 s. At this time, the vehicle was traveling at a speed of 83.0 km/h (61.6 mi/h) and an exit angle of 1.0 degree. At 0.529 s the undercarriage of the vehicle contacted the top of the barriers, and at 0.900 s the left front tire contacted the top, field side of the barrier. The left rear tire contacted the top, field side of the barrier at 0.990 s, and the left front tire returned to the traffic side of the barrier at 1.206 s. By 1.475 s the left front tire touched ground on the traffic side of the barrier and the vehicle began to yaw toward the barriers. The vehicle impacted the traffic face of the barrier again at 1.665 s, and then lost contact with the barriers again at 2.148 s.

Figure 5.1.1. Vehicle/installation geometrics for test 474550-2.

Figure 5.1.2. Vehicle before test 474550-2.

Brakes on the vehicle were applied at 2.5 s after impact. The vehicle subsequently came to rest 25.9 m (85.0 ft) downstream of the end of the barrier and 2.3 m (7.5 ft) toward the field side of the traffic face of the barrier. Sequential photographs of the test period are shown in Appendix C, Figures C.2.1 and C.2.2.

5.4 DAMAGE TO TEST ARTICLE

Damage to the barriers is shown in Figures 5.4.1 and 5.4.2. The upstream end of the installation was pulled longitudinally 128 mm (5.0 inches) and the downstream end 5 mm (0.2 inch). The vehicle was in contact with the installation from 1.36 m (4.4 ft) upstream of joint 8-9, all along segment 9, and 1.87 m (6.1 ft) along segment 10. The vehicle then contacted the traffic face of the installation at various locations. Maximum dynamic movement of the barriers toward the field side was 1.10 m (3.6 ft), at which the barriers remained for a permanent deformation of 1.10 m (3.6 ft).

5.5 VEHICLE DAMAGE

Most of the damage to the vehicle was to the left front quarter, as shown in Figure 5.5.1. Structural damage was imparted to the left lower A-arm and left side firewall and floor pan area. Also damaged were the front bumper, hood, grill, radiator, fan, left and right front quarter panels, left door, and left front and rear tire and wheel rim. Maximum exterior crush of the vehicle was 400 mm (15.7 inches) in both the side plane and front plane at the left front corner near bumper height. Maximum occupant compartment deformation was 21 mm (0.8 inches) in the left floor pan area near the toe pan, and there was very slight separation of the seam between the floor pan and firewall. Photographs of the interior of the vehicle are shown in Figure 5.5.2. Exterior vehicle crush and occupant compartment measurements are shown in Appendix B, Tables B.2.1 and B.2.2.

5.6 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 of *NCHRP Report 350*.

In the longitudinal direction, occupant impact velocity was 4.9 m/s (16.1 ft/s) at 0.108 s, maximum 0.010-s ridedown acceleration was -3.5 g’s from 0.109 to 0.119 s, and the maximum 0.050-s average was -5.6 g’s between 0.020 and 0.070 s. In the lateral direction, the occupant impact velocity was 6.2 m/s (20.3 ft/s) at 0.108 s, the highest 0.010-s occupant ridedown acceleration was 6.2 g’s from 0.257 to 0.267 s, and the maximum 0.050-s average was 8.2 g’s between 0.044 and 0.094 s.

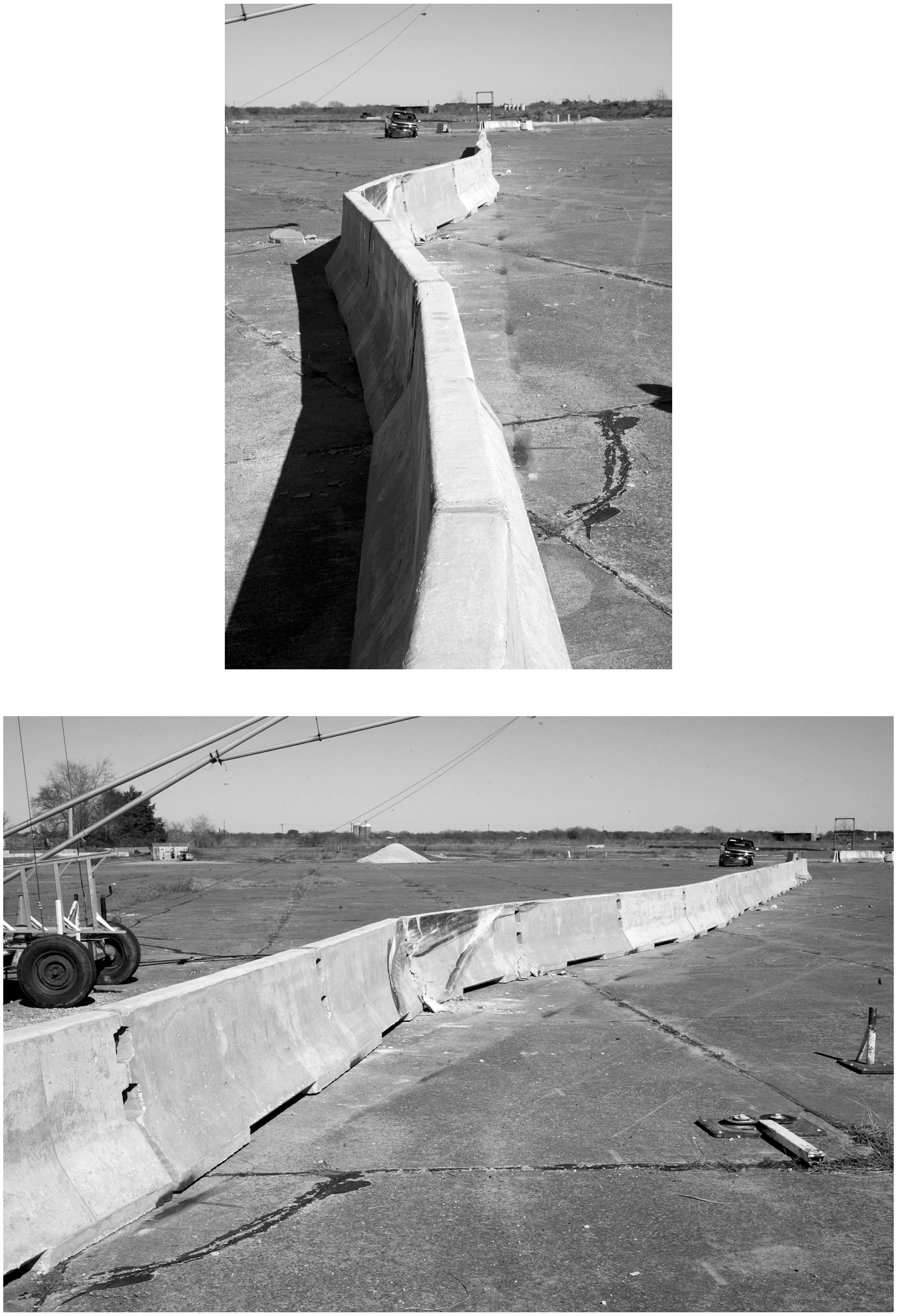


Figure 5.4.1. Vehicle trajectory after test 474550-2.

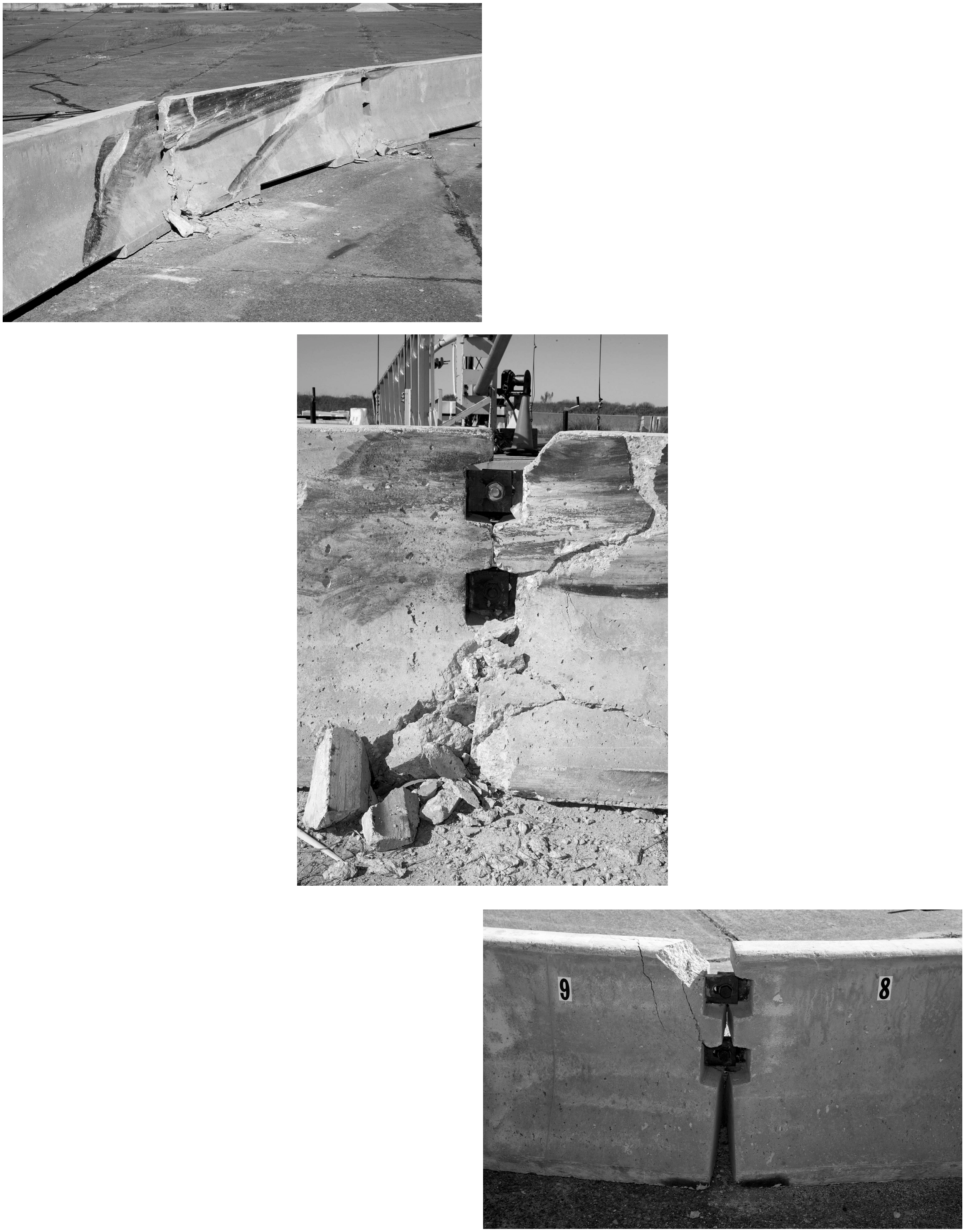


Figure 5.4.2. Lapped splice barrier installation after test 474550-2.

Figure 5.5.1. Vehicle after test 474550-2.

Before Test

After Test

Figure 5.5.2. Interior of vehicle for test 474550-2.

These data and other information pertinent to the test are presented in Figure 5.6.1. Vehicle angular displacements are presented in Appendix D, Figure D.2.1, and vehicle accelerations versus time traces are shown in Appendix E, Figures E.2.1 through E.2.6.

5.7 ASSESSMENT OF TEST RESULTS

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

Structural Adequacy

A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.

Result: The lapped splice connection concrete barriers contained and redirected the pickup truck. The vehicle did not penetrate or underride the installation. Although the vehicle did reach the top and straddle the barrier, it subsequently returned to the traffic side. Maximum movement of the barrier was 1.10 m (3.6 ft)

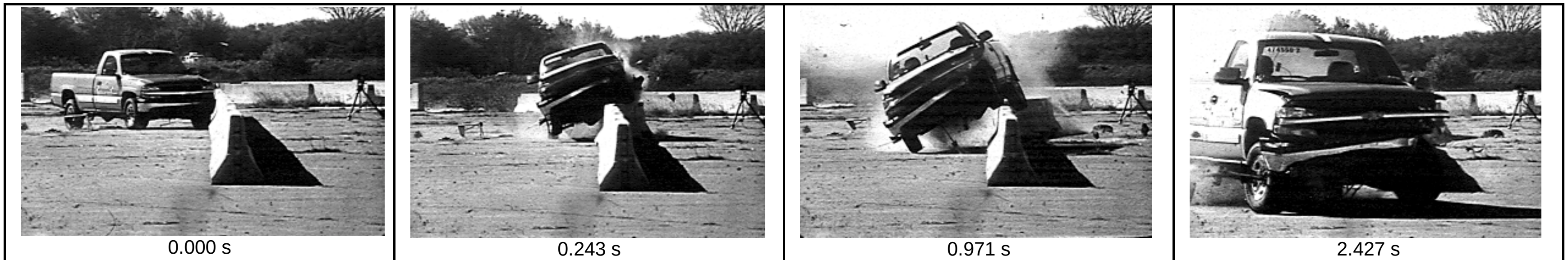
Occupant Risk

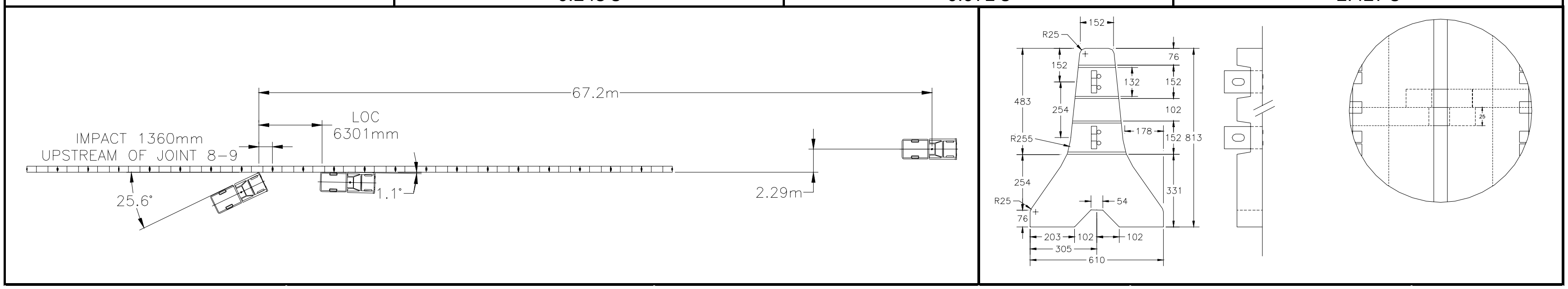
D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment that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

Result: No detached elements, fragments, or other debris was 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 21 mm (0.8 inch) in the driver's side floor pan near the toe pan.

