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16. Abstract

A new limited-slip portable concrete barrier (PCB) connection is presented in this report which allows a PCB to be attached to a concrete bridge deck or pavement. The performance of the new limited-slip barrier connection is demonstrated through full-scale crash tests. The new attachment scheme allows PCB's to be deployed immediately adjacent to a vertical drop-off with no loss of function.

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DEVELOPMENT OF A LIMITED-SLIP PORTABLE CONCRETE BARRIER CONNECTION

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Research Report 1959-1
Contract No. 7-1959, Task A

Sponsored by the
Texas Department of Transportation

November 1993

TEXAS TRANSPORTATION INSTITUTE
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IMPLEMENTATION STATEMENT

A new procedure for anchoring portable concrete barriers (PCB) to concrete pavements and bridge decks is presented in this report. The new procedure is intended to be used in situations where it is necessary to use PCB's immediately adjacent to a vertical drop-off associated with the free edge of a bridge deck or pavement. The intent of the new procedure is to allow errant vehicles to be safely redirected while at the same time keeping the PCB from being pushed over the edge of the drop-off. The new anchoring procedure is ready for immediate implementation.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was W. Lynn Beason, P.E. #55905.

ACKNOWLEDGMENTS

This research study was conducted under the sponsorship of TxDOT. Working closely with the Texas Transportation Institute researchers were Mark A. Marek, John J. Panak, Van M. McElroy, and William D. Dillon. Their comments, suggestions, and cooperative spirit were appreciated.

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SUMMARY

Past experience regarding the performance of portable concrete barriers (PCB's) suggests that barriers which are not attached to the supporting surface experience significant lateral displacements during the impact of an errant vehicle. This observation caused TxDOT engineers to question whether it was acceptable to deploy PCB's immediately adjacent to vertical drop offs. This report presents results relating to the performance of PCB's which are installed immediately adjacent to a vertical drop off.

Results of full-scale crash tests presented in this report show that unattached PCB's deployed next to vertical drop-offs are capable of redirecting errant vehicles. However, the PCB's appear to be easily knocked over the edge of the vertical drop-off. This situation was judged to be unacceptable.

A significant effort was expended to develop a method to attach PCB's to bridge decks and/or concrete pavements with four steel pins which are inserted into holes drilled through each PCB involved in the barrier deployment. The pins go through the PCB and into holes drilled in the underlying bridge deck or pavement. The connection thus developed is referred to as the limited-slip PCB connection.

Results of two full-scale crash tests show that PCB's which are connected to underlying concrete pavements or bridge decks with the new limited-slip connection are capable of redirecting a 4,500-lb (2,043-kg) 3/4-ton pickup impacting at an angle of 25 degrees with a speed of 62.1 mph (100 km/h). The vehicles involved in this test were successfully redirected, and the PCB was not knocked over the edged of the vertical drop-off. Based on this, the limited-slip PCB connection is recommended for immediate use.

INTRODUCTION

Over the past years, several different types of longitudinal barriers have been developed which are based on the general shape of the popular New Jersey concrete barriers. Such barriers have gained widespread acceptance throughout the United States. These barriers include bridge rails and portable barriers as well as other permanent barriers.

This report focuses on the use of portable concrete barriers (PCB's) used in temporary work zones where it is necessary to position the barrier immediately adjacent to a vertical drop-off. In this situation, there is no space behind the barrier to allow for lateral displacement during the impact of an errant vehicle. The discussion is limited to the performance of two different types of PCB's which are commonly used by the Texas Department of Transportation (TxDOT). The barrier types under evaluation employ the popular New Jersey safety shape and are classified according to the type of barrier connection used. The two types of connections investigated were the grid slot connection and the channel/angle splice connection. In both cases the barrier sections are typically manufactured in 30 ft (9.1 m) barrier lengths.

Evaluation of full-scale crash test data associated with PCB's suggest that these barriers typically experience lateral deflections of approximately 2 ft (.61 m) when subjected to the impact of a 4,500 lb (2,043 kg) full-size automobile traveling at a speed of 60 mph (96.6 km/h) and impacting with an angle of 25 degrees. This amount of lateral displacement presents no apparent problems for the errant vehicle if the barrier system is located on a flat, level surface with unlimited room for lateral displacement. However, TxDOT engineers felt that there was potential for a problem if portable barriers were positioned along the edge of a pavement or bridge deck immediately adjacent to a vertical drop-off.

Researchers at the Texas Transportation Institute were contacted by TxDOT engineers to render a preliminary opinion regarding potential problems associated with the use of a PCB deployed next to a vertical drop-off. It was reported to TxDOT that the results of approximate analyses suggested that there was indeed potential for a problem involving either penetration of an errant vehicle or the dislocation of the PCB over the edge of the vertical drop-off. Based on this response, TxDOT decided to initiate an effort to determine if there is a real problem and to recommend steps to deal with the problem if it exists.

It should be noted that there were extremely tight time constraints placed on TTI researchers by TxDOT because it was necessary to have a solution to this problem as quickly as possible to prevent construction delays on a particular project that was in progress. Therefore, it was necessary to rely heavily on engineering and approximate analyses so that the project could proceed quickly to the crash testing phase and not throw the planned construction project off schedule. There was no time for the usual computer studies and extensive evaluation of the situation.

The remainder of this report is divided into three major sections. The first section presents a discussion of the development of a new technique for attaching a PCB to an unreinforced concrete pavement or bridge deck so that the lateral displacement of the barrier system will be limited during the impact of an errant vehicle. This is followed by a discussion of the results of five crash tests which were intended to explore the limits of performance of portable barrier segments which are deployed next to vertical drop-offs. These tests involved the evaluation of the performance of unattached portable barriers and portable barriers which were attached using a newly developed attachment technique. The final section of this report presents conclusions and recommendations for the use of PCB's next to vertical drop-offs.

DEVELOPMENT OF A LIMITED-SLIP PCB CONNECTION

The objective of the proposed research was to identify and demonstrate an acceptable procedure for the use of PCB's immediately adjacent to a vertical drop-off on a concrete pavement or bridge deck. It was not clear at the outset of the project whether it would be necessary to develop a new limited-slip attachment scheme or whether an unmodified PCB could perform the required function. All involved in the project felt that there was a chance that an unanchored PCB which incorporates a channel/angle splice connection could serve the intended function. This would clearly provide the most economical solution to the problem if it would work. Therefore, an unanchored PCB was to be tested before the project was complete.

While it was felt that the cost of a crash test was justifiable to determine if an unmodified PCB could be used, all involved recognized that there was significant probability that an unanchored system would not work. Therefore, a major effort was focused on the development of a limited-slip attachment scheme for PCB's in case the performance of the unanchored PCB's was not acceptable. Development of the limited-slip barrier connection was begun immediately upon confirmation of the proposed project so that no time would be lost if the unattached PCB was able to perform.

The remainder of this section is devoted to a discussion of the development of a limited-slip PCB connection procedure which would allow the barrier to be placed on the edge of a pavement immediately adjacent to a vertical drop-off. The PCB should also be able to successfully redirect an errant vehicle without being knocked off of the edge of the pavement.

The basic constraints issued by TxDOT engineers were that the system had to be developed on a very tight schedule with almost no margin for mistakes. The system developed had to employ standard TxDOT PCB sections since there was no time for a new system to be fabricated. Modifications to the pavement could not involve holes drilled completely through the pavement or positive attachments to the concrete pavement. Because of the consequences associated with a vehicle exiting the roadway with a large vertical drop-off, the portable barrier had to be able to provide a level of protection consistent with permanent barrier installations. Finally, because there was almost no tolerance for lost time due to mistakes, all major decisions in the project had to be confirmed by an *ad hoc* committee which consisted of knowledgeable engineers and researchers from TxDOT and TTI.

There are few potential attachment concepts that would be consistent with the constraints discussed above. A meeting of the *ad hoc* committee resulted in the selection of a single concept which all members of the committee felt would have a reasonable chance of success. Researchers at TTI then initiated a major effort to refine the concept as discussed below.

The limited-slip barrier attachment concept selected for development involved the modification of each 30-ft (9.1 m) PCB segment so that four 1 1/4-in. (3.18 cm) steel pins could be inserted into holes drilled through the PCB and into holes drilled partially through the concrete pavement. The diameters of the steel pins were selected on the assumption that the impact force would be resisted by two pins. The holes drilled through the barrier segments and into the concrete pavement were 1 3/8-in. (3.49 cm) diameter so that the 1 1/4-in. (3.18 cm) diameter steel pins could be easily inserted.

The 1 3/8-in. (3.49 cm) diameter holes were drilled through the barrier segment and into the concrete pavement at controlled angles as shown in Figure 1. The purpose of drilling the holes at an angle was to provide a vertical reaction between the pin and barrier so that the overturning moment associated with the impact force could be resisted more effectively than would be the case if the holes were drilled vertically. The smaller the angle of the hole with respect to the horizontal, the greater the resistance to overturning. In addition, the smaller the angle, the greater the area of PCB concrete available to resist the impact force. However, the smaller the pin angle, the less bridge deck or pavement concrete area was available to resist the impact force. Therefore, a strength trade-off had to be considered in determining the pin angle. Approximate analyses were used to select as large an angle as possible, given the stated performance requirements.

The entry point for each pin hole on the barrier face was selected to be 6 1/2 in. (16.5 cm) up from the first break of the impact face of the barrier as shown in Figure 1. In the first crash test discussed later in this report, the angle between the centerline of the hole and the horizontal plane was set at 53.1 degrees. This angle corresponds to a 3-4-5 slope. Based on a questionable outcome in the first test, the situation was re-evaluated, and the

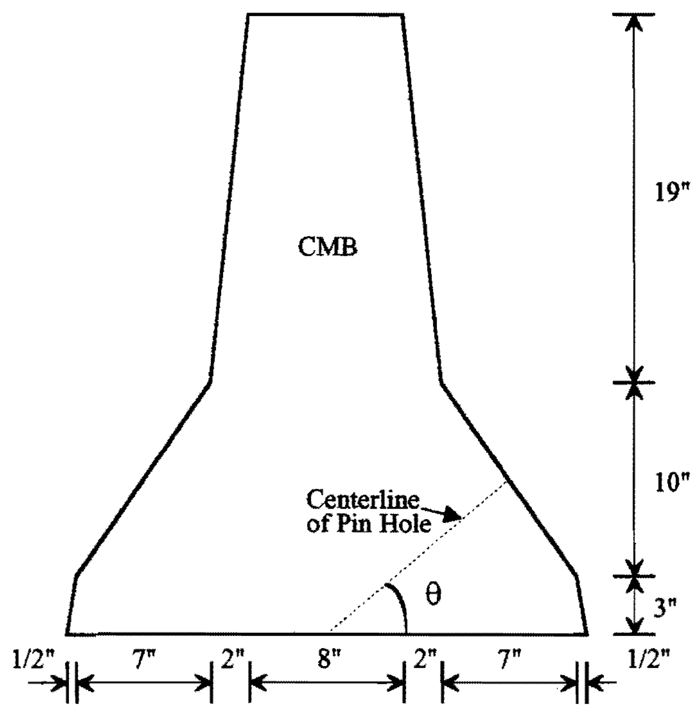


Figure 1. Schematic of steel pin location.

angle of the pin holes was reduced to 40.1 degrees with respect to the horizontal axis. Based on crash test results discussed later in this report, it became clear that the reduction of the angle marginally improved the performance of the PCB system. However, in retrospect, we believe that minor variations in the angle of the pins which will be inherent in the fabrication process will not have a major influence on the performance of the barrier.

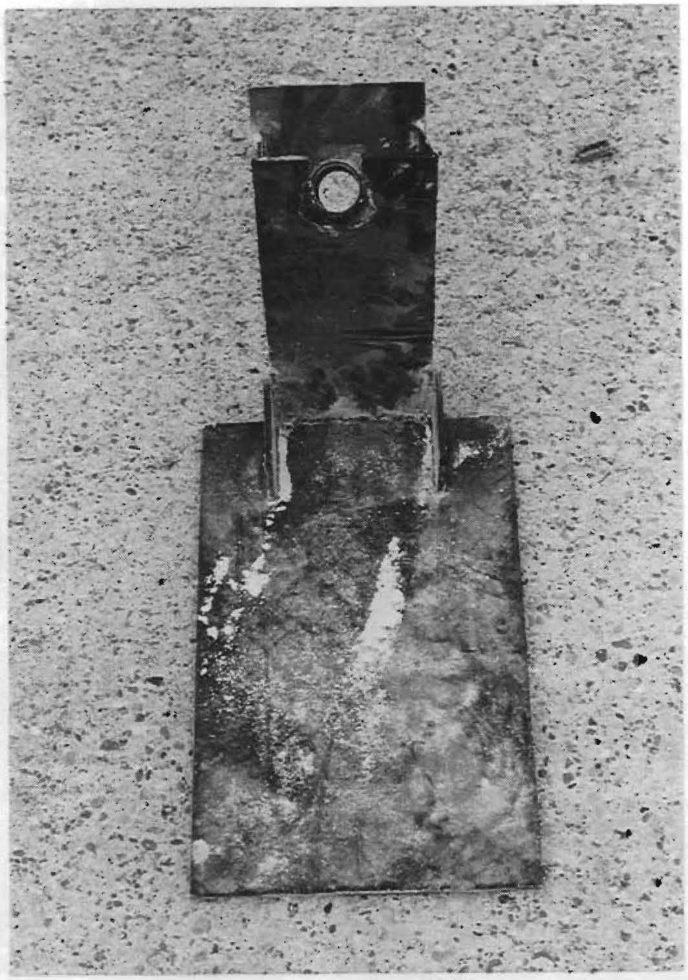
Four holes were drilled in each 30-ft (9.14 m) PCB barrier section. The precise spacing of the holes is not considered to be critical to the performance of the system because of the lateral stiffness associated with the PCB barrier section. All that is required is that each barrier segment be pinned to the pavement with four 1 1/4-in.(3.18 cm) steel pins spaced relatively evenly along the length of the barrier. The two outer holes were spaced approximately 5 ft (1.52 m) from the ends of the barrier segments in the current project with the other two holes spaced evenly between the two outer holes. The precise longitudinal hole spacing in a given situation will depend upon the spacing of the reinforcing bar. Once the contractor begins to drill holes, he should be able to quickly identify a hole spacing that will work for his particular barrier segments.

The general procedure developed to modify and install the PCB on a pavement section involves three major steps:

1. The PCB's must be drilled,
2. The drilled PCB's must be transported to the deployment site and positioned as desired,
3. The pavement must be drilled to accommodate the steel pins, and
4. The steel pins must be inserted to fix the PCB in place.

Each of these steps is discussed below.

The most difficult part of the modification procedure was drilling the holes through the PCB at the angles specified. To aid in this process, a specialized steel drill guide was fabricated. Figure 2 presents two photographs of the steel drill guide. As shown, the drill guide consists of a steel tube which is fixed into the proper position with a steel frame. The steel frame is welded to a horizontal foot plate which rests on the pavement. The procedure used was to place the steel drill guide against the barrier face and to secure it in place with the weight of the drill operator as shown in Figure 3. Then, the drill operator inserted the drill bit through the guide and drilled the hole as shown in Figure 3. Occasionally during



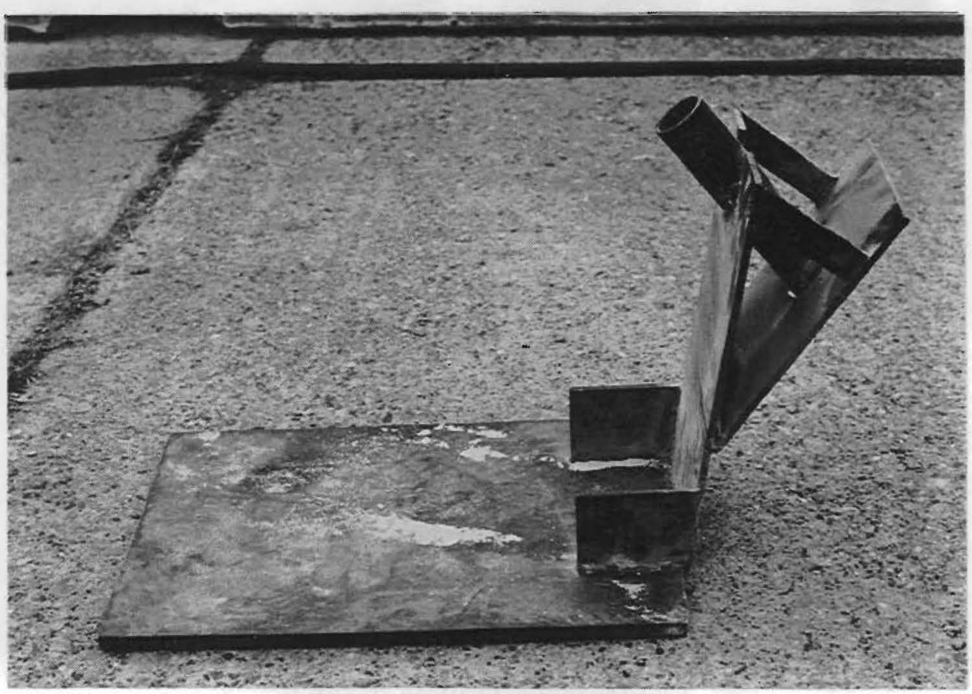


Figure 2. Steel drill guide.

Figure 3. Drilling of PCB.

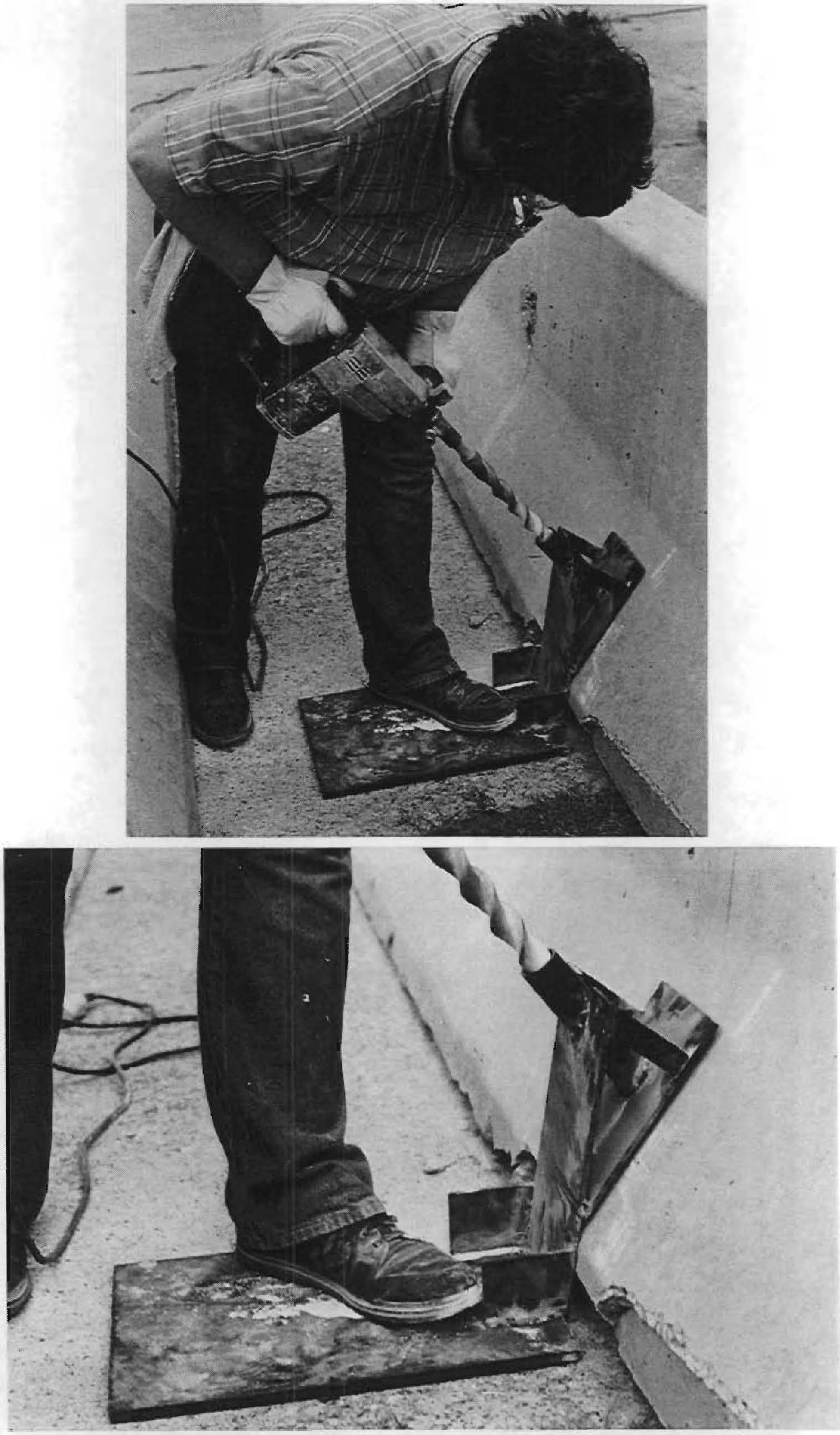


Figure 3. Drilling of PCB.

this process, the drill bit struck a reinforcing bar. When this happened, the hole was abandoned, and the drilling operation was moved about 6 in. (15.24 cm) to the left or right where a new hole was started.

Once the holes were drilled, the barrier segments were ready to be transported to the deployment site and set into place. In the crash tests conducted during this project, the barriers were placed flush with the edge of an unreinforced concrete pavement.

Once the barrier segments were set into place, the predrilled holes in the barrier segments were used as a guide for drilling holes into the underlying pavement. The depth of penetration of the drill bit into the underlying pavement was controlled by limiting the depth of penetration of the drill bit to 21 in. (53.3 cm). By limiting the depth of penetration of the drill bit to 21 in. (53.3 cm), vertical penetration into the underlying pavement was limited to a depth slightly in excess of 5 in. (12.7 cm), depending on the flatness of the pavement. Thus, typical bridge decks would not be penetrated by this operation. Figure 4 presents two photographs of a technician simulating the final drilling operation.

Once the bridge deck holes were drilled, compressed air was used to clean the concrete powder from the holes so that the steel pins could be fully inserted. Then the barriers were fastened into place by inserting 20 1/2-in. (52.1 cm) long steel pins through the holes in the PCB sections and into the concrete pavement.

Complete details of the final limited-slip PCB connection scheme are presented in Appendix A.

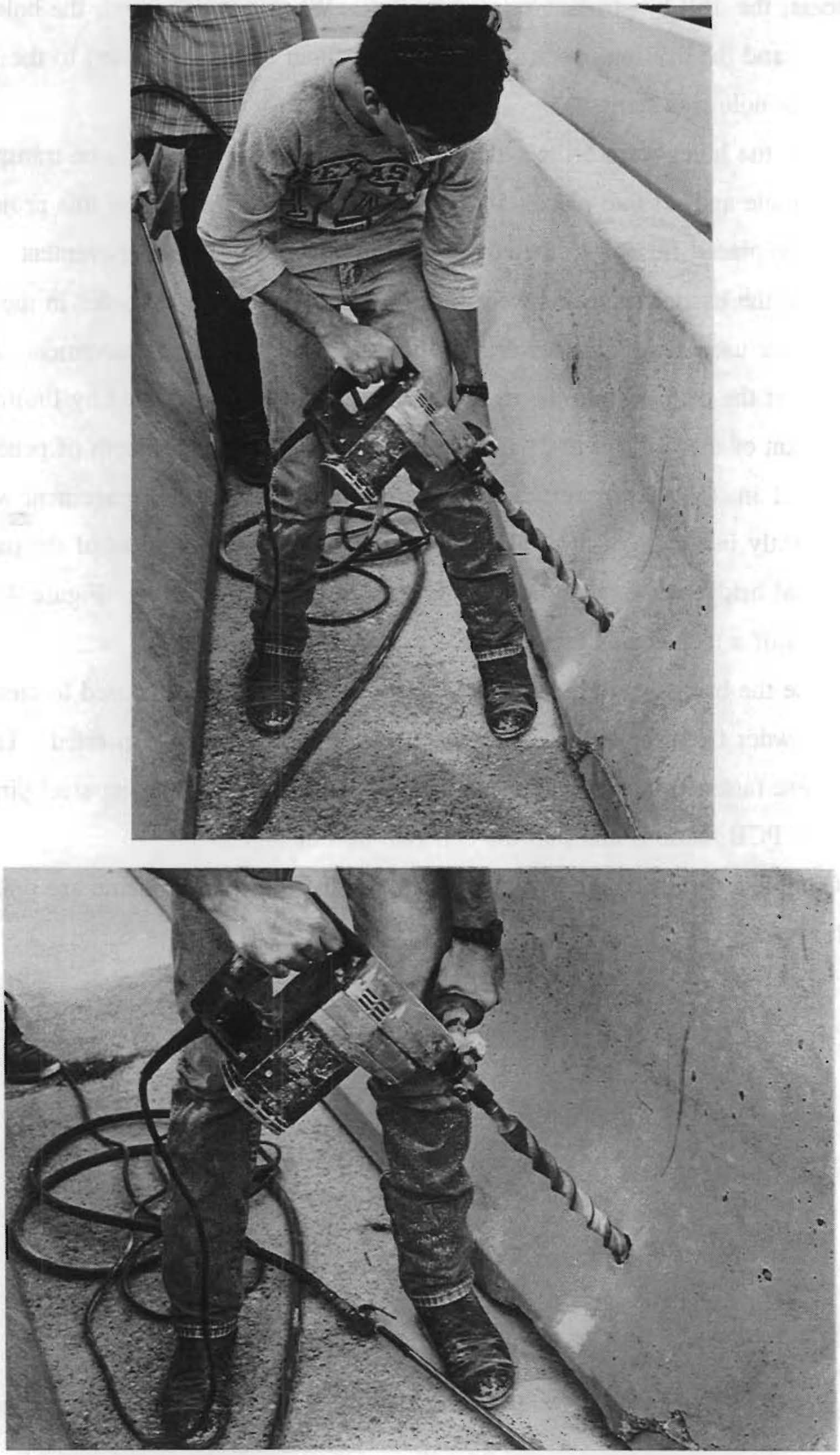


Figure 4. Drilling of pavement.

FULL-SCALE CRASH TESTS

There is sufficient information available in the literature to understand the general performance of PCB's with respect to occupant risk and vehicle stability. Therefore, there was no reason to retest the PCB's to demonstrate that the general performance characteristics associated with the New Jersey safety shape are acceptable. The only question to be answered in the current research was whether or not a PCB deployed along the edge of a vertical drop-off is structurally capable of successfully redirecting an errant vehicle without being pushed over the edge by the force of the impact.

Because of the consequences associated with failure of the system, the *ad hoc* research committee decided that this portable barrier deployment should be tested to the full strength requirements for a permanent longitudinal barrier. The criteria in effect at the time of the project were the criteria presented in NCHRP 230. The NCHRP 230 strength test requires that permanent longitudinal barriers be capable of being subjected to the impact of a 4,500-lb (2,043 kg) full-size automobile with a speed of 60 mph (96.6 km/h) and an angle of 25 degrees (1). However, the decision was made to test the installation with the more stringent strength characteristics described in NCHRP 350 (2). These criteria involve the impact of a 4,500-lb (2,043 kg) 3/4-ton pickup with a speed of 62.1 mph (100 km/h) and an angle of 25 degrees. The last crash test was conducted at a reduced speed [45 mph (72.5 km/h)] to determine the performance of an unrestrained PCB installation in a low speed work zone.

A total of five full-scale crash tests were conducted during this project. All tests involved the testing of PCB's installed on the edge of the existing concrete pavement at the TTI test track. The existing concrete pavement consists of an unreinforced surface with a nominal thickness of 7.5 in.(19.1 cm). Because the pavement is unreinforced and its thickness is roughly equivalent to or less than that of a typical bridge deck, it is believed that the results of the tests provide conservative estimates of the performance of the systems installed on a fully reinforced bridge deck.

An excavation was conducted at the edge of the pavement to simulate a vertical drop-off. The excavation was approximately 3 ft (0.91 m) deep and 4 ft (1.22 m) wide as shown in Figure 5. This excavation was continued for the full length of the barrier installation so that the barrier would be completely free to drop-off of the edge of the pavement.

As stated above, five full-scale crash tests were conducted in the current project to evaluate the performance of PCB's which are deployed immediately adjacent to the edge of a concrete pavement or bridge deck. The order of testing was selected to minimize the development time. In all cases, the barrier was impacted at about 5 ft (1.52 m) upstream of an interior barrier joint. This location was selected because it was believed that it provides the most critical situation for the system. The results of the tests are briefly summarized below.

Test 1959A-1 was conducted using four 30-ft (9.14 m) long barrier segments which were connected together with standard TxDOT channel/angle splice connections and pinned to the concrete pavement with four steel pins installed at an angle of 53.1 degrees from the horizontal axis. Four barrier segments were selected for testing because, in most situations, the primary barrier vehicle interaction is complete within a relatively short distance (usually less than 10 ft (3.05 m). The barrier was impacted upstream of the middle barrier joint. Because the rotation of the barrier was excessive, the vehicle ended up on top of the barrier in a relatively stable condition, having slid along the top of the barrier. The barrier remained anchored to the pavement reasonably well by the steel pins. If the length of the test installation would have been a few segments longer, the vehicle would probably have been brought safely to a controlled stop. However, because the barrier installation was too short, the vehicle slid off the end of the fourth barrier segment and rolled two complete times. It was the combined judgement of those who witnessed the test that the vehicle would not have rolled if the barrier installation would have been longer. The results associated with this test are summarized in Figure 6.

After the somewhat unsuccessful outcome associated with the first test, the second test to evaluate the performance of an unanchored PCB was used. By performing this test next, a reasonable period of time was purchased to fully analyze the results from the first test and make the necessary adjustments to the steel pin attachments. The barrier installation used in test 1959A-2 incorporated nine 30-ft (9.14 m) long barrier segments which were connected together with standard TxDOT channel/angle splice connections. The vehicle impacted the barrier upstream of the fourth barrier connection. The vehicle was successfully redirected.

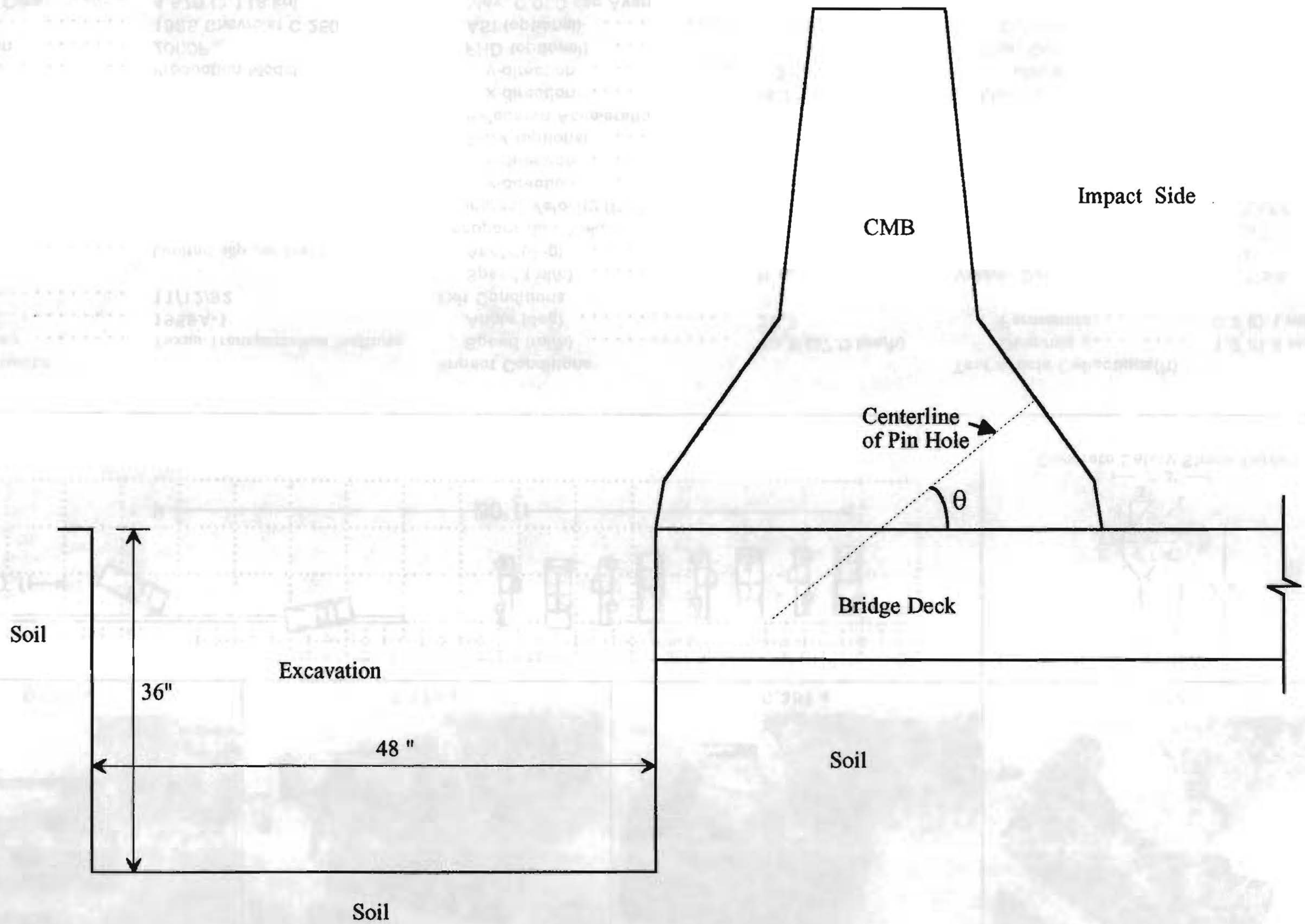
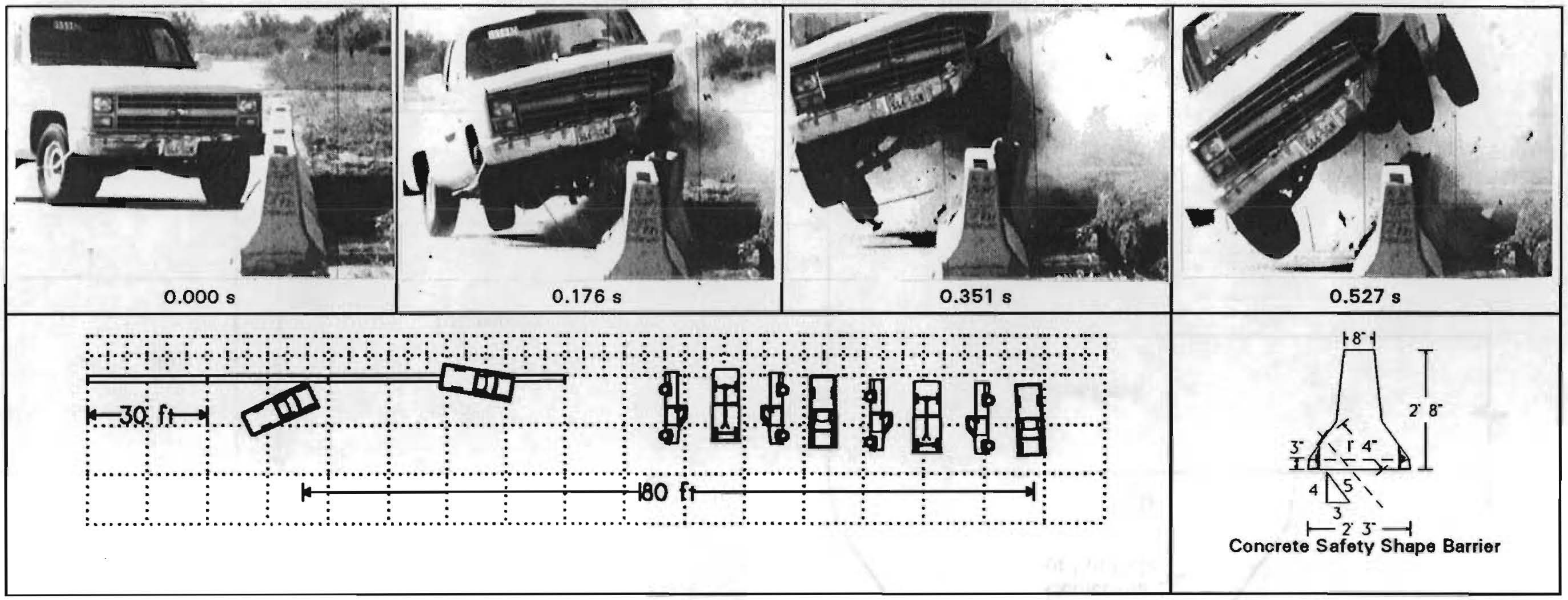


Figure 5. Schematic of test installation.



General Information	
Test Agency	Texas Transportation Institute
Test No.	1959A-1
Date	11/12/92
Test Article	
Type	Limited slip concrete barrier connection
Installation Length (ft)	120.0 (36.6 m)
Size and/or dimension and material of key elements	32 inch (81.3 m) high Concrete
Soil Type and Condition	N/A
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1985 Chevrolet C-250
Mass (lb) Curb	4,670 (2,118 kg)
Test Inertial	4,410 (2,000 kg)
Dummy	N/A
Gross Static	4,410 (2,000 kg)

Impact Conditions	
Speed (mi/h)	60.3 (97.0 km/h)
Angle (deg)	25.7
Exit Conditions	
Speed (mi/h)	N.A.
Angle (deg)	Roll-over
Occupant Risk Values	
Impact Velocity (ft/s)	
x-direction	22.7 (6.9 m/s)
y-direction	-18.4 (5.6 m/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-4.7
y-direction	6.2
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Averages (g's)	
x-direction	-10.8
y-direction	11.5
z-direction	-4.6

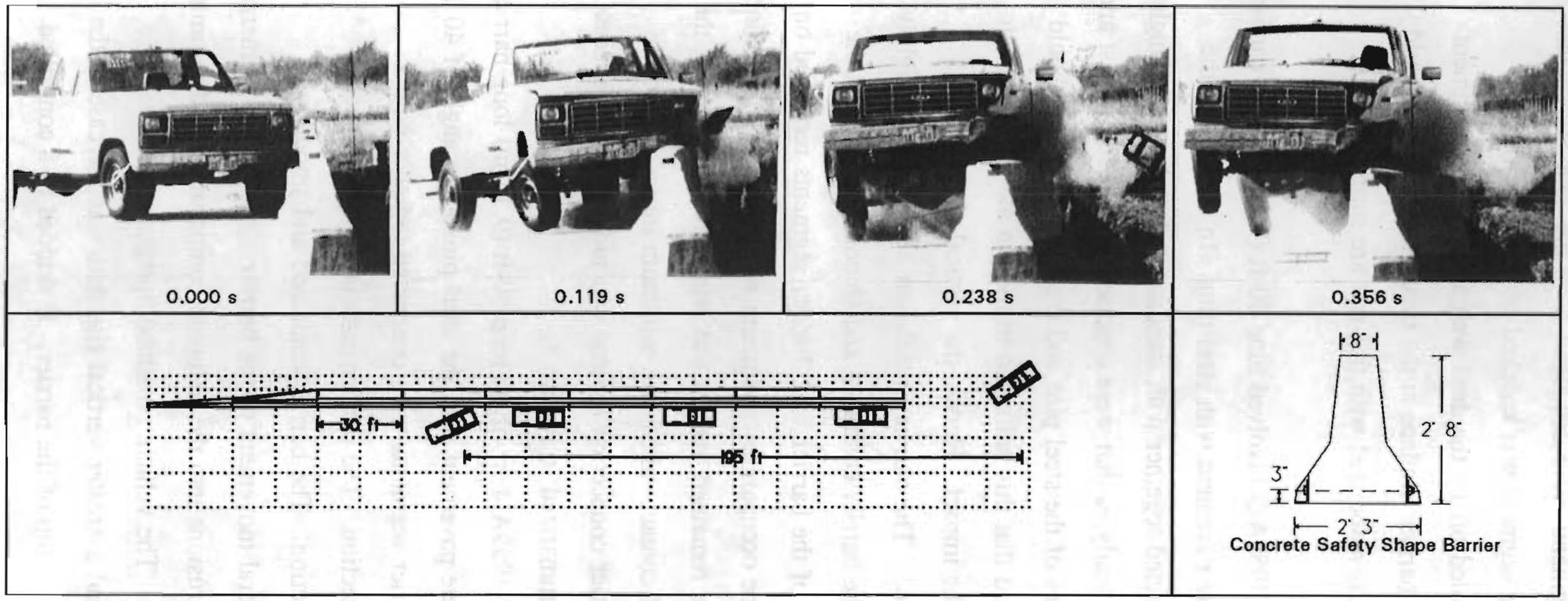
Test Article Deflections(ft)	
Dyanmic	1.3 (0.4 m)
Permanent	0.3 (0.1 m)
Vehicle Damage	
Exterior	
VDS	11LFQ-5, 11LD-2, 10L&T-5
CDC	11FLAK4, 11LDAS1, 10LDAO3
Interior	
OCDI	AS2221112
Maximum Exterior Vehicle Crush (in)	16.5(42.0 cm)
Max. Occ. Compart. Deformation (in)	9.5 (24.0 cm)
Post-Impact Behavior	
Max. Roll Angle (deg)	Roll-over
Max. Pitch Angle (deg)	Roll-over
Max. Yaw Angle (deg)	Roll-over

Figure 6. Summary sheet for test 1959A-1.

