Technical Report Documentation Page

1. REPORT No.
636405-2

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE
Dynamic Tests Of An Energy Absorbing Barrier Employing Steel Drums

5. REPORT DATE
October 1970

6. PERFORMING ORGANIZATION

7. AUTHOR(S)
Nordlin, E.F.; Woodstrom, J.H., and Doty, R.N.

8. PERFORMING ORGANIZATION REPORT No.
636405-2

9. PERFORMING ORGANIZATION NAME AND ADDRESS
State of California
Department of Public Works
Division of Highways
Materials and Research Department

10. WORK UNIT No.

11. CONTRACT OR GRANT No.

12. SPONSORING AGENCY NAME AND ADDRESS

13. TYPE OF REPORT & PERIOD COVERED

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration

16. ABSTRACT

The results of three full scale vehicle impact tests of an energy absorbing barrier employing 55 gallon tight-head steel drums are reported. The 19.6' long test barriers were designed as gore installations. They were placed in front of a modified California Type 8 Bridge Approach Guardrail for the tests, which were conducted with 1968 sedans weighing approximately 4700 lbs. and traveling at speeds of from 54 to 64 mph. The tests were run head-on and at 9* with the barrier axis into the barrier nose and at 11* with the barrier axis midway along the side of the barrier.

The head-on and angle impacts into the nose of the barrier resulted in vehicle passenger compartment decelerations less than the 12 G limit suggested by the Federal Highway Administration. Vehicle damage was moderate. The vehicle remained stable and upright during impact. During these high speed impacts, almost all the drums in the barriers were crushed to some extent. Extensive repairs were required to restore the barrier to a functional unit after each test.

The impact into the side of the barrier did not produce completely satisfactory results. The vehicle was redirected, but partially by the bridge approach guardrail behind the barrier.

17. KEYWORDS
Barriers, dynamic tests, impact tests, attenuation, bumpers, cushioning, energy absorbers, kinematics, vehicle dynamics

18. No. OF PAGES:
68

19. DRI WEBSITE LINK
http://www.dot.ca.gov/hq/research/researchreports/1969-1970/70-18.pdf

20. FILE NAME
70-18.pdf

HIGHWAY RESEARCH REPORT

DYNAMIC TESTS OF AN

SERIES XXII

STATE OF CALIFORNIA

BUSINESS AND TRANSPORTATION AGENCY

DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

NO. M & R 636405—2

Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration October, 1970

STATE OF CALIFORNIA—TRANSPORTATION AGENCY
RONALD REAGAN, Governor

DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS
MATERIALS AND RESEARCH DEPARTMENT
5900 FOLSOM BLVD., SACRAMENTO 95819

October 1970
M & R No. 636405-2
Final Report

Mr. J. A. Legarra
State Highway Engineer

Dear Sir:

Submitted herewith is a research report entitled:

DYNAMIC TESTS OF AN

ENERGY ABSORBING BARRIER EMPLOYING

STEEL DRUMS

SERIES XXII

ERIC F. NORDLIN
Principal Investigator

James H. Woodstrom and Robert N. Doty
Co-Investigators

Assisted by
J. Jay Folsom
Roger L. Stoughton

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

ABSTRACT

REFERENCE: Nordlin, E. F., Woodstrom, J. H., and Doty, R. N., "Dynamic Tests of an Energy Absorbing Barrier Employing Steel Drums", State of California, Department of Public Works, Division of Highways, Materials and Research Department. Research Report 636405-2, October, 1970.

ABSTRACT: The results of three full scale vehicle impact tests of an energy absorbing barrier employing 55 gallon tight-head steel drums are reported. The 19.6' long test barriers were designed as gore installations. They were placed in front of a modified California Type 8 Bridge Approach Guardrail for the tests, which were conducted with 1968 sedans weighing approximately 4700 lbs. and traveling at speeds of from 54 to 64 mph. The tests were run head-on and at 9° with the barrier axis into the barrier nose and at 11° with the barrier axis midway along the side of the barrier.

The headon and angle impacts into the nose of the barrier resulted in vehicle passenger compartment decelerations less than the 12 G limit suggested by the Federal Highway Administration. Vehicle damage was moderate. The vehicle remained stable and upright during impact. During these high speed impacts, almost all the drums in the barriers were crushed to some extent. Extensive repairs were required to restore the barrier to a functional unit after each test.

The impact into the side of the barrier did not produce completely satisfactory results. The vehicle was redirected, but partially by the bridge approach guardrail behind the barrier.

The results of the three tests indicate that the barrier's effectiveness in reducing the severity of most impacts is such that it should be used operationally on an experimental basis. However, future refinements in the design need to be made, particularly with regard to redirection of vehicles that collide with the side of the barrier.

This report includes descriptions of the electronic and photographic data acquisition systems employed and the procedures used to analyze the data obtained with these systems.

A study of accident statistics and human tolerance to deceleration is also summarized. This study indicated that the deceleration imparted to the impacting vehicle should be as low as possible - perhaps lower than in some current criteria.

KEY WORDS: Barriers, dynamic tests, impact tests, attenuation, bumpers, cushioning, energy absorbers, kinematics, vehicle dynamics

ACKNOWLEDGEMENTS

This work was accomplished in cooperation with the United States Department of Transportation, Federal Highway Administration, as Item D-4-69 of Work Program HPR-PR-1(8), Part 2, Research. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Federal Highway Administration.