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

Result: The vehicle remained upright during and after the collision period.





General Information	
Test Agency	Texas Transportation Institute
Test No.	474550-2
Date	12/19/02
Test Article	
Type	Median Barrier
Name	Montana Lapped Splice Connection CMB
Installation Length (m)	64.0
Material or Key Elements	New Jersey Shaped Concrete Median Barriers With Lapped Splice Connection
Soil Type and Condition	Concrete Surface, Dry
Test Vehicle	
Type	Production
Designation	2000P
Model	1999 Chevrolet 2500 Pickup
Mass (kg)	
Curb	2302
Test Inertial	2163
Dummy	N/A
Gross Static	2163

Impact Conditions	
Speed (km/h)	99.3
Angle (deg)	25.6
Exit Conditions	
Speed (km/h)	83.0
Angle (deg)	1.0
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	4.9
y-direction	6.2
THIV (km/h)	27.1
Ridedown Accelerations (g's)	
x-direction	-3.5
y-direction	6.2
PHD (g's)	6.7
ASI	1.00
Max. 0.050-s Average (g's)	
x-direction	-5.6
y-direction	8.2
z-direction	-2.8

Test Article Deflections (m)	
Dynamic	1.10
Permanent	1.10
Working Width	1.45
Vehicle Damage	
Exterior	
VDS	11FL2
CDC	11FLEW2
Maximum Exterior Vehicle Crush (mm)	400
Interior	
OCDI	LF0001000
Max. Occ. Compart. Deformation (mm)	21
Post-Impact Behavior (during 1.0 s after impact)	
Max. Yaw Angle (deg)	29.9
Max. Pitch Angle (deg)	-12.5
Max. Roll Angle (deg)	34.9

Figure 5.6.1. Summary of results for lapped splice connection barrier (test 474550-2).

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 25.9 m (85.0 ft) downstream of the end of the installation and 2.3 (7.5 ft) m toward the field side of the traffic face of the barriers.

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 4.9 m/s (16.1 ft/s) and longitudinal occupant ridedown was -3.5 g's.

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 1.0 degree, which was 4 percent of the impact angle.

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: (FHWA, 1998)

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

6.0 SUMMARY AND CONCLUSIONS

6.1 SUMMARY OF TEST RESULTS

6.1.1 Modified Pin-and-Loop Barrier (Test No. 474550-1)

The modified pin-and-loop barrier contained and redirected the pickup truck. The vehicle did not penetrate or underride the installation. Although the vehicle straddled the barrier, it did not go over the installation. Maximum movement of the barriers was 1.27 m (4.2 ft). No detached elements, fragments, or other debris was present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 20 mm (0.8 inch) in the left side floor pan near the toe pan. The vehicle remained upright during and after the collision period. The vehicle did not intrude into adjacent traffic lanes as it came to rest 61.8 m (202.8 ft) downstream of impact and 3.8 m (12.5 ft) toward the field side of the face of the barriers. Longitudinal occupant impact velocity was 4.8 m/s (15.7 ft/s) and longitudinal ridedown acceleration was -3.3 g's. Exit angle at loss of contact with the barriers was 4.4 degrees, which was 17 percent of the impact angle.

6.1.2 Lapped Splice Connection Barrier (Test No. 474550-2)

The lapped splice connection concrete barriers contained and redirected the pickup truck. The vehicle did not penetrate or underride the installation. Although the vehicle did reach the top and straddle the barrier, it subsequently returned to the traffic side. Maximum dynamic movement of the barrier was 1.10 m (3.6 ft). No detached elements, fragments, or other debris was present to penetrate or to show potential for penetrating the occupant compartment or to present undue hazard to others in the area. Maximum occupant compartment deformation was 21 mm (0.8 inch) in the driver's side floor pan near the toe pan. The vehicle remained upright during and after the collision period. The vehicle came to rest 25.9 m (85.0 ft) downstream of the end of the installation and 2.3 m (7.5 ft) toward the field side of the traffic face of the barriers. Longitudinal occupant impact velocity was 4.9 m/s (16.1 ft/s) and longitudinal occupant ridedown was -3.5 g's. Exit angle at loss of contact was 1.0 degree, which was 4 percent of the impact angle.

6.2 CONCLUSIONS

As shown in Tables 6.2.1 and 6.2.2, both of the Montana DOT barriers met the specifications for *NCHRP Report 350* test designation 3-11.

Table 6.2.1. Performance evaluation summary for MDT modified pin-and-loop barrier (test no. 474550-1).

Test Agency: Texas Transportation Institute | Test No.: 474550-1 | Test Date: 12/13/2002

NCHRP Report 350 **Test 3-11 Evaluation Criteria**	**Test Results**	**Assessment**
<u>Structural Adequacy</u> A. *Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.*	The modified pin-and-loop barrier contained and redirected the pickup truck. Although the vehicle straddled the barrier, it did not go over the installation. Maximum movement of the barriers was 1.27 m (4.2 ft).	Pass
<u>Occupant Risk</u> D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*	No detached elements, fragments, or other debris was present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 20 mm (0.8 inch) in the left side floor pan near the toe pan.	Pass
F. *The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.*	The vehicle remained upright during and after the collision period.	Pass
<u>Vehicle Trajectory</u> K. *After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*	The vehicle did not intrude into adjacent traffic lanes as it came to rest 61.8 m (202.8 ft) downstream of impact and 3.8 m (12.5 ft) toward the field side of the face of the barriers.	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 4.8 m/s (15.7 ft/s) and longitudinal ridedown acceleration was -3.3 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 with the barriers was 4.4 degrees, which was 17 percent of the impact angle.	Pass*

*Criterion K and M are preferable, not required.

Table 6.2.2. Performance evaluation summary for MDT lapped splice connection barrier (test no. 474550-2).

Test Agency: Texas Transportation Institute | Test No.: 474550-2 | Test Date: 12/19/2002

NCHRP Report 350 **Test 3-11 Evaluation Criteria**	**Test Results**	**Assessment**
Structural Adequacy A. *Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.*	The lapped splice connection concrete barriers contained and redirected the pickup truck. Although the vehicle did reach the top and straddle the barrier, it subsequently returned to the traffic side. Maximum movement of the barrier was 1.10 m (3.6 ft).	Pass
Occupant Risk D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*	No detached elements, fragments, or other debris was present to penetrate or to show potential for penetrating the occupant compartment or to present undue hazard to others in the area. Maximum occupant compartment deformation was 21 mm (0.8 inch) in the driver's side floor pan near the toe pan.	Pass
F. *The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.*	The vehicle remained upright during and after the collision period.	Pass
Vehicle Trajectory K. *After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*	The vehicle came to rest 25.9 m (85.0 ft) downstream of the end of the installation and 2.3 m (7.5 ft) toward the field side of the traffic face of the barriers.	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 4.9 m/s (16.1 ft/s) and longitudinal occupant ridedown was -3.5 g's.	Pass
M. *The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.*	Exit angle at loss of contact was 1.0 degree, which was 4 percent of the impact angle.	Pass*

*Criterion K and M are preferable, not required.

7.0 REFERENCES

American Association of State Highway and Transportation Officials (1996), AASHTO Guide.

Federal Highway Administration (FHWA) Memorandum (August 29, 1998).entitled *ACTION: National Cooperative Highway Research Program (NCHRP) 350 Hardware Compliance Dates*.

Michie, Jarvis D. (March 1981), *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program Report 230, Transportation Research Board, National Research Council, Washington, D.C.

Ross, Jr., H.E., Sicking, D. L., Zimmer, R. A., and Michie, J. D. (1993), *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.

APPENDIX A. CRASH TEST PROCEDURES AND DATA ANALYSIS

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

A.1 ELECTRONIC INSTRUMENTATION AND DATA PROCESSING

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

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

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

All accelerometers are calibrated annually according to Society of Automotive Engineers (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-ms average ridedown acceleration. WinDigit calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with a 60-Hz digital filter, and acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted using TRAP.

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

A.2 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.

A.3 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 flashbulb 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 BetaCam, a VHS-format video camera and recorder, and still cameras were used to record and document conditions of the test vehicle and installation before and after the test.

A.4 TEST VEHICLE PROPULSION AND GUIDANCE

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

APPENDIX B. TEST VEHICLE PROPERTIES AND INFORMATION

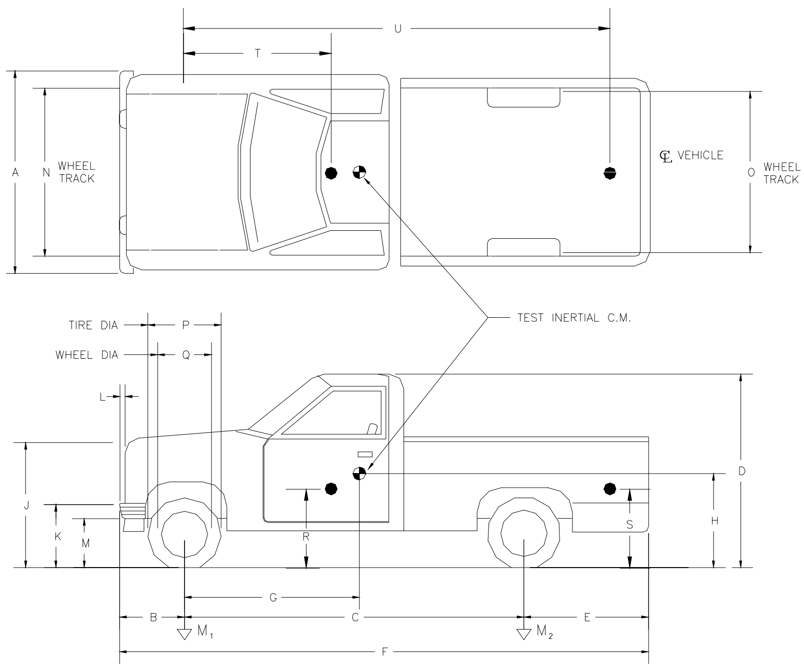
DATE: 12/13/02 TEST NO.: 474550-1 VIN NO.: 1GCFC24T3YE367586

YEAR: 2000 MAKE: Chevrolet MODEL: 2500 Pickup

TIRE INFLATION PRESSURE: ______ ODOMETER: 117841 TIRE SIZE: 225 75R16

MASS DISTRIBUTION (kg) LF 623 RF 605 LR 419 RR 433

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:



● Denotes accelerometer location.

NOTES: ______

ENGINE TYPE: V-8

ENGINE CID: 5.3 L

TRANSMISSION TYPE:

X AUTO

__ MANUAL

OPTIONAL EQUIPMENT:

8 LUG

New body style

DUMMY DATA:

TYPE: ______

MASS: ______

SEAT POSITION: ______

GEOMETRY - (mm)

A 1820	E 1340	J 1090	N 1670	R 725
B 840	F 5560	K 650	O 1680	S 910
C 3380	G 1384.5	L 90	P 740	T 1430
D 1865	H	M 370	Q 440	U 3410

MASS - (kg)	CURB	TEST INERTIAL	GROSS STATIC
M_1	1268	1228	
M_2	853	852	
M_T	2121	2080	

Figure B.1.1. Vehicle properties for test 474550-1.

Table B.1.1. Exterior crush measurements for test 474550-1.

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	Front bumper	950	400	840	400	320	220	110	40	0	-420
2	Front bumper	950	420	1050	0	20	N/A	N/A	350	420	+1650

[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).

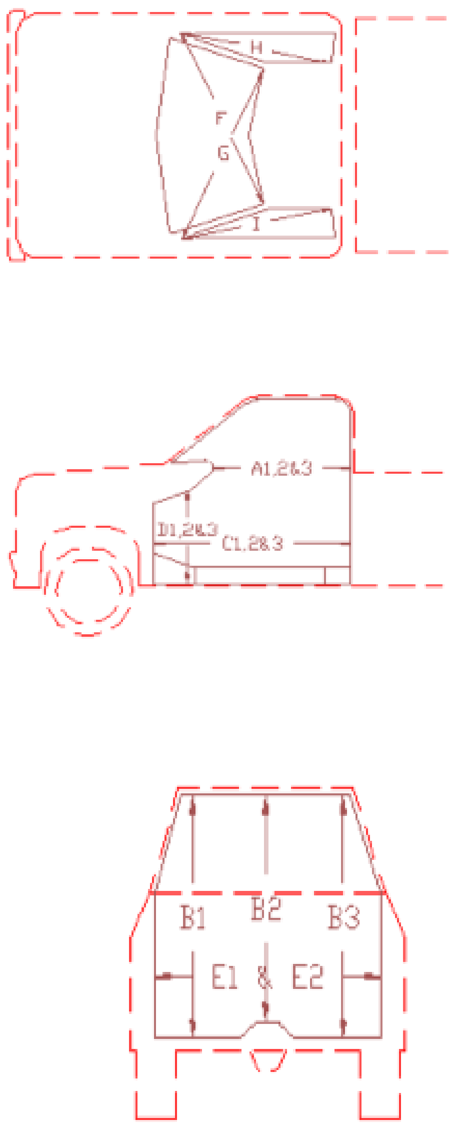
***Measure and document on the vehicle diagram the location of the maximum crush.

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

Table B.1.2. Occupant compartment measurements for test 474550-1.