However, all of the downstream barrier segments were dislodged from the concrete pavement in a domino fashion. Once the first barrier segment was knocked off the edge of the pavement, the next barrier segment was pulled off by the dead weight of the first segment and so on. We believe that the amount of barrier in place at the time of the impact would have been knocked off the deck. The results associated with this test are summarized in Figure 7.

The barrier installation used in test 1959A-3 involved nine 30-ft (9.14 m) long barrier segments which were pinned to the concrete pavement with steel pins. In addition to the steel pins, the barrier segments were connected together with standard TxDOT channel/angle splice connections. Based on approximate analyses that were conducted between the first and third tests, the angle between the centerlines of the steel pins and the horizontal axis would be reduced to 40.1 degrees. It was believed that this reduction in the pin angle should help to limit the rotation of the barrier during the impact. Hence, the vertical rise of the impacting vehicle would be better controlled. The barrier installation was impacted slightly ahead of the fourth barrier connection. The barrier contained and smoothly redirected the test vehicle with limited lateral movement of the barrier. All barrier segments remained on the deck. There were no intrusions into the occupant compartment and minimal deformation of the occupant compartment. The vehicle remained upright and relatively stable during the collision. The vehicle trajectory at loss of contact indicated a minimum intrusion into the adjacent traffic lanes. Therefore, this barrier connection scheme was judged to be a success. The results associated with this test are summarized in Figure 8.

The barrier installation used in test 1959A-4 involved nine 30-ft (9.14 m) long barrier segments which were pinned to the concrete pavement with the steel pins at an angle of 40.1 degrees with the horizontal axis. The barrier segments were connected together with a standard ungrouted TxDOT grid-slot connection. The barrier installation was impacted slightly ahead of the second barrier connection. The barrier contained and smoothly redirected the test vehicle with limited lateral movement of the barrier. All barrier segments remained on the deck. There were no intrusions into the occupant compartment and minimal deformation of the occupant compartment. The vehicle remained upright and relatively stable during the collision. The vehicle had a greater vertical rise than was the case in the third test. As such, the vehicle ended up on top of the barrier. It skidded to a controlled

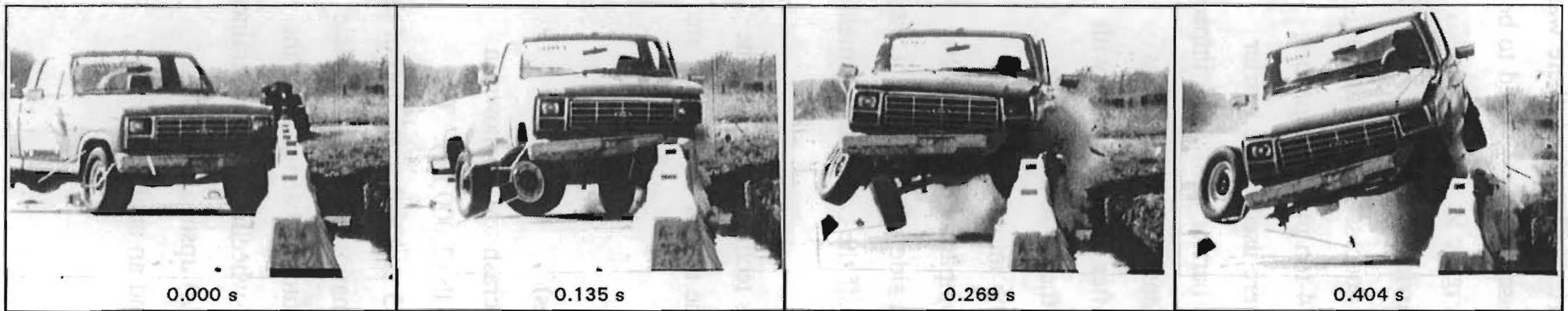


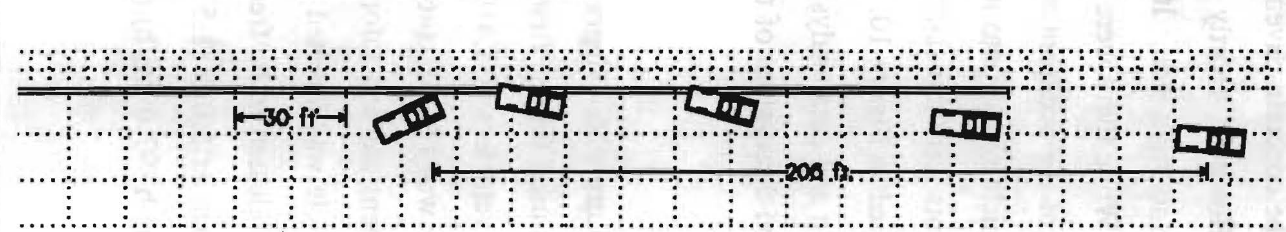
General Information	
Test Agency	Texas Transportation Institute
Test No.	1959A-2
Date	12/02/92
Test Article	
Type	Limited slip concrete barrier connection
Installation Length (ft)	270.0 (82.3 m)
Size and/or dimension and material of key elements	32 inch (81.3 m) high Concrete
Soil Type and Condition	N/A
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1986 Ford F-250
Mass (lb) Curb	4,409 (2,000 kg)
Test Inertial	4,409 (2,000 kg)
Dummy	N/A
Gross Static	4,409 (2,000 kg)

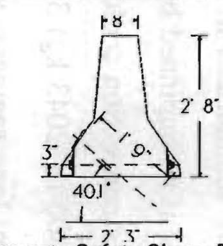
Impact Conditions	
Speed (mi/h)	61.9 (99.6 km/h)
Angle (deg)	26.1
Exit Conditions	
Speed (mi/h)	N/A
Angle (deg)	2.7
Occupant Risk Values	
Impact Velocity (ft/s)	
x-direction	19.3 (5.9 m/s)
y-direction	-23.1 (7.0 m/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-10.2
y-direction	9.0
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Averages (g's)	
x-direction	-7.3
y-direction	12.5
z-direction	-5.1

Test Article Deflections(ft)	
Dyanmic	(Moved off of
Permanent	bridge deck)
Vehicle Damage	
Exterior	
VDS	11LFQ-6
CDC	11LFEW5
Interior	
OCDI	AS0011000
Maximum Exterior Vehicle Crush (in)	15.7(40.0 cm)
Max. Occ. Compart. Deformation (in)	3.6 (9.1 cm)
Post-In.pact Behavior	
Max. Roll Angle (deg)	-20.4
Max. Pitch Angle (deg)	-12.8
Max. Yaw Angle (deg)	26.7

Figure 7. Summary sheet for test 1959A-2.







Concrete Safety Shape Barrier

General Information	
Test Agency	Texas Transportation Institute
Test No.	1959A-3
Date	12/09/92
Test Article	
Type	Limited slip concrete barrier connection
Installation Length (ft)	270.0 (82.3 m)
Size and/or dimension and material of key elements	32 inch (81.3 m) high Concrete
Soil Type and Condition	N/A
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1986 Ford F-250
Mass (lb) Curb	4,008 (1,818 kg)
Test Inertial	4,409 (2,000 kg)
Dummy	N/A
Gross Static	4,409 (2,000 kg)

Impact Conditions	
Speed (mi/h)	60.6 (97.5 km/h)
Angle (deg)	26.2
Exit Conditions	
Speed (mi/h)	N/A
Angle (deg)	N/A
Occupant Risk Values	
Impact Velocity (ft/s)	
x-direction	25.3 (7.7 m/s)
y-direction	-23.1 (7.1 m/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-3.4
y-direction	11.5
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Averages (g's)	
x-direction	-8.0
y-direction	12.7
z-direction	-5.6

Test Article Deflections(ft)	
Dyanmic	1.3 (0.4 m)
Permanent	0.4 (0.1 m)
Vehicle Damage	
Exterior	
VDS	11LFQ4
CDC	11LFEW1
Interior	
OCDI	AS0023000
Maximum Exterior Vehicle Crush (in)	15.7(40.0 cm)
Max. Occ. Compart. Deformation (in)	1.4 (3.5 cm)
Post-Impact Behavior	
Max. Roll Angle (deg)	45.1
Max. Pitch Angle (deg)	18.5
Max. Yaw Angle (deg)	-48.2

Figure 8. Summary sheet for test 1959A-3.

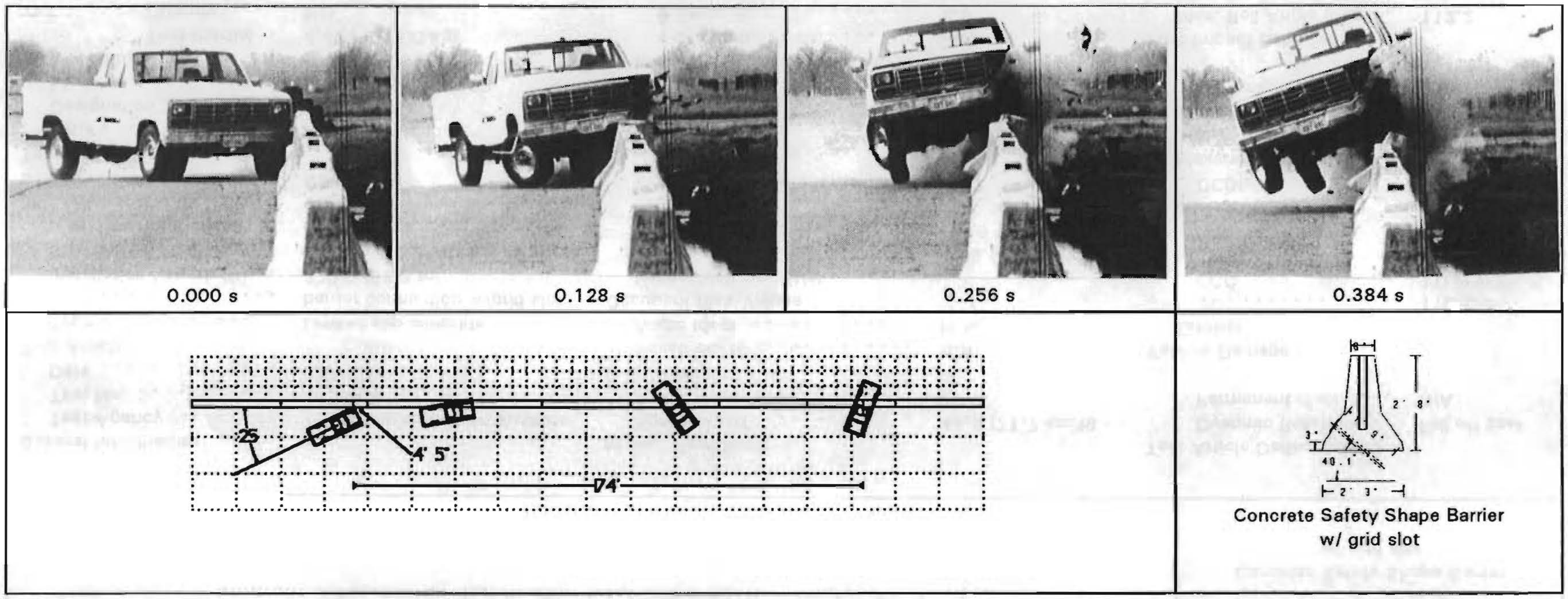
stop after traveling 174 ft (57.1 m) and remained on top of the barrier. Therefore, there was no intrusion into the adjacent traffic lanes. This barrier connection scheme was judged to be a success. The results associated with this test are summarized in Figure 9.

Test 1959A-5 was conducted to determine if an unpinned barrier installation employing a standard ungrouted TxDOT grid slot connection could successfully redirect a low speed [45 mph (72.5 km/h)] impact of a 4,500-lb (2043 kg) 3/4-ton pickup impacting with an angle of 25 degrees. Nine 30-ft (9.14 m) long segments were used in the barrier installation. The impact point was located just ahead of the second barrier joint. The impact knocked two barrier sections off of the edge of the concrete pavement. The vehicle was successfully redirected back onto the roadway. However, shortly after loss of contact with the barrier, the vehicle rolled completely over on its right side. It then skidded a short distance and rolled back to an upright position. While there were no intrusions into the occupant compartment and minimal deformation of the occupant compartment, the results were not judged to be acceptable because the vehicle rolled onto its side. In addition, it was not considered acceptable that two barrier segments were knocked off the concrete pavement. The results associated with this test are summarized in Figure 10.

Detailed discussions of the instrumentation and data analysis techniques used in the crash tests are presented in Appendix B. Detailed discussions of the results of each test are presented below.

RESULTS FOR TEST 1959A-1 (4,410 lb/60.3 mph/20.4 degrees)

A 1985 Chevrolet C-20 pickup truck was used for the first crash test as shown in Figures 11 and 12. The test inertia mass of the vehicle was 4,410 lb (2,000 kg). The distance to the lower edge of the vehicle bumper was 18.3 in. (46.5 cm) and to the top of the bumper was 27.4 in. (69.5 cm). Additional dimensions and information on the test vehicle are given in Figure 45 in Appendix C. The vehicle was directed into the barrier using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the barrier 5.0 ft (1.5 m) upstream from the center of the length of need at a speed of 60.3 mph (97.0 km/h) and an angle of 25.7 degrees.

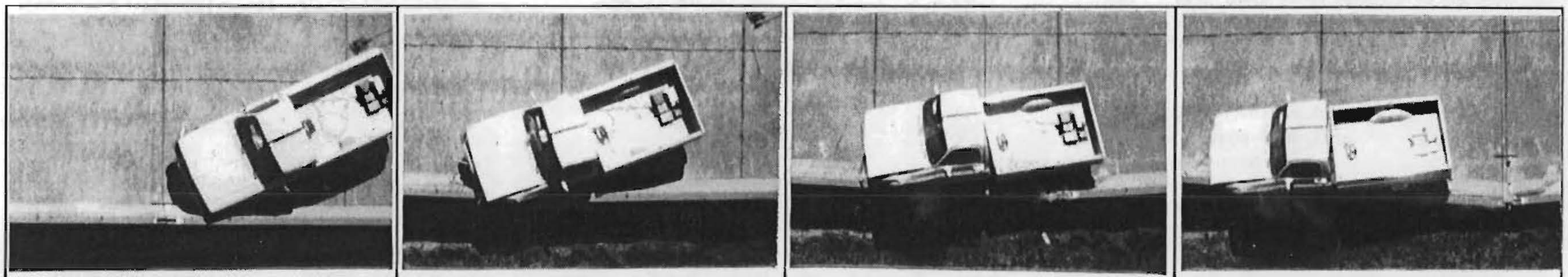


General Information	
Test Agency	Texas Transportation Institute
Test No.	1959A-4
Date	2/16/93
Test Article	
Type	Limited slip concrete barrier connection w/grid slot
Installation Length (ft)	270.0 (82.3 m)
Size and/or dimension and material of key elements	32 inch (81.3 m) high Concrete
Soil Type and Condition	N/A
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1986 Ford F-250
Mass (lb) Curb	4,239 (1,923 kg)
Test Inertial	4,409 (2,000 kg)
Dummy	N/A
Gross Static	4,409 (2,000 kg)

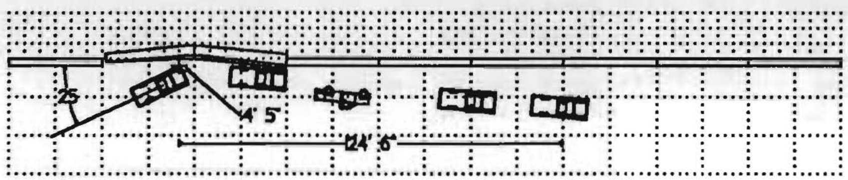
Impact Conditions	
Speed (mi/h)	60.9 (97.9 km/h)
Angle (deg)	23.7
Exit Conditions	
Speed (mi/h)	N/A
Angle (deg)	N/A
Occupant Risk Values	
Impact Velocity (ft/s)	
x-direction	18.3 (5.6 m/s)
y-direction	-19.8 (7.1 m/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-6.0
y-direction	10.4
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Averages (g's)	
x-direction	-7.2
y-direction	9.5
z-direction	-4.8

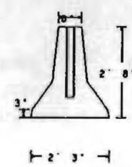
Test Article Deflections(ft)	
Dyanmic Rotation	1.3 (0.4 m)
Permanent displ.	0.8 (0.2 m)
Vehicle Damage	
Exterior	
VDS	11LFQ4
CDC	11LFEW1
Interior	
OCDI	AS0001000
Maximum Exterior Vehicle Crush (in)	8.3 (21.0 cm)
Max. Occ. Compart. Deformation (in)	3.5 (8.9 cm)
Post-Impact Behavior	
Max. Roll Angle (deg)	44.4
Max. Pitch Angle (deg)	-17.4
Max. Yaw Angle (deg)	67.4

Figure 9. Summary sheet for test 1959A-4.



0.000 s	0.156 s	0.312 s	0.467 s





Concrete Safety Shape Barrier
w/ grid slot

General Information	
Test Agency	Texas Transportation Institute
Test No.	1959A-5
Date	03/09/93
Test Article	
Type	Limited slip concrete barrier connection w/grid slot
Installation Length (ft)	270.0 (82.3 m)
Size and/or dimension and material of key elements	32 inch (81.3 m) high Concrete
Soil Type and Condition	N/A
Test Vehicle	
Type	Production Model
Designation	2000P
Model	1985 Chevrolet C-20
Mass (lb) Curb	4,427 (2,008 kg)
Test Inertial	4,409 (2,000 kg)
Dummy	N/A
Gross Static	4,409 (2,000 kg)

Impact Conditions	
Speed (mi/h)	44.6 (71.7 km/h)
Angle (deg)	25.0
Exit Conditions	
Speed (mi/h)	N.A.
Angle (deg)	N.A.
Occupant Risk Values	
Impact Velocity (ft/s)	
x-direction	15.9 (4.9 m/s)
y-direction	-13.9 (4.22 m/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-4.0
y-direction	-9.8
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Averages (g's)	
x-direction	-4.6
y-direction	5.6
z-direction	-4.3

Test Article Deflections(ft)	
Dyanmic Rotation	Fell off deck
Permanent displ.	N/A
Vehicle Damage	
Exterior	
VDS	11LFQ-5
CDC	11LFEW2
Interior	
OCDI	AS0001000
Maximum Exterior Vehicle Crush (in)	15.7(40.0 cm)
Max. Occ. Compart. Deformation (in)	1.0 (2.6 cm)
Post-Impact Behavior	
Max. Roll Angle (deg)	112.2
Max. Pitch Angle (deg)	9.3
Max. Yaw Angle (deg)	39.0

Figure 10. Summary sheet for test 1959A-5.

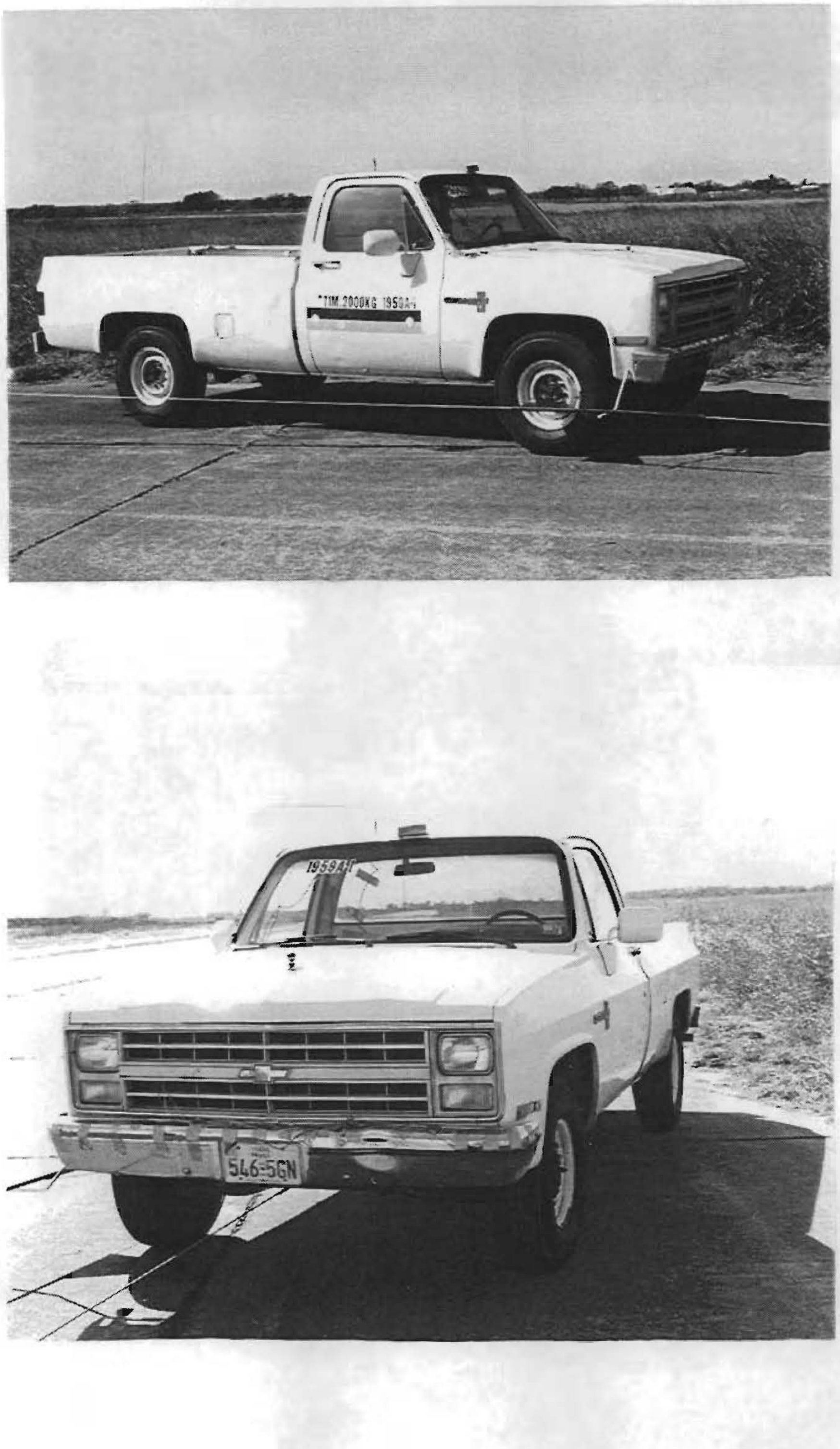


Figure 11. Test vehicle used in 1959A-1.

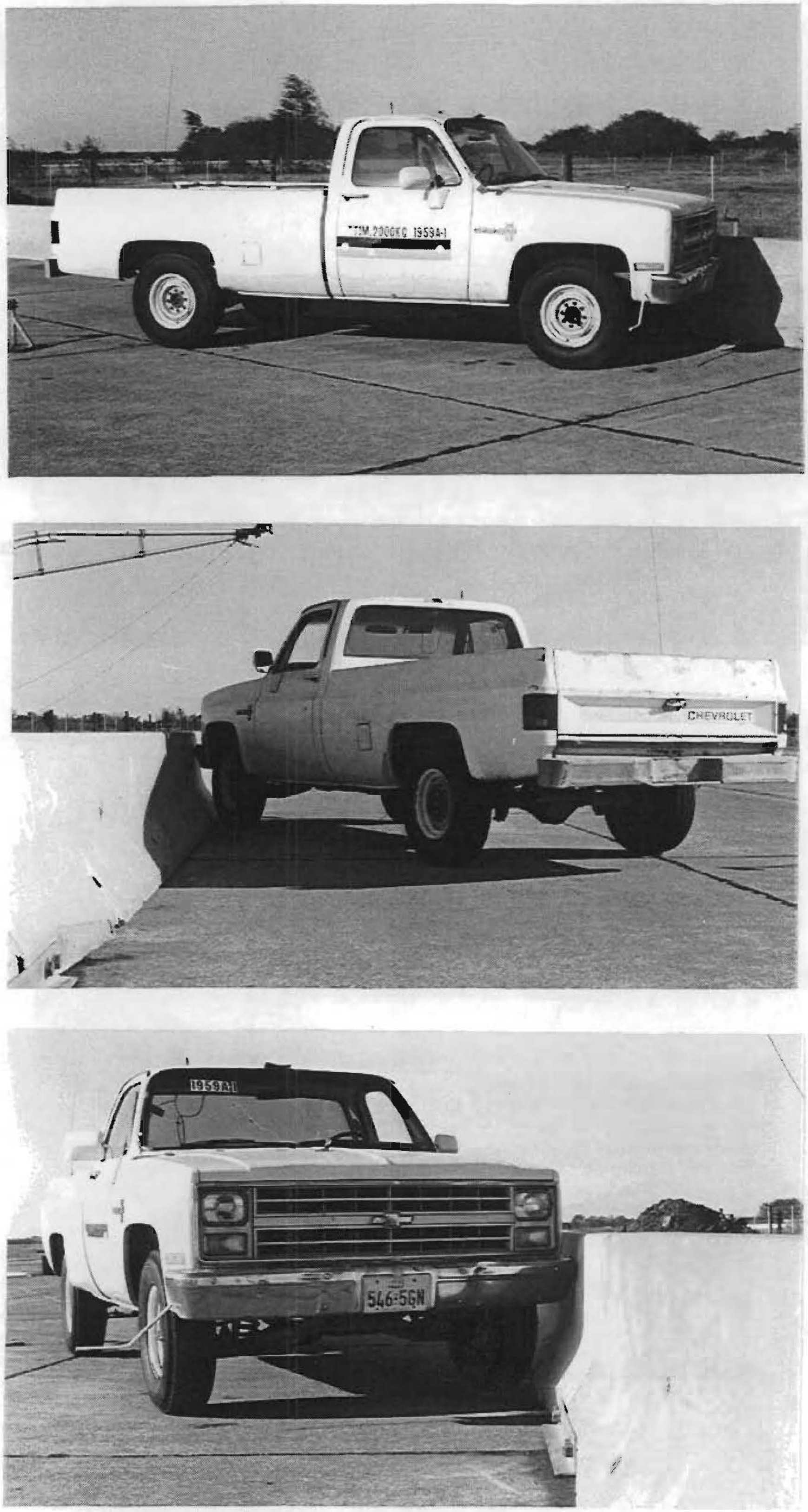


Figure 12. Vehicle/barrier geometrics (test 1959A-1).

The barrier installation consisted of four 30-ft (9.14 m) long barrier segments, each connected to the concrete pavement with four steel pins oriented at an angle of 53.1 degrees. In addition, the barrier segments were attached together with a standard channel/angle splice connection. The barrier installation is shown in Figures 13 and 14.

The left front tire of the test vehicle began to climb the face of the barrier upon impact. Shortly thereafter, the left front tire aired out. As the vehicle continued to climb the barrier, the undercarriage of the vehicle made contact with the top of the barrier. At approximately 0.221 second, the rear of the vehicle made contact with the barrier face. The vehicle yawed clockwise until the entire left side of the vehicle had crossed over the center of the barrier. As the vehicle began to descend, the right front wheel made contact with the ground at 0.571 second. With the rear of the vehicle still airborne, the left front wheel made contact with the top of the barrier at 0.660 second. As the vehicle exited the installation, the left rocker-panel came into contact with the end of the barrier at 1.007 second. This snagging of the end of the barrier as the vehicle was almost perpendicular to the barrier contributed to the subsequent rolling of the vehicle. Subsequent to exiting the installation, the vehicle rolled over 720 degrees. The brakes were applied at 1.57 seconds after impact (although this proved somewhat ineffective). The vehicle came to rest upright 180 ft (54.9 m) from the point of impact. Sequential photographs are shown in Figure 50 in Appendix D.

As can be seen in Figures 15 and 16, the barrier received minimal damage, although there was cosmetic damage (i.e., tire marks) on the face of the barrier. Maximum permanent movement of the barrier was 16.1 in. (40.8 cm). The vehicle was in contact with the barrier for 65.0 ft (19.8 m).

The entire vehicle sustained extensive damage as shown in Figure 17. Maximum crush at the left front corner of the vehicle was 16.5 in. (42.0 cm). The left front wheel was pushed rearward 8.3 in. (21.0 cm) and the roof was shifted 9.5 in. (24.0 cm). The floor, roof, and dashboard in the occupant compartment area were deformed. In addition, damage was sustained to the front bumper, grill, hood, radiator, windshield, and left front control arms, and all of the body panels were dented.

Impact speed was 60.3 mph (97.0 km/h) and the angle of impact was 25.7 degrees. The speed of the vehicle when parallel to the barrier was 47.9 mph (77.1 km/h). The vehicle lost contact with the barrier traveling at an undetermined speed and rolled 720

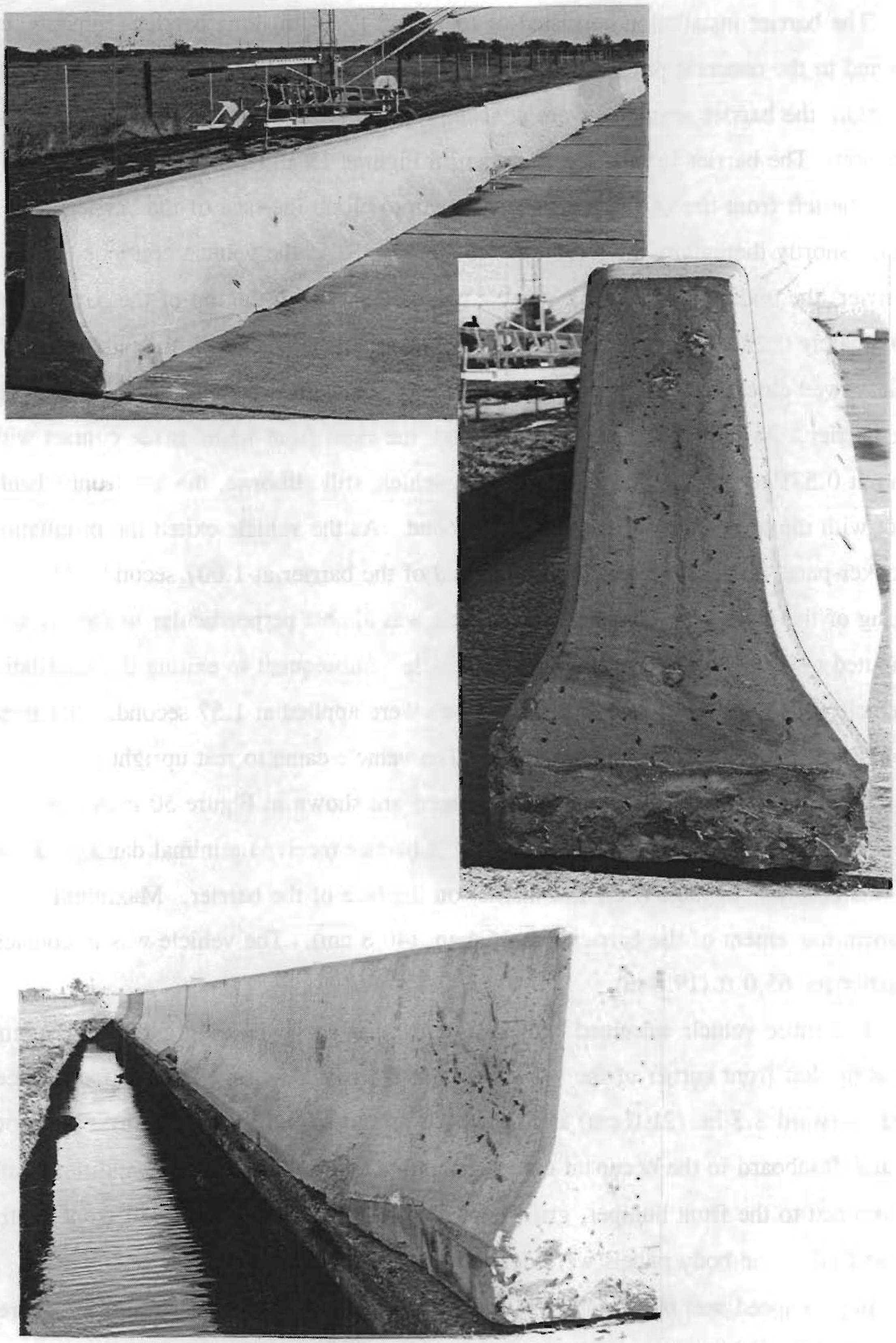


Figure 13. Limited-slip concrete barrier connection test 1959A-1 installation.

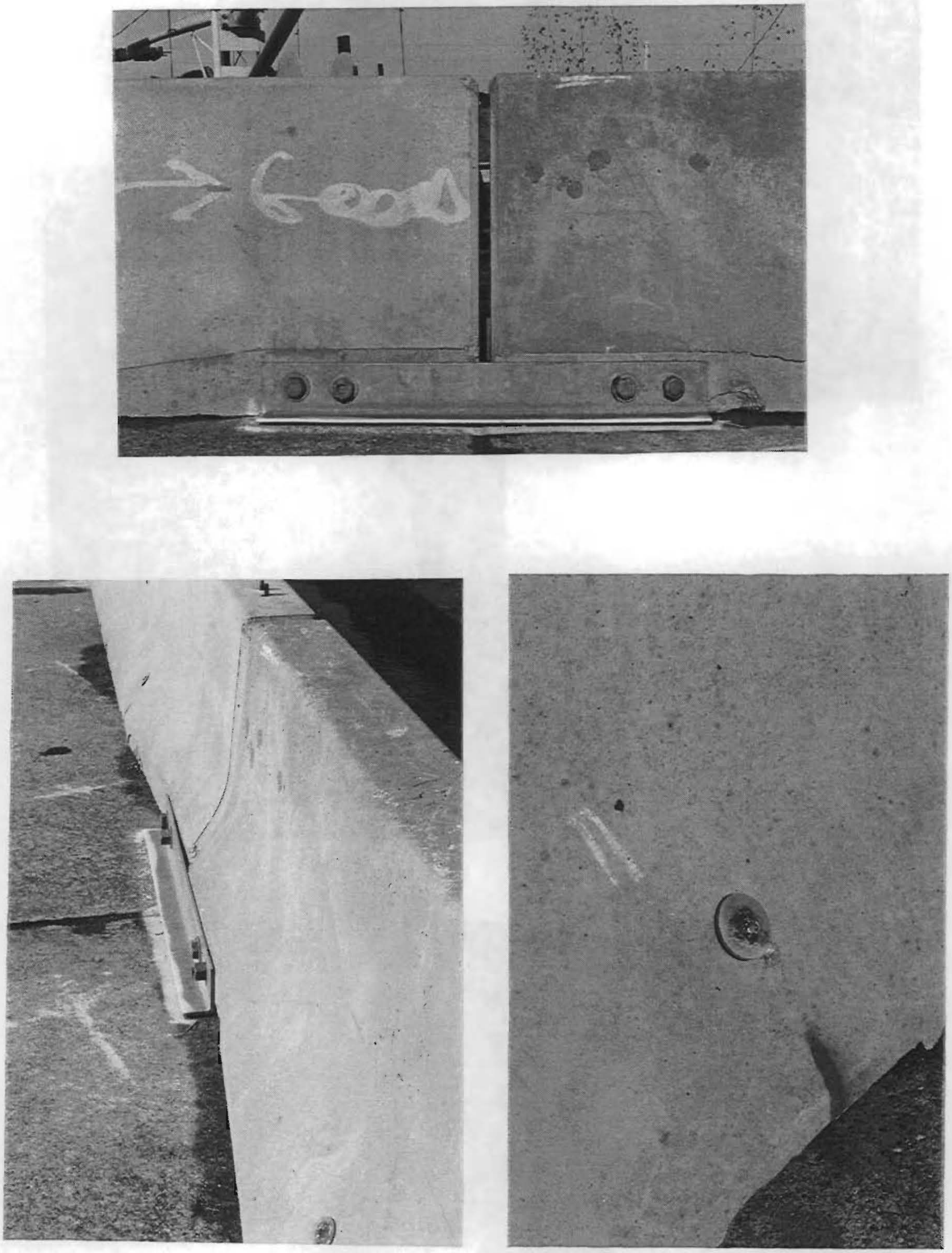


Figure 14. Connection details for limited-slip concrete barrier test 1959A-1.