The following staff members of the Materials and Research Department performed an extensive amount of the detailed work required to complete this testing program: William Chow, Richard Johnson, Delmar Gans, Merle Wilson, and William Schemel installed and calibrated the instrumentation on the vehicles, anthropometric dummies, and barriers and assisted in the processing and interpretation of the electronic data. Robert Mortensen and Lewis Green provided the data and documentary photographic coverage of the tests. Wallace Ames, Roger Pelkey, Joseph Halterman, Robert Field, Joseph Eagan, Lee Staus, and Al Rybicki assisted in the design and construction of the barriers, instrumented the test car, conducted the tests, and assisted with the data analysis and assembly of the written and film reports.

TABLE OF CONTENTS

I. INTRODUCTION

This research project was initiated because of a concern about the increasing incidence and the relative severity of accidents involving errant vehicles impacting fixed objects located adjacent to California's freeways. On the California freeway system in 1967 and 1968, about one-half of all the fatalities, an average of 430 a year, were caused by ran-off-the-road type accidents. Of this number, 225 fatalities (over 25% of all freeway fatalities) were the result of hitting a fixed object. The types struck most frequently were abutments and piers, bridge rails, guardrail at fixed objects, steel sign poles, light poles, and cable type median barriers.

In an attempt to decrease the frequency of these relatively severe ran-off-the-road accidents, the California Division of Highways is now striving to provide a minimum of 30 feet of recovery area alongside the traveled way into which an out-of-control vehicle can intrude without striking an immovable or unprotected fixed object. This area will provide the "forgiving quality" that allows the driver of the distressed vehicle a reasonable chance for recovery.

Within this program, every effort is first made to eliminate the fixed object. If it cannot be eliminated, an attempt is then made to incorporate breakaway features. In this regard, all lighting standards and roadside sign supports on new California freeways are now "breakaway". In cases where the fixed object can neither be eliminated nor made to yield, protection in the form of guardrail is now being provided.

Recent improvements in bridge approach guardrailing, confirmed by full scale tests[1,2], should minimize the probability of impact into the ends of bridge barrier rails. However, one of the remaining problems for which no satisfactory solution has been developed is protection from hazardous fixed objects located in the gore area at freeway off ramps. Collisions with the concrete wedge-shaped deflectors and/or large overhead sign supports often found in these gores are usually very severe. Consequently, the California Division of Highways has been involved in a research program to investigate and/or develop energy absorption barriers for use in gore areas for the last two years in an effort to alleviate this problem.

An energy absorbing barrier is a cushioning device that can be placed in front of or around a fixed object. The barrier will absorb a large portion of the energy involved in a high speed head-on or oblique angle impact, thereby reducing the deceleration force on the vehicle, and will usually decrease the severity of the injuries sustained by the vehicular occupants. Some of the variables that must be considered when designing these barriers include vehicle size, shape, speed, crushability, passenger compartment layout and construction; impact angle; occupant age, size, sex, physical condition, and use and type of restraint systems; and the physical limitations of space and, in some cases, anchorages on the freeway itself.

The California Division of Highways Materials and Research Department has tested three types of energy absorption barriers to date. These barriers employed (1) water-filled plastic cells, (2) 55-gallon tight-head steel drums, and (3) plastic drums containing sand. The results of eight tests of barriers employing water-filled plastic cells will be documented in a report entitled "Dynamic Tests of an Energy Absorbing Barrier Employing Water-Filled Cells" to be available about November, 1970. The testing of a barrier employing sand-filled plastic containers is still in progress. The three tests reported herein were of barriers containing 55 gallon tight-head steel drums as the primary energy absorbing mode.

The results of research at the Texas Transportation Institute (TTI) of Texas A & M University indicated that the resistance to deformation of modified 55 gallon tight-head steel drums could be effectively utilized to decelerate a standard size vehicle traveling 60 mph[3]. A series of tests at TTI consisted of three 50-60 mph headon tests and three 40-50 mph tests at angles of 20° (one test) and 30° (two tests) with the barrier axis. The weights of the test vehicles varied from 3200 to 4400 pounds. Although the results of these six TTI tests were generally favorable, additional testing using heavier vehicles (4700 lbs.+) impacting headon and at 10°-15° angles into the front and side of the barrier were felt to be more representative of the conditions encountered on California highways. The utilization of a fendering system similar to that employed for the water-filled cell barrier[4] was also considered advisable. Consequently, the series of three tests reported herein was conducted.

II. OBJECTIVE

The objective of this research was to conduct instrumented vehicular impact tests of energy absorbing barriers incorporating 55 gallon tight-head steel drums and, based upon the results of these tests, determine the degree to which these barriers would minimize the hazards created by many existing gore separation structures and other fixed objects. The criteria itemized below were used to evaluate the barrier design:

1. The impact severity for the occupants of errant vehicles involved in head-on collisions into fixed objects located in gores must be reduced to a survivable level at impact velocities of 60 mph and less.

2. The energy absorbing barrier should be at least as effective as California's current anchored "W" beam guardrail in redirecting vehicles impacting at oblique angles into the side of the barrier.

3. The barrier components should not be susceptible to dislodgement or ejection onto the traveled way such that they become a hazard to adjacent traffic when an impact occurs.

