TECHNICAL MEMORANDUM 505-10

Texas Transportation Institute
Texas A&M Research Foundation

# TEXAS T1 BRIDGE RAIL SYSTEMS

A Test and Evaluation Report on Contract No. CPR-11-5851

U.S. Department of Transportation
Federal Highway Administration

by

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These crash tests and evaluations were conducted under the Office of Research and Development, Structures and Applied Mechanics Division's Research Program on Structural Systems in Support of Highway Safety (4S Program). The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the Federal Highway Administration.

April 1971

## SUMMARY OF RESULTS

High speed films were examined to determine the reduction in velocity produced by a collision incident, and to estimate the average total impact force (Average $G_{Total}$), and its components parallel (Average $G_{Long}$) and perpendicular (Average $G_{Lat}$) to the barrier. A discussion of the method of photographic analysis is contained in Appendix A, and the results are tabulated in Table 1. It is recognized that during a collision peak values of unit impact force occur as shown in the accelerometer traces in Appendix B. It is further recognized that such peak values may be two to three or more times the magnitude of the average values presented in this report, and that these peak values may be very significant in the design of barrier systems and connections. The relationship between average loads and peak loads is not resolved in this study. Average values of impact force have been computed and presented in this report and shed some light on the significance of the relationship of the forces parallel and perpendicular to a barrier as shown in Table 1.

Two crash tests (T1-A and T1-B) on a Texas Highway Department T1 Rail show that the system is strong enough to restrain the test vehicles. Vehicle damage was moderate in the lower speed test but severe in the higher speed test. Snagging, which occurred in Tests T1-A and T1-B, accounts for high components of impact force parallel to the railing system and large reduction in velocity. Comparison of the results of these two tests with the test on a modified barrier (T1-D) show that the

| | DATA FROM FILMS | | | | | COMPUTED RESULTS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SPEED* | SPEED** | SPEED | DISPLACEMENT | | CHANGE IN SPEED | | | AVERAGE DECELERATION | | |
| | $V_1$ | $V_2$ | $V_3$ | $S_{LAT}$ | $S_{LONG}$ | $(V_1-V_2)$ | $(V_1-V_3)$ | $(V_2-V_3)$ | $G_{LAT}$ | $G_{LONG}$ | $G_{TOTAL}$ |
| | (ft/sec) | (ft/sec) | (ft/sec) | (ft) | (ft) | (ft/sec) | (ft/sec) | (ft/sec) | (g's) | (g's) | (g's) |
| T1-A | 65.2 | 40.2 | 39.2 | 2.5 | 13.1 | 25.0 | 26.0 | 1.0 | 4.7 | 2.2 | 5.2 |
| T1-B | 82.7 | 41.3 | 39.1 | 3.5 | 13.0 | 41.4 | 43.6 | 2.2 | 5.4 | 4.7 | 7.2 |
| T1-C | 85.0 | 61.1 | 58.3 | 5.2 | 15.0 | 23.9 | 26.7 | 2.8 | 3.9 | 2.2 | 4.5 |
| T1-D | 90.1 | 80.4 | 79.7 | 3.3 | 14.5 | 9.7 | 10.4 | 0.7 | 6.8 | 0.2 | 6.8 |

NOTES:

*$V_1$ is the speed of the vehicle at impact.

**$V_2$ is the speed of the vehicle when it becomes parallel to the rail.

$V_3$ is the speed of the vehicle at loss of contact with the rail.

$F_{LAT}$ = Vehicle weight x $G_{LAT}$

$F_{LONG}$ = Vehicle weight x $G_{LONG}$

$F_{TOTAL}$ = Vehicle weight x $G_{TOTAL}$

$\mu = F_{LONG}/F_{LAT}$

| | COMPUTED AVERAGE IMPACT FORCE | | | |
|---|---|---|---|---|
| | $F_{LAT}$ | $F_{LONG}$ | $F_{TOTAL}$ | $\mu$ |
| | (lbs.) | (lbs.) | (lbs.) | |
| T1-A | 8,740 | 4,090 | 9,670 | 0.47 |
| T1-B | 21,170 | 18,420 | 28,220 | 0.87 |
| T1-C | 14,310 | 8,070 | 16,520 | 0.56 |
| T1-D | 24,620 | 720 | 24,620 | 0.03 |

Table 1. Test Data Summary and Analysis

average longitudinal impact force is greatly reduced by eliminating snagging, but the added W-Section makes a stronger system and produces a higher component of force perpendicular to the barrier. An examination of Table 1 shows that the average total deceleration under similar conditions of impact (T1-B and T1-D) are nearly identical. However, the component of force parallel to the barrier is much less and the damage rating is considerably less in a collision with the modified rail system.

Damage Ratings

The National Safety Council published a "Vehicle Damage Scale for Traffic Accident Investigators" in 1968. This damage rating scale, developed in the NSC Traffic Accident Data Project, consists of photographs of automobiles damaged in accidents. Fourteen observers compared the photographs of vehicles damaged in Tests A, B, C and D with the NSC pictures. The results of the comparisons are listed in Table 2.

The letters LFQ and FL in the table refer to the location of the damage as defined in the NSC rating scale. Some observers compared the test vehicle with LFQ (Left Front Quarter) photographs, and others with FL (Front Left) photographs.

Details of individual tests are presented in the following pages, and an evaluation of the several tests is included at the end of the report.

| OBSERVER | TEST NUMBER | | | |
|---|---|---|---|---|
| | T1-A | T1-B | T1-C | T1-D |
| 1 | LFQ-5 | LFQ-7 | LFQ-4 | LFQ-5 |
| 2 | LFQ-5 | FL-7 | LFQ-5 | LFQ-6 |
| 3 | FL-5 | LFQ-7 | LFQ-5 | LFQ-5 |
| 4 | FL-2 | LFQ-7 | LFQ-4 | LFQ-6 |
| 5 | FL-6 | LFQ-7 | LFQ-4 | LFQ-6 |
| 6 | LFQ-5 | FL-7 | LFQ-5 | LFQ-4 |
| 7 | FL-4 | FL-7 | FL-2 | FL-4 |
| 8 | LFQ-6 | FL-3 | FL-2 | FL-2 |
| 9 | FL-7 | FL-5 | FL-3 | FL-3 |
| 10 | LFQ-5 | FL-7 | FL-4 | FD-4 |
| 11 | LFQ-6 | FD-6 | LFQ-4 | FL-6 |
| 12 | FL-4 | FD-6 | FL-4 | FD-4 |
| 13 | LFQ-4 | FD-6 | LFQ-4 | FL-4 |
| 14 | FL-4 | LFQ-7 | FL-4 | FD-4 |
| AVERAGE (14 Observations) | 4.9 | 6.4 | 3.9 | 4.5 |

Table 2. Vehicle Damage Ratings

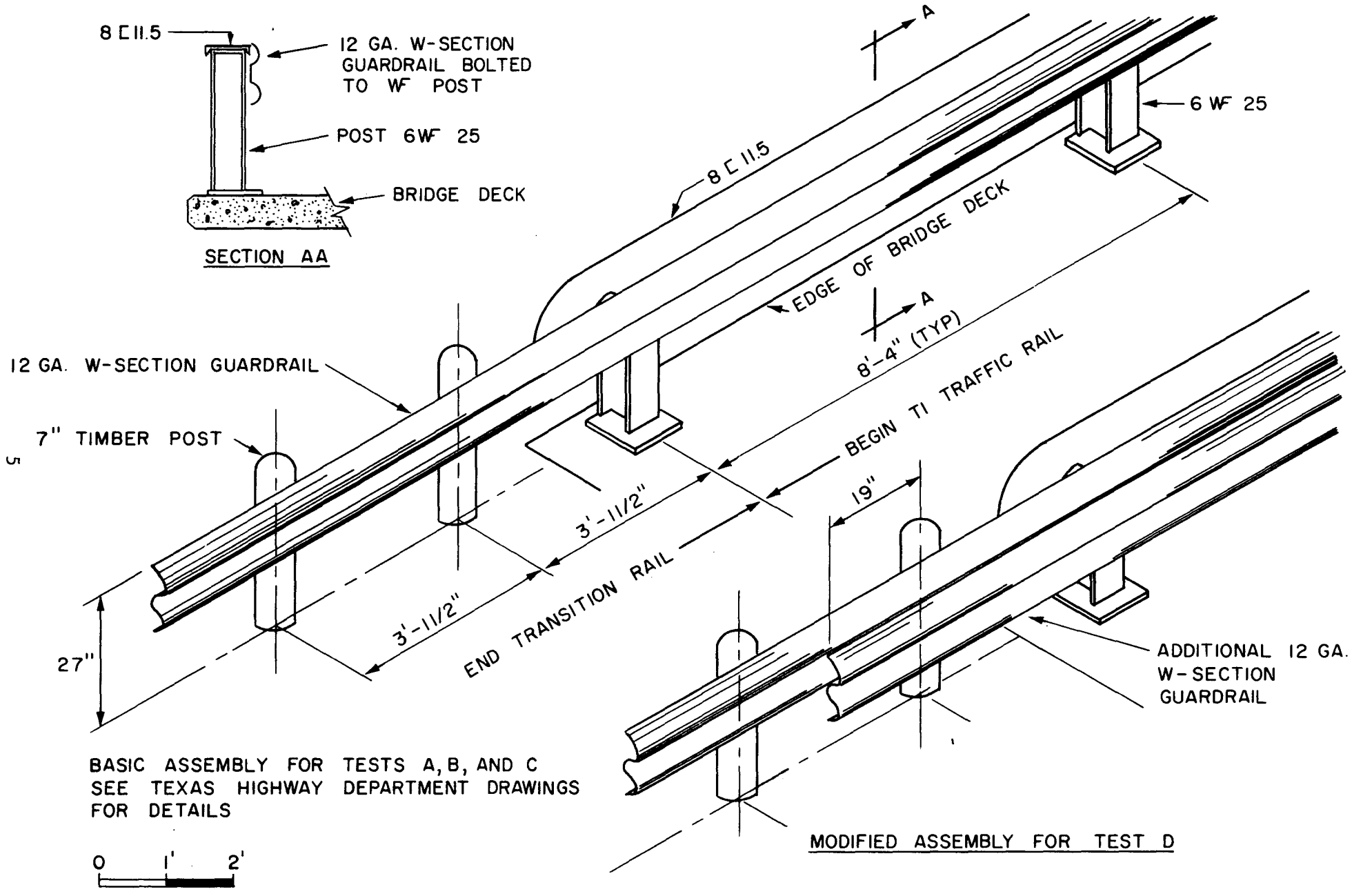
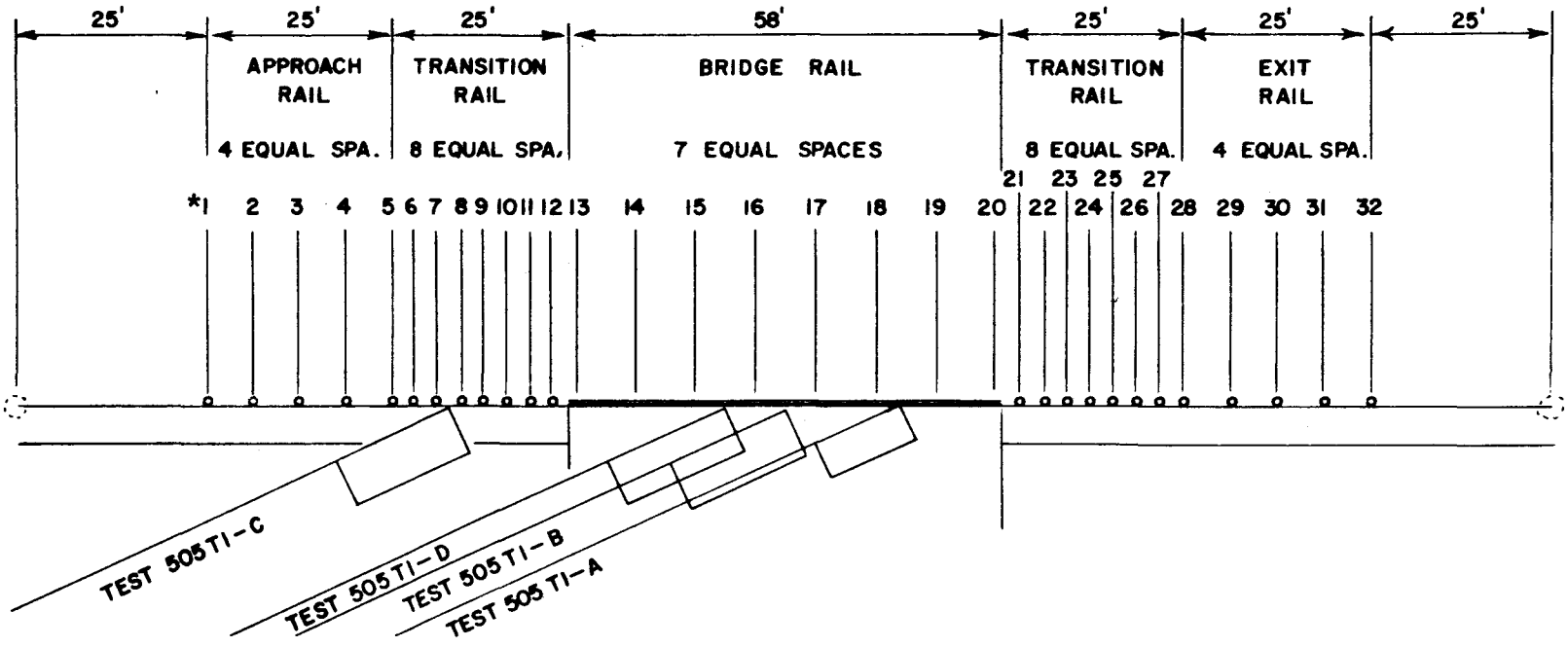



FIGURE 1, TEXAS TI PROTECTIVE BARRIER




| TEST NUMBER | 505TI-A** | 505TI-B** | 505TI-C | 505TI-D*** |
|---|---|---|---|---|
| IMPACT ANGLE | 25° | 25° | 25° | 25° |
| VEHICLE WEIGHT (LBS.) | 1860 | 3920 | 3670 | 3620 |
| IMPACT VELOCITY (MPH) | 44.5 | 56.4 | 58.0 | 61.4 |

* REFERS TO POST NUMBERS

** STANDARD TI

*** MODIFIED TI

FIGURE 2, SUMMARY OF TESTS.

## DETAILS OF INDIVIDUAL TESTS

### Test T1-A Results

The 1860 lb. vehicle, traveling 44.5 mph, impacted the bridge rail section at an angle of 25°. Figure 3, the Position-Time Diagram, illustrates this test. The bridge rail contained and redirected the vehicle.

The average total impact force caused by the collision of this lightweight vehicle traveling at moderate speed is estimated to be 9672 lbs. (1860 lbs. x 5.2 g's). The T1 barrier was designed in accordance with the AASHO Standard Specifications for Bridges (1964 Interim Specifications) which produces a rail strong enough to restrain an impact force greater than that applied in this crash test.[1] The 12 gage W-section was deformed at its lower edge during the collision to the extent that the crash vehicle snagged post number 19 (T = 150 msec, approximately) before being redirected by coming into contact with the 11.5 lb. channel. These events in the collision incident caused the vehicle to be slowed from 65.2 fps (44.5 mph) to 39.2 fps (26.7 mph). The average lateral component of impact force is estimated to be 8,740 pounds, and the average longitudinal component of impact force is estimated to be 4,090 pounds. The photographs clearly indicate that the impact attenuation was provided by the vehicle, since the barrier was not displaced during the collision incident.