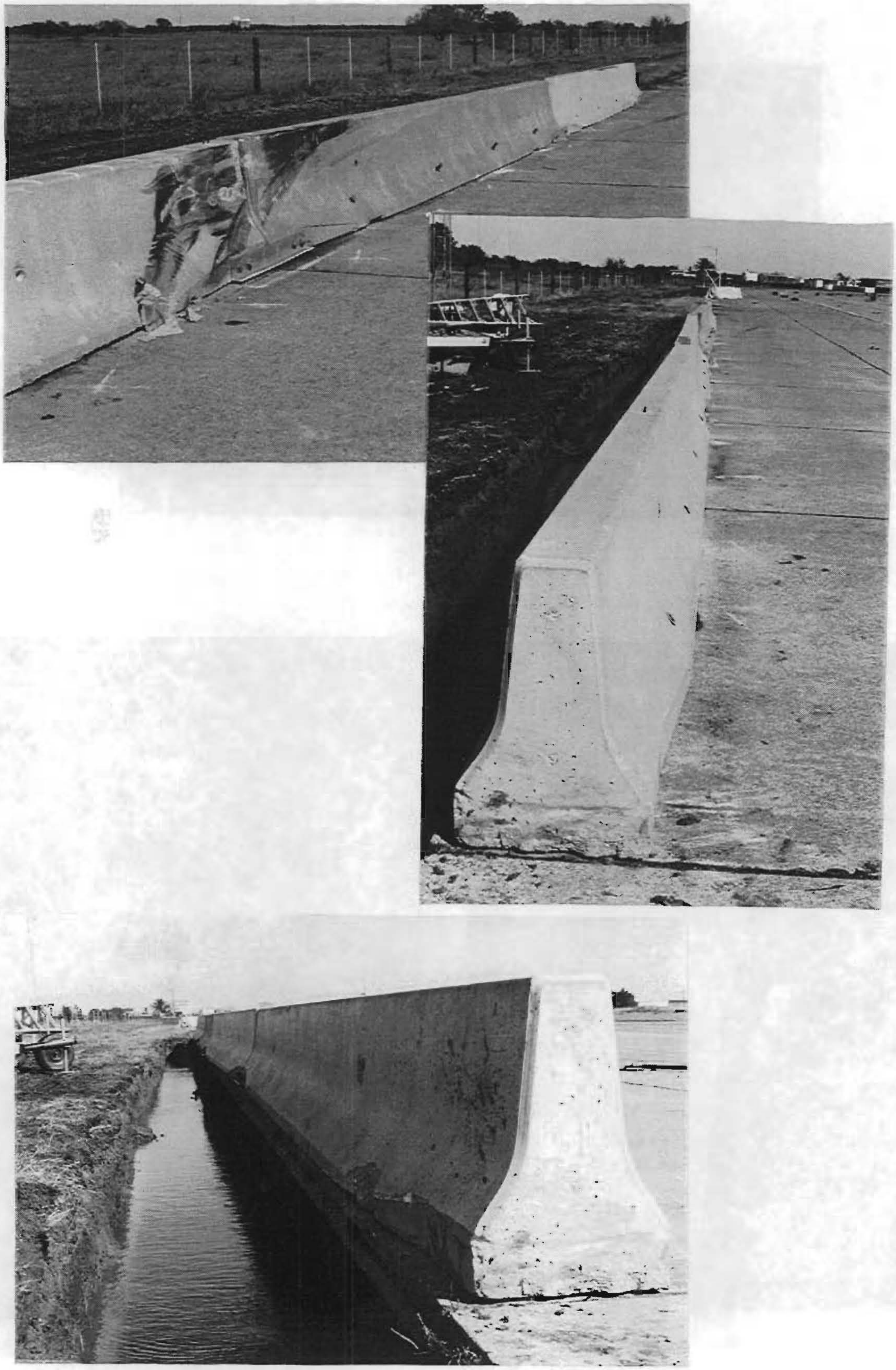


Figure 15. Post test damage to limited-slip concrete barrier connection installation (1959A-1).

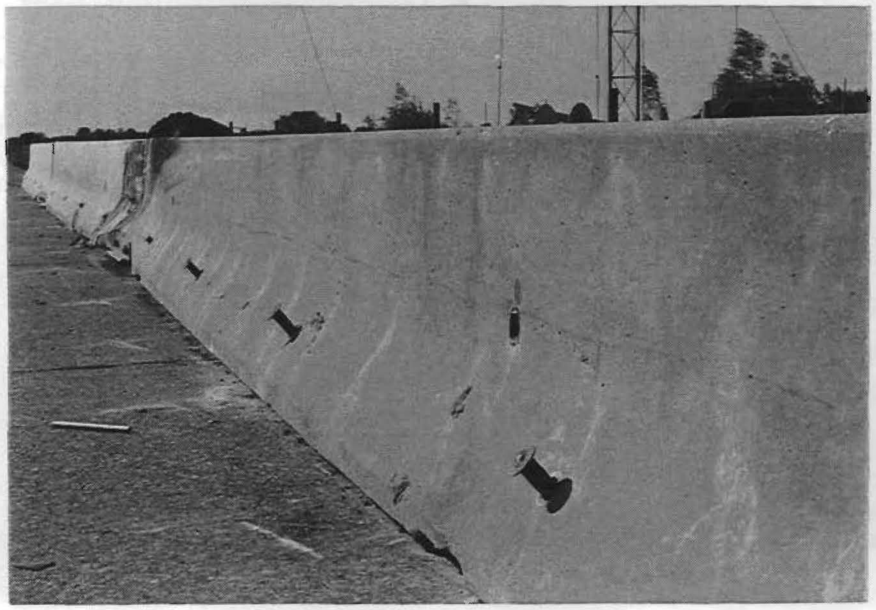
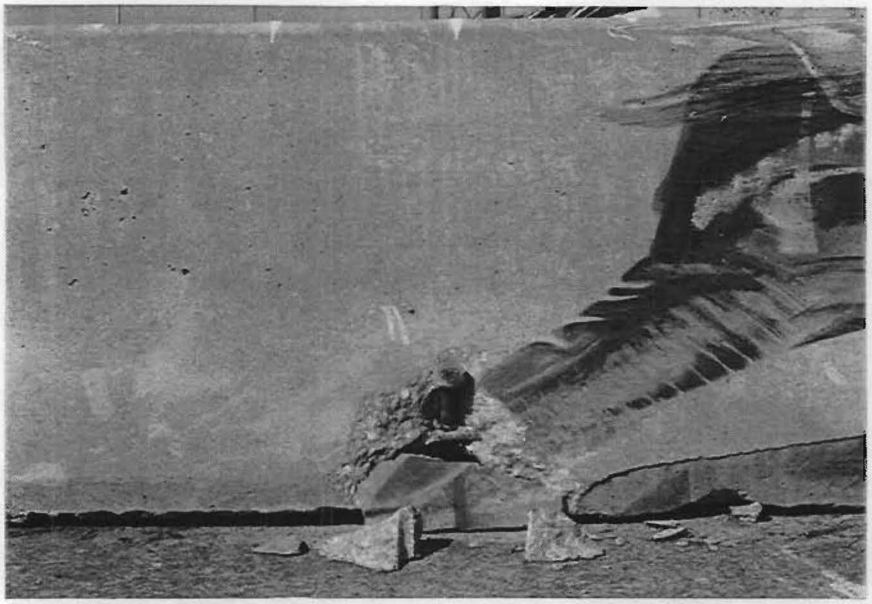


Figure 16. Details of damage to concrete barrier anchorage points (test 1959A-1).



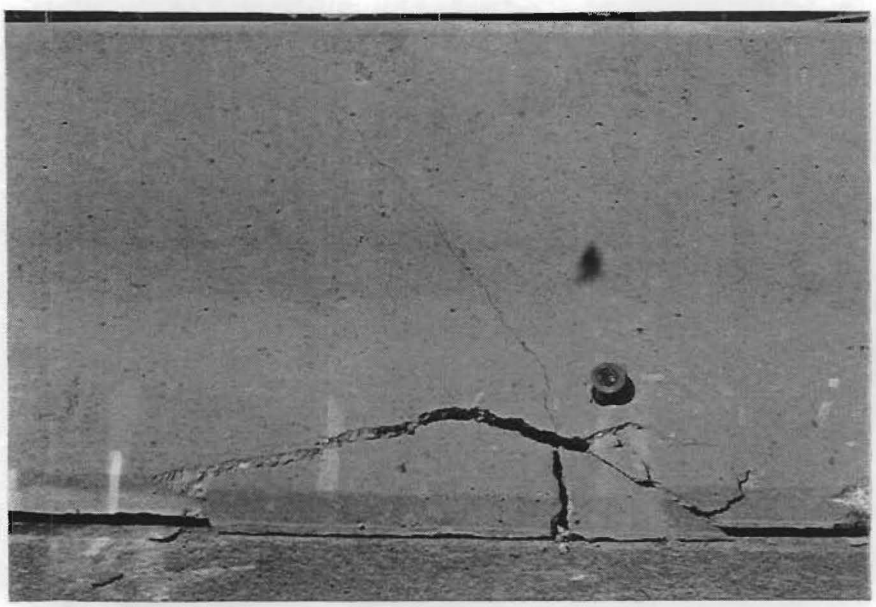


Figure 16. Details of damage to concrete barrier anchorage points (test 1959A-1 continued).

Figure 17. Post test damage to vehicle (test 1959A-1).

degrees. Data from the accelerometer located at the center of gravity were digitized for evaluation of occupant risk factor and were computed as follows. In the longitudinal direction, occupant impact velocity was 22.7 ft/s (6.9 m/s) at 0.162 second; the highest 0.010-second average ridedown acceleration was -4.7 g between 0.720 and 0.730 second; and the maximum 0.050-second average acceleration was -10.8 g between 0.055 and 0.105 second. Lateral occupant impact velocity was -18.4 ft/s (5.6 m/s) at 0.126 second; the highest 0.010-second occupant ridedown acceleration was 6.2 g between 0.210 and 0.220 second; and the maximum 0.050-second average acceleration was 11.5 g between 0.047 and 0.097 second. These data and other pertinent information from the test are summarized in Figure 6. Vehicular angular displacements are displayed in Figure 55 in Appendix E. Vehicular accelerations versus time traces filtered at SAE J211 (Class 180) are presented in Figures 56 through 58 in Appendix E.

DETAILED RESULTS FOR TEST 1959A-2 (4,409 lb/61.9 mph/26.1 degrees)

A 1986 Ford F-250 pickup truck was used for the crash test as shown in Figures 18 and 19. Test inertia mass of the vehicle was 4,409 lb (2,000 kg). The distance to the lower edge of the vehicle bumper was 19.7 in. (50.0 cm) and to the top bumper was 29.1 in. (73.9 cm). Additional dimensions and information on the test vehicle are given in Figure 46 in Appendix C. The vehicle was directed into the barrier using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the barrier 5.0 ft (1.5 m) upstream of the end of the fourth barrier at a speed of 61.9 mph (99.6 km/h) and an angle of 26.1 degrees.

The barrier installation consisted of nine 30-ft (9.14 m) long barrier segments which were not connected to the concrete pavement. However, the barrier segments were attached together with a standard channel/angle splice connection. The barrier installation is shown in Figures 20.

The left front tire began to climb the face of the barrier upon impact. Shortly thereafter, the barrier began to displace as the vehicle climbed the face of the barrier. At approximately 0.127 second, the right front wheel of the vehicle lost contact with the roadway. The rear of the vehicle made contact with the barrier at 0.234 second and began to climb the face of the barrier. Simultaneous to the rear of the pickup contacting the barrier,

Figure 18. Test vehicle used in test 1952A-2.

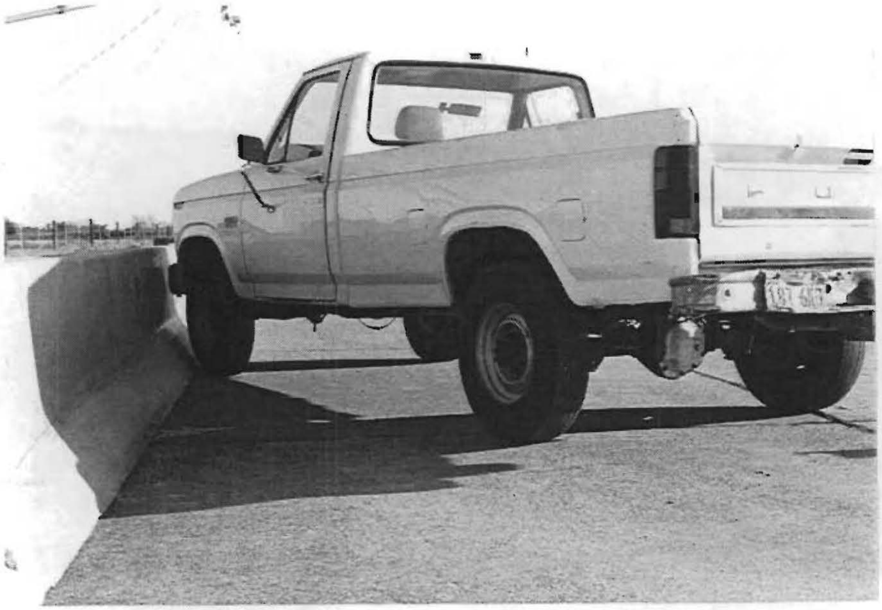


Figure 19. Vehicle/barrier geometrics (test 1959A-2).

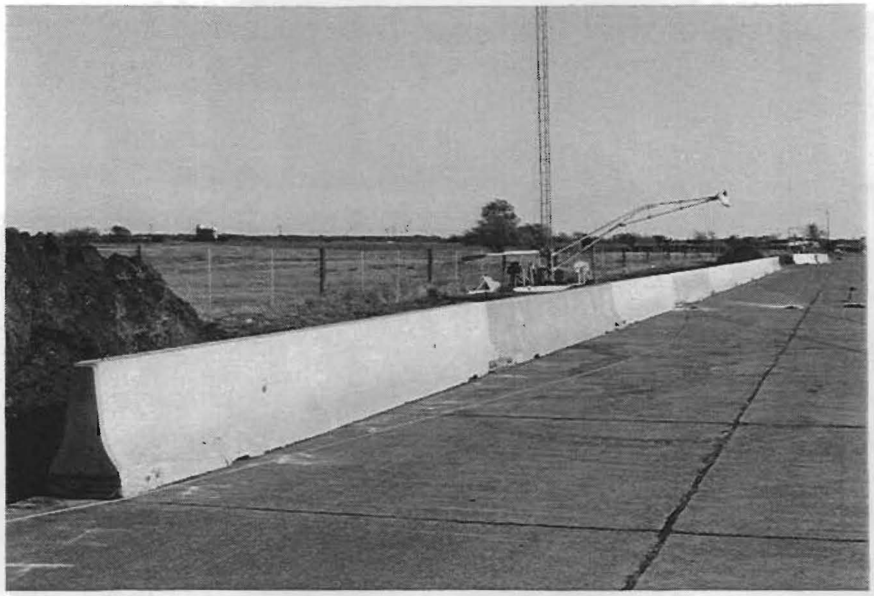


Figure 20. Limited-slip concrete barrier connection test 1959A-2 installation.

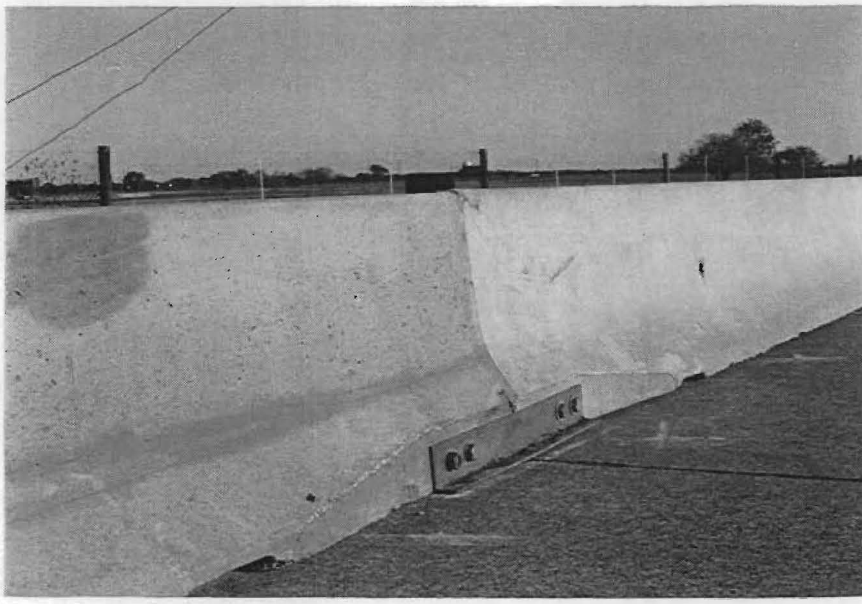


Figure 20. Limited slip concrete barrier connection test 1959A-2 installation (continued).

the barrier began to fall off the edge of the bridge deck. The vehicle traveled down the barrier airborne. As it descended back down toward the roadway, the vehicle made contact with the sixth barrier in the installation. The front wheels of the vehicle came back into contact with the roadway just as the vehicle impacted the end of the seventh barrier in a snagging manner. Upon impacting the end of the eighth barrier, the left front wheel was torn from the vehicle at approximately 1.517 seconds. The brakes were applied 4.3 seconds after impact. The vehicle came to rest 195 ft (59.5 m) from the point of impact. Sequential photographs of the impact are shown in Figure 51 in Appendix D.

As can be seen in Figures 21 and 22, the barrier received a moderate amount of damage. All of the barrier segments downstream from the impact point were knocked off the concrete pavement. The majority of the damage to the barrier was sustained by the torsional forces placed on the barrier while falling from the bridge deck. Damage to the face of the barrier was only cosmetic (i.e., tire marks). The vehicle was in contact with the barrier for 155.0 ft (47.3 m).

The entire vehicle sustained extensive damage as shown in Figure 23. Maximum crush at the left front corner of the vehicle was 15.7 in. (40.0 cm). The left front wheel was torn from the spindle, and the entire front end shifted 3.9 in. (10 cm) to the right. The floor pan and dashboard were deformed on the left side of the occupant compartment. In addition, damage was sustained to the front bumper, grill, hood, radiator, windshield, and left front axle beam. All the body panels were dented.

Impact speed was 61.9 mph (99.6 km/h) and the angle of impact was 26.1 degrees. The speed of the vehicle at time of parallel was 56.6 mph (91.1 km/h). The vehicle lost contact with the barrier traveling at an undetermined speed and exited at an angle of approximately 2.7 degrees to the barrier. Data from the accelerometer located at the center of gravity were digitized for evaluation of occupant risk factor and were computed as follows. In the longitudinal direction, occupant impact velocity was 19.3 ft/s (5.9 m/s) at 0.175 second; the highest 0.010-second average ridedown acceleration was -10.2 g between 0.936 and 0.946 second; and the maximum 0.050-second average acceleration was -7.3 g between 0.066 and 0.116 second. Lateral occupant impact velocity was -23.1 ft/s (7.0 m/s) at 0.124 second; the highest 0.010-second occupant ridedown acceleration was 9.0 g between 0.217 and 0.227 second; and the maximum 0.050-second average acceleration was 12.5 g

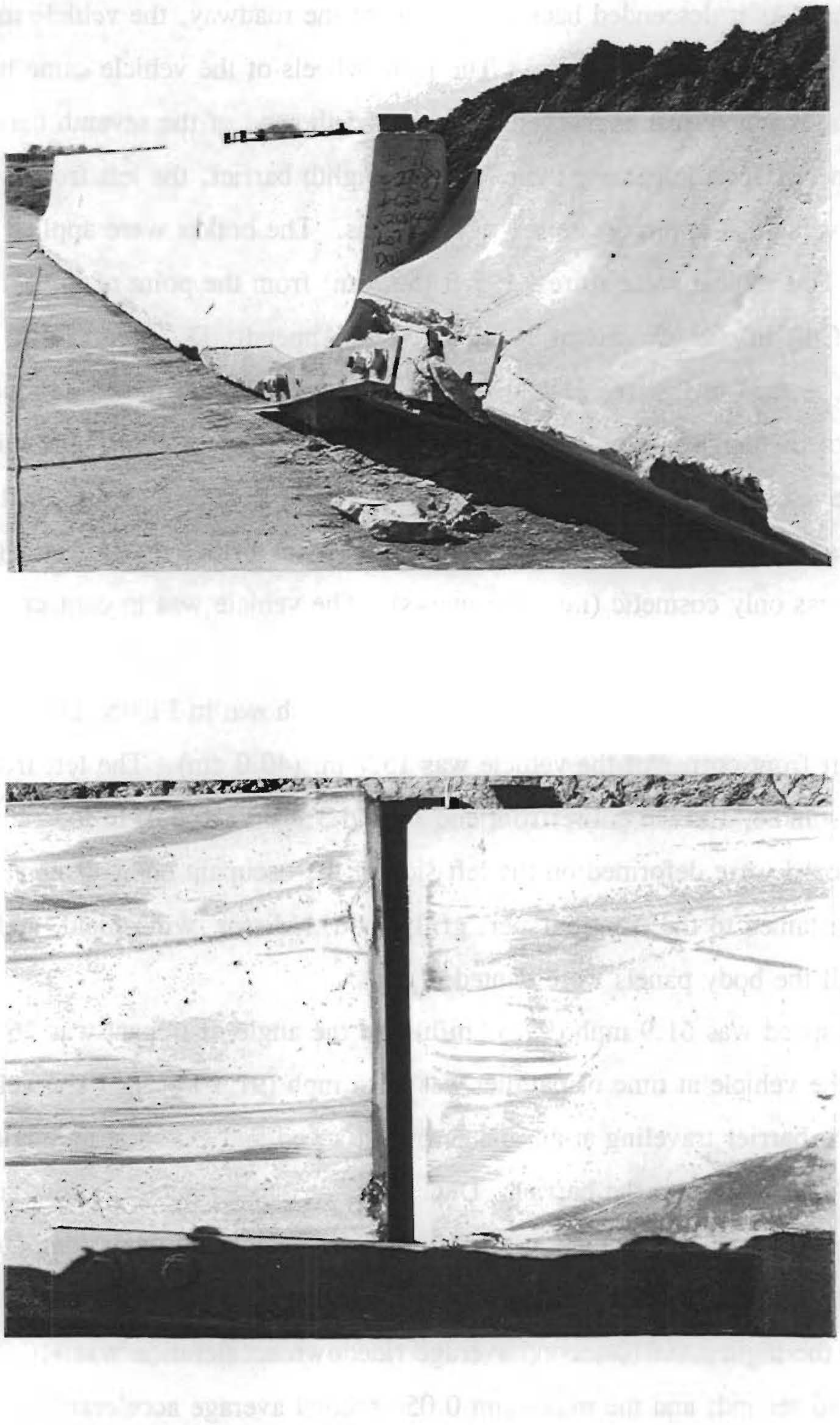


Figure 21. Details of damage to concrete barrier anchorage points(test 1959A-2).

Figure 22. Post test damage to limited slip concrete barrier connection installation (1959A-2).

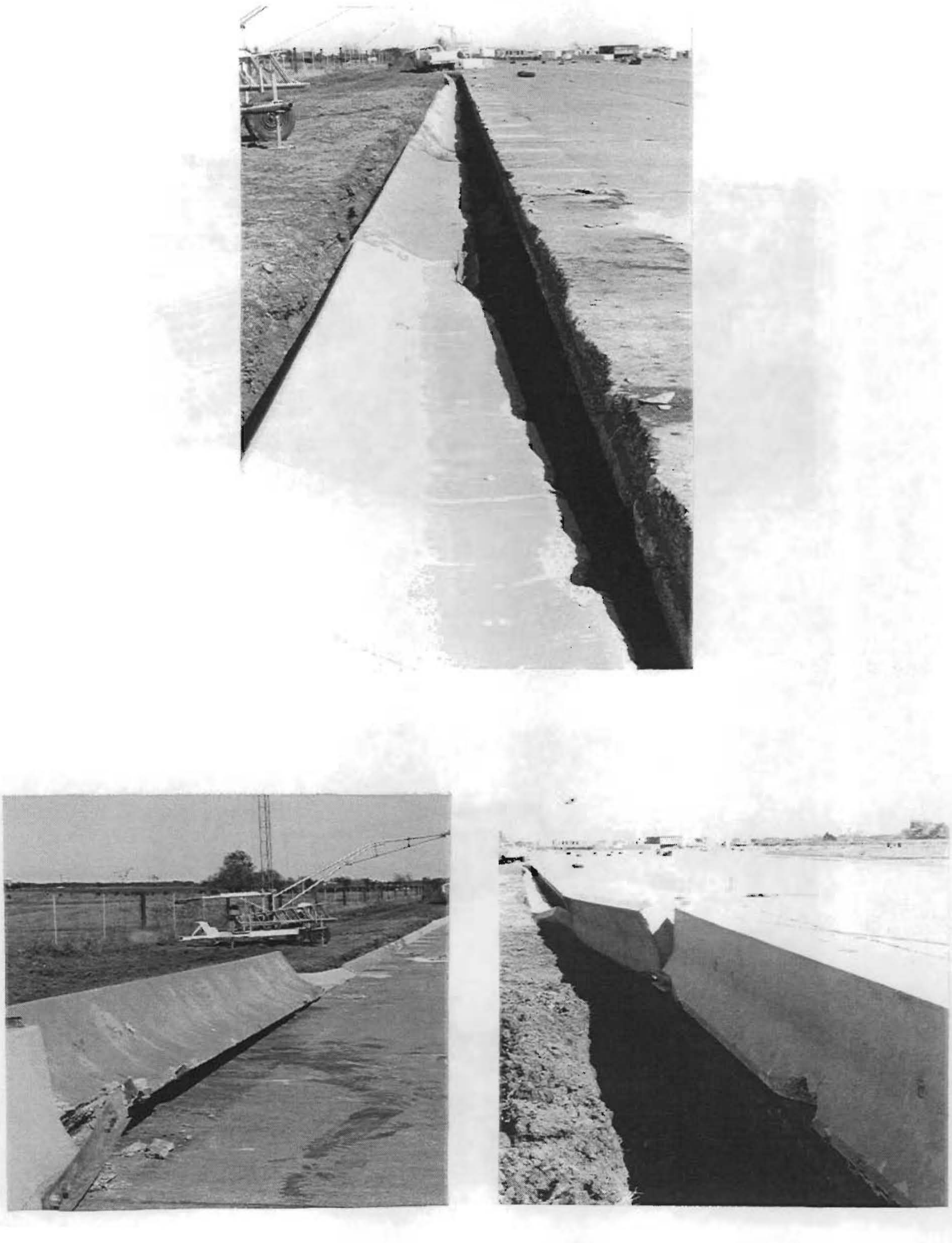


Figure 22. Post test damage to limited slip concrete barrier connection installation (1959A-2).

Figure 23. Post test damage to vehicle (test 1952A-2).

Figure 23. Post test damage to vehicle (test 1959A-2) continued.

between 0.065 and 0.115 second. These data and other pertinent information from the test are summarized in Figure 7. Vehicular angular displacements are displayed in Figure 59 in Appendix E. Vehicular accelerations versus time traces filtered at SAE J211 (Class 180) are presented in Figures 60 through 62 in Appendix E.

DETAILED RESULTS FOR TEST 1959A-3 (4,409 lb/60.6 mph/26.2 degrees)

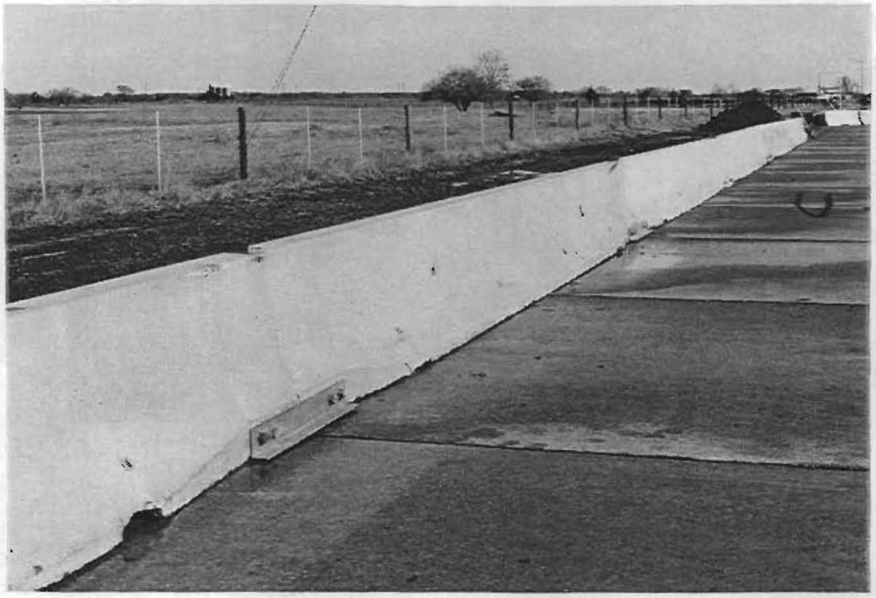
A 1986 Ford F-250 pickup truck was used for the crash test as shown in Figures 24 and 25. Test inertia mass of the vehicle was 4,409 lb (2,000 kg). The distance to the lower edge of the vehicle bumper was 18.7 in. (47.5 cm) and to the top of the bumper was 28.2 in. (71.6 cm). Additional dimensions and information on the test vehicle are given in Figure 47 in Appendix C. The vehicle was directed into the barrier using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the barrier 5.0 ft (1.5 m) upstream of the end of the fourth barrier at a speed of 60.6 mph (97.5 km/h) and an angle of 26.2 degrees.

The barrier installation consisted of nine 30-ft (9.14 m) long barrier segments, each connected to the concrete pavement with four steel pins oriented at an angle of 40.1 degrees. In addition, the barrier segments were attached together with a standard channel/angle splice connection. The barrier installation is shown in Figures 26 and 27.

The left front tire of the test vehicle began to climb the face of the barrier upon impact. At approximately 0.107 second, the right front tire of the vehicle lost contact with the roadway. The right rear tire of the vehicle lost contact with the roadway as the rear of the vehicle made contact with the barrier at approximately 0.208 second. As the vehicle traveled parallel to the barrier, the vehicle continued to climb. The vehicle traveled down the barrier airborne. As the vehicle descended back down toward the roadway, the right front tire of the vehicle made contact with the roadway at approximately 0.528 second. The left front tire followed, contacting the roadway at 0.971 second. The left rear tire came down and made contact with the top of the barrier at 1.006 seconds, subsequently contacting the roadway. The vehicle lost contact with the barrier at approximately 1.174 seconds. The brakes were applied, and the vehicle came to rest 206 ft (62.8 m) from the point of impact. Sequential photographs are shown in Figure 52 in Appendix D.

Figure 24. Test vehicle used in 1959A-3.

Figure 25. Vehicle/barrier geometrics (test 1959A-3).



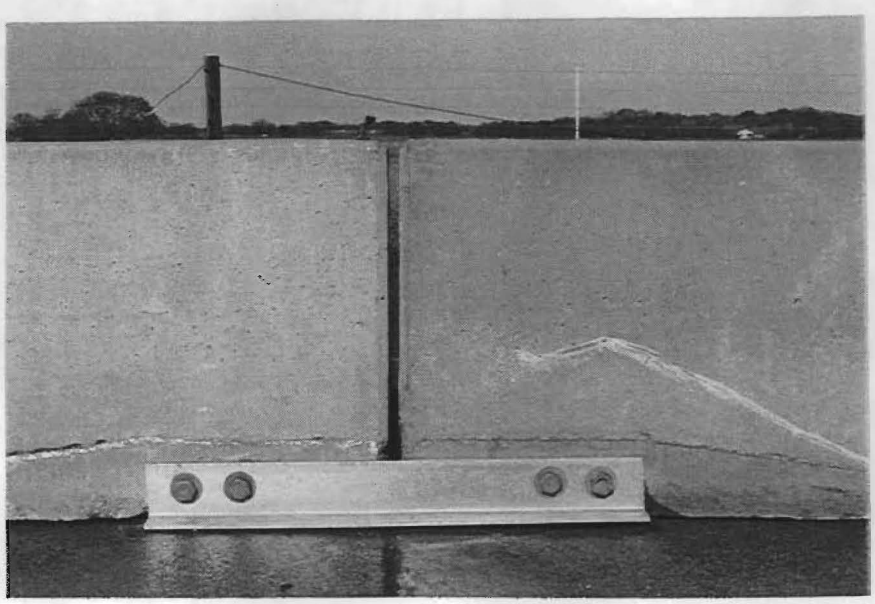


Figure 26. Limited slip concrete barrier connection test 1959A-3 installation.

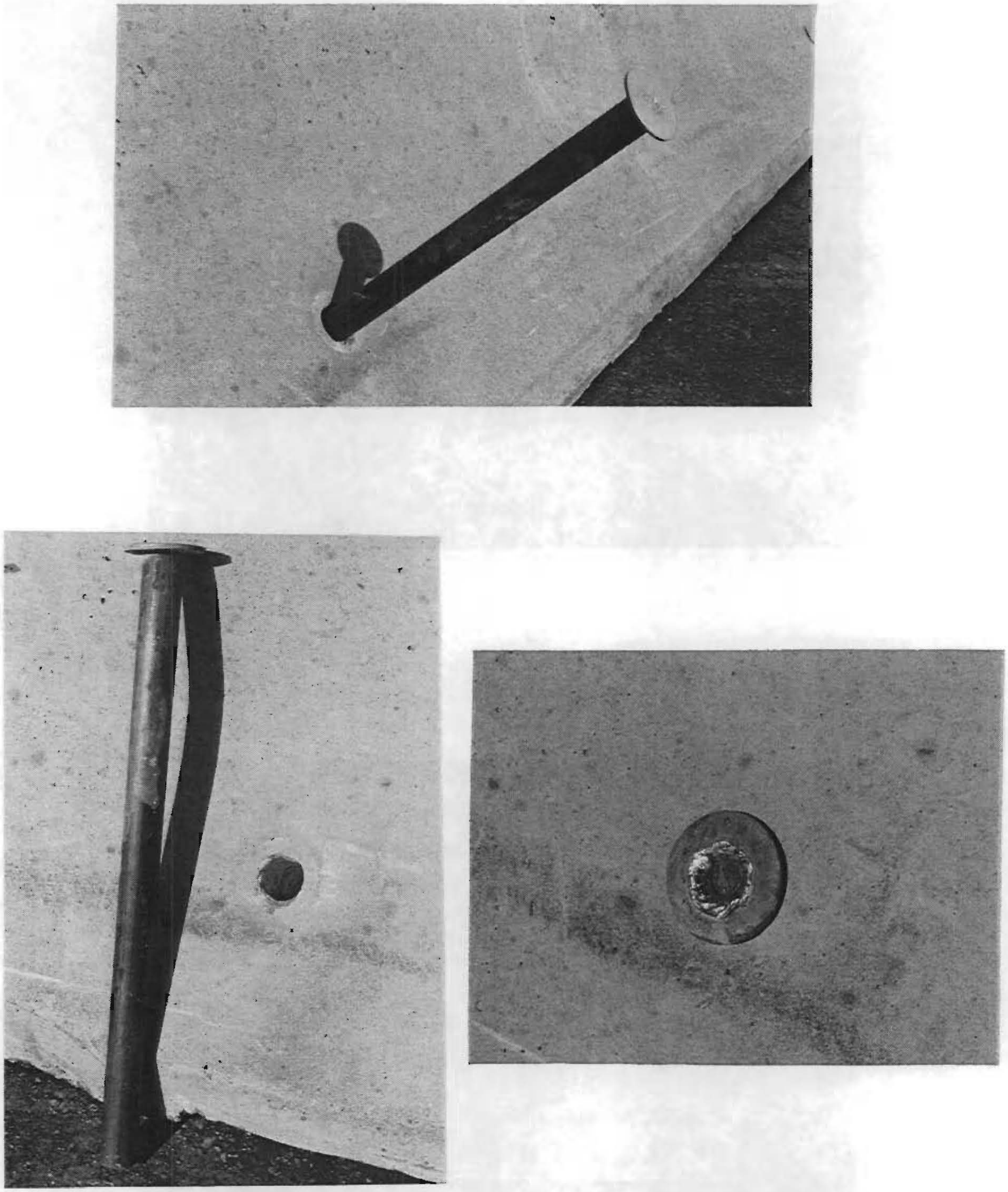


Figure 27. Details of anchor rods used to fix barrier to roadway (test 1959A-3).

As can be seen in Figures 28 and 29, the barrier received minimal damage. There was cosmetic damage (i.e., tire marks) on the face of the barrier. Maximum permanent movement of the barrier was 5 in. (12.7 cm). The vehicle was in contact with the barrier for 155.0 ft (47.3 m).

The entire vehicle sustained moderate damage as shown in Figure 30. Maximum crush at the left front corner of the vehicle was 15.7 in. (40.0 cm). The right front wheel was displaced from the spindle, and the entire front end shifted 7.9 in. (20 cm) to the right. The floor pan was deformed on the left side of the occupant compartment. In addition, damage was sustained to the front bumper, grill, hood, radiator, windshield, and left front axle beam. Most of the body panels were scraped or bent.

Impact speed was 60.6 mph (97.5 km/h) and the angle of impact was 26.2 degrees. The speed of the vehicle at time of parallel was 50.2 mph (80.8 km/h). The vehicle lost contact with the barrier while traveling at an undetermined speed and exit angle. Data from the accelerometer located at the center of gravity were digitized for evaluation of occupant risk factor and were computed as follows. In the longitudinal direction, occupant impact velocity was 20.9 ft/s (6.4 m/s) at 0.168 second; the highest 0.010-second average ridedown acceleration was -3.4 g between 0.199 and 0.209 second; and the maximum 0.050-second average acceleration was -8.0 g between 0.060 and 0.110 second. Lateral occupant impact velocity was -23.1 ft/s (7.1 m/s) at 0.125 second; the highest 0.010-second occupant ridedown acceleration was 11.5 g between 0.202 and 0.212 second; and the maximum 0.050-second average acceleration was 12.7 g between 0.062 and 0.112 second. These data and other pertinent information from the test are summarized in Figure 8. Vehicular angular displacements are displayed in Figure 63 in Appendix E. Vehicular accelerations versus time traces filtered at SAE J211 (Class 180) are presented in Figures 64 through 65 in Appendix E.

DETAILED RESULTS FOR TEST 1959A-4 (4,409 lb/60.9 mph/23.7 degrees)

A 1986 Ford F-250 pickup truck, shown in Figures 31 and 32, was used for the crash test. Test inertia mass of the vehicle was 4,409 lb (2,000 kg). The distance to the lower edge of the vehicle bumper was 18.9 in. (48.0 cm) and 28.5 in. to the top of the bumper was (72.5 cm). Additional dimensions and information on the test vehicle are given in Figure 48

Figure 28. Post test damage to limited slip concrete barrier connection installation (1959A-3).

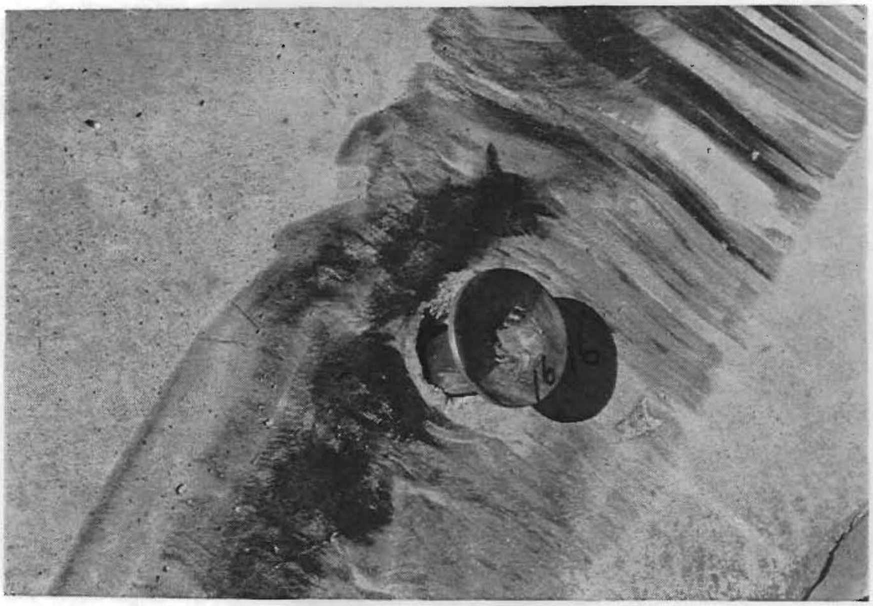


Figure 29. Details of damage sustained to barrier and anchor rods (test 1959A-3).