4. First cost and maintenance costs should be economically feasible.

5. On-site repair time should be minimal because of the safety hazards to maintenance personnel and adjacent traffic when field repairs are in progress.

III. CONCLUSIONS

The results of the three full scale tests reported herein indicate that the hazards presented by many existing gore separation structures and other fixed objects can be significantly reduced by providing protection with energy absorbing barriers incorporating 55 gallon tight-head steel drums.

The electronically measured decelerations, confirmed by analysis of the photographic data, indicated that occupants of full size vehicles (4700 lbs. including occupants) impacting these barriers at 60 mph will, in most cases, sustain little or no injury if wearing a lap belt and shoulder harness, minor injuries if wearing only a lap belt, and moderate injuries if unrestrained.

The fendering system tested did not satisfactorily redirect a vehicle impacting midway along the side of the barrier at an 11° angle with the barrier axis. Also, the debris that resulted from this collision would definitely have been hazardous to adjacent traffic. Consequently, the fendering system included on the test barriers should not be used for an operational installation. Further developmental work on a fendering system is required. However, the test barrier's effectiveness if struck within 10° of headon is such that its inability to redirect vehicles colliding with its side should not preclude its use in trial installations.

The reported average first cost of each of three freeway installations of energy absorbing barriers incorporating 55 gallon drums near Houston, Texas, was $3,600. As would be the case with most barriers, some on-site preparation was included in this cost. These barriers contained no fendering systems. The drums themselves, as used for the tests reported herein, cost $9 each delivered to our test site. Thus, the total cost of the drums per test barrier was $369.

The maintenance costs for this barrier would probably be relatively high. Although no routine maintenance should be required, with the possible exception of checking the cable tension, relatively mild impacts will probably necessitate considerable repair work to restore the barrier's effectiveness. However, much of this work could be accomplished prior to proceeding to the barrier site by prefabricating barrier modules. On-site repair time could be relatively short if prefabricated modules were used.

IV. DESCRIPTION OF TEST BARRIER

Reference 5 contains a discussion of the structural strength of the front of a vehicle in terms of crash survivability. The author concluded that this crush strength can be designed so that a passenger, restrained properly with lap and shoulder belts, can survive collisions at high impact velocities. However, unrestrained or lap-belt restrained passengers will be subjected to secondary collisions in the passenger compartment the severity of which is dependent on their velocity, relative to the vehicle's velocity, at impact. This relative velocity can vary widely depending on the passenger's size and position and the vehicle's fore-structure crushability. Therefore, the author concluded that a refined automobile design would not in itself be a satisfactory aid to passengers using lap belts or no restraint. In other words, a barrier, which can provide a long stopping distance relative to the crush distance provided by the vehicle, is the only effective means of decelerating a vehicle slowly enough to protect passengers that are not fully restrained.

As stated earlier, the records of the California Highway Patrol for the years 1967 and 1968 show that about 25% of all California's freeway fatalities occurred when vehicles ran off the road and collided with fixed objects. Another tabulation of California freeway fixed-object fatal accidents for the years 1965 through 1967 contains a total of 640 for this three year period. Of this number, 548 involved a vehicle traveling at an estimated speed of over 50 mph at impact with 171 of these 548 traveling over 70 mph. A further breakdown of this total of 640 accidents indicates that 376 standard sized cars, 159 compact cars, and 105 other miscellaneous vehicles were involved. These results indicate that energy absorbing barriers must be designed to cushion impacts of standard size cars traveling at high speeds.

In an effort to determine the most prevelent impact angle, forty-seven California Highway Patrol accident reports involving fatalities at gore installations during 1965-1967 were examined and classified (See Table 1, next page). This data was based on the sketches of the accident site included in the CHP officer's reports. In many cases, no barriers were present so the impact angle was estimated assuming an energy absorbing barrier was in place. Also, funds were not available to locate and examine all the police reports involving gores. Thus, the sample was small and the accuracy of the data definitely subject to question. In any event, the study indicated that a number of collisions were side angle impacts (most less than 10°); hence, energy absorbing barriers should be capable of redirecting vehicles impacting at oblique angles in addition to effectively decelerating vehicles impacting headon.

Table No. 1

Analysis of 47 Freeway Fatal

Accidents Involving Gores

Category	1965	1966	1967	Total
Angle of Impact[1,2]				
Headon[3]	6	5	8	19
Flat Angle (≤ 10°)	4	8	6	18
Large Angle (> 10°)	3	4	1	8
Location[1]				
Nose	11	12	12	35
Side	2	6	4	12
Barrier or Object				
Concrete	2	11	5	18
Guardrail	8	6	8	22
Pole[4]	2	1	2	5
Concrete Curb	1	0	1	2

[1]When a pole was impacted, an imaginary barrier was assumed in front of it and the vehicle path was studied to determine the location and angle of a hypothetical barrier impact.

[2]No estimate was made on two accidents.

[3]Includes broadside impacts.

[4]Includes both sign posts and lighting standards.

Note: The 1966 and 1967 accidents all involved one fatality per accident.

Thus, the test barrier was designed to decelerate a 4700 pound vehicle impacting headon or at an angle of 10° with the barrier axis at an impact velocity of 60 mph without subjecting the vehicular passenger compartment to an average deceleration greater than 10 G's. (This choice of a relatively shallow 10° angle has since been justified, at least to some extent, by reports from several other states indicating that in-service energy absorbing barriers are being impacted headon in almost all cases.) The construction details for the barrier are shown on Exhibit 1.