A damage rating of 4.9 indicates moderate damage to the vehicle.

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[1] "Interim Specifications for Bridge Railings," American Association of of State Highway Officials, 1964.

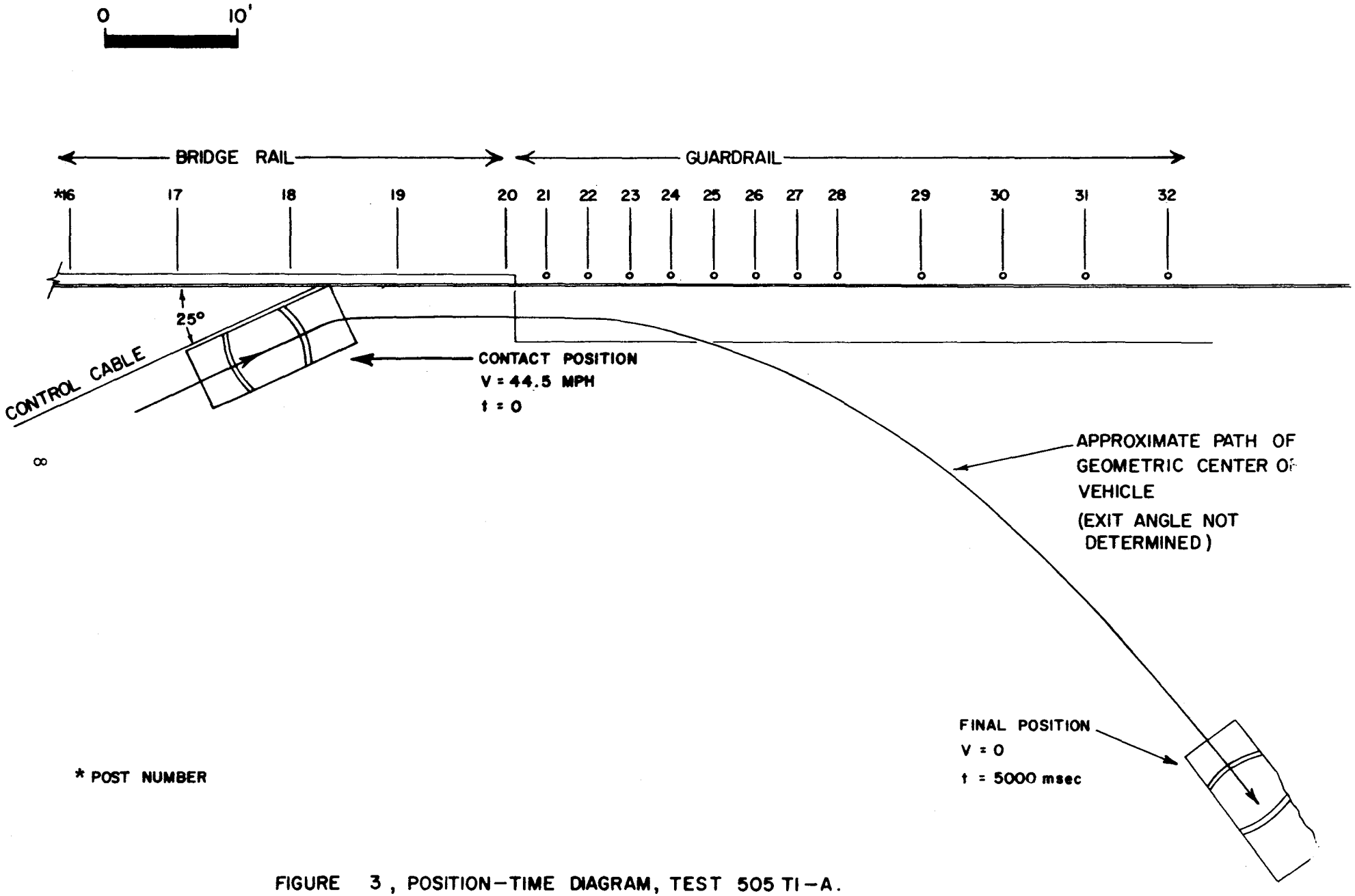


FIGURE 3, POSITION-TIME DIAGRAM, TEST 505 TI-A.

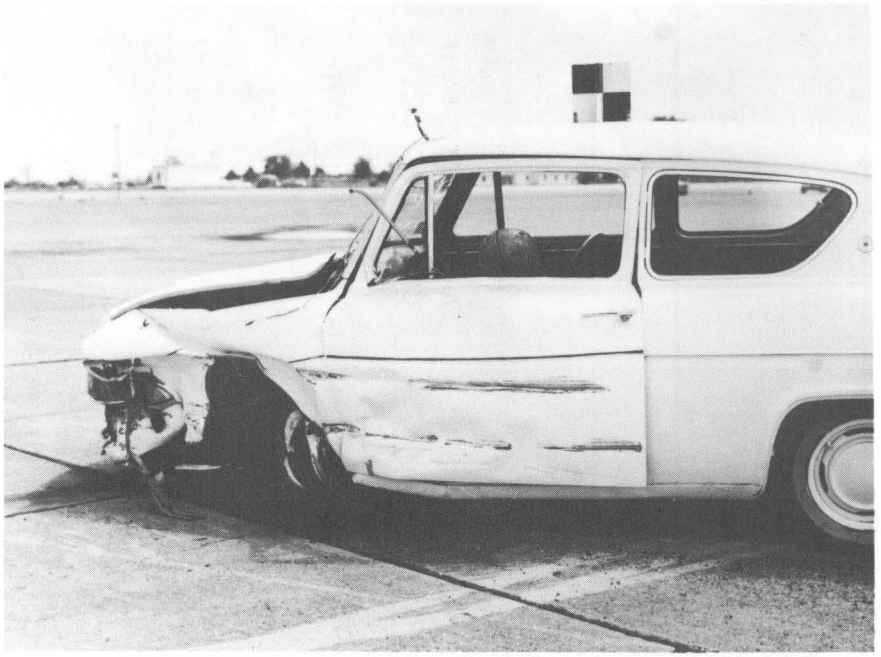

TABLE 3

SUMMARY OF HIGH-SPEED FILM CRASH TEST DATA

Test T1-A

Vehicle Weight = 1860 lb (1958 Anglia, 2-door)

Impact Angle = 25°

Velocity at Impact = 44.5 mph or 65.2 fps

Change in Velocity
During Rail Contact = 17.8 mph or 26.0 fps

Deflection of Barrier: Negligible

Damage to Barrier: Slight

Damage to Vehicle = Moderate (Damage Rating: 4.9)

Probability of Injury
To Unrestrained Occupants: 50%[2]

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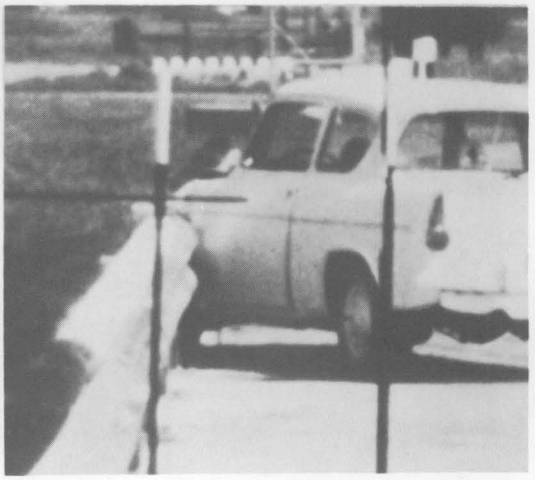
[2]"Tentative Service Requirements For Bridge Rail Systems," NCHRP Report 86, R.M. Olson, E.R. Post, and W.F. McFarland, Highway Research Board, 1970, p. 15.

T = -20 msec

T = 0 msec



T = 60 msec

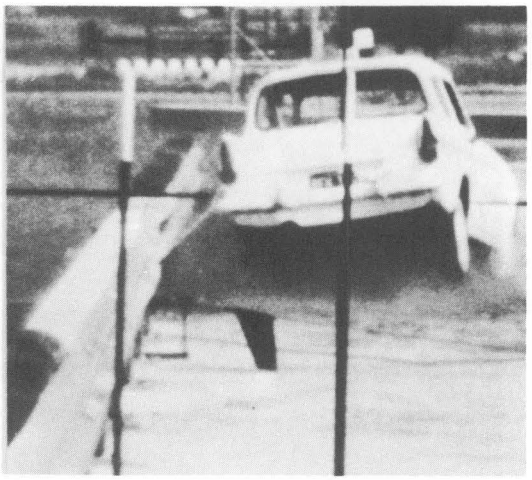
T = 120 msec

T = 180 msec

Figure 4, Sequential Photographs of Test T1-A.

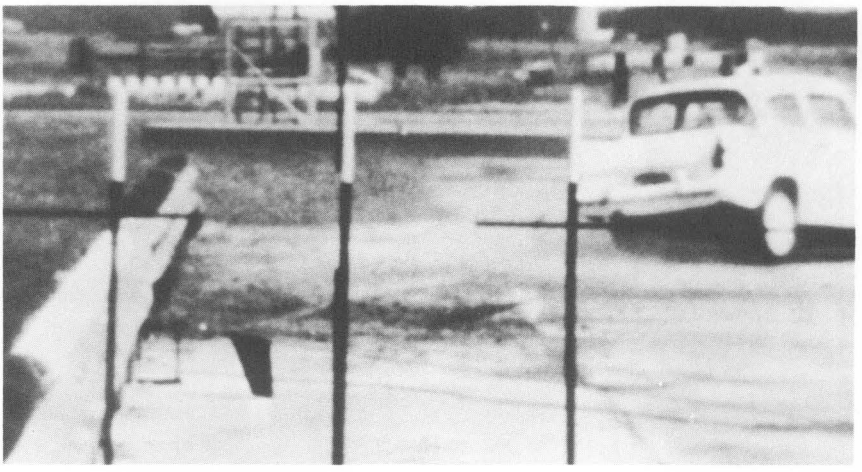
T = 300 msec

T = 480 msec



T = 680 msec

T = 1680 msec



T = 2080 msec

Figure 4 (continued)


Figure 5, Vehicle Before Test T1-A.

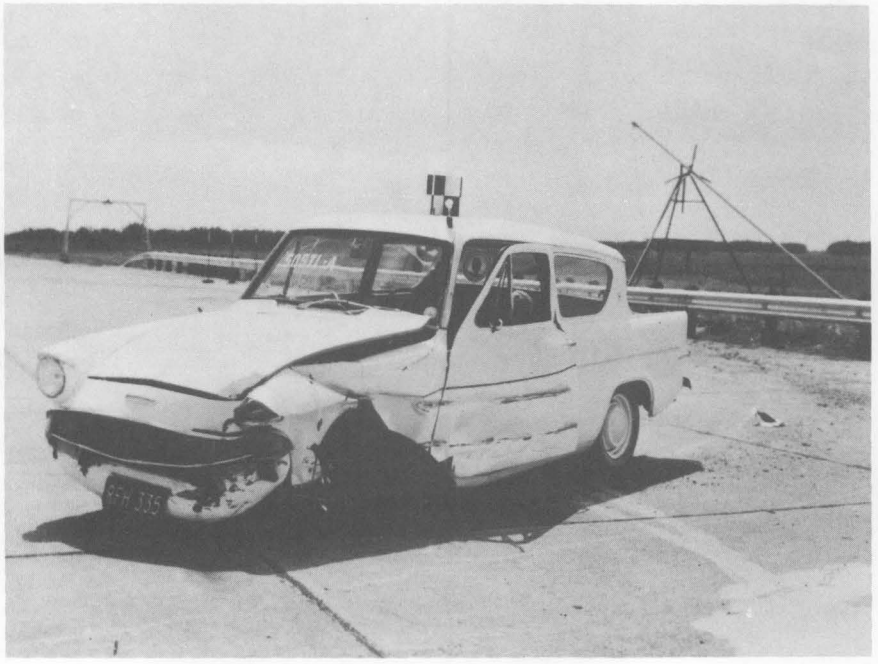



Figure 6. Vehicle After Test T1-A.

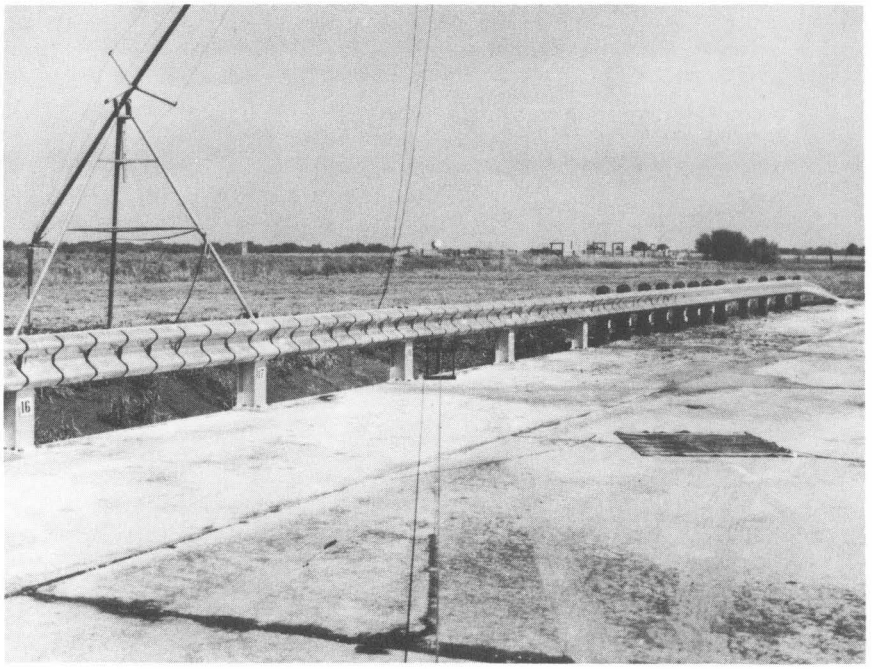



Figure 7, Impact Area Before Test T1-A.

