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16. Abstract

An end treatment was developed and crash tested to shield the ends of the concrete safety shape barrier (CSSB) and other narrow rigid objects. It was designed as a temporary treatment for use primarily in construction zones. Steel barrels, some empty and some containing sand ballast, were used in conjunction with collapsing W-beam (guardrail) in the design. Factors considered in its development were cost, portability, ease of installation, and the use of readily available components.

Four full-scale vehicular crash tests were conducted to evaluate the impact behavior of the design. Since the treatment was intended for temporary use, it was decided that test conditions (vehicle weight, impact speed and impact angle) recommended for permanent roadside appurtenances were not appropriate. The basic difference between the selected conditions and those recommended for permanent installations involved the impact speed. A 50 mph (80.5 km/h) impact speed was used in lieu of the 60 mph (96.5 km/h) speed used for permanent appurtenances. As a result of the crash tests it was concluded that the design was acceptable in terms of impact performance.

Due to relatively large lateral displacements that may occur from side hits near the nose, caution is advised in its use in narrow medians or other areas where such displacements may create an undue hazard to motorists. These exceptions notwithstanding, there are numerous applications, including most roadside locations, where lateral movement would pose no problem.

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End Treatment(s), Crash Test(s), Construction, Work Zone(s), Temporary Safety, Concrete Barrier(s)

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AN END TREATMENT FOR CONCRETE BARRIERS USED IN WORK ZONES

by

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Research Report 262-2

Research Study No. 2-18-79-262
Safety Devices for Highway Work Zones

Sponsored by
State Department of Highways and Public Transportation

in cooperation with
U.S. Department of Transportation
Federal Highway Administration

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Texas Transportation Institute
Texas A&M University
College Station, Tx

(Revised February 1983)

DISCLAIMER

KEY WORDS

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ACKNOWLEDGMENTS

This research study was conducted under a cooperative program between the Texas Transportation Institute, the Texas State Department of Highways and Public Transportation, and the Federal Highway Administration. Harold Cooner, John Nixon, and David Hustace of the SDHPT worked closely with the researchers, and their comments and suggestions were appreciated.

ABSTRACT

An end treatment was developed and crash tested to shield the ends of the concrete safety shape barrier (CSSB) and other narrow rigid objects. It was designed as a temporary treatment for use primarily in construction zones. Steel barrels, some empty and some containing sand ballast, were used in conjunction with collapsing W-beam (guardrail) in the design. Factors considered in its development were cost, portability, ease of installation, and the use of readily available components.

Four full-scale vehicular crash tests were conducted to evaluate the impact behavior of the design. Since the treatment was intended for temporary use, it was decided that test conditions (vehicle weight, impact speed, and impact angle) recommended for permanent roadside appurtenances were not appropriate. The basic difference between the selected conditions and those recommended for permanent installations involved the impact speed. A 50 mph (80.5 km/h) impact speed was used in lieu of the 60 mph (96.5 km/h) speed used for permanent appurtenances. As a result of the crash tests it was concluded that the design was acceptable in terms of impact performance.

Due to relatively large lateral displacements that may occur from side hits near the nose, caution is advised in its use in narrow medians or other areas where such displacements may create an undue hazard to motorists. These exceptions notwithstanding, there are numerous applications, including most roadside locations, where lateral movement would pose no problem.

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INTRODUCTION

The concrete safety shaped barrier (CSSB) has gained widespread implementation during the past several years. Initially it was installed in the median of divided roadways to prevent crossover head-on accidents, where it came to be known as the concrete median barrier (CMB). Early installations were cast in place, but precast units have since been developed and are now used at many sites to reduce costs and expedite installation. With the development of portable precast units, the barrier has also gained wide acceptance as a temporary positive barrier for work zones. More recently the barrier has been used on certain high-volume facilities as a permanent roadside barrier to shield hazards such as rigid objects or embankments. In this capacity it is replacing the standard W-beam roadside barrier.

In all of the above-mentioned applications, the concrete safety shape barrier has proven to be both a cost-effective and a crashworthy barrier. However, when the barrier must be terminated within the "clear zone", the exposed end poses a serious hazard to the motorist. Four acceptable end treatments are now available: (1) Flare the barrier end out of the clear zone (at an acceptable flare angle) or bury the end in a cut slope. This option is available for roadside barrier application only. (2) Use the guardrail energy absorbing terminal (GREAT) (1), which is a proprietary system. (3) Use the median barrier breakaway cable terminal. (4) Use an approved crash cushion.

In many cases the barrier end cannot be flared out of the clear zone or buried due to roadway geometrics or other constraints. Although the GREAT system has proven to be a crashworthy end treatment, its use has been limited by its relatively high cost. Similarly, alternate 3 has not been widely used due to its relatively high cost, marginal impact performance for the small car, and lack of portability. Approved crash cushions are also costly and require more space than is often available.

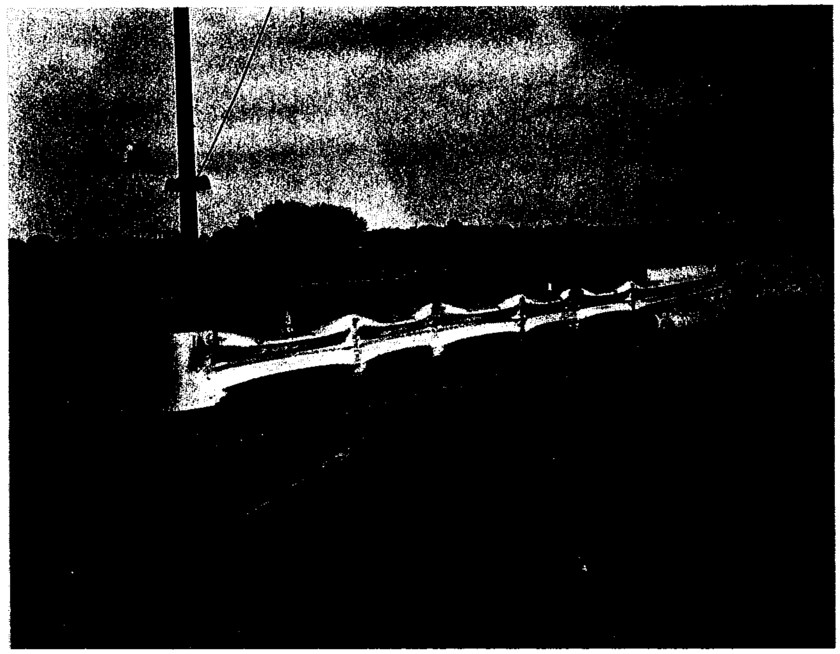
In view of the wide use of the concrete safety shape barrier and its increasing use in construction zones where space is often very limited, Texas Transportation Institute (TTI) engineers and Texas highway engineers have been seeking a relatively inexpensive end treatment that can be used in construction zones. Recent tests by TTI indicate that a safe and relatively inexpensive weakened beam/barrel crash cushion has been designed.

The purpose of the research reported herein was to develop an alternate end treatment for the CSSB for use in work zones. The Texas State Department of Highways and Public Transportation (TSDHPT) desired that the alternate treatment be reasonably portable, relatively inexpensive, that it be constructed from readily available materials, and that it be relatively narrow.

END TREATMENT

An end treatment must perform as a crash cushion if hit head-on and as a longitudinal barrier if hit downstream from the nose. Design of a system to satisfy both requirements presents special problems. To achieve the first function a series of 55-gallon steel drums in a single row was used, some empty, some partially filled with sand, and some completely filled with sand. The standard W-beam used on roadside barriers was used to assist in redirecting the vehicle for side hits. However, the W-beam had to be weakened in the axial direction to keep impact forces within a tolerable range for head-on hits. The weakened beam/barrel end treatment is shown in Figure 1. For a head-on impact the W-beam guardrail buckles in the weakened areas shown in details 2 and 3 of Figure 2. The W-beam then folds out as the vehicle continues its forward movement. The vehicle is also slowed by crushing of the empty barrels and by accelerating the sand-filled barrels from rest. The combination of these three energy transfer mechanisms decelerates the vehicle well within acceptable limits. The weakened W-beam supported by the sand-filled barrels will also smoothly redirect an errant vehicle for most of the expected side impact conditions. A detailed analysis of the impact behavior of the cushion can be found in Appendix C.

Other notable features of the weakened beam/barrel cushion are its size and construction. As shown in Figure 2 the end treatment is only slightly wider than the concrete safety shape barrier. Thus it can be utilized in very narrow construction zones. The end treatment is constructed of readily available materials, and its components can be preconstructed and assembled at the work site. Furthermore, the end treatment is not attached to the surface on which it rests. It is, however, attached to the first segment of



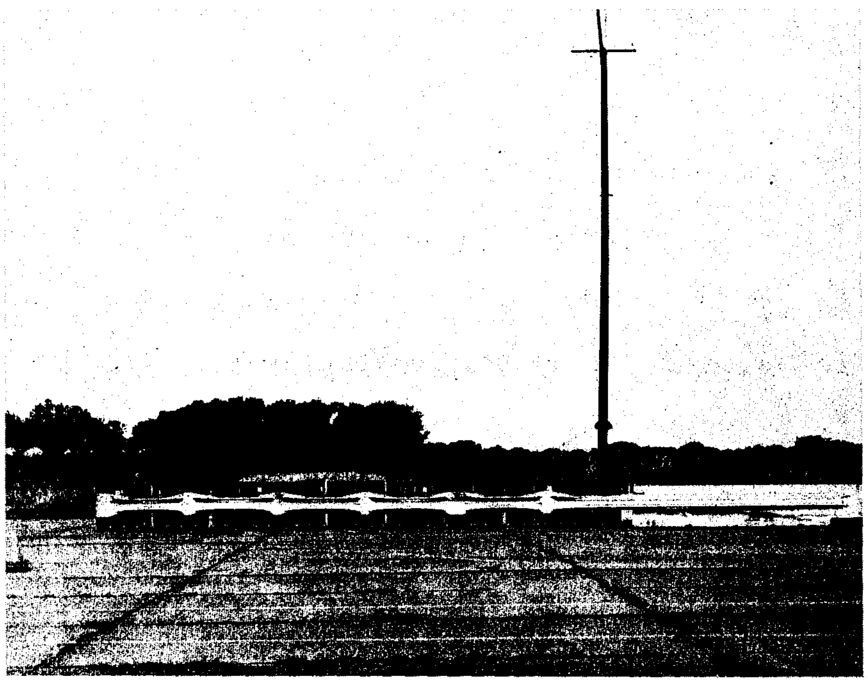


Figure 1. Portable Crash Cushion

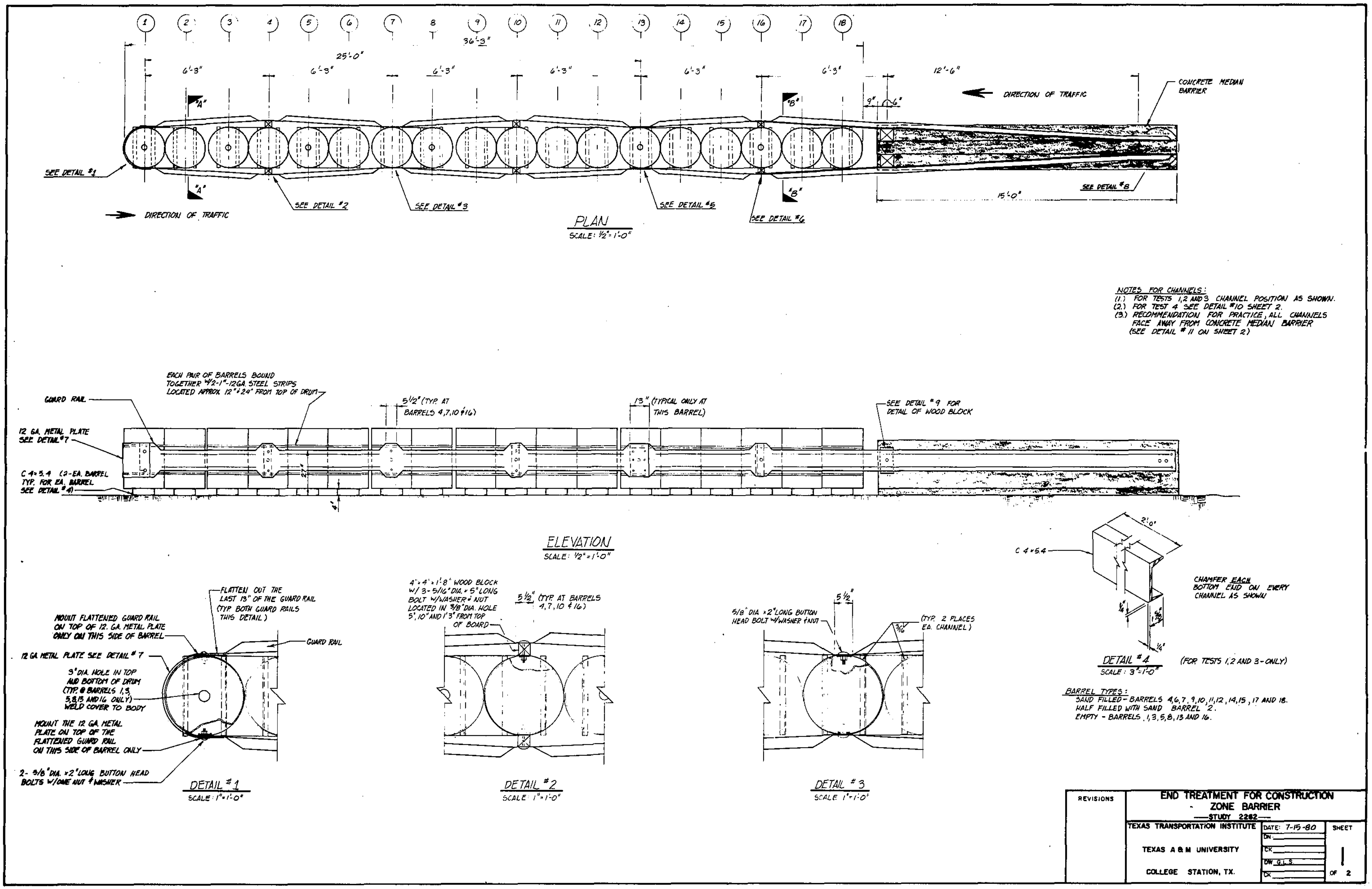


Figure 2. End Treatment for Construction Zone Barrier

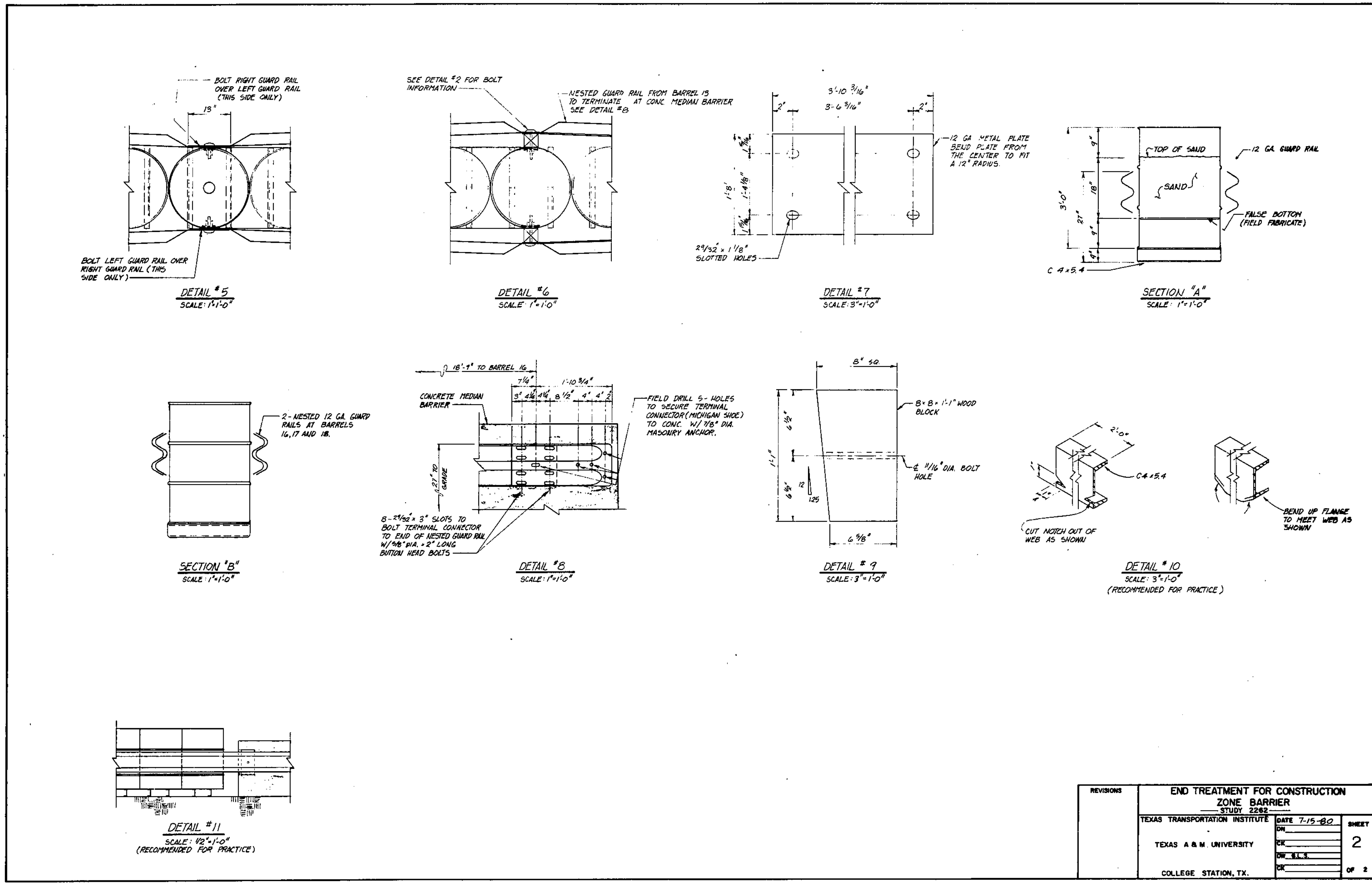


Figure 2. End Treatment for Construction Zone Barrier (continued)

the precast concrete barrier system. It is also to be noted that the precast segments were not attached or anchored in any way to the concrete surface on which they were placed. A detailed explanation of the costs of the end treatment can be found in Appendix D.

IMPACT PERFORMANCE CRITERIA

After a review of the literature it was determined that there were no nationally recognized standards that addressed the recommended test and evaluation criteria for temporary or work zone appurtenances. Transportation Research Circular 191 contained recommended test procedures and evaluation criteria for permanent roadside appurtenances. Selection of crash test conditions (vehicle size, impact speed, impact angle) was therefore made jointly by TTI and SDHPT engineers. Factors considered in the subjective selection process included exposure time, traffic speeds in work zones, costs, and the state-of-the-art regarding temporary end treatments. As a result of this process, the test conditions described in the following section were chosen. Results of each test were evaluated in terms of the recommended performance criteria (structural adequacy, severity, and post impact trajectory) presented in reference 2.

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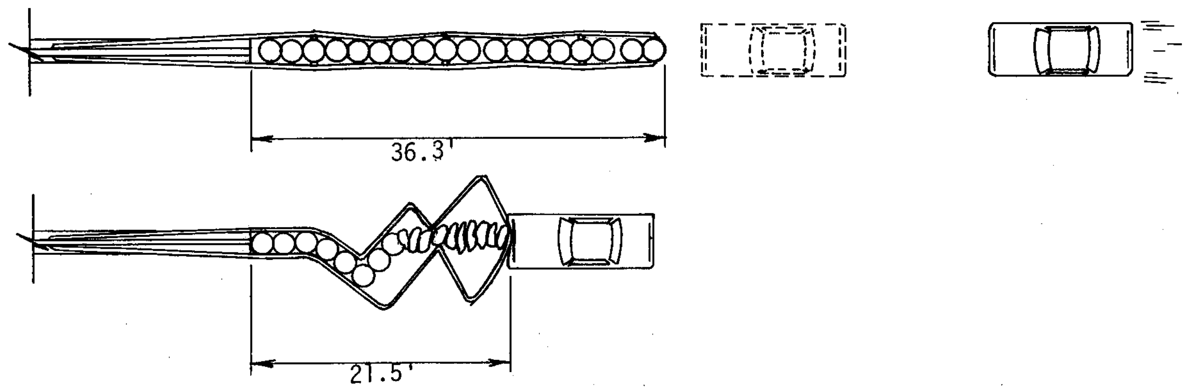

Test No.	2262-3
Date	8/4/80
Installation	
Drawing No.	2262-1,2
Length, ft (m)	82 (25)
Vehicle Type	1976 Chevrolet Vega
Vehicle Mass, lb (kg)	2480 (1125)
Impact Point	Barrel 1
Impact Angle, deg	0
Impact Speed, mph (kph)	48.4 (77.9)
Stopping Distance, ft (m)	14.8 (4.51)
Vehicle Accelerations, g's	
Peak 50 msec Average	
Lateral	0
Longitudinal	13.3
Average Over Stopping Distance	5.3
Vehicle Damage Classification	
TAD	12FD4
Vehicle Damage Classification	12FDEW5

Figure 3. Summary of Test 3

CRASH TEST RESULTS

Four full-scale crash tests were conducted on the end treatment. The test conditions and results are summarized in Table 1. The tests are described in greater detail on the following pages. Sequential photographs selected from high-speed films of the tests are presented in Appendix A. Accelerometer traces as well as roll, pitch, and yaw rates are presented in Appendix B.

Test 3*

Test 3, summarized in Figure 3, was selected to evaluate the severity of a small car, head-on impact. In this test a 2280 lb (1030 kg) vehicle impacted the nose of the device head-on at 50 mph. The test vehicle was smoothly decelerated to a stop over a distance of 14.3 ft (4.4 m). The average acceleration over the stopping distance was 5.5 g's, which is well below the desirable limit of 8 g's. Damage incurred by the test vehicle is shown in Figure 4. Damage to the test installation is shown in Figure 5.

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*Tests 1 and 2 were conducted during previous research (see Research Report 2262-1) and were unrelated to the work reported herein.

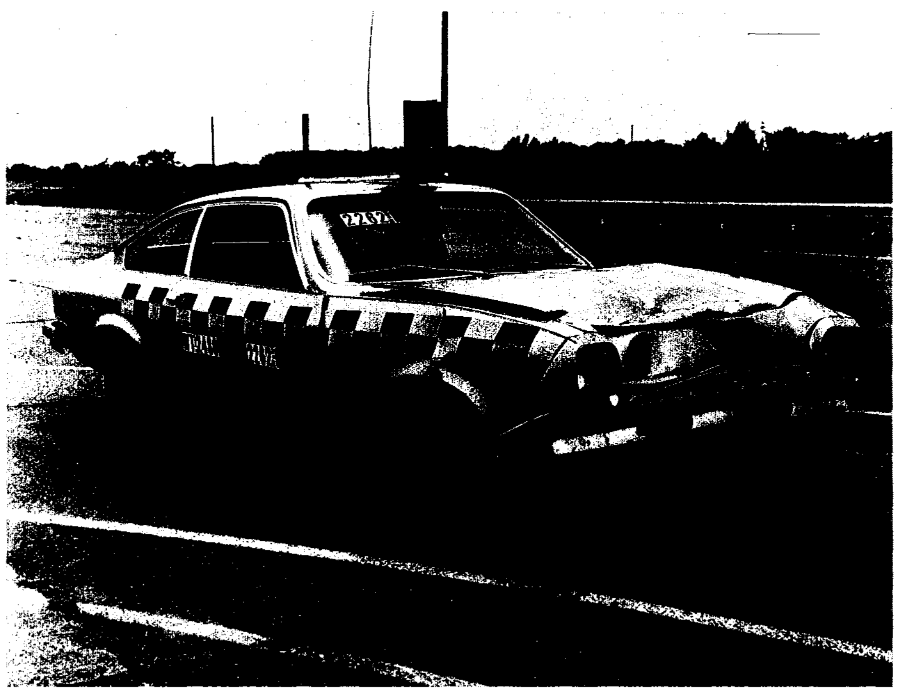


Figure 4. Test Vehicle Before and After Test 3

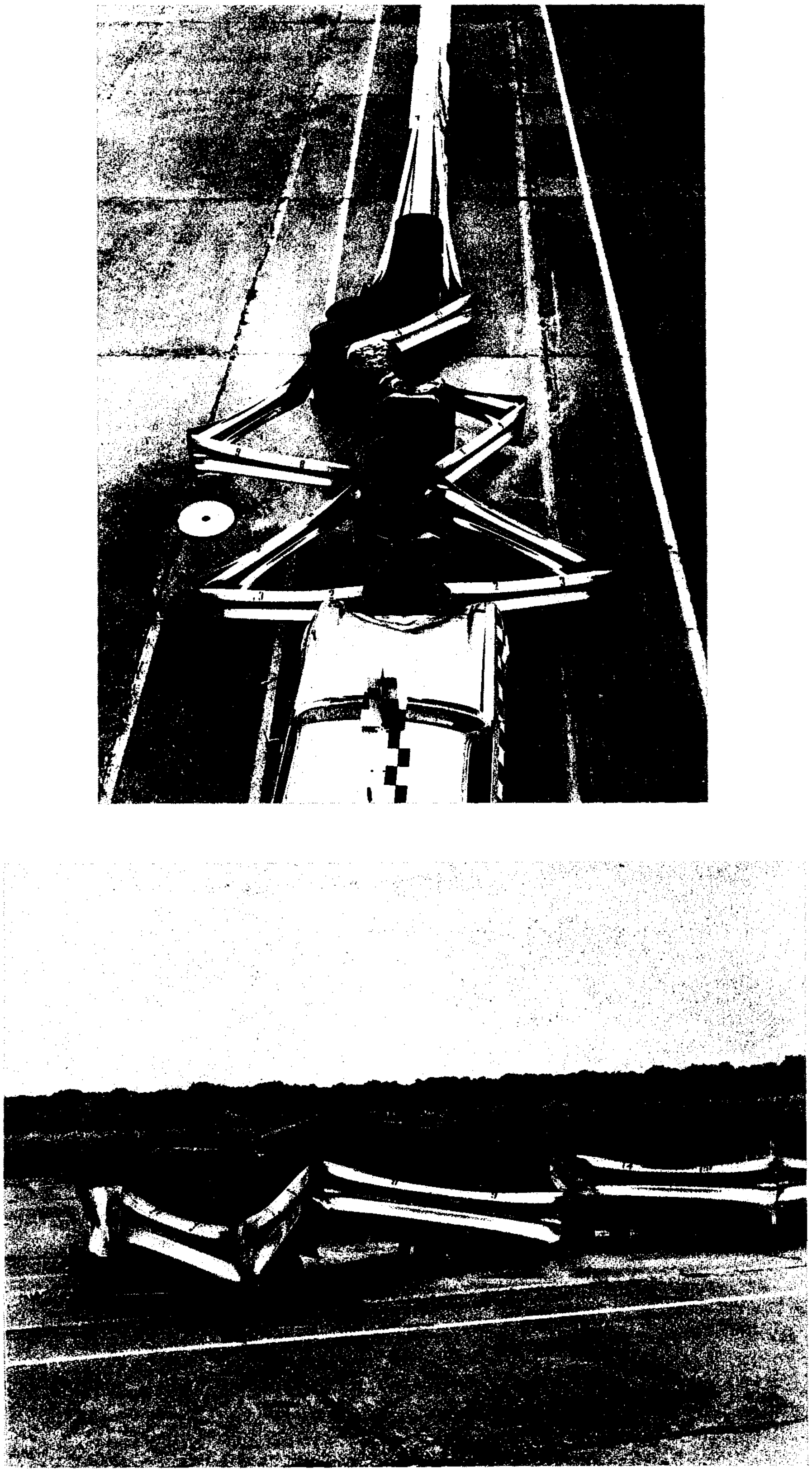


Figure 5. Test Installation After Test 3

TABLE 1.
SUMMARY AND RESULTS OF CRASH TESTS OF END TREATMENT
FOR CONCRETE BARRIERS USED IN WORK ZONES

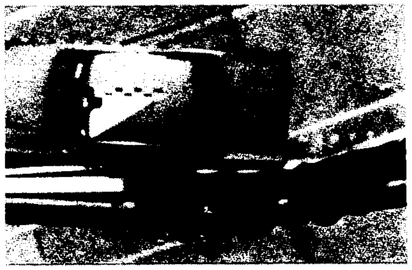
TEST NO.	VEHICLE WEIGHT lb (kg)	IMPACT SPEED mph (km/h)	ANGLE OF IMPACT (deg)	POINT OF IMPACT	VEHICLE STOPPING DISTANCE ft (m)	CUSHION DISPLACEMENT		BARRIER DISPLACEMENT		VEHICLE ACCELERATION DATA (g's)			VEHICLE DAMAGE CLASSIFICATION	
						Long. ft (m)	Lat. ft (m)	Long. ft (m)	Lat. ft (m)	PEAK 50 ms AVG Long.	PEAK 50 ms AVG Lat.	AVG OVER STOPPING DISTANCE	TAD[a]	SAE[b]
3	2480 (1125)	48.4 (77.9)	0	Nose	14.3 (4.4)	13.5 (4.1)	6 (1.8)	0 (0)	0 (0)	13.2	0	5.5	12FD4	12FDEW5
4	4500 (2040)	48.6 (78.2)	15	Barrel No. 14	-	0.4 (0.1)	2.9 (0.9)	0 (0)	2.3 (0.7)	2.1	4.0	N/A[c]	10LFQ3	10LFMS3
5	4500 (2040)	51.1 (82.2)	0	Nose	19.5 (5.9)	14.0 (4.3)	6.5 (2.0)	0.3 (0.1)	0 (0)	9.3	1.2	4.5	12FC4	12FCEW4
6	2350 (1065)	58.9 (94.8)	15	Barrel No. 3	-	10.5 (3.2)	18.0 (5.5)	0 (0)	0 (0)	6.4	5.4	N/A[c]	10LFQ4	10LFEW4

[a]See reference 3.
[b]See reference 4.
[c]Not applicable.