Truck

Occupant Compartment Deformation



	BEFORE	AFTER
A1	934	934
A2	930	930
A3	932	932
B1	1100	1100
B2	1060	1060
B3	1107	1107
C1	1362	1355
C2	1349	1349
C3	1375	1375
D1	325	305
D2	130	130
D3	327	327
E1	1597	1597
E2	1607	1607
F	1490	1490
G	1490	1490
H	1255	1255
I	1262	1262
J	1525	1525

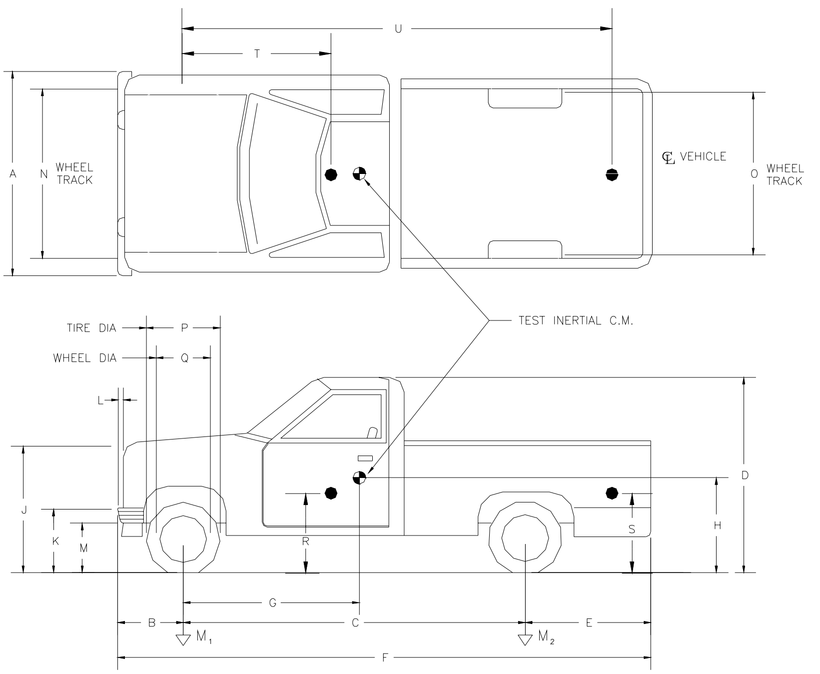
DATE: 12/19/02 TEST NO.: 474550-2 VIN NO.: 1GCGC24U9XE209989

YEAR: 1999 MAKE: Chevrolet MODEL: 2500 Pickup

TIRE INFLATION PRESSURE: ______ ODOMETER: 82112 TIRE SIZE: 245 75R16

MASS DISTRIBUTION (kg) LF 627 RF 615 LR 456 RR 465

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:



● Denotes accelerometer location.

NOTES: ______

ENGINE TYPE: V-8

ENGINE CID: 6.0 L

TRANSMISSION TYPE:

__ AUTO

X MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE:

MASS:

SEAT POSITION:

GEOMETRY – (mm)

A	1820	E	1340	J	1120	N	1670	R	735
B	840	F	5560	K	670	O	1680	S	920
C	3380	G	1439.2	L	90	P	740	T	1420
D	1880	H		M	390	Q	440	U	3380

MASS – (kg)	CURB	TEST INERTIAL	GROSS STATIC
M_1	1320	1242	
M_2	982	921	
M_T	2302	2163	

Figure B.2.1. Vehicle properties for test 474550-2.

Table B.2.1. Exterior crush measurements for test 474550-2.

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width** (CDC)	Direct Damage Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	At front bumper	870	400	800	400	350	150	80	40	0	-400
2	At front bumper	870	400	1050	0	30	N/A	N/A	350	400	+1650

[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).

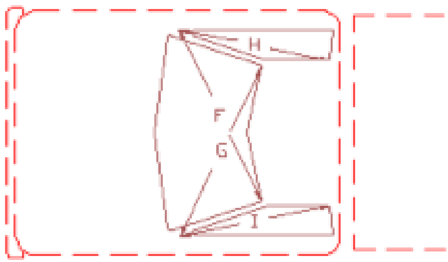
***Measure and document on the vehicle diagram the location of the maximum crush.

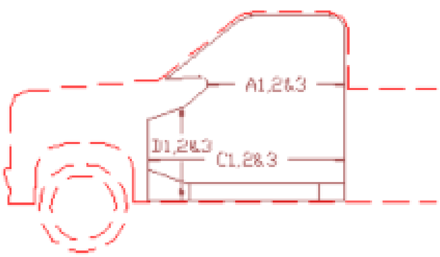
Note: Use as many lines/columns as necessary to describe each damage profile.

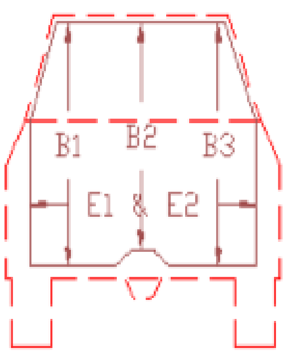
Table B.2.2. Occupant compartment measurements for test 474550-2.

Truck

Occupant Compartment Deformation







	BEFORE	AFTER
A1	926	926
A2	947	947
A3	932	932
B1	1107	1102
B2	1056	1056
B3	1107	1107
C1	1368	1350
C2	1351	1351
C3	1370	1370
D1	327	306
D2	156	156
D3	328	328
E1	1622	1622
E2	1615	1615
F	1475	1475
G	1475	1475
H	1280	1280
I	1265	1265
J	1534	1534

APPENDIX C. SEQUENTIAL PHOTOGRAPHS

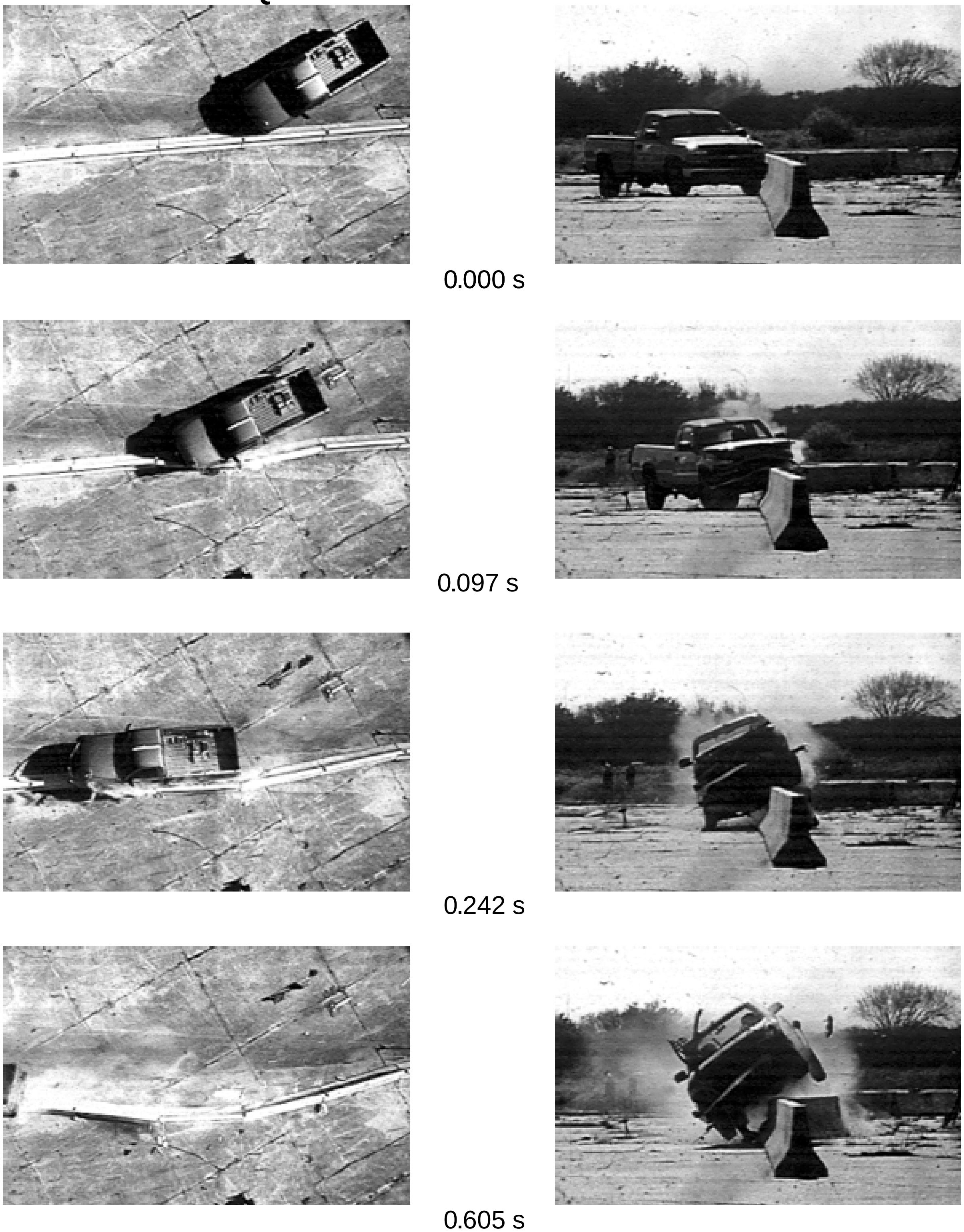
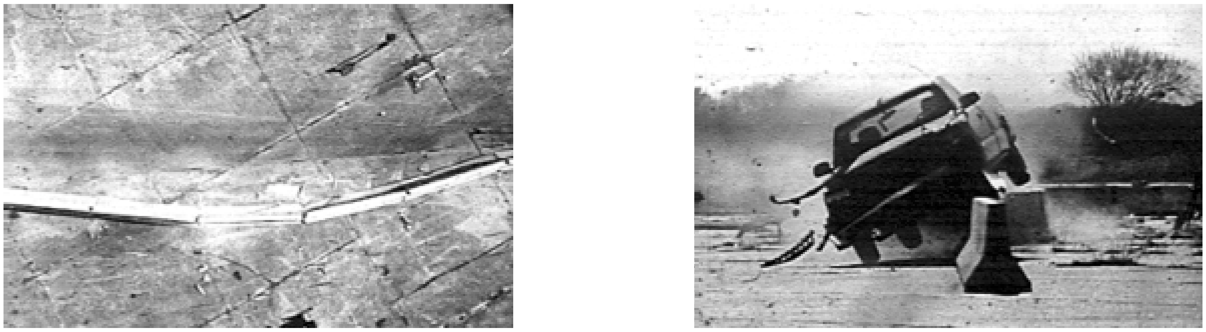
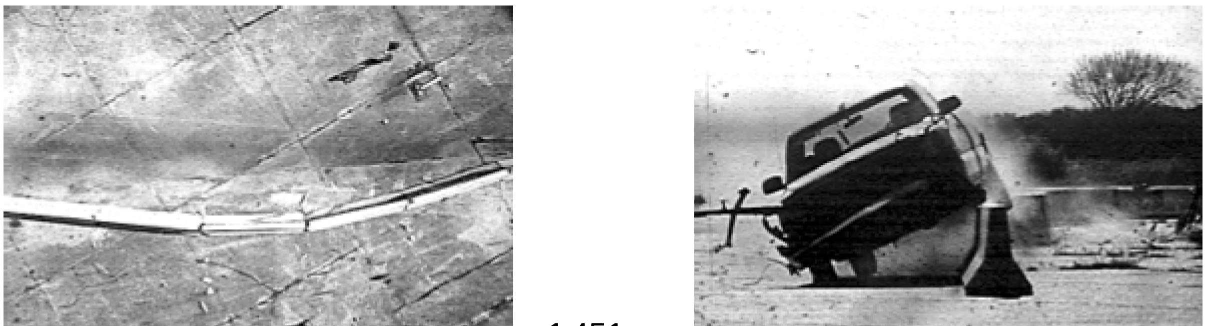


Figure C.1.1. Sequential photographs for test 474550-1 (overhead and frontal views).

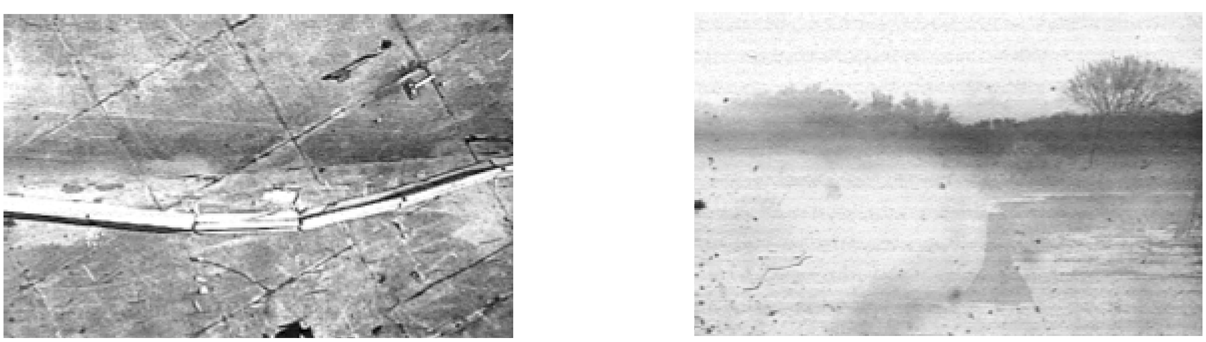


0.967 s



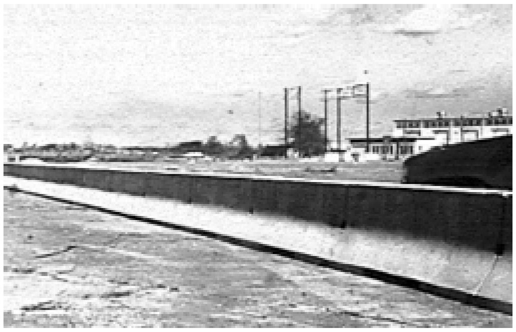
1.451 s

2.418 s

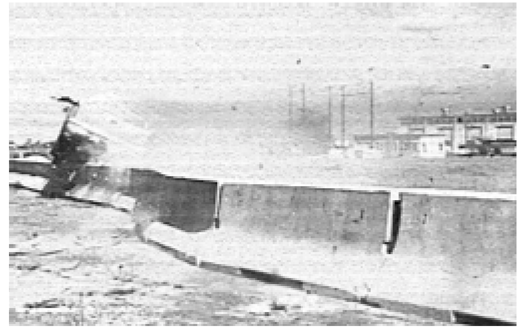


3.869 s

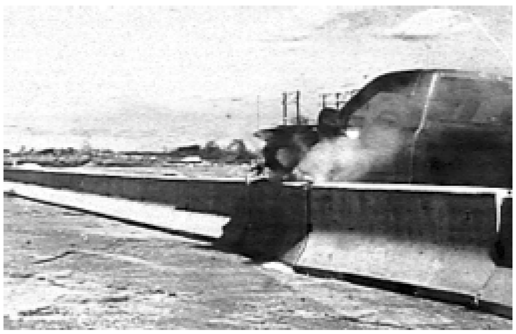
Figure C.1.1. Sequential photographs for test 474550-1 (overhead and frontal views) (continued).