The primary energy absorbing media used for the test barrier were 55 gallon tight-head steel drums. Forty-one of these drums, which were approximately 24" in diameter and weighed 38 pounds each, were used for each barrier. The drums contained 18 gage tops and bottoms and 20 gage sides. The tops and bottoms each contained one 7" diameter hole to decrease the magnitude of the force required to crush the drum (see Figure 1 below). The barrier design procedure used was developed and reported by the Texas Transportation Institute[3]. The design calculations are included as Appendix A of this report.

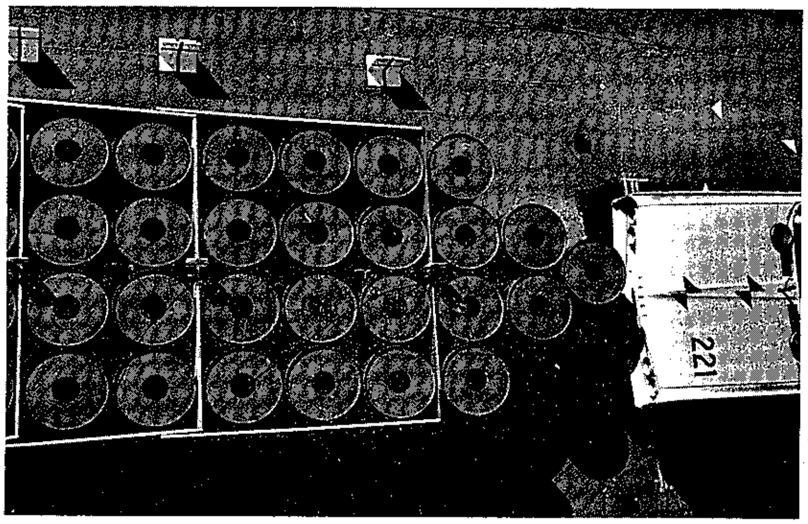


FIGURE 1

In an effort to provide an effective redirective capability, a system consisting of three one-inch thick plywood diaphragms and eight one-inch thick plywood fender panels was utilized for the first test barrier. The diaphragms were intended to provide support for the fender panels and to transmit the lateral component of the impact force to the cable system when oblique angle impacts occurred. Although not of primary importance, it was felt that the lateral distribution of the impact forces provided by the diaphragms during an offset headon impact would also be of some benefit.

The fender panels, attached to the diaphragms using steel hinges, were intended to act as beams when resisting the lateral component of the impact forces. The trailing edge of each fender panel overlapped the leading edge of the next rearward panel in a "fish scale" manner such that barrier crush would not be restricted during a headon impact. Light springs were used to maintain the fender panels in the "closed" position prior to activation of the barrier by an impacting vehicle.

The test barrier was placed in front of a California Type 8 Bridge Approach Guardrail (BAGR) to simulate a gore installation (Exhibit 2). Two concrete anchor blocks were cast in place in front of the barrier. Four 3/4 inch wire ropes were attached to fabricated steel "T" sections embedded in these concrete anchors (see Figure 2 below). The wire rope was threaded between the drums so that the drums would be free to slide backward during impact and then attached to the BAGR using swaged fittings. A slight pre-impact tensile force was placed on the cables. The cables were aligned in a straight line to minimize the cable slack, and subsequent lateral movement, that develops during an oblique angle impact. Figure 3 below shows the cables sloping up from the front anchor block. The anchor block and sloping cables were located such that the front drums would receive as much lateral support as possible while still keeping the cables low enough to minimize the possibility of snagging the impacting vehicle.