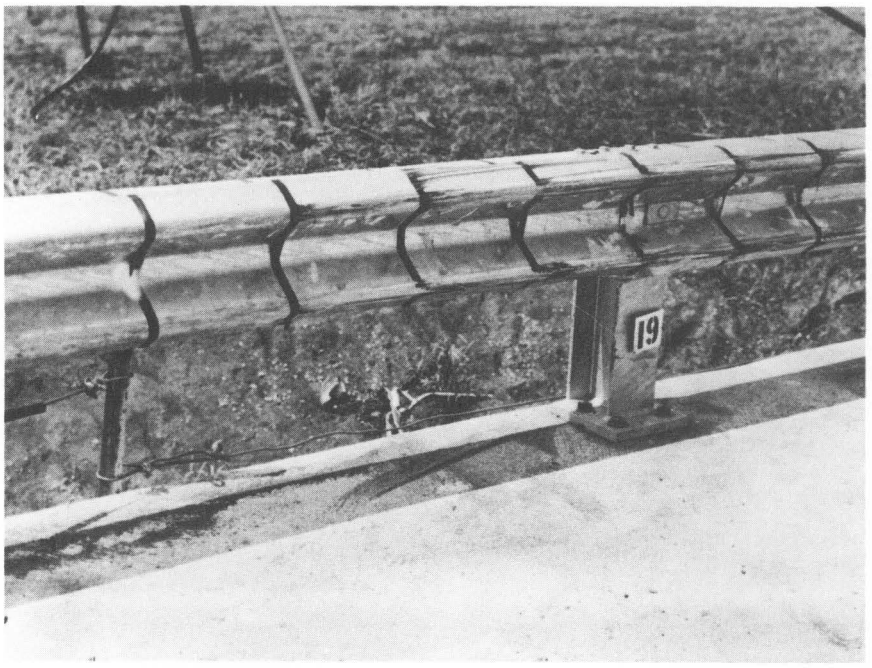


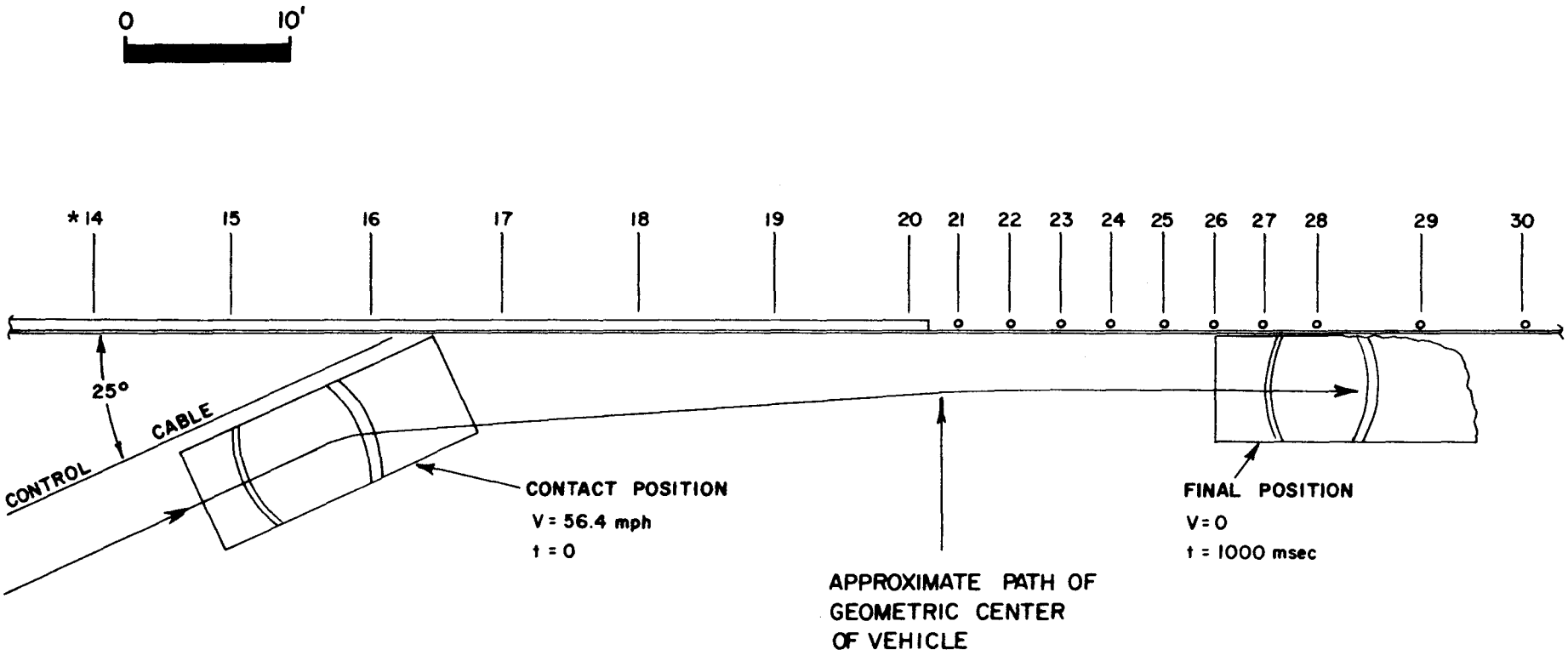

Figure 8, Impact Area After Test T1-A.

Test T1-B Results

The 3920 lb. vehicle contacted the guardrail at a 25° angle while traveling 56.4 mph. The Position-Time Diagram, Figure 9, depicts the vehicle-barrier interaction. Figure 10 shows sequential photographs of the collision.

The average total impact force estimated to be 28,224 lbs. (3920 lbs. x 7.2 g's) indicates that the T1 barrier, designed in accordance with AASHO Standard Specifications for Highway Bridges (1964 Interim Specifications) is strong enough to restrain an impact force greater than that applied in this test.[1] Under the force of impact the 12 gage W-section was deformed into the plastic range and fractured (Figure 14) permitting the crash vehicle to snag post number 17, producing an average longitudinal component of impact force of 18,420 pounds, and an average lateral component of impact force of 21,170 pounds. The average total impact force accounts for the extensive damage to the vehicle (see Figure 12), which provided major portion of the impact attenuation in this collision incident since the barrier displacement was negligible (see Figure 10).

A damage rating of 6.4 is indicative of the severe vehicle damage produced by the collision with this strong system.




* POST NUMBER

FIGURE 9, POSITION–TIME DIAGRAM, TEST 505 TI–B.

TABLE 4

SUMMARY OF HIGH-SPEED FILM CRASH TEST DATA

Test T1-B

Vehicle Weight = 3920 lb (1961 Ford, 4-door)

Impact Angle = 25°

Velocity at Impact = 56.4 mph or 82.7 fps

Change in Velocity = 29.7 mph or 43.6 fps

Deflection of Barrier: Negligible

Damage to Barrier: Moderate

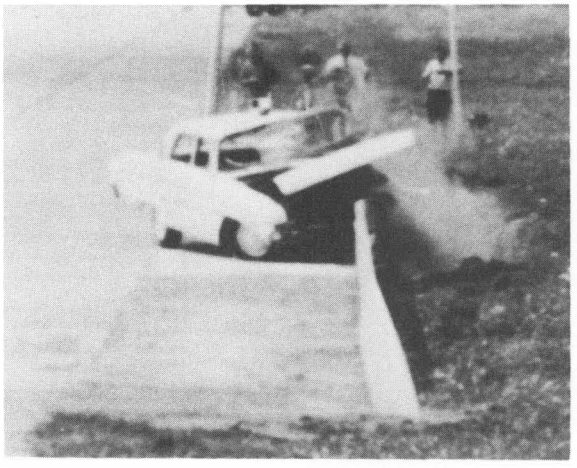
Damage to Vehicle: Severe (Damage Rating: 6.4)

Probability of Injury
To Unrestrained Occupants: 85%[2]

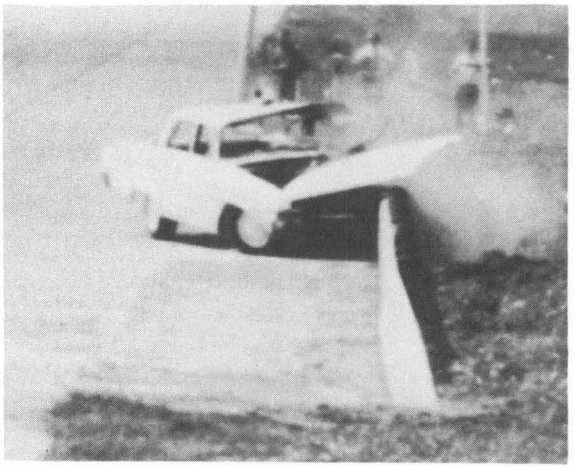
T = -90 msec

T = 0 msec

T = 45 msec

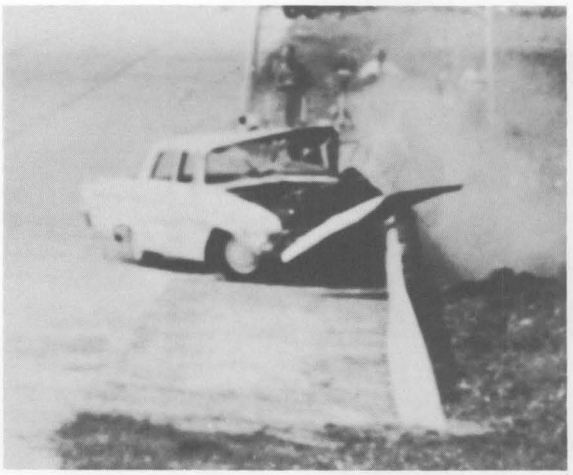


T = 135 msec



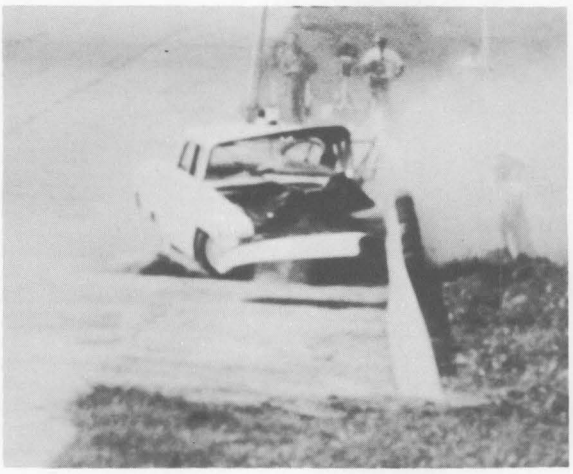
T = 225 msec

Figure 10, Sequential Photographs of Test T1-B.

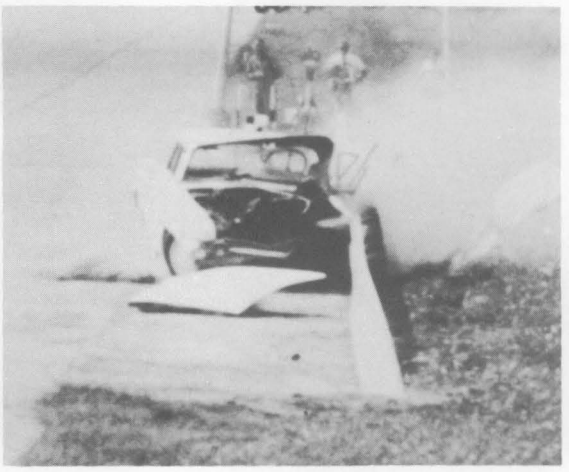


T = 315 msec

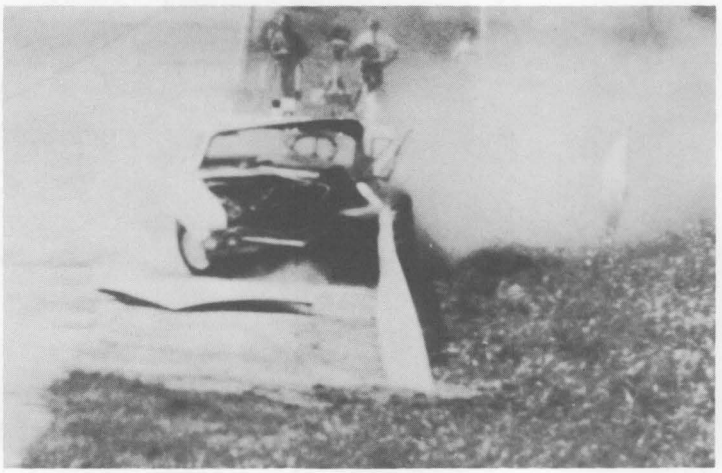
T = 450 msec



T = 540 msec



T = 630 msec



T = 720 msec

Figure 10 (continued)

Figure 11, Vehicle Before Test T1-B.

Figure 12, Vehicle After Test T1-B.

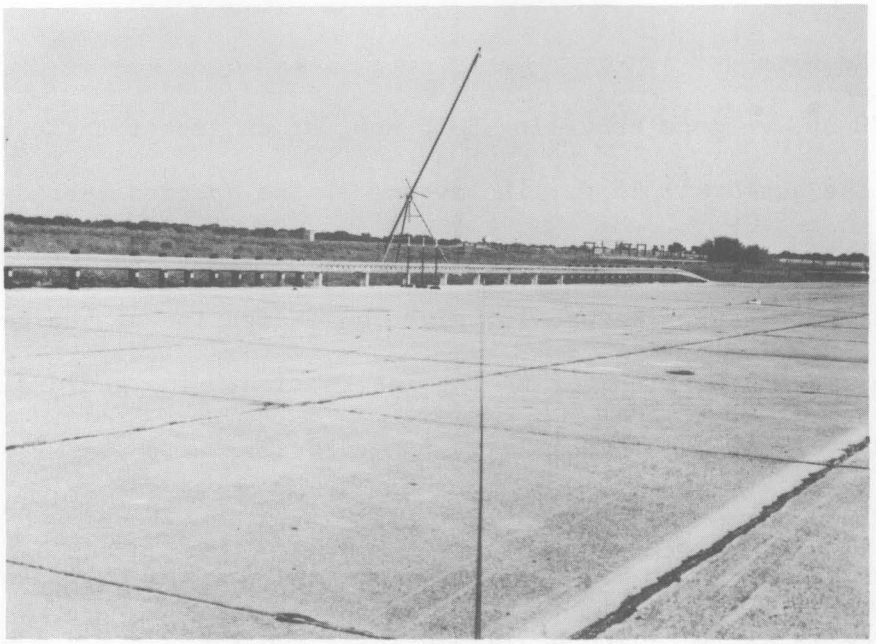


Figure 13, Impact Area Before Test T1-B.

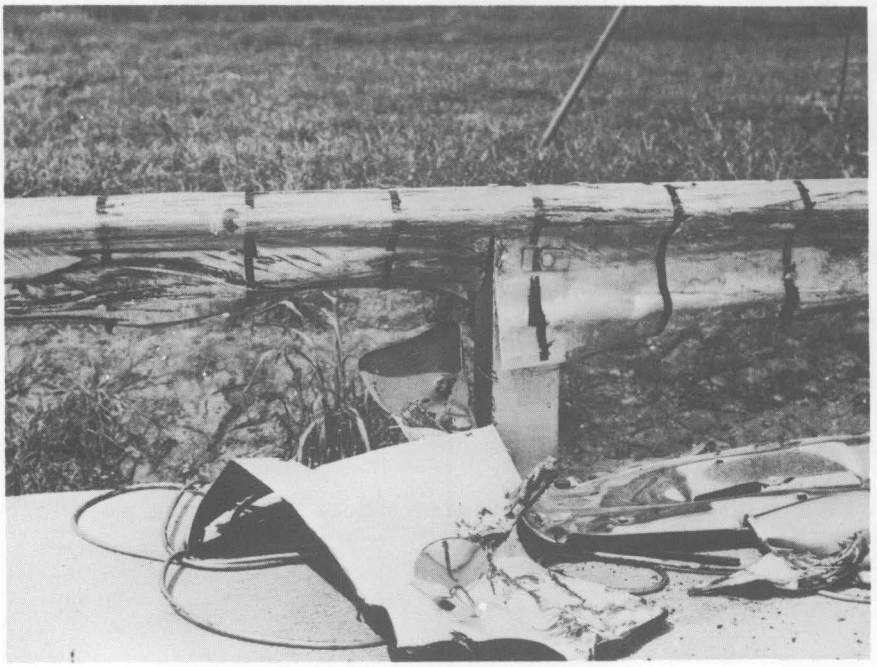


Figure 14, Impact Area After Test T1-B.