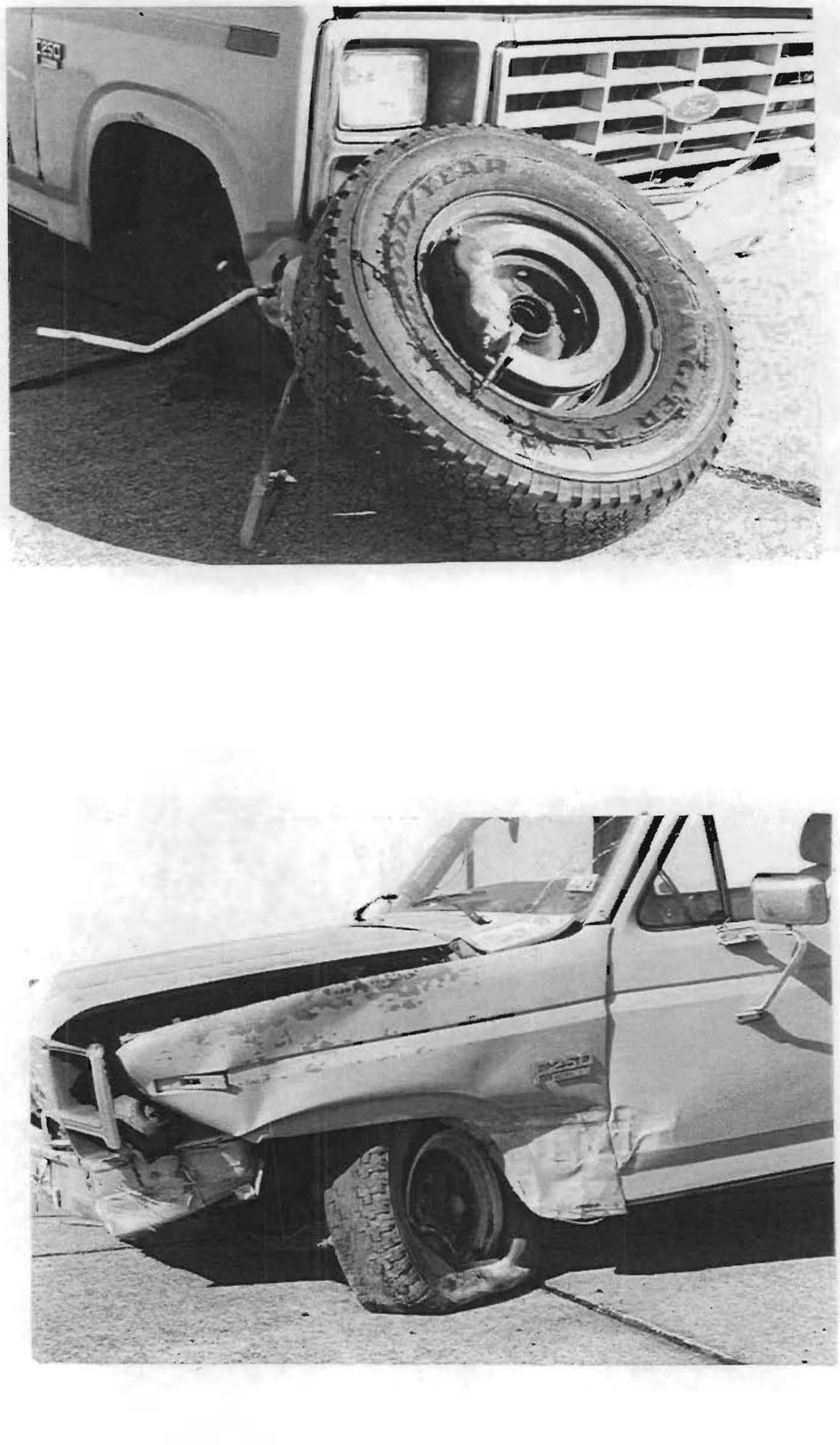


Figure 30. Post test damage to vehicle (test 1959A-3).

Figure 30. Post test damage to vehicle (test 1959A-3) continued.

Figure 31. Test vehicle used in 1959A-4.

Figure 32. Vehicle/barrier geometrics (test 1959A-4).

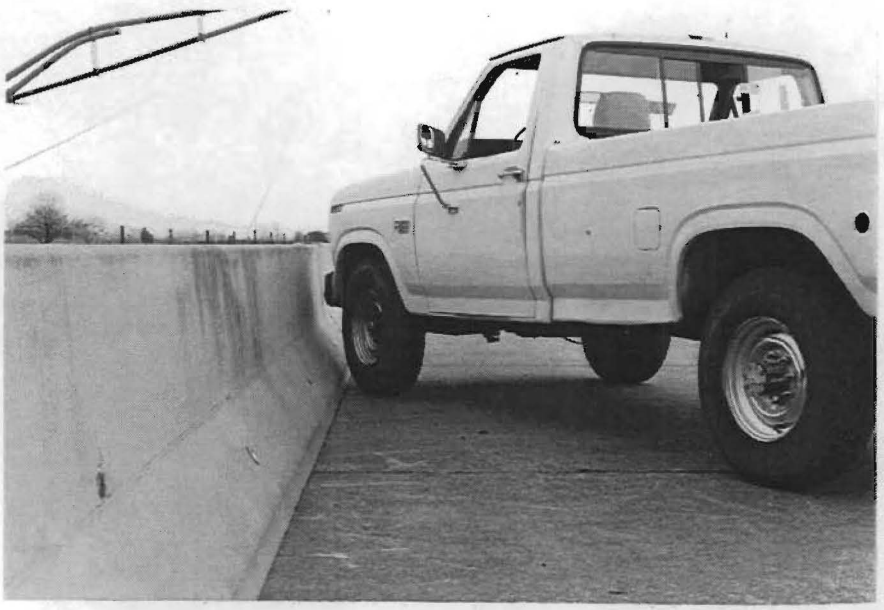


Figure 32. Vehicle/barrier geometrics (test 1959A-4) continued.

in Appendix C. The vehicle was directed into the barrier using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the barrier 5.0 ft (1.5 m) upstream of the end of the second barrier at a speed of 60.9 mph (97.9 km/h) and an angle of 23.7 degrees.

The barrier installation consisted of nine 30-ft (9.14 m) long barrier segments which were each connected to the concrete pavement with four steel pins oriented at an angle of 40.1 degrees. In addition, the barrier segments were attached together with a standard ungrouted grid slot connection. The barrier installation is shown in Figures 33 and 34.

The left front tire began to climb the face of the barrier upon impact. At approximately 0.147 second, the right front tire of the vehicle lost contact with the roadway. As the rear of the vehicle made contact with the barrier at approximately 0.220 second, the right rear tire of the vehicle lost contact with the roadway. The vehicle continued to climb and yaw clockwise airborne. By 0.419 second, the left front tire was atop the barrier. As the vehicle descended, the right front tire of the vehicle made contact with the roadway at approximately 0.537 second. The right rear tire contacted the face of the barrier at 0.637 second. At 0.880 second, the vehicle impacted the top of the barrier at the bottom-center of the left door. The left front tire followed, contacting the roadway at 1.000 second. At 1.541 second, the left rear tire contacted the barrier and the left rear quarter panel of the vehicle impacted the top of the barrier. The right rear wheel impacted the top of the barrier at 2.695. The vehicle came to rest with the front wheels on the roadway and the rear wheels behind and atop the barrier. This occurred 174.0 ft (53.0 m) from the point of impact. Sequential photographs are shown in Figure 53 in Appendix D.

As can be seen in Figures 35 and 36, the barrier received moderate damage at the grid slot ends of the barrier. Other damage was cosmetic (i.e., tire marks and gouges) and was limited to the face of the barrier. Maximum permanent movement of the barrier was 9 in. (22.9 cm). The vehicle was in contact with the barrier for 174.0 ft (53.0 m).

The vehicle sustained moderate damage as shown in Figure 37. Maximum crush at the left front corner of the vehicle was 15.7 in. (40.0 cm). The floor pan was deformed 5.5 in. (14.0 cm) into the occupant compartment on the left side. In addition, damage was sustained to the front bumper, grill, hood, radiator, windshield, and left front axle beam.

Figure 33. Limited slip concrete barrier with grid-slot connection (test installation 1959A-4).

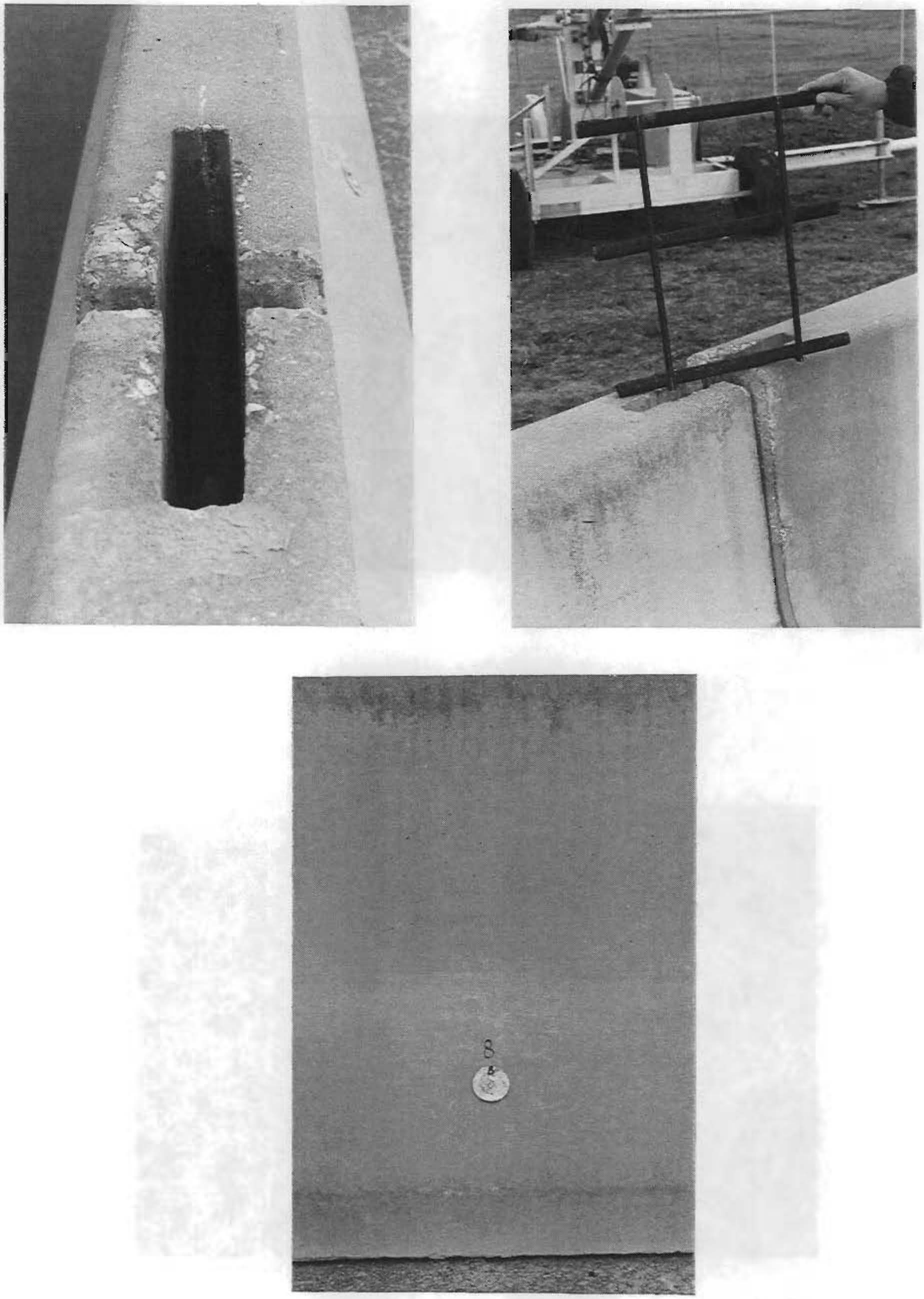


Figure 34. Connection details for limited slip concrete barrier with grid-slot connection (test installation 1959A-4).

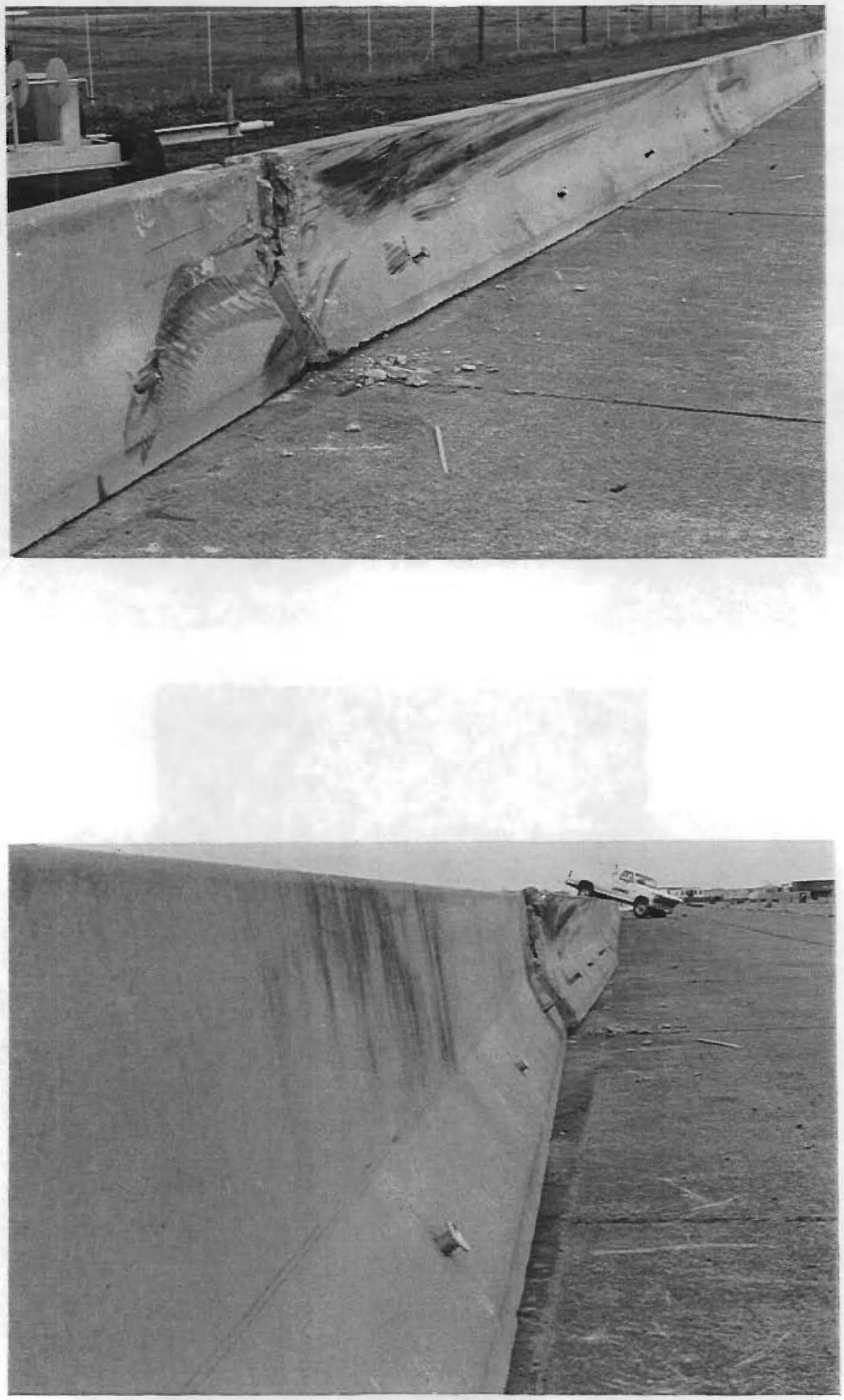


Figure 35. Post test damage to installation 1959A-4.

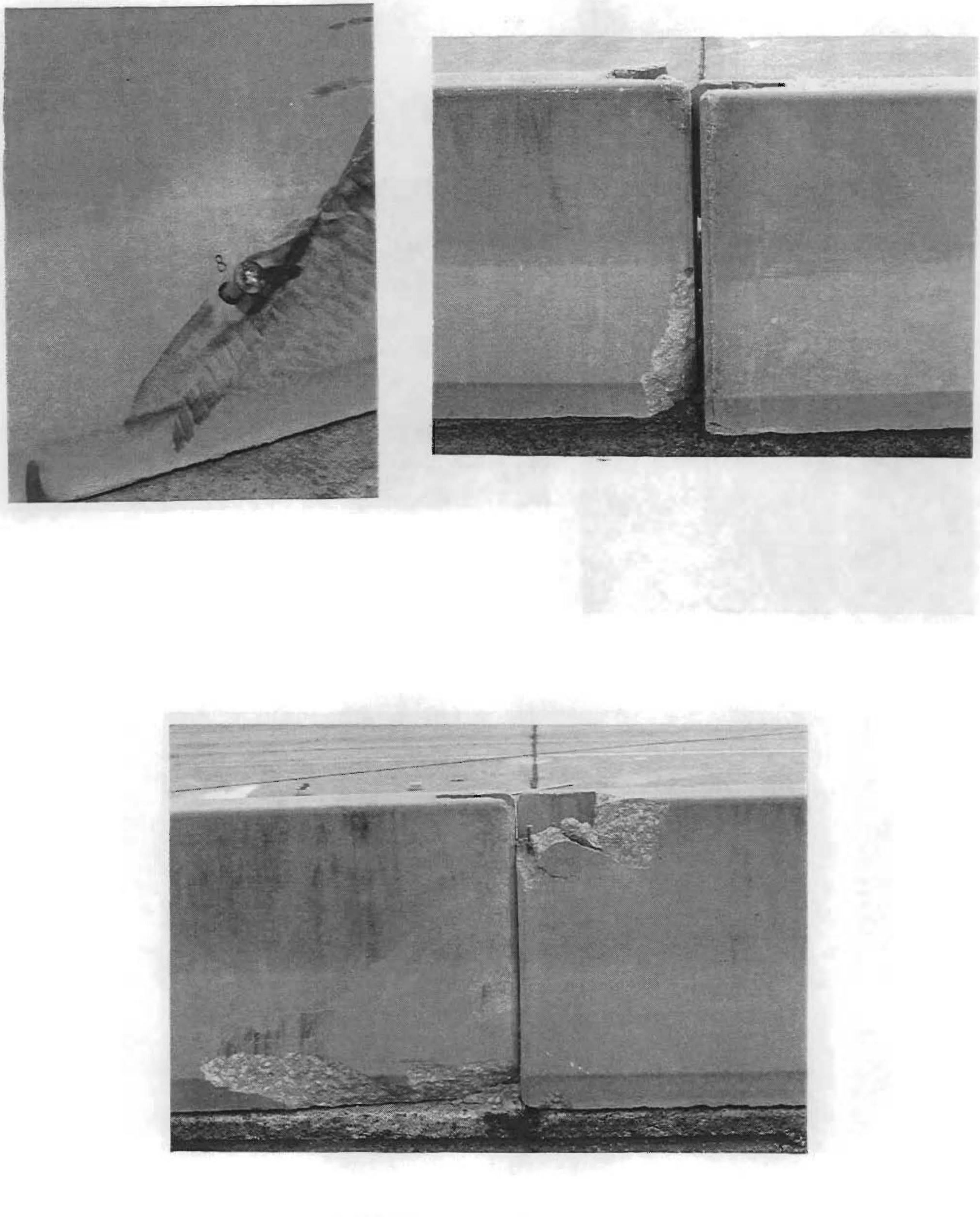


Figure 36. Details of damage to concrete barrier anchorage points (test 1959A-4).

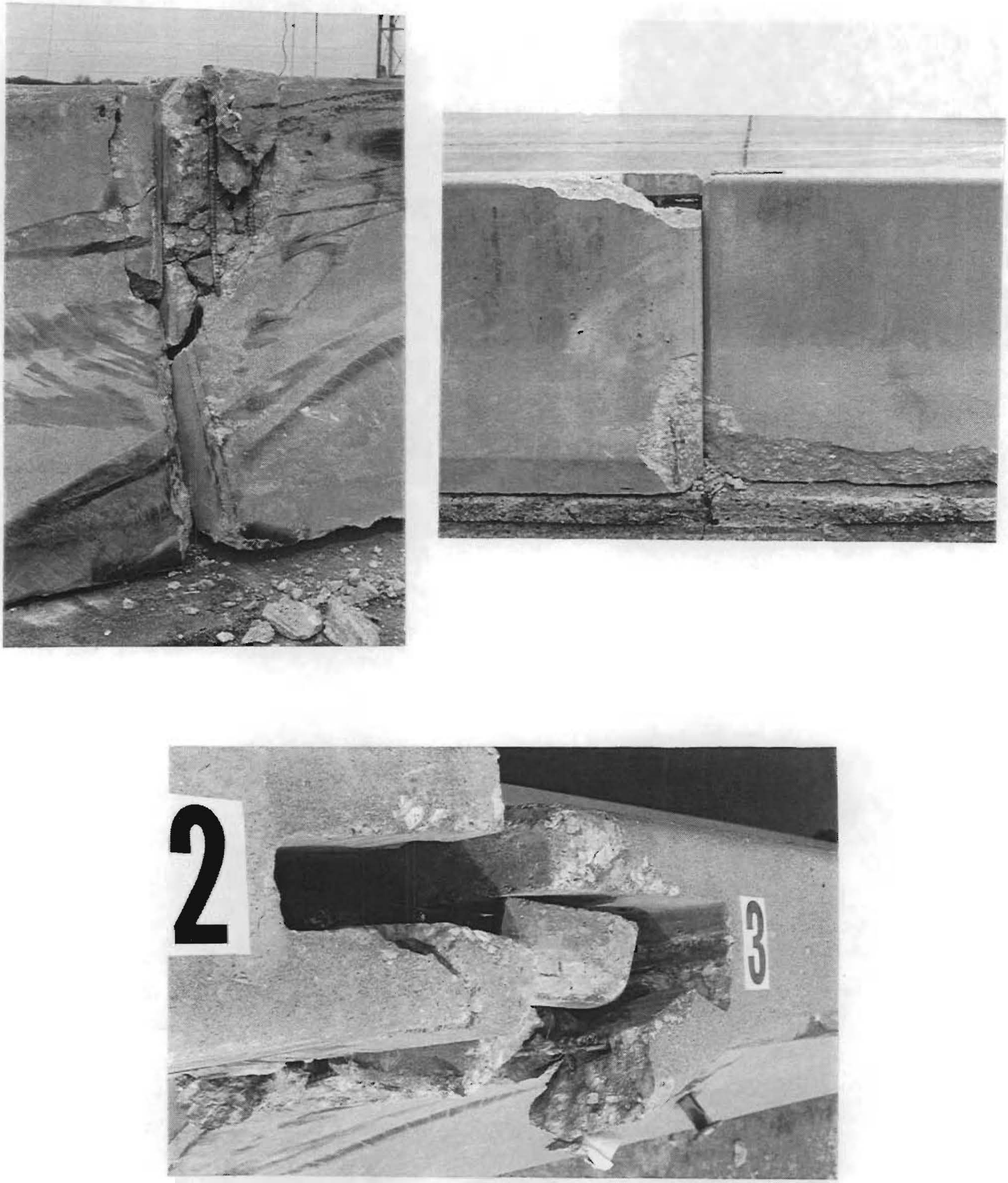


Figure 36. Details of damage to concrete barrier anchorage points (test 1959A-4) continued.

Figure 37. Post test damage to vehicle (1959A-4).

Most of the left side body panels were scraped or bent. The frame and drive-shaft were bent.

Impact speed was 60.9 mph (97.9 km/h), and the angle of impact was 23.7 degrees. The speed of the vehicle at time of parallel was 48.9 mph (78.6 km/h). The vehicle remained in contact with and came to rest atop the barrier installation. Data from the accelerometer located at the center of gravity were digitized for evaluation of occupant risk factor and were computed as follows. In the longitudinal direction, occupant impact velocity was 18.3 ft/s (5.6 m/s) at 0.178 second; the highest 0.010-second average ridedown acceleration was -6.0 g between 0.251 and 0.261 second; and the maximum 0.050-second average acceleration was -7.2 g between 0.065 and 0.114 second. Lateral occupant impact velocity was -19.8 ft/s (6.0 m/s) at 0.120 second; the highest 0.010-second occupant ridedown acceleration was 10.4 g between 0.210 and 0.220 second; and the maximum 0.050-second average acceleration was 9.5 g between 0.046 and 0.096 second. These data and other pertinent information from the test are summarized in Figure 9. Vehicular angular displacements are displayed in Figure 67 in Appendix E. Vehicular accelerations versus time traces filtered at SAE J211 (Class 180) are presented in Figures 68 through 70 in Appendix E.

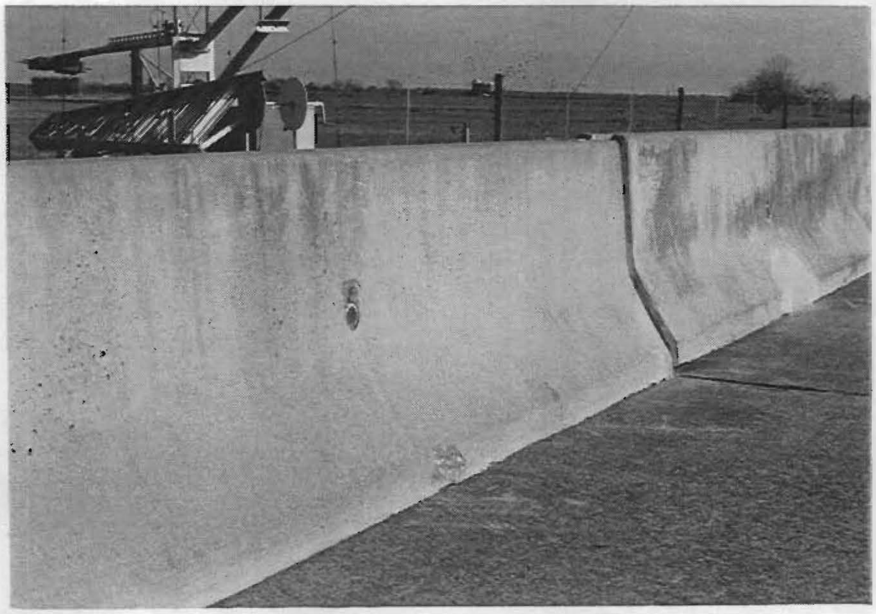
DETAILED RESULTS FOR TEST 1959A-5 (4,409 lb/44.6 mph/25.0 degrees)

A 1985 Chevrolet C-20 pickup truck, shown in Figures 38 and 39, was used for the crash test. Test inertia mass of the vehicle was 4,409 lb (2,000 kg). The distance to the lower edge of the vehicle bumper was 20.1 in. (51.1 cm) and to the top of the bumper was 29.5 in. (74.9 cm). Additional dimensions and information on the test vehicle are given in Figure 49 in Appendix C. The vehicle was directed into the barrier using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the barrier 4.5 ft (1.4 m) upstream of the end of the second barrier at a speed of 44.6 mph (71.7 km/h) and an angle of 25 degrees.

The barrier installation consisted of nine 30-ft (9.14 m) long barrier segments which were not connected to the concrete pavement. The barrier segments were attached together with a standard, ungrouted grid-slot connection. The barrier installation is shown in Figures 40 and 41.

Figure 38. Test vehicle used in 1959A-5.

Figure 39. Vehicle/barrier geometrics (test 1959A-5).



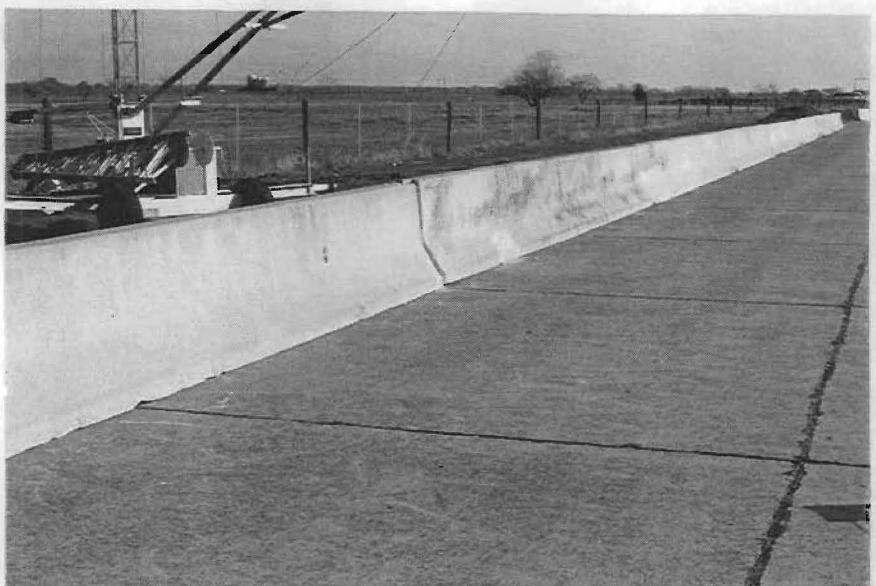


Figure 40. Limited slip concrete barrier with grid-slot connection (test installation 1959A-5).

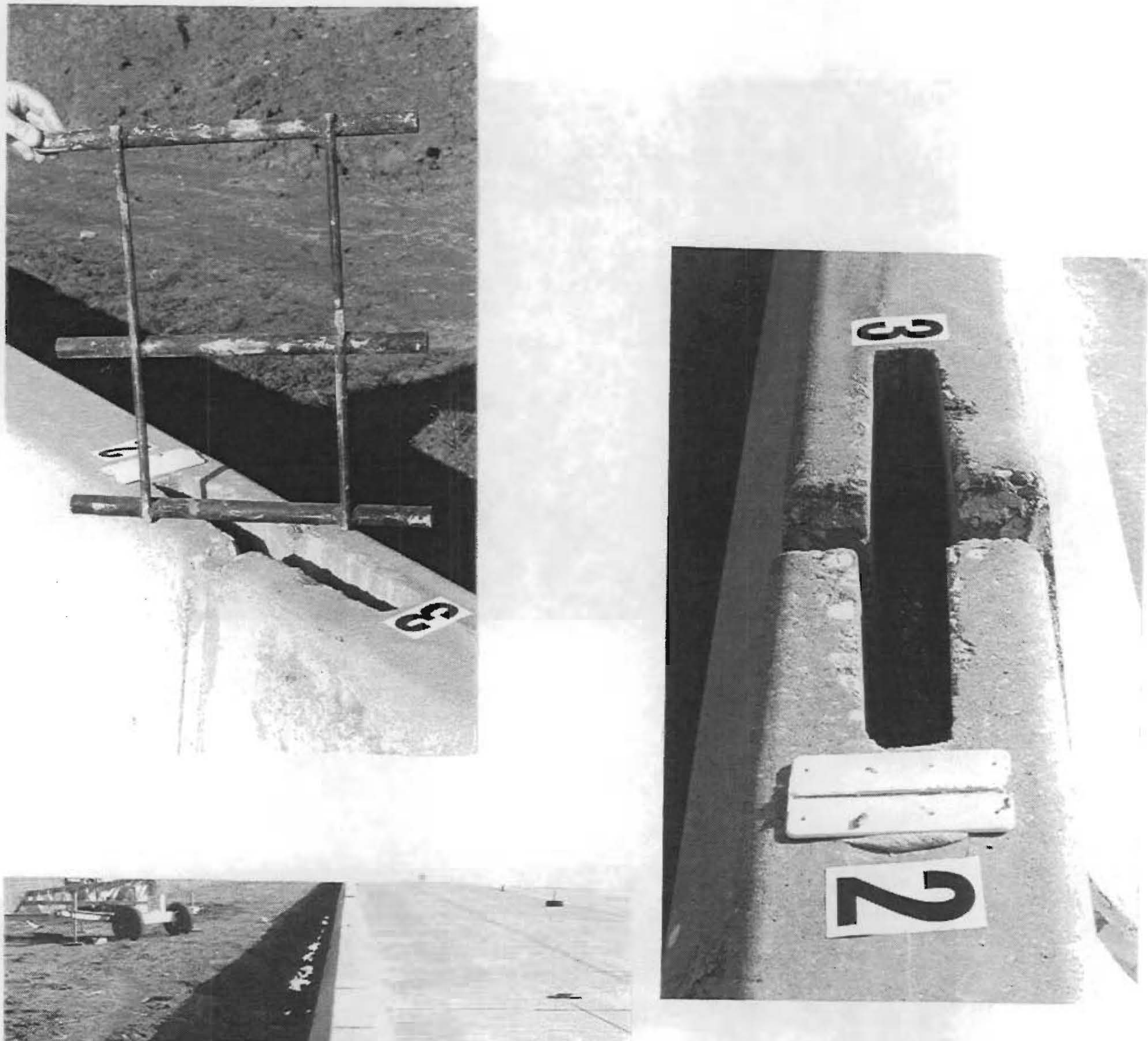


Figure 41. Connection detail for limited slip concrete barrier with grid slot connection (test installation 1959A-5).

The left front tire began to climb the face of the barrier upon impact. At approximately 0.027 second, the left front tire lost contact with the roadway and began climbing the barrier. The barrier section which was struck and the downstream contiguous barrier section began to displace rearward. By 0.190 second, the left rear tire had also lost contact with the ground and was beginning to climb the barrier. The vehicle was traveling at an average speed of approximately 35.3 mph (56.8 km/h) while parallel to the barrier. Shortly after the left rear wheel began climbing the barrier, the right front tire lost contact with the roadway. As the vehicle continued traveling down the installation, the vehicle continued to climb until, at 0.289 second, the left front tire was atop the barrier installation. The second and third barrier segments meanwhile continued to rotate until they were displaced from the bridge deck. The vehicle rolled clockwise as the undercarriage and left front tire of the vehicle impacted the end of the already inclined, rotating barrier. As the vehicle exited the installation, the vehicle rolled over onto its right side, and the entire side of the vehicle was in contact with the roadway at 1.320 seconds. As the vehicle slid along on its side, it yawed clockwise. By 3.461 seconds, the vehicle was upright again, and both rear tires were in contact with the roadway. The vehicle came to rest 124.5 ft (38.0 m) from the point of impact. Sequential photographs are shown in Figure 54 in Appendix D.

As can be seen in Figure 42, the barrier received moderate damage at the grid slot ends of the barrier. Other damage was cosmetic (i.e., tire marks and gouges) and was limited to the face of the barrier. The second and third barrier segments were displaced from the bridge deck. The vehicle was in contact with the barrier for 13.5 ft (4.1 m).

The vehicle sustained moderate damage as shown in Figure 43. Maximum crush at the left front corner of the vehicle was 15.7 in. (40.0 cm). The floor pan was deformed 4.3 in. (11.0 cm) into the left side of the occupant compartment. In addition, damage was sustained to the front bumper, grill, hood, radiator, and all of the left front suspension components. Most of the right side body panels were scraped and/or bent. The frame was bent on the right side.

Impact speed was 44.6 mph (71.7 km/h), and the angle of impact was 25.0 degrees. The speed of the vehicle at time of parallel was 35.3 mph (56.8 km/h). The vehicle exited the installation, rolled clockwise onto its right side, and then rolled counterclockwise back into an upright position. Data from the accelerometer located at the center of gravity were

Figure 42. Post test damage to installation 1959A-5.

Figure 42. Post test damage to installation 1959A-5.

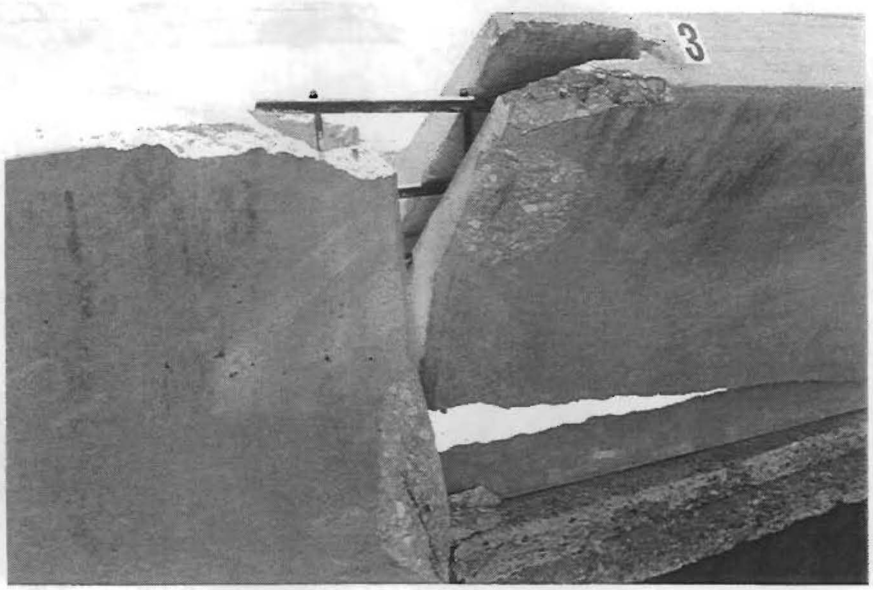


Figure 42. Post test damage to installation (1959A-5) continued.