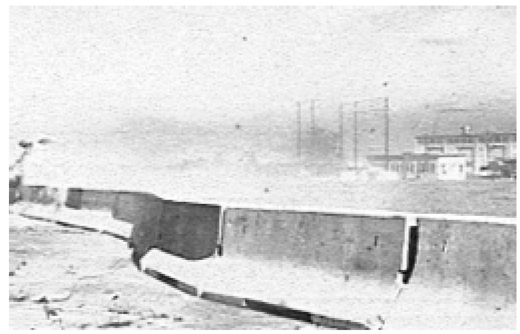
0.000 s



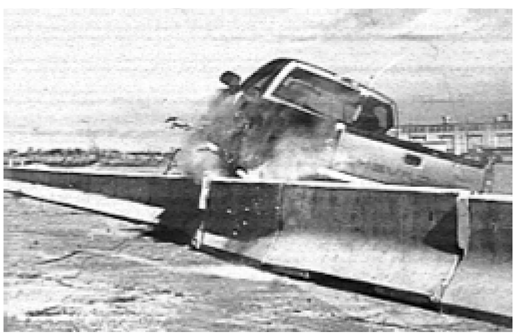
0.967 s



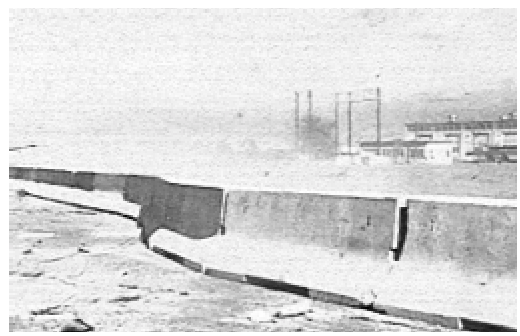
0.097 s



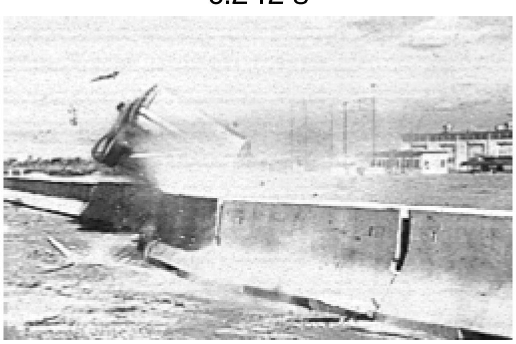
1.451 s



0.242 s



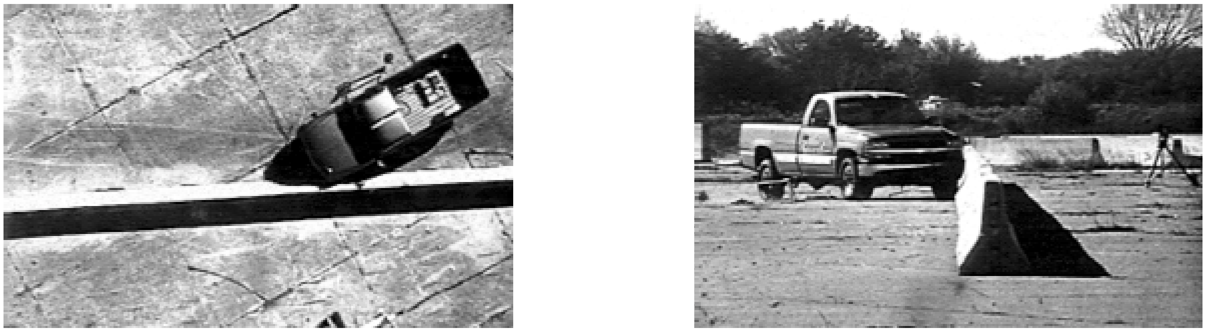
2.418 s



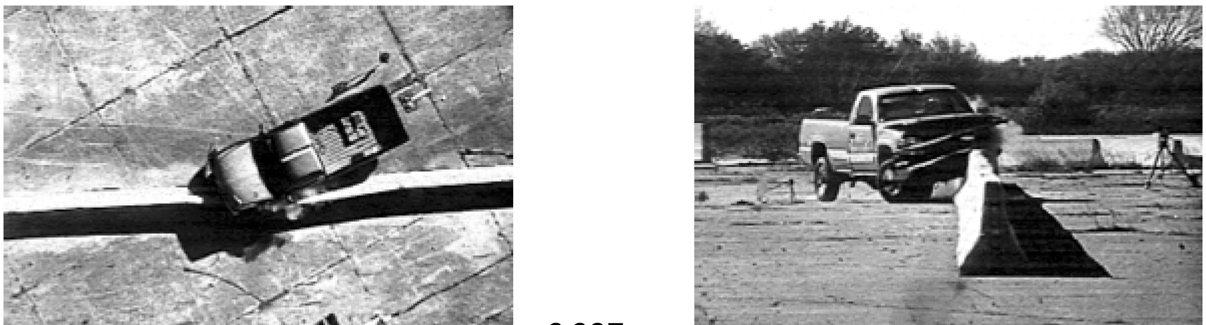
0.605 s

3.869 s

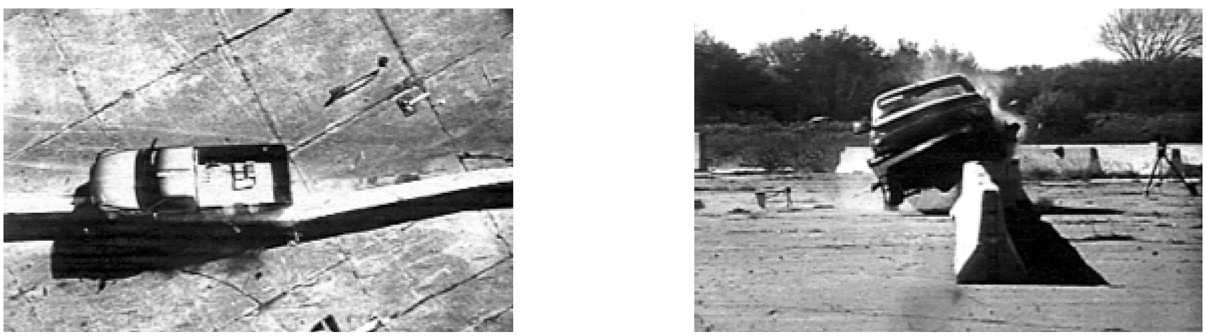
Figure C.1.2. Sequential photographs for test 474550-1 (rear view).



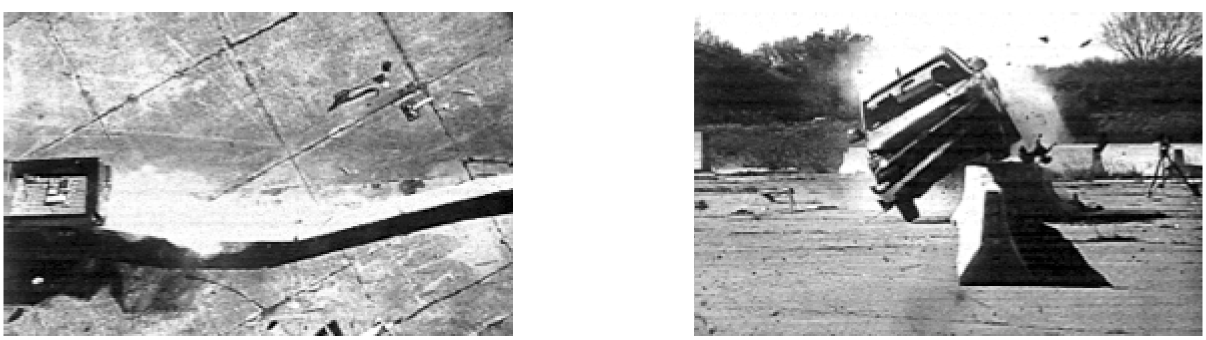
0.000 s



0.097 s

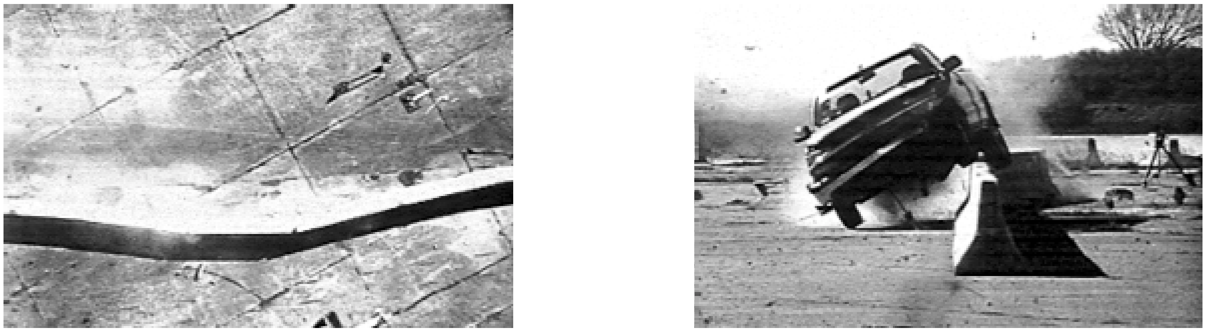


0.243 s

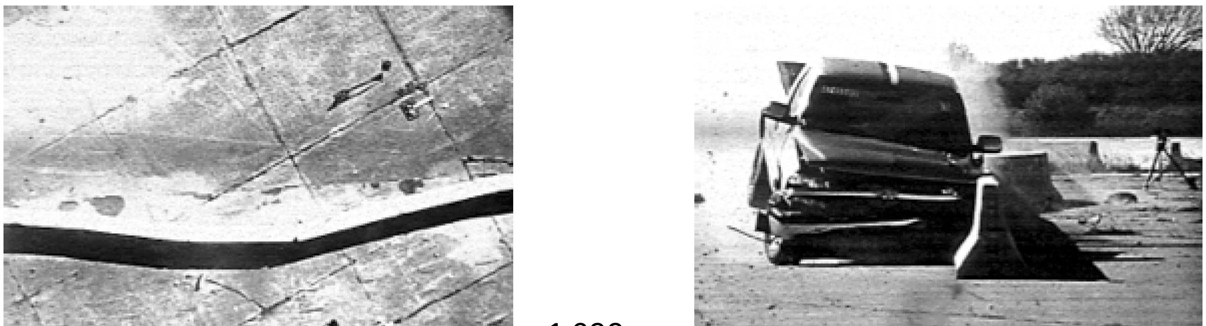


0.485 s

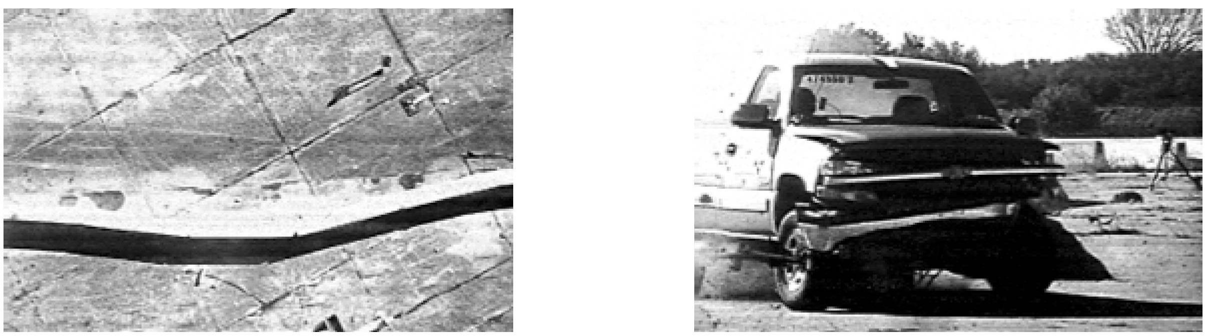
Figure C.2.1. Sequential photographs for test 474550-2 (overhead and frontal views).



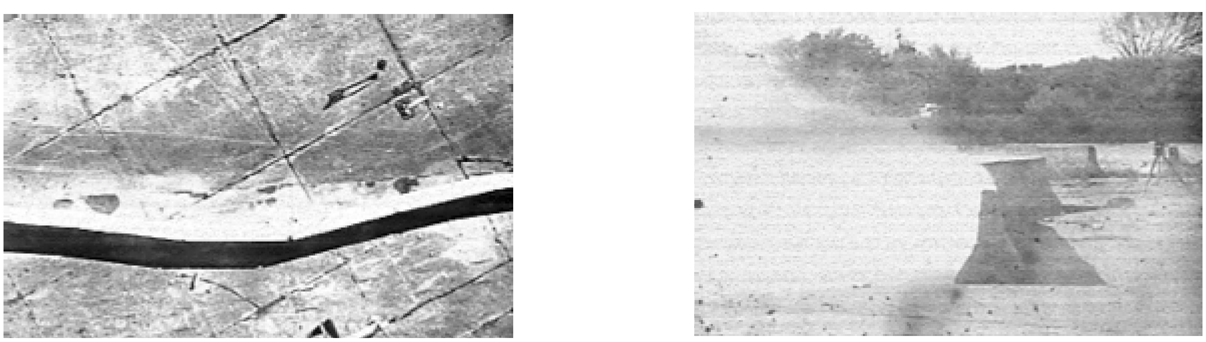
0.971 s



1.699 s

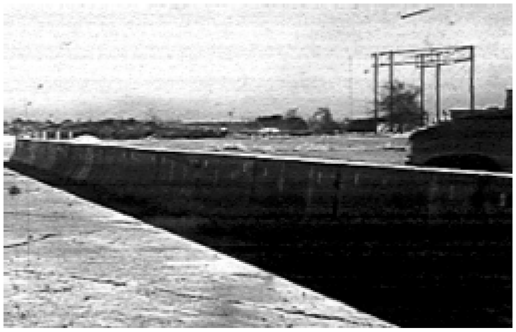


2.427 s



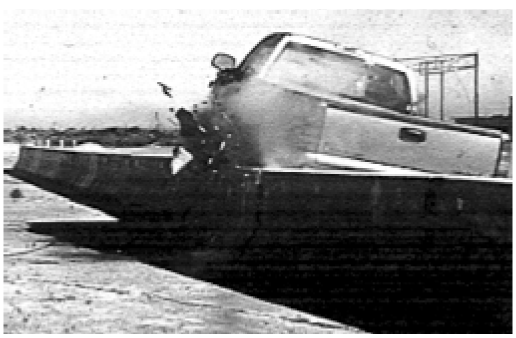
4.126 s

Figure C.2.1. Sequential photographs for test 474550-2 (overhead and frontal views) (continued).