Test 4

Test 4 was selected to evaluate the redirective capabilities of the treatment for impacts near the interface with the concrete barrier. Figure 6 contains a summary of test 4. For this test a 4500 lb (2040 kg) vehicle impacted barrel 16 at 48.6 mph (78.2 km/h) and 15 degrees. The test vehicle was smoothly redirected and the maximum 50 ms average deceleration was 4.5 g's, which is below the acceptable 5 g limit. As shown in Figure 7, vehicle damage was relatively light. Figure 8 shows the damaged cushion and barrier. Restoration of the device involved only realignment.

Note that the treatment and the end of the concrete barrier moved laterally 2.9 ft (0.88 m) during impact. It should be remembered that neither the end treatment nor the precast concrete barrier segments were anchored or attached to the concrete surface.



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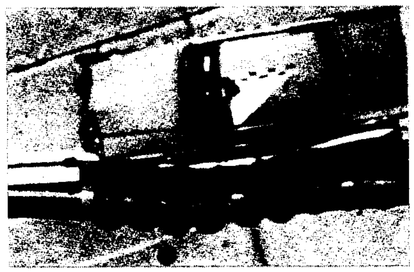

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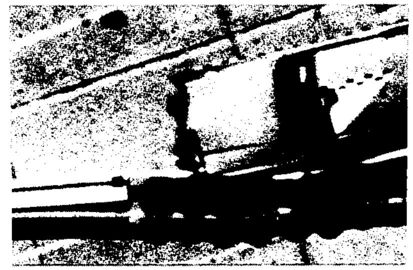

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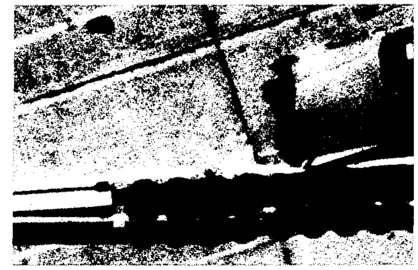

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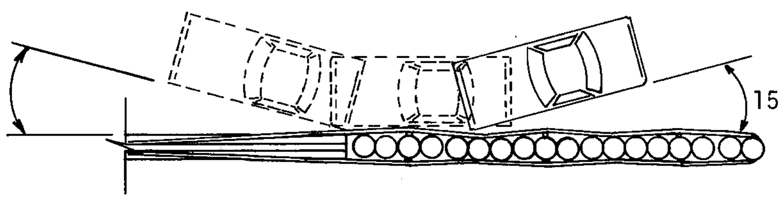
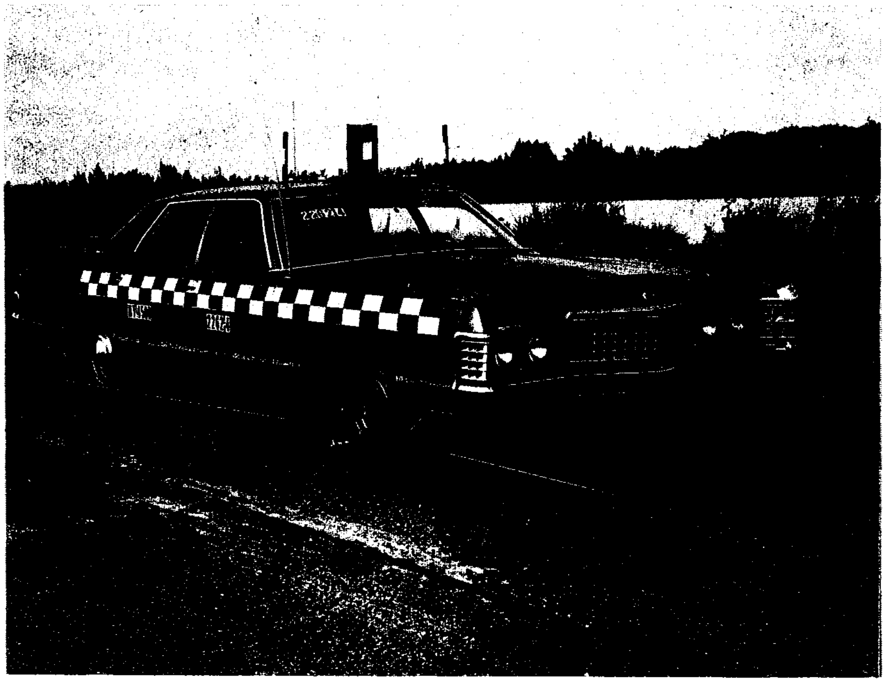


Test No.	2262-4
Date	8/12/80
Installation	
Drawing No.	2262-1,2
Max. Deflection, ft (m)	2.9 (0.9)
Vehicle Type	1972 Mercury Monterey
Vehicle Mass, lb (kg)	4500 (2040)
Impact Point	Barrel 14
Angle, deg	
Impact	15
Exit	8

Speed, mph (kph)	
Impact	48.6 (78.2)
Exit	44.7 (71.9)
Vehicle Accelerations, g	
Peak 50 msec Average	
Lateral	4.0
Longitudinal	2.1
Vehicle Damage Classification	
TAD	10LFQ4
SAE	10LFMW3

Figure 6. Summary of Test 4



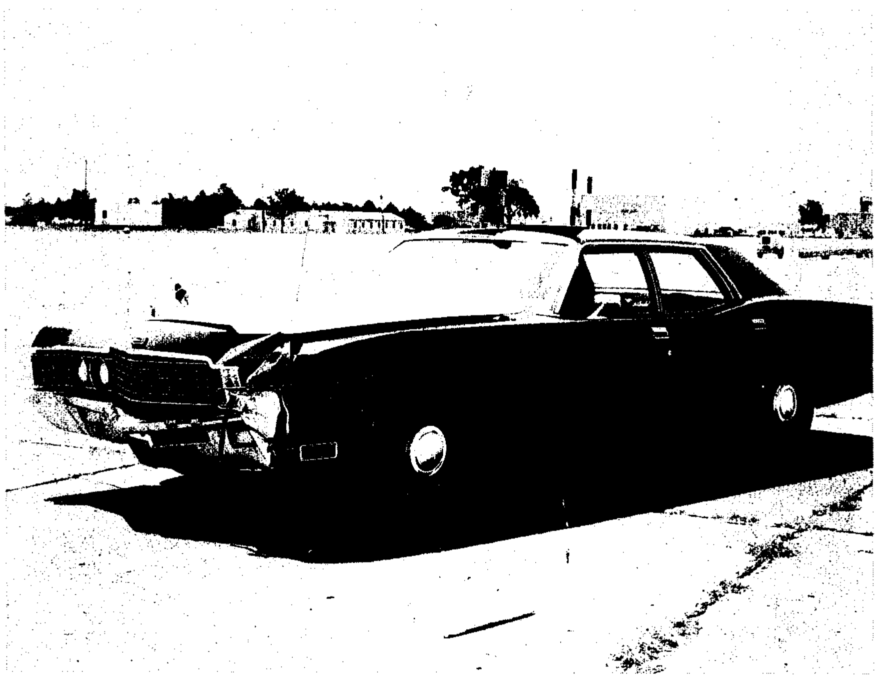
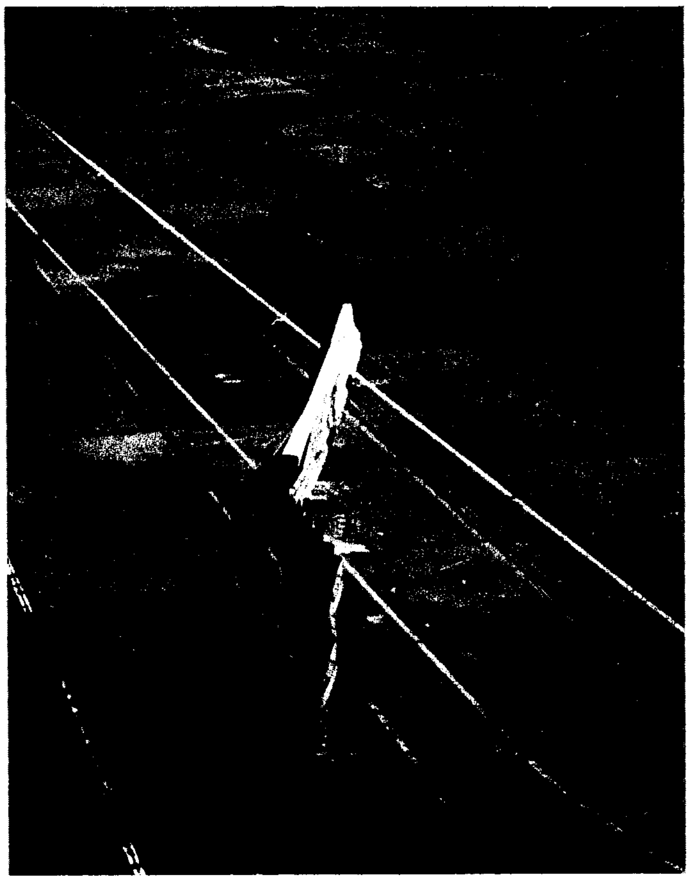


Figure 7. Test Vehicle Before and After Test 4



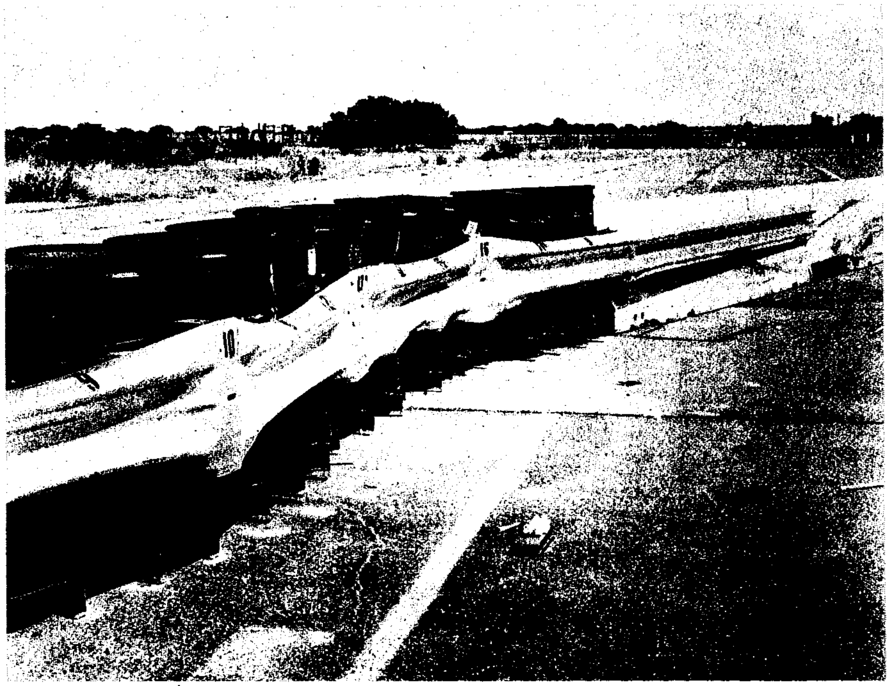
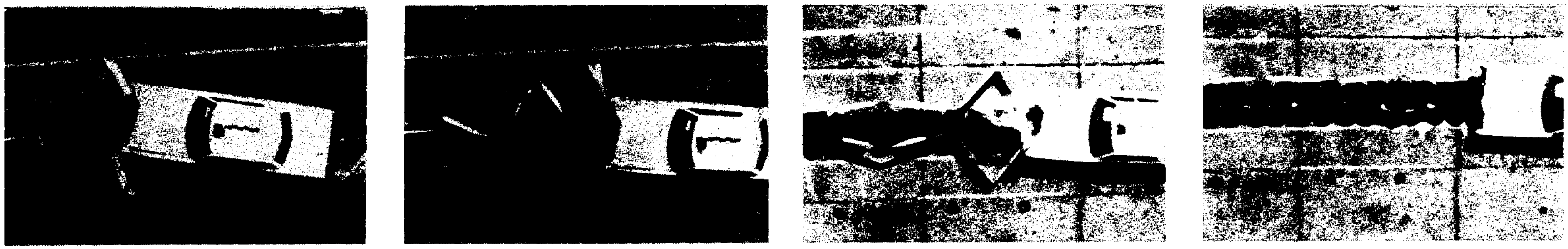


Figure 8. Test Installation After Test 4

Test 5

Test 5 was selected to evaluate the severity of a large car, head-on impact. The test is summarized in Figure 9. The test vehicle was a 4500 lb Mercury Monterey which impacted head-on into the treatment at 51 mph (82 km/h). The test vehicle was uniformly decelerated to a halt. The stopping distance was 19.5 ft (5.9 m) and the average acceleration over the stopping distance was 4.5 g's, which is well below acceptable limits. Vehicle damage was not severe, as shown in Figure 10. Damage to the treatment is shown in Figure 11. The cushion required complete replacement as can be expected after an impact of this nature.



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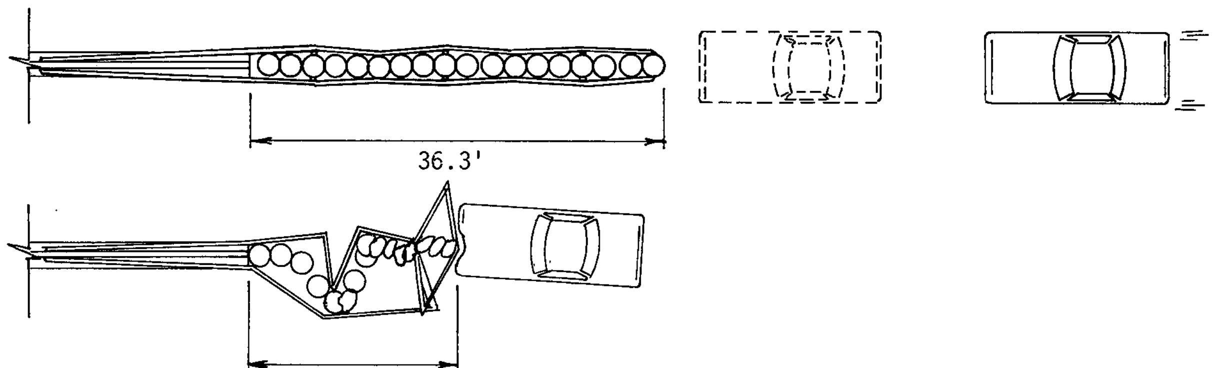
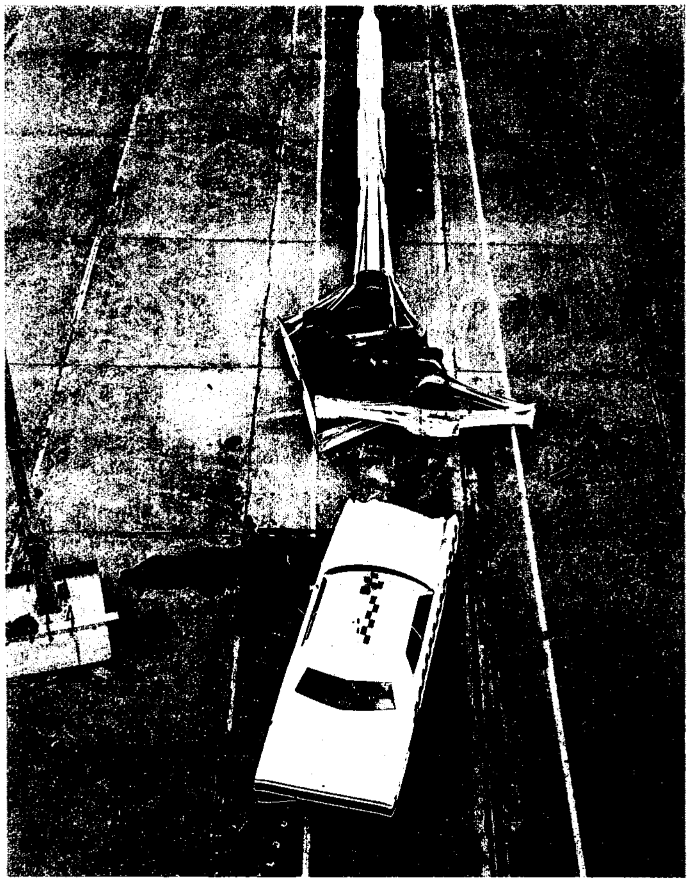


Test No.	2262-5
Date	8/15/80
Installation	
Drawing No.	2262-1,2
Length, ft (m)	82 (25)
Vehicle Type	1972 Mercury Monterey
Vehicle Mass, lb (kg)	4500 (2040)
Impact Point	Barrel 1
Impact Angle, deg	0
Impact Speed, mph (kph)	51.1 (82.2)

Stopping Distance, ft (m)	19.5 (5.9)
Vehicle Accelerations, g	
Peak 50 msec Average	
Lateral	1.2
Longitudinal	9.3
Average Over Stopping Distance	4.5
Vehicle Damage Classification	
TAD	12FC4
SAE	12FCEW4

Figure 9. Summary of Test 5

Figure 10. Test Vehicle Before and After Test 5



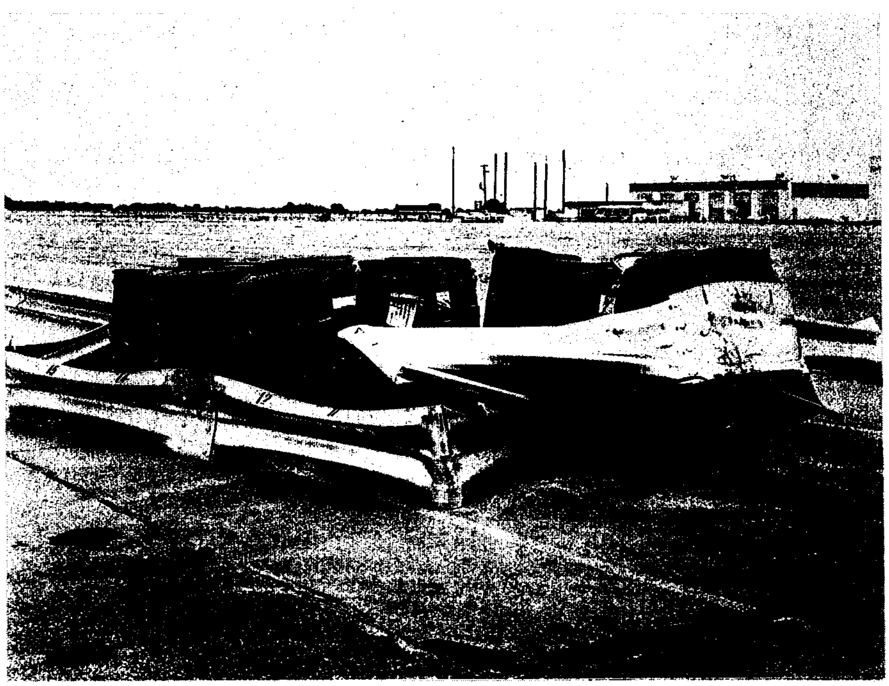


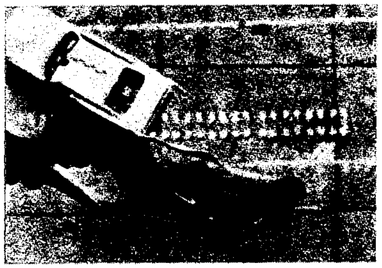
Figure 11. Test Installation After Test 5

Test 6

After viewing films of the previous tests, a decision was made to chamfer the ends of the channels under the barrels as shown in detail 10 of Figure 2. This modification was made to allow the barrels to slide laterally more easily without tipping over.

Test 6 was selected to examine the redirective capabilities of the treatment when impacted by a small car near the nose of the device. Impact speed was intended to be 50 mph (80.5 m/h) but was actually 58.9 mph (94.8 km/h). (Tow truck driver did not get the word.) Figure 12 contains a summary of this test. The test vehicle was a 1975 Chevrolet Vega weighing about 2250 lb (1022 kg). The test vehicle was smoothly redirected by the cushion, but damage to the left front wheel caused the vehicle to turn back into the concrete barrier which caused additional sheet metal damage to the car. Figure 13 shows the damage incurred by the test vehicle. The crash cushion was knocked back approximately 18 ft (5.5 m) due to the collision as shown in Figure 14. The maximum 50 ms average lateral deceleration of the test vehicle was 5.4 g's, only slightly in excess of the recommended 5 g limit. It is clear that the limit would not have been exceeded if the design impact speed of 50 mph (80.5 km/h) had been met. The maximum 50 ms average longitudinal deceleration of 6.4 g's is well below the recommended 10 g limit for side impacts. After observing the motion of the treatment during this test it was decided to recommend that all channels face the same direction as shown in Figure 2, detail 11. This modification will further facilitate sliding of the barrels and therefore increase the stability of the cushion.

The results of test 6 show that portions of the end treatment can be expected to move laterally some distance if impacted on the side near the



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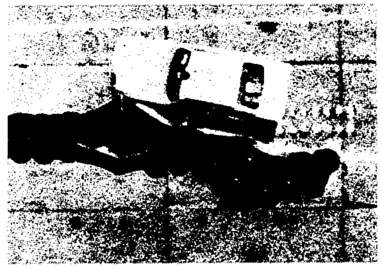

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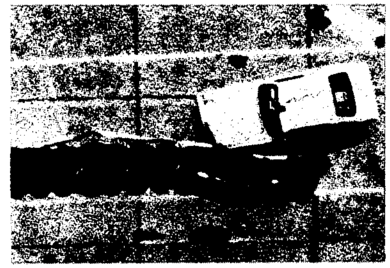

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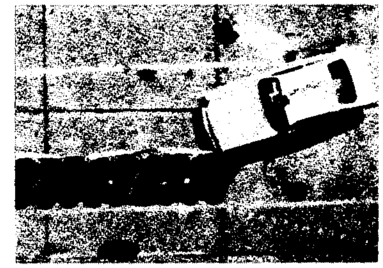

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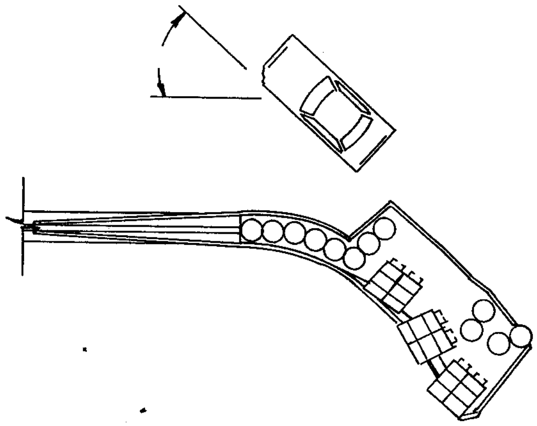
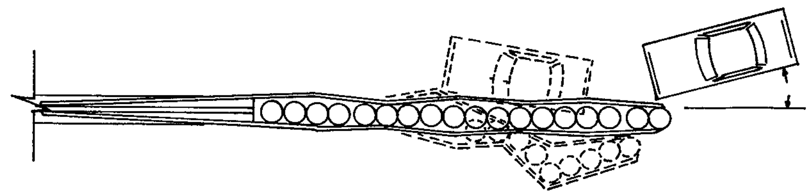




Test No.	2262-6
Date	8/21/80
Installation	
Drawing No.	2262-1,2
Length, ft (m)	82 (25)
Vehicle Type	1975 Chevrolet Vega
Vehicle Mass, lb (kg)	2350 (1065)
Impact Point	Barrel 14
Angle, deg	
Impact	15
Exit	14

Speed, mph (kph)	
Impact	58.9 (94.8)
Exit	27.5 (44.2)
Vehicle Accelerations, g	
Peak 50 msec Average	
Lateral	5.4
Longitudinal	6.4
Vehicle Damage Classification	
TAD	10LFQ4
SAE	10LFEW4