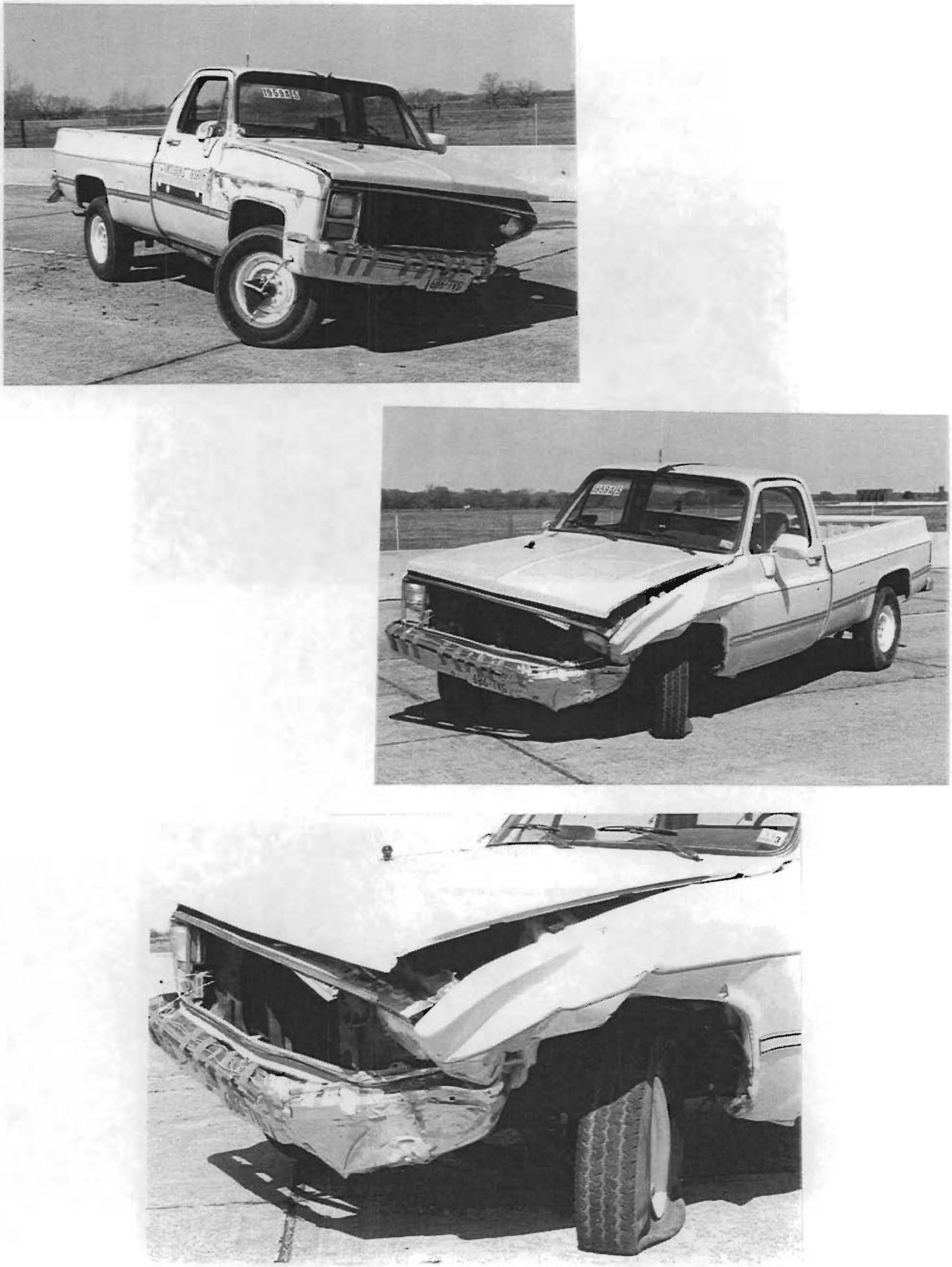


Figure 43. Post test damage to vehicle (1959A-5).

digitized for evaluation of occupant risk factor and were computed as follows. In the longitudinal direction, occupant impact velocity was 15.9 ft/s (4.9 m/s) at 0.210 second; the highest 0.010-second average ridedown acceleration was -4.0 g between 0.979 and 0.989 second; and the maximum 0.050-second average acceleration was -4.5 g between 0.027 and 0.077 second. Lateral occupant impact velocity was -13.9 ft/s (4.22 m/s) at 0.159 second; the highest 0.010-second occupant ridedown acceleration was -9.8 g between 1.308 and 1.318 second; and the maximum 0.050-second average acceleration was 5.6 g between 0.067 and 0.116 second. These data and other pertinent information from the test are summarized in Figure 10. Vehicular angular displacements are displayed in Figure 71 in Appendix E. Vehicular accelerations versus time traces filtered at SAE J211 (Class 180) are presented in Figures 72 through 74 in Appendix E.

CONCLUSIONS

A new procedure has been developed to attach PCB's to concrete pavements or bridge decks. The new attachment procedure allows the PCB's to be deployed immediately adjacent to vertical drop-offs without loss of function. The new attachment procedure involves the connection of the portable barrier sections to the pavement using steel pins which are inserted into holes drilled through the barrier and into the concrete bridge deck or pavement. These steel pins are capable of fully resisting the shear force imparted to the barrier by the impact and of partially resisting the overturning moment.

The new attachment procedure was shown to be effective with PCB's which employ typical TxDOT channel/angle splice and grid slot connections. The crash tests used to prove the effectiveness of the concept involved 4,500-lb (2,043 kg) 3/4-ton pickups impacting with speeds of 62.1 mph (100 km/h) at impact angles of 25 degrees. These criteria are representative of the strength criteria presented in NCHRP 350 for the testing of permanent barrier installations and are more severe than the analogous criteria presented in NCHRP 230.

Further, results of tests conducted with unanchored barriers suggest that, while this system is capable of redirecting an errant vehicle, the portable barrier sections will be dislodged from the pavement during the impact. This was the case even with a low speed [45 mph (72.5 km/h)] impact. Once the PCB has been dislodged from the pavement, the drop-off will be left unprotected for the next errant vehicle. Further, if the temporary barrier is originally deployed above another roadway, it is possible that the dislodged barrier sections will be introduced as a sudden hazard into the secondary roadway. Therefore, results of these tests would suggest that it is not acceptable to deploy PCB immediately adjacent to a vertical drop-off.

A new limited-slip barrier connection has been developed which allows a PCB to be attached to concrete pavement or bridge deck. The new connection can be used to successfully anchor a PCB to the concrete roadway in cases where it is necessary to deploy the PCB immediately adjacent to a vertical drop-off. The performance of the system has been demonstrated through full-scale crash tests. Immediate implementation of the new limited-slip barrier connection is recommended.

APPENDIX A.
FABRICATION DETAILS FOR LIMITED SLIP CONNECTION

SUMMARY OF LIMITED-SLIP BARRIER MODIFICATION

The limited-slip barrier modification consists of drilling each 30-ft (9.1-m) barrier segment with four 1 3/8-in (3.49-cm) diameter holes. The entry point for each holes is located 6 1/2 in. (16.51 cm) up from the first break in the barrier face as shown in Figure 44. The centerline of the holes should make an angle of 40.1 degrees with respect to a horizontal axis.

The four holes are to be spaced along the length of the barrier as shown in Figure 44. However, it should be noted that the longitudinal spacing of the four holes is not believed to be critical. Therefore, as suggested in Figure 44, we feel that the precise placement of the holes can be varied by as much as plus or minus 18 in. (45.72 cm) without cause for concern.

The modification to the bridge deck or concrete pavement is accomplished by first placing the predrilled barrier segments in the desired position. Then, the predrilled holes in the barrier segments are used as guides for drilling the concrete bridge deck or pavement. The depth of penetration into the underlying concrete surface is controlled by limiting the depth of penetration to 21 in. (53.34 cm). This results in a vertical penetration of the bridge deck or pavement of slightly more than 5 in. (12.7 cm) in the worst case situation. This vertical penetration is not sufficient to produce a hole completely through most concrete bridge decks.

Each barrier segment is then secured in place by inserting four 1 1/4-in. (3.18-cm) diameter steel pins which are 20 1/2 in. (52.07 cm) long into the holes. Figure 44 presents a sketch of the steel pins. The pins were designed on the basis of a minimum yield strength of 36 ksi (248 mPa). In addition, it is suggested that the pins have a steel washer welded to the top at an angle of about 5 degrees so that the washer will lie flush with the barrier surface as shown in Figure 44. The purpose of the washer is to permit easy removal of the pins when the barrier deployment is complete.

The limited-slip barrier attachment is intended for use with PCB's which employ the standard TxDOT channel/angle spice connection or the standard TxDOT grid slot connection.

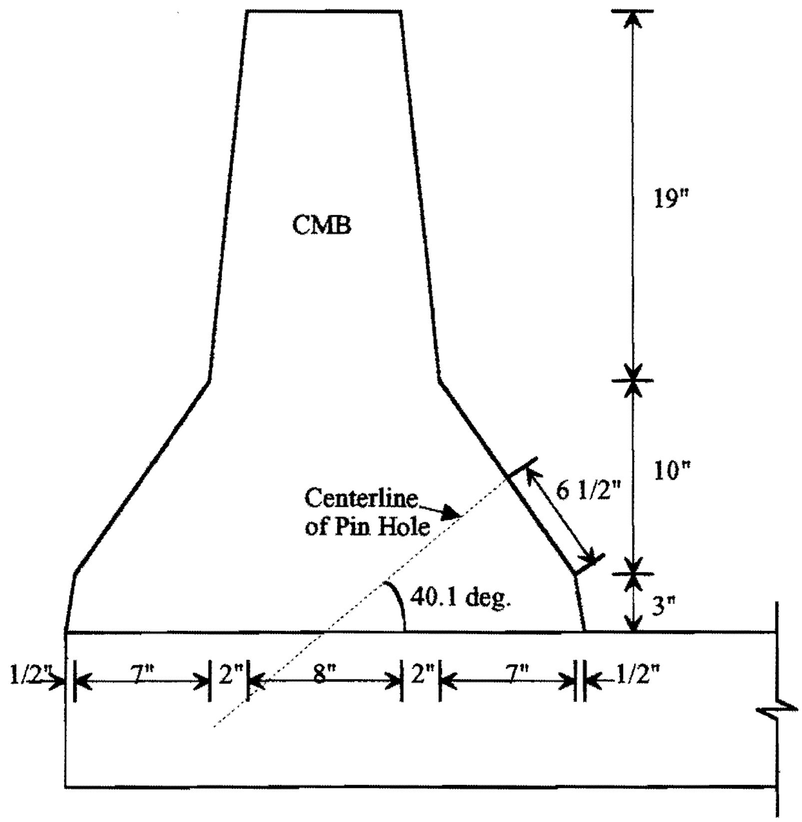


Figure 44. Fabrication details for limited slip pin connection.

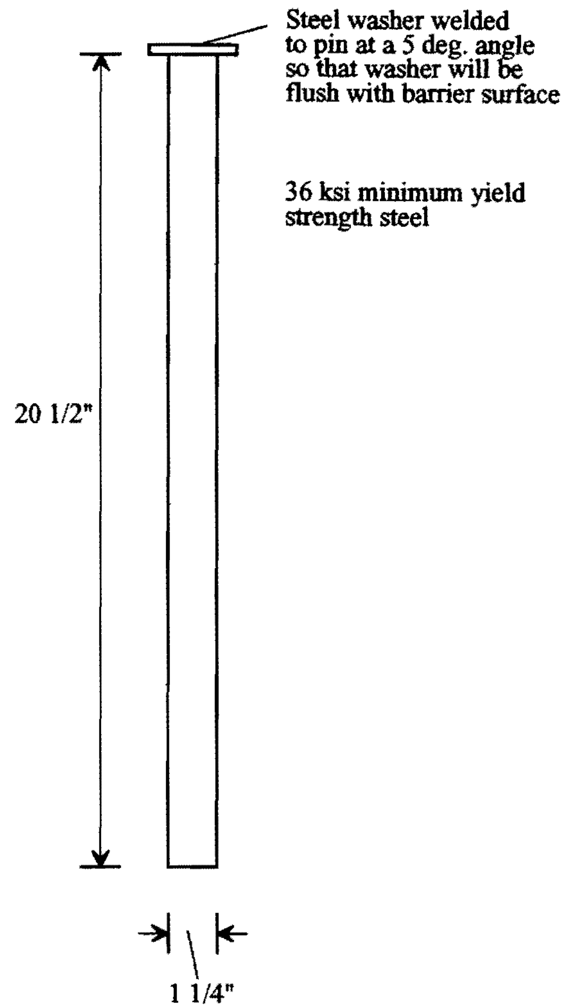
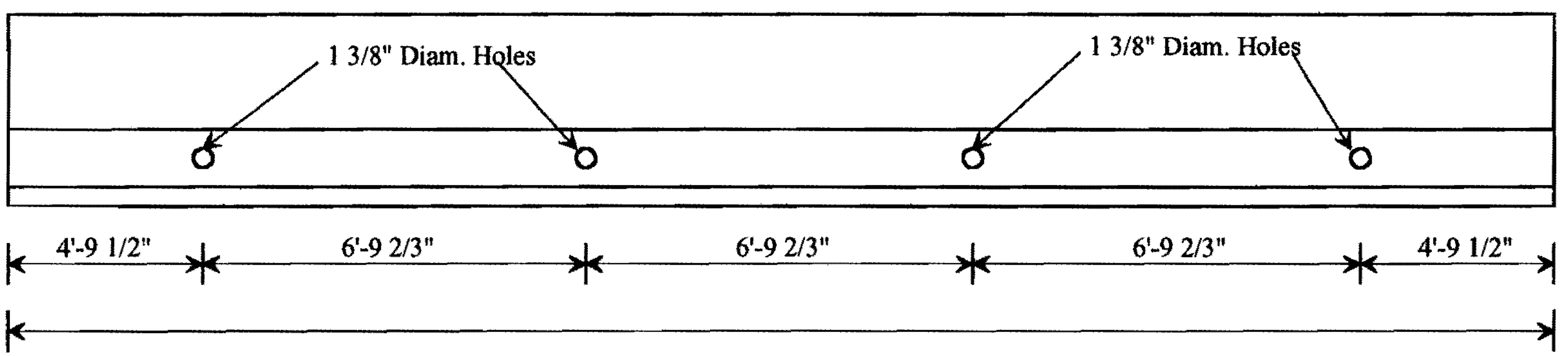


Figure 44. Fabrication details for limited slip pin connection (continued).



SIDE VIEW

Hole spacings can be varied by plus or minus 18 in. as required

Figure 44. Fabrication details for limited slip pin connection (continued).

APPENDIX B.
INSTRUMENTATION AND DATA ANALYSIS

INSTRUMENTATION AND DATA ANALYSIS

ELECTRONIC INSTRUMENTATION AND DATA PROCESSING

The test vehicles used in this project were instrumented with three solid-state angular rate transducers to measure yaw, pitch, and roll rates; a triaxial accelerometer was mounted at the vehicle's center of gravity to measure longitudinal, lateral, and vertical acceleration levels; and a back-up biaxial accelerometer was installed in the rear of the vehicle to measure longitudinal and lateral acceleration levels. The accelerometers were a strain gauge type with linear millivolt output proportional to acceleration.

The electronic signals from the accelerometers and transducers were transmitted to a base station by means of a constant-bandwidth, FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Provision was made for the transmission of calibration signals before and after the test, and an accurate time reference signal was simultaneously recorded with the data. Pressure sensitive contact switches on the bumpers were actuated just prior to impact by wooden dowels. These indicated the elapsed time over a known distance in order to provide a measurement of impact velocity. The initial contact also produced an "event" mark on the data record to establish the exact instant of contact with the barrier.

The multiplex of data channels transmitted on one radio frequency was received at a data acquisition station and demultiplexed into separate tracks of Intermediate Range Instrumentation Group (I.R.I.G.) tape recorders. After the test, the data were played back from the tape machines, filtered with a SAE J211 Class 180 filter, and digitized using a microcomputer for analysis and evaluation of impact performance. The digitized data were then processed using two computer programs: DIGITIZE and PLOTANGLE. Brief descriptions on the functions of these two computer programs are as follows.

The DIGITIZE program uses digitized data from vehicle-mounted linear accelerometers to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 10-millisecond average ridedown acceleration. The DIGITIZE program also calculates vehicle impact velocity and the change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-millisecond intervals in each of the three directions are computed. Acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted from the digitized data of the vehicle-mounted linear accelerometers using a commercially available software package (QUATTRO PRO).

The PLOTANGLE program uses the digitized data from the yaw, pitch, and roll rate charts to compute angular displacement in degrees at 0.00067-second intervals and then instructs a plotter to draw a reproducible plot of yaw, pitch, and roll versus time. It should be noted that these angular displacements are sequence dependent with the sequence being yaw-pitch-roll for the data presented herein. These displacements are in reference to the vehicle-fixed coordinate system, with the initial position and orientation of the vehicle-fixed coordinate system being that which existed at initial impact.

PHOTOGRAPHIC INSTRUMENTATION AND DATA PROCESSING

Photographic coverage of the tests included three high-speed cameras: one overhead with a field of view perpendicular to the ground and directly over the impact point; one placed with field of view parallel to and aligned with the face of the barrier at the downstream end; and a third placed perpendicular to the front of the barrier. A flash bulb, visible from each camera and activated by a pressure sensitive tape switch, was positioned on the impacting vehicle to indicate the instant of contact with the barrier. 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 professional video camera, a 3/4-in. video recorder, and a 35-mm camera were used for documentary purposes to record conditions of the test vehicles and the barrier before and after the test.

TEST VEHICLE PROPULSION AND GUIDANCE

Each test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding each test vehicle was tensioned along the vehicle travel path. The guide cable was threaded through a guide rod attached to the front spindle of each test vehicle. An additional steel cable was attached to the front of each test vehicle, passed to and around a pulley near the impact point and to and around an additional pulley mounted to the tow vehicle, and then anchored to the ground. This configuration allowed the tow vehicle to move away from the test site with a 2-to-1 speed ratio between the test vehicle and tow vehicle. Immediately prior to impact with the barrier, each test vehicle was released to became free-wheeling and unrestrained. The vehicles remained free-wheeling (i.e., no steering or braking inputs) until they cleared the immediate area of the test site. At that time, brakes on the vehicles were activated to bring the vehicles to safe and controlled stops.

APPENDIX C.
GEOMETRICS OF CRASH TEST VEHICLES

DATE: 11/12/92 TEST NO.: 1959A-1 VIN NO.: 1GCG24M5FS104060 MAKE: Chevrolet

MODEL: C-250 YEAR: 1985 ODOMETER: 94706 GVW:

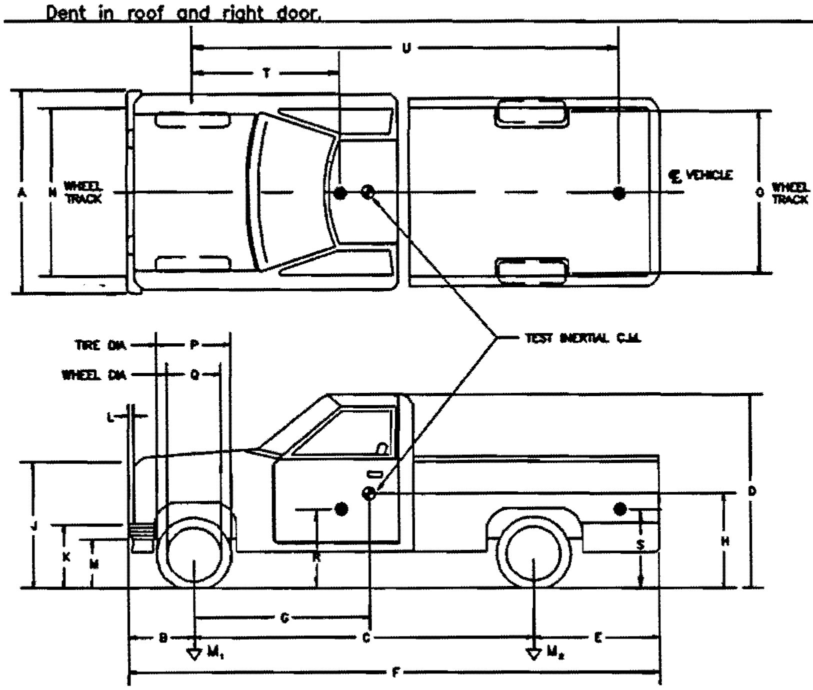
TIRE SIZE: LT 235-8R16 TIRE INFLATION PRESSURE: TREAD TYPE:

MASS DISTRIBUTION (lb) LF 1243 RF 1188 LR 977 RR 1001

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:

Crack in windshield marked.

Dent in roof and right door.



● Denotes accelerometer location.

NOTES: Rear 1.2 in left of centerline

ENGINE TYPE: V-8

ENGINE CID: 5.7 Liter

TRANSMISSION TYPE:

— AUTO

X MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE:

MASS:

SEAT POSITION:

Metric Conversion:
1 in = 25.4 mm
1 lb = 0.454 kg

GEOMETRY - (in)

A 79.0	E 49.6	J 45.7	N 65.4	R 26.6
B 31.7	F 212.8	K 27.4	O 65.6	S 40.4
C 131.5	G 59.0	L 2.2	P 31.1	T 60.8
D 72.1	H	M 18.3	Q 17.5	U 166.5

MASS - (lb)	CURB	TEST INERTIAL	GROSS STATIC
M_1	2590	2432	
M_2	2080	1978	
M_T	4670	4410	

Figure 45. Vehicle properties for test 1959A-1.

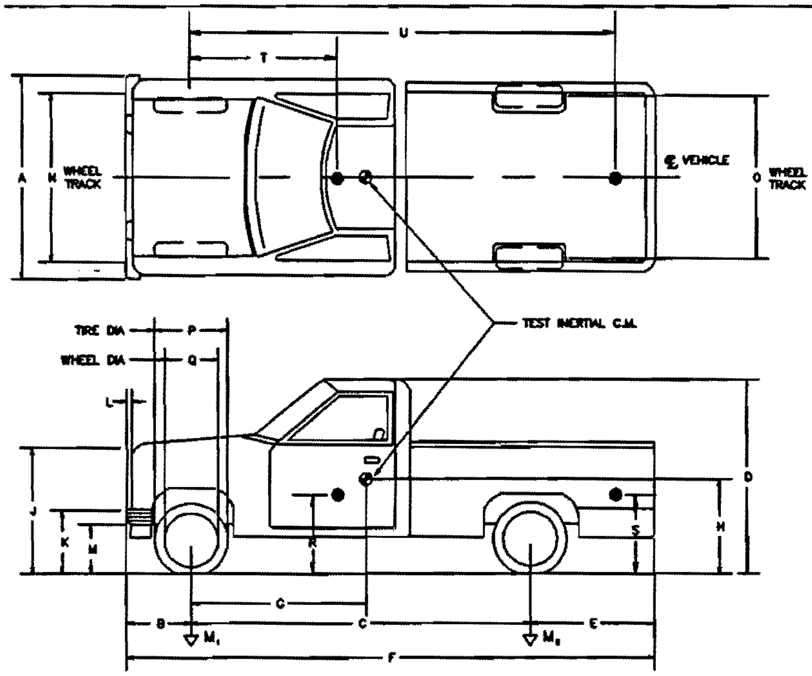
DATE: 12/02/92 TEST NO.: 1959A-2 VIN NO.: 1FTHF25YXGNB14435 MAKE: Ford

MODEL: F-250 YEAR: 1986 ODOMETER: 51905 GVW:

TIRE SIZE: 7.50-16LT TIRE INFLATION PRESSURE: TREAD TYPE:

MASS DISTRIBUTION (lb) LF 1191 RF 1058 LR 1023 RR 1138

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:



● Denotes accelerometer location.

NOTES: Rear 0.6 in right of centerline

ENGINE TYPE: 6 cylinder

ENGINE CID: 4.9 Liter

TRANSMISSION TYPE:

— AUTO

X MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE:

MASS:

SEAT POSITION:

Metric Conversion:
1 in = 25.4 mm
1 lb = 0.454 kg

GEOMETRY – (in)

A	77.2	E	50.4	J	45.3	N	64.0	R	28.9
B	27.0	F	210.4	K	29.1	O	64.8	S	43.3
C	133.1	G	65.2	L	0.8	P	29.9	T	64.2
D	74.0	H		M	19.7	Q	17.3	U	163.8

MASS – (lb)	CURB	TEST INERTIAL	GROSS STATIC
M_1	2249	2249	
M_2	2161	2161	
M_T	4410	4410	

Figure 46. Vehicle properties for test 1959A-2.

DATE: 12/09/92 TEST NO.: 1959A-3 VIN NO.: 1FTHF25Y9GNA85297 MAKE: Ford

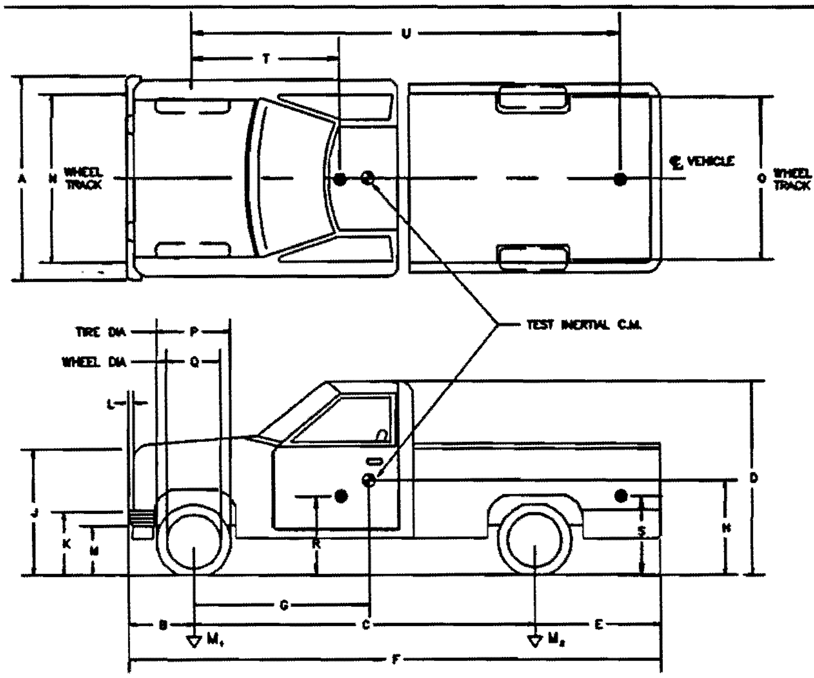
MODEL: F-250 YEAR: 1986 ODOMETER: 107382 GVW:

TIRE SIZE: LT 245/75R16 TIRE INFLATION PRESSURE: TREAD TYPE:

MASS DISTRIBUTION (lb) LF 1142 RF 1144 LR 1076 RR 1047

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:

Crack in windshield marked.



● Denotes accelerometer location.

NOTES: Rear 0.8 in right of centerline

ENGINE TYPE: 6 cylinder

ENGINE CID: 4.9 Liter

TRANSMISSION TYPE:

— AUTO

X MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE:

MASS:

SEAT POSITION:

Metric Conversion:
1 in = 25.4 mm
1 lb = 0.454 kg

GEOMETRY - (in)

A 76.6	E 50.0	J 44.7	N 65.0	R 28.2
B 26.6	F 210.1	K 28.2	O 64.6	S 39.8
C 133.5	G 58.8	L 1.4	P 29.5	T 65.0
D 72.6	H	M 18.7	Q 17.5	U 86.0

MASS - (lb)	CURB	TEST INERTIAL	GROSS STATIC
M_1	2244	2286	
M_2	1764	2123	
M_T	4008	4409	

Figure 47. Vehicle properties for test 1959A-3.

DATE: 02/09/93 TEST NO.: 1959A-4 VIN NO.: 1FTHF25H9GKA05238 MAKE: Ford

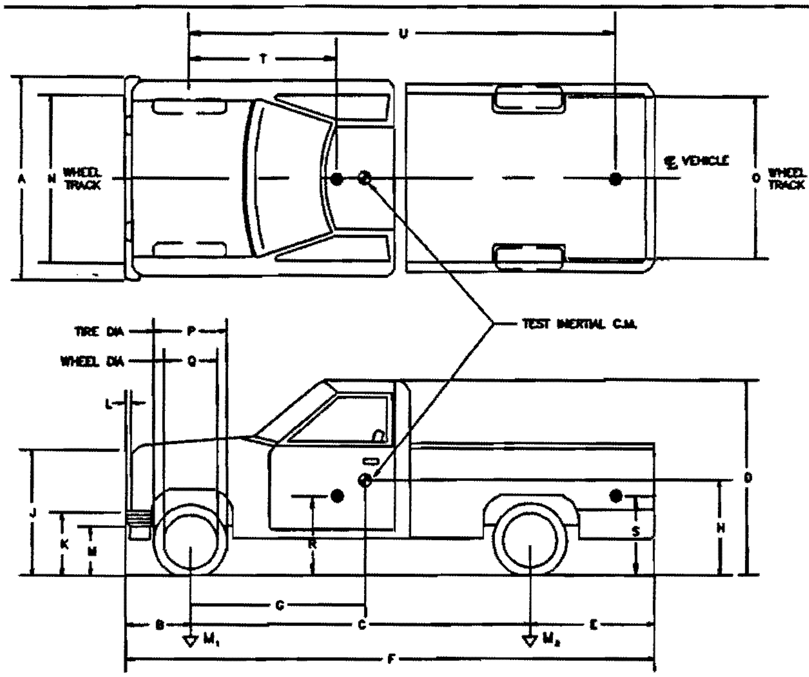
MODEL: F-250 YEAR: 1986 ODOMETER: 67790 GVW:

TIRE SIZE: 7.50 R16LT TIRE INFLATION PRESSURE: TREAD TYPE:

MASS DISTRIBUTION (lb) LF 1209 RF 1236 LR 985 RR 976

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:

Crack in windshield marked.



● Denotes accelerometer location.

NOTES:

ENGINE TYPE: 8 cyl gas

ENGINE CID: 5.8 liters

TRANSMISSION TYPE:

X AUTO

— MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE:

MASS:

SEAT POSITION:

Metric Conversion:
1 in = 25.4 mm
1 lb = 0.454 kg

GEOMETRY - (in)

A	76.0	E	52.8	J	46.1	N	65.7	R	29.5
B	28.3	F	214.8	K	28.5	O	64.4	S	40.9
C	133.7	G	59.5	L	1.6	P	31.9	T	59.8
D	73.2	H		M	18.9	Q	17.5	U	167.5

MASS - (lb)	CURB	TEST INERTIAL	GROSS STATIC
M_1	2482	2445	
M_2	1753	1960	
M_T	4235	4405	

Figure 48. Vehicle properties for test 1959A-4.

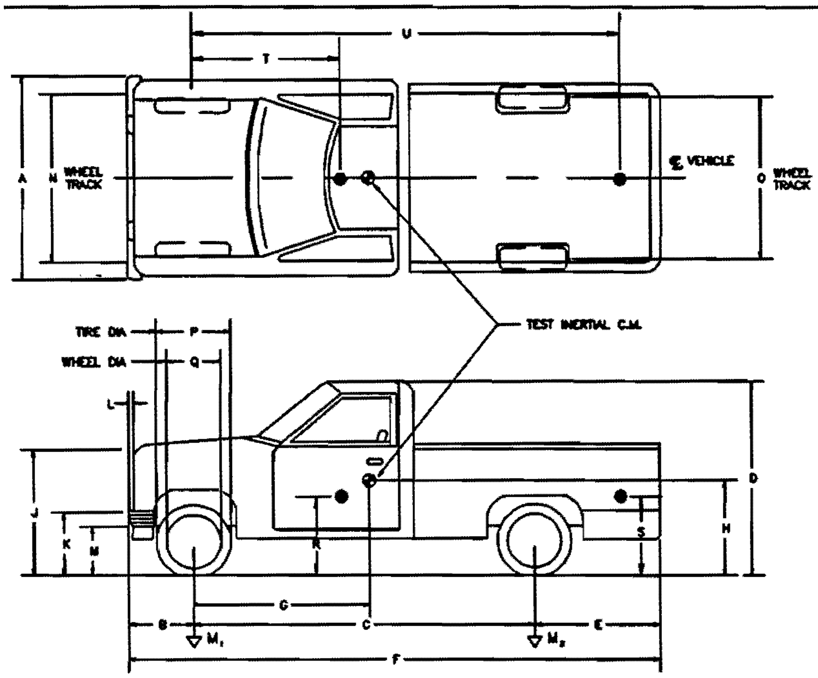
DATE: 03/09/93 TEST NO.: 1959A-5 VIN NO.: 1GCGC24M4FF435026 MAKE: Chevrolet

MODEL: C-20 YEAR: 1985 ODOMETER: 80590 GVW:

TIRE SIZE: 8.75-16.5LT TIRE INFLATION PRESSURE: TREAD TYPE:

MASS DISTRIBUTION (lb) LF 1281 RF 1250 LR 889 RR 1008

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:



● Denotes accelerometer location.

NOTES: Rear 0.8 in right of centerline

ENGINE TYPE: 8 cyl gas

ENGINE CID: 350

TRANSMISSION TYPE:

X AUTO

— MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE:

MASS:

SEAT POSITION:

Metric Conversion:
1 in = 25.4 mm
1 lb = 0.454 kg

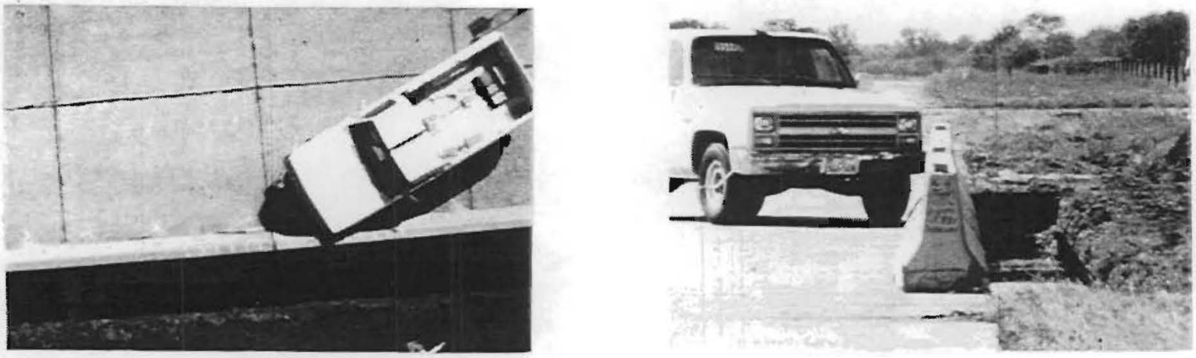
GEOMETRY - (in)

A 77.6	E 48.0	J 47.6	N 65.9	R 41.5
B 31.7	F 211.2	K 29.5	O 65.9	S 41.5
C 131.5	G 59.5	L 3.3	P 31.1	T 58.7
D 74.8	H	M 20.1	Q 17.6	U 168.9

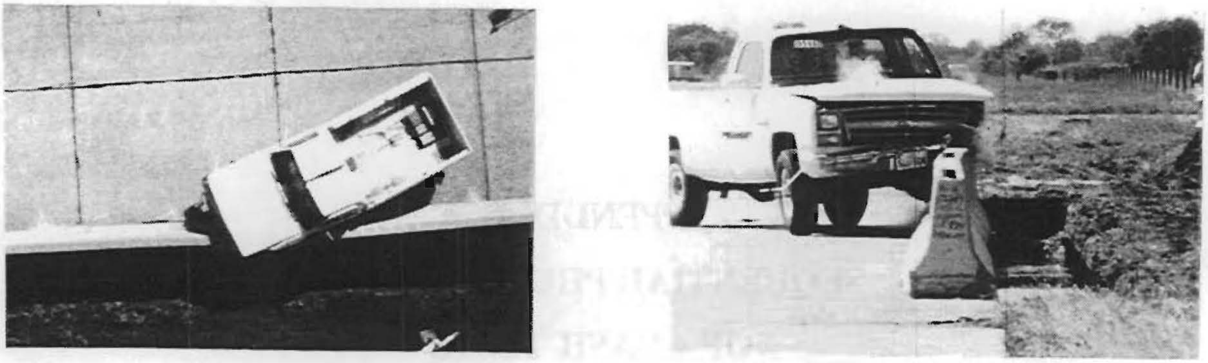
MASS - (lb)	CURB	TEST INERTIAL	GROSS STATIC
M_1	2531	2414	
M_2	1896	1995	
M_T	4427	4409	

Figure 49. Vehicle properties for test 1959A-5.