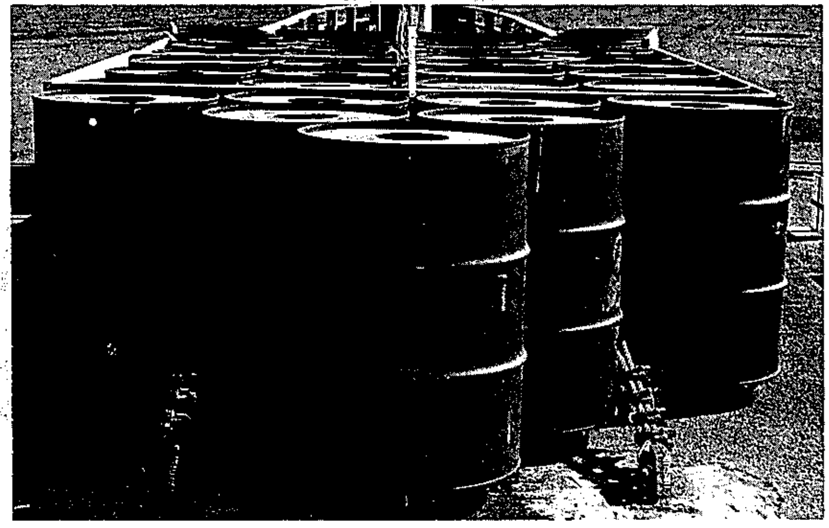


FIGURE 2

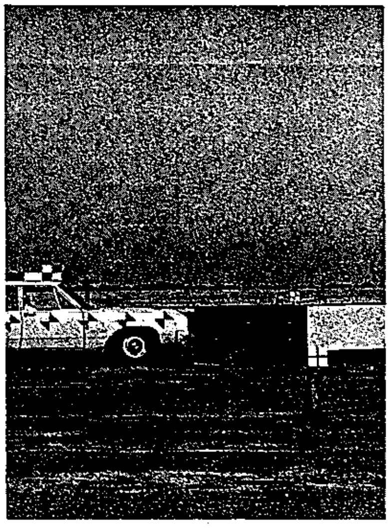


FIGURE 3

The barrier was elevated four inches above the ground with one "U" bolt chair bolted to the bottom of each drum. The drums were attached together at all points of contact with 5/8 inch bolts and washers. For Test 221, bolts were placed 2" below the drum tops and 2" above the drum bottoms; wood spacer blocks were used between drums (see Figure 4 below). For Tests 222 and 223, the bolts were located at the two rolling hoops and a steel washer was placed between the drums so that the cable could be threaded between the drums more easily. Since the drums were bolted together, in a relatively rigid assembly, some of the "U" bolt chairs were not in contact with the slightly irregular ground surface at all times.

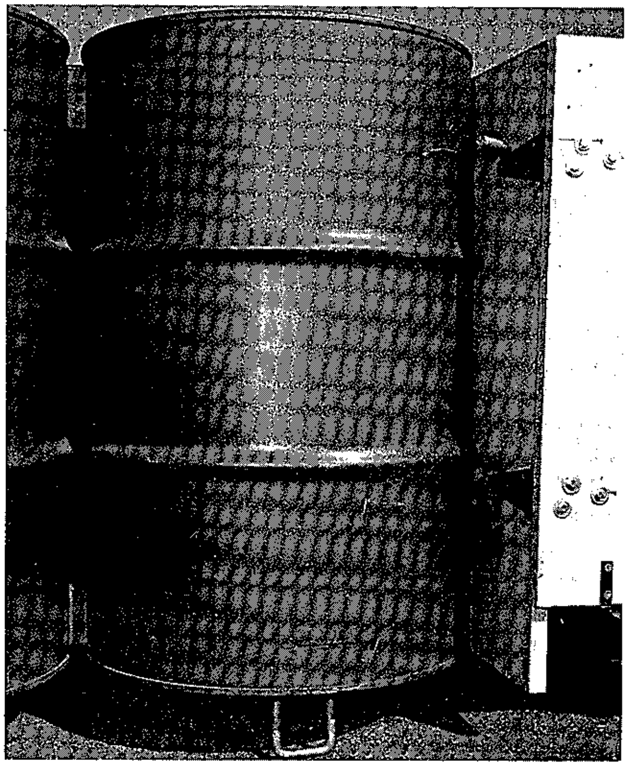


FIGURE 4

Bolts were used in lieu of the welded connections used in the TTI test barriers because, although slightly more expensive initially, it was felt that the bolted connections would simplify and accelerate barrier repairs.

V. DESCRIPTION OF TESTING

Introduction

All of the tests reported herein were conducted on an unused portion of a runway at the Lincoln Municipal Airport, Lincoln, California. The test vehicles used for this series were 1968 Dodge sedans. Two anthropometric dummies were placed in the front seat of the vehicles and restrained with lap belts. The driver, Stan, weighs 165 lbs. and is a 50th percentile male. The passenger, Sam, weighs 210 lbs. and is a 95th percentile male. Targets were placed on the sides and top of the car for use in the analysis of the high speed data film obtained during each test. The vehicle was remotely operated from a control car which followed it in along the approach line until just before impact. A trip switch cut off the ignition in the test vehicle 10 feet prior to impact. A more complete description of the control system is given in Reference 6.