Figure 12. Summary of Test 6

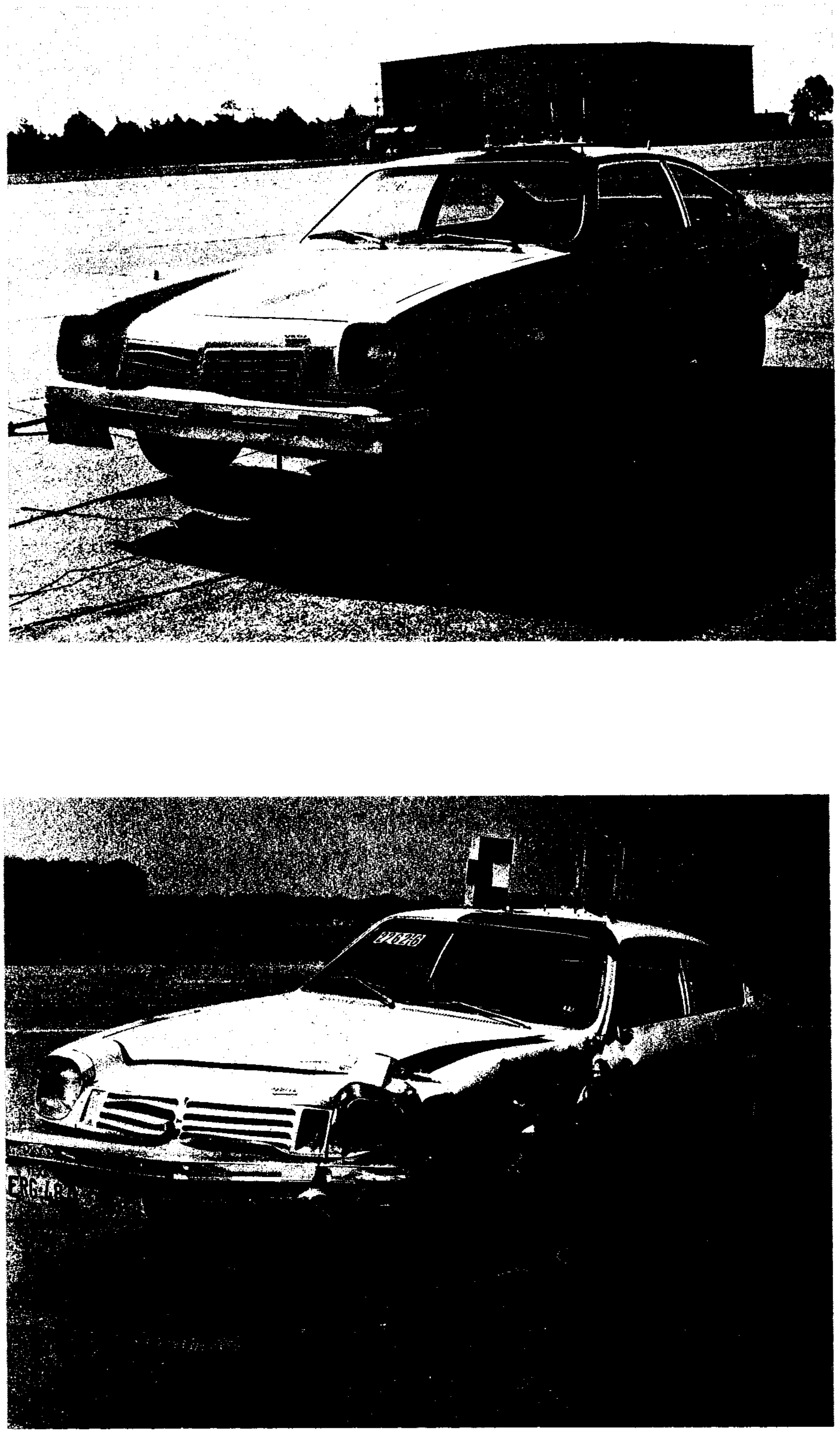
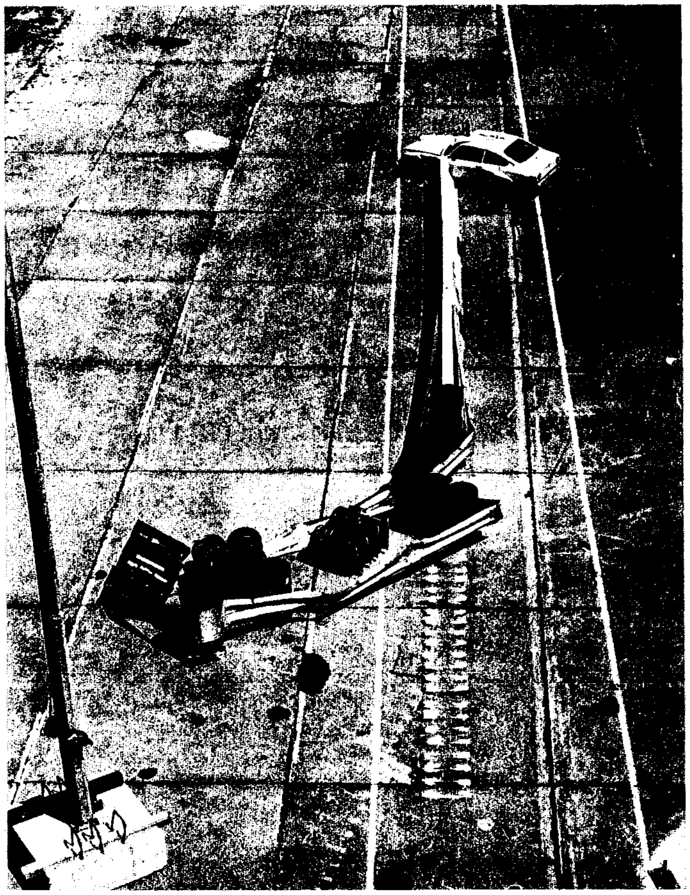


Figure 13. Test Vehicle Before and After Test 6



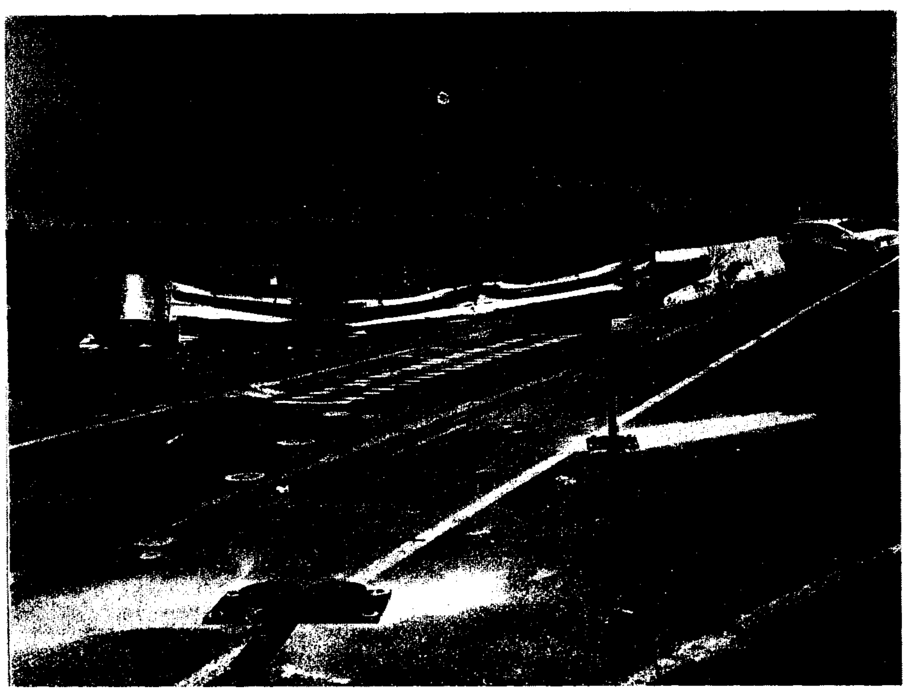


Figure 14. Test Installation After Test 6

nose. As a consequence, the treatment should be used with discretion at locations where such movement may create an undue hazard to other traffic, such as in a narrow median. Note that, as shown in Figure 12, the test vehicle lost contact with the front of the cushion before it was deflected more than 6 ft. Therefore, the terrain behind the cushion needs to be smooth and level for more than 6 ft to assure proper performance of the end treatment. These limitations notwithstanding, there are numerous other locations, including most roadside applications, where the lateral movement would pose no problem.

SUMMARY AND CONCLUSIONS

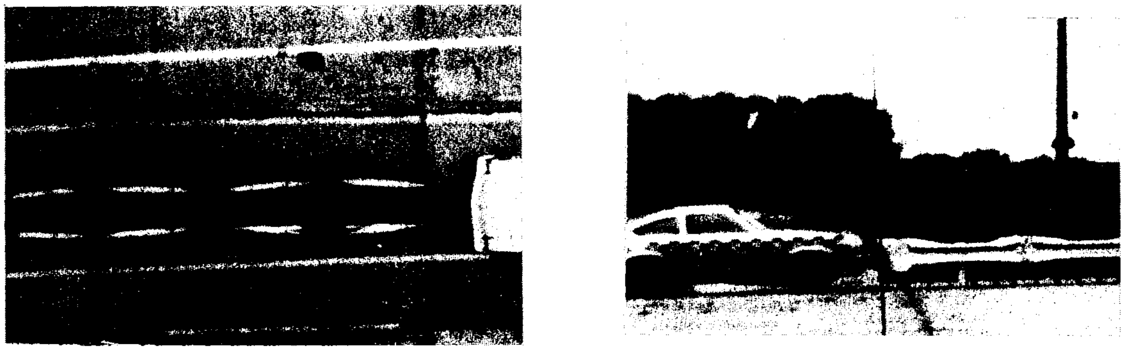
An end treatment was developed and crash tested to shield the ends of the concrete safety shape barrier (CSSB) and other narrow rigid objects. It was designed as a temporary treatment for use primarily in construction zones. Steel barrels, some empty and some containing sand ballast, were used in conjunction with collapsing W-beam (guardrail) in the design. Factors considered in its development were cost, portability, ease of installation, and the use of readily available components.

Four full-scale vehicular crash tests were conducted to evaluate the impact behavior of the design. Since the treatment was intended for temporary use, it was decided that test conditions (vehicle weight, impact speed, and impact angle) recommended for permanent roadside appurtenances were not appropriate. The basic difference between the selected conditions and those recommended for permanent installations involved the impact speed. A 50 mph (80.5 km/h) impact speed was used in lieu of the 60 mph (96.5 km/h) speed used for permanent appurtenances. As a result of the crash tests it was concluded that the design was acceptable in terms of impact performance.

Due to relatively large lateral displacements that may occur from side hits near the nose, caution is advised in its use in narrow medians or other areas where such displacements may create an undue hazard to motorists. These exceptions notwithstanding, there are numerous applications, including most roadside locations, where lateral movement would pose no problem.

APPENDIX A

SEQUENTIAL PHOTOGRAPHS



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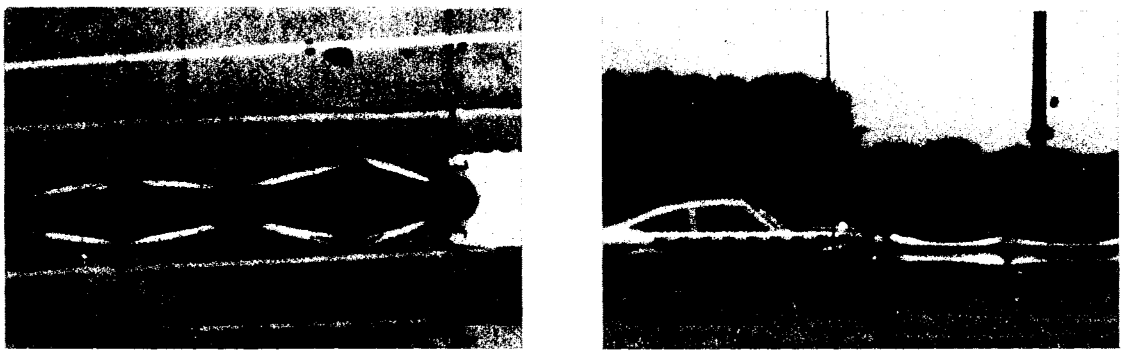

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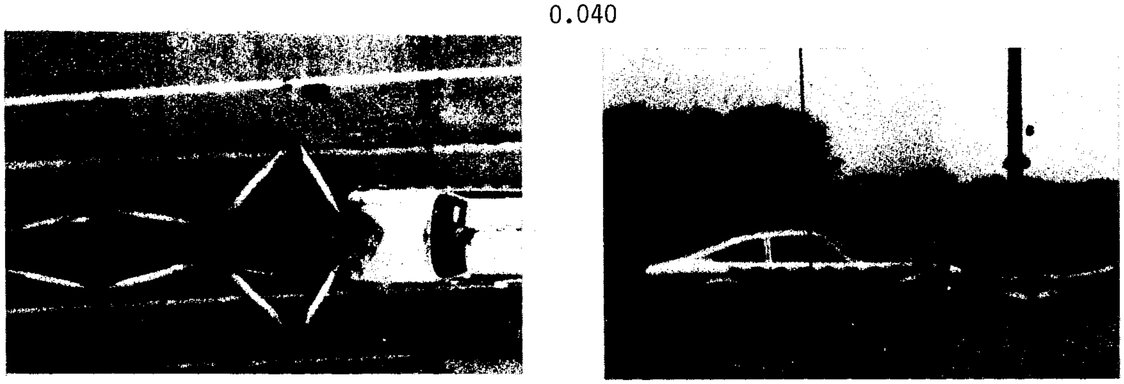

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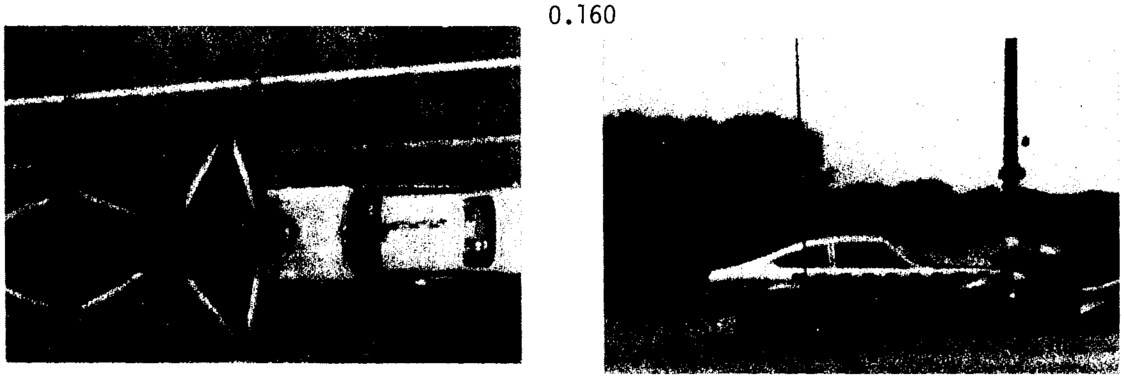

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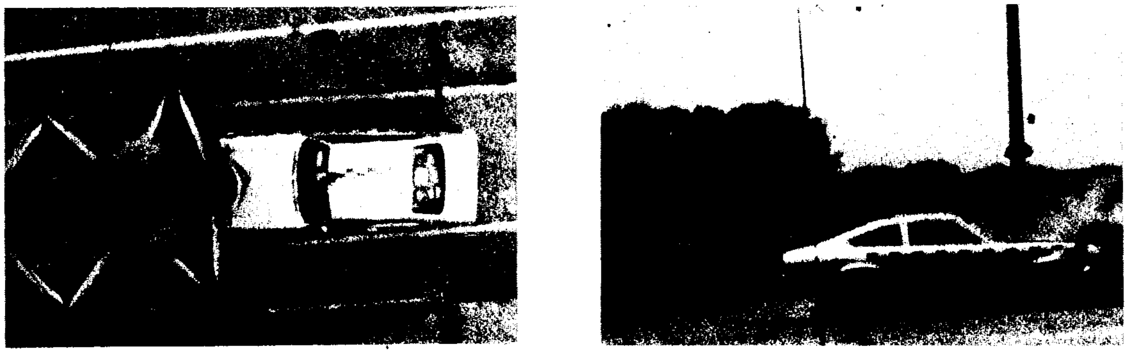
Figure 15. Sequential Photographs for Test 3



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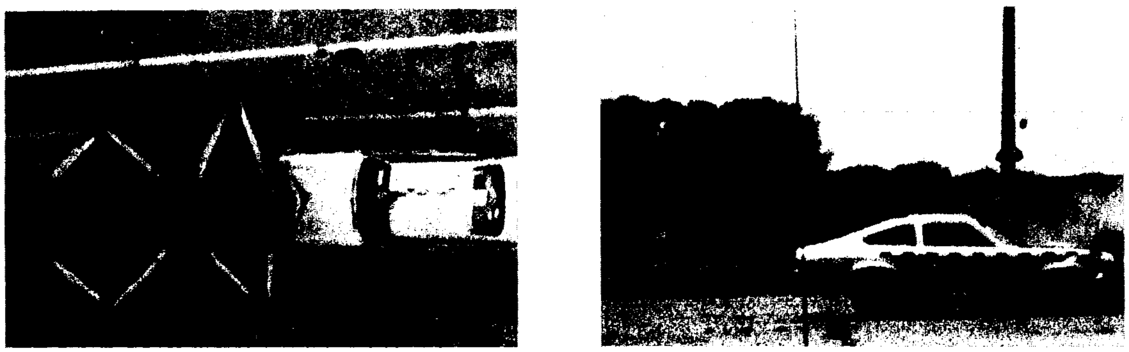

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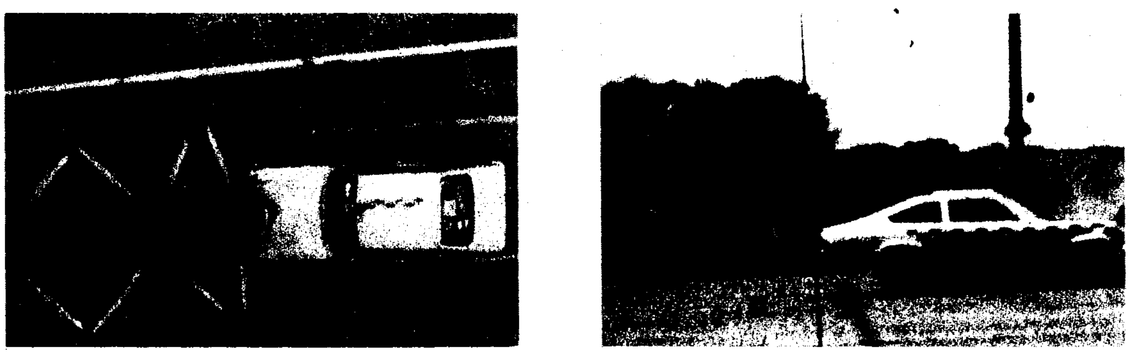

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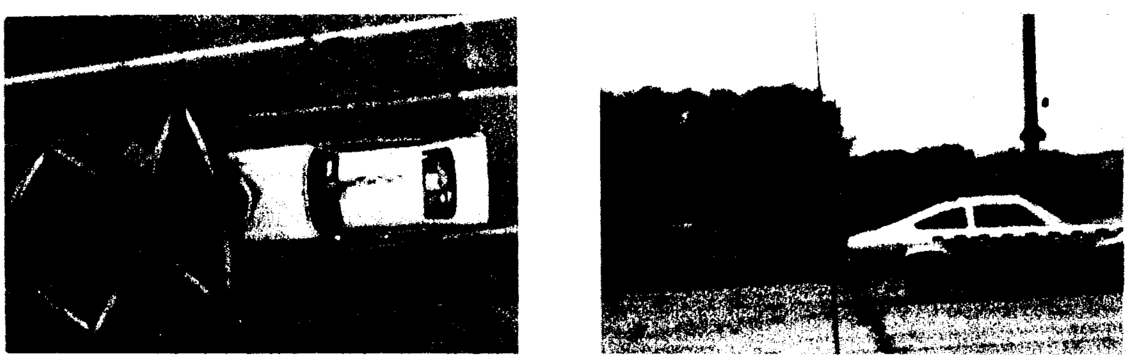

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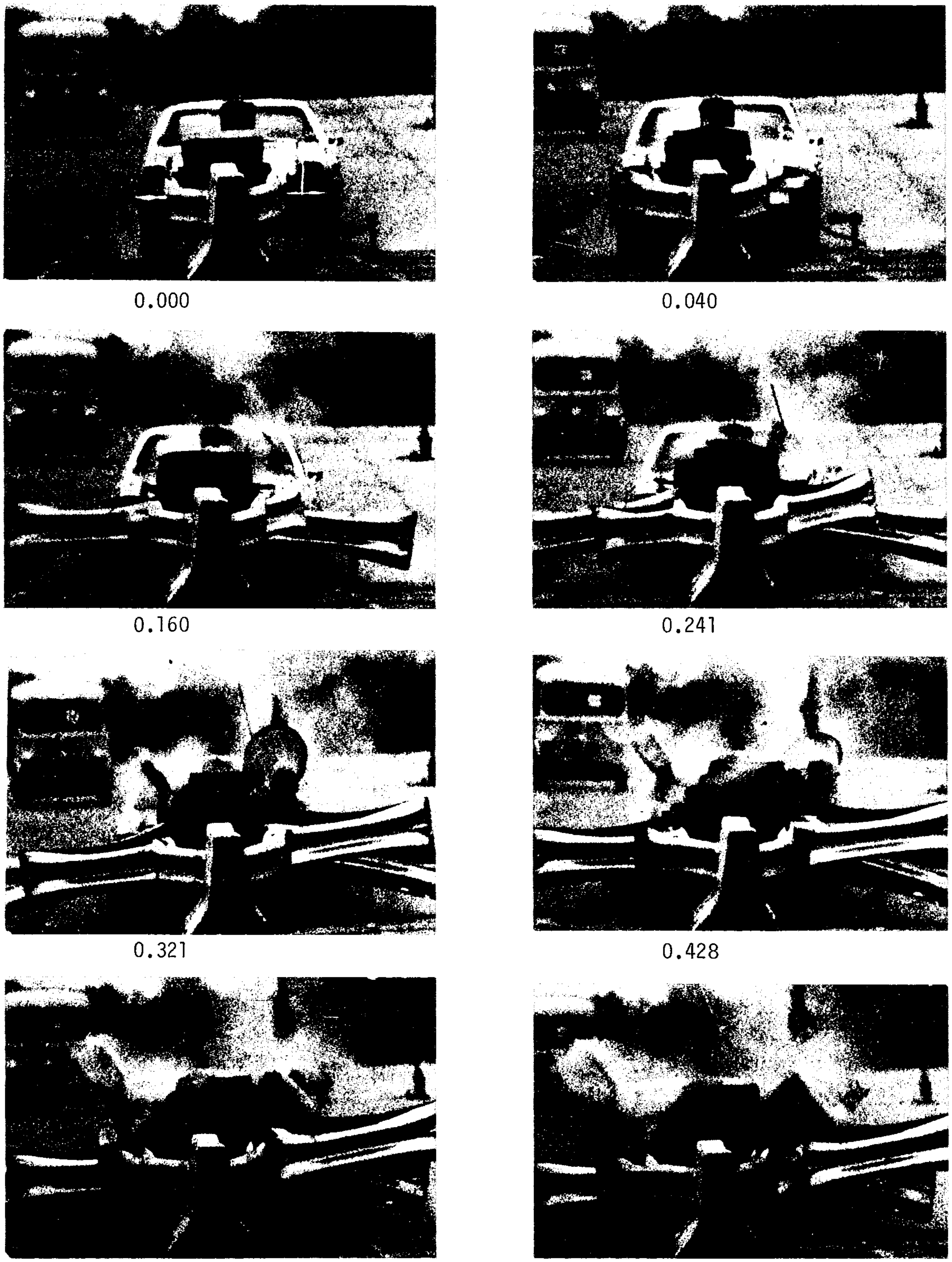
Figure 15. Sequential Photographs for Test 3 (continued)



0.000 0.040

0.160 0.241

0.321 0.428

0.615 0.802

Figure 15. Sequential Photographs for Test 3 (continued)

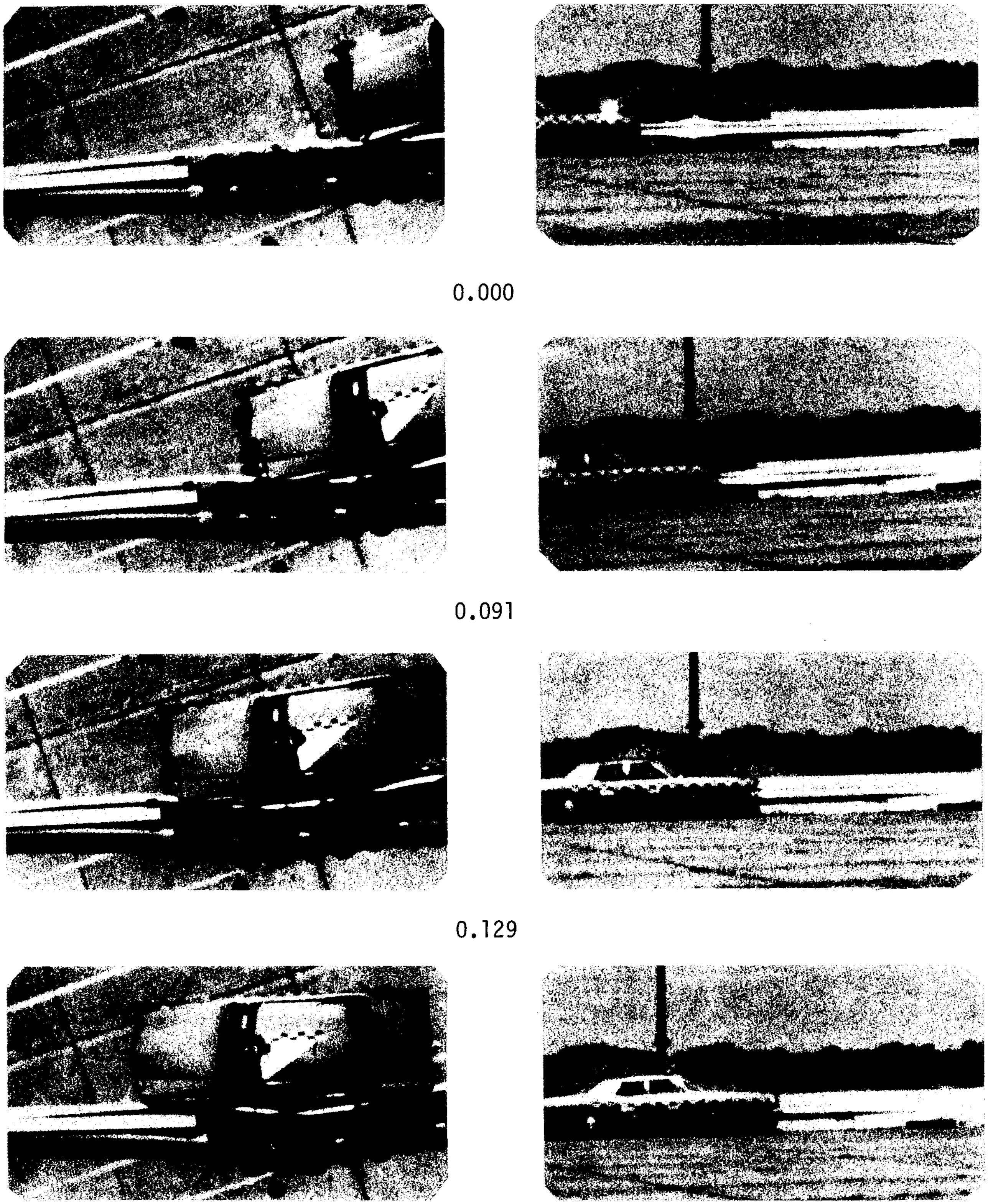


Figure 16. Sequential Photographs for Test 4

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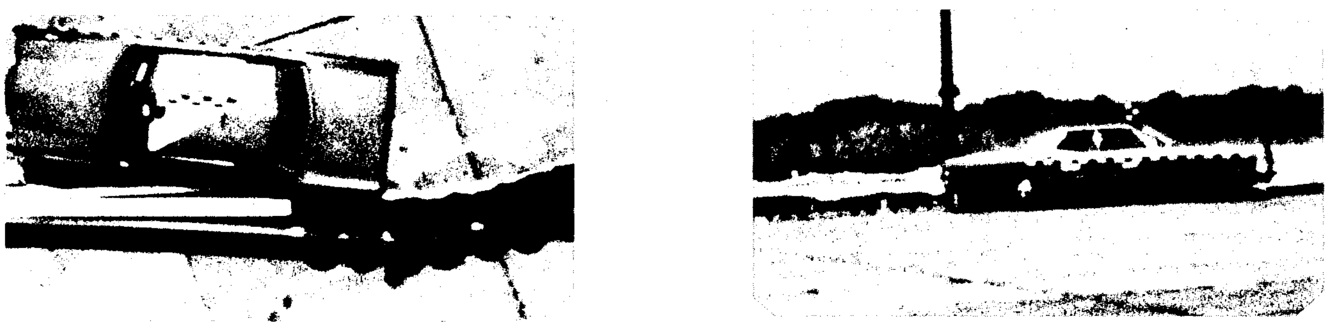

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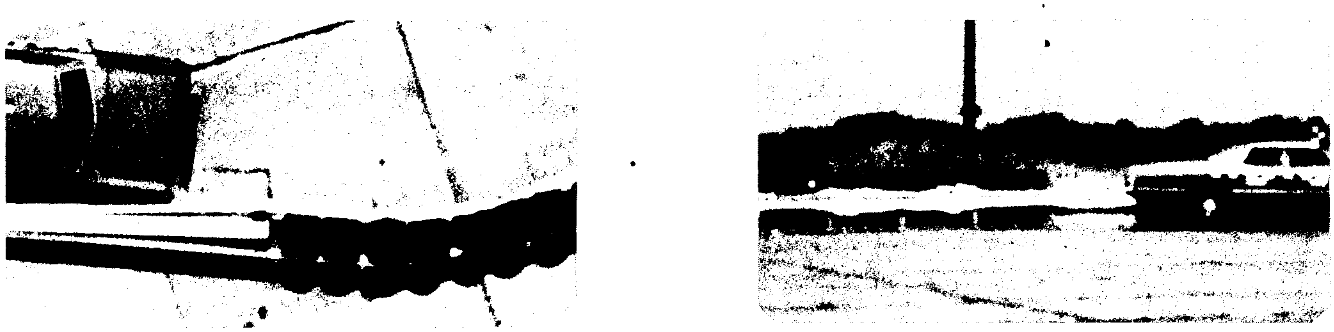