Test T1-C Results

A 3670 lb. vehicle traveling 58.0 mph, at an impact angle of 25°, contacted the guardrail 15 ft. in advance of the guardrail-bridge rail interface. The Position-Time Diagram, Figure 15, and the motion picture sequential photographs, Figure 16, given an indication of the behavior of the vehicle and barrier during the interaction. The guardrail contained and redirected the vehicle as intended.

The average total impact force in this test is estimated to be 16,515 lbs. (3670 lbs. x 4.5 g's). The average lateral component of impact force is estimated to be 14,310 lbs., and the average longitudinal component of impact force is estimated to be 8,070 lbs. The barrier is capable of significant lateral displacement as shown in Figure 20 and thus provides impact attenuation capabilities not available in the stronger T1 bridge rail. The average lateral and longitudinal components of impact force are considerably smaller than those estimated for test T1-B. The vehicle weights and speeds were comparable in the two tests, but a 21-inch displacement of the transition rail resulted in a much reduced impact force. Such a force reduction owing to rail displacement was predicted in the final report of an NCHRP study.[2] The transition rail to bridge rail connection was adequate to provide structural continuity between the two systems.

The damage rating of 3.9 indicates moderate damage to the colliding vehicle.

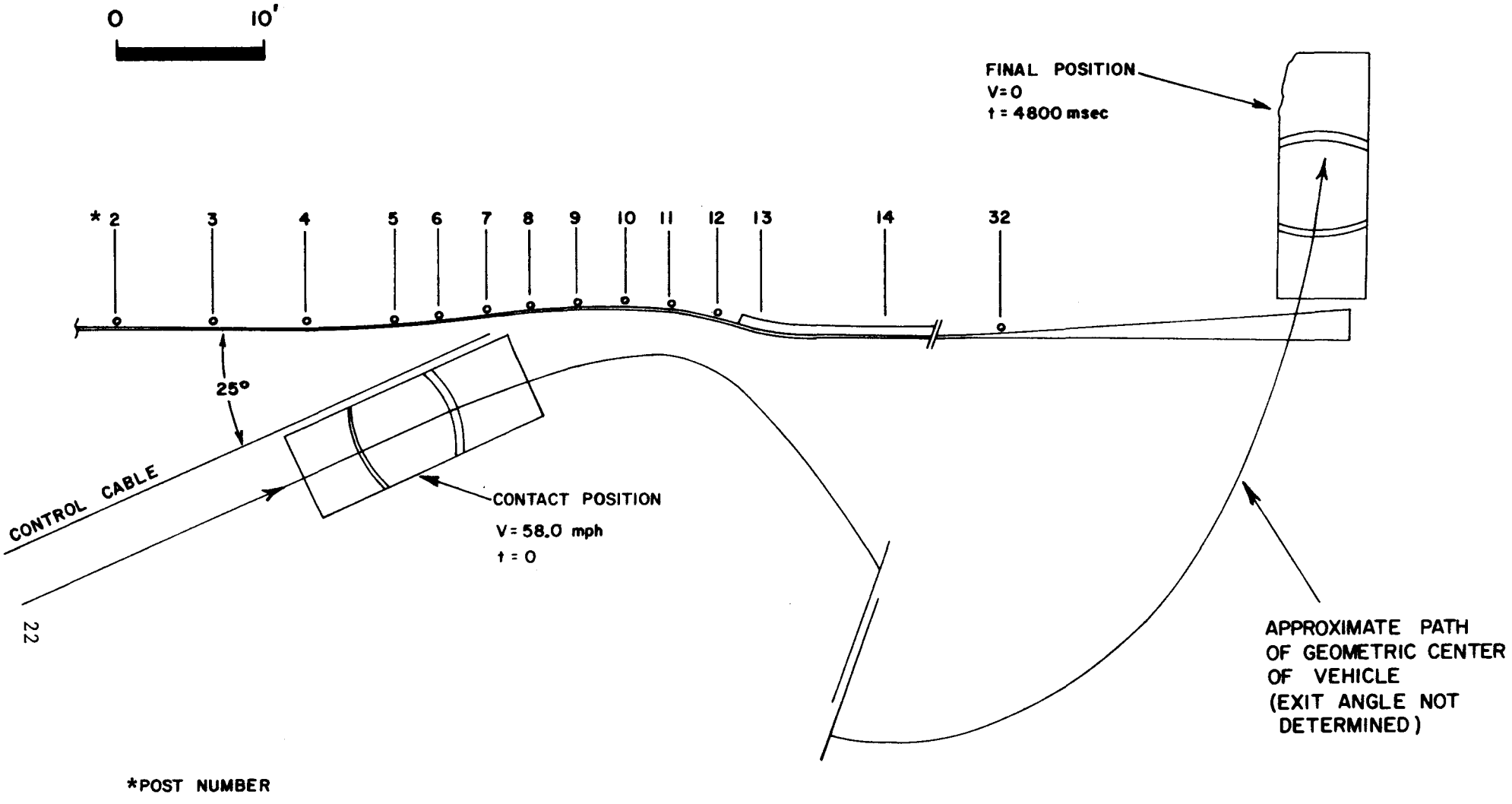



FIGURE 15, POSITION–TIME DIAGRAM, TEST 505 TI–C.

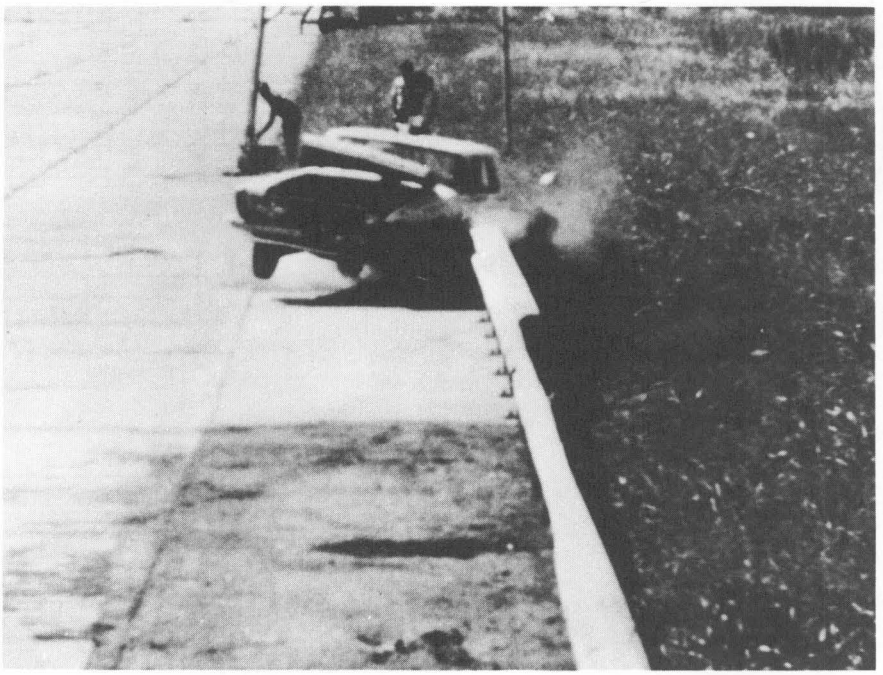


TABLE 5

SUMMARY OF HIGH-SPEED FILM CRASH TEST DATA

Test T1-C

Vehicle Weight = 3670 lb (1965 Plymouth, 4-door)

Impact Angle = 25°

Velocity at Impact = 58.0 mph or 85.0 fps

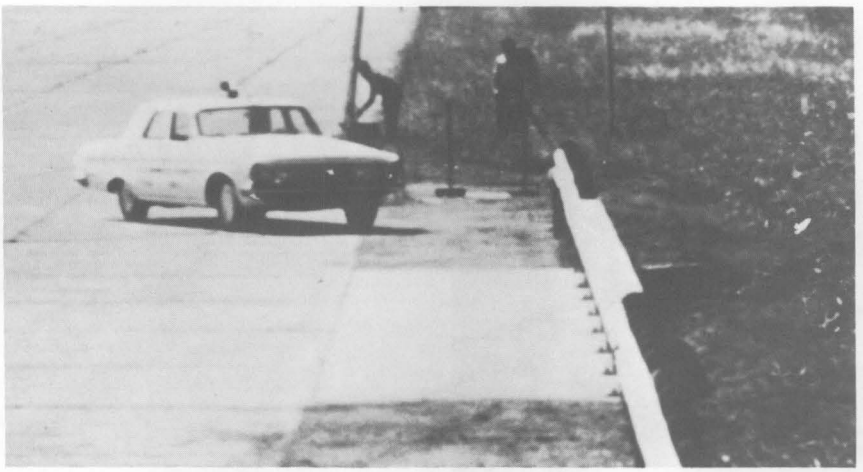
Change in Velocity = 18.2 mph or 26.7 fps

Deflection of Guardrail: 21 in.

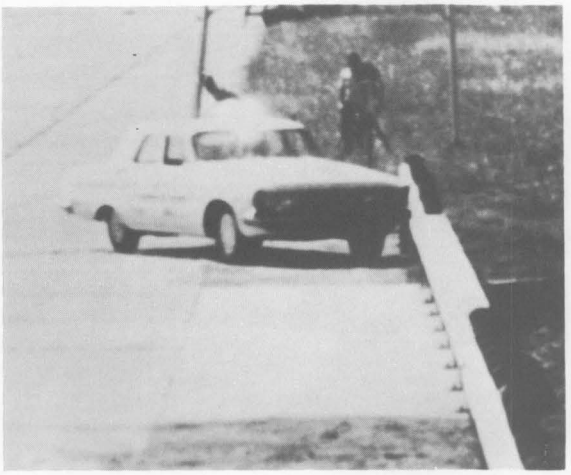
Damage to Guardrail: Moderate

Damage to Vehicle: Moderate (Damage Rating: 3.9)

Probability of Injury
To Unrestrained Occupants: 30%[(2)]



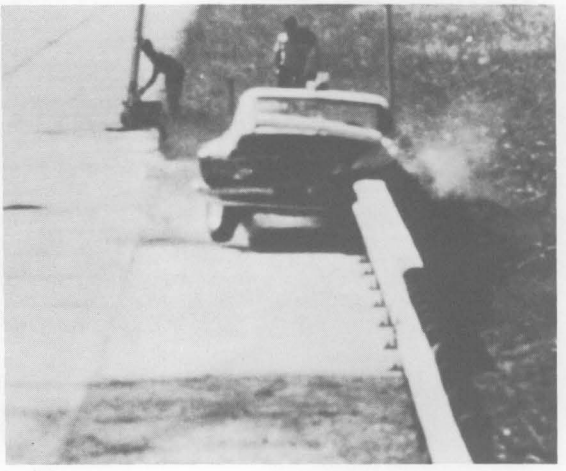
T = -90 msec



T = 0

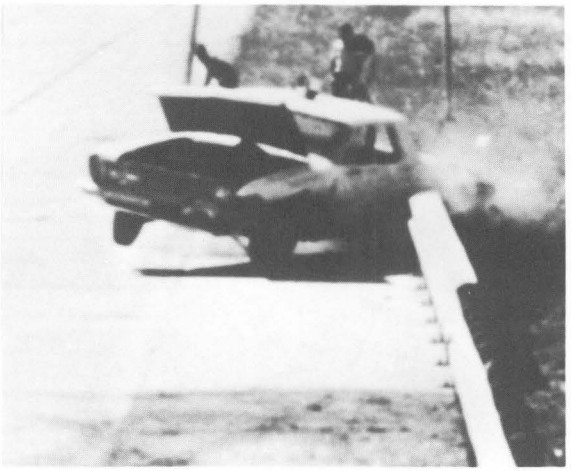
T = 45 msec

T = 90 msec

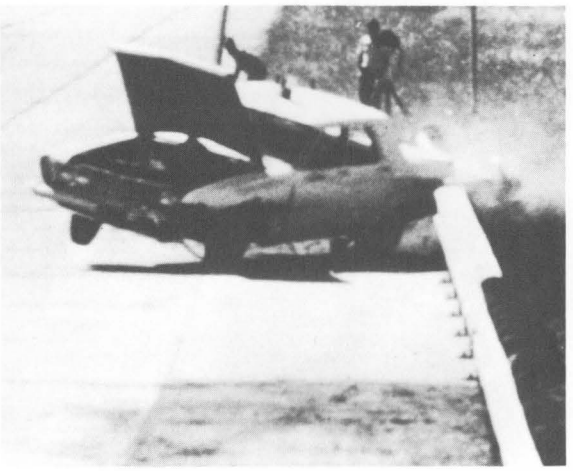


T = 135 msec

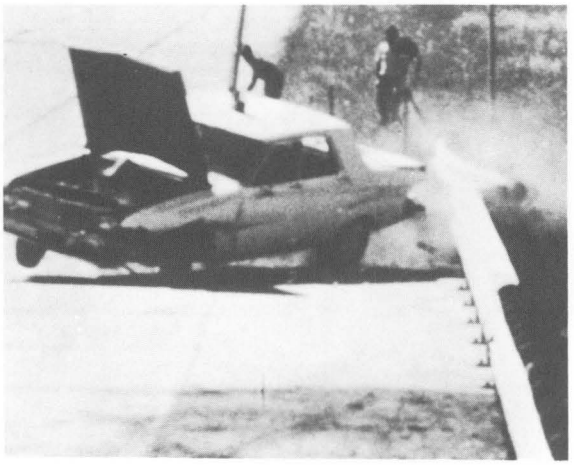
Figure 16, Sequential Photographs of Test T1-C.



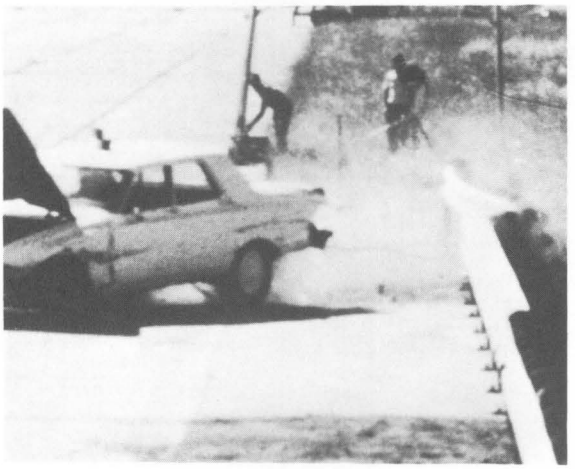
T = 225 msec



T = 270 msec



T = 315 msec



T = 405 msec

T = 450 msec

Figure 16 (continued)

Figure 17, Vehicle Before Test T1-C.

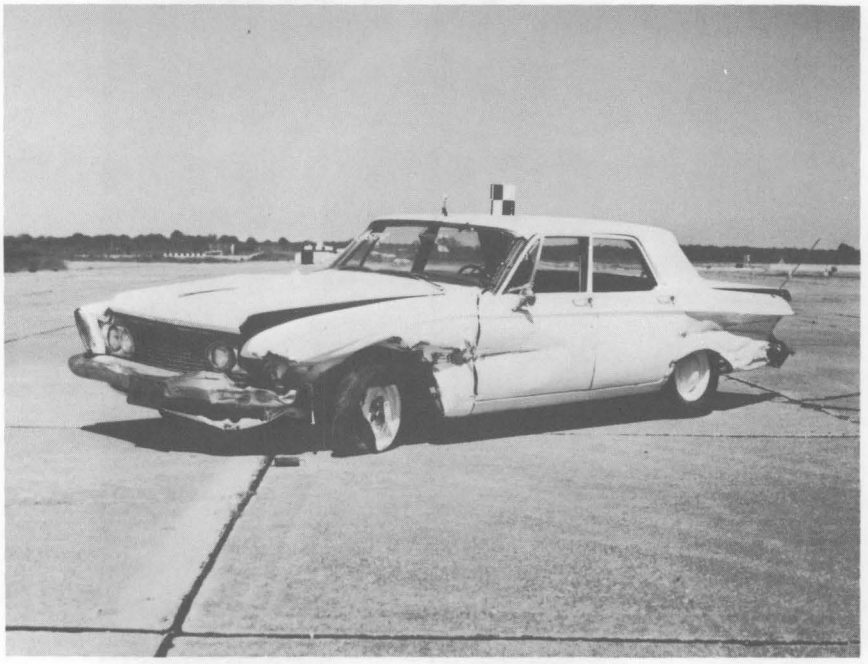


Figure 18, Vehicle After Test T1-C.