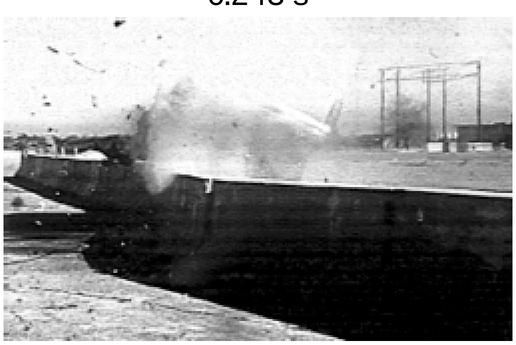


0.000 s

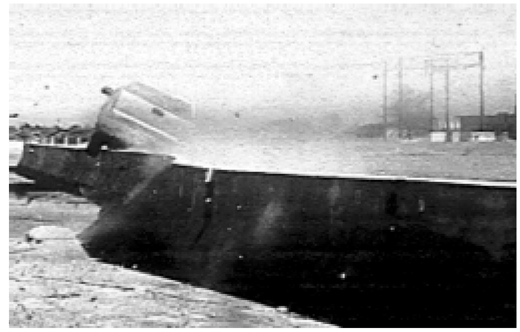
0.097 s



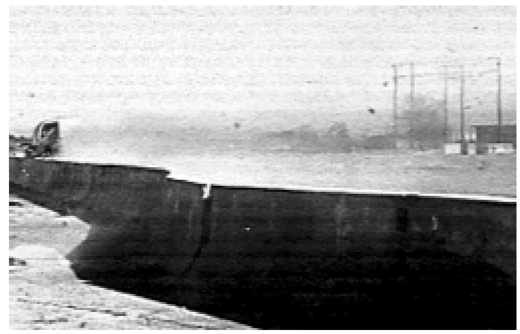
0.243 s



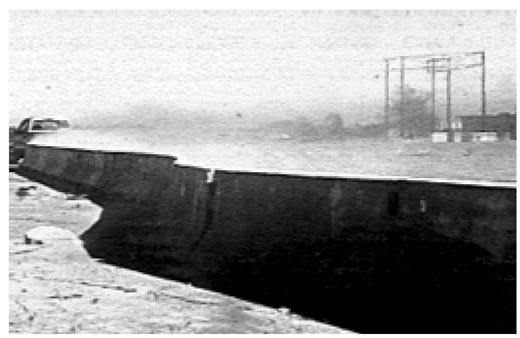
0.485 s



0.971 s



1.699 s



2.427 s

4.126 s

Figure C.2.2. Sequential photographs for test 474550-2 (rear view).

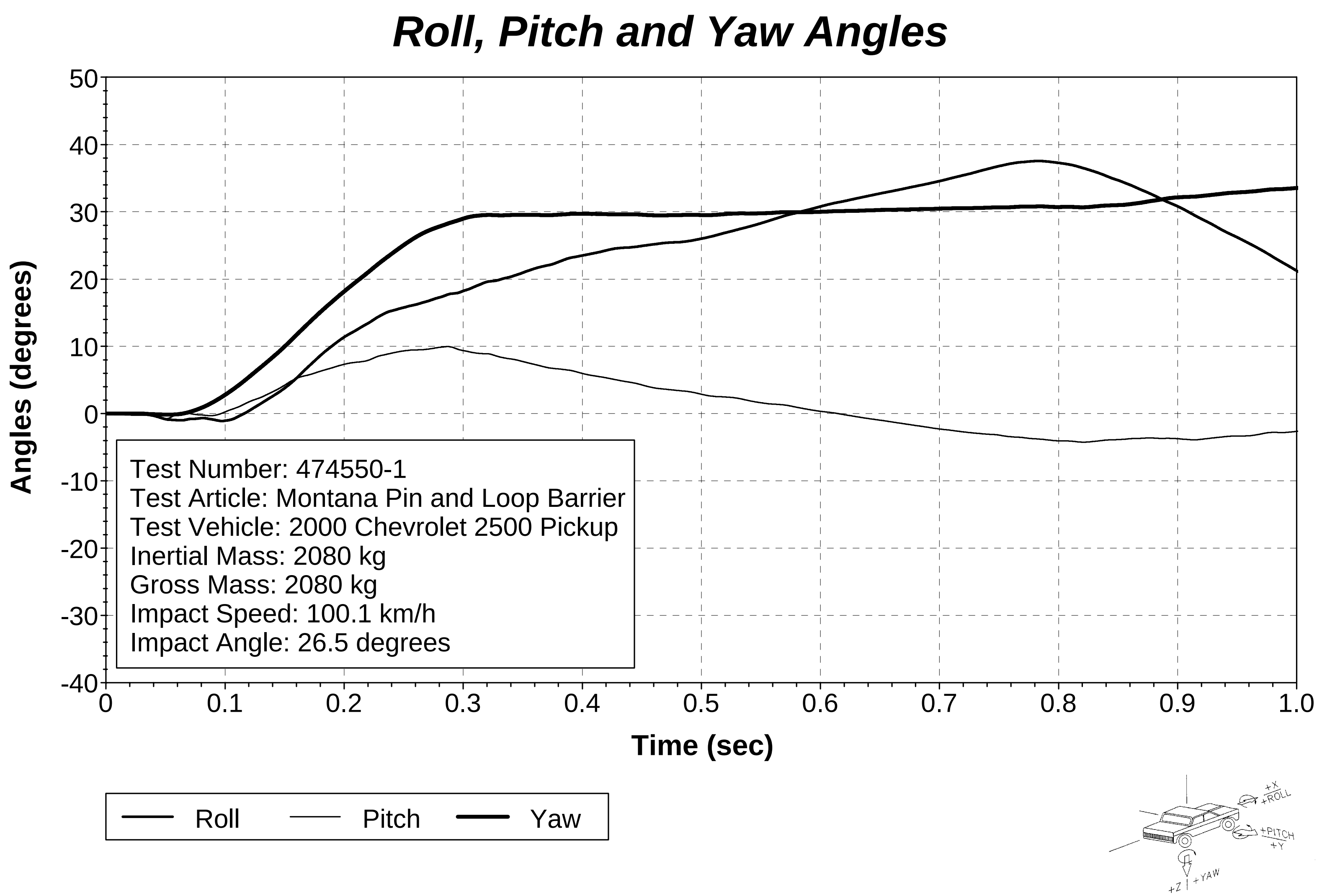


Figure D.1.1. Vehicle angular displacements for test 474550-1.

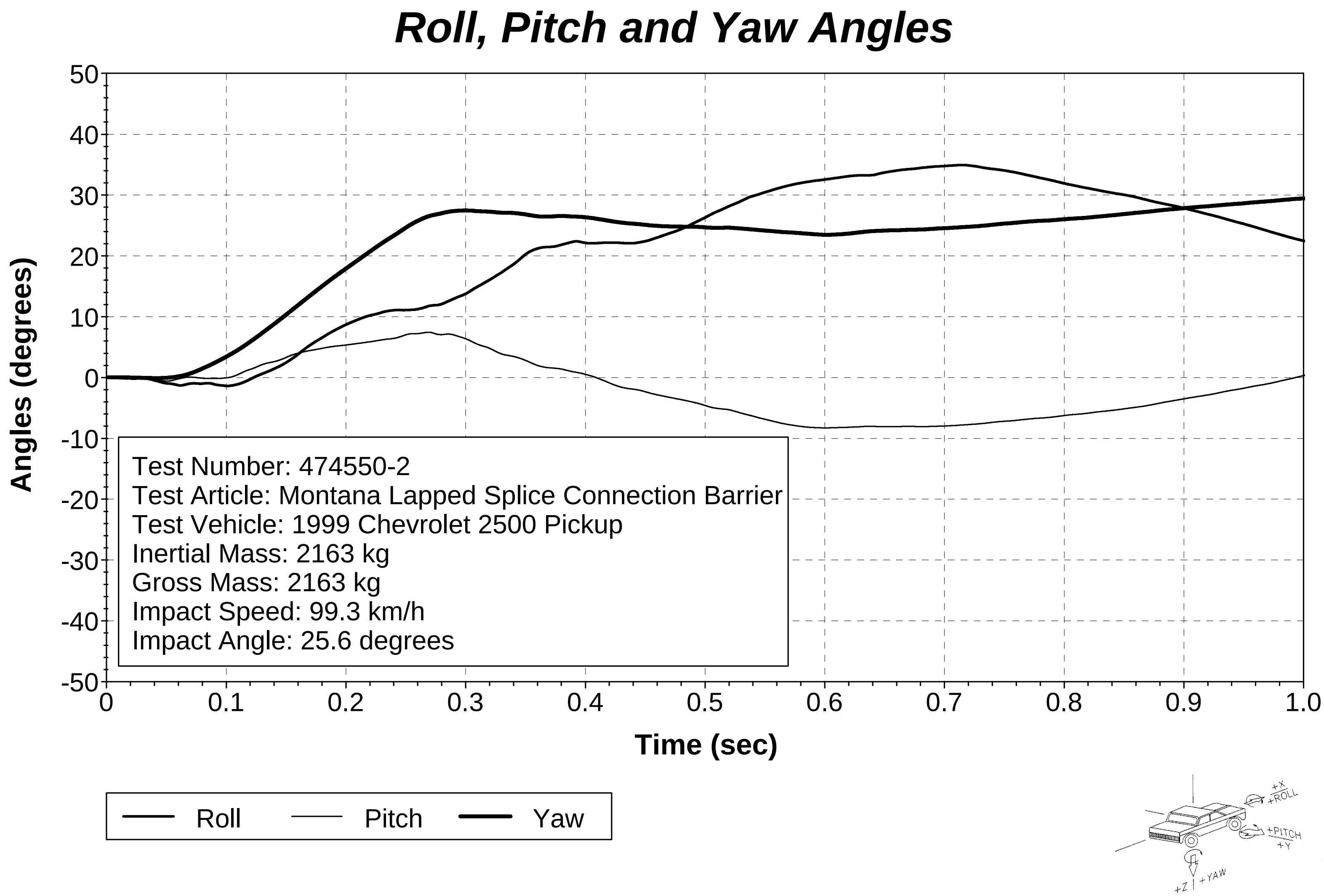


Figure D.2.1. Vehicle angular displacements for test 474550-2.

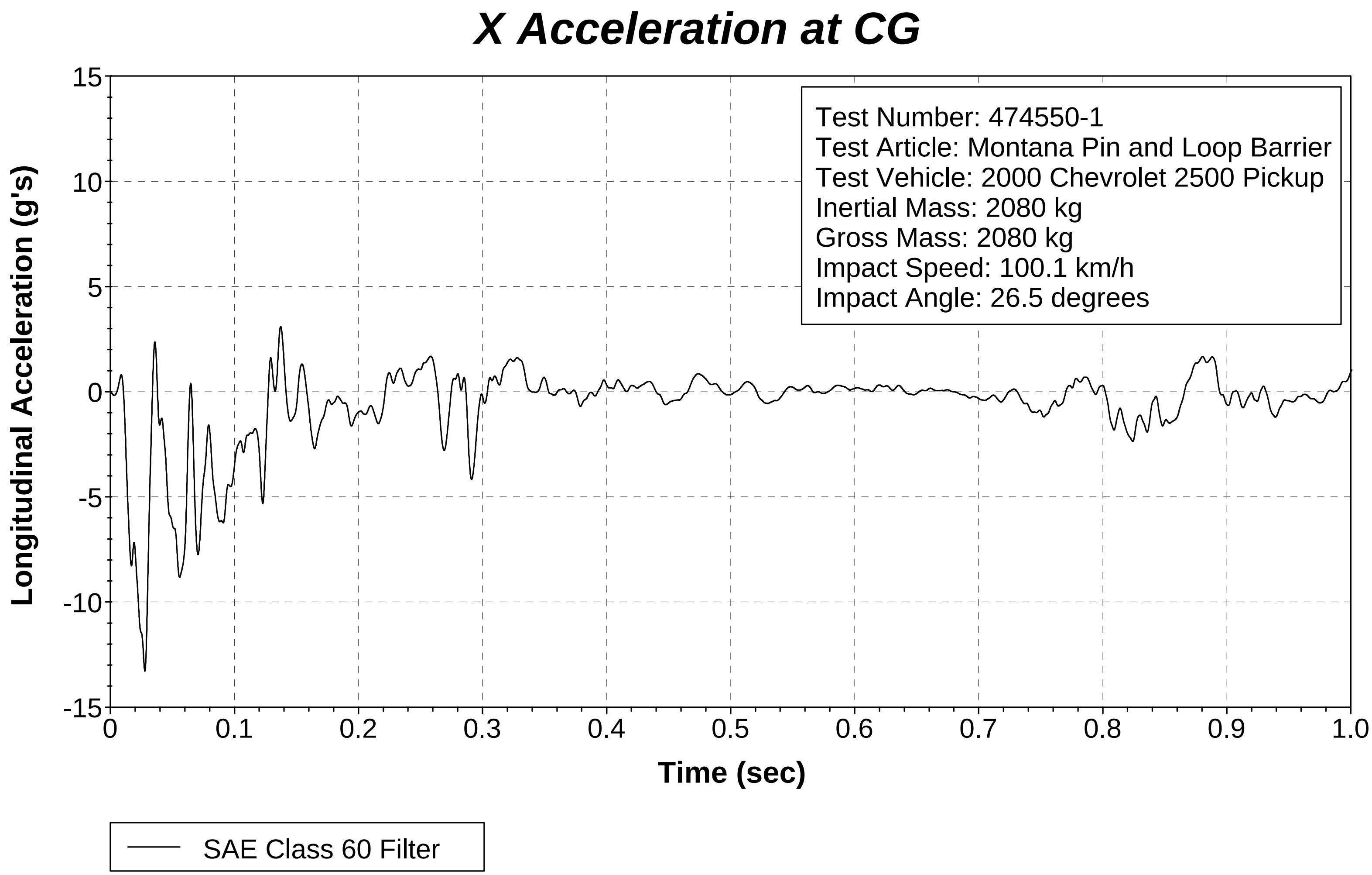


Figure E.1.1. Vehicle longitudinal accelerometer trace for test 474550-1 (accelerometer located at center of gravity).