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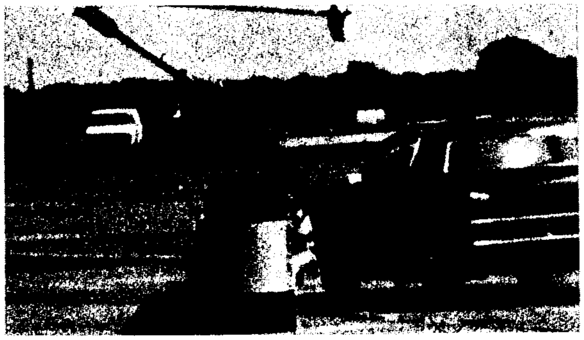
Figure 16. Sequential Photographs for Test 4 (continued)



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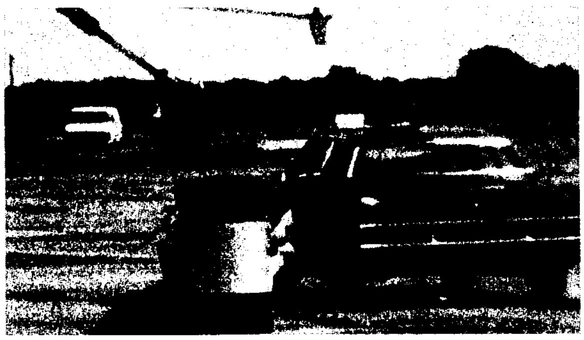

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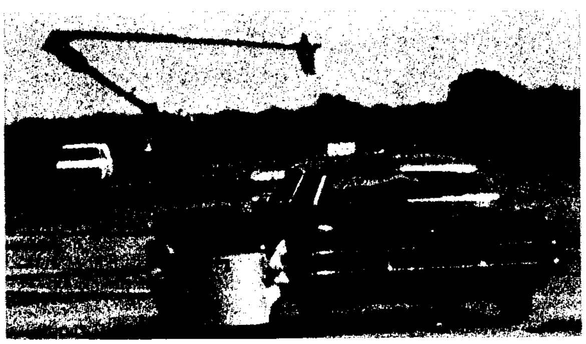

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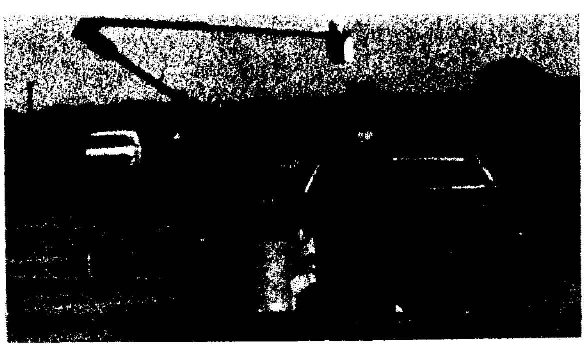

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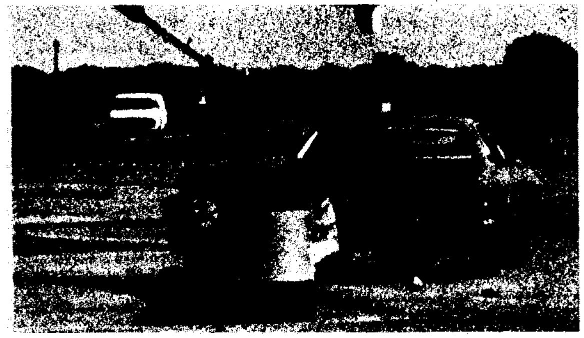

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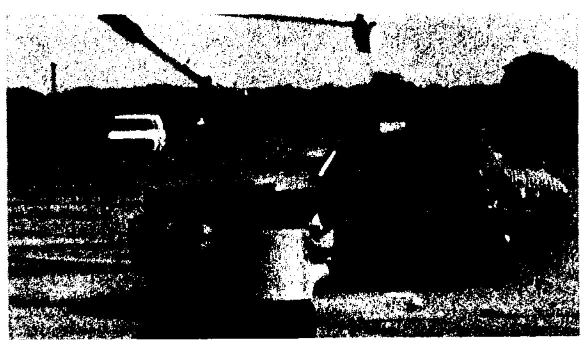

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Figure 16. Sequential Photographs for Test 4 (continued)

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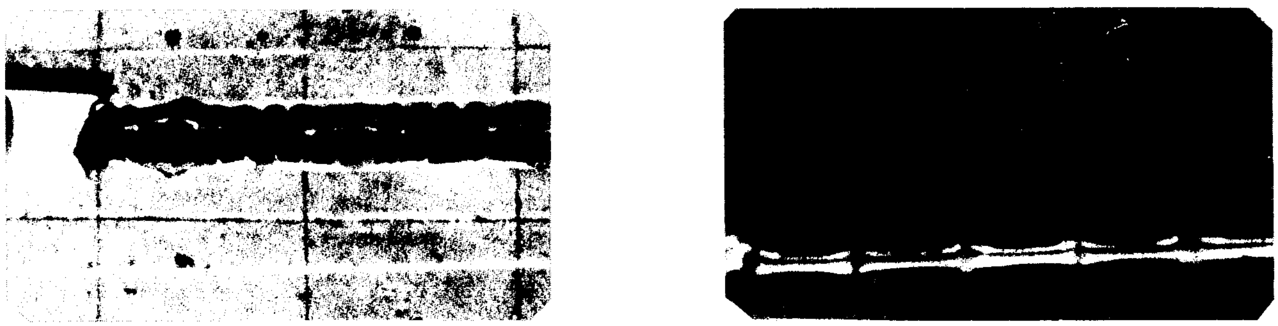

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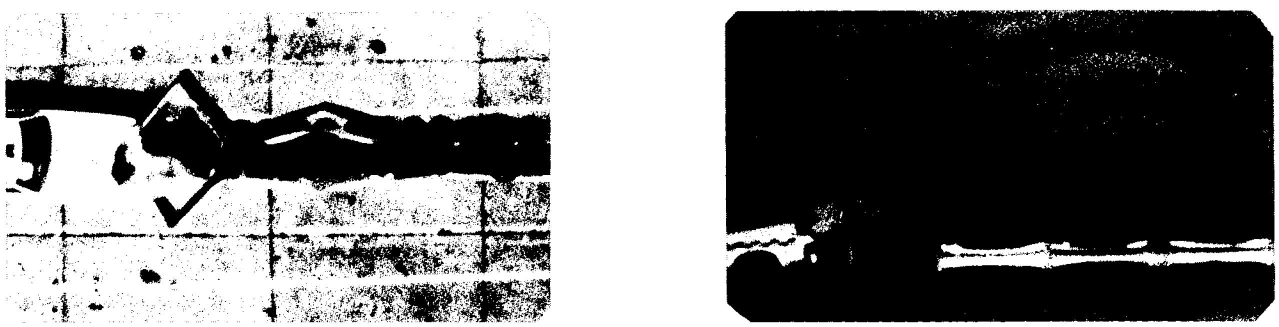

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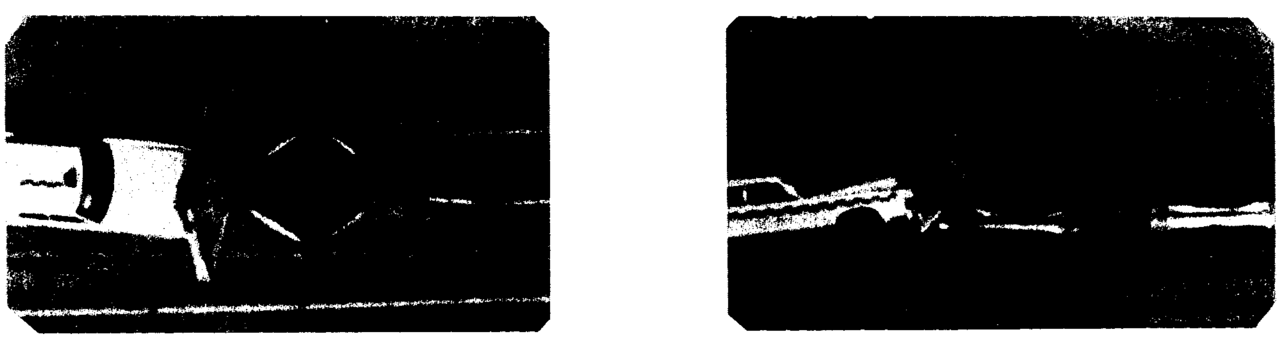

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Figure 17. Sequential Photographs for Test 5

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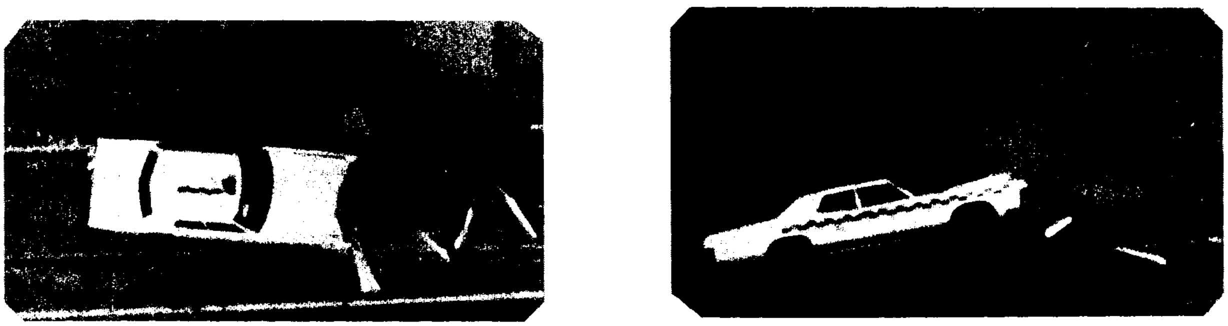

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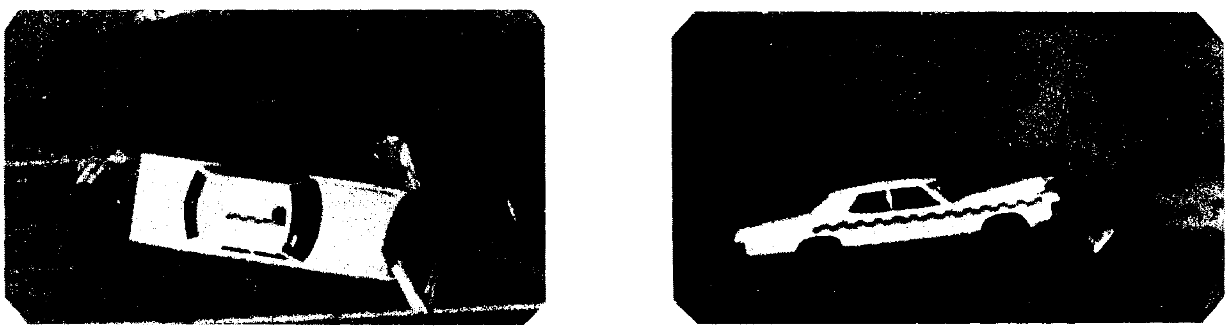

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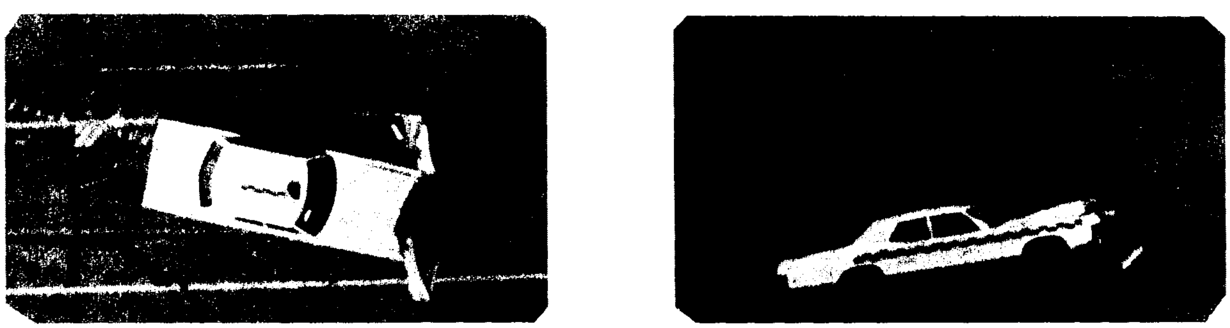

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Figure 17. Sequential Photographs for Test 5 (continued)

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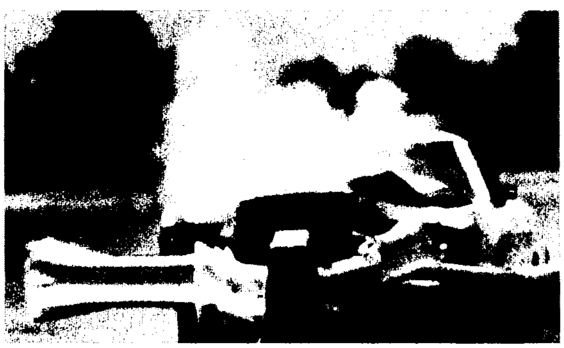

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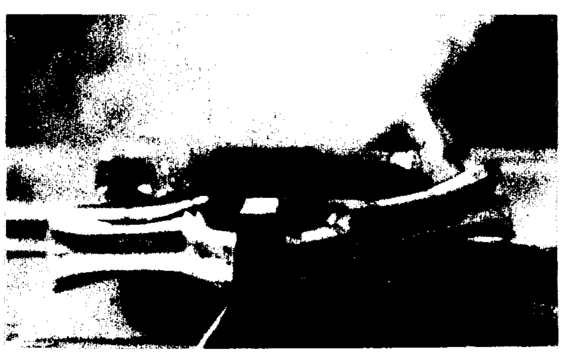

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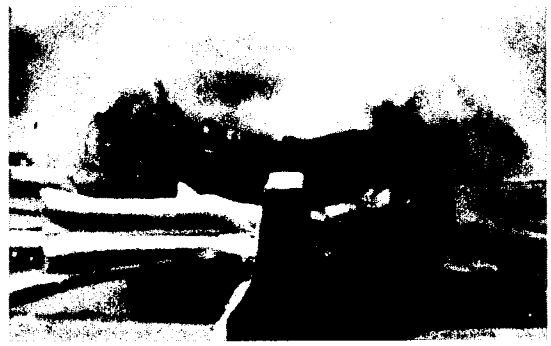

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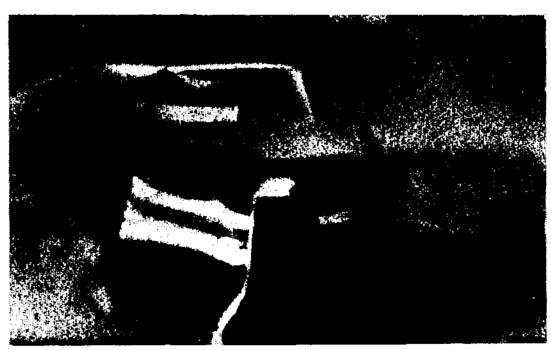

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Figure 17. Sequential Photographs for Test 5 (continued)

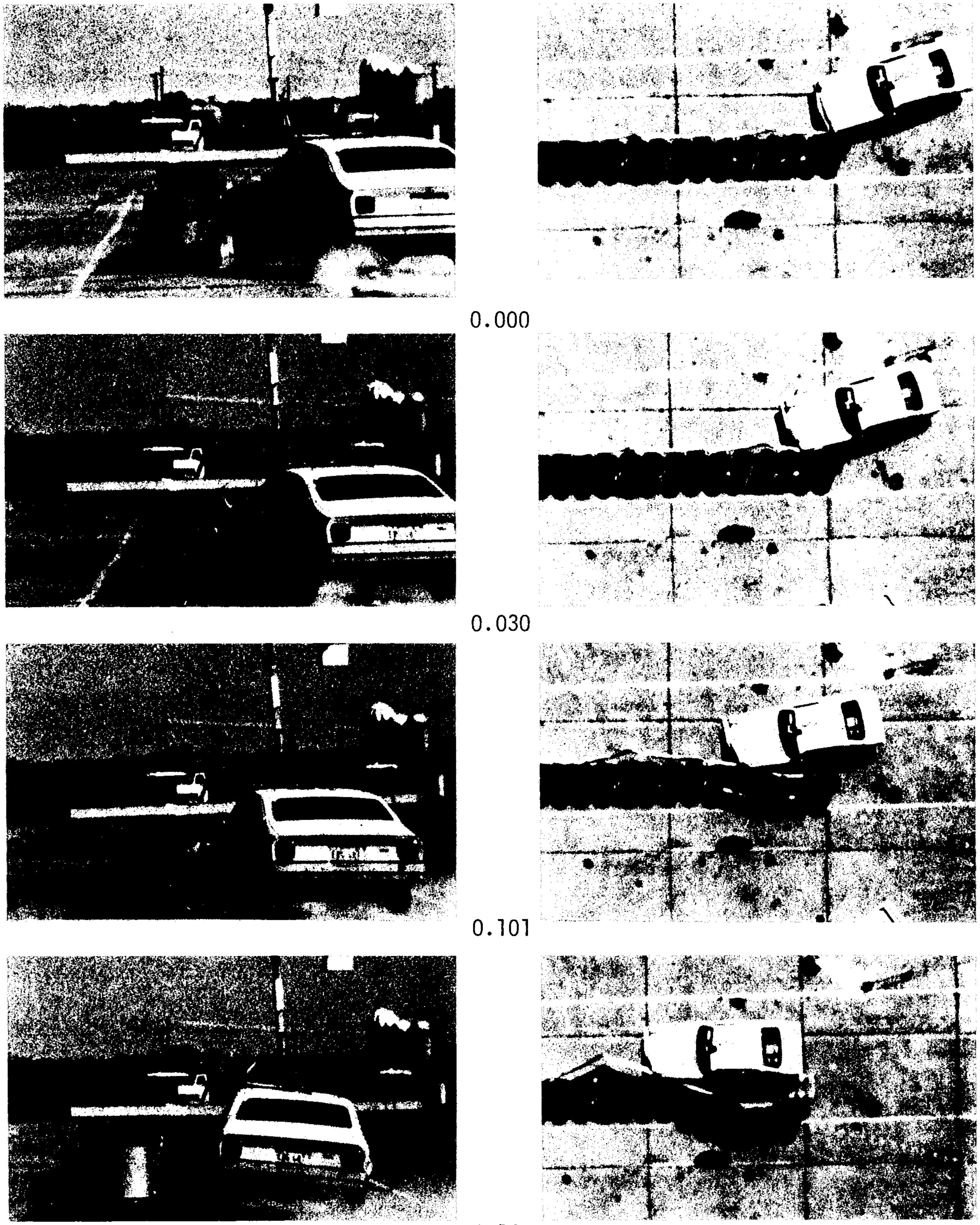

Figure 18. Sequential Photographs for Test 6

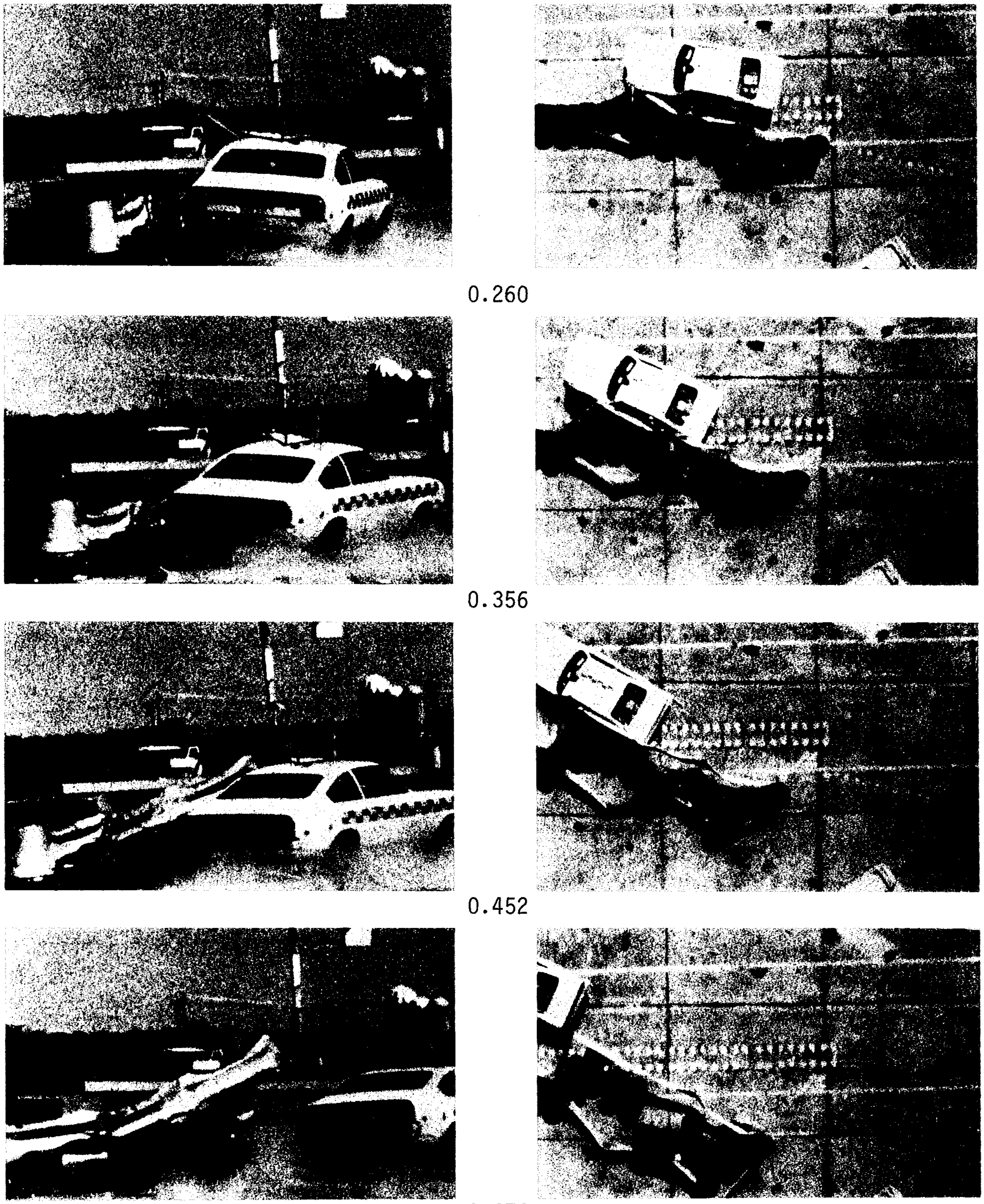

Figure 18. Sequential Photographs for Test 6 (continued)

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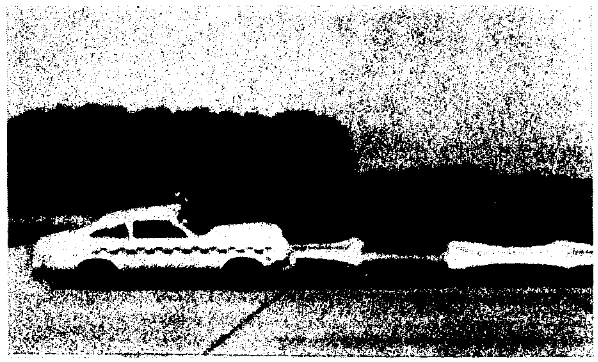

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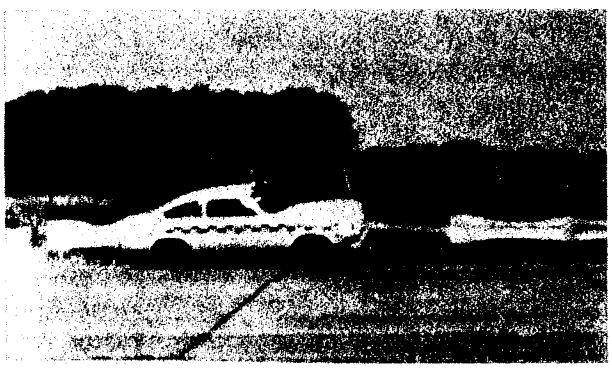

0.260

0.356

0.452

0.674

Figure 18. Sequential Photographs for Test 6 (continued)