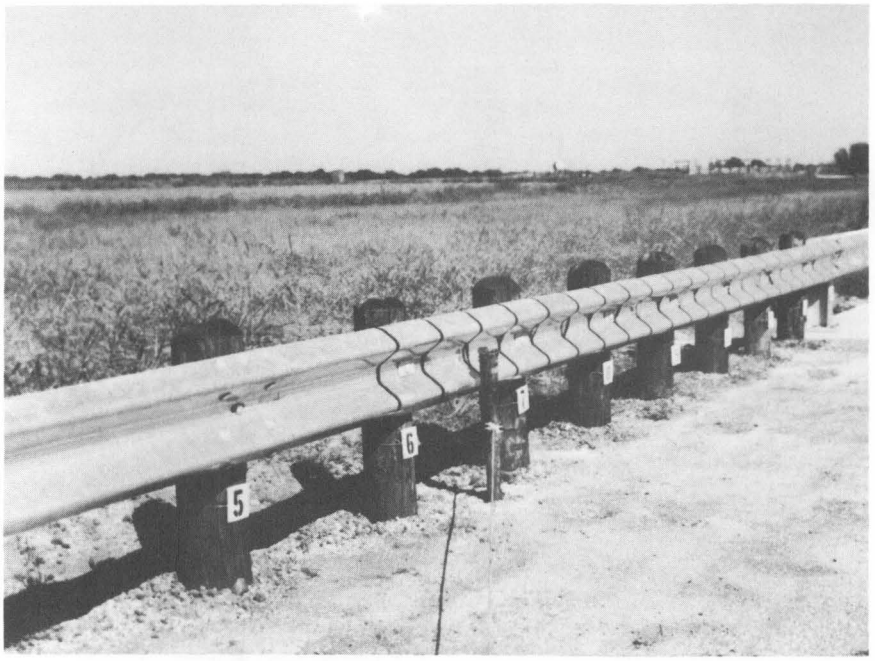



Figure 19, Guardrail Installation Before Test T1-C.

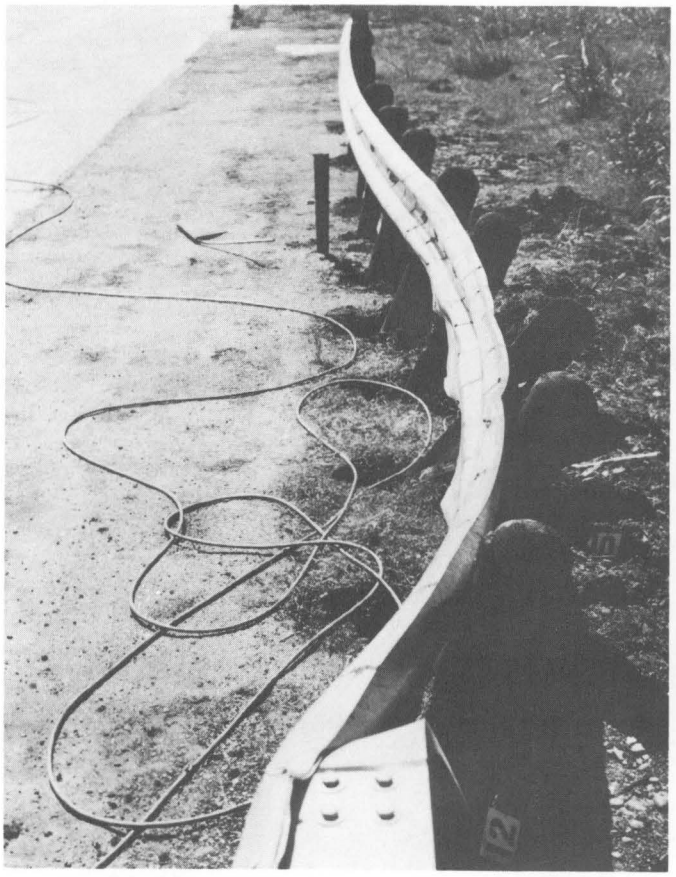


Figure 20, Guardrail Installation After Test T1-C.

Test T1-D Results

The Texas T1 bridge rail was modified for Test T1-D as shown in Figure 1. An overlapping W-section guardrail was added to the bridge rail section of the barrier system. The 3620 lb. vehicle, traveling 61.4 mph collided with the barrier bridge rail section at an angle of 25°. The Position-Time Diagram, Figure 21, and the motion picture sequential photographs, Figure 22, show the vehicle-barrier interaction during the collision. The protective barrier contained and redirected the vehicle.

The average total impact force in this test is estimated to be 24,616 lbs. (3620 lbs. x 6.8 g's). It is apparent that the overlapped 12 gage W-sections provided a stronger system between posts; thus the lateral deceleration component was 26 percent larger than in Test T1-B; however, the longitudinal component was only 4 percent of that produced in Test T1-B. It is significant that the average total g's in these two tests were nearly the same (see Table 1); but the damage rating in the modified rail test was in the moderate range, whereas a severe damage rating resulted in Test T1-B. Elimination of snagging accounts for the reduction in damage, because the longitudinal component of deceleration was reduced to 0.2 g. The average lateral component of impact force is estimated to be 24,620 pounds; however, the average longitudinal component of impact force is estimated to be only 720 pounds.

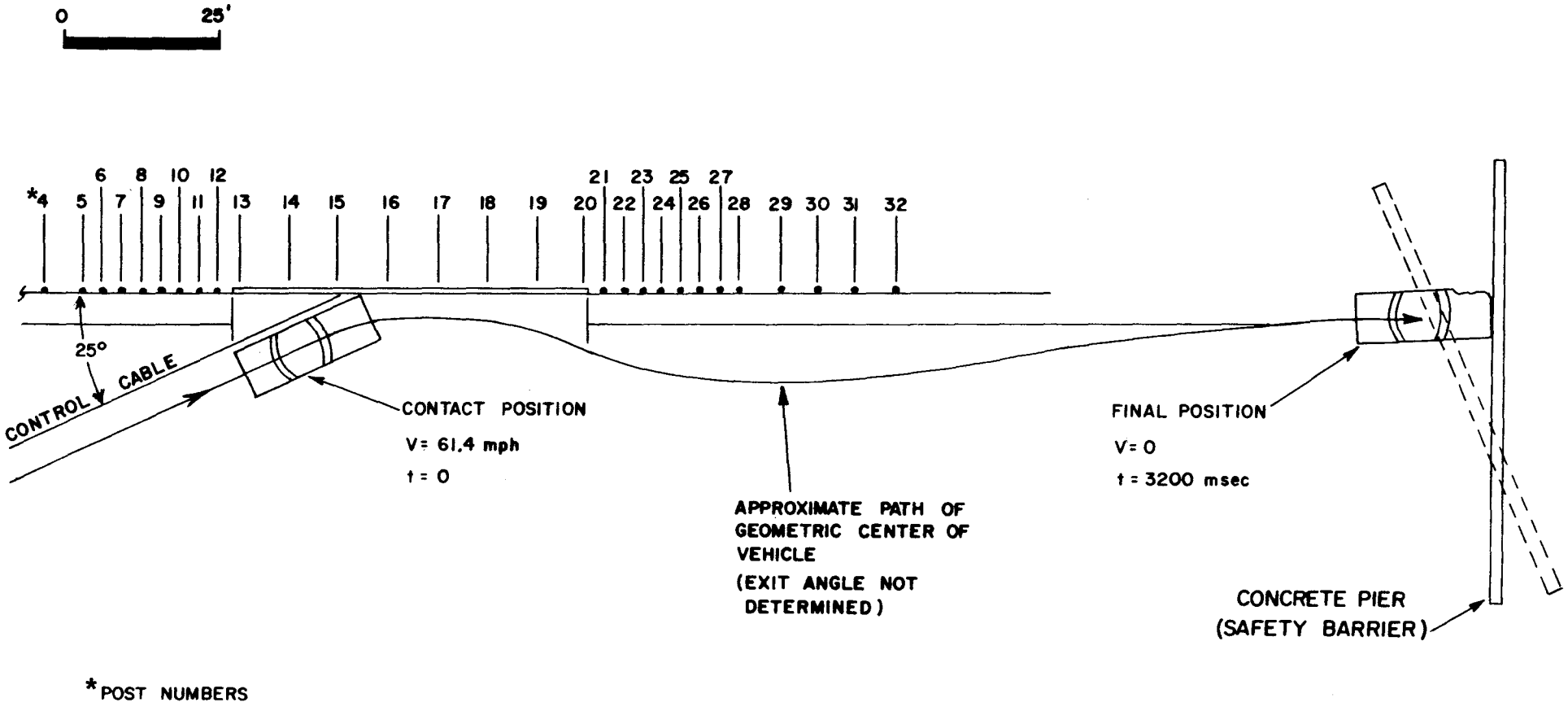



FIGURE 21, POSITION—TIME DIAGRAM, TEST 505 TI-D.

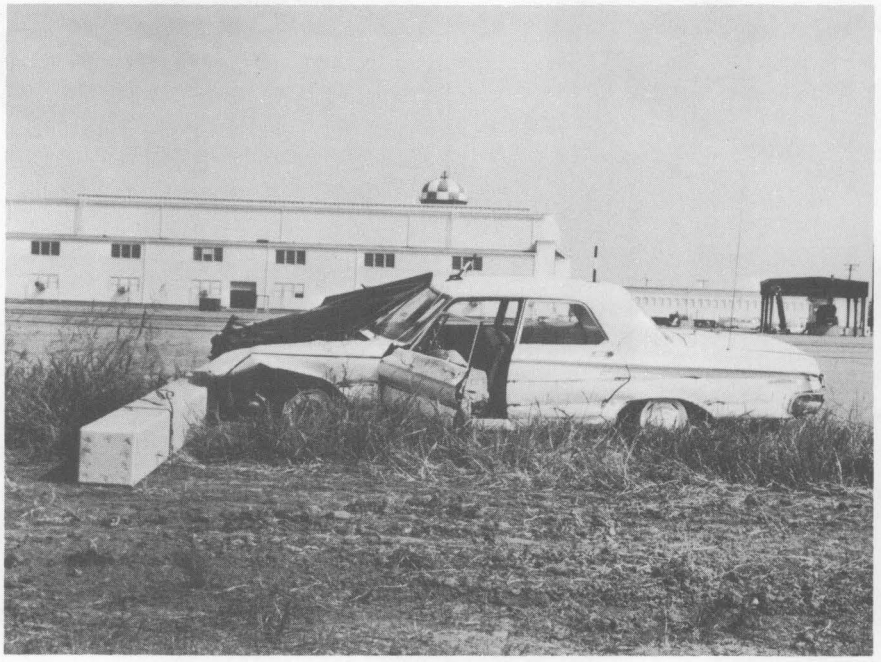


TABLE 6

SUMMARY OF HIGH-SPEED FILM CRASH TEST DATA

Test T1-D

Vehicle Weight = 3620 lb (1964 Dodge, 4-door)

Impact Angle = 25°

Velocity at Impact = 61.4 mph or 90.1 fps

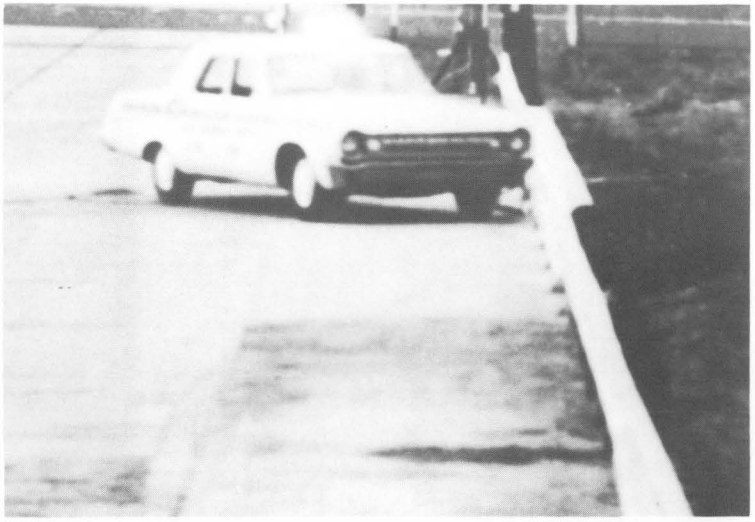
Change in Velocity = 7.1 mph or 10.4 fps

Deflection of Barrier: 2 in.