Instrumentation

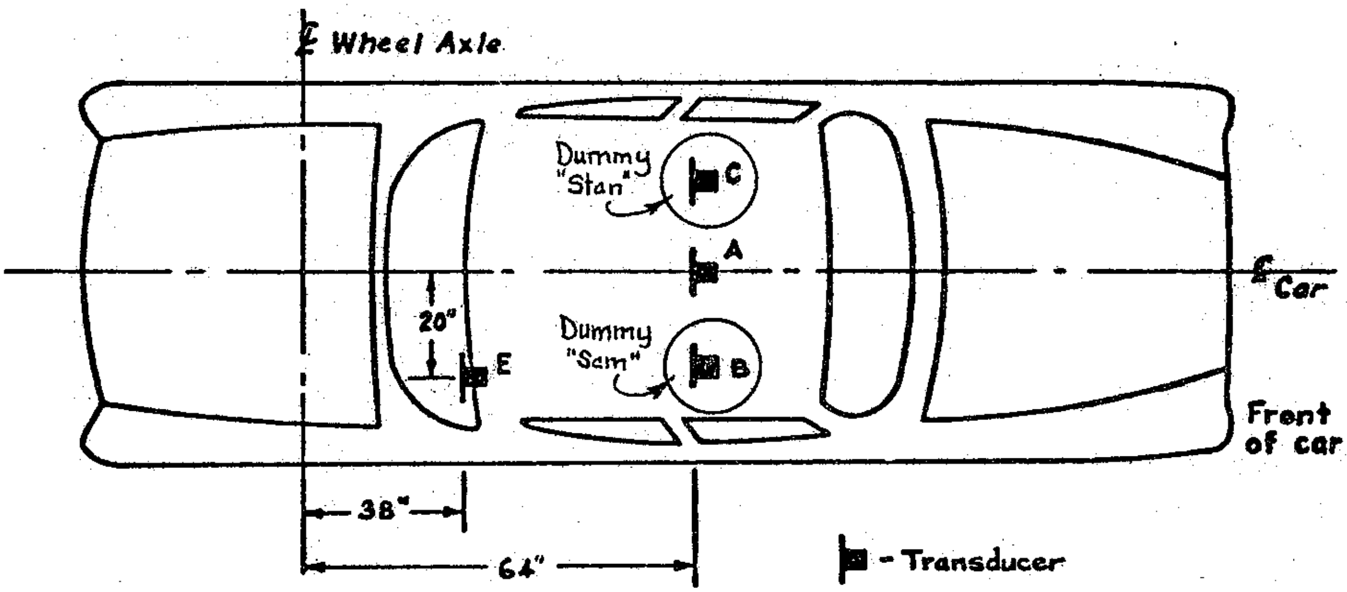
For Tests 221 and 222, a telemetry instrumentation system on loan from the Federal Highway Administration was used[7]. It consisted of seven channels of FM telemetry for use in the crash vehicle and/or dummies and seven hardwire channels for use on the test barrier and back-up bridge approach guardrail. The system included seven accelerometers and two seat belt force transducers and all the necessary signal conditioning equipment. The dynamic data from these transducers was recorded on a 14 channel analog magnetic tape recorder. For Tests 222 (partial) and 223, data from instrumentation on the test vehicle was transmitted through an umbilical cord (hardwire) system. All the accelerometers in the test vehicle and the dummies were of the unbonded strain gage type. Those used with the telemetry system were Statham Model A514TC accelerometers. Those used with the hardwire system were Statham Model A400TC accelerometers. Additional data regarding the vehicular and barrier instrumentation is included on Plates 1 and 2, pages 11 and 12.

Impact-O-Graphs (mechanical stylus devices designed to measure acceleration) were placed in the chest cavity of the dummy located in the passenger position and also on the floor of the test vehicle. Even though the Impact-O-Graphs respond in a velocity mode rather than an acceleration mode if subjected to a frequency above 23 Hz, they were used for comparative evaluations of the severity of the three collisions.

Plate 1

CALIFORNIA DIVISION OF HIGHWAYS

VEHICLE INSTRUMENTATION



Test #221

CHANNEL NO.	LOCATION[1]	DESCRIPTION[2]
1	A	100 "G" longitudinal accelerometer (T)
2	E	100 "G" longitudinal accelerometer (T)
3	C	50 "G" longitudinal accelerometer (T)
4	C	50 "G" lateral accelerometer (T)
5	C	50 "G" vertical accelerometer (T)
6	C	Force meter in "Stan's" chest (T)
7	C	Lap belt tension transducer, "Stan" (T)

Test #222

1	A	100 "G" longitudinal accelerometer (T)
2	A	50 "G" lateral accelerometer (T)
3	E	100 "G" longitudinal accelerometer (T)
4	E	100 "G" lateral accelerometer (T)
5	C	50 "G" longitudinal accelerometer (T)
6	C	50 "G" lateral accelerometer (T)
7	C	50 "G" vertical accelerometer (T)
A	A	50 "G" lateral accelerometer (U)
B	E	100 "G" longitudinal accelerometer (U)
C	E	50 "G" lateral accelerometer (U)
D	B	50 "G" longitudinal accelerometer (U)

Test #223

1	A	100 "G" longitudinal accelerometer (U)
2	A	50 "G" lateral accelerometer (U)
3	C	50 "G" longitudinal accelerometer (U)
4	C	50 "G" lateral accelerometer (U)
5	E	50 "G" longitudinal accelerometer (U)

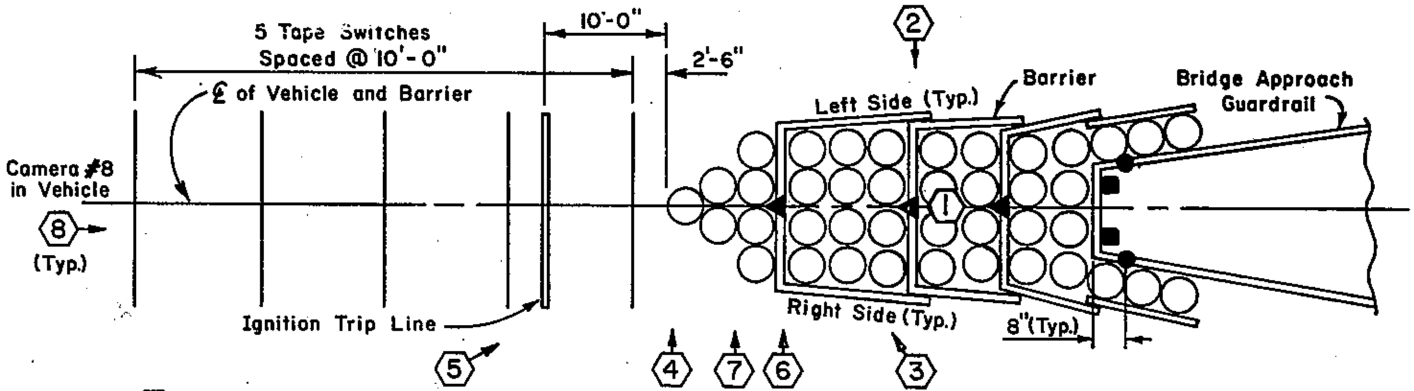
Notes:

[1] A and E on vehicle floor; B and C on back of dummy's chest cavity.