APPENDIX B

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

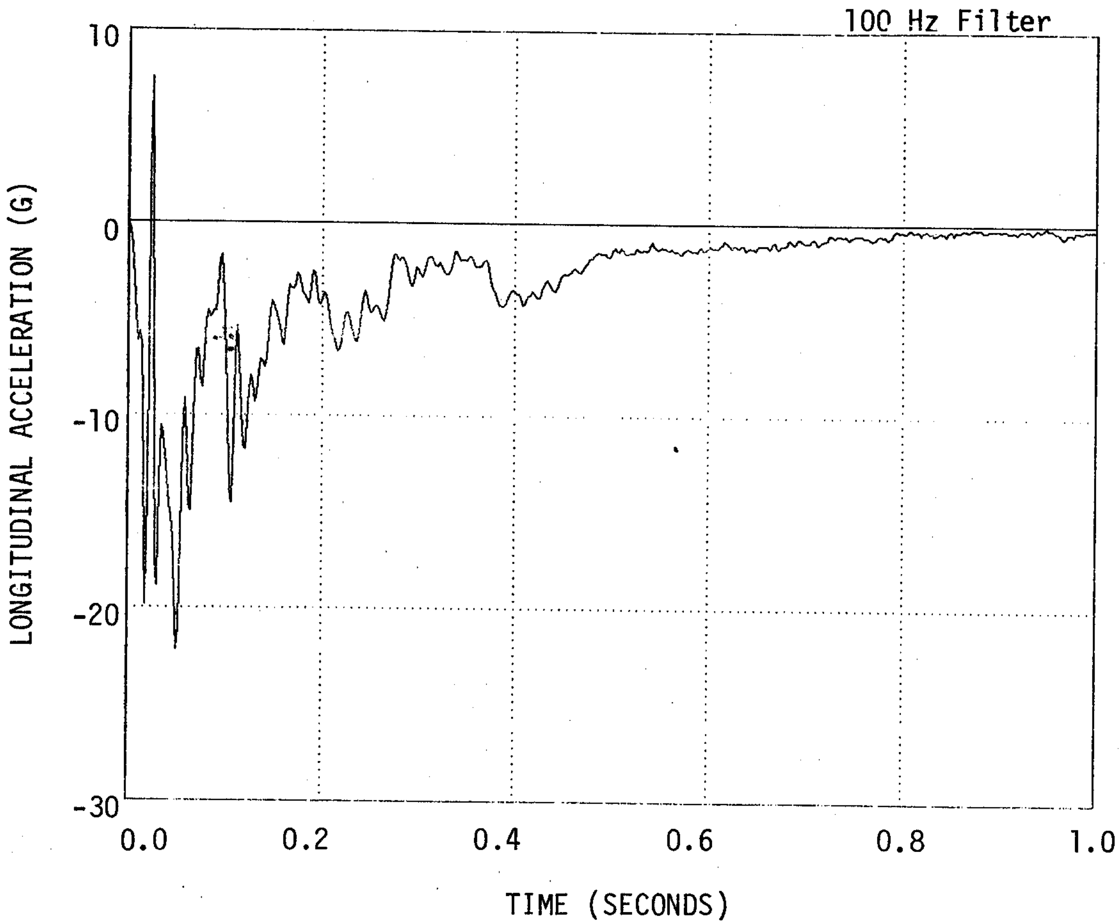

Figure 19. Vehicle Longitudinal Acceleration for Test 3

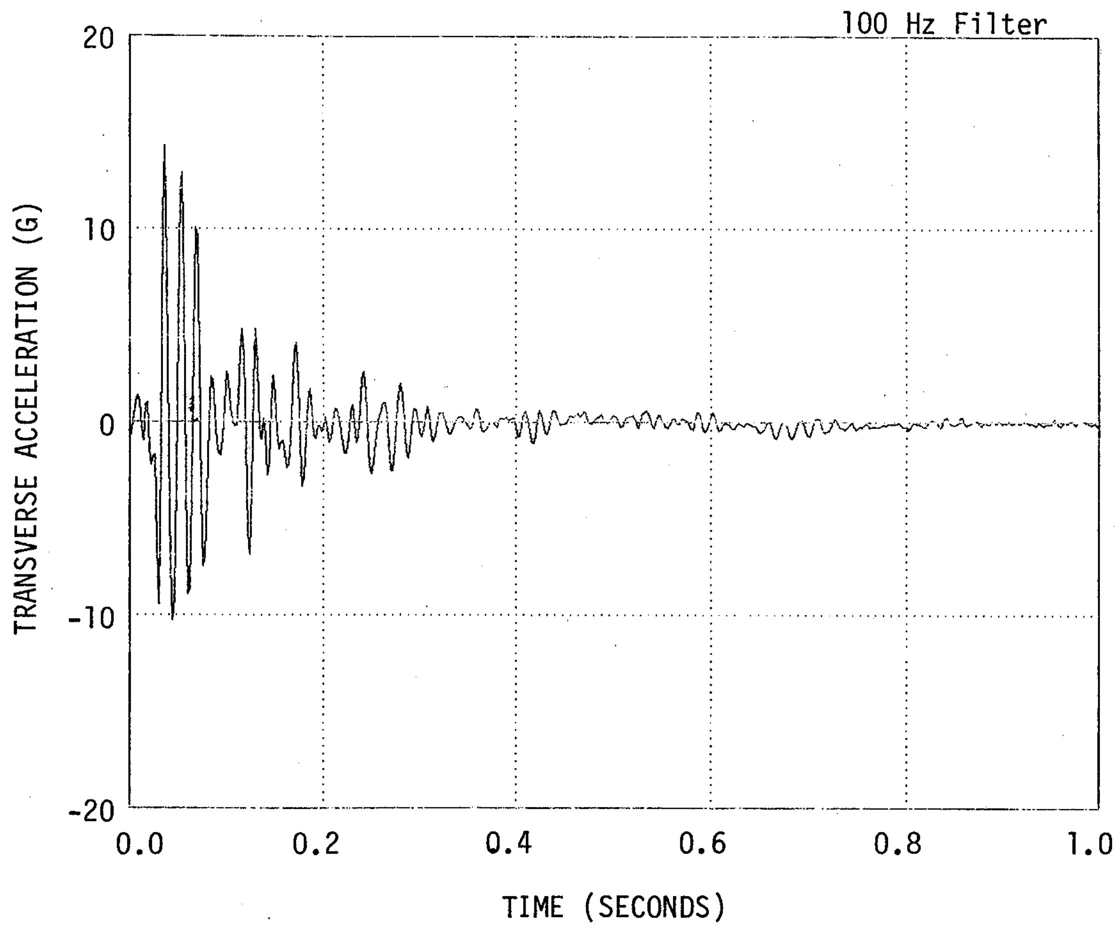

Figure 20. Vehicle Transverse Acceleration for Test 3

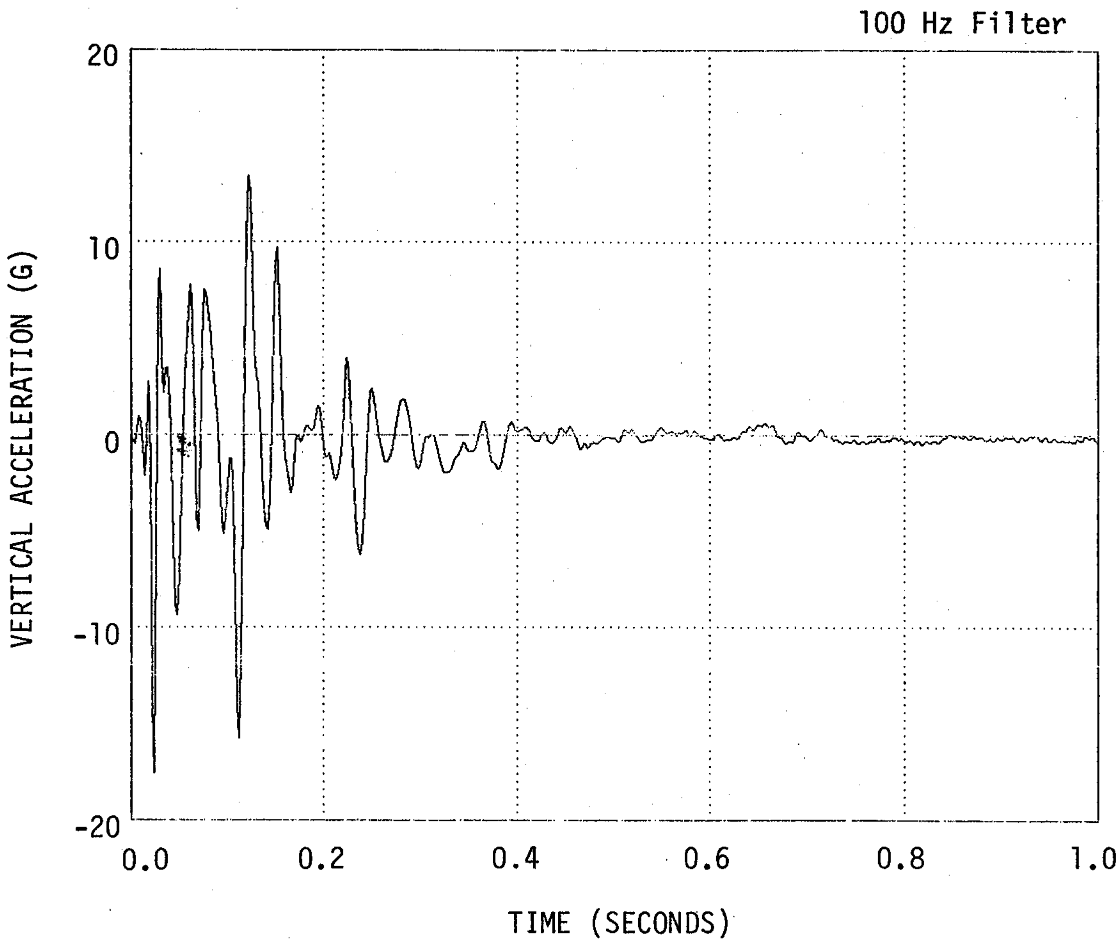

Figure 21. Vehicle Vertical Acceleration for Test 3

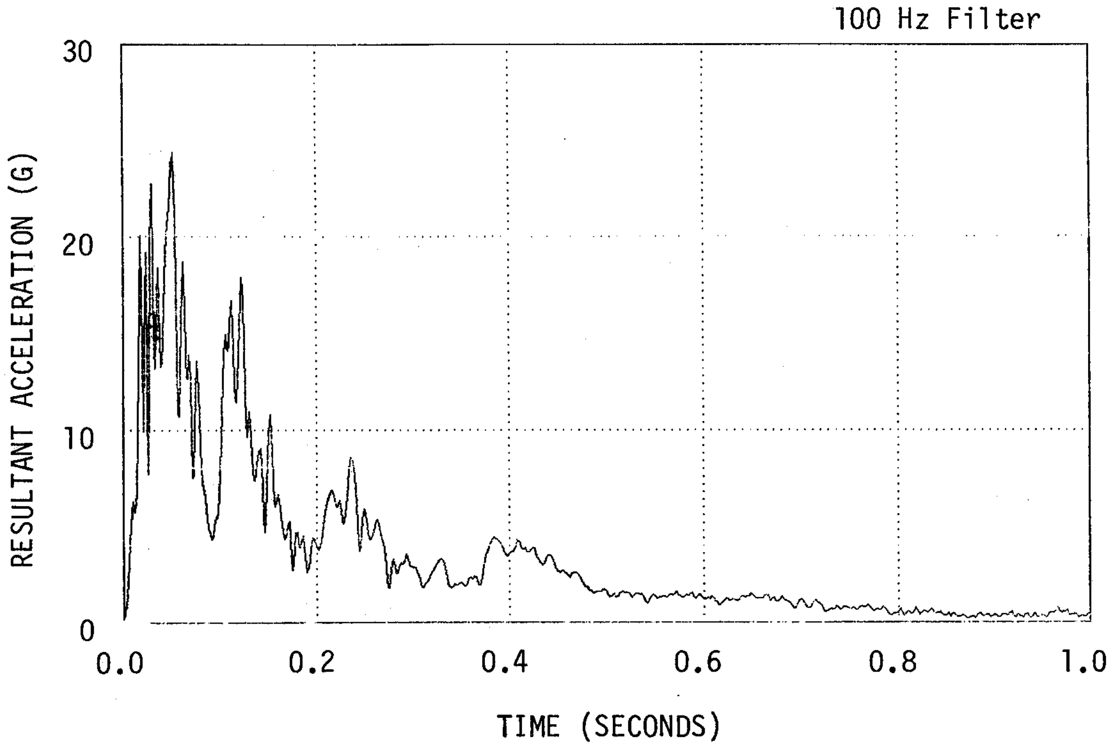

Figure 22. Vehicle Resultant Acceleration for Test 3

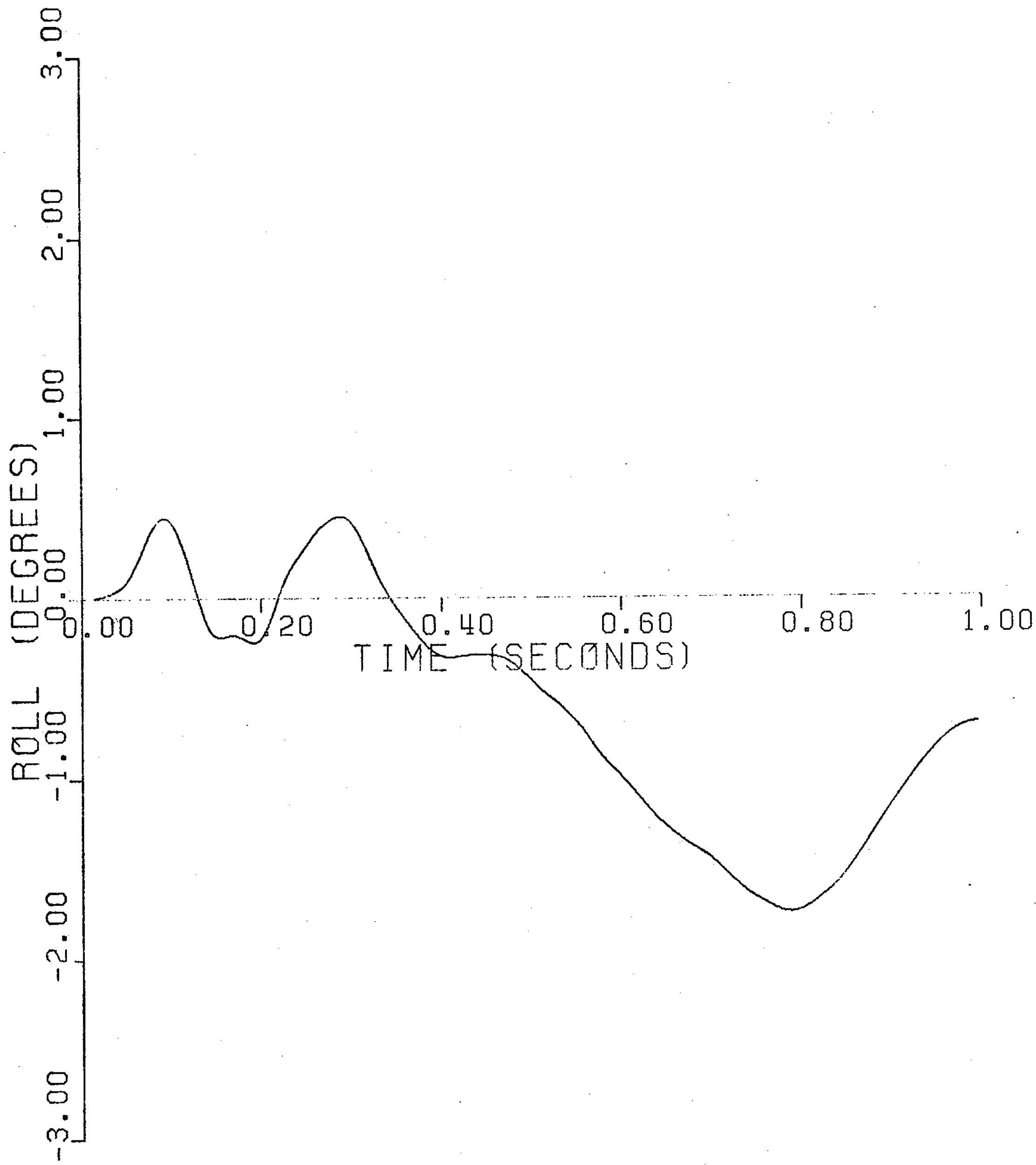

Figure 23. Vehicle Roll for Test 3

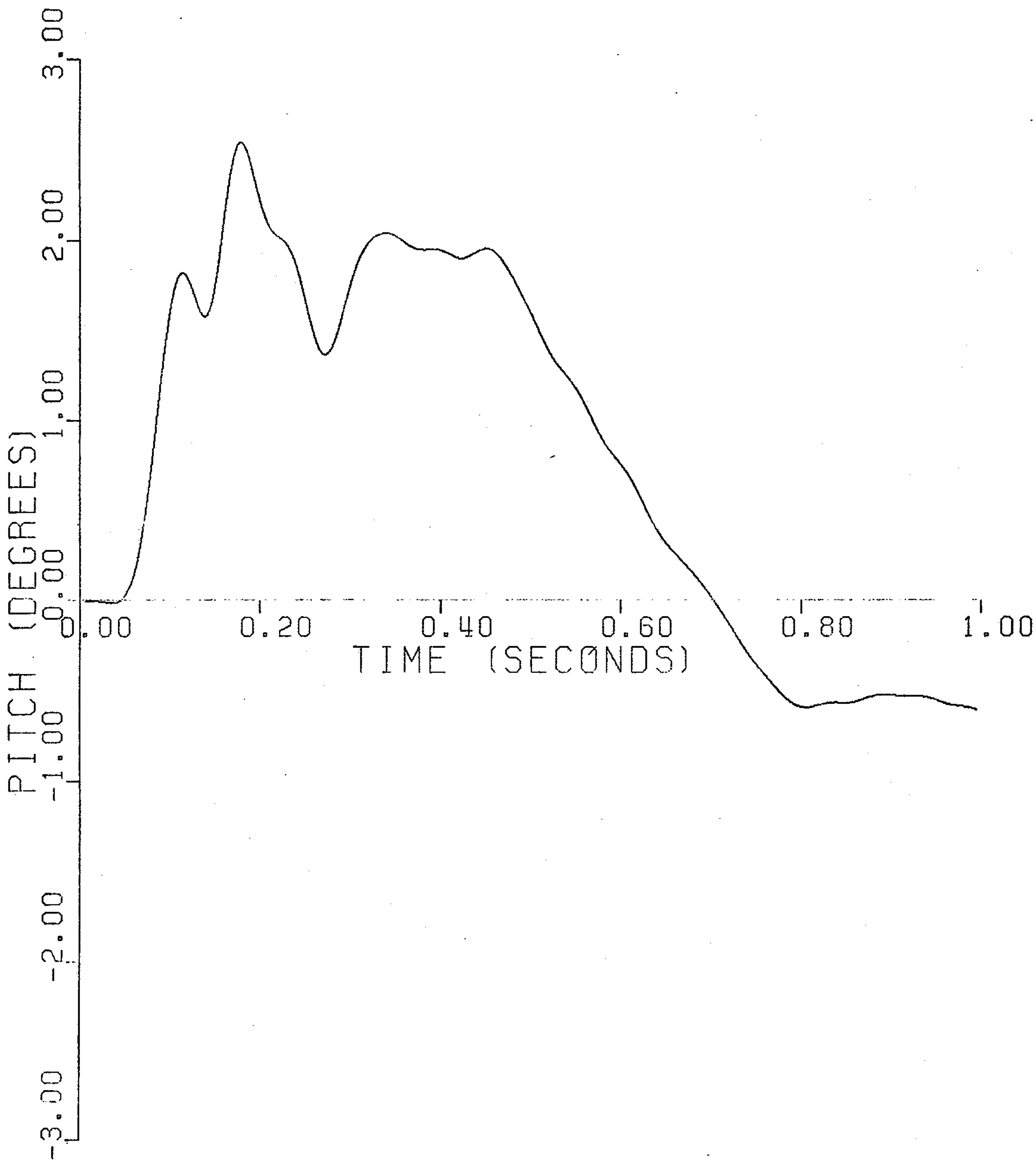

Figure 24. Vehicle Pitch for Test 3

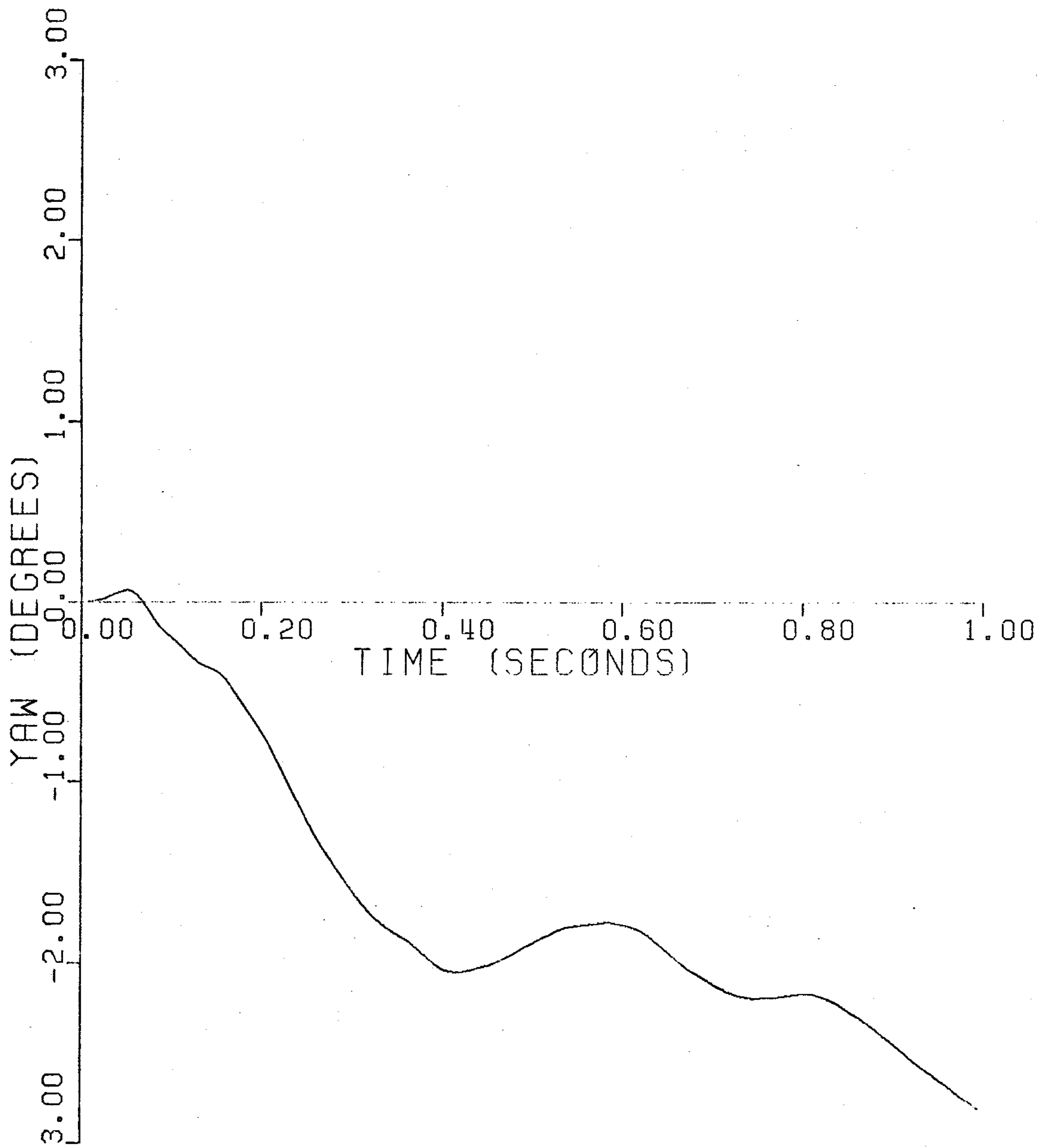

Figure 25. Vehicle Yaw for Test 3

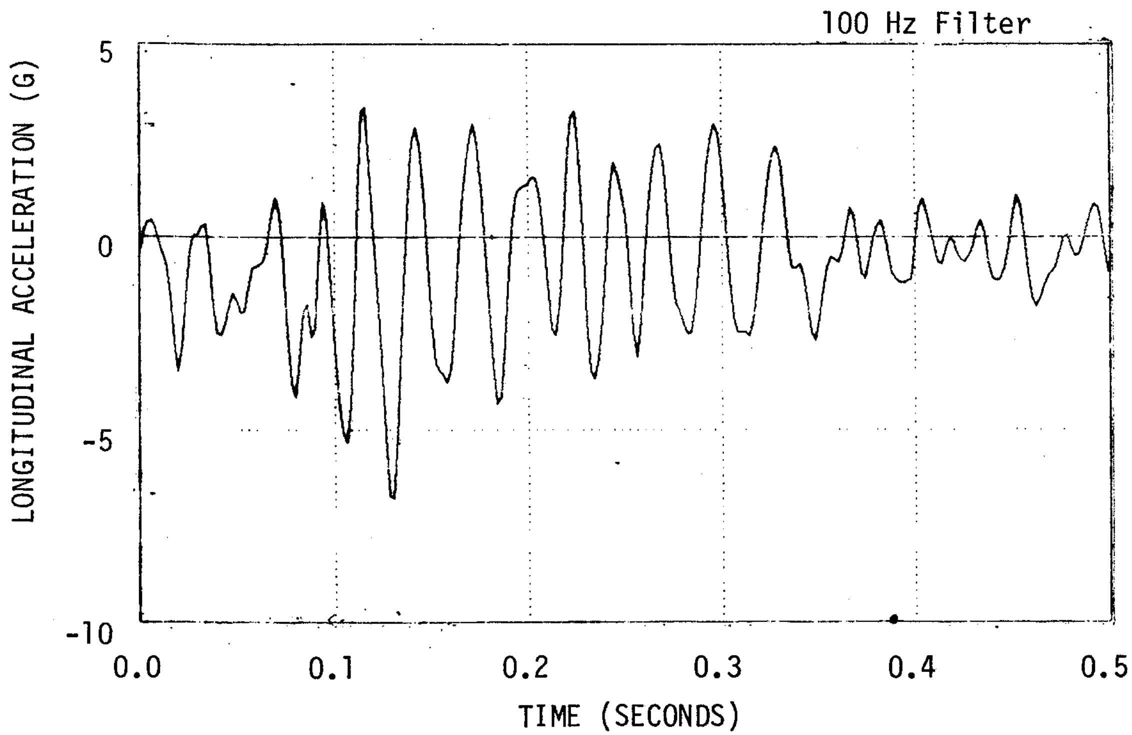

Figure 26. Vehicle Longitudinal Acceleration for Test 4

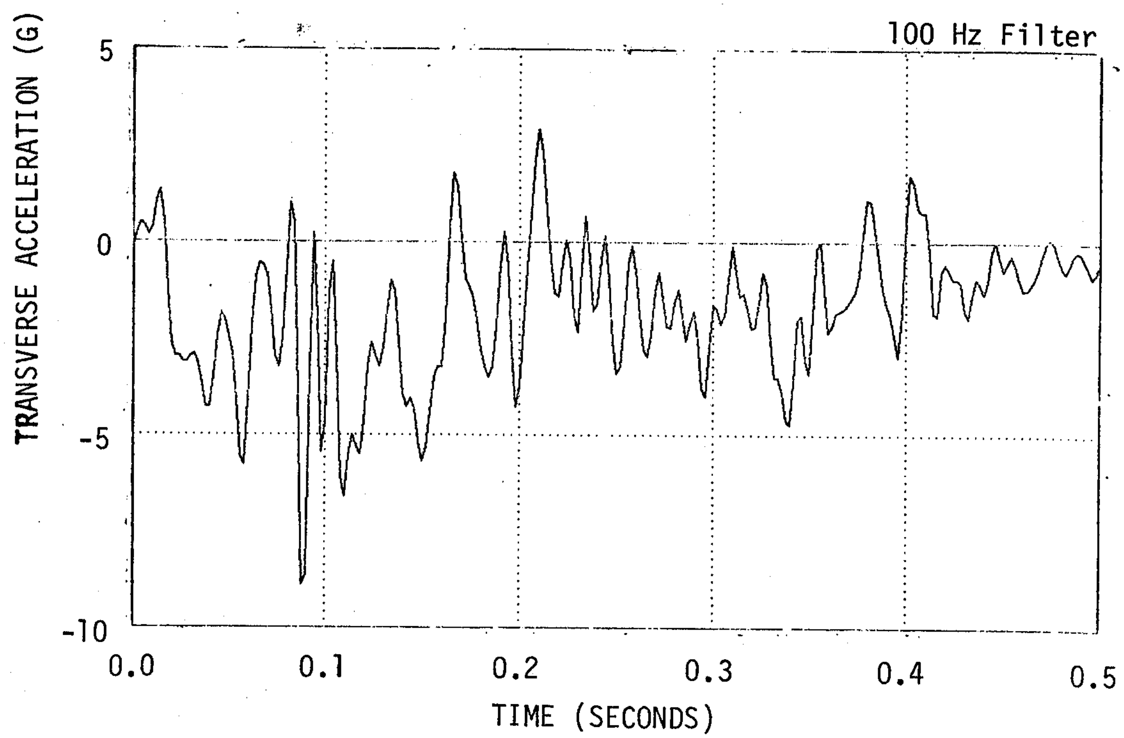

Figure 27. Vehicle Transverse Acceleration for Test 4

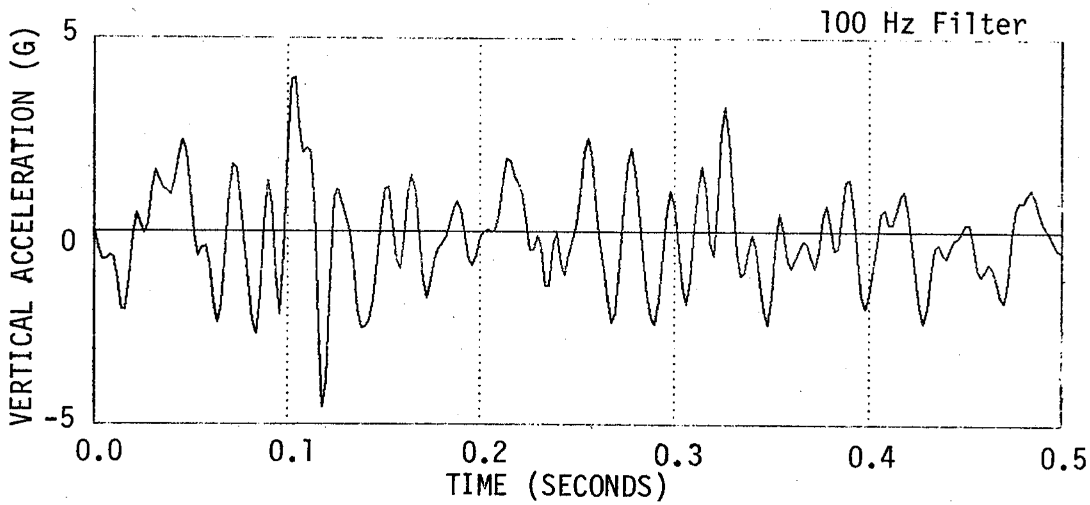

Figure 28. Vehicle Vertical Acceleration for Test 4

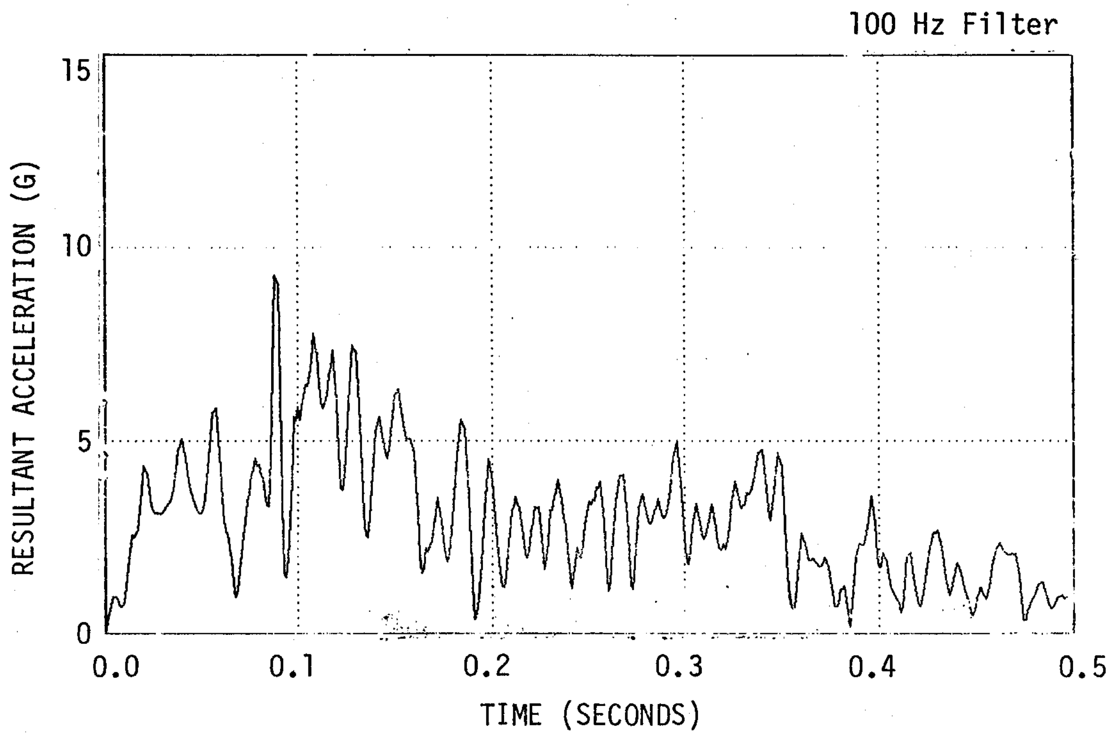

Figure 29. Vehicle Resultant Acceleration for Test 4

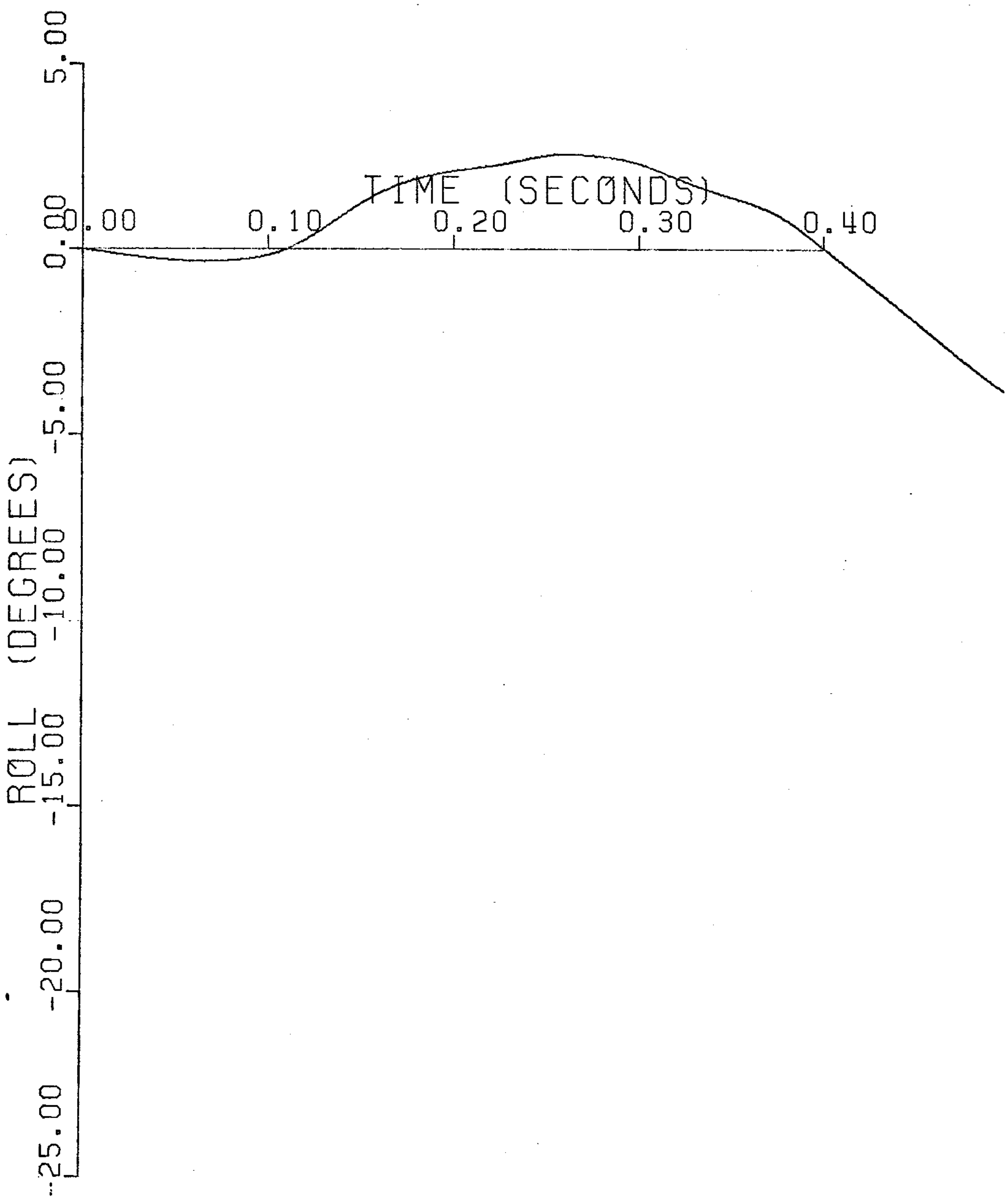

Figure 30. Vehicle Roll for Test 4

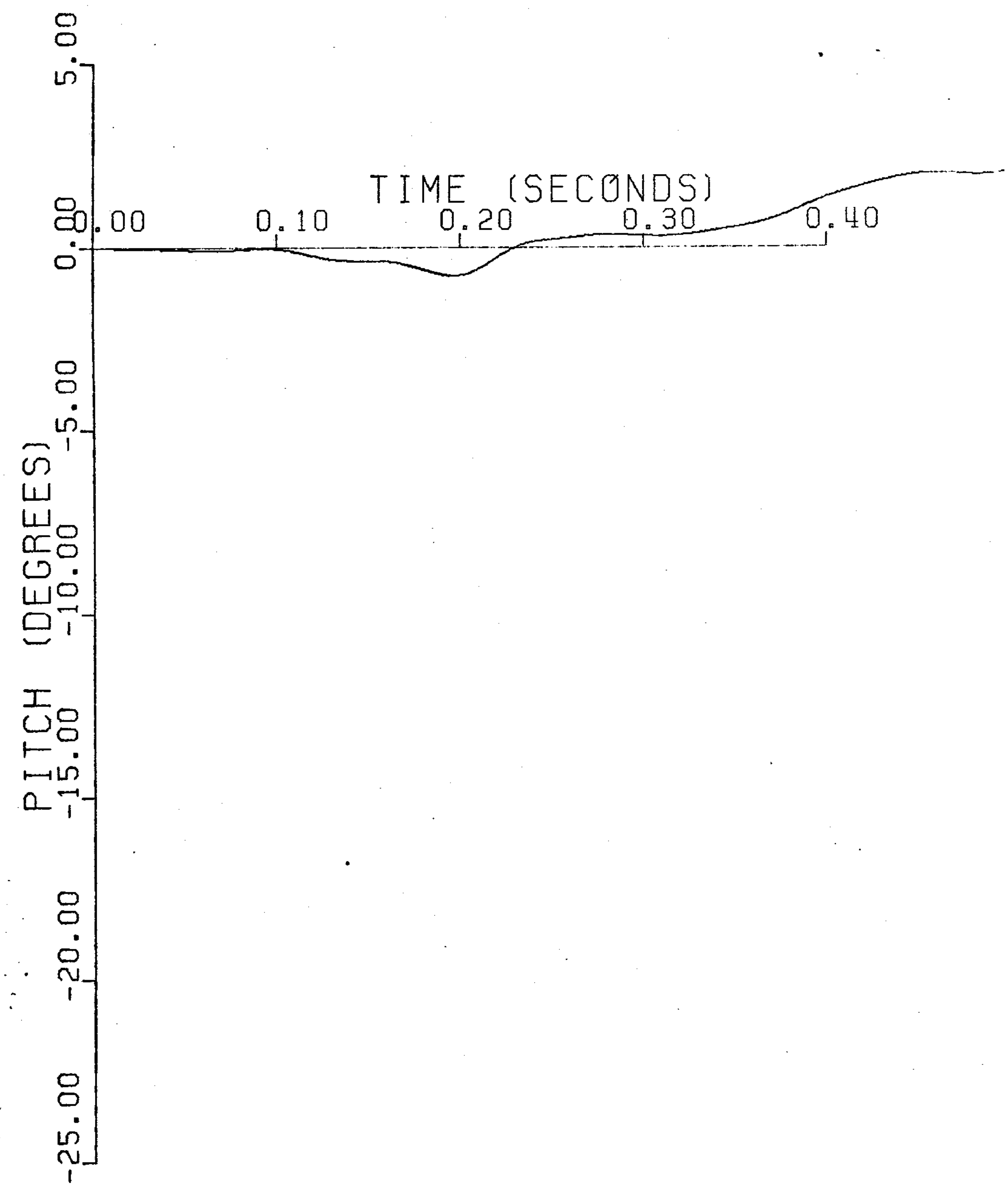

Figure 31. Vehicle Pitch for Test 4

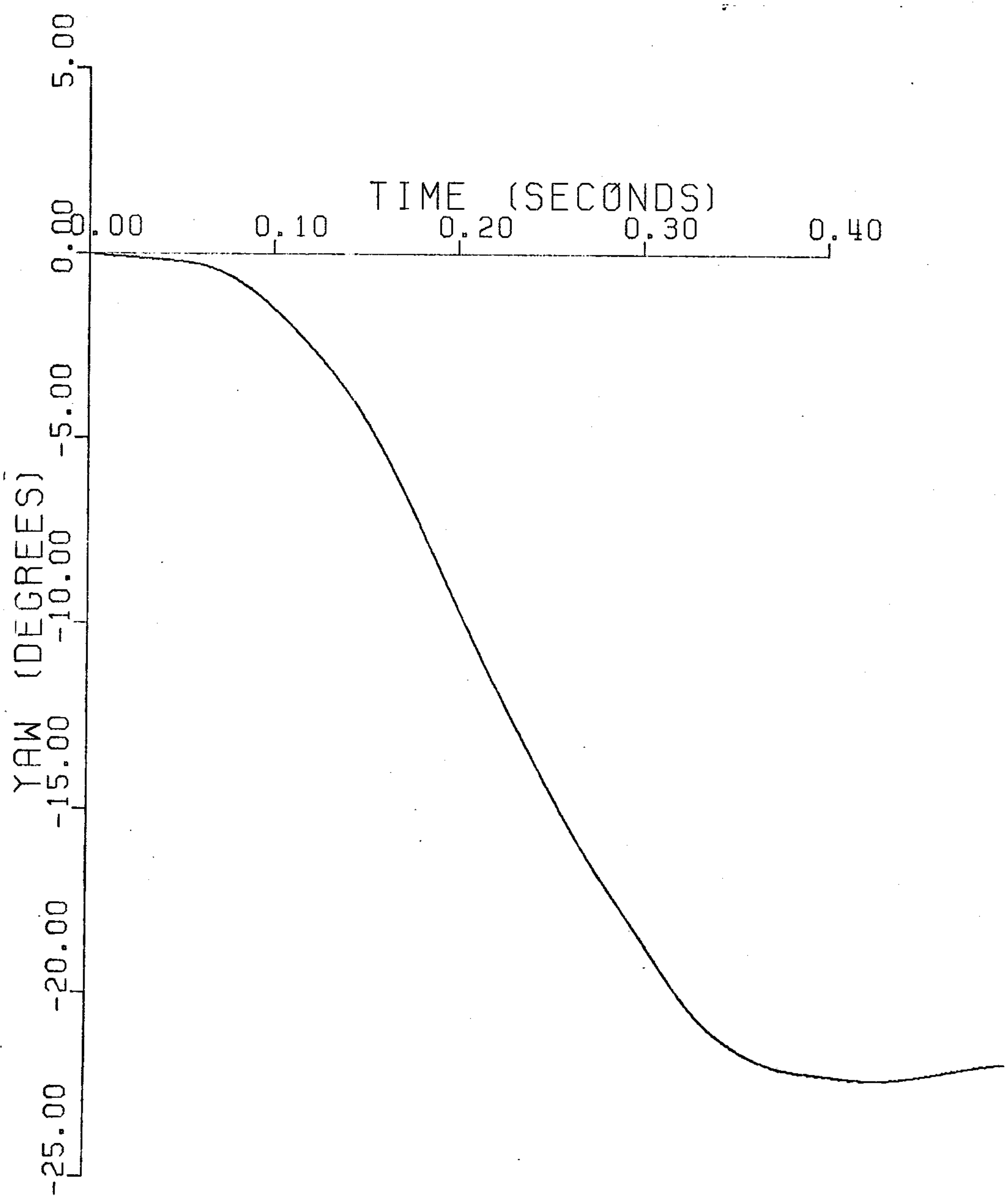

Figure 32. Vehicle Yaw for Test 4

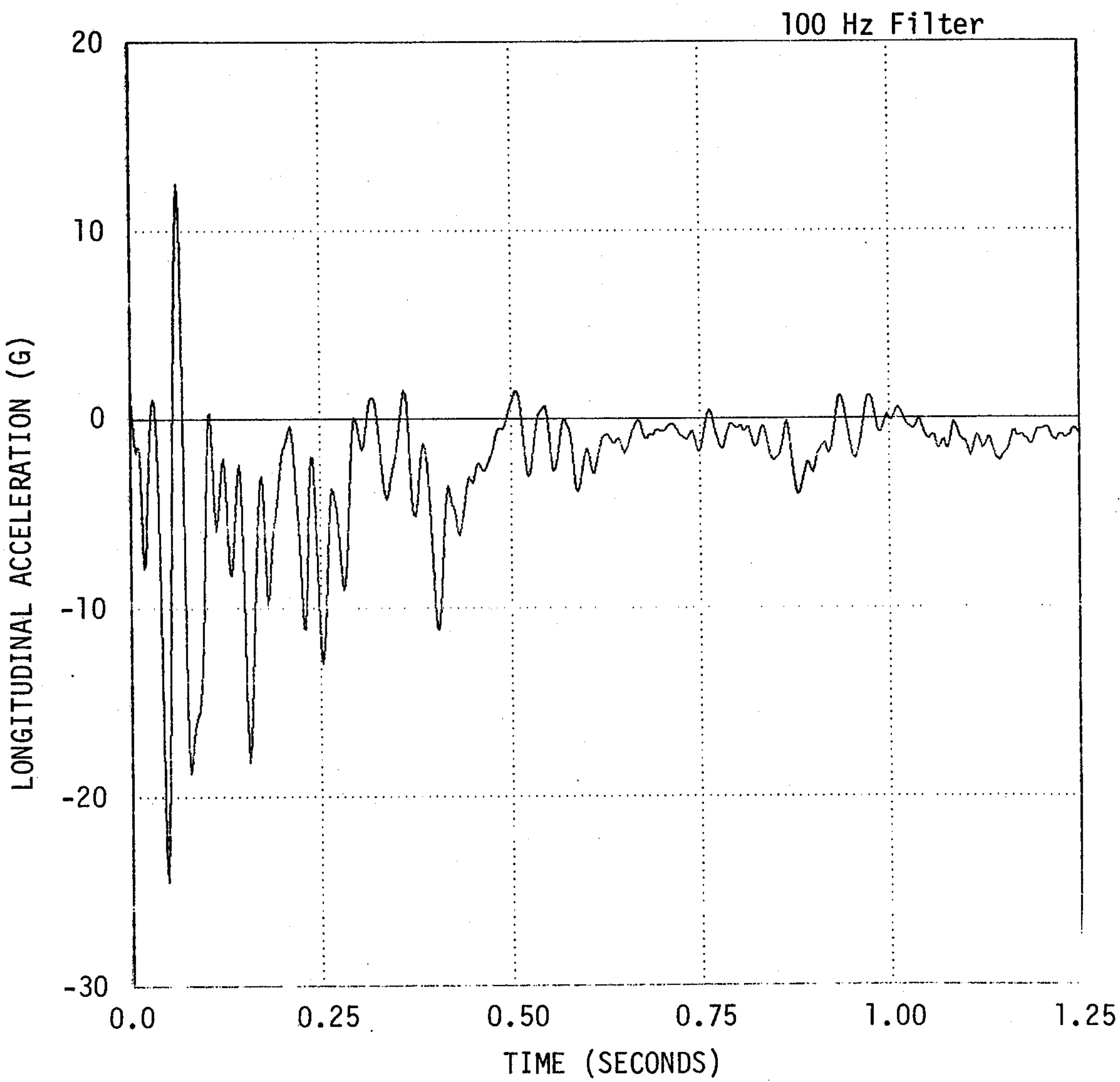

Figure 33. Vehicle Longitudinal Acceleration for Test 5

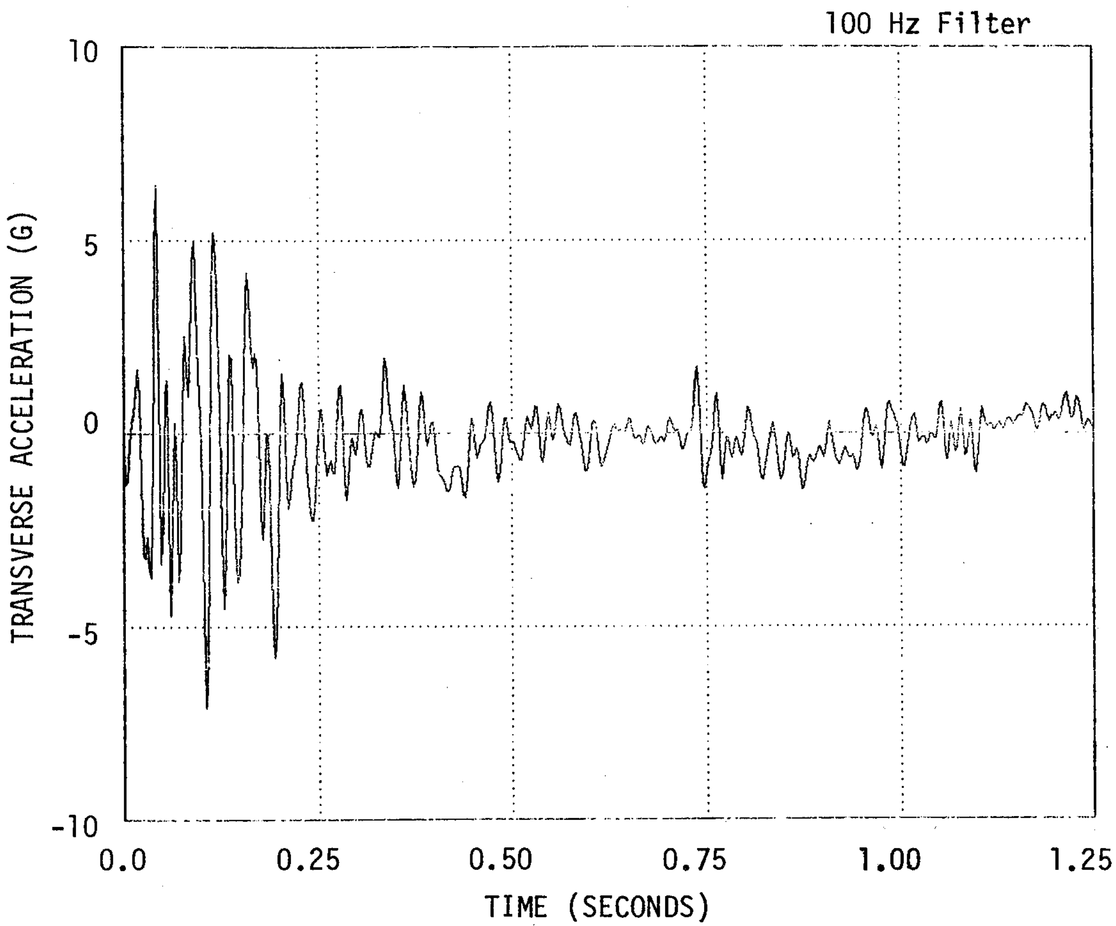

Figure 34. Vehicle Transverse Acceleration for Test 5

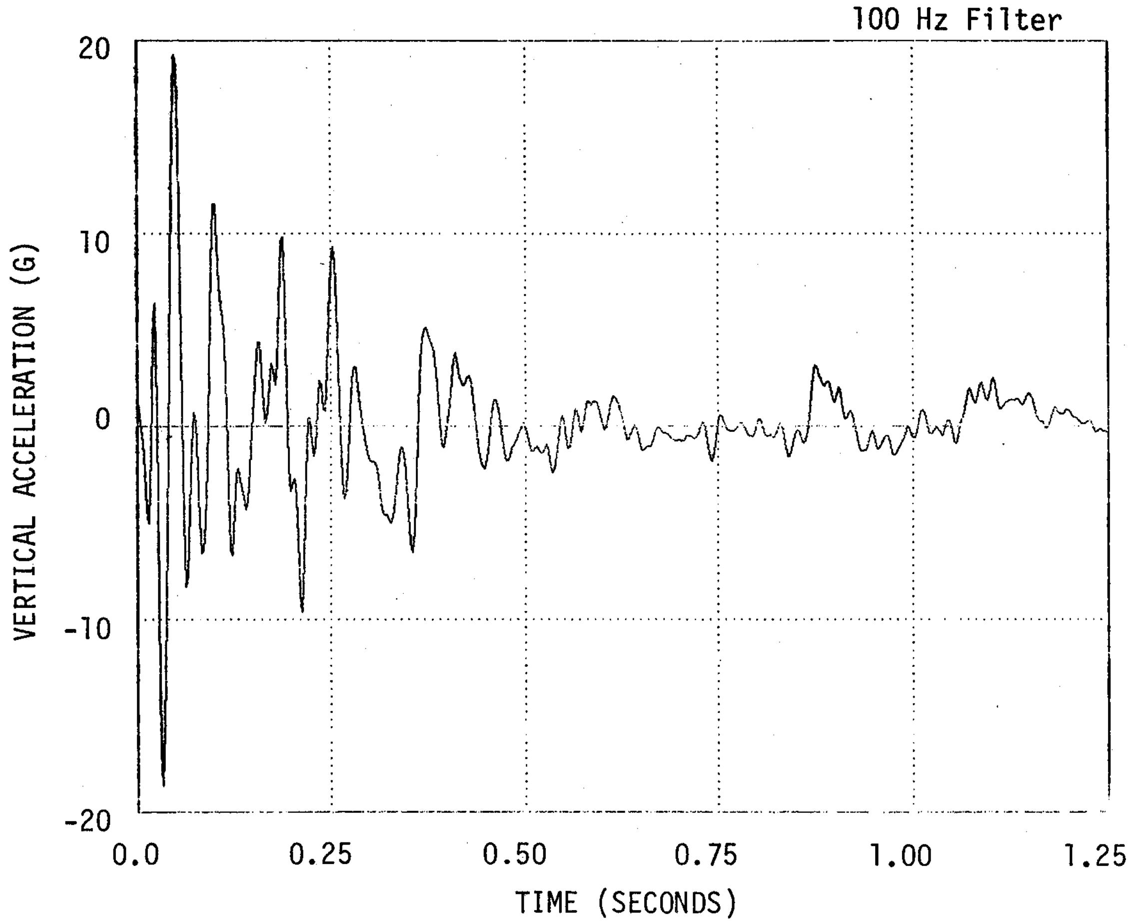

Figure 35. Vehicle Vertical Acceleration for Test 5

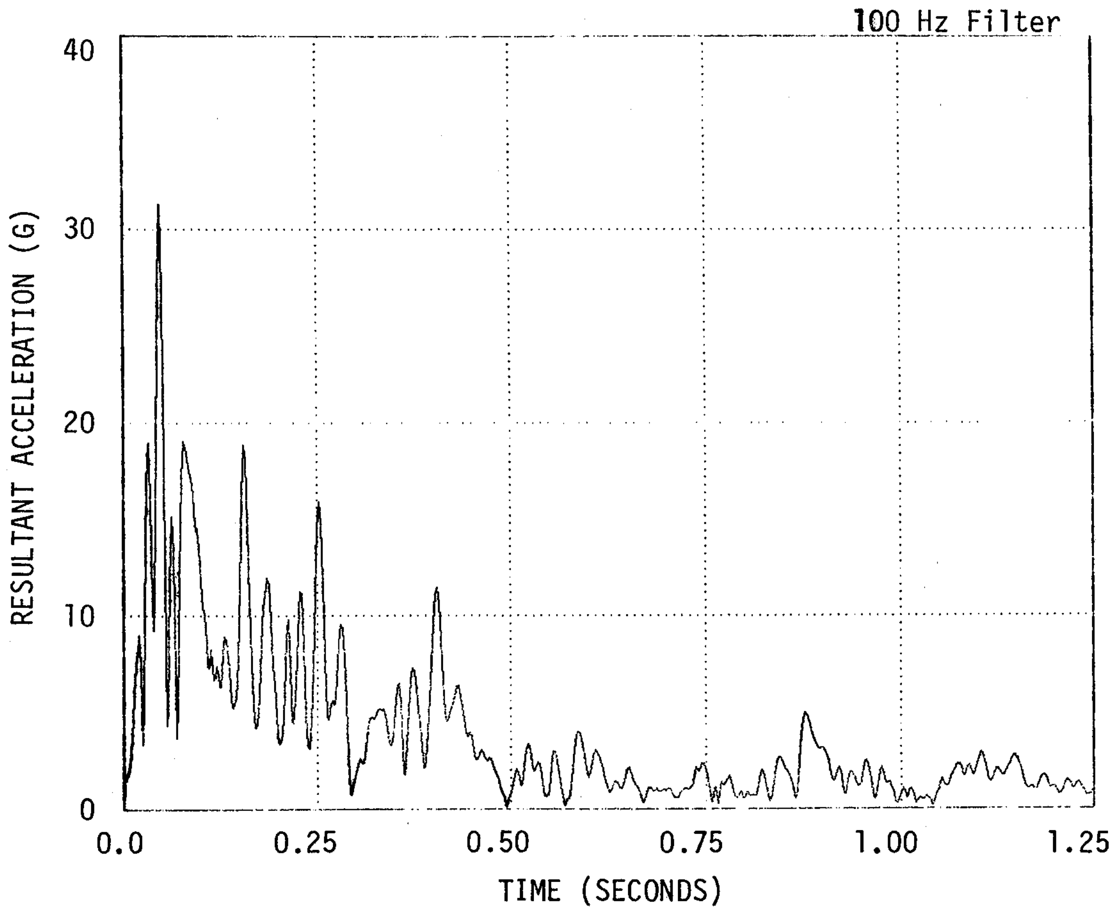

Figure 36. Vehicle Resultant Acceleration for Test 5

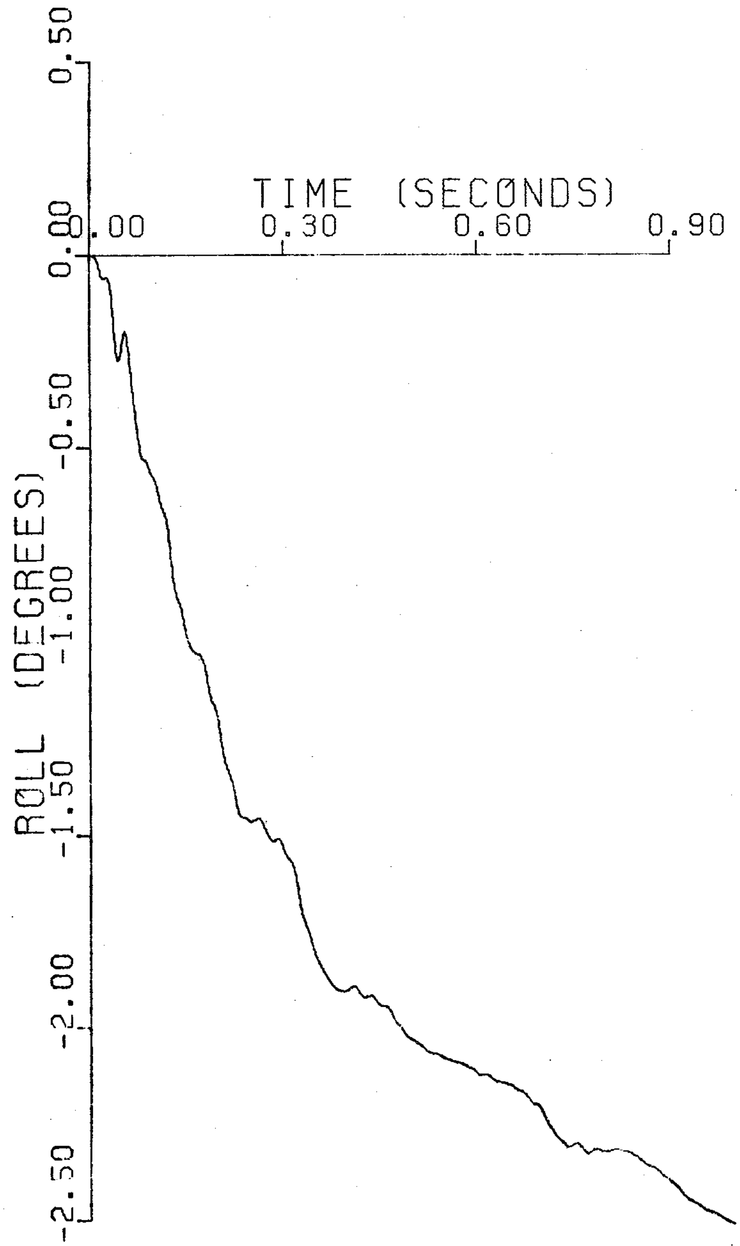

Figure 37. Vehicle Roll for Test 5

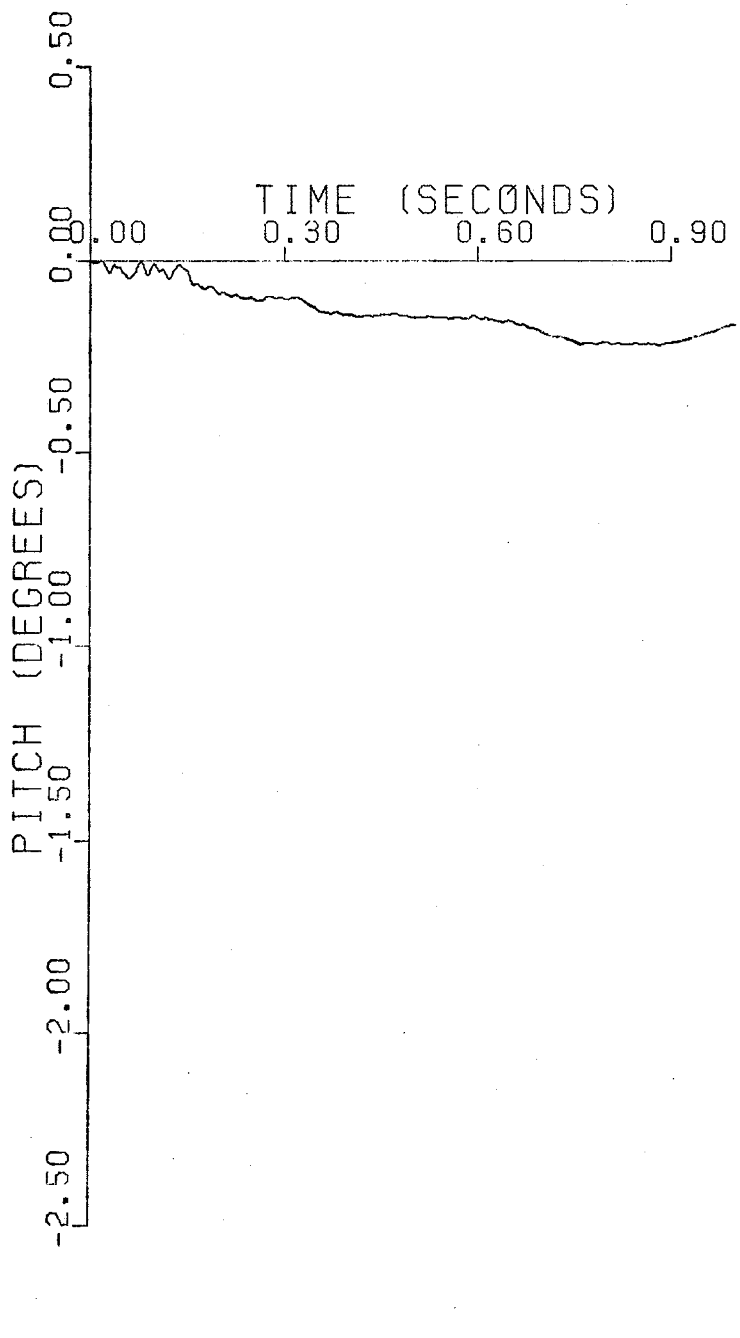

Figure 38. Vehicle Pitch for Test 5

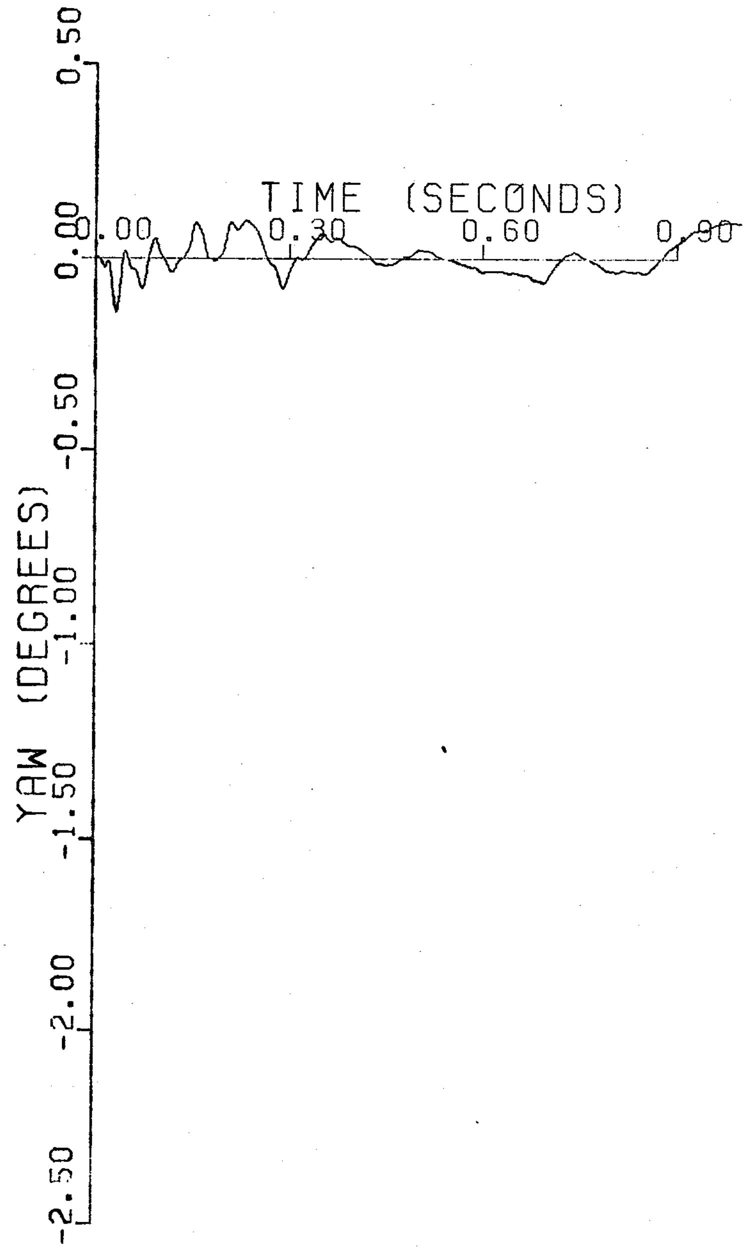

Figure 39. Vehicle Yaw for Test 5

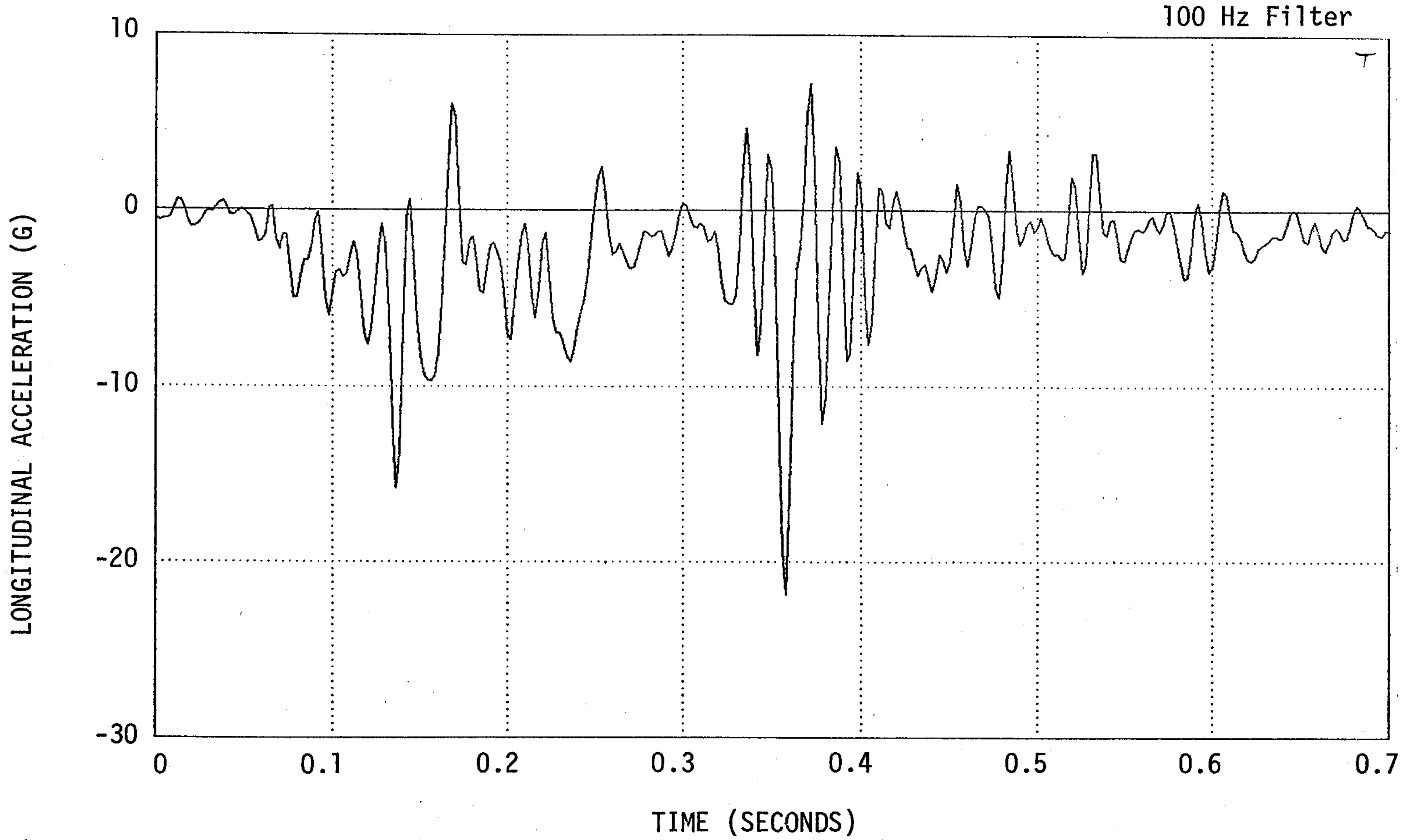

Figure 40. Vehicle Longitudinal Acceleration for Test 6

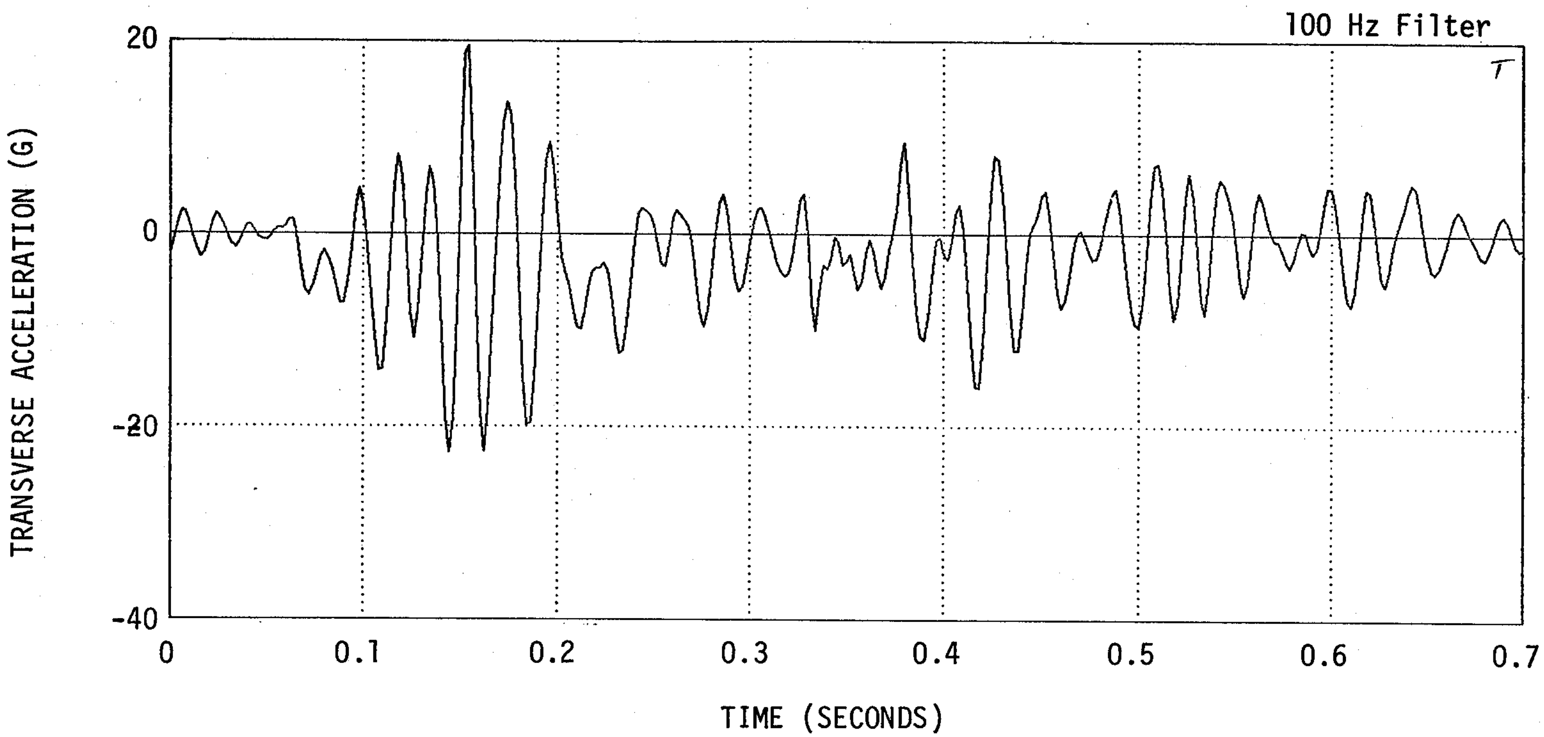

Figure 41. Vehicle Transverse Acceleration for Test 6

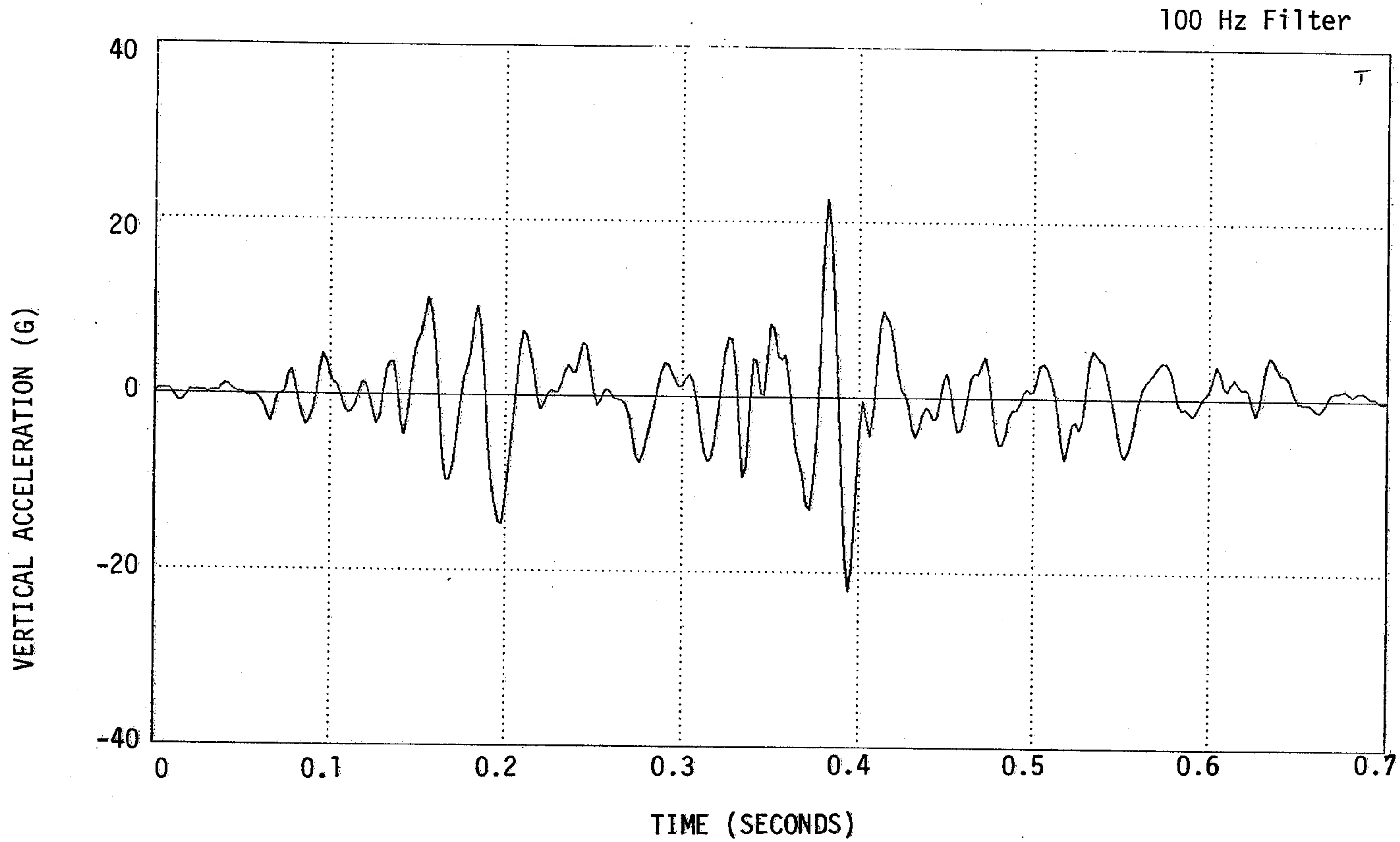

Figure 42. Vehicle Vertical Acceleration for Test 6

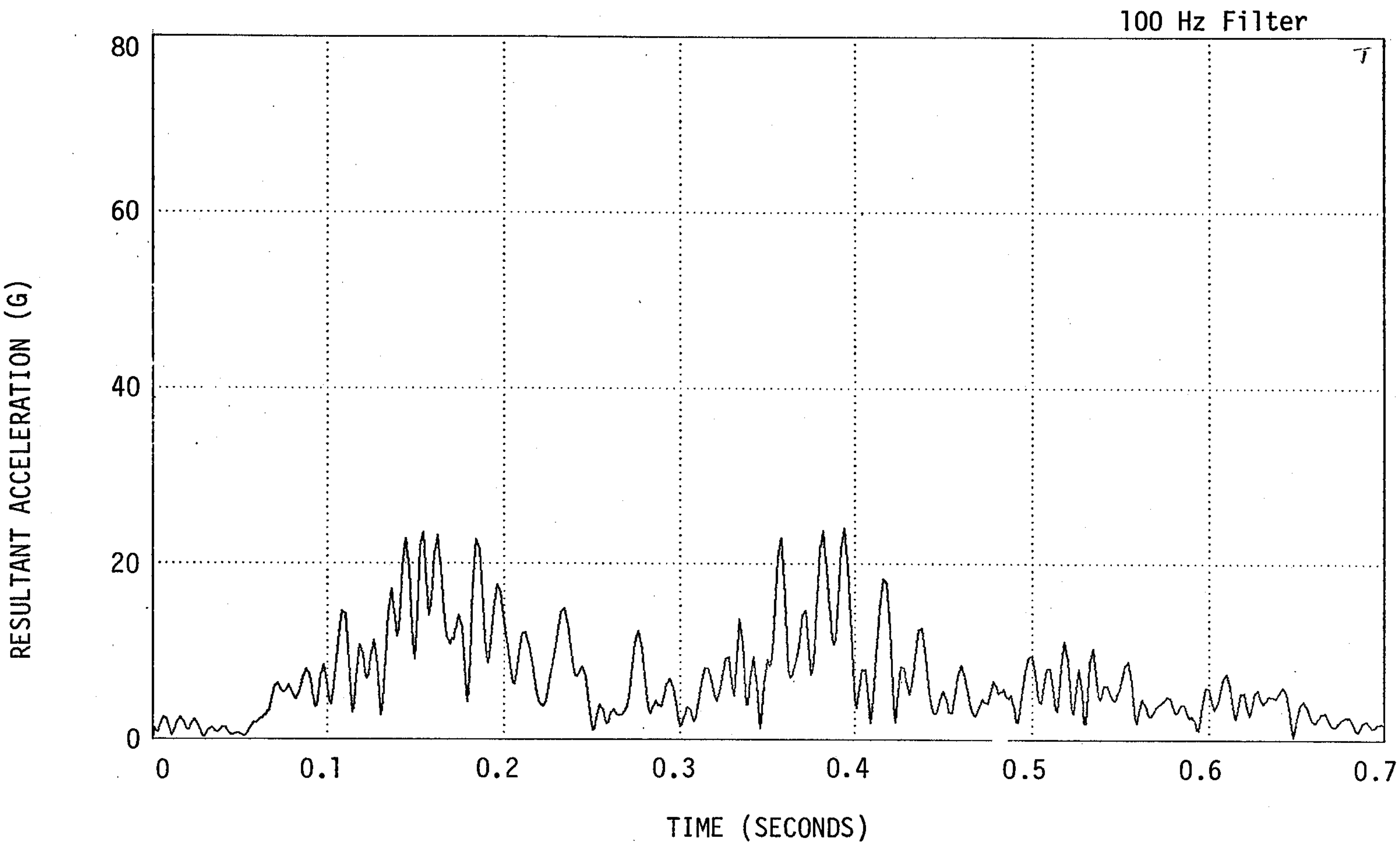

Figure 43. Vehicle Resultant Acceleration for Test 6

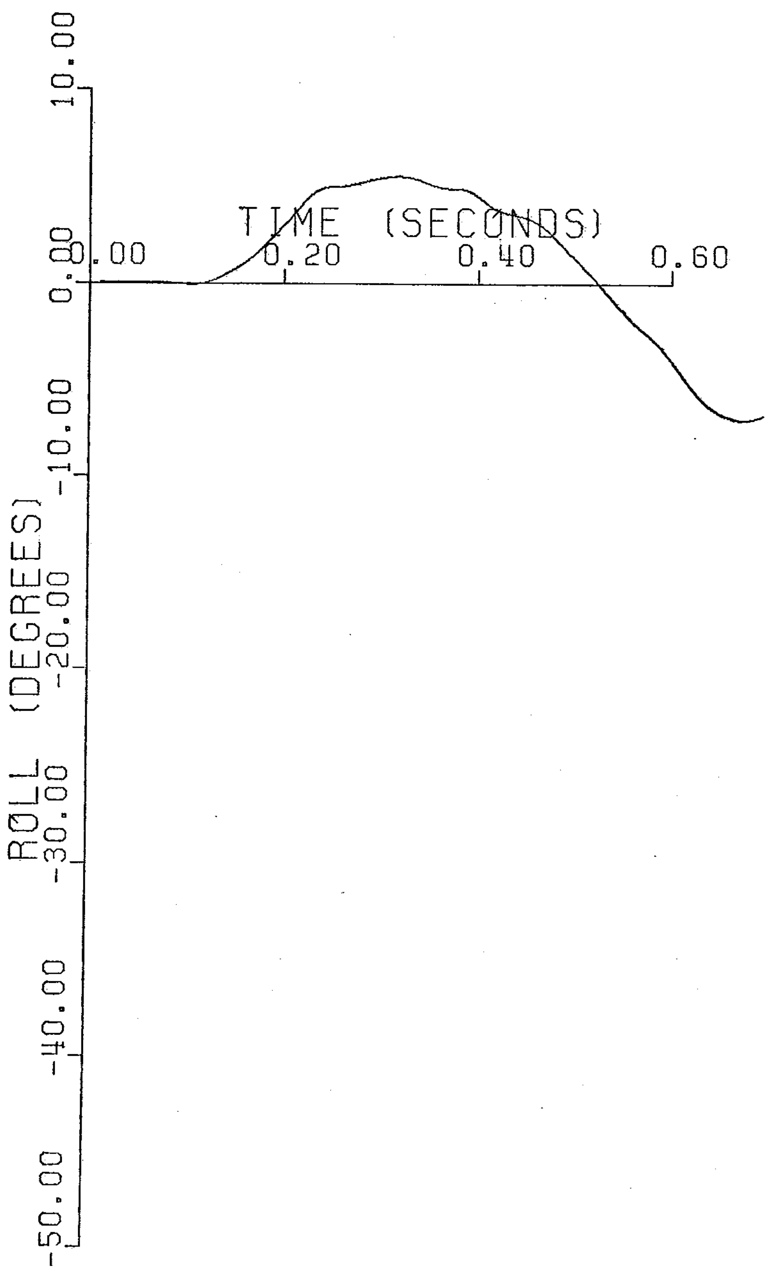

Figure 44. Vehicle Roll for Test 6

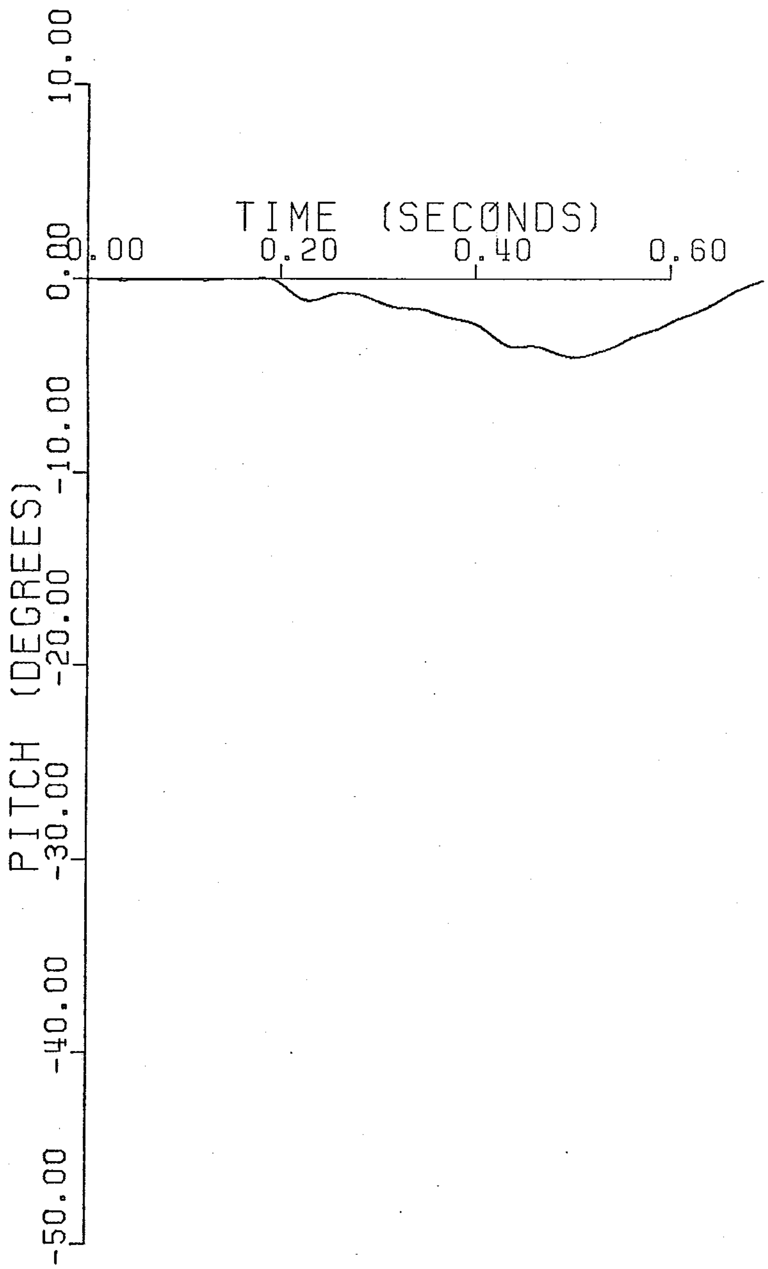

Figure 45. Vehicle Pitch for Test 6

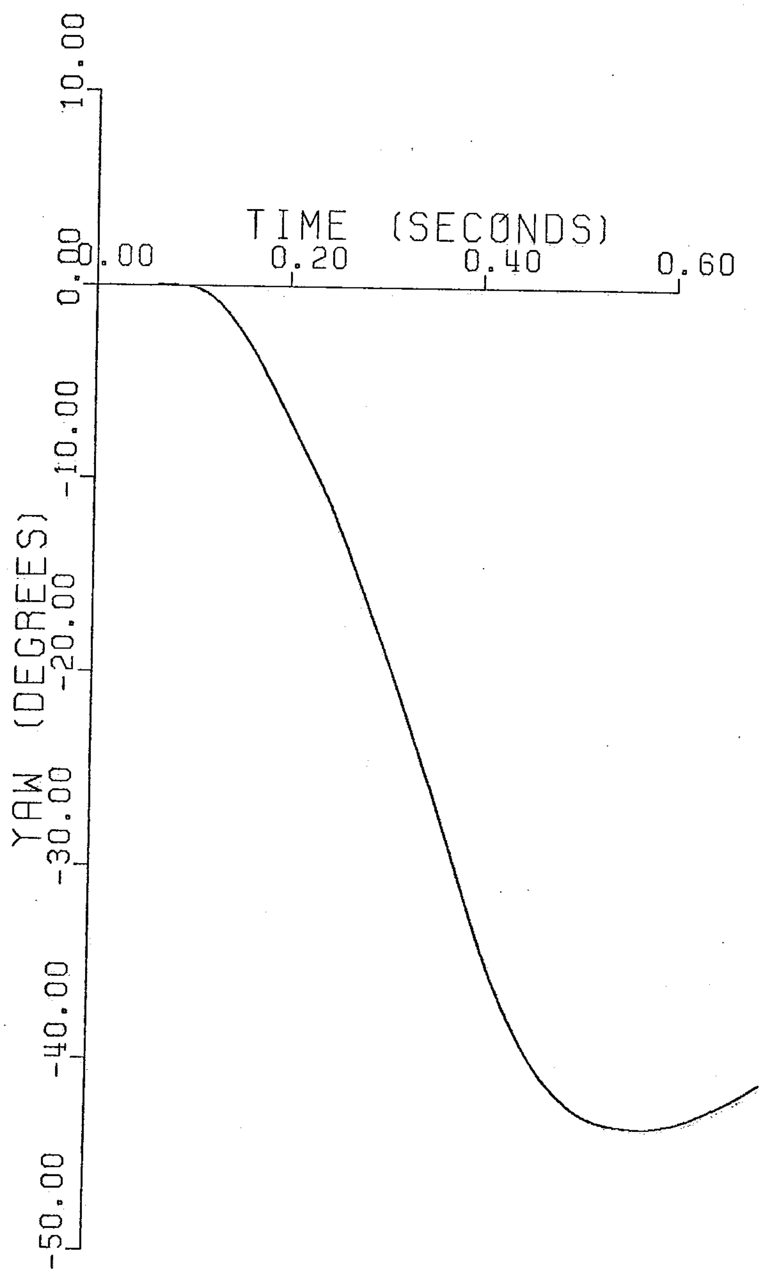

Figure 46. Vehicle Yaw for Test 6

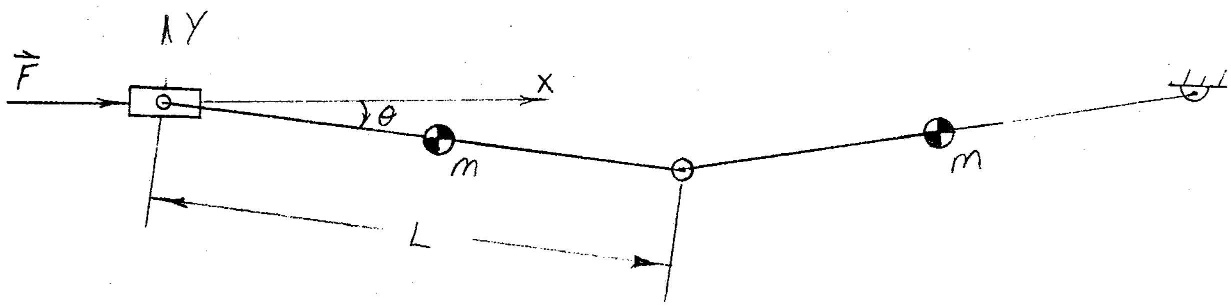

Figure 47. Slider-Crank Mechanism

APPENDIX C

ENERGY AND MOMENTUM ANALYSIS

C-1. VEHICLE-CUSHION INTERACTION FOR HEAD-ON IMPACT

A vehicle impacting head-on with the weakened beam/barrel crash cushion can be analyzed by applying the laws of conservation of energy and momentum. The law of conservation of energy can be applied when an impacting vehicle crushes a barrel or collapses a weakened W-beam. The law of conservation of momentum is applicable to the acceleration of a sand-filled barrel from rest. Complete analysis of head-on impact for both 4500 lb (2043 kg) and 2480 lb (1125 kg) vehicles is summarized in Tables C-1 and C-2. The predicted average accelerations from these tables are 7.5 g's and 5.5 g's for 2480 lb (1125 kg) and 4500 lb (2043 kg) vehicles, respectively. These predicted accelerations are higher than the measured test accelerations. The discrepancy between the measured and predicted accelerations is largely the result of the barrels not remaining in a straight line. An impacting vehicle is not slowed as much when a barrel is knocked out of line as when the barrel is crushed or accelerated to the speed of the vehicle. A more detailed explanation of the formulas used in the momentum analysis of the tests in Appendix C-2 can be found in "A Crash Cushion for Narrow Objects" (5). The weight of sand to be used in each barrel was determined by an iterative procedure using the formulas given in Appendix C-2 and in the previous reference (5).

TABLE C-1
SUMMARY OF ENERGY AND MOMENTUM ANALYSIS OF HEAD-ON IMPACT OF 2480 LB (1125 KG) VEHICLE WITH WEAKENED BEAM/DRUM END TREATMENT.

EVENT(S)	CRUSH DRUM 1	ACCELERATE GUARD RAIL	CRUSH DRUM 2 & DECELERATE GUARD RAIL	ACCELERATE DRUM 2 & DECELERATE GUARD RAIL	CRUSH DRUM 3 & DECELERATE GUARD RAIL	CRUSH DRUM 4 & DECELERATE GUARD RAIL	ACCELERATE DRUM 4 & DECELERATE GUARD RAIL