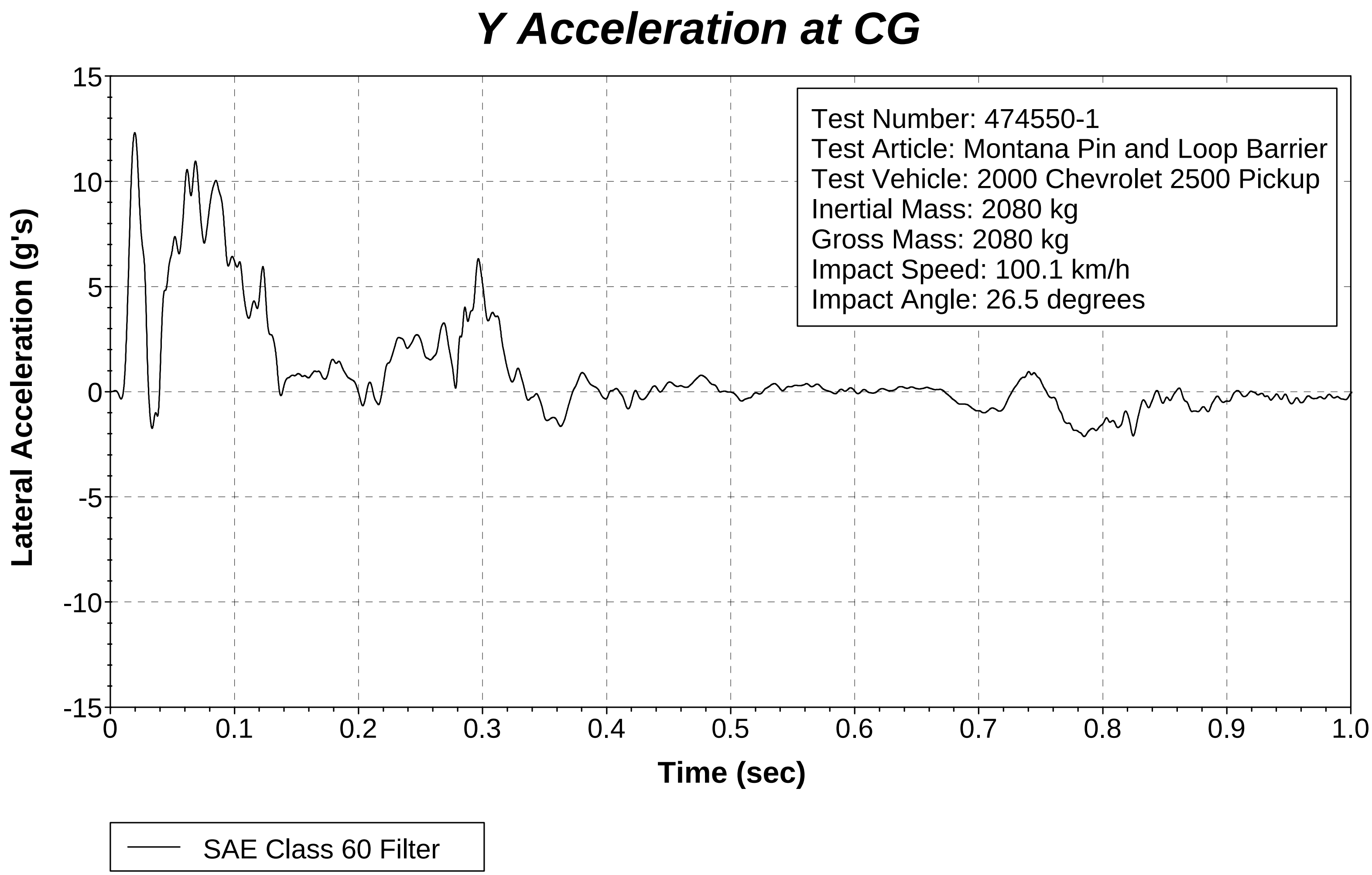


Figure E.1.2. Vehicle lateral accelerometer trace for test 474550-1 (accelerometer located at center of gravity).

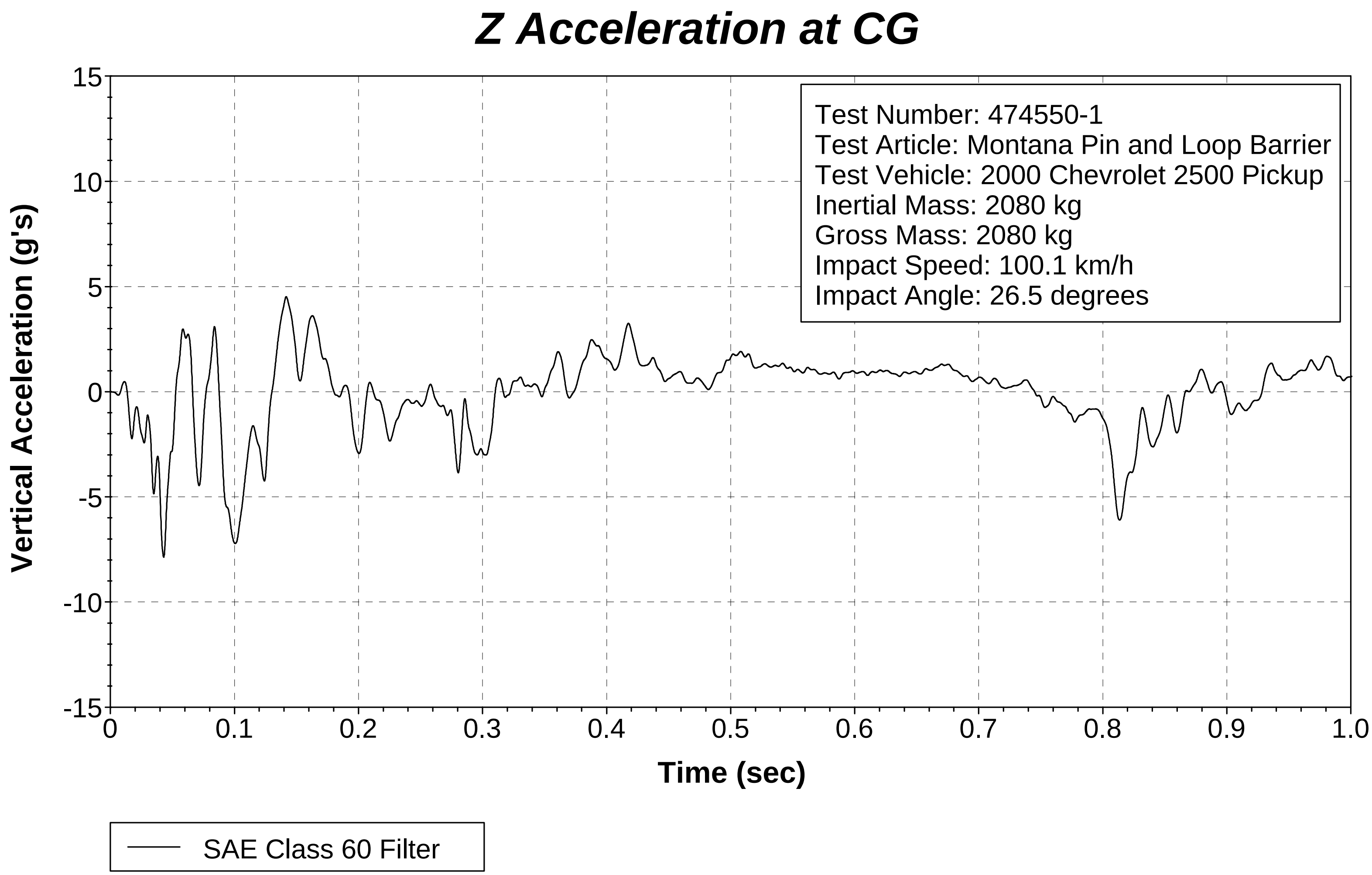


Figure E.1.3. Vehicle vertical accelerometer trace for test 474550-1 (accelerometer located at center of gravity).

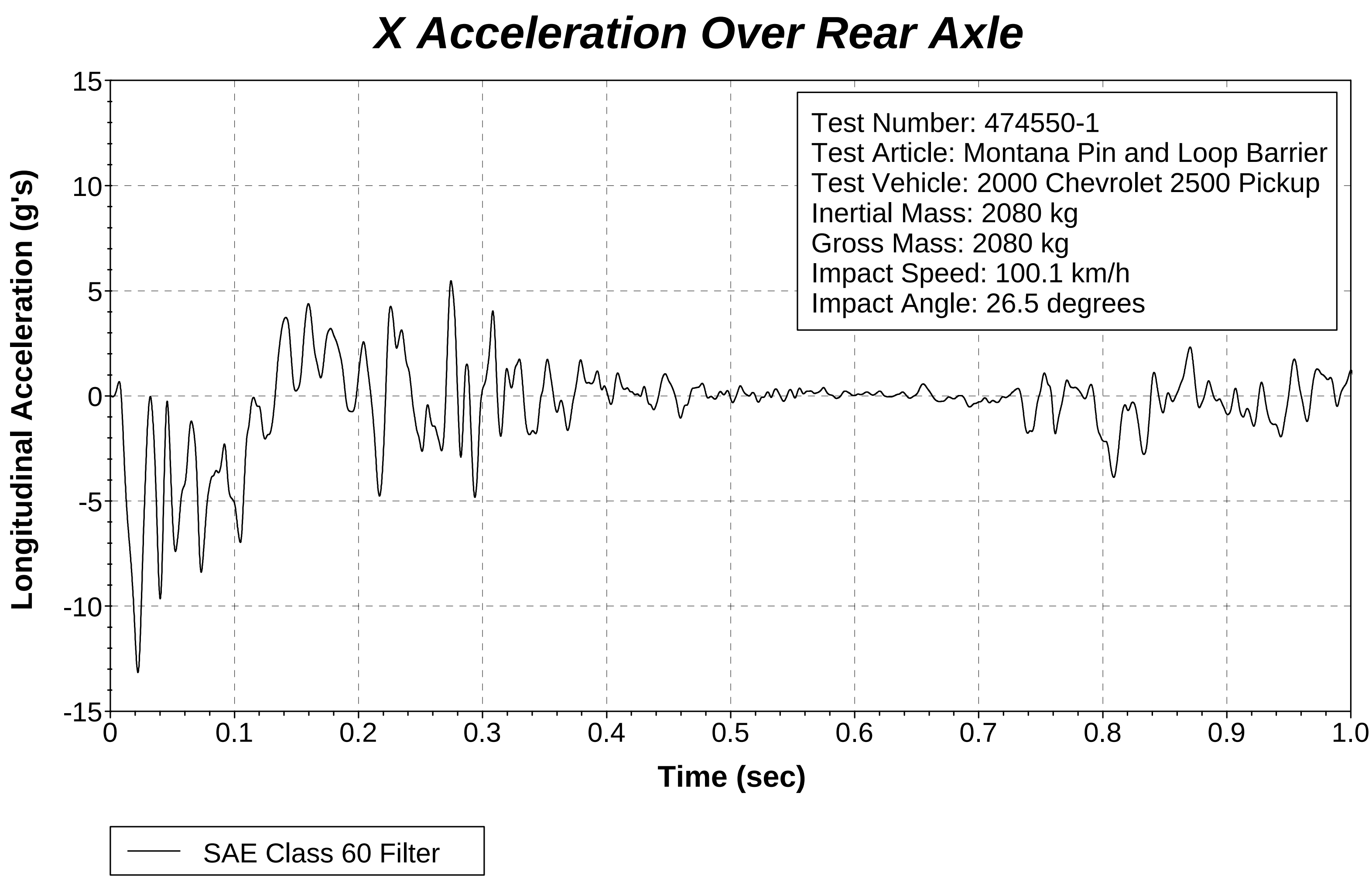


Figure E.1.4. Vehicle longitudinal accelerometer trace for test 474550-1 (accelerometer located over rear axle).

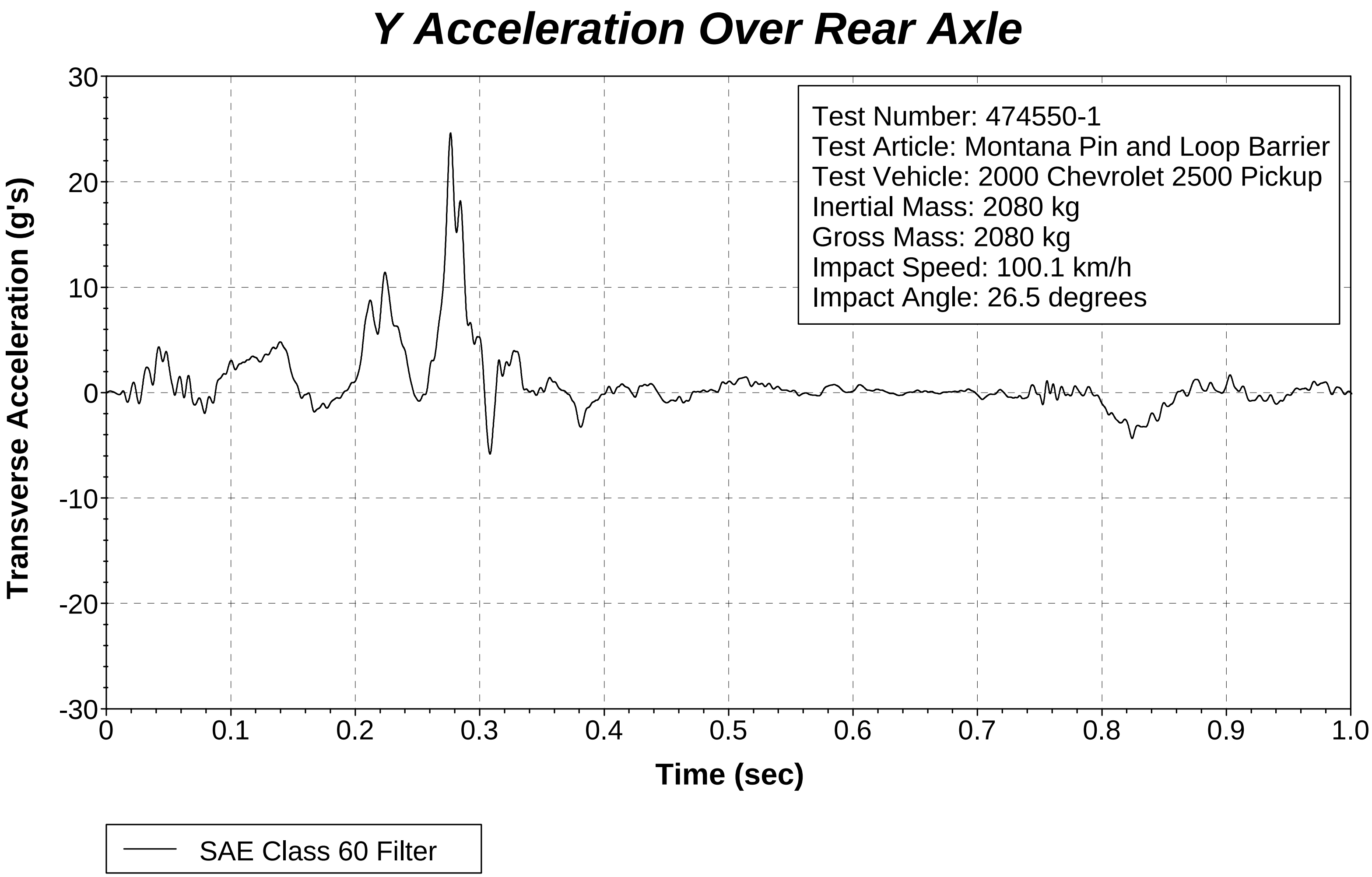


Figure E.1.5. Vehicle lateral accelerometer trace for test 474550-1 (accelerometer located over rear axle).