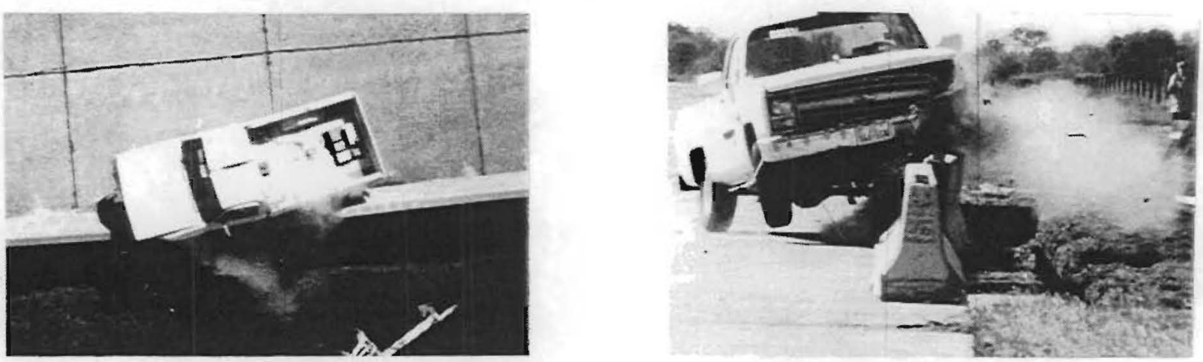
APPENDIX D.
SEQUENTIAL PHOTOGRAPHS OF CRASH TESTS



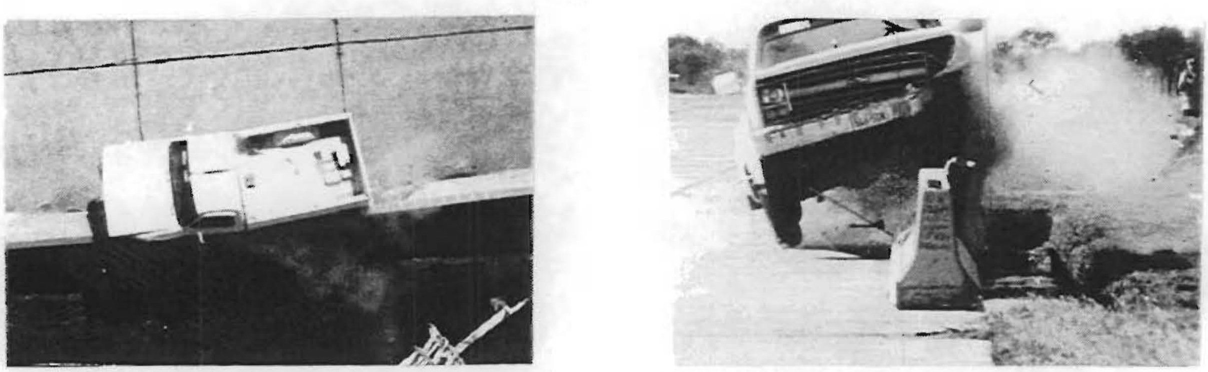
0.000 s



0.088 s

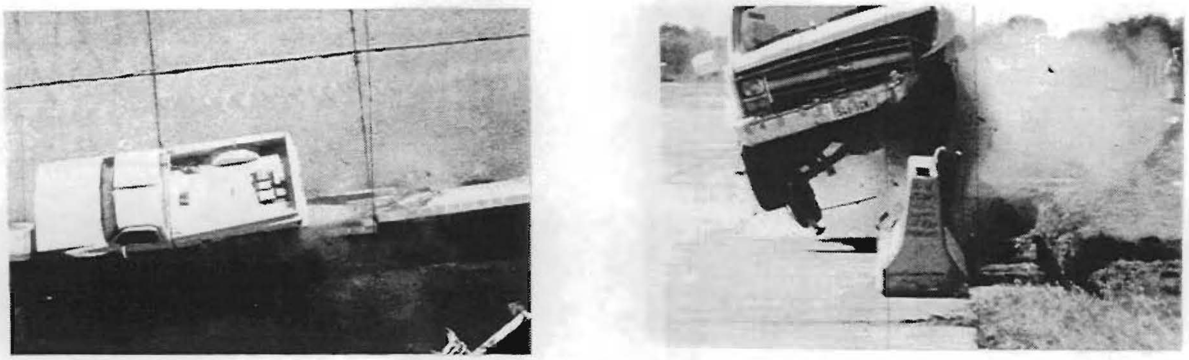


0.176 s

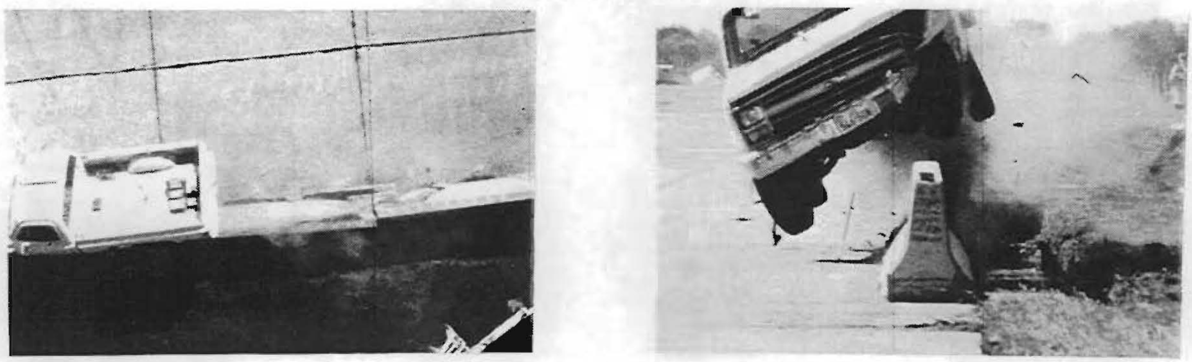


0.264 s

Figure 50. Sequential photographs for test 1959A-1. (overhead and frontal views),

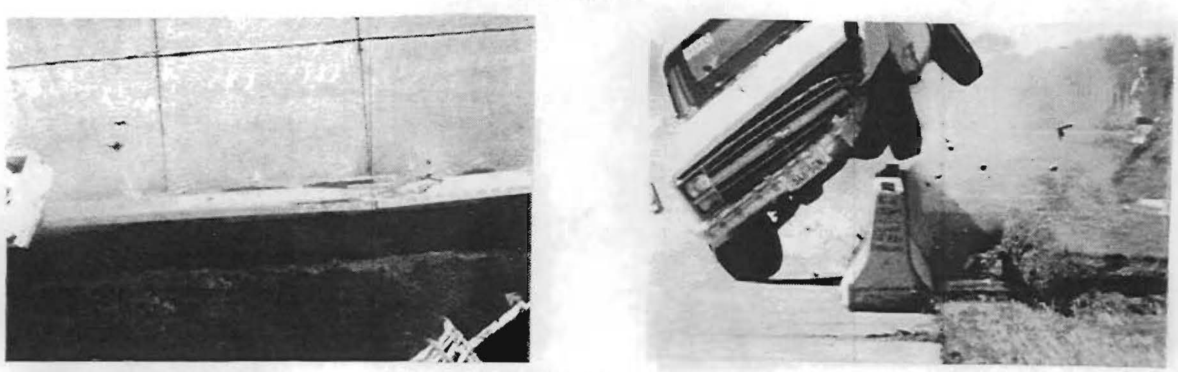


0.351 s



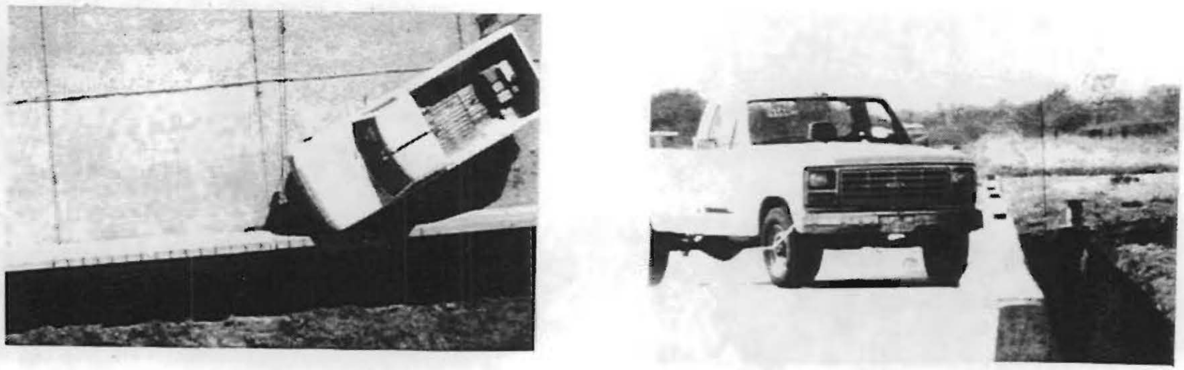
0.439 s

0.527 s

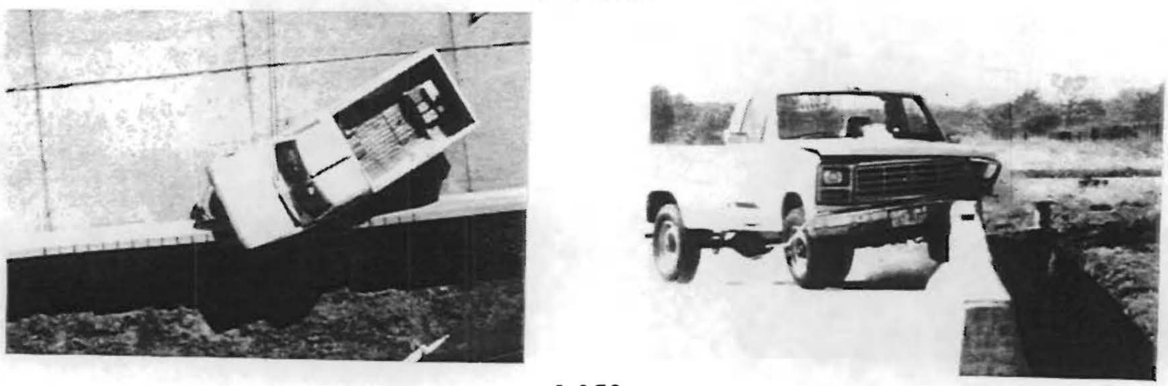


0.615 s

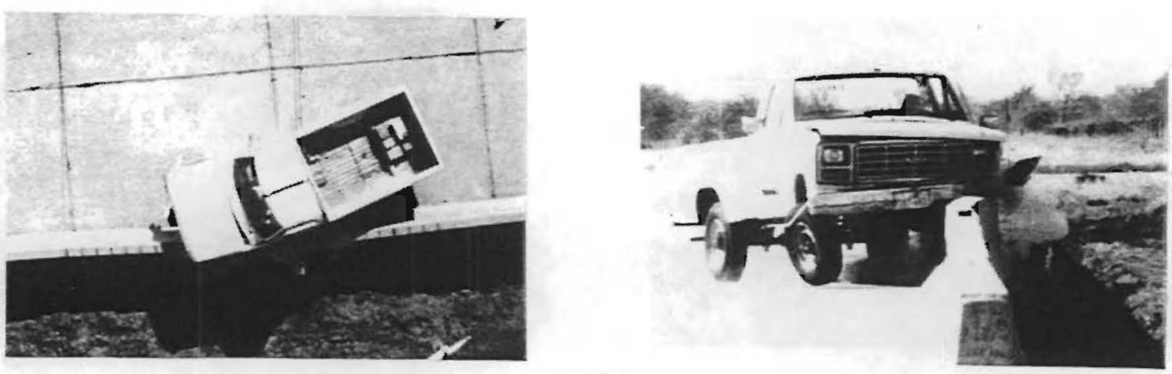
Figure 50. Sequential photographs for test 1959A-1.
(overhead and frontal views continued).



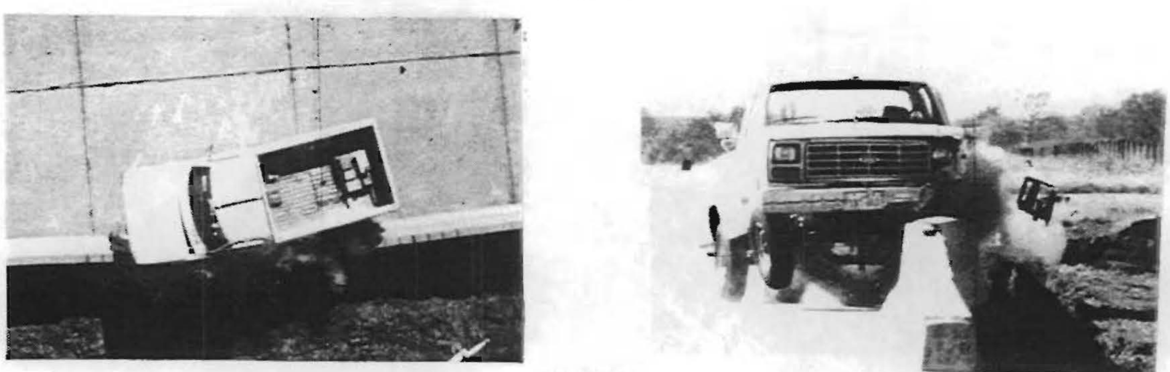
0.000 s



0.059 s

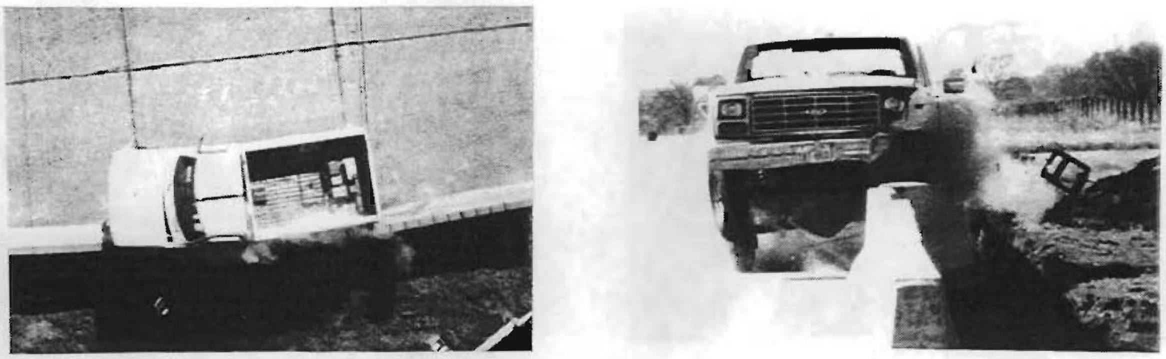


0.119 s



0.178 s

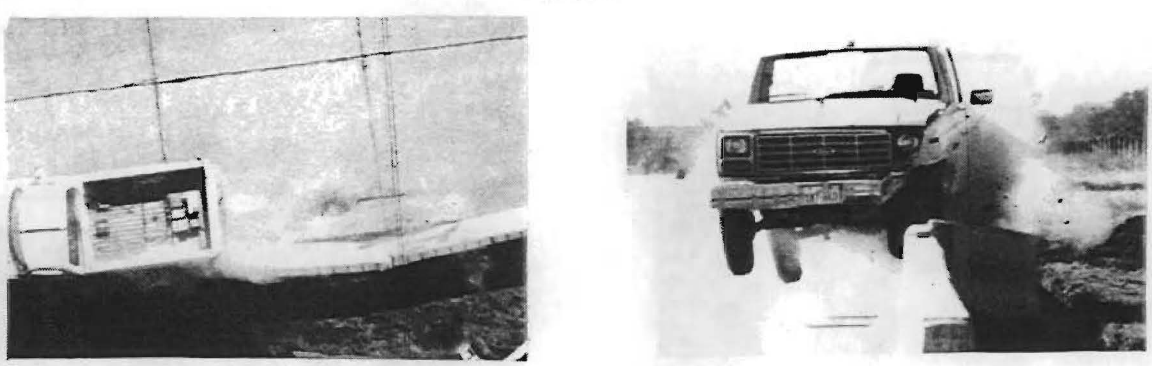
Figure 51. Sequential photographs for test 1959A-2.
(overhead and frontal views)



0.238 s

0.297 s

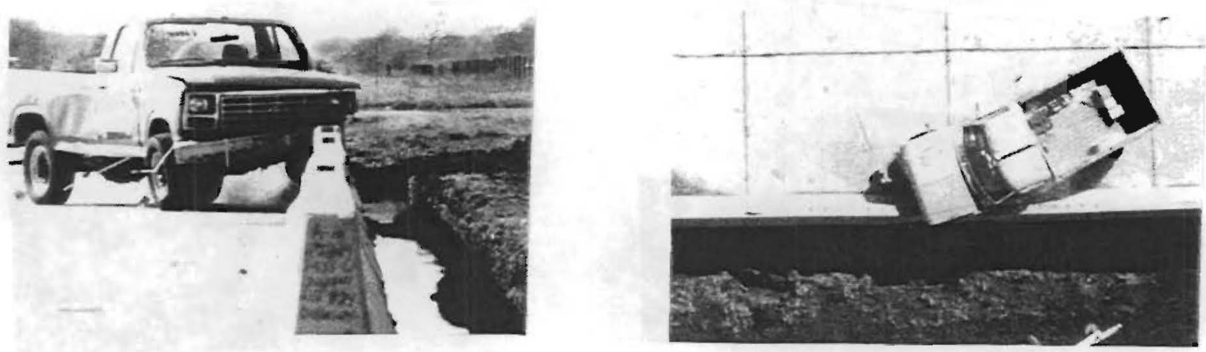
0.356 s



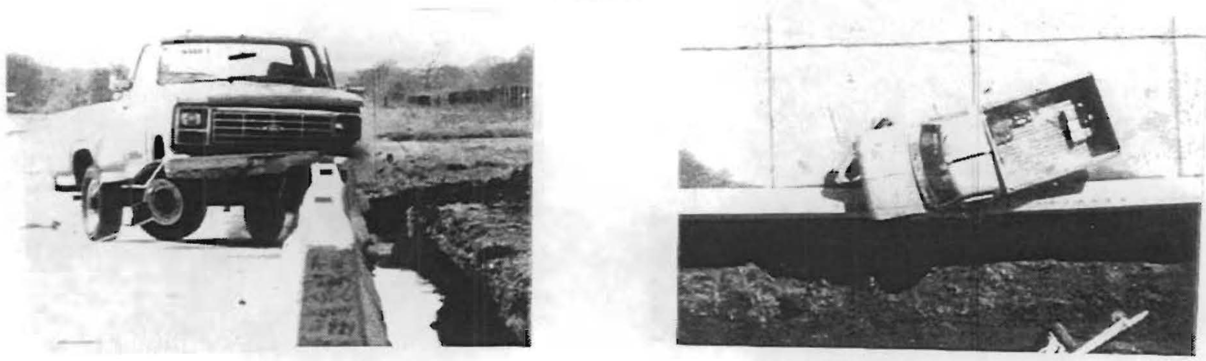
0.416 s

Figure 51. Sequential photographs for test 1959A-2.
(overhead and frontal views continued).

0.000 s



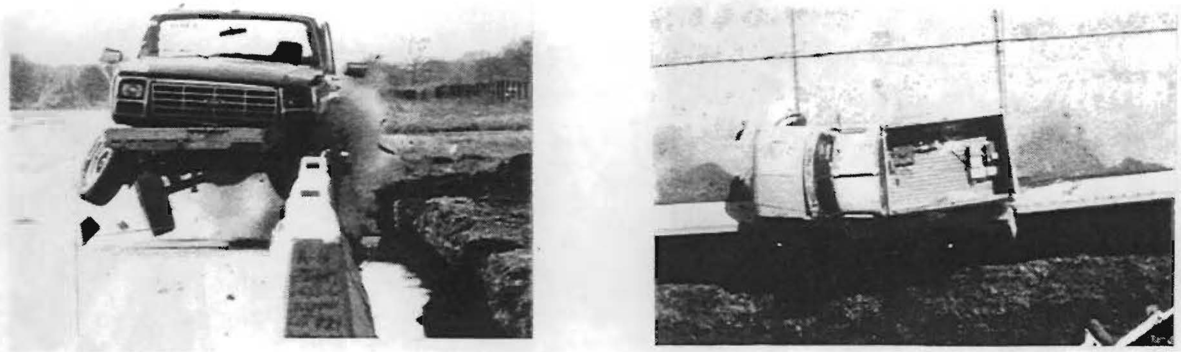
0.067 s



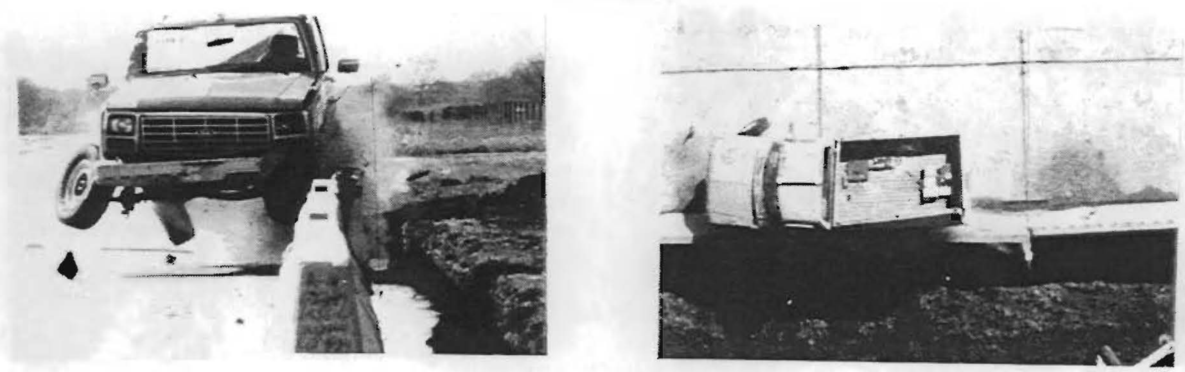
0.135 s

0.202 s

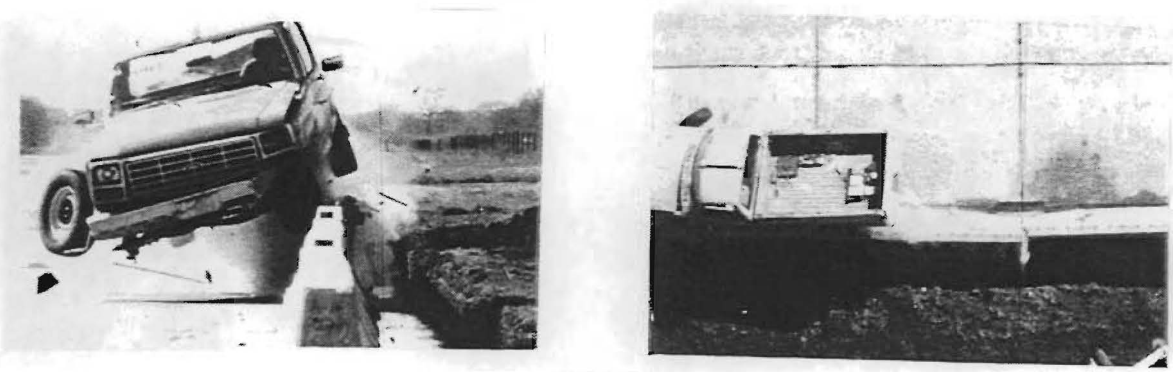
Figure 52. Sequential photographs for test 1959A-3. (overhead and frontal views).



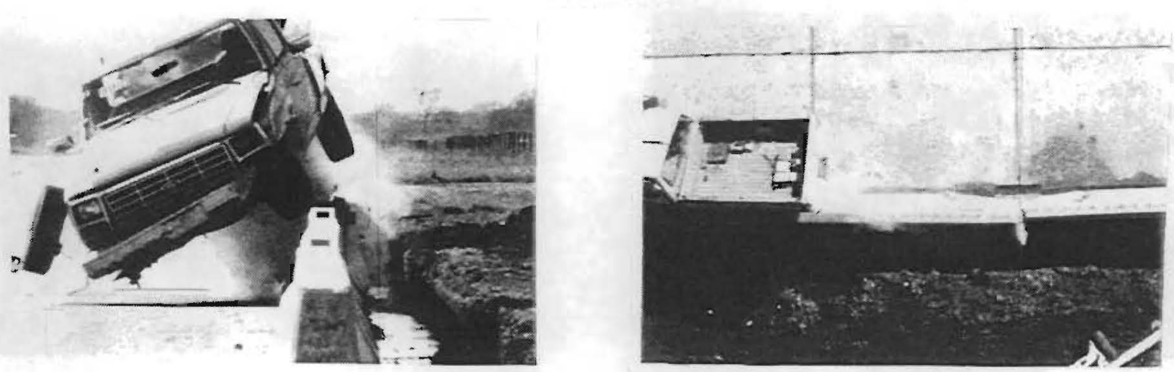
0.269 s



0.337 s

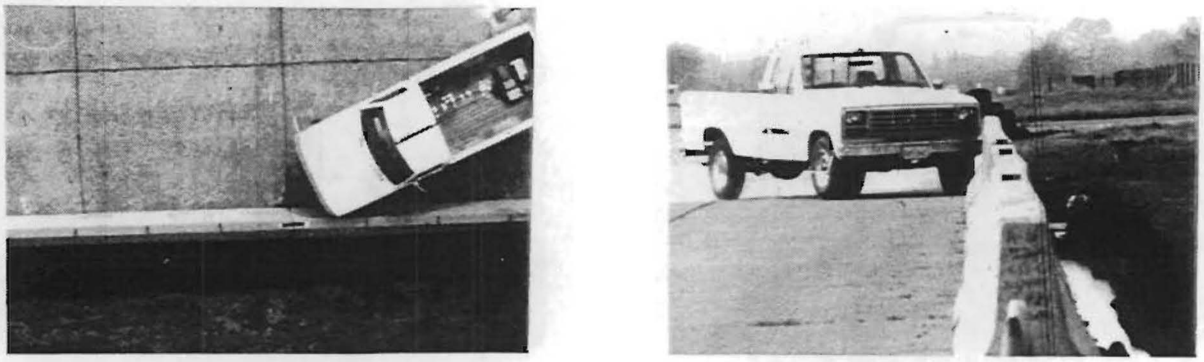


0.404 s

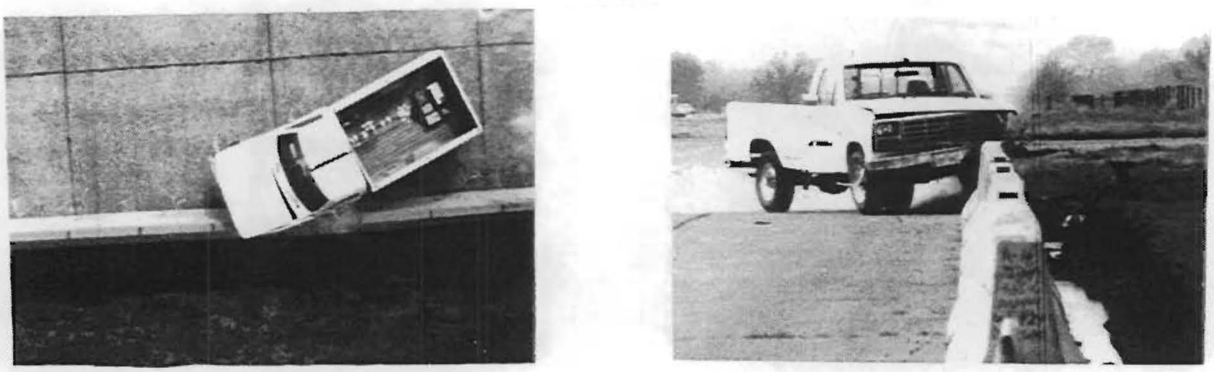


0.471 s

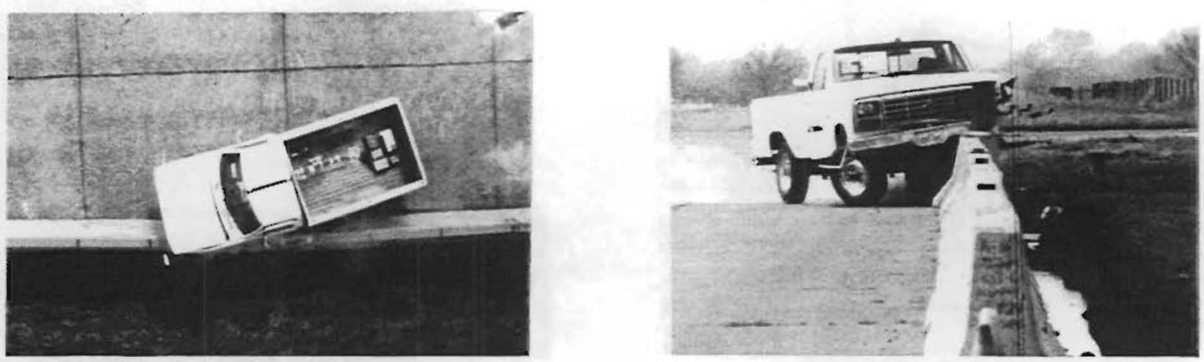
Figure 52. Sequential photographs for test 1959A-3.
(overhead and frontal views continued).



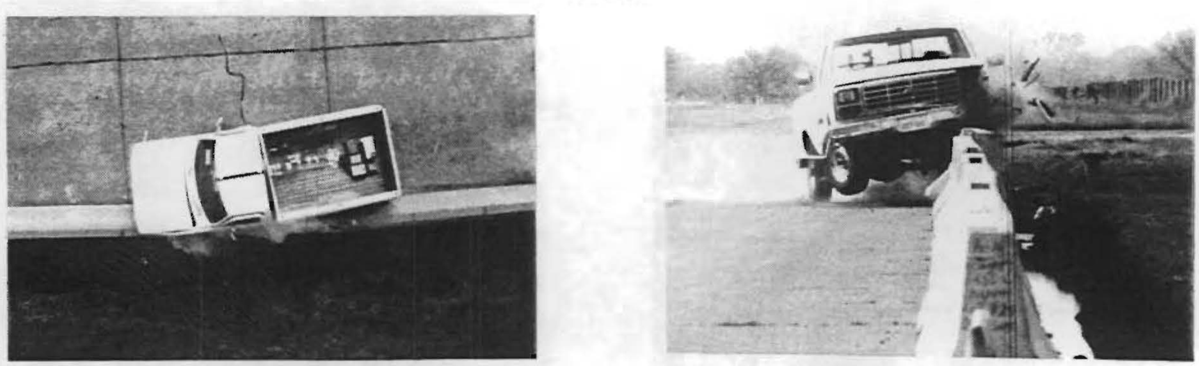
0.000 s



0.064 s

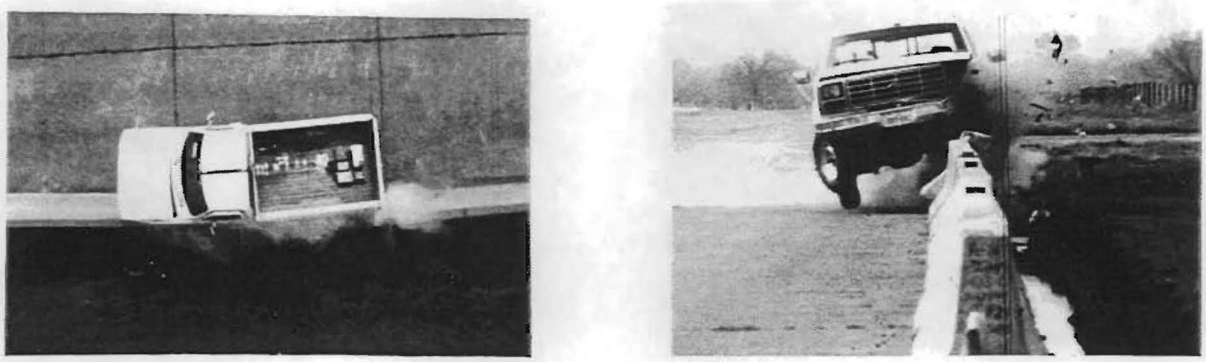


0.128 s

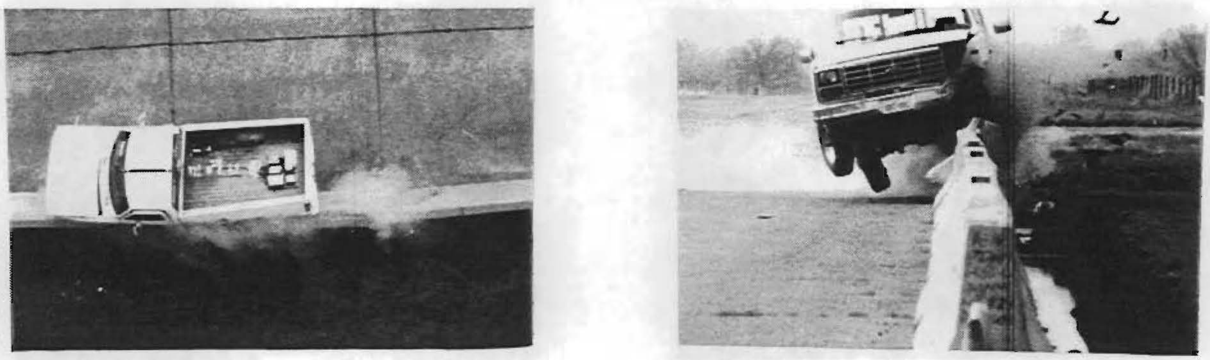


0.192 s

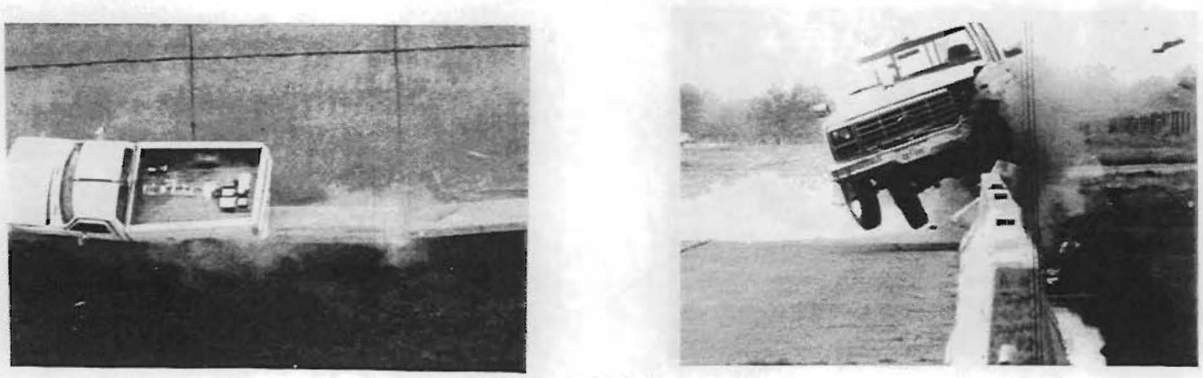
Figure 53. Sequential photographs for test 1959A-4.
(overhead and frontal views).



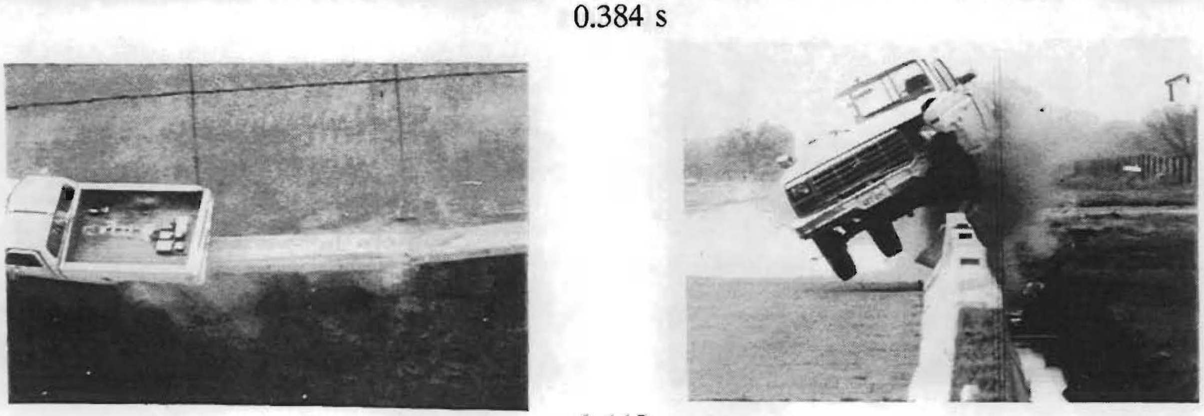
0.256 s



0.320 s

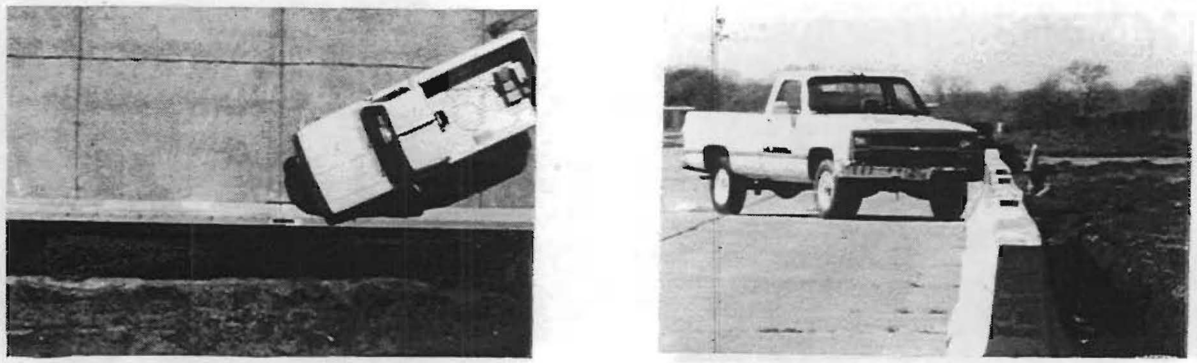


0.384 s

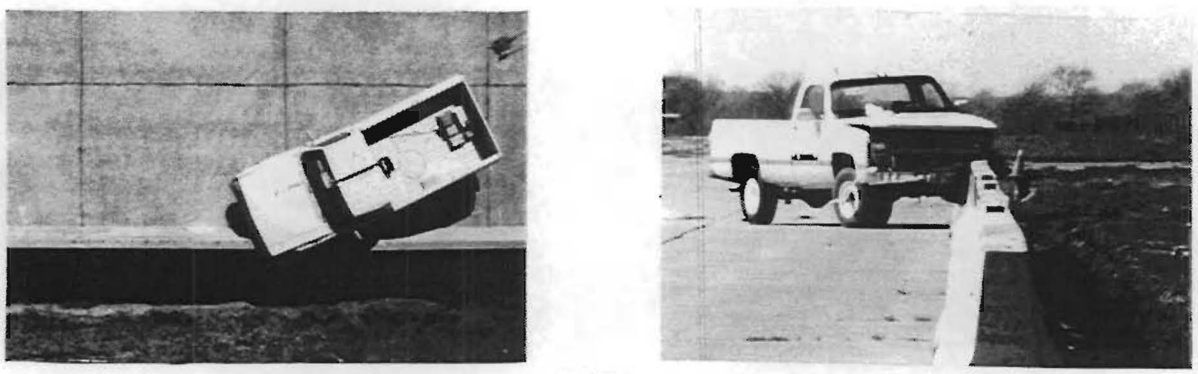


0.448 s

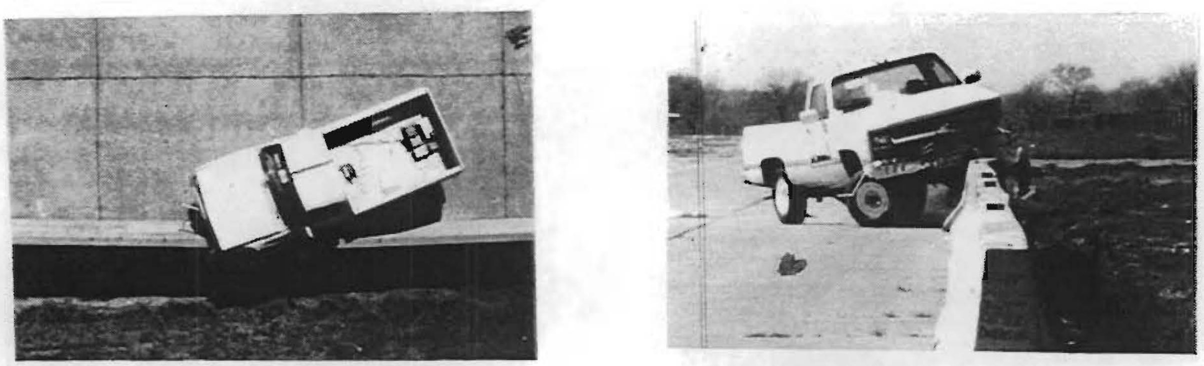
Figure 53. Sequential photographs for test 1959A-4.
(overhead and frontal views continued).



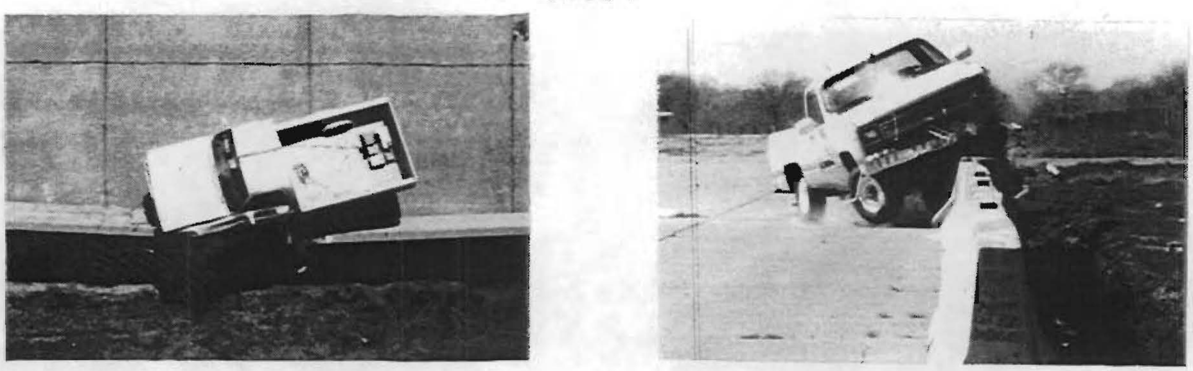
0.000 s



0.078 s

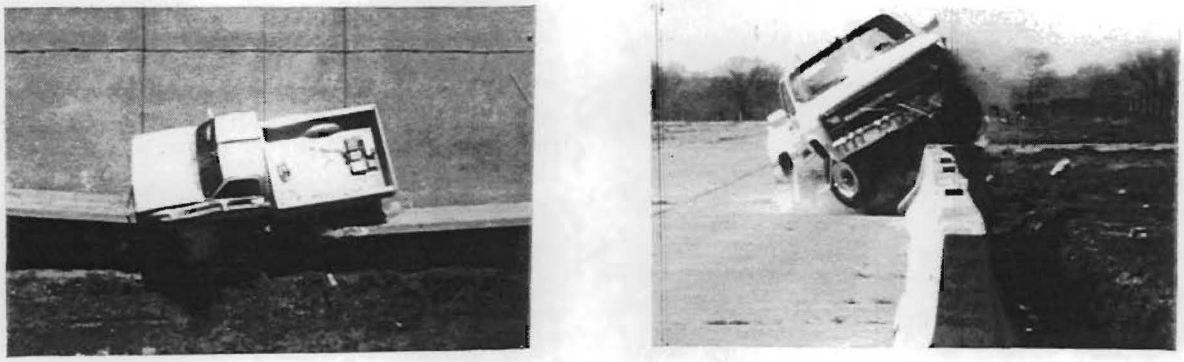


0.156 s

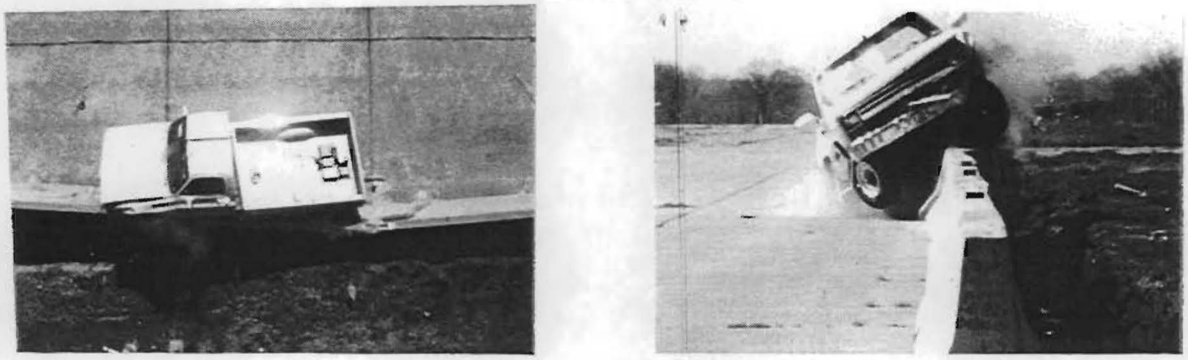


0.234 s

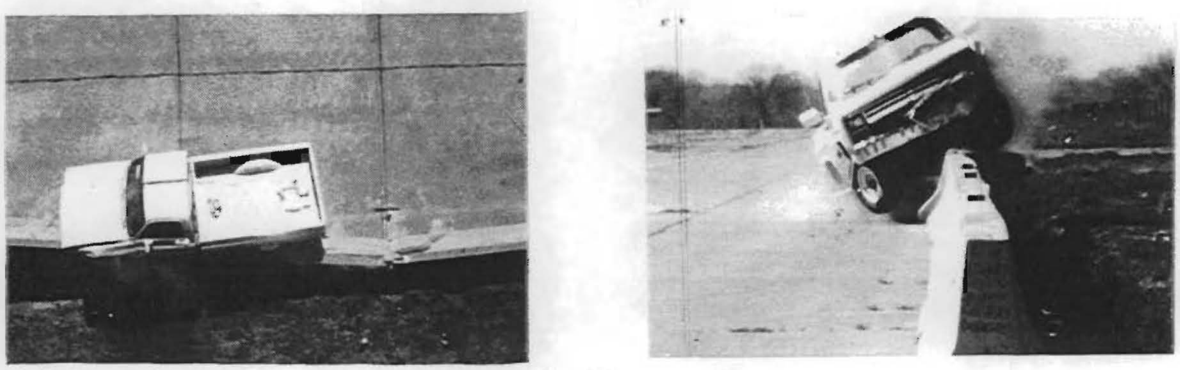
Figure 54. Sequential photographs for test 1959A-5.
(overhead and frontal views).