INITIAL VELOCITY (ft/sec)	71.1	66.0	61.8	61.8	54.4	49.6	49.4
INITIAL WEIGHT (lb)	2480	2515	2515	2515	2900	2935	2935
MOMENTUM (ft-lb/sec)	176,300	166,000	155,400	154,430	157,800	145,600	145,000
INITIAL KINETIC ENERGY (ft-lb)	194,800	170,300	149,300	149,300	133,500	112,200	111,300
CHANGE IN WEIGHT (lb)	35	0	0	385	35	0	735
CHANGE IN KINETIC ENERGY (ft-lb)	-27,000	-20,800	0	3700	-22,500	-1,100	1,200
FINAL WEIGHT (lb)	2450	2515	2515	2900	2935	2935	3670
FINAL VELOCITY (ft/sec)	66.0	61.8	61.8	54.4	49.6	49.4	39.8
LONGITUDINAL DISPLACEMENT (ft)	1.50	0.33	0.333	0.125	1.50	0.33	0.125
AVERAGE ACCELERATION (g's)	7.2	25.0	0.0	107	5.2	0.9	107

TABLE C-1 (CONTINUED)
SUMMARY OF ENERGY AND MOMENTUM ANALYSIS OF HEAD-ON IMPACT OF 2480 LB (1125 KG) VEHICLE WITH WEAKENED BEAM/DRUM END TREATMENT.

EVENT(S)	CRUSH DRUM 5 & DECELERATE GUARD RAIL	CRUSH DRUM 6	ACCELERATE DRUM 6	CRUSH DRUM 7	ACCELERATE DRUM 7	ACCELERATE GUARD RAIL	CRUSH DRUM 8 & DECELERATE GUARD RAIL	CRUSH DRUM 9	ACCELERATE DRUM 9
INITIAL VELOCITY (ft/sec)	39.8	33.5	33.2	27.7	27.4	23.5	22.8	14.6	14.0
INITIAL WEIGHT (lb)	3670	3705	3705	4440	4440	5175	5175	5210	5210
MOMENTUM (ft-lb/sec)	146,100	124,200	123,000	123,000	121,700	121,700	118,000	76,100	72,940
INITIAL KINETIC ENERGY (ft-lb)	90,200	64,600	63,300	53,000	51,700	44,400	41,800	17,300	16,000
CHANGE IN WEIGHT (lb)	35	0	735	0	735	0	35	0	735
CHANGE IN KINETIC ENERGY (ft-lb)	26,200	-1,300	0	-1,300	0	-2,800	24,600	0	-1,300
FINAL WEIGHT (lb)	3705	3705	4440	4440	5175	5175	5120	5120	5945
FINAL VELOCITY (ft/sec)	33.5	33.2	27.7	27.4	23.5	22.8	14.6	14.0	12.3
LONGITUDINAL DISPLACEMENT (ft)	1.5	0.33		0.33			1.75	0.33	
AVERAGE ACCELERATION (g's)	4.8	16.5		11.5			2.7	1.5	

The last two rows have merged cells. 0.33 ft and 16.5 g's cover CRUSH DRUM 6 and ACCELERATE DRUM 6. 0.33 ft and 11.5 g's cover CRUSH DRUM 7, ACCELERATE DRUM 7 and ACCELERATE GUARD RAIL. 0.33 ft and 1.5 g's cover CRUSH DRUM 9 and ACCELERATE DRUM 9.

TABLE C-1 (CONTINUED)
SUMMARY OF ENERGY AND MOMENTUM ANALYSIS OF HEAD-ON IMPACT OF
2480 LB (1125 KG) VEHICLE WITH WEAKENED BEAM/DRUM END TREATMENT.

EVENT(S)	CRUSH DRUM 10	ACCELERATE DRUM 10	CRUSH DRUM 11	ACCELERATE DRUM 11	CRUSH DRUM 12	ACCELERATE DRUM 12	CRUSH DRUM 13
INITIAL VELOCITY (ft/sec)	12.3	11.7	10.4	9.8	8.8	8.2	7.5
INITIAL WEIGHT (lb)	5945	5945	6680	6680	7415	7415	8150
MOMENTUM (ft-lb/sec)	73,100	69,600	69,500	65,500	65,500	60,800	60,800
INITIAL KINETIC ENERGY (ft-lb)	14,000	12,700	11,300	10,000	8,900	7,600	7,100
CHANGE IN WEIGHT (lb)	0	735	0	735	0	735	0
CHANGE IN KINETIC ENERGY (ft-lb)	-1300	0	-1300	0	-1300	0	7,100
FINAL WEIGHT (lb)	5945	6680	6680	7415	7415	8150	8150
FINAL VELOCITY (ft/sec)	11.7	10.4	9.8	8.8	8.2	7.5	0
LONGITUDINAL DISPLACEMENT (ft)	0.46		0.33		0.46		0.78
AVERAGE ACCELERATION (g's)	1.5		1.4		0.7		1.1

TABLE C-2
SUMMARY OF ENERGY AND MOMENTUM ANALYSIS OF HEAD-ON IMPACT OF 4500 LB (2043 KG) VEHICLE WITH WEAKENED BEAM/DRUM END TREATMENT.

EVENT(S)	CRUSH DRUM 1	ACCELERATE GUARD RAIL	CRUSH DRUM 2 & DECELERATE GUARD RAIL	ACCELERATE DRUM 2 & DECELERATE GUARD RAIL	CRUSH DRUM 3 & DECELERATE GUARD RAIL	CRUSH DRUM 4 & DECELERATE GUARD RAIL	ACCELERATE DRUM 4 & DECELERATE GUARD RAIL
INITIAL VELOCITY (ft/sec)	74.9	72.3	69.6	69.6	64.6	62.5	62.4
INITIAL WEIGHT (lb)	4500	4535	4535	4535	4920	4955	4955
MOMENTUM (ft-lb/sec)	337,000	328,000	316,000	316,000	317,000	310,000	309,000
INITIAL KINETIC ENERGY (ft-lb)	393,000	368,000	341,000	341,000	319,000	301,000	300,000
CHANGE IN WEIGHT (lb)	35	0	0	385	35	0	735
CHANGE IN KINETIC ENERGY (ft-lb)	-27,000	-26,800	0	4700	-22,300	-1000	1300
FINAL WEIGHT (lb)	4535	4535	4535	4920	4955	4955	5690
FINAL VELOCITY (ft/sec)	72.3	69.6	69.6	64.6	62.5	62.4	54.4
LONGITUDINAL DISPLACEMENT (ft)	1.50	0.33	0.33	0.25	1.5	0.33	0.125
AVERAGE ACCELERATION (g's)	4.0	17.9	0	41.7	2.8	0.6	116

TABLE C-2 (CONTINUED)
SUMMARY OF ENERGY AND MOMENTUM ANALYSIS OF HEAD-ON IMPACT OF
4500 LB (2043 KG) VEHICLE WITH WEAKENED BEAM/DRUM END TREATMENT.

EVENT(S)	ACCELERATE DRUM 9	CRUSH DRUM 10	ACCELERATE DRUM 10	CRUSH DRUM 11	ACCELERATE DRUM 11	CRUSH DRUM 12	ACCELERATE DRUM 12	CRUSH DRUM 13	ACCELERATE GUARD RAIL
INITIAL VELOCITY (ft/sec)	36.8	33.4	33.2	30.4	30.2	27.8	27.6	25.6	22.0
INITIAL WEIGHT (lb)	7230	7965	7965	8700	8700	9435	9435	10,170	10,205
MOMENTUM (ft-lb/sec)	266,000	266,000	265,000	265,000	263,000	263,000	260,000	260,000	225,000