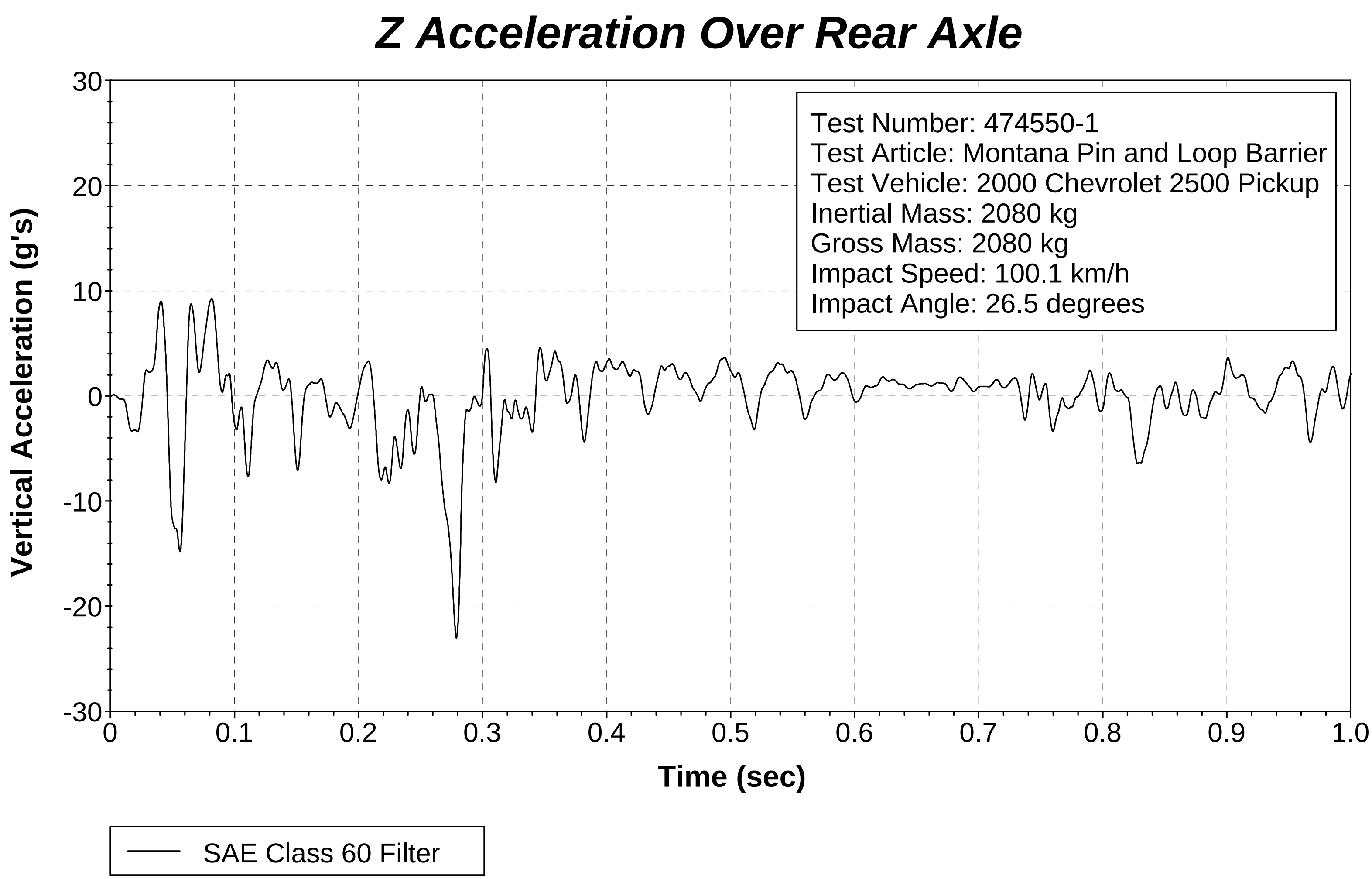


Figure E.1.6. Vehicle vertical accelerometer trace for test 474550-1 (accelerometer located over rear axle).

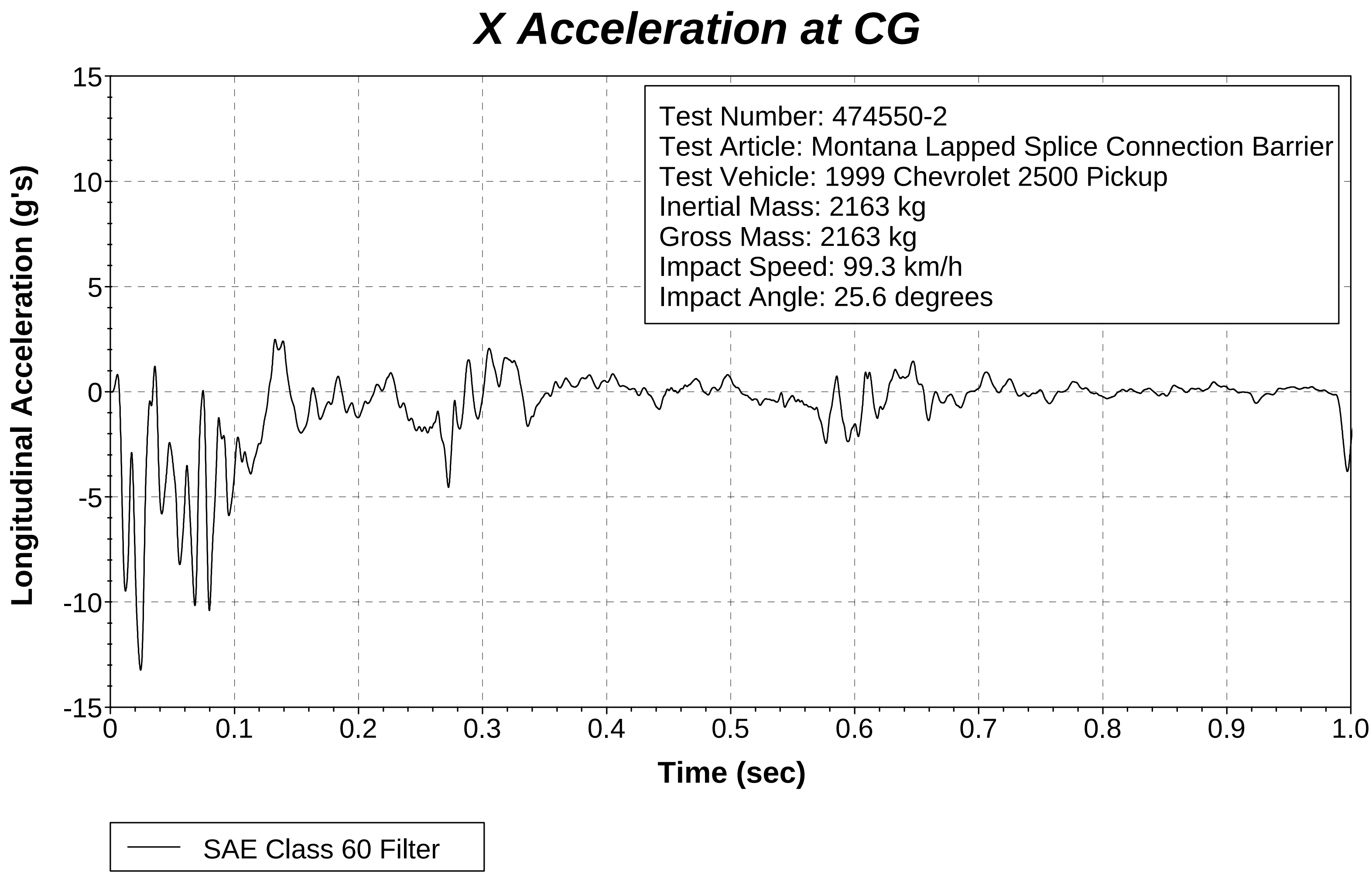


Figure E.2.1. Vehicle longitudinal accelerometer trace for test 474550-2 (accelerometer located at center of gravity).

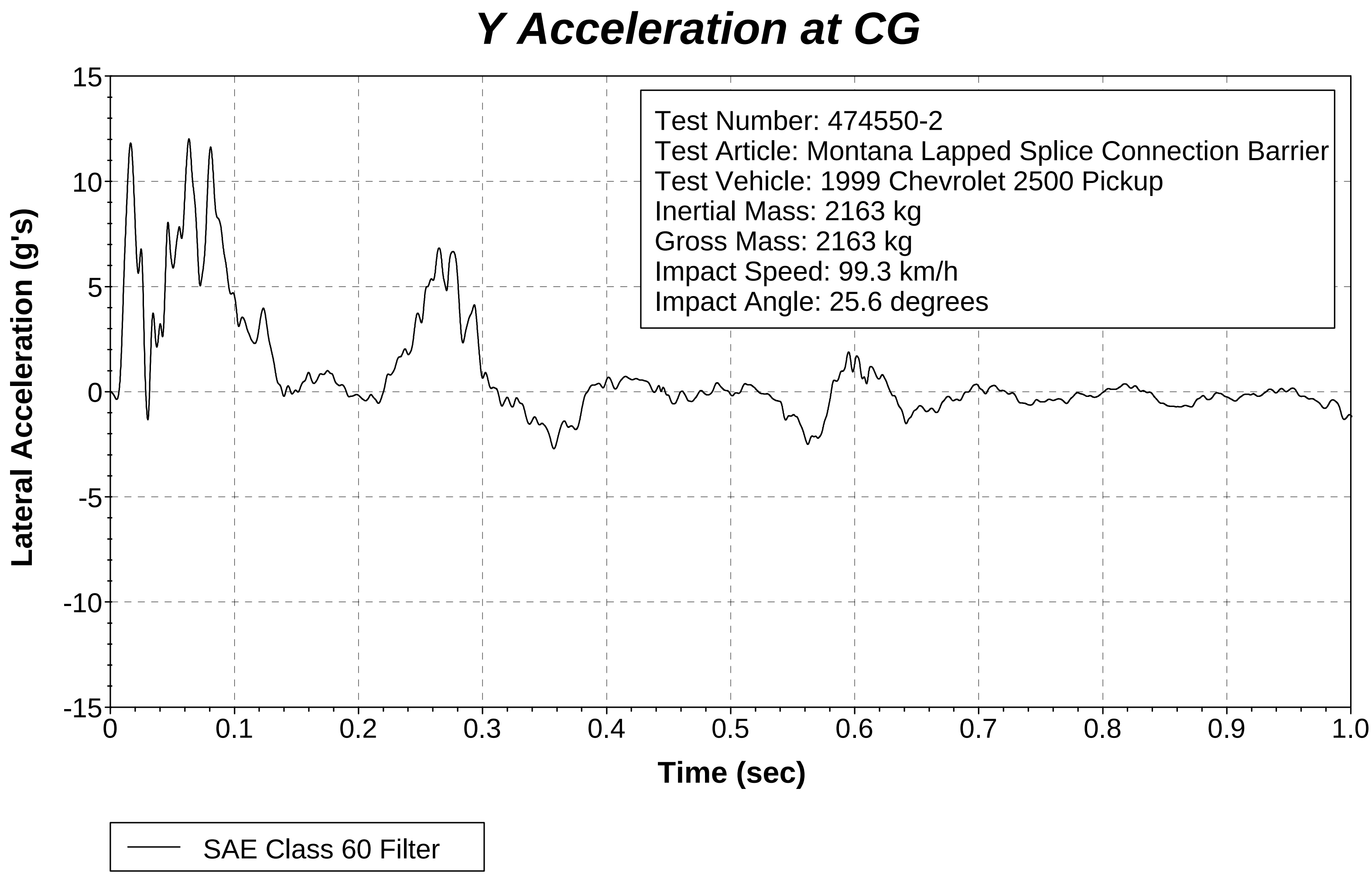


Figure E.2.2. Vehicle lateral accelerometer trace for test 474550-2 (accelerometer located at center of gravity).