0.312 s



0.389 s



0.467 s

0.545 s

Figure 54. Sequential photographs for test 1959A-5.
(overhead and frontal views continued).

APPENDIX E.

ACCELEROMETER TRACES AND PLOTS OF ROLL, PITCH, AND YAW RATES

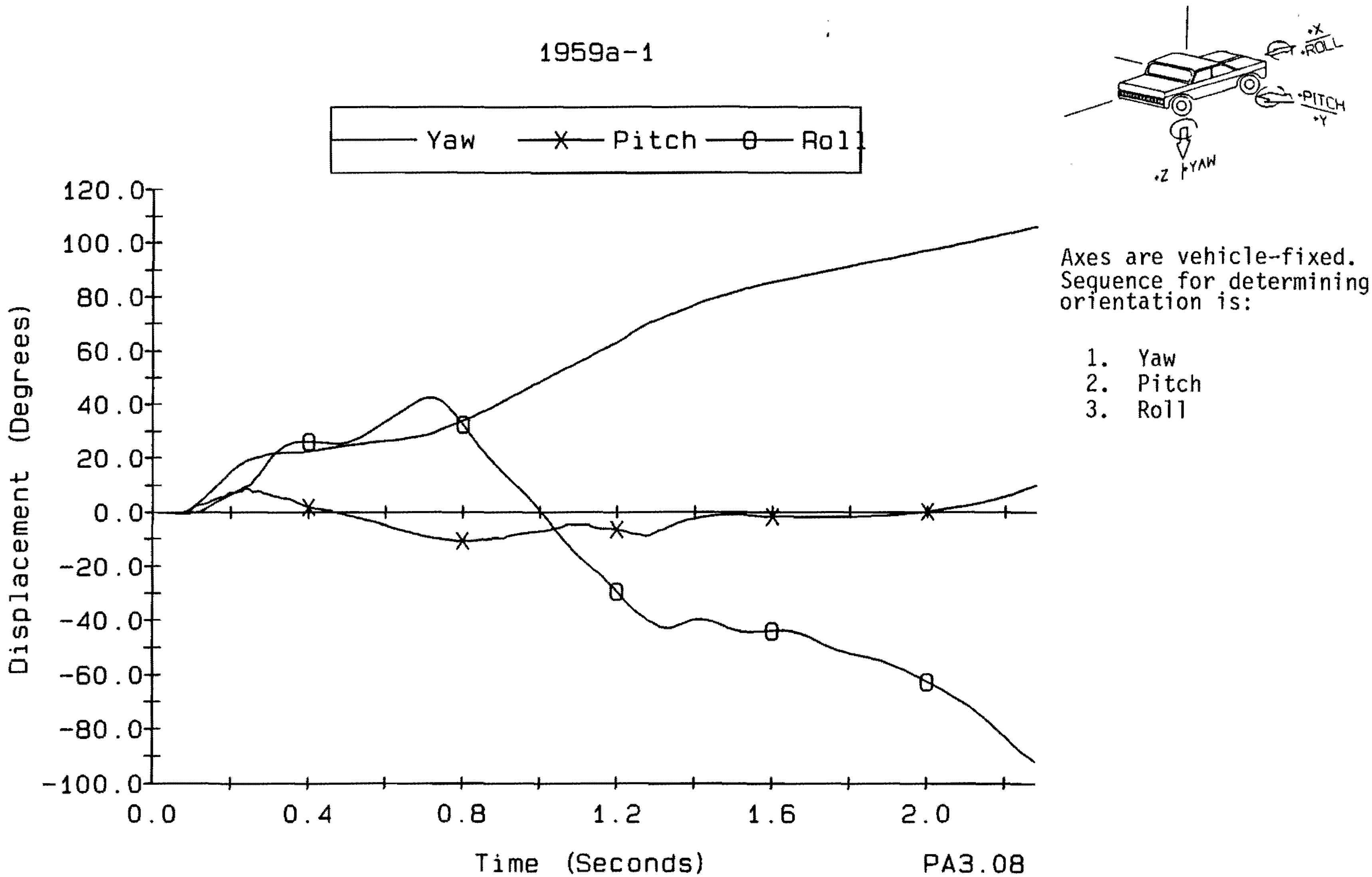


Figure 55. Vehicle angular displacements for test 1959A-1.

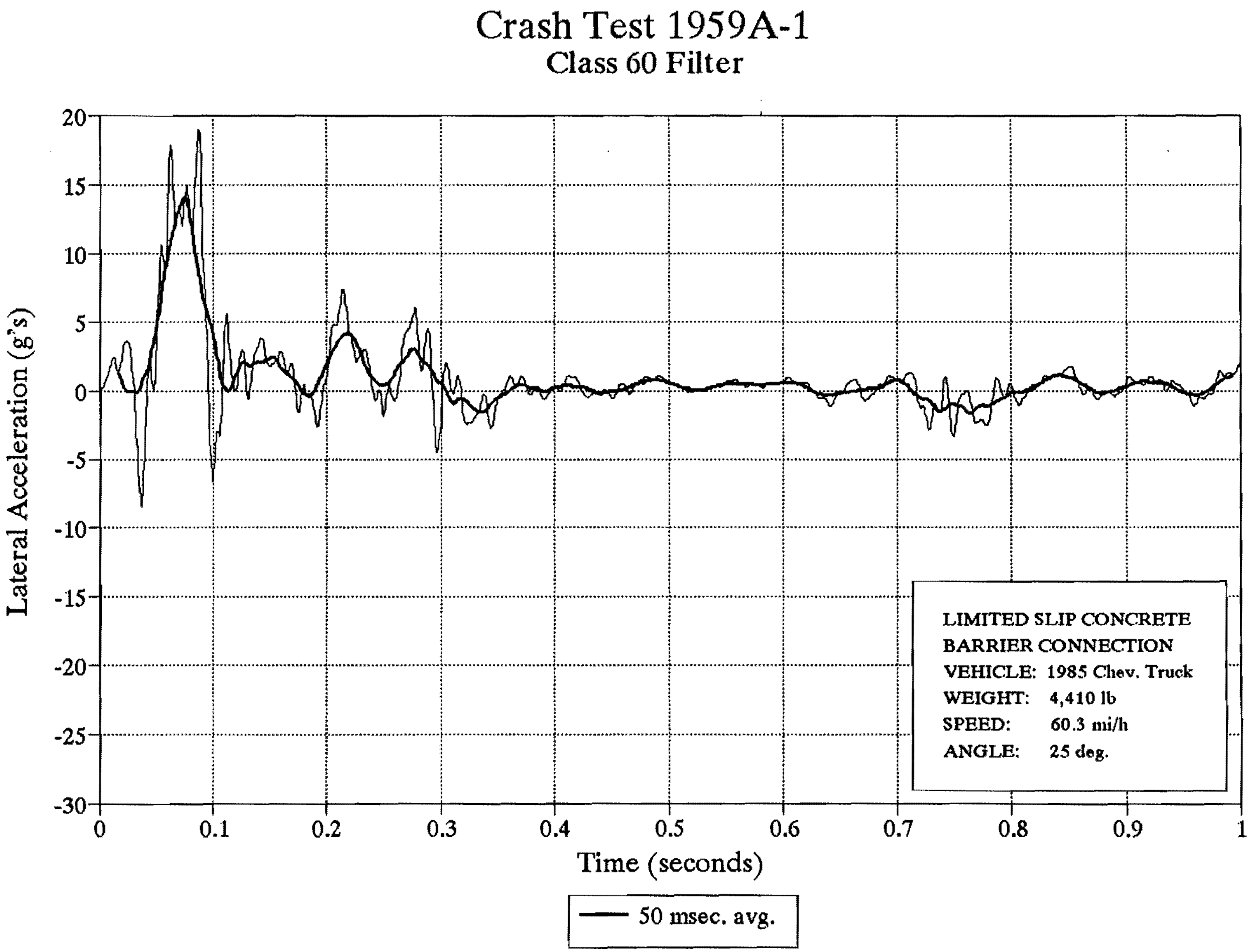


Figure 56. Lateral accelerometer trace for test 1959A-1.

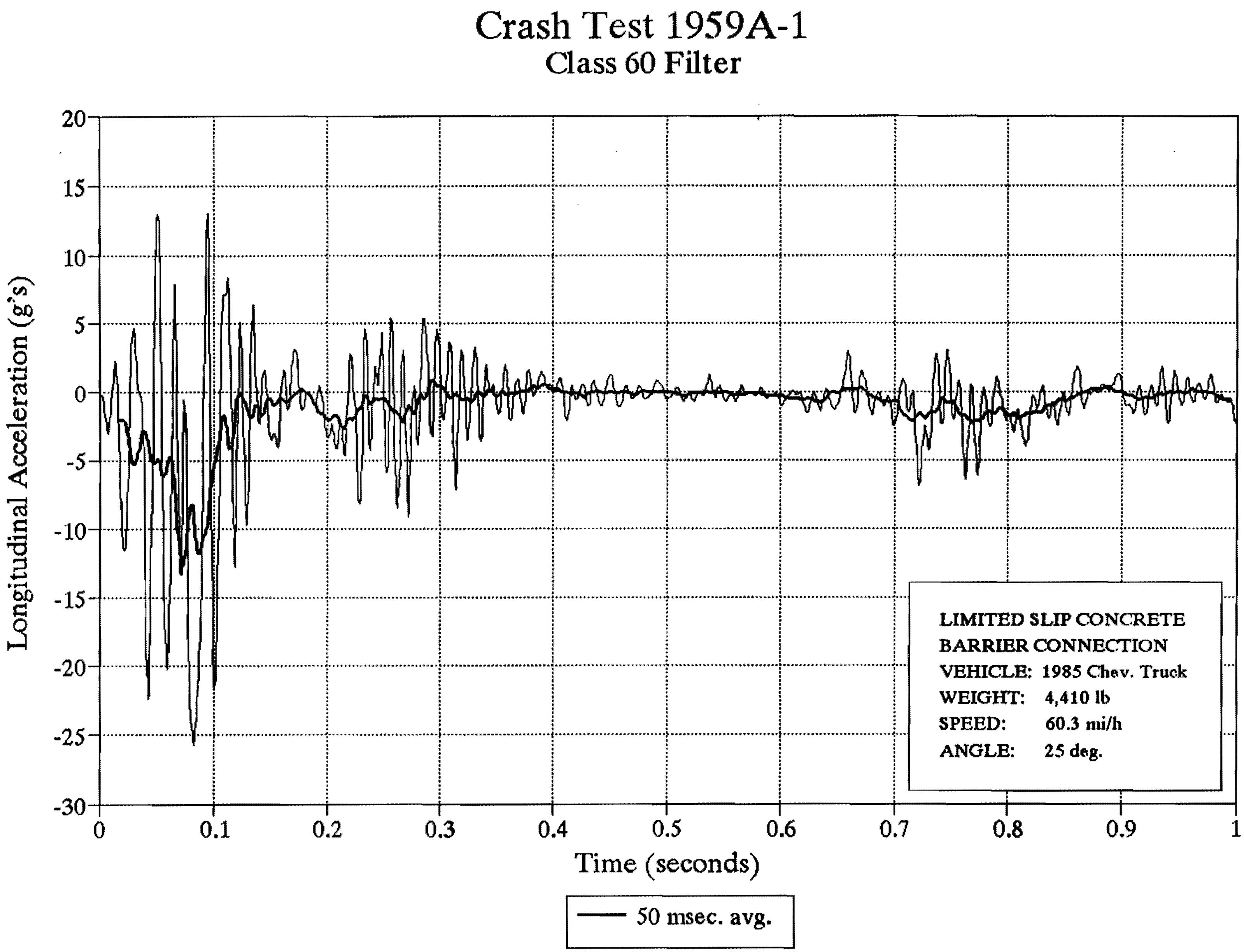


Figure 57. Longitudinal accelerometer trace for test 1959A-1.

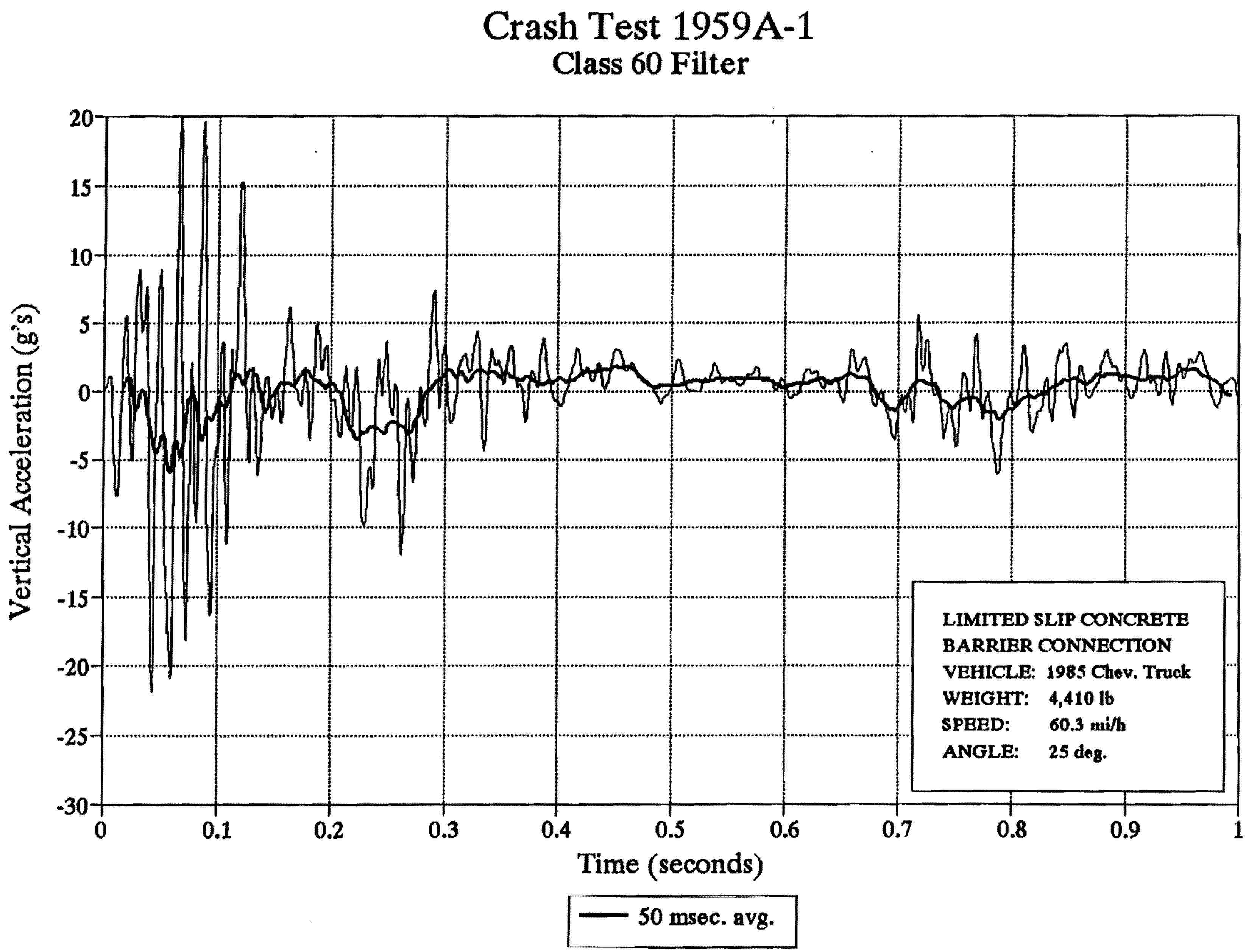


Figure 58. Vertical accelerometer trace for test 1959A-1.

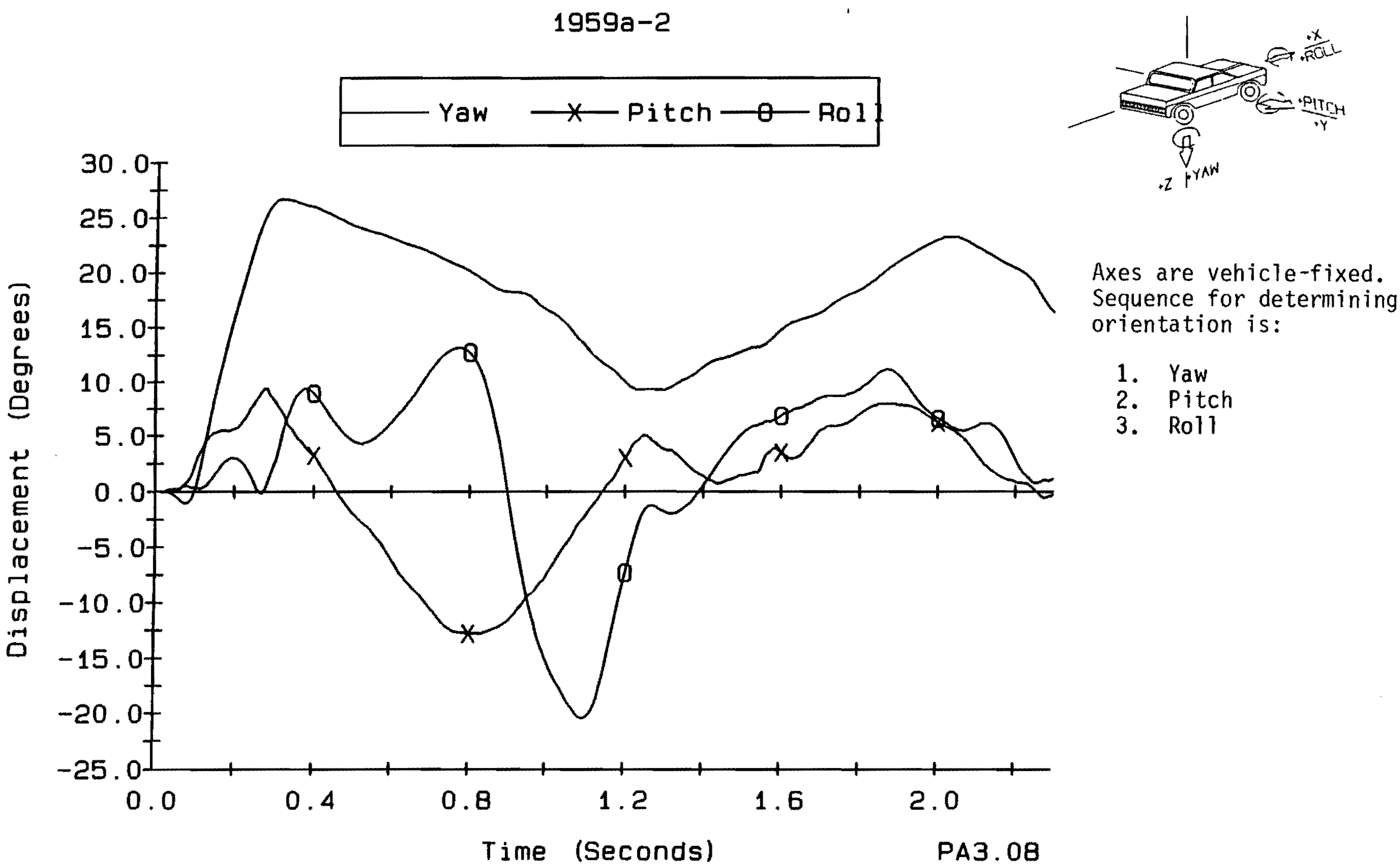


Figure 59. Vehicle angular displacements for test 1959A-2.

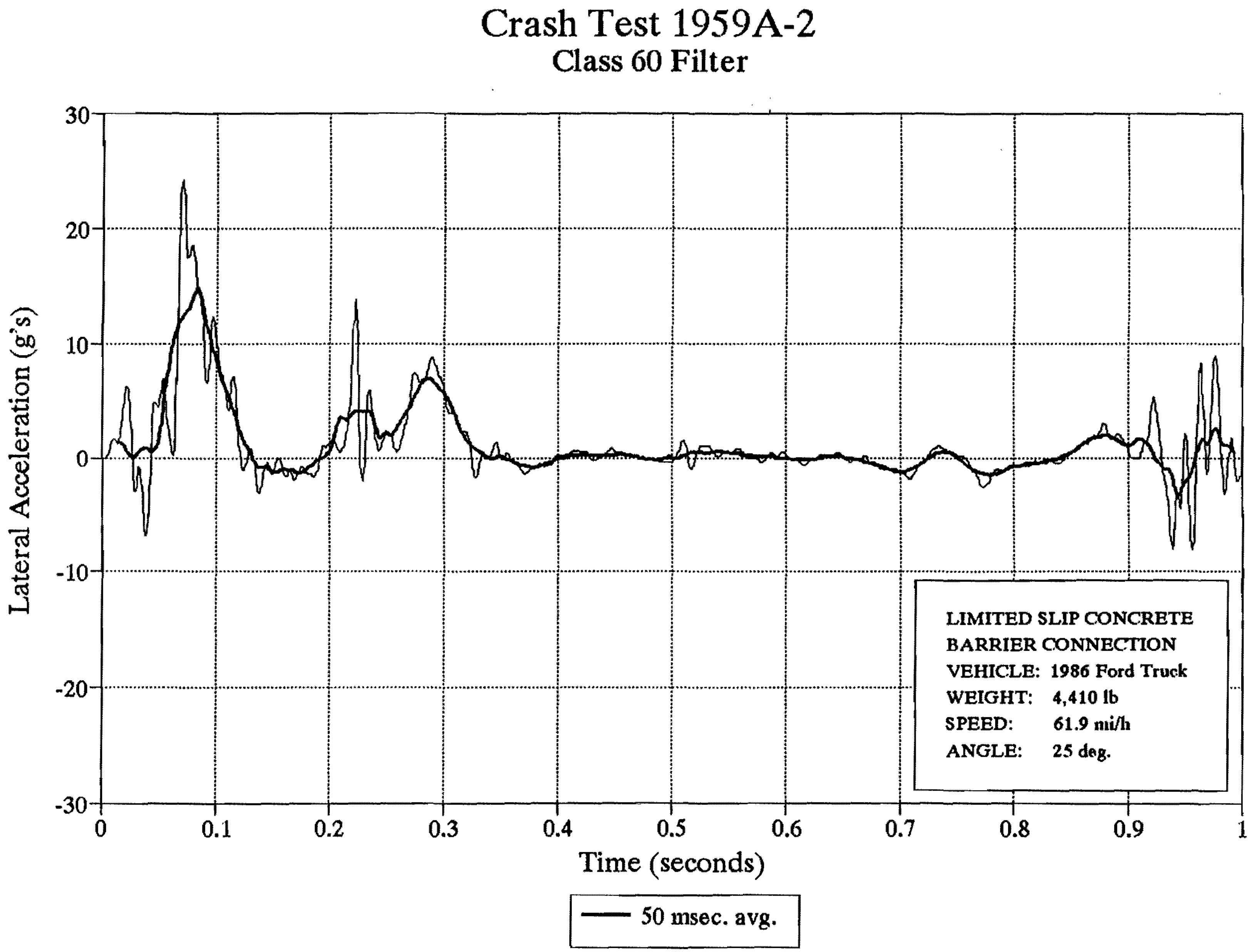


Figure 60. Lateral accelerometer trace for test 1959A-2.

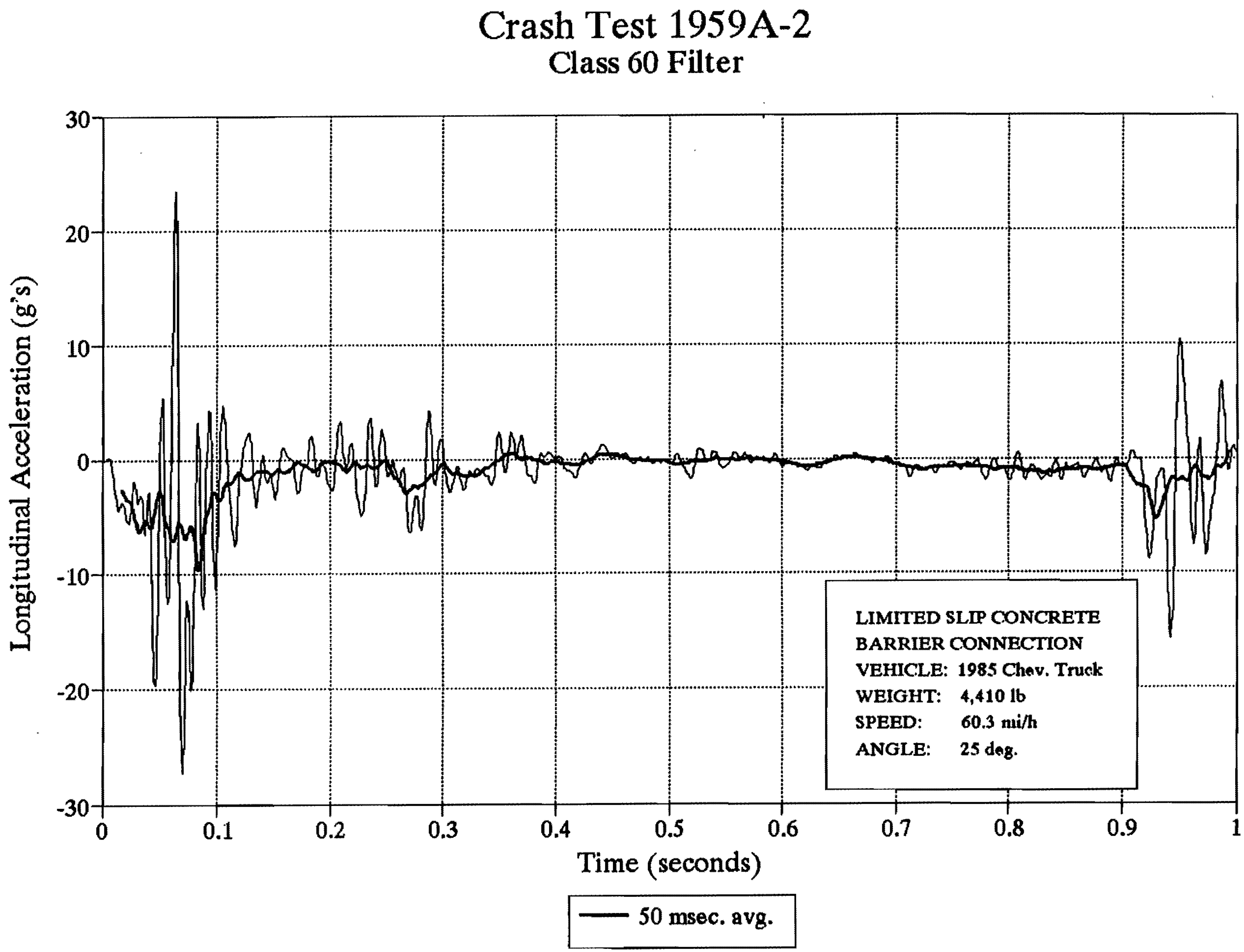


Figure 61. Longitudinal accelerometer trace for test 1959A-2.

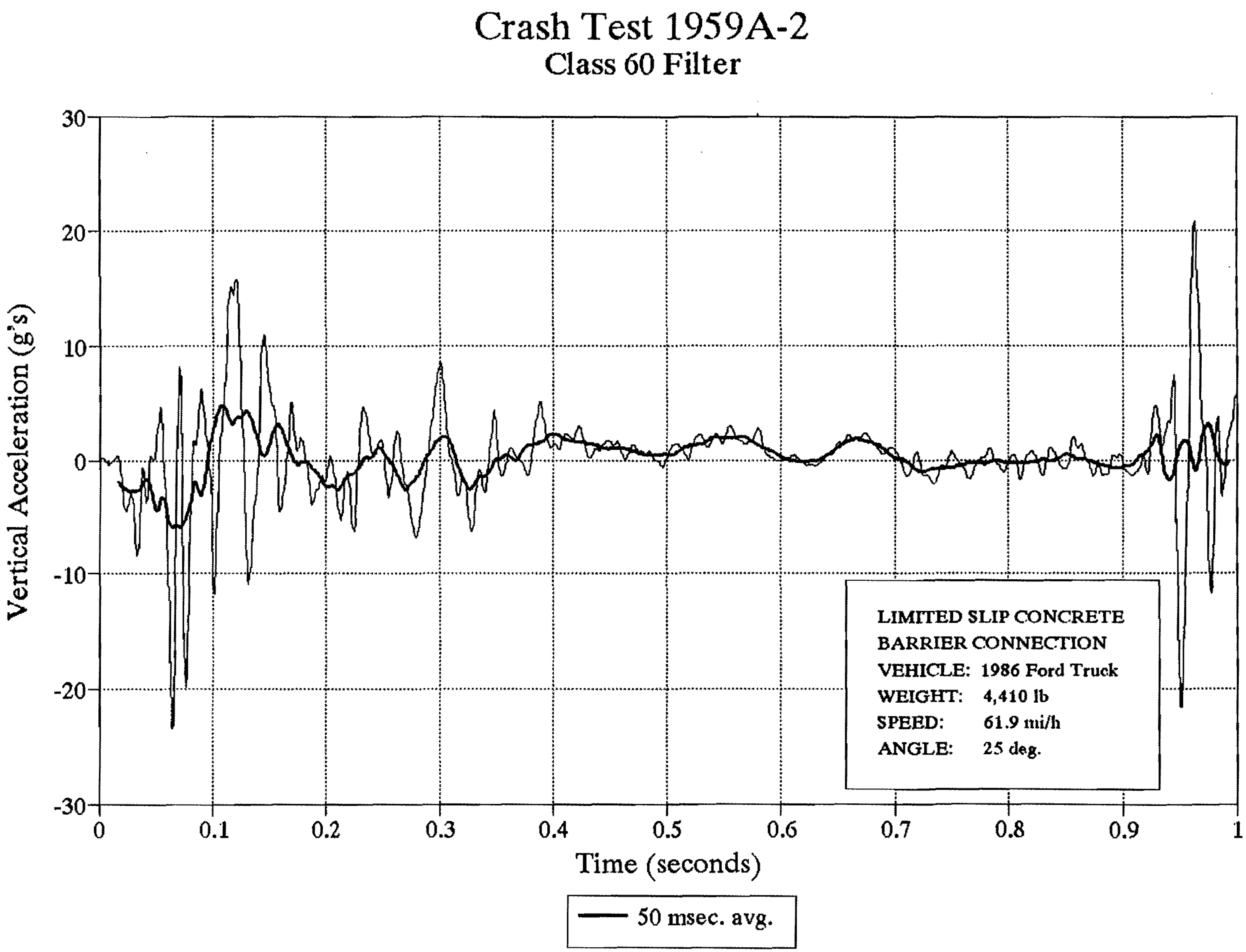
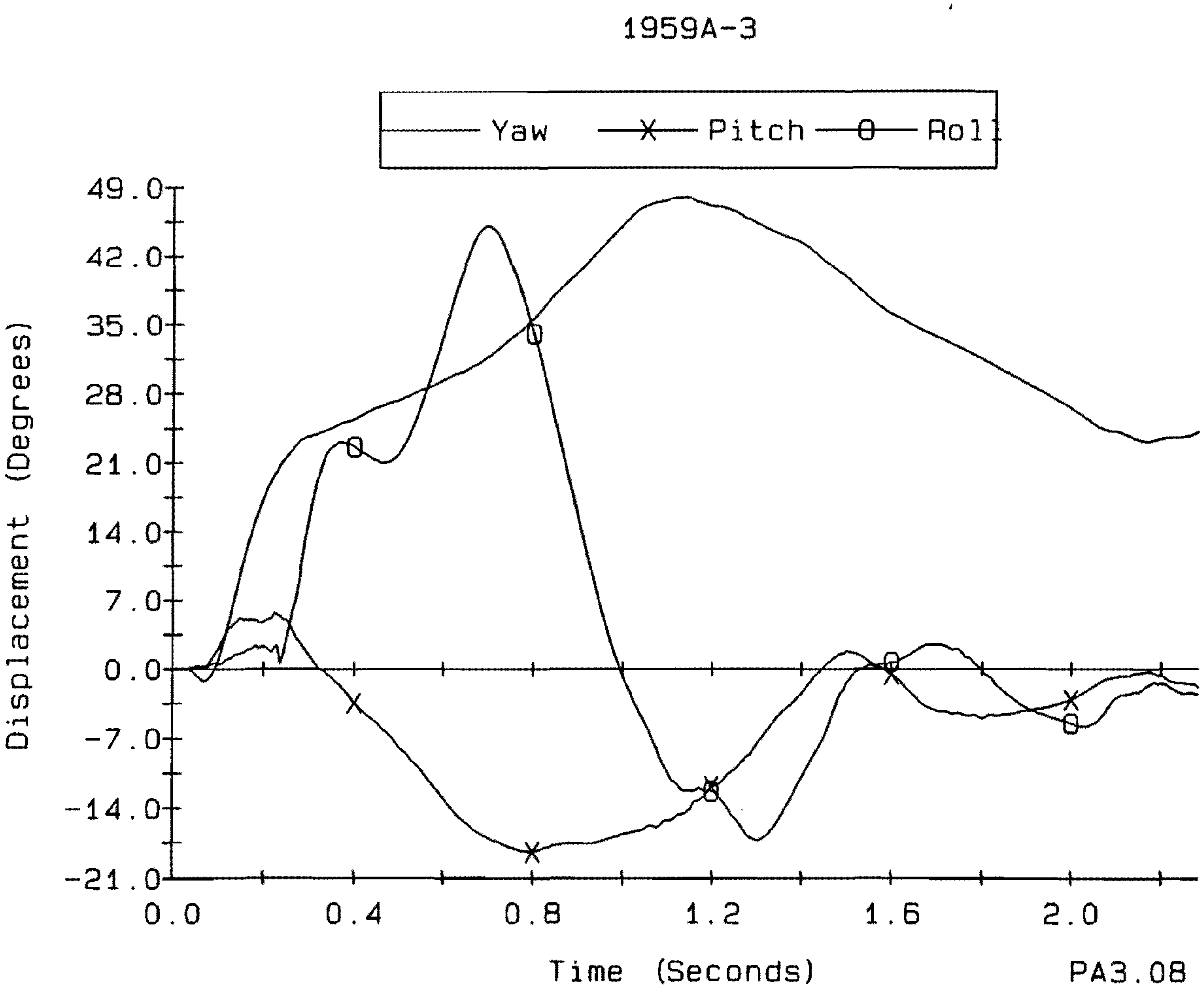
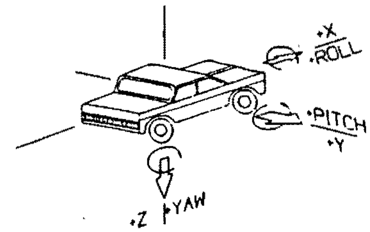


Figure 62. Vertical accelerometer trace for test 1959A-2.





Axes are vehicle-fixed.
Sequence for determining
orientation is:

1. Yaw
2. Pitch
3. Roll

Figure 63. Vehicle angular displacements for test 1959A-3.

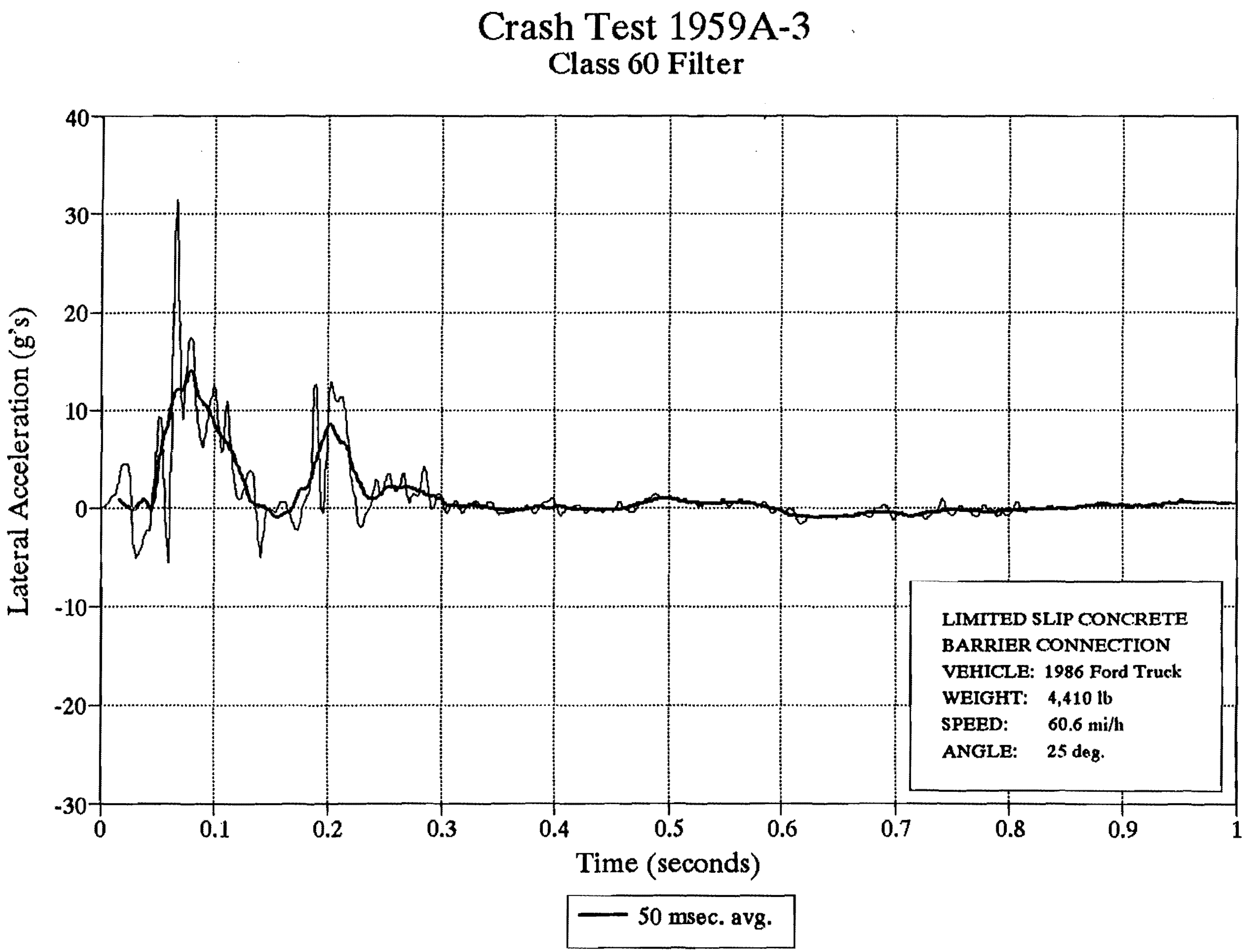


Figure 64. Lateral accelerometer trace for test 1959A-3.