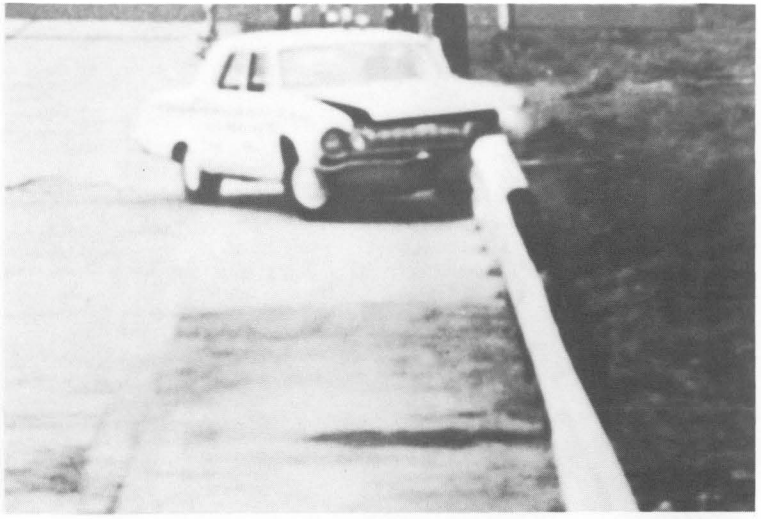
Damage to Barrier: Slight

Damage to Vehicle: Moderate (Damage Rating: 4.5)

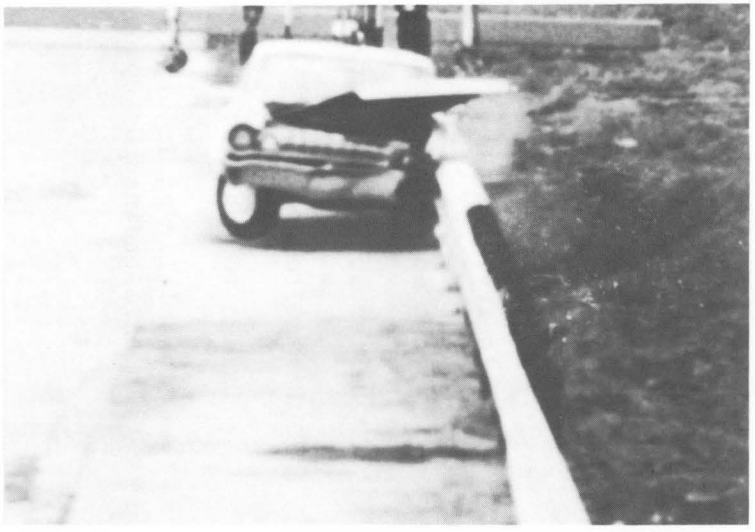
Probability of Injury
To Unrestrained Occupant: 45%[2]



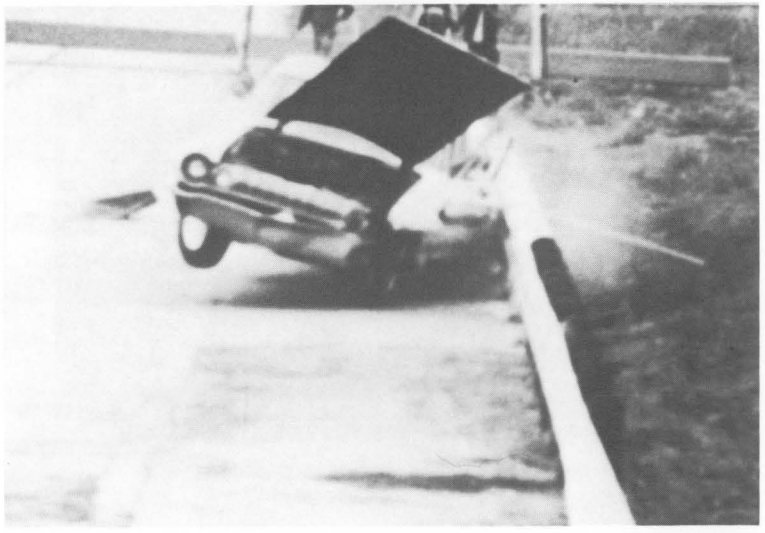
T = 0 msec



T = 45 msec



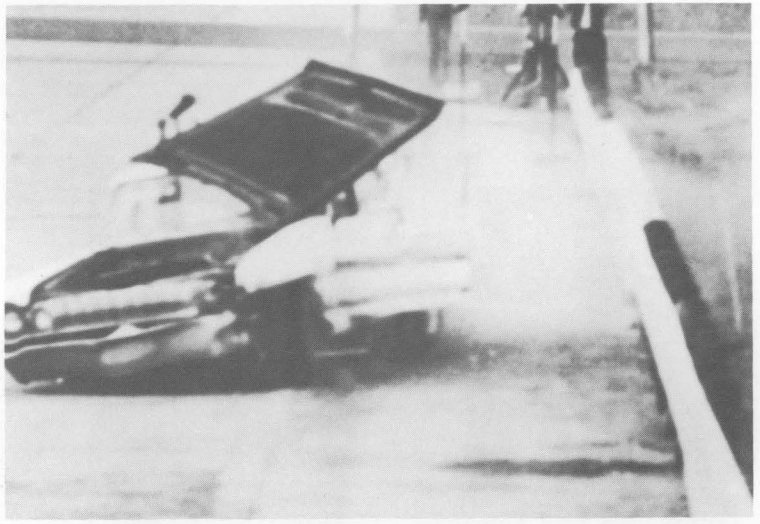
T = 90 msec



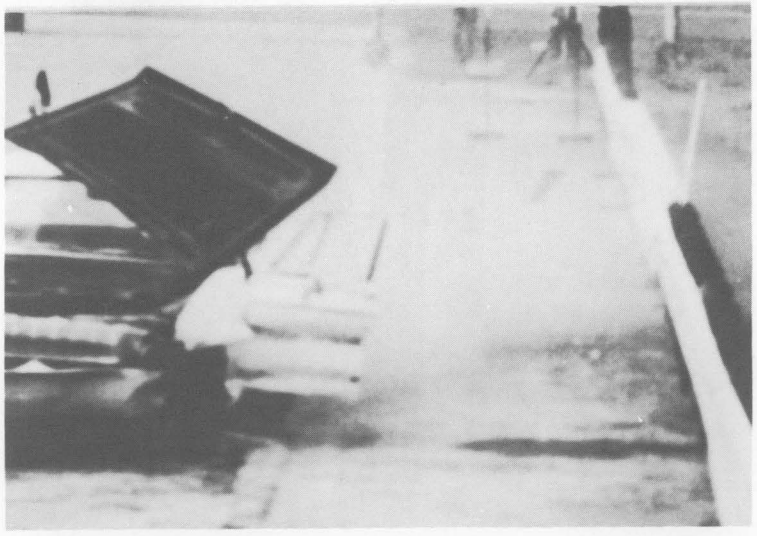
T = 180 msec

Figure 22, Sequential Photographs of Test T1-D.

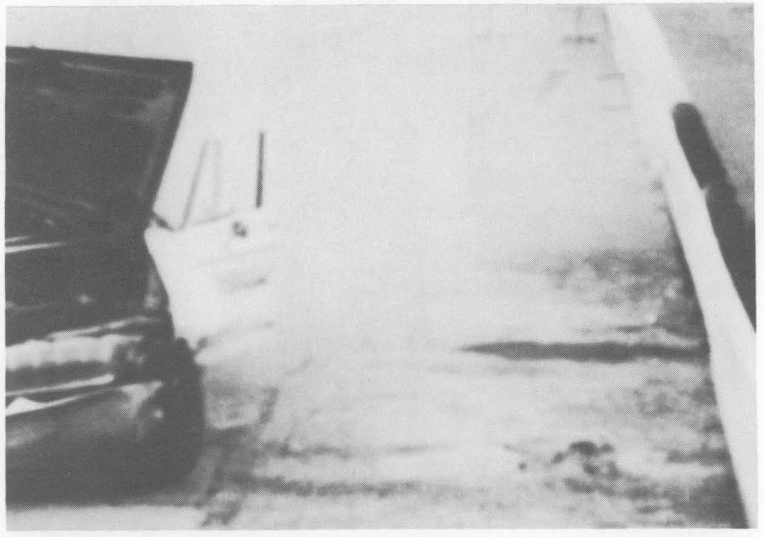
T = 260 msec



T = 395 msec



T = 575 msec



T = 755 msec

Figure 22 (continued)

Figure 23, Vehicle Before Test T1-D.

Figure 24, Vehicle After Test T1-D.

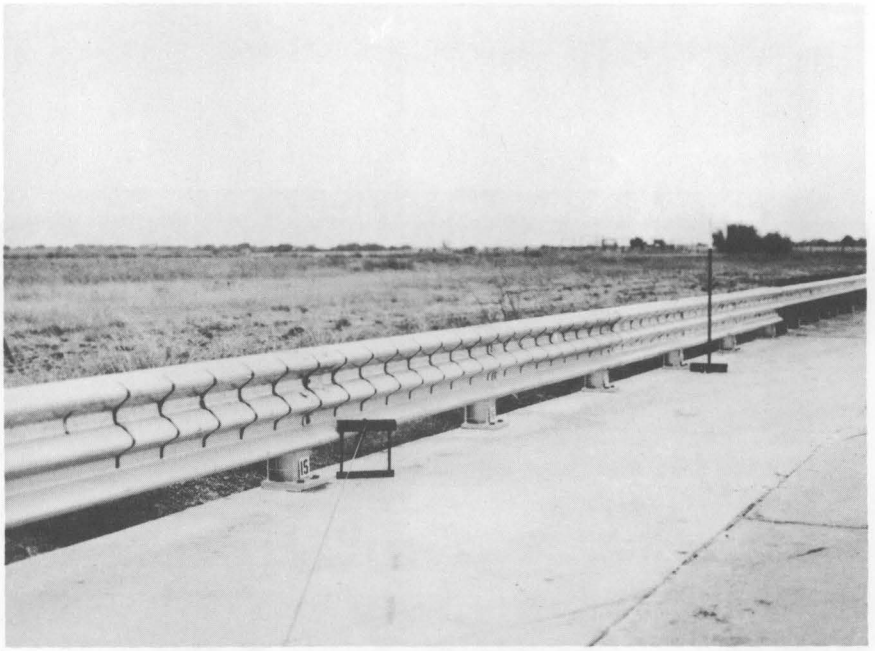


Figure 25, Barrier Before Test T1-D.

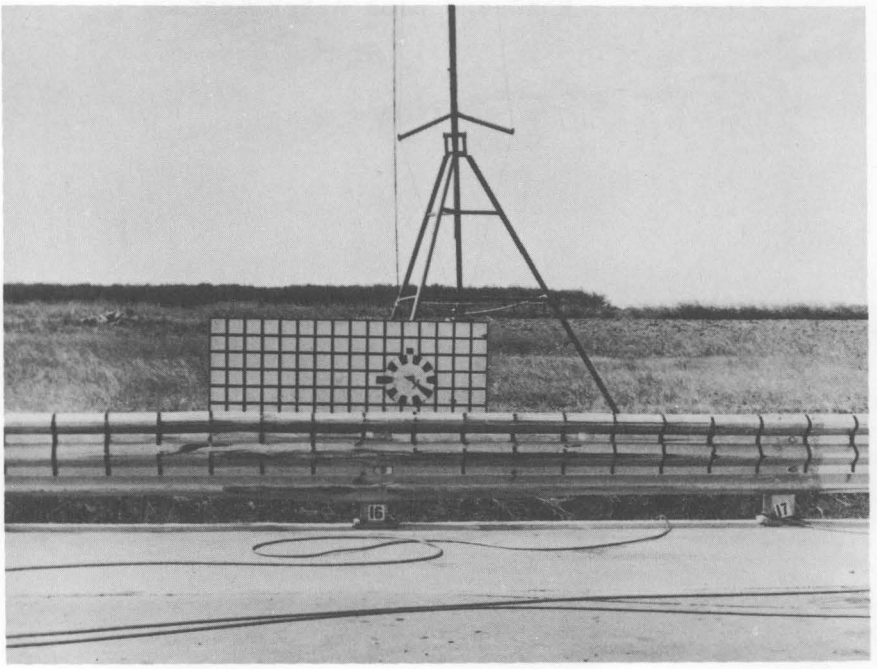


Figure 26, Barrier After Test T1-D.

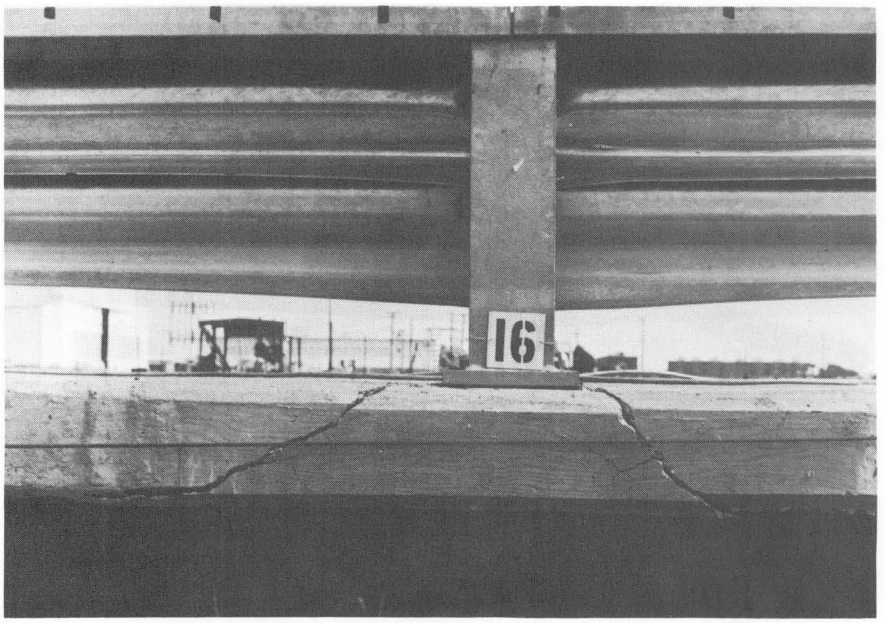



Figure 27, Rail and Slab After Test T1-D.

## CONCLUSION AND EVALUATION

In four of four full-scale vehicle crash tests, it was found that the Texas T1 protective barrier is an effective vehicle containment and redirection system. The tests ranged in severity from an 1860 lb vehicle traveling 44.5 mph to a 3670 lb vehicle traveling 58.0 mph. All tests were conducted at an impact angle of 25°. Damage to the bridge rail section of the test barrier was relatively minor. Damage to the transition guardrail section in a single test was extensive. Vehicle damage ranged from moderate to severe. The Texas T1 bridge rail is a rigid system which undergoes negligible lateral displacements during a vehicle collision. The transition rail connection had adequate strength.

On the basis of the tests conducted, it appears that maintenance costs of the T1 Bridge Rail System should be nominal. The usual damage in a high-speed collision consists of localized deformations to the impacted W-section, and cracking of the bridge slab in the pattern shown by Figure 27. The bridge slab cracking appears to be a diagonal tension-type crack which results from the punching shear load generated by the base plate of the bridge rail support post. Although the concrete cracks in the collision area appear to be severe, the structural integrity of the slab is maintained by the steel reinforcement.

It is the opinion of the authors that these cracks may be repaired by placing a lateral load on the support post to force the crack open, grouting the crack with epoxy, and then reversing the lateral load to close the crack. The structural integrity of the bridge rail system does not appear to be damaged significantly by these diagonal tension cracks. Damage to the W-section rail is reduced by adding an additional, partially overlapping, W-section as in the modified T1 test (T1-D).

Tentative service requirements suggested in NCHRP Report 86 are listed below:

1. A bridge rail system must laterally restrain a selected vehicle.
2. A bridge rail system must minimize vehicle decelerations.
3. A bridge rail system must smoothly redirect a colliding vehicle.
4. A bridge rail system must remain intact following a collision.
5. A bridge rail system which serves vehicles and pedestrians must provide protection for vehicle occupants and pedestrians.
6. A bridge rail system must have a compatible approach rail or other device to prevent collisions with the end of the bridge rail system.
7. A bridge rail system must define yet permit adequate visibility.
8. A bridge rail must project inside the face of any required curb.
9. A bridge rail system must be susceptible of quick repair.
10. The foregoing requirements must be met by giving emphasis first to safety, second to economics, and third to aesthetics.