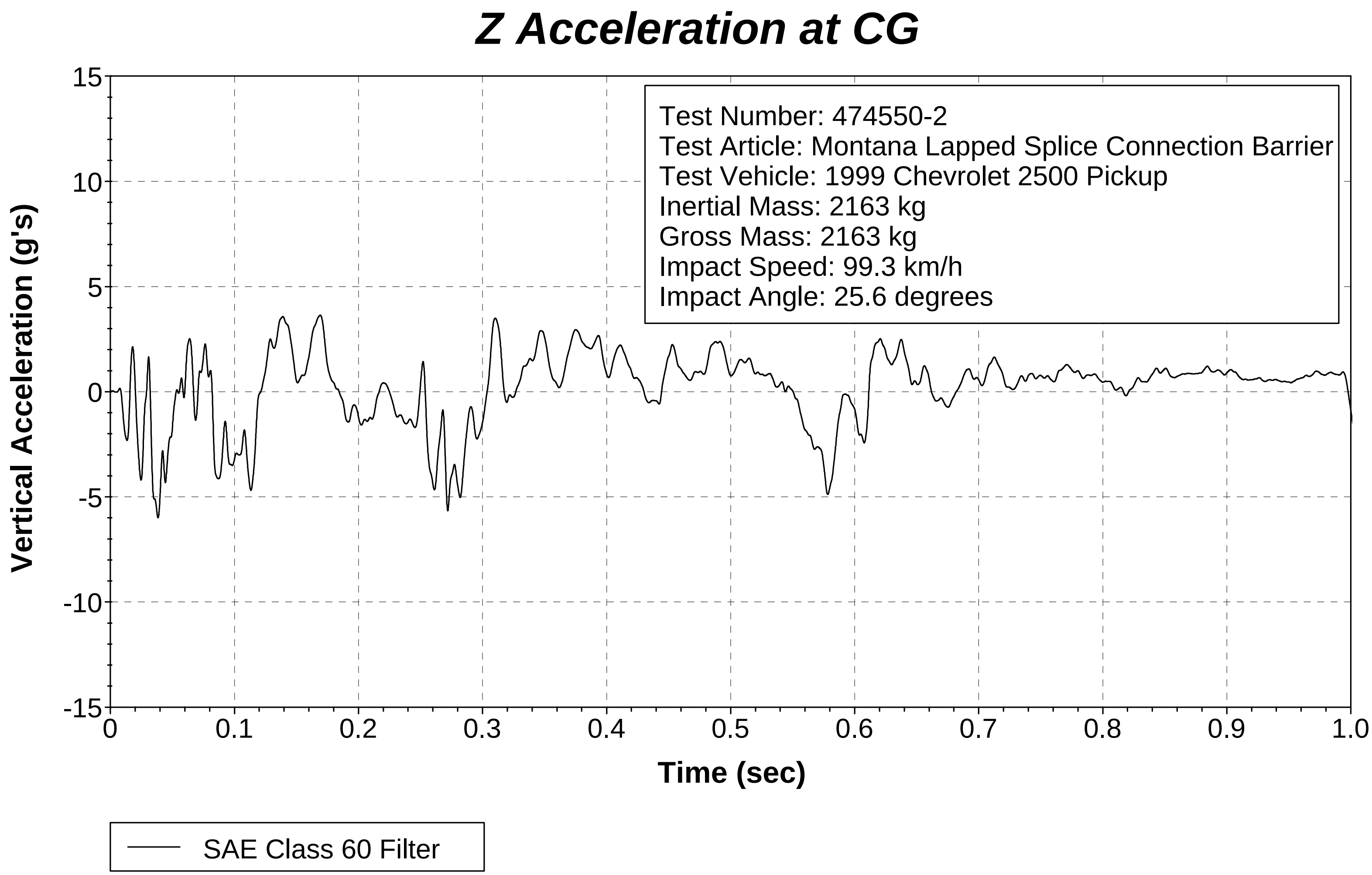


Figure E.2.3. Vehicle vertical accelerometer trace for test 474550-2 (accelerometer located at center of gravity).

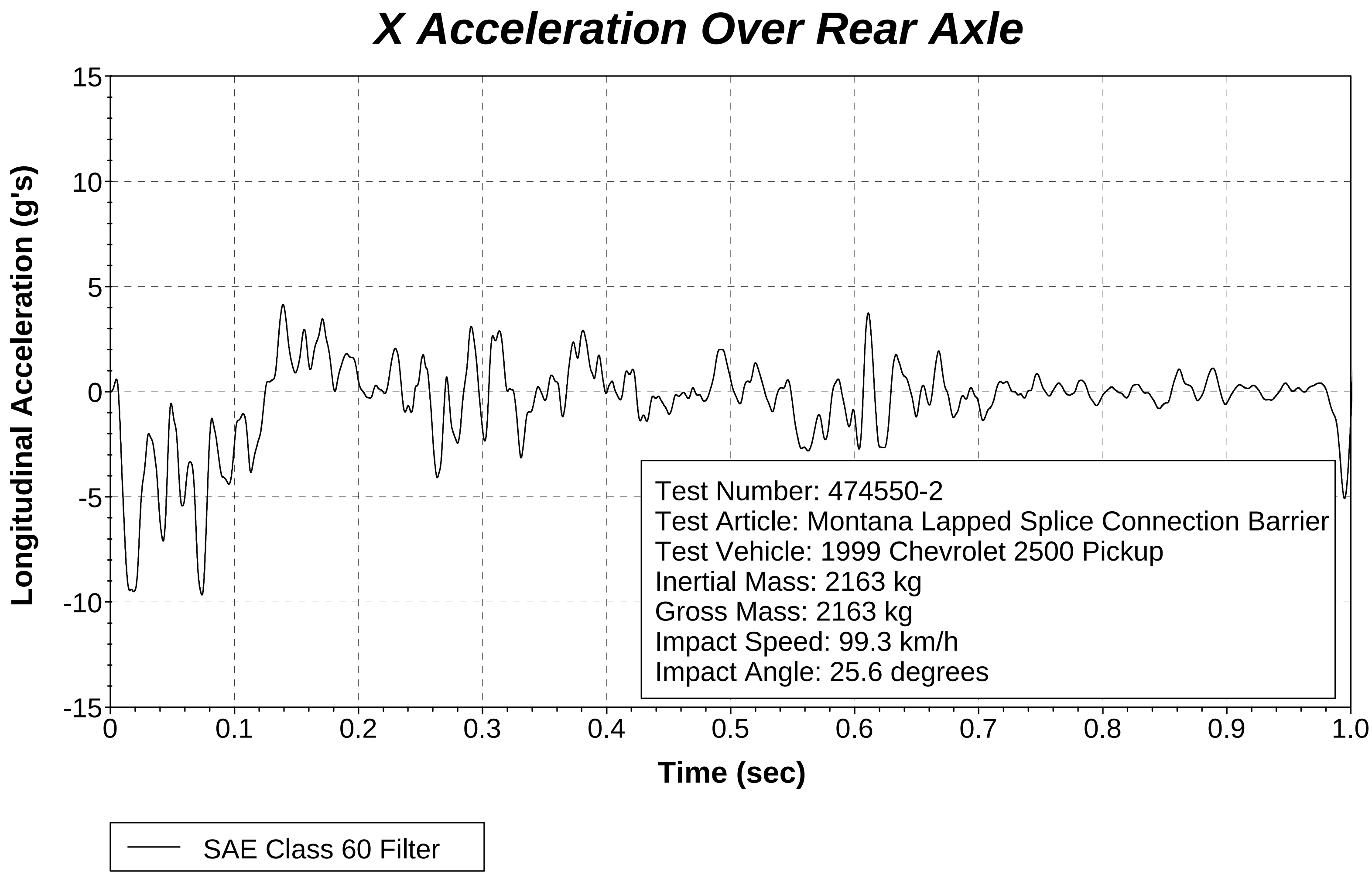


Figure E.2.4. Vehicle longitudinal accelerometer trace for test 474550-2 (accelerometer located over rear axle).

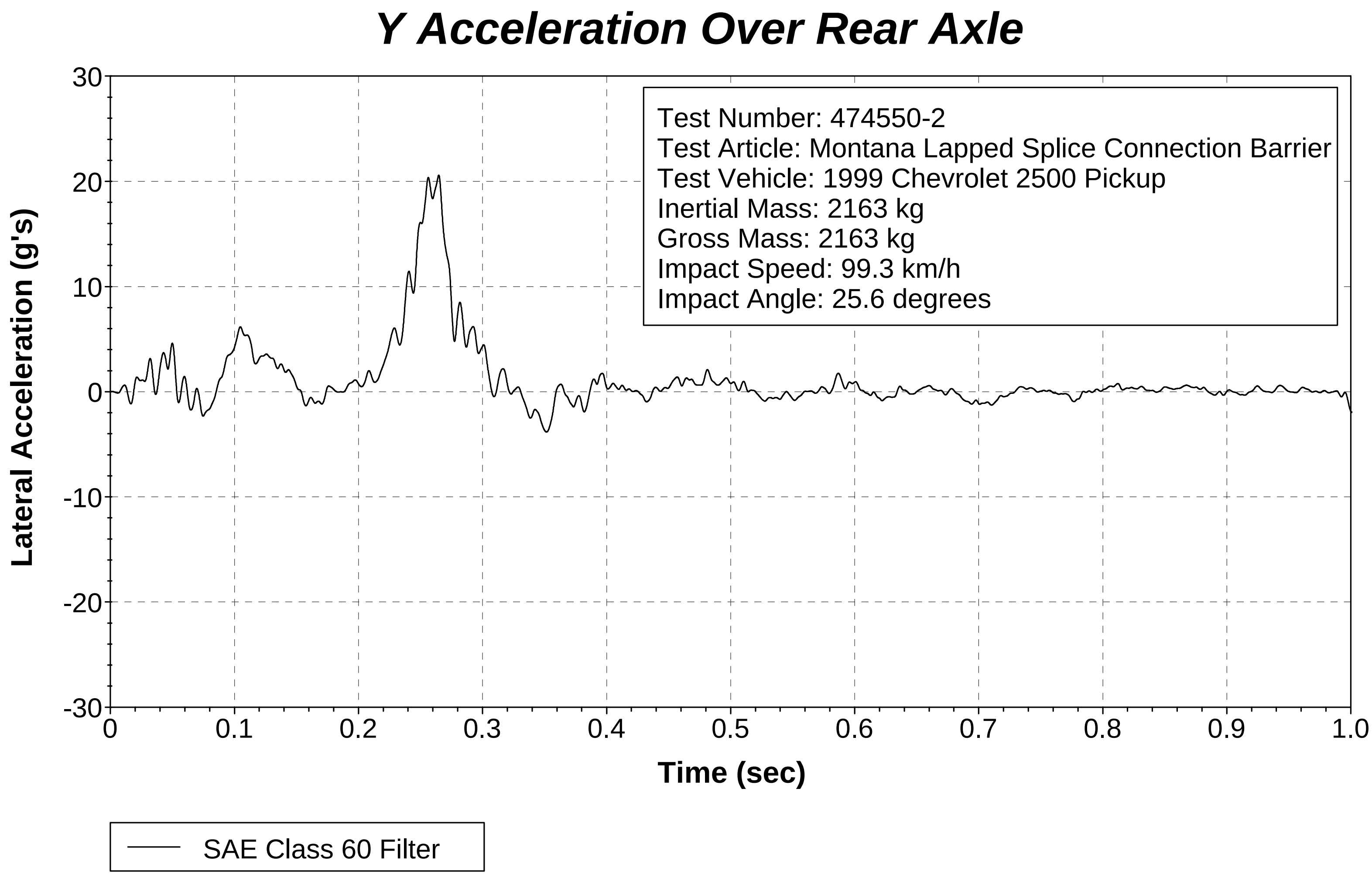


Figure E.2.5. Vehicle lateral accelerometer trace for test 474550-2 (accelerometer located over rear axle).

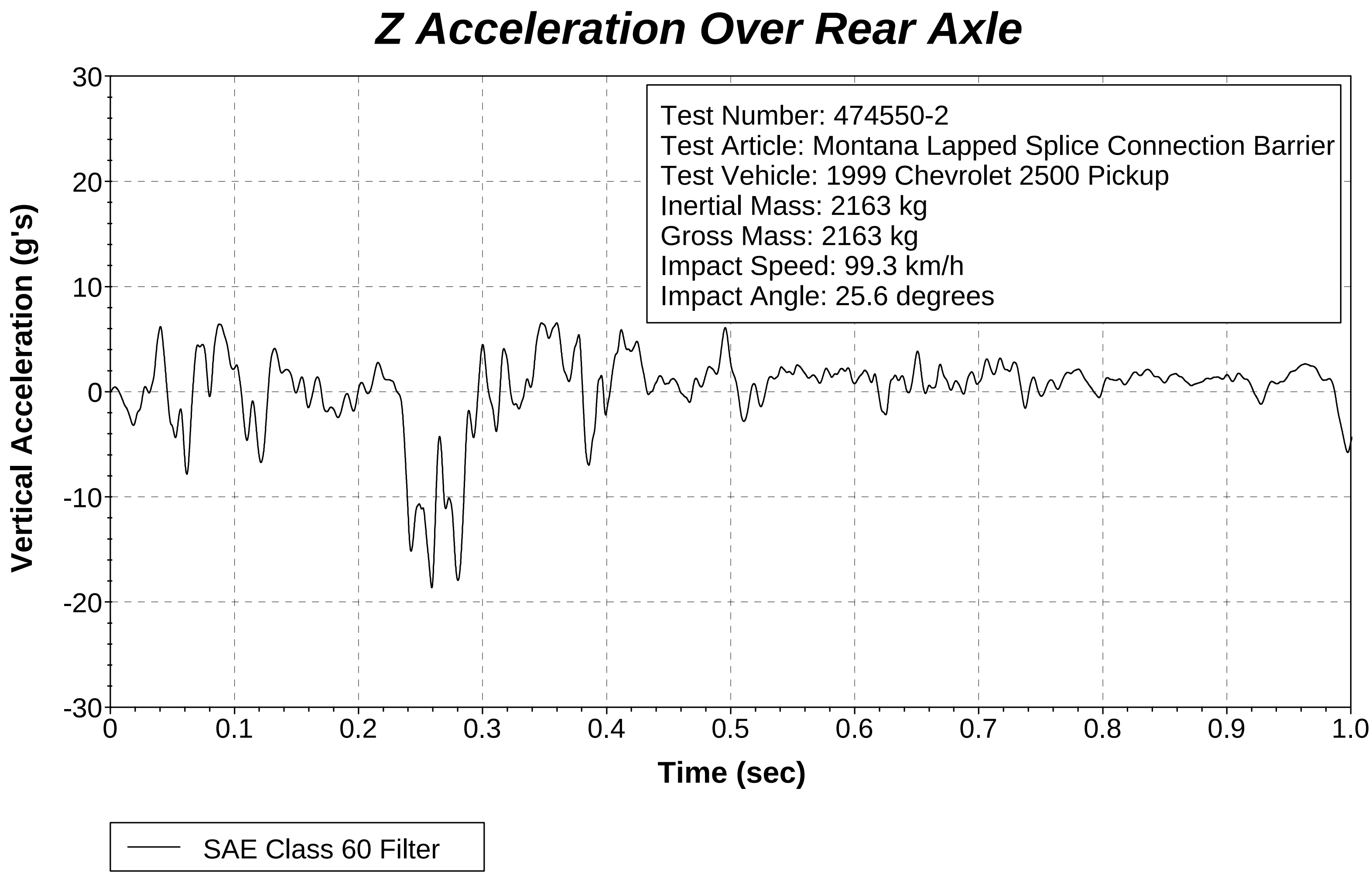


Figure E.2.6. Vehicle vertical accelerometer trace for test 474550-2 (accelerometer located over rear axle).