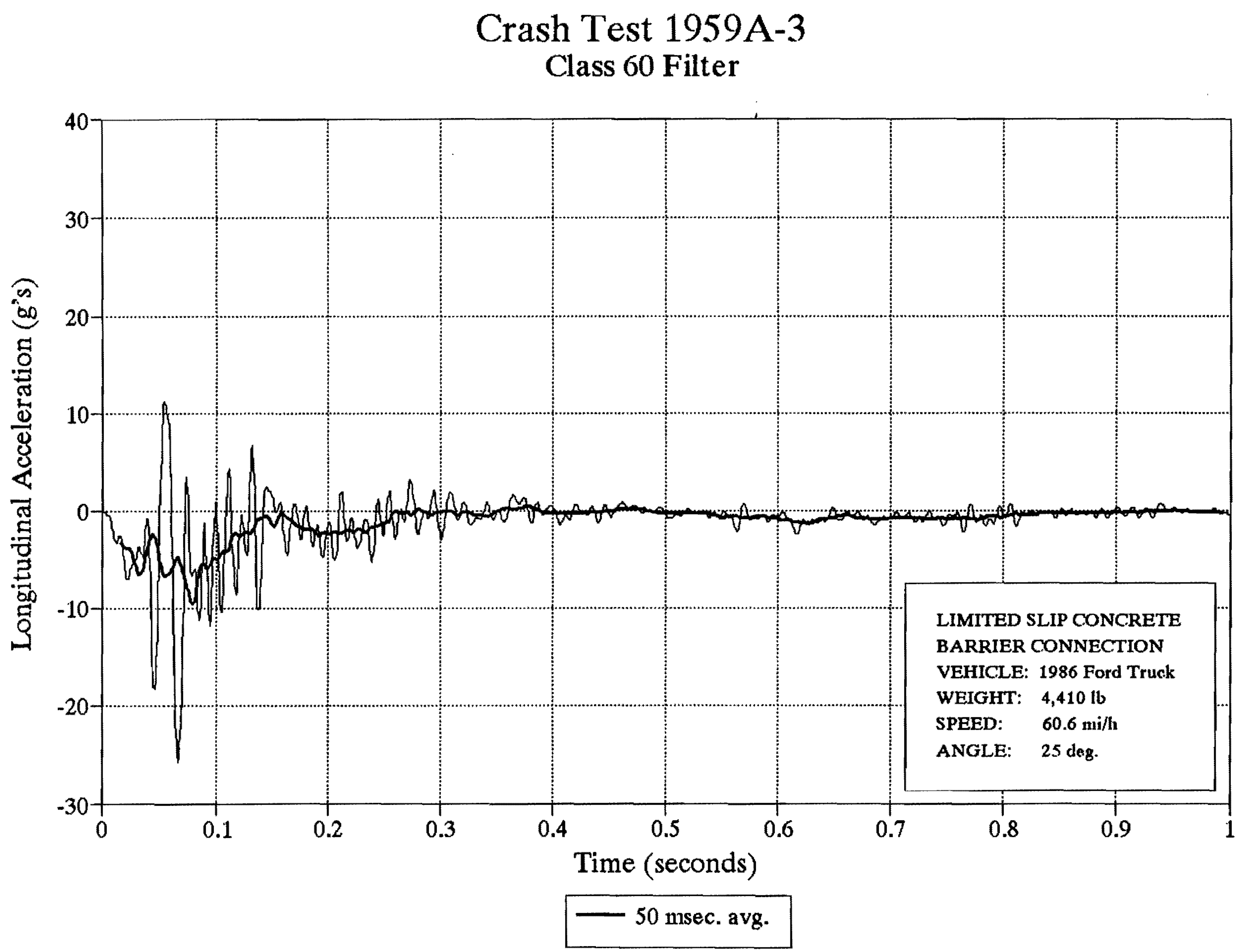


Figure 65. Longitudinal accelerometer trace for test 1959A-3.

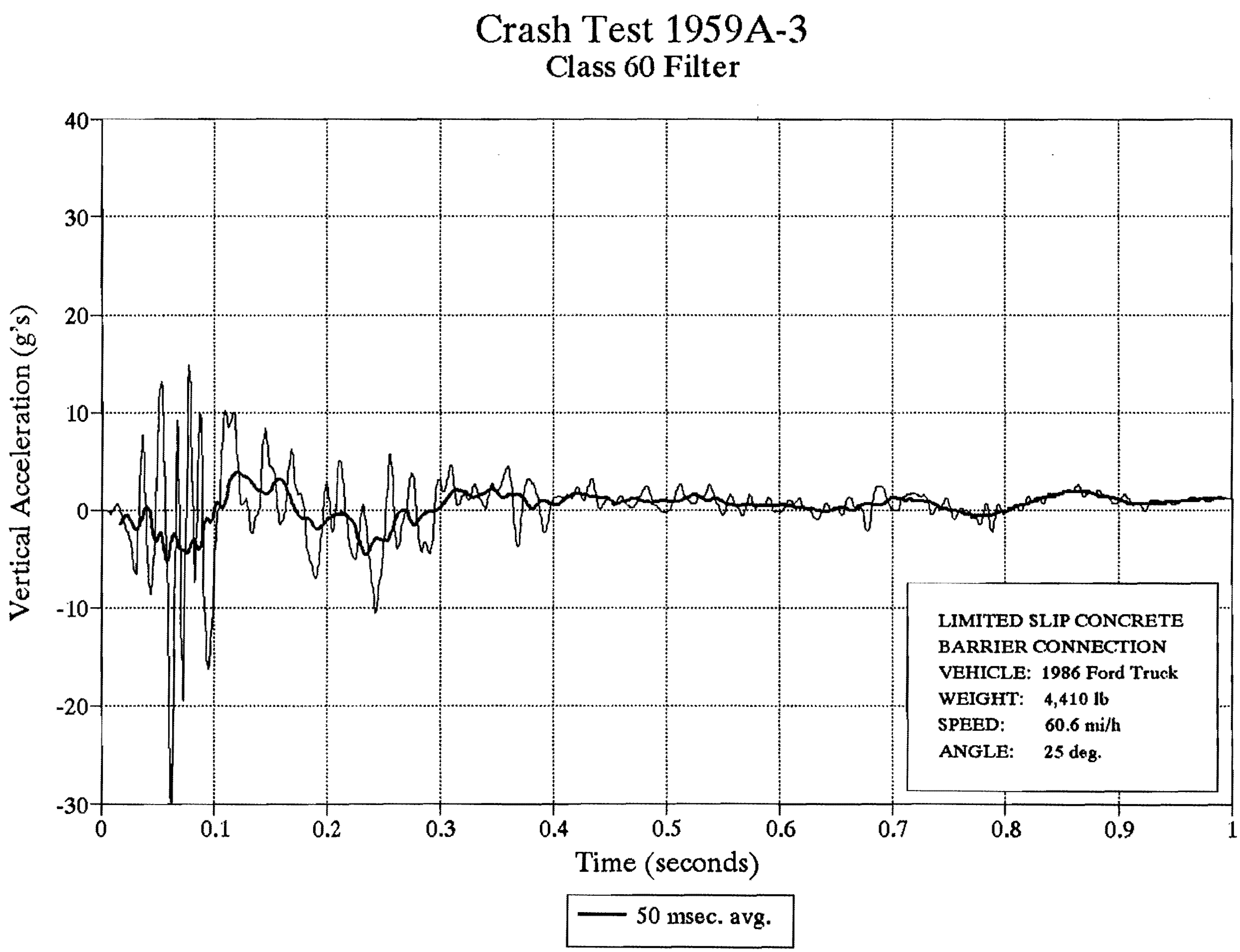


Figure 66. Vertical accelerometer trace for test 1959A-3.

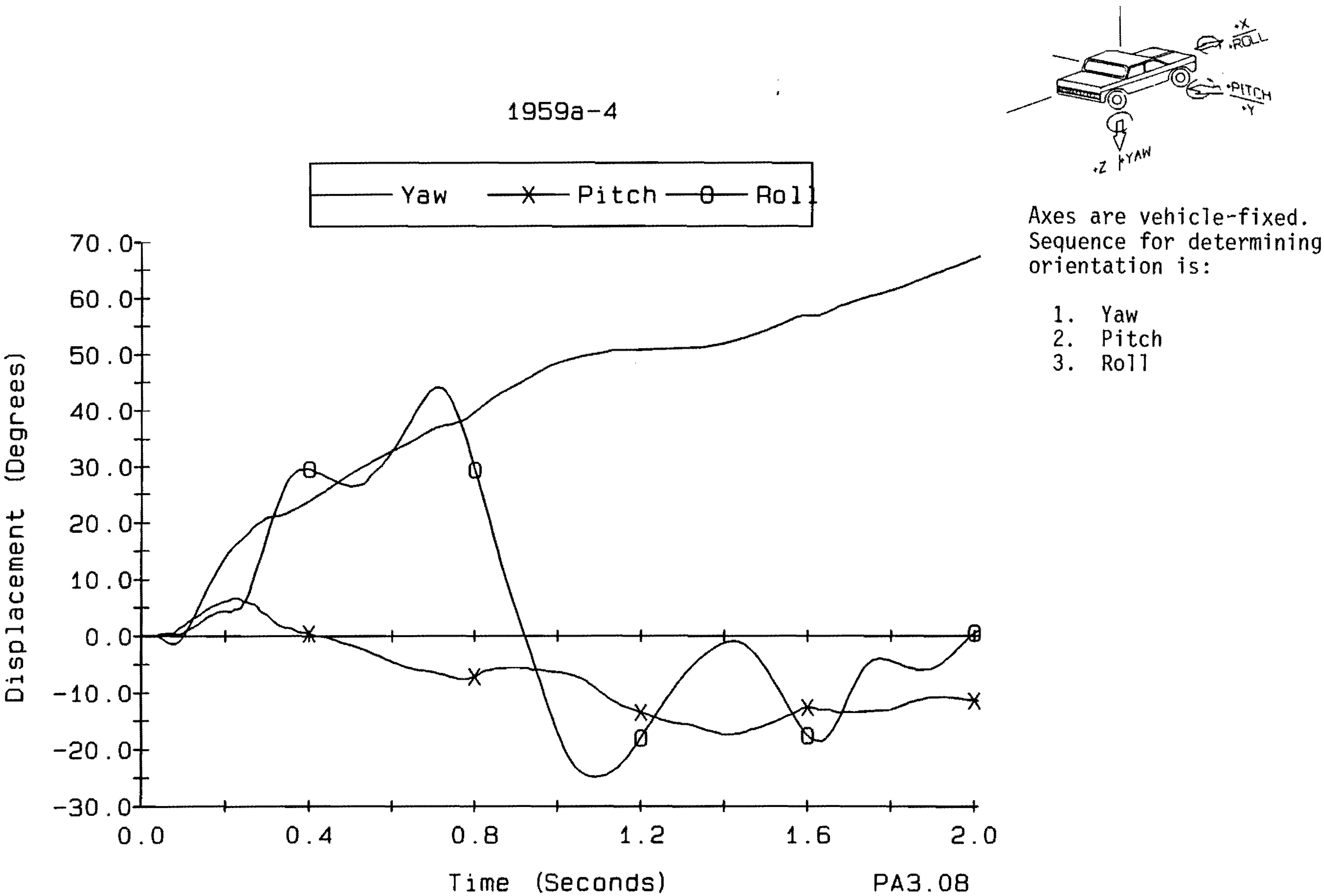


Figure 67. Vehicle angular displacements for test 1959A-4.

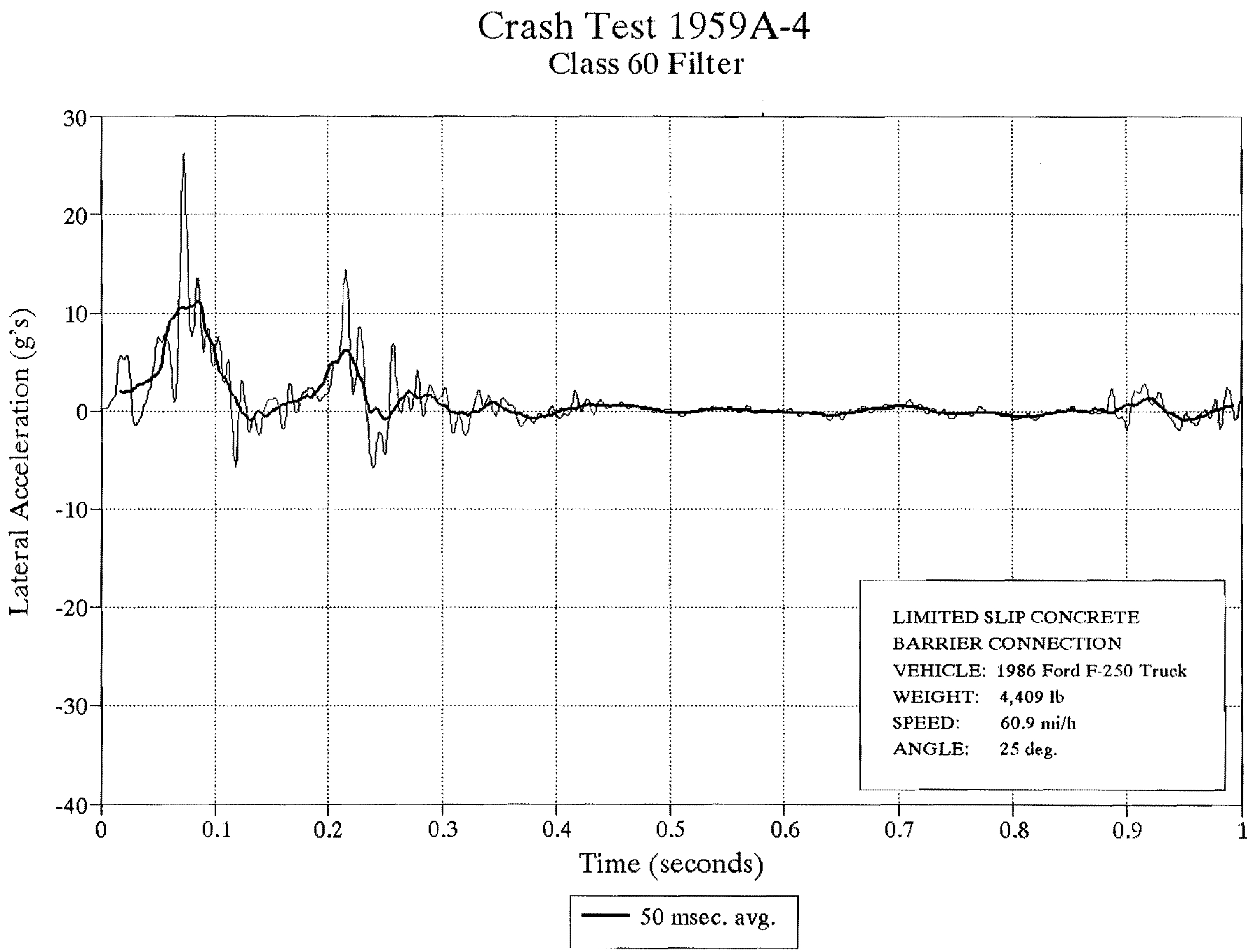


Figure 68. Lateral accelerometer trace for test 1959A-4.

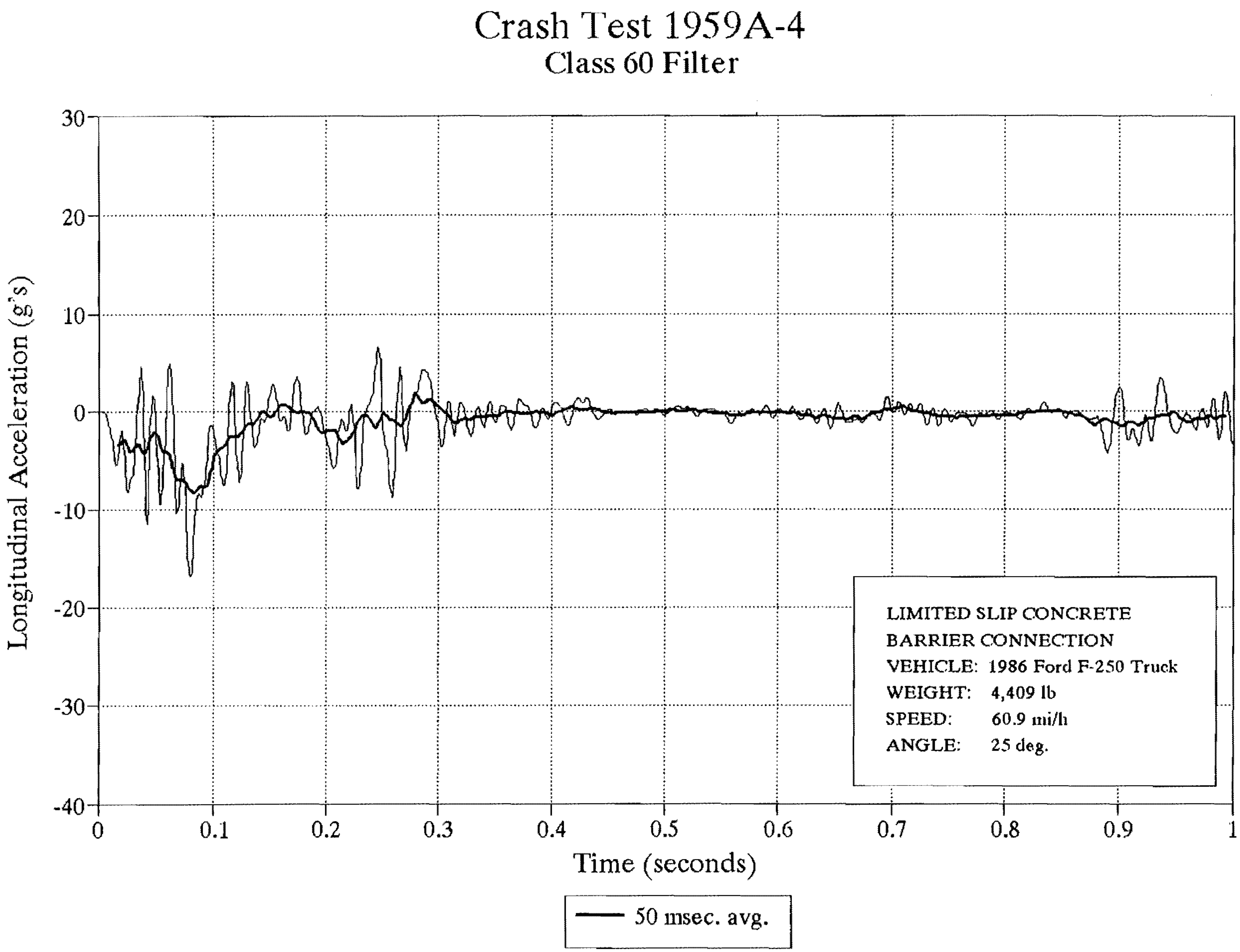


Figure 69. Longitudinal accelerometer trace for test 1959A-4.

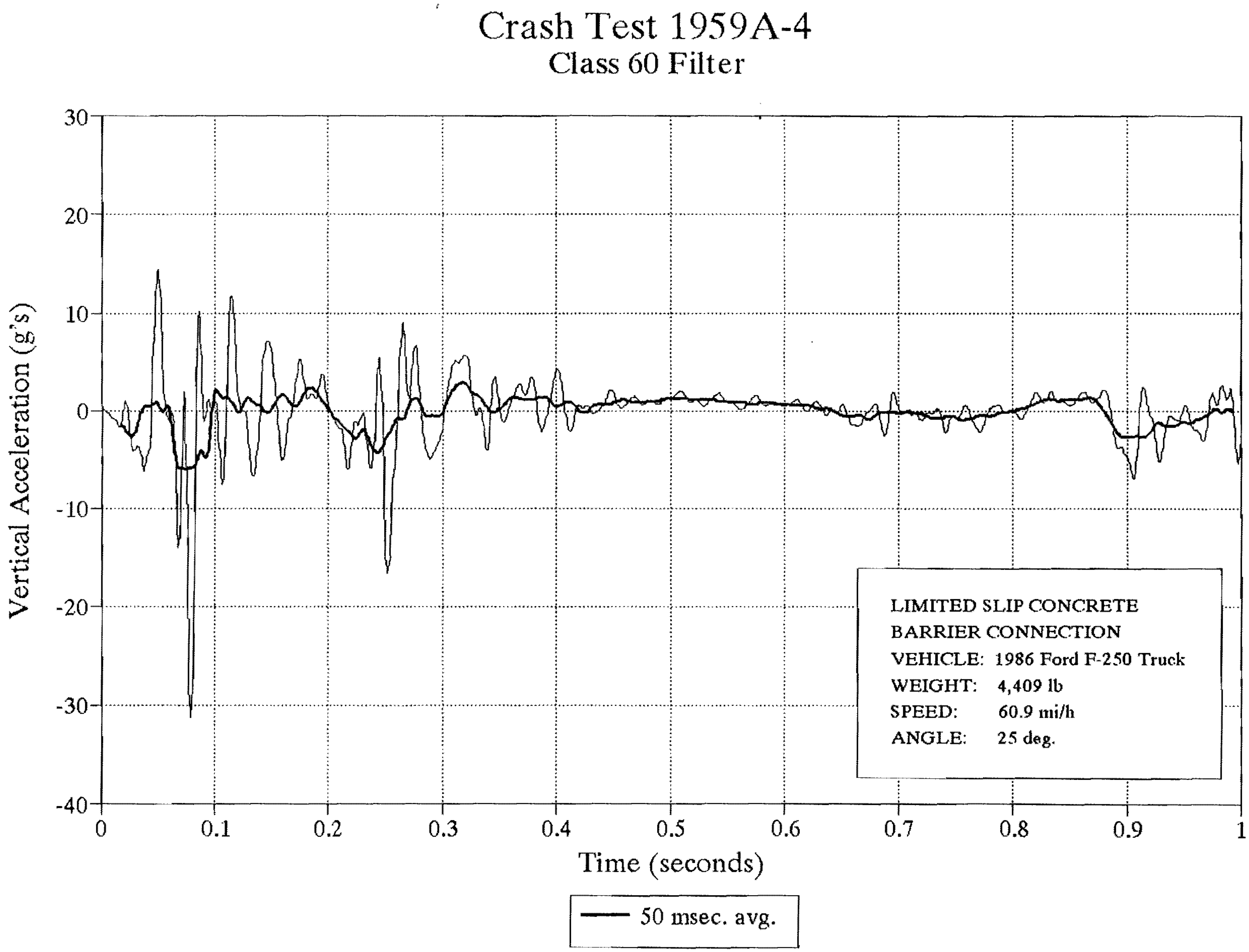


Figure 70. Vertical accelerometer trace for test 1959A-4.

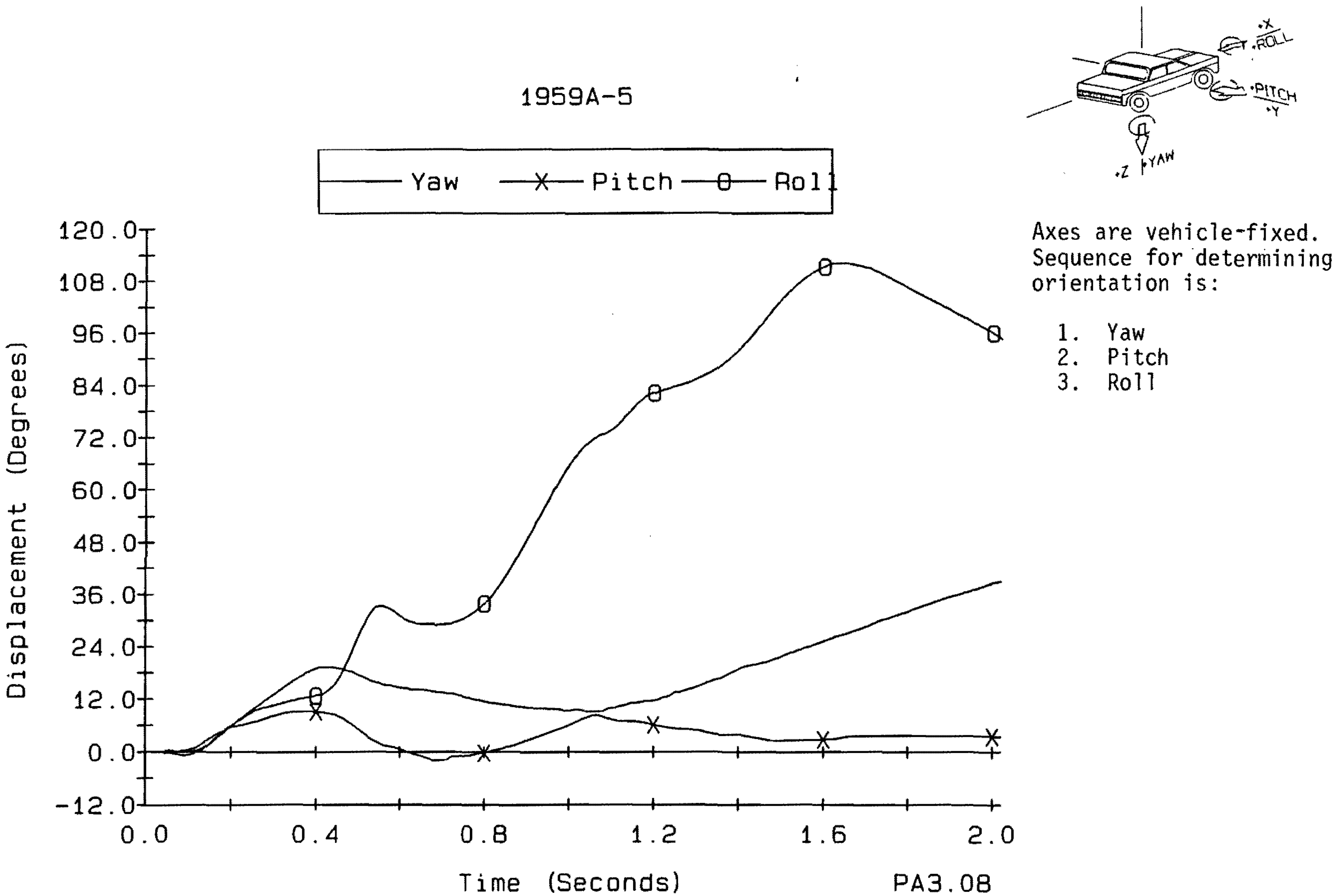


Figure 71. Vehicle angular displacements for test 1959A-5.

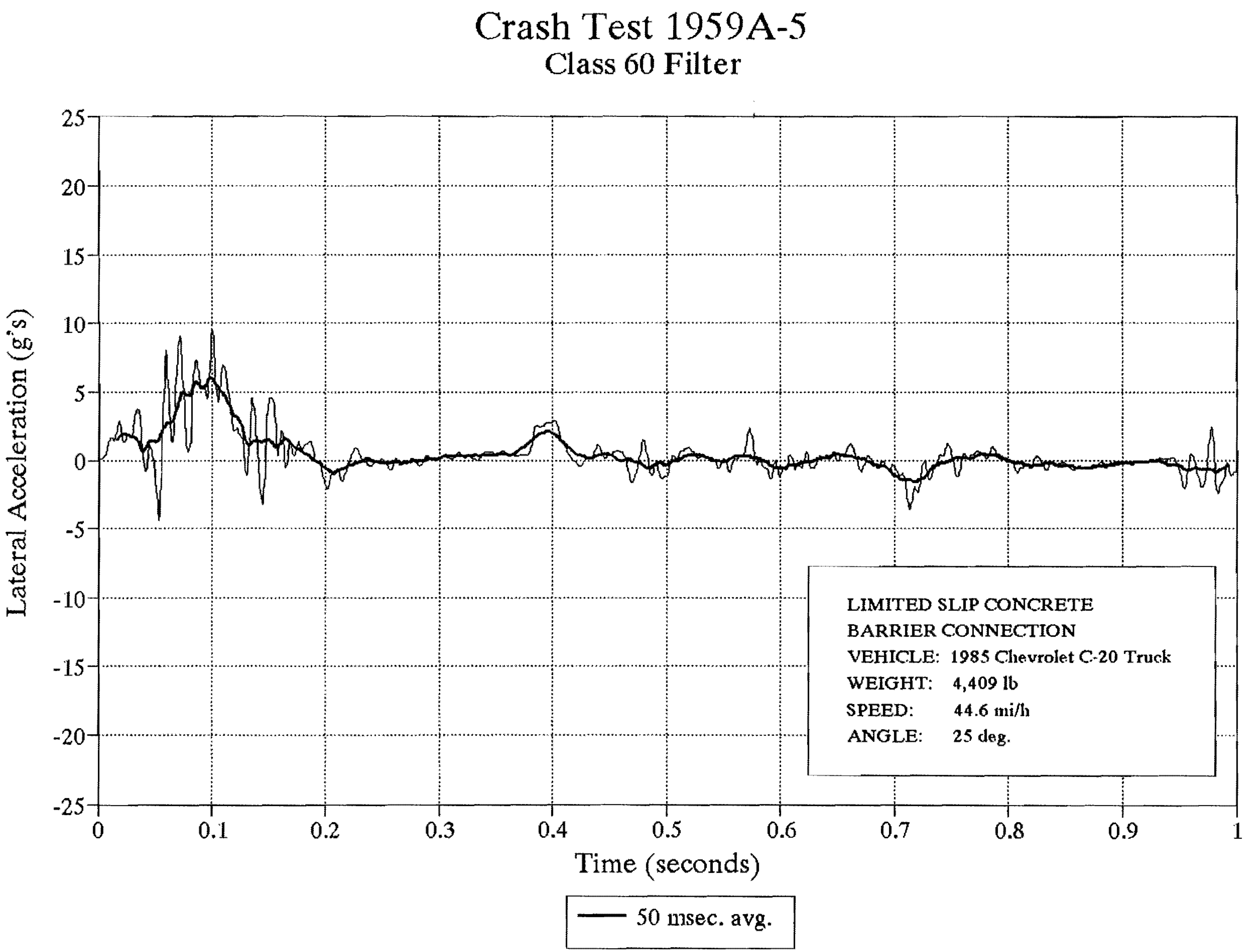


Figure 72. Lateral accelerometer trace for test 1959A-5.

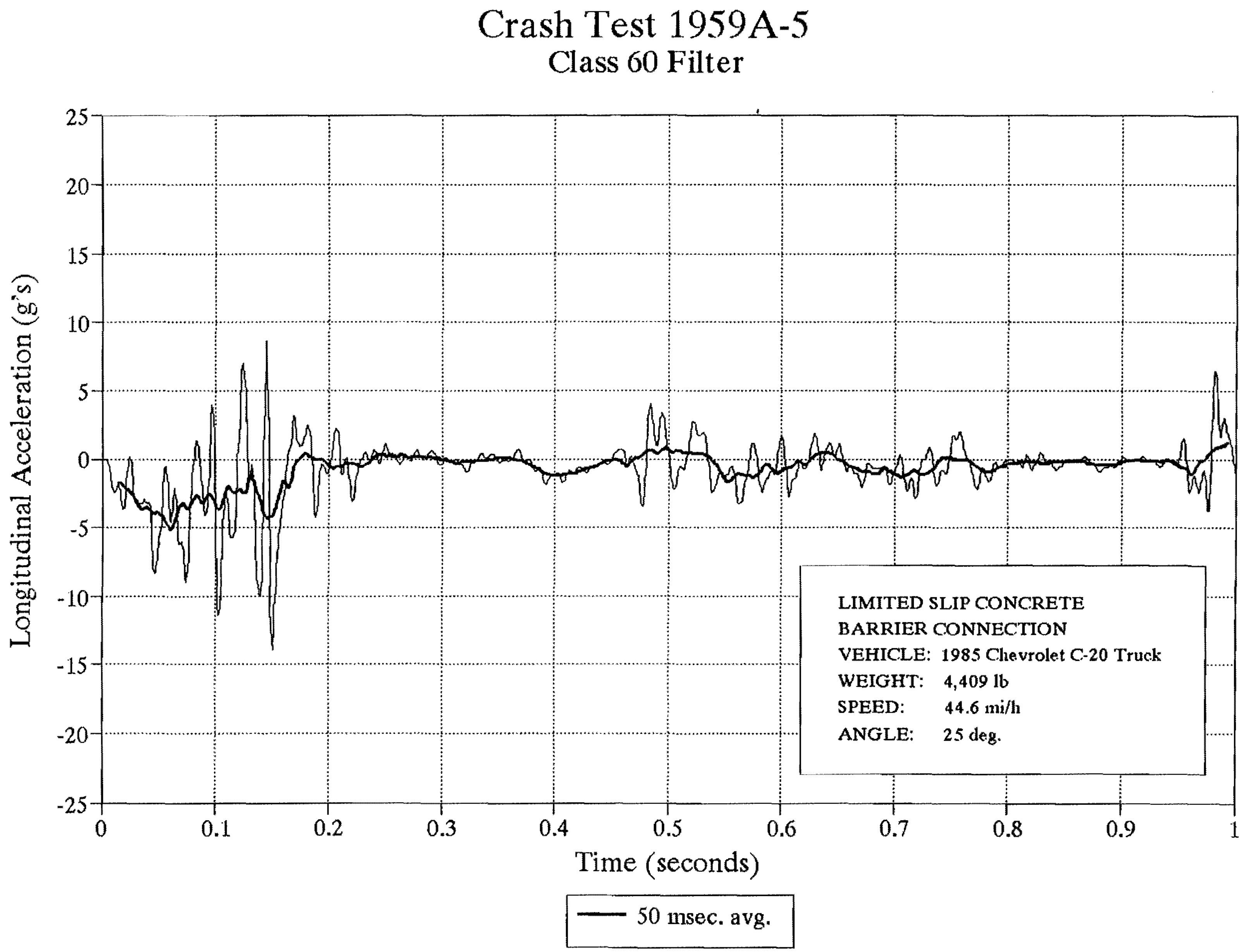


Figure 73. Longitudinal accelerometer trace for test 1959A-5.

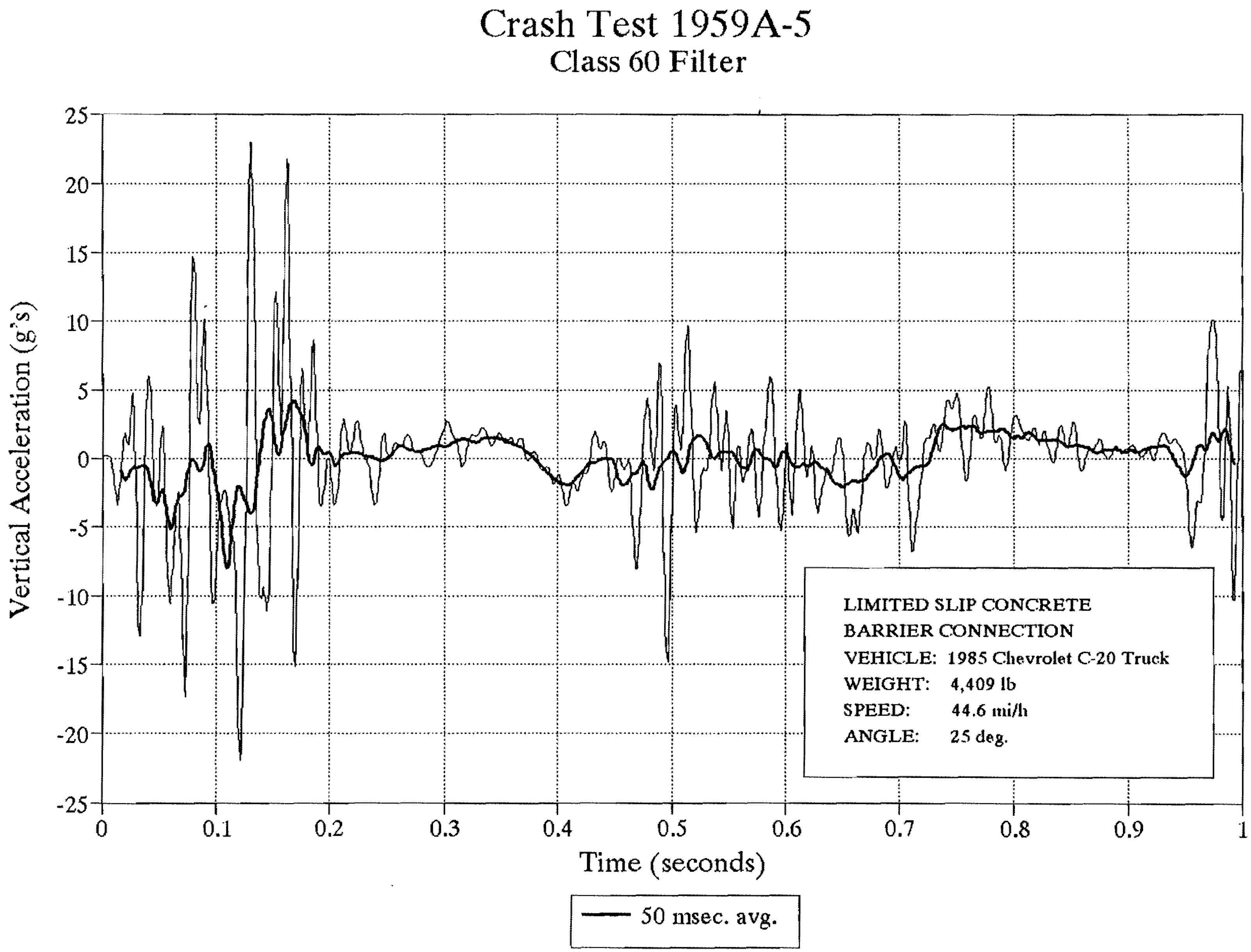


Figure 74. Vertical accelerometer trace for test 1959A-5.

REFERENCES

1. Michie, Jarvis, "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," NCHRP Report 230, Transportation Research Board, Washington, DC, 1981.

2. Ross, H. E., Jr., D. L. Sicking, R. A. Zimmer, and J. D. Michie, "Recommended Procedures for the Safety Performance Evaluation of Highway Features," NCHRP Report 350, Transportation Research Board, Washington, DC, 1993.