[2] (T) = FM telemetry, (U) = umbilical cord.

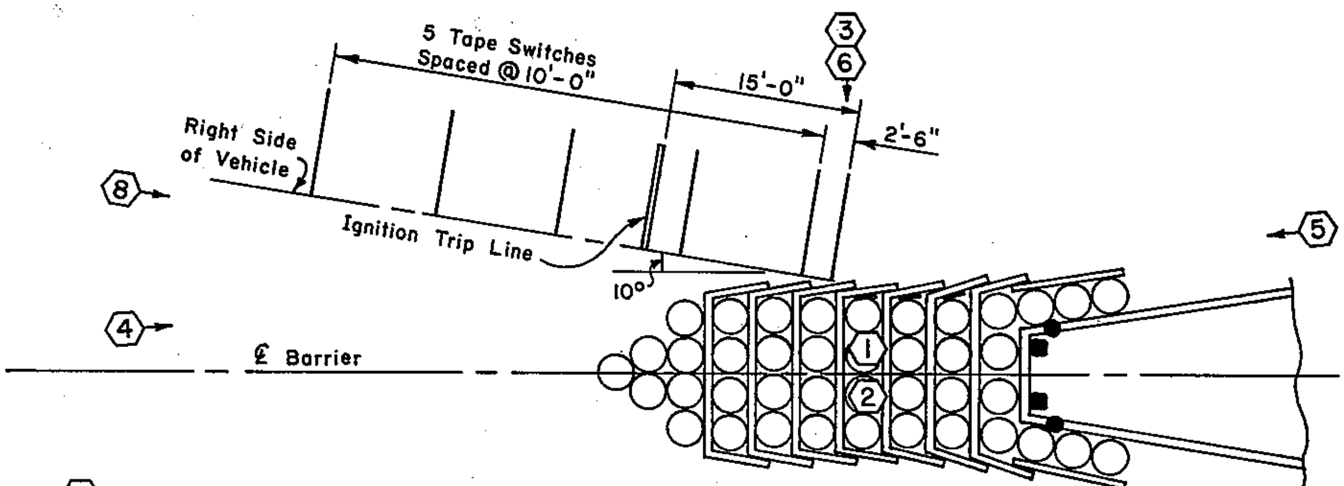
Plate 2

CAMERA AND INSTRUMENTATION LOCATIONS AT BARRIER



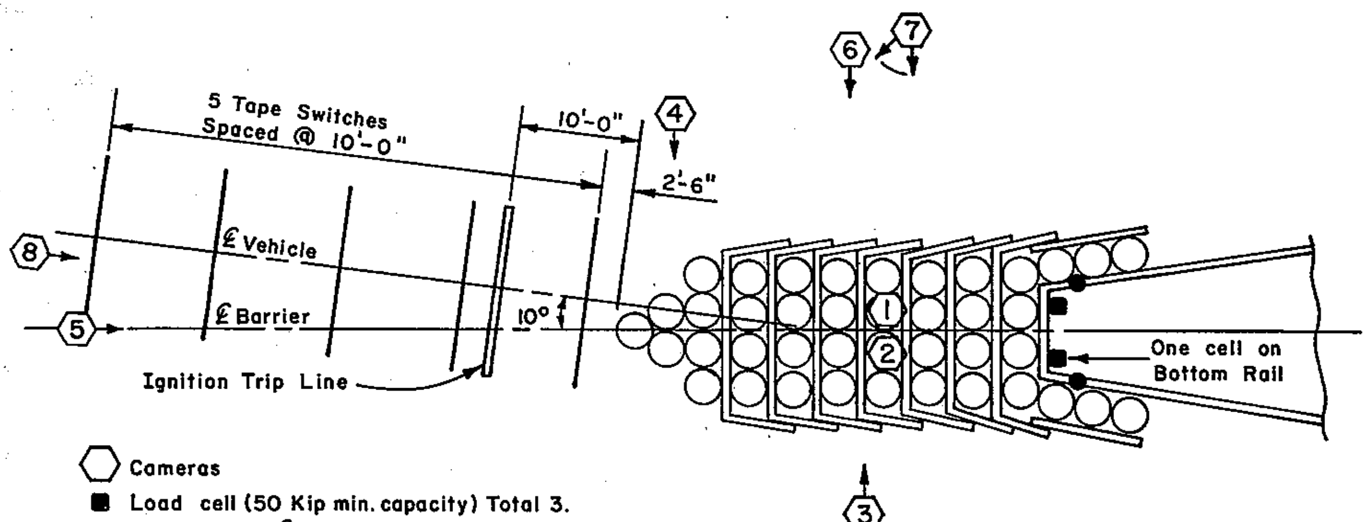
TEST 221

- Cameras
- Accelerometer (200 G's) Total 3.
- Load cell (50 Kip min. capacity) Total 4.
- Strain gage (℄ top surface, upper & lower rails, ℄ 8" behind nose of steel barrier) Total 4.