Evaluations of vehicle-barrier interaction on the basis of these service requirements is presented in Table 7. The evaluations were made using information from high-speed films, a National Safety Council damage rating scale, estimates of probable injuries from Figures 7 and 8 of NCHRP Report 86, and examination of the barrier after each test. Safety, economics, and aesthetics (Service Requirement 10) are evaluated in the table by assigning a numerical value for each test. It is recognized that the vehicle weight, speed, and consequently impact force varied widely between tests. The evaluation of each item was made with these facts in mind.

| Service Requirement | T-1 Bridge Rail Test T1-A | T-1 Bridge Rail Test T1-B | Transition Rail Test T1-C | Modified T-1 Bridge Rail Test T1-D |
|---|---|---|---|---|
| 1 | Adequate lateral restraint is provided by each of these barriers, penetration and vaulting do not occur. | | | |
| 2 | $G_{TOTAL}$ = 5.2<br>Vehicle Damage Rating: 4.9<br>Probability of Injury: 50% | $G_{TOTAL}$ = 7.2<br>Vehicle Damage Rating: 6.4<br>Probability of Injury: 85% | $G_{TOTAL}$ = 4.5<br>Vehicle Damage Rating: 3.9<br>Probability of Injury: 30% | $G_{TOTAL}$ = 6.8<br>Vehicle Damage Rating: 4.5<br>Probability of Injury: 45% |
| 3 | Good redirection, Slight snagging. See Figure 4 | Poor redirection, Severe snagging. See Figure 10 | Good redirection. See Figure 16 | Fair redirection. See Figure 22 |
| 4 | Each barrier remained intact following the collision. | | | |
| 5 | Not applicable | Not applicable | Not applicable | Not applicable |
| 6 | Yes | Yes | This approach rail is compatible geometrically and has adequate connection to bridge rail. | Yes |
| 7 | Each barrier satisfies the requirement for delineation, and does not obstruct driver's sight distance. | | | |
| 8 | No curb | No curb | No curb | No curb |
| 9 | No repairs required | Replaced W-section | Replaced posts and W-section | No repairs required |
| 10 | SAFETY: 3<br>ECONOMICS:<br>Vehicle Repair: 2<br>Barrier Repair: 2<br>AESTHETICS: 1 | SAFETY; 4<br>ECONOMICS:<br>Vehicle Repair: 4<br>Barrier Repair: 3<br>AESTHETICS: 1 | SAFETY: 1<br>ECONOMICS:<br>Vehicle Repair: 1<br>Barrier Repair: 4<br>AESTHETICS: 1 | SAFETY: 2<br>ECONOMICS:<br>Vehicle Repair: 3<br>Barrier Repair: 1<br>AESTHETICS: 1 |

Table 7. Evaluation of Barriers Using Tentative Service Requirements

# A P P E N D I X  A

Photographic Data

## PHOTOGRAPHIC DATA

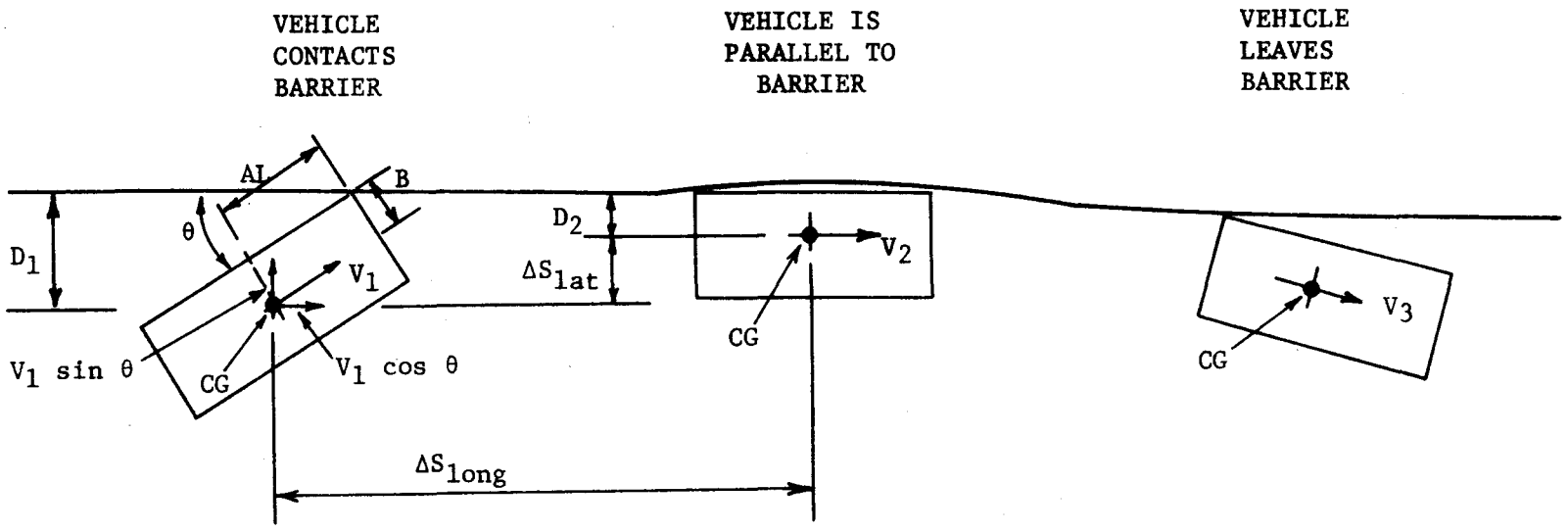
The method employed to compute change in velocity and average deceleration components is defined in Figure A1. The values substituted in the governing equations were taken from data acquired by frame to frame analysis of high-speed films of the collision incident in each test. The data and results from computation are contained in Tables A1, A2, A3, and A4.

Velocities $V_1$, $V_2$, and $V_3$, the directed speeds of the colliding vehicle, were determined by measuring the displacement of some reference mark on the vehicle over an interval of time. $V_1$ was calculated over a time interval just prior to impact; $V_2$, when the vehicle became parallel to the rail; and $V_3$, when the vehicle lost contact with the rail.

The finite increment of displacement, $\Delta S_{lat}$, is computed using Equation (2) in Figure A1. Dimension $D_1$ is computed using AL and B for each vehicle and the angle $\theta$ for each test. Dimension $D_2$ is estimated from high-speed films obtained from a camera located parallel to the bridge rail.

The distance $\Delta S_{long}$ is observed from high-speed film using a camera placed perpendicular to the bridge rail.

The average decelerations perpendicular and parallel to the rail (Average $G_{lat}$ and Average $G_{long}$) are computed by Equations (3) and (4) shown in Figure A1. The average total deceleration (Average $G_{total}$) is defined as the vector sum of these components, as shown in Figure A1.




GOVERNING EQUATIONS:

(1) $\Delta V = V_3 - V_1$

(2) $\Delta S_{lat} = D_1 - D_2$

(3) Average $G_{lat} = \dfrac{(V_1 \sin \theta)^2}{2g\Delta S_{lat}}$

(4) Average $G_{long} = \dfrac{(V_1 \cos \theta)^2 - V_2^2}{2g\Delta S_{long}}$

(5) Average $G_{total} = \left[(\text{Avg. } G_{lat})^2 + (\text{Avg. } G_{long})^2\right]^{1/2}$

Figure A1, GEOMETRIC REPRESENTATION OF PHOTOGRAPHIC ANALYSIS

TABLE A1

TEST 505 T1-A

High-Speed Film Data

| Time (msec) | | Displacement (ft) | |
|---|---|---|---|
| -69 | | -4.5 | $V_1$ = 65.2 ft/sec |
| -46 | | -3.0 | |
| -23 | | -1.5 | |
| 0 | Impact | 0 | |
| 10 | | 0.7 | |
| 20 | | 1.3 | |
| 31 | | 2.0 | |
| 41 | | 2.6 | |
| 51 | | 3.3 | |
| 61 | | 3.8 | |
| 71 | | 4.4 | |
| 82 | | 4.9 | |
| 92 | | 5.5 | |
| 102 | | 5.9 | |
| 112 | | 6.4 | |
| 122 | | 6.8 | |
| 143 | | 7.6 | |
| 163 | | 8.4 | |
| 184 | | 9.2 | |
| 204 | | 10.1 | |
| 225 | | 10.9 | |
| 245 | | 11.7 | |
| 265 | | 12.5 | |
| 286 | | 13.4 | $V_2$ = 40.2 ft/sec |
| 306 | | 14.2 | |
| 327 | | 15.0 | |
| 347 | | 15.9 | |
| 367 | | 16.6 | |
| 388 | | 17.5 | |

| Time (msec) | Displacement (ft) |
|---|---|
| (Continued) | |
| 408 | 18.3 |
| 429 | 19.1 |
| 449 | 19.9 |
| 469 | 20.7 |
| 490 | 21.4 |
| 510 | 22.3 |
| 531 | 23.1 |
| 551 | 23.8 |
| 571 | 24.6 |
| 592 | 25.3 |
| 612 | 26.1 |
| 633 | 26.8 |
| 653 | 27.5 |
| 674 | 28.3 |
| 694 | 29.0 |
| 714 | 29.8 |
| 735 | 30.4 |
| 755 | 31.1 |
| 776 | 31.8 |
| 796 | 32.5 |
| 816 | 33.2 |
| 837 | 33.8 |
| 857 | 34.5 |
| 878 | 35.2 |
| 898 | 35.8 |
| 918 | 36.4 |
| 939 | 37.1 |
| 959 | 37.7 |

$V_3$ = 39.2 ft/sec

TABLE A2

TEST 505 T1-B

High-Speed Film Data

| Time (msec) | | Displacement (ft) | |
|---|---|---|---|
| -81 | | -6.7 | |
| -71 | | -5.8 | |
| -61 | | -5.1 | |
| -51 | | -4.2 | |
| -41 | | -3.4 | |
| -31 | | -2.5 | |
| -20 | | -1.7 | |
| -10 | | -0.9 | |
| 0 | Impact | 0 | $V_1$ = 82.7 ft/sec |
| 10 | | 0.8 | |
| 20 | | 1.6 | |
| 31 | | 2.4 | |
| 41 | | 3.2 | |
| 51 | | 4.0 | |
| 61 | | 4.8 | |
| 71 | | 5.6 | |
| 82 | | 6.4 | |
| 92 | | 7.2 | |
| 102 | | 7.9 | |
| 112 | | 8.6 | |
| 122 | | 9.2 | |
| 133 | | 9.9 | |
| 143 | | 10.5 | |

| Time (msec) | Displacement (ft) | |
|---|---|---|
| (Continued) | | |
| 153 | 11.1 | |
| 163 | 11.6 | |
| 173 | 12.0 | |
| 184 | 12.5 | |
| 194 | 12.9 | |
| 204 | 13.4 | |
| 214 | 13.8 | |
| 224 | 14.2 | |
| 234 | 14.6 | *$V_2$ = 41.3 ft/sec |
| 245 | 14.9 | |
| 255 | 15.4 | |
| 265 | 15.8 | |
| 275 | 16.2 | |
| 286 | 16.6 | |
| 306 | 17.4 | |
| 326 | 18.2 | |
| 347 | 19.0 | *$V_3$ = 39.1 ft/sec |
| 367 | 19.8 | |
| 388 | 20.5 | |
| 408 | 21.3 | |
| 428 | 22.0 | |

*Vehicle snagged post No. 17, and consequently did not become parallel to the rail; sidewise skidding and loss of contact for only a short time interval do not permit determination of these values to the accuracy reported in other tests in this series.

TABLE A3

TEST 505 T1-C

High-Speed Film Data

| Time (msec) | | Displacement (ft) | |
|---|---|---|---|
| -60 | | -5.1 | $V_1$ = 85.0 ft/sec |
| -50 | | -4.3 | |
| -40 | | -3.4 | |
| -30 | | -2.6 | |
| -20 | | -1.7 | |
| -10 | | -0.9 | |
| 0 | Impact | 0 | |
| 10 | | 0.9 | |
| 20 | | 1.7 | |
| 30 | | 2.5 | |
| 40 | | 3.4 | |
| 50 | | 4.2 | |
| 60 | | 5.0 | |
| 72 | | 5.9 | |
| 82 | | 6.7 | |
| 92 | | 7.6 | |
| 103 | | 8.3 | |
| 113 | | 9.2 | |
| 123 | | 9.9 | |
| 133 | | 10.7 | |
| 144 | | 11.4 | |
| 154 | | 12.1 | |
| 164 | | 12.8 | |

| Time (msec) | Displacement (ft) | |
|---|---|---|
| (Continued) | | |
| 174 | 13.6 | |
| 184 | 14.3 | |
| 195 | 15.1 | |
| 205 | 15.7 | |
| 215 | 16.4 | |
| 225 | 17.1 | $V_2$ = 61.1 ft/sec |
| 236 | 17.8 | |
| 246 | 18.4 | |
| 256 | 19.1 | |
| 266 | 19.7 | |
| 277 | 20.3 | |
| 287 | 20.9 | |
| 297 | 21.5 | |
| 308 | 22.1 | |
| 318 | 22.6 | |
| 328 | 23.3 | |
| 338 | 23.9 | |
| 348 | 24.6 | |
| 359 | 25.2 | |
| 369 | 25.8 | |
| 379 | 26.4 | |
| (Continued) | | |

Table A3 (Continued)

Test 505 T1-C

| Time (msec) | Displacement (ft) | |
|---|---|---|
| (Continued) | | |
| 390 | 26.9 | |
| 400 | 27.6 | |
| 410 | 28.2 | |
| 420 | 28.9 | |
| 430 | 29.5 | |
| 441 | 30.2 | |
| 451 | 30.8 | |
| 461 | 31.4 | |
| 472 | 32.0 | |
| 482 | 32.6 | |
| 492 | 33.2 | $V_3$ = 58.3 ft/sec |
| 502 | 33.8 | |
| 512 | 34.4 | |
| 523 | 35.1 | |
| 533 | 35.7 | |
| 543 | 36.2 | |
| 554 | 36.9 | |
| 564 | 37.4 | |
| 574 | 38.0 | |
| 584 | 38.6 | |
| 594 | 39.2 | |
| 605 | 39.8 | |

TABLE A4

TEST 505 T1-D

High-Speed Film Data

| Time (msec) | | Displacement (ft) | |
|---|---|---|---|
| -81 | | -7.3 | |
| -70 | | -6.2 | |
| -58 | | -5.1 | |
| -46 | | -4.1 | |
| -35 | | -3.1 | |
| -23 | | -2.1 | |
| -12 | | -1.0 | |
| 0 | Impact | 0 | $V_1$ = 90.1 ft/sec |
| 13 | | 1.2 | |
| 26 | | 2.3 | |
| 39 | | 3.5 | |
| 51 | | 4.5 | |
| 64 | | 5.6 | |
| 77 | | 6.6 | |
| 90 | | 7.7 | |
| 103 | | 8.7 | |
| 116 | | 9.7 | |
| 129 | | 10.6 | |
| 141 | | 11.7 | |
| 154 | | 12.7 | |
| 167 | | 13.7 | |
| 180 | | 14.7 | |
| 193 | | 15.8 | |
| 206 | | 16.8 | |
| 219 | | 17.8 | $V_2$ = 80.4 ft/sec |
| 231 | | 18.8 | |
| 244 | | 19.8 | |

| Time (msec) | Displacement (ft) | |
|---|---|---|
| (Continued) | | |
| 257 | 20.8 | |
| 270 | 21.8 | |
| 283 | 22.8 | |
| 296 | 23.9 | |
| 309 | 24.9 | |
| 321 | 25.9 | $V_3$ = 79.7 ft/sec |
| 334 | 26.9 | |
| 347 | 28.0 | |
| 360 | 28.9 | |
| 373 | 30.0 | |
| 386 | 31.1 | |
| 399 | 32.0 | |
| 412 | 33.1 | |
| 424 | 34.1 | |
| 437 | 35.1 | |
| 450 | 36.1 | |
| 463 | 37.1 | |
| 476 | 38.1 | |
| 489 | 39.1 | |
| 502 | 40.1 | |
| 514 | 41.0 | |
| 527 | 42.1 | |
| 540 | 43.1 | |
| 553 | 44.0 | |
| 566 | 45.0 | |
| 579 | 46.0 | |

# A P P E N D I X  B

## Accelerometer Data

# ACCELEROMETER DATA

An attempt was made to reconcile the data recorded on accelerometers mounted parallel and perpendicular to the longitudinal axis of the colliding vehicle with the data observed from high-speed films of the collision incident. Such reconciliation was not affected during the course of this study. However, the accelerometer traces are included in this appendix for consideration by readers of this report.