INITIAL KINETIC ENERGY (ft-lb)	153,000	138,000	137,000	125,000	123,000	113,000	112,000	103,500	76,500
CHANGE IN WEIGHT (lb)	735	0	735	0	735	0	735	35	0
CHANGE IN KINETIC ENERGY (ft-lb)	0	-1300	0	-1300	0	-1300	0	-27,000	-6500
FINAL WEIGHT (lb)	7965	7965	8700	8700	9435	9435	10,170	10,205	10,205
FINAL VELOCITY (ft/sec)	33.4	33.2	30.4	30.2	27.8	27.6	25.6	22.0	21.0
LONGITUDINAL DISPLACEMENT (ft)	0.33	0.58		0.33		0.46		1.50	
AVERAGE ACCELERATION (g's)	11.8	6.9		7.1		4.0		2.2	

TABLE C-2 (CONTINUED)
SUMMARY OF ENERGY AND MOMENTUM ANALYSIS OF HEAD-ON IMPACT OF 4500 LB (2043 KG) VEHICLE WITH WEAKENED BEAM/DRUM END TREATMENT.

EVENT(S)	CRUSH DRUM 14	ACCELERATE DRUM 14	CRUSH DRUM 15	ACCELERATE DRUM 15	CRUSH DRUM 16	CRUSH DRUM 17	ACCELERATE DRUM 17	CRUSH DRUM 18	ACCELERATE DRUM 18
INITIAL VELOCITY (ft/sec)	21.0	20.8	19.4	19.2	18.0	13.2	12.9	12.1	11.8
INITIAL WEIGHT (lb)	10,205	10,205	10,940	10,940	11,675	11,710	11,710	12,445	12,445
MOMENTUM (ft-lb/sec)	214,000	213,000	213,000	210,000	210,000	155,000	15,000	151,000	
INITIAL KINETIC ENERGY (ft-lb)	70,000	68,700	63,900	62,600	58,700	31,700	30,400	28,300	27,000
CHANGE IN WEIGHT (lb)	0	735	0	735	0	0	735	0	735
CHANGE IN KINETIC ENERGY (ft-lb)	-1,300	0	-1,300	0	-2,700	-1,300	0	-1,300	0
FINAL WEIGHT (lb)	10,205	10,940	10,940	11,675	11,710	11,710	12,445	12,445	13,180
FINAL VELOCITY (ft/sec)	20.8	19.4	19.2	18.0	13.2	12.9	12.1	11.8	11.1
LONGITUDINAL DISPLACEMENT (ft)	0.33		0.33		1.50	0.33		1.08	
AVERAGE ACCELERATION (g's)	3.0		2.4		1.6	1.3		0.3	

TABLE C-2 (CONTINUED)
SUMMARY OF ENERGY AND MOMENTUM ANALYSIS OF HEAD-ON IMPACT OF 4500 LB (2043 KG) VEHICLE WITH WEAKENED BEAM/DRUM END TREATMENT.

EVENT(S)	CRUSH DRUM 5 & DECELERATE GUARD RAIL	CRUSH DRUM 6	ACCELERATE DRUM 6	CRUSH DRUM 7	ACCELERATE DRUM 7	ACCELERATE GUARD RAIL	CRUSH DRUM 8 & DECELERATE GUARD RAIL	CRUSH DRUM 9 & DECELERATE GUARD RAIL
INITIAL VELOCITY (ft/sec)	54.4	51.6	51.4	45.5	45.3	40.4	39.7	37.0
INITIAL WEIGHT (lb)	5690	5725	5725	6460	6460	7195	7195	7230
MOMENTUM (ft-lb/sec)	309,000	295,000	294,000	294,000	293,000	293,000	286,000	268,000
INITIAL KINETIC ENERGY (ft-lb)	262,000	237,000	263,000	208,000	207,000	185,000	176,000	154,000
CHANGE IN WEIGHT (lb)	35	0	735	0	735	0	35	0
CHANGE IN KINETIC ENERGY (ft-lb)	-26,400	-1300	0	-1300	0	-8700	-23,000	-1100
FINAL WEIGHT (lb)	5725	5725	6460	6460	7195	7195	7230	7230
FINAL VELOCITY (ft/sec)	51.6	51.4	45.5	45.3	40.7	39.7	37.0	36.8
LONGITUDINAL DISPLACEMENT (ft)	1.5	0.46		0.58			1.5	
AVERAGE ACCELERATION (g's)	3.1	20.0		13.2			2.1	

C-2. SAMPLE CALCULATIONS

For impact with an empty barrel, the kinetic energy of the vehicle is reduced by the energy required to crush a barrel. The energy required to dynamically crush an 18 gage steel drum was found by Ivey (2) to be 27 kip-ft (36.6 Kj). Therefore by applying the law of conservation of energy the change in velocity of the vehicle can be estimated.

$$KE_i - \Delta KE = KE_F$$

$$\frac{1}{2} m V_i^2 - \Delta KE = \frac{1}{2} m V_F^2$$

$$V_F = \sqrt{\frac{m V_i^2 - 2\Delta KE}{m}}$$

where

V_i = velocity of vehicle prior to crushing the barrel

V_F = velocity of vehicle after crushing the barrel

m = mass of vehicle

ΔKE = energy required to crush a barrier

When a vehicle impacts a sand-filled barrel, the barrel is first crushed approximately 4 in. (10.2 cm) and is then accelerated to the velocity of the vehicle. By linearizing the force vs. deflection curve used to determine the energy required to crush a barrel, the energy required to partially crush a barrel can be estimated. Thus the law of conservation of kinetic energy can be applied as shown previously. The law of conservation of momentum can then be applied as follows:

$$m_v V_1 = (m_B + m_v) V_2$$

$$V_2 = V_1 \left(\frac{m_v}{m_B + m_v}\right)$$

where

V_i = velocity of vehicle after partially crushing barrel

m_V = mass of vehicle and barrels impacted previously

m_B = mass of barrel impacted

V_2 = velocity of vehicle after impact with barrel

The velocity change due to impact with a weakened beam guardrail section can be estimated by modeling the guardrail as a slider crank mechanism. The kinetic energy of a slider crank mechanism, as shown in Figure 47, can be determined in terms of the position and velocity of the slider. The kinetic energy of the mechanism is