- Cameras
- Load cell (50 Kip min. capacity) Total 4.
- Strain gage (℄ top surface, upper & lower rails. ℄ 8" behind nose of steel barrier) Total 4.
- Strain gage on Fender Panel, Total 3.

TEST 222



- Cameras
- Load cell (50 Kip min. capacity) Total 3.
- Strain gage (℄ top surface, upper & lower rails. ℄ 8" behind nose of steel barrier) Total 4.

TEST 223

Photography

High speed photography was used to study the vehicular, dummy, and barrier kinematics for all three tests. Eight photosonic cameras operating at frame rates of 200-400 frames per second were placed as shown on Plate 2, page 12. Cameras 1 and 2 were mounted overhead. Camera number 8 was placed in the crash car to record the movement of the dummies. Red-orange "pips" were placed on the edge of the film at a rate of 1000±5 per second, using Adtrol timing light generators, to provide a means of determining the frame rate of each camera.

As the test vehicle crossed the tape switches shown on Plate 2, flash bulbs in view of the cameras were triggered. In addition to providing a common time reference for all the cameras, these flashes were used to compute the impact speed of the test vehicle using the distance between the tape switches and the frame rates of the cameras. Additional tape switches were placed adjacent to these tape switches to reference the electronic data to impact and to the photographic data.

The ignition trip line was a taut cord placed approximately nine inches above the ground that tripped a switch mounted on the front bumper of the vehicle, hence shutting off the ignition.

Appendix B contains a discussion of the data obtained with the photographic, mechanical, and electrical data acquisition systems described above.

VI. TEST RESULTS

Summaries of Each Test

Test 221. A 4690 pound 1968 Dodge sedan impacted the barrier headon at a speed of 64.2 mph. The vehicle axis was offset 6" from the barrier axis at impact. Deceleration was relatively constant. The record of the accelerometers on the floor of the vehicle indicated that the barrier bottomed out to some degree because the peak recorded deceleration occured near the end of the event. The maximum average 50 millisecond (ms) vehicle passenger compartment deceleration, based on accelerometer data, was 10.3 G's. The average deceleration (based on impact velocity and the total passenger compartment stopping distance) was 8.4 G's.

This magnitude of deceleration exceeds the tolerable limits for unrestrained occupants (see Discussion, pages 26 to 30). Thus, unrestrained occupants probably would have sustained moderate to severe injuries. Occupants restrained by lap belts or lap belts and shoulder harnesses would probably have sustained no more than moderate injuries.

There was a noticeable vertical force imparted to the vehicle as shown by the vehicular rise in Figure 5, below. The rise was caused, at least in part, by the right front wheel riding up on the cable. There was virtually no vehicular "rebound".

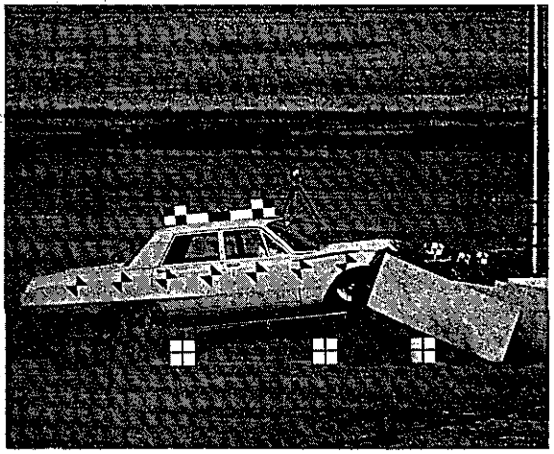


FIGURE 5

Vehicular damage consisted of some bumper deformation, a cracked windshield, a jammed door on the right front side, damage to both front quarter panels, 3.4 inches of steering column collapse (energy absorbing steering column), and some dashboard deformation (see Figures 6 and 7, below). Maximum vehicular crush was 16.5 inches.

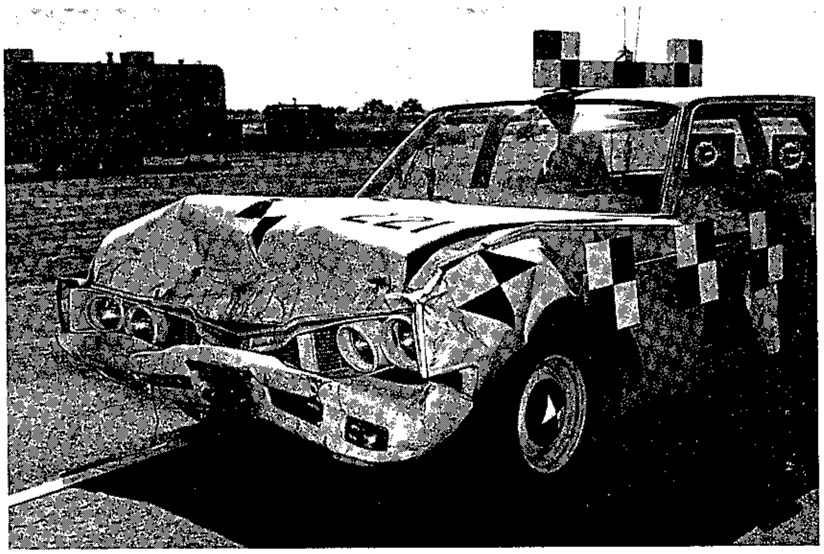


FIGURE 6