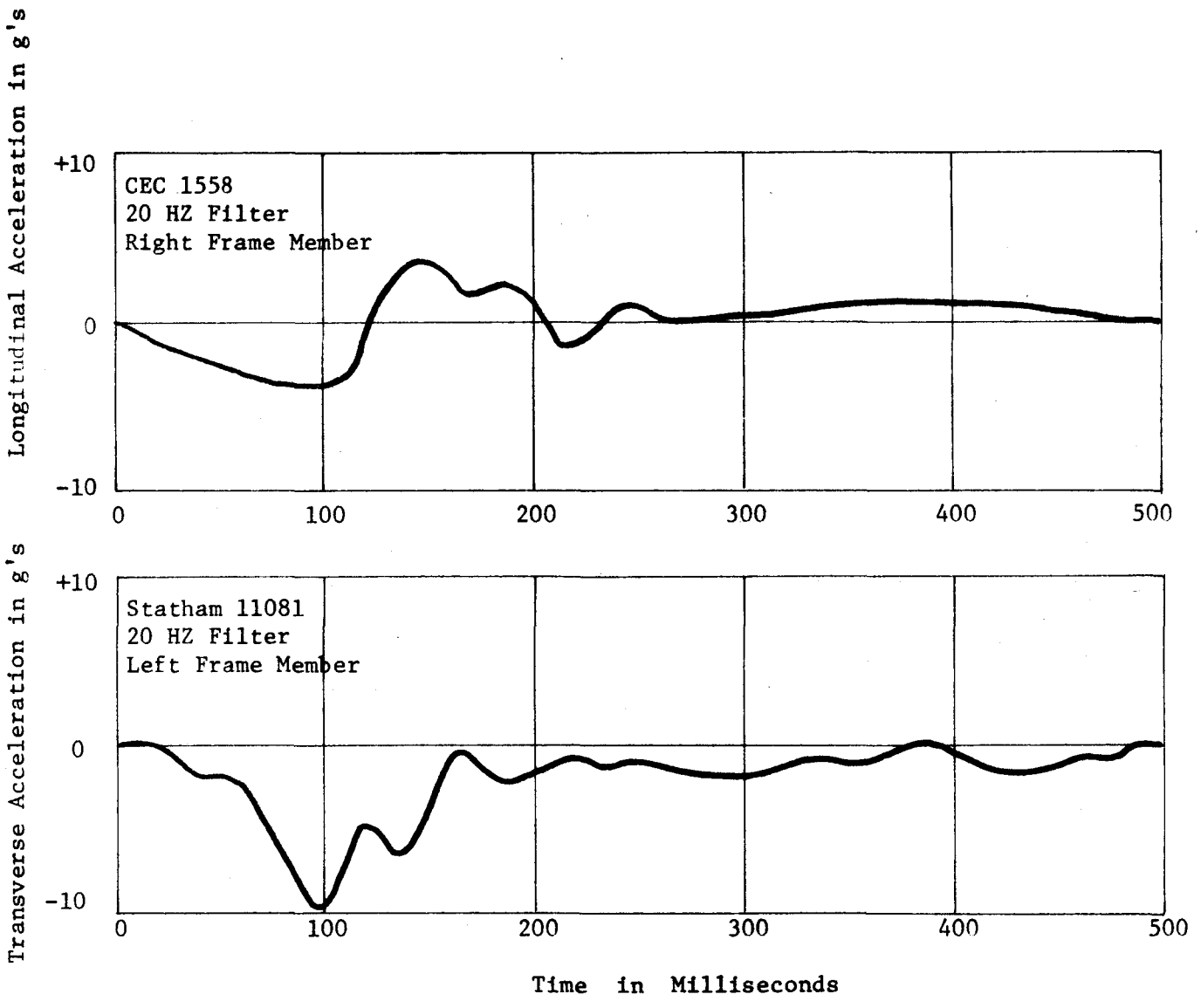



Figure B1, Accelerometer Data, Test 505T1-A.

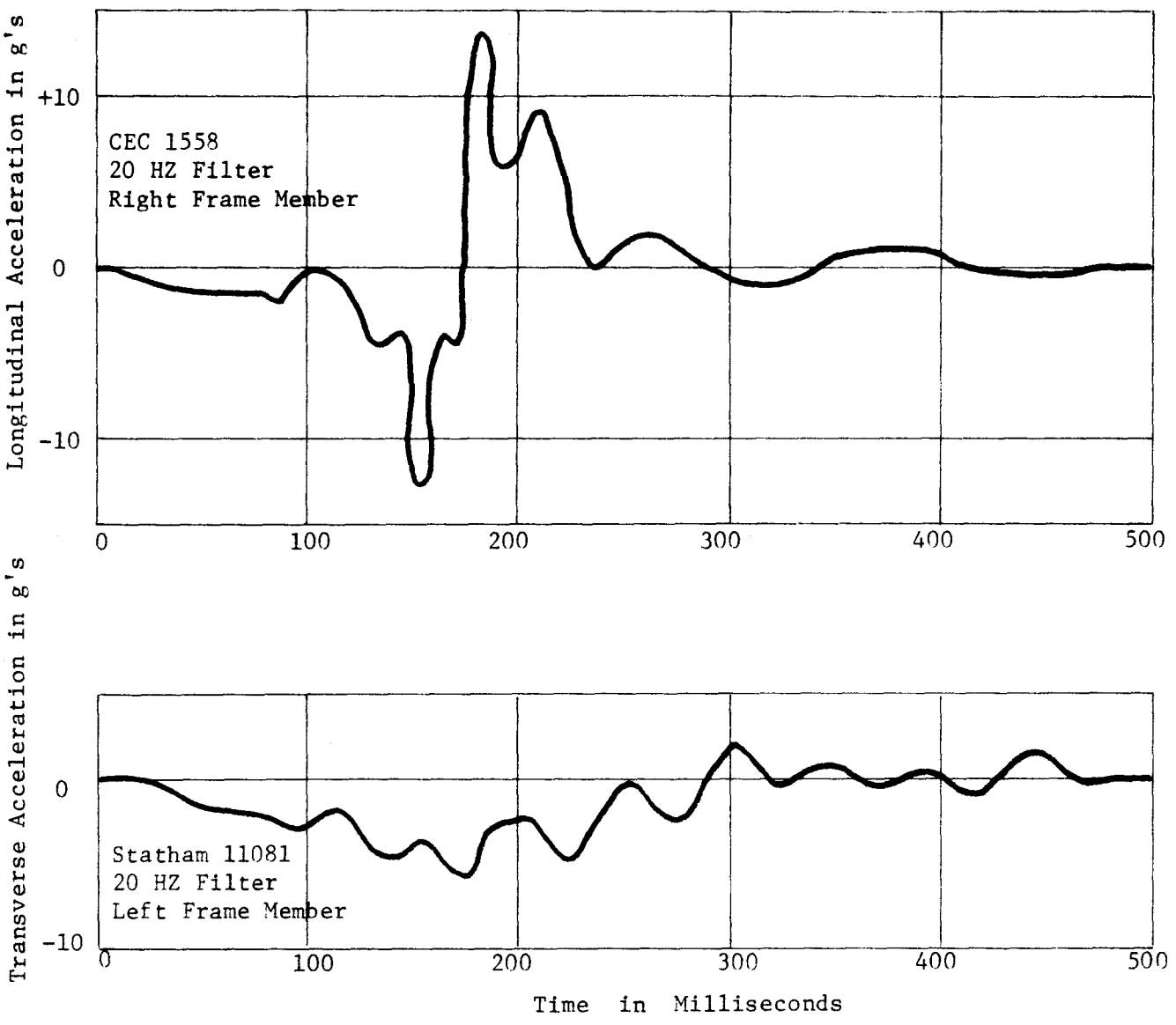



Figure B2, Accelerometer Data, Test 505T1-B.

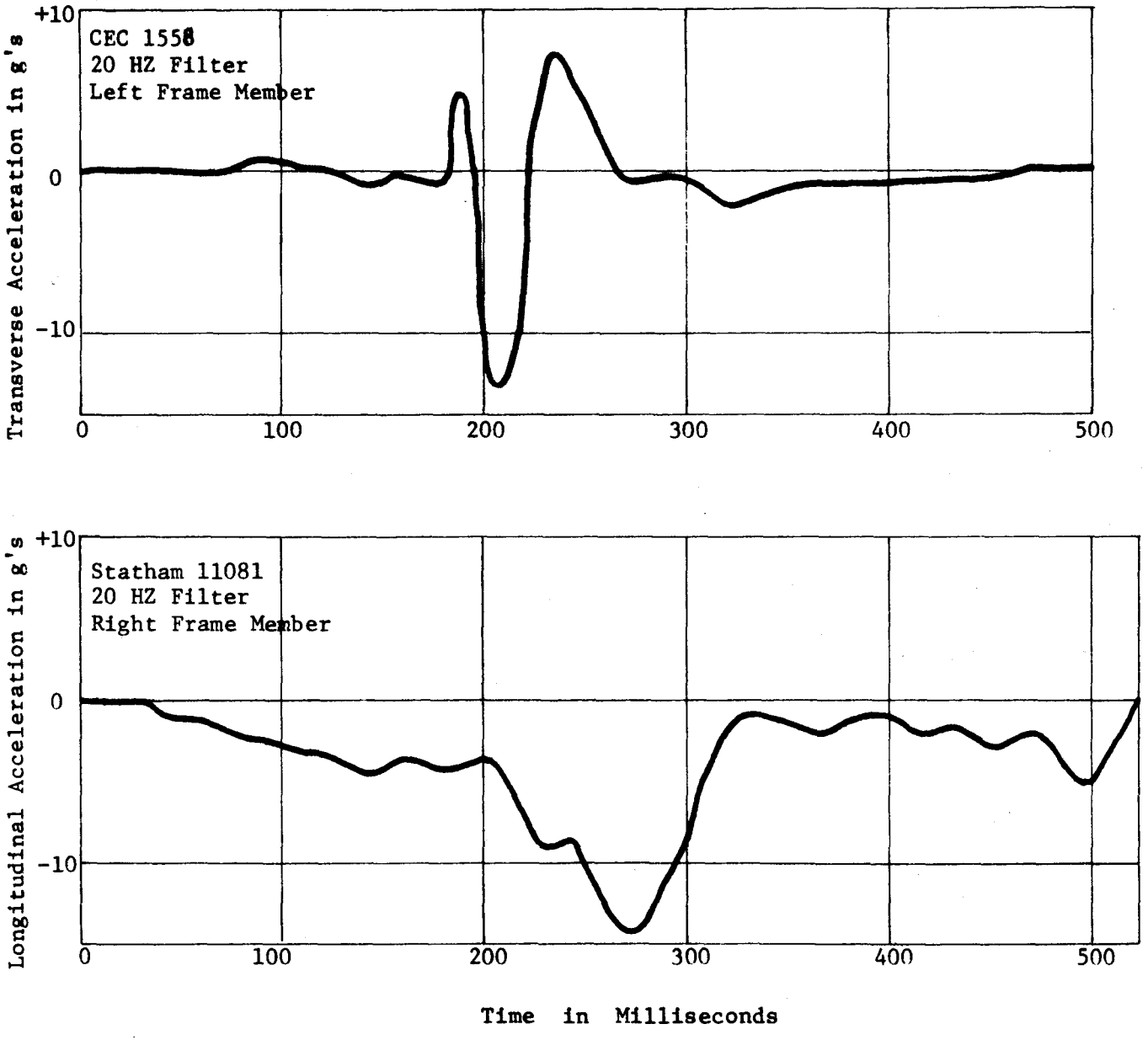



Figure B3, Accelerometer Data, Test 505T1-C.

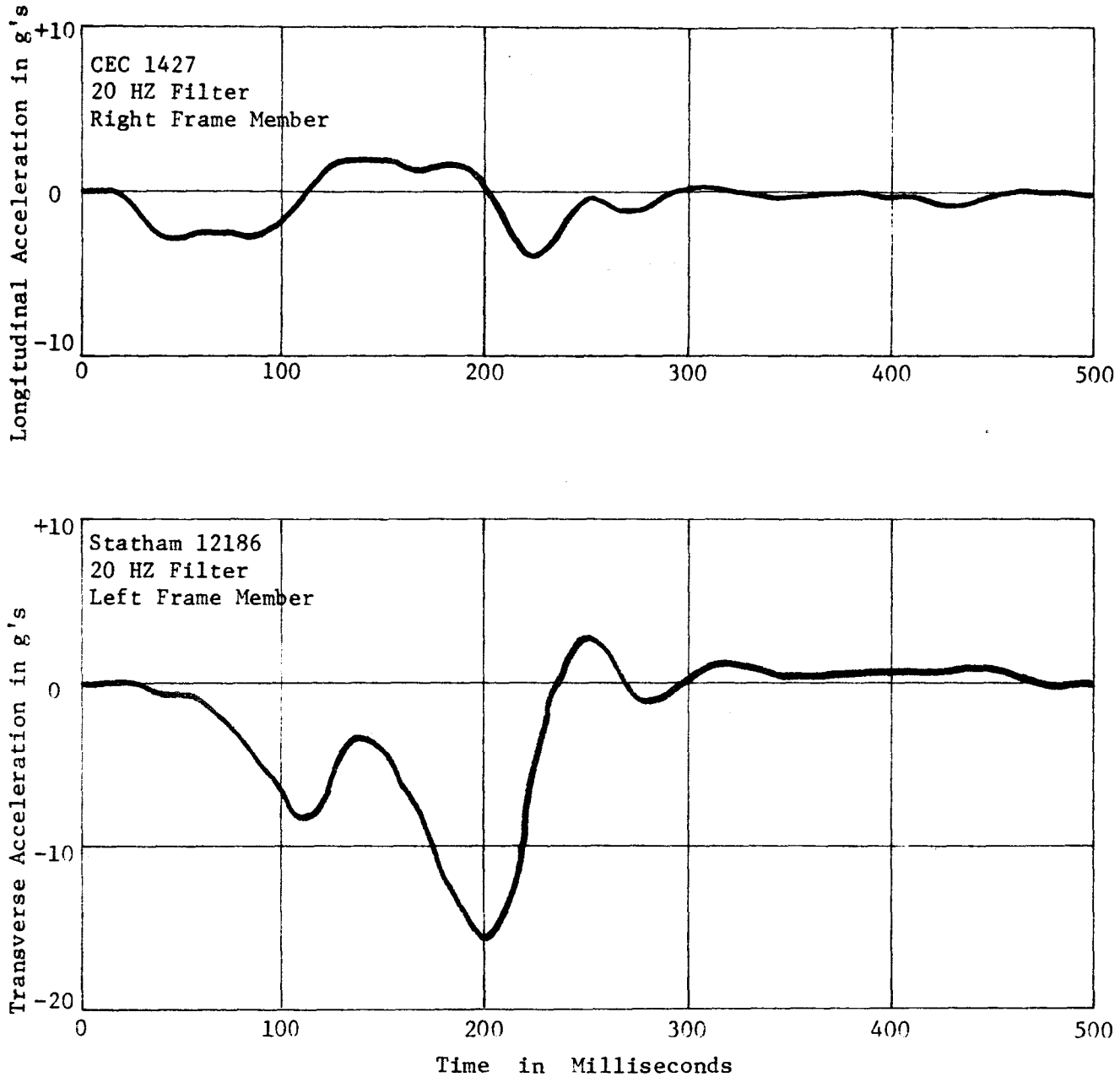



Figure B4, Accelerometer Data, Test 505T1-D.