$$KE = \frac{1}{2} m V_{CG_{AB}} + \frac{1}{2} I_{CG_{AB}} \dot{\theta}^2 + \frac{1}{2} I_{C_{BC}} \dot{\theta}^2$$

where

KE = kinetic energy of slider crank mechanism

$V_{CG_{AB}}$ = velocity of the center of gravity of link AB

$I_{CG_{AB}}$ = mass moment of inertia of link AB about its center of gravity

$\dot{\theta}$ = angular velocity of mechanism

m = mass of each link, 47.6 lb (21.6 kg)

L = length of each link, 6.25 ft (1.91 m)

The variables on the right side of the equation above can be expressed in terms of the displacement and velocity of point A as shown below.

$$V_{CG_{AB}} = \dot{X}\,\tau + \dot{\theta} K X \frac{L}{2}\,(\cos\theta\tau - \sin\theta\tau)$$

where

X = displacement of point A

$\dot{X}$ = velocity of point A

θ = angular displacement of guardrail members

$$\cos\theta = \frac{L - X + \frac{X}{2}}{L} = 1 - \frac{X}{2L}$$

$$\sin\theta = \frac{X}{L} - \frac{X^2}{4L^2}$$

$$\theta = \cos^{-1}\left(1 - \frac{X}{2L}\right)$$

$$\theta = \frac{\dot{X}}{4LX - X^2}$$

$$V_{CG_{AB}} = \dot{X}_\tau + \frac{\dot{X}}{4LX - X^2} K X \left(\frac{L}{2}\left(1 - \frac{X}{2L}\right)_\tau - \frac{L}{2}\;\frac{X}{L} - \frac{X^2}{4L^2}\right)$$

$$V_{CG_{AB}} = \dot{X}_\tau - \frac{L}{2}\;\frac{X}{L} - \frac{X^2}{4L^2}\left(\frac{\dot{X}}{4LX - X^2}\right)_\tau - \frac{L}{2}\left(1 - \frac{X}{2L}\right)\left(\frac{\dot{X}}{4LX - X^2}\right)$$

$$V_{CG_{AB}} = \frac{3}{4}\dot{X}_\tau - \left(\frac{(2L - X)\dot{X}}{8L\;\frac{X}{L} - \frac{X^2}{4L^2}}\right)$$

$$V^2_{CG_{AB}} = \dot{X}^2 \left(\frac{1}{2} - \frac{L^2}{4X^2 - 16xL}\right)$$

$$I_{CG_{AB}} = \frac{1}{12} m L^2$$

$$I_{C_{BC}} = \frac{1}{3} m L^2$$

The kinetic energy of the guardrail system can now be written as shown below.

$$KE = m \dot{X}^2 \frac{3x^2 - 12xL - 4L^2}{12x(X - 4L)}$$

Thus the change in kinetic energy of the guardrail system can be calculated if the initial and final values of the displacement, X, and the velocity, $\dot{X}$, of point A are known. The law of conservation of energy can be applied as shown previously to estimate the velocity change of the vehicle.

APPENDIX D

END TREATMENT COSTS

END TREATMENT COSTS

Material costs and labor requirements for end treatment fabrication and installation are shown in Table D-1. Material costs were obtained through telephone bids and invoices for materials purchased during end treatment construction. Labor requirements for fabrication were estimated from published productivity standards for industrial operations (6). Labor requirements for end treatment installation were estimated from observations of installation of the tested appurtenance.

As shown in Table D-1, total material costs for the end treatment are approximately $1188.00. Also shown in this table is that total labor requirements for fabrication and installation of this safety treatment are less than 80 man-hours. If labor cost is $15.00 per man-hour, total costs for the crash cushion would be approximately $2685.00. Thus, the initial cost of the end treatment is low compared to other available end treatments.

Estimates of repair costs for the tests conducted are shown in Table D-2. The average cost of repairing the barrier after the four tests was approximately $1075.00. In view of the severity of the test conditions, this repair cost is not considered high.

TABLE D-1. END TREATMENT INSTALLATION COSTS

MATERIALS	TTI COST ($)
Steel Drums	54.00
W-Beam Guardrail	495.00
C4 x 5.4 Steel Channels	146.00
Sand	60.00
Miscellaneous	433.00
TOTAL	$1188.00

LABOR REQUIREMENTS	MAN-HOURS
Shop Fabrication	45.0
Site Installation	34.0
TOTAL	79.0

TOTAL COST @ $15.00/MAN-HR $2685.00

TABLE D-2. END TREATMENT REPAIR COSTS

REPLACEMENT OF DAMAGED DRUMS	
Expendable Material Replacement	$7.10/drum
Shop Fabrication Labor (includes material salvage)	1.3 man-hr/drum
REPAIR OF END TREATMENT	
Test 3	
Material Replacement	$398.00
Labor	30.8 man-hr
TOTAL COST @ $15.00/MAN-HR	$860.00
Test 4	
Material Replacement	0.00
Labor	8.0 man-hr
TOTAL COST @ $15.00/MAN-HR	$120.00
Test 5	
Material Replacement	$1500.00
Labor	70.0 man-hr
TOTAL COST @ $15.00/MAN-HR	$2550.00
Test 6	
Material Replacement	$300.00
Labor	22.0 man-hr
TOTAL COST @ $15.00/MAN-HR	$630.00

REFERENCES

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6. "Means Building Construction Cost Data," Robert Snow Means Co., Inc., Construction Consultants and Publishers, 100 Construction Plaza, Kingston, MA, 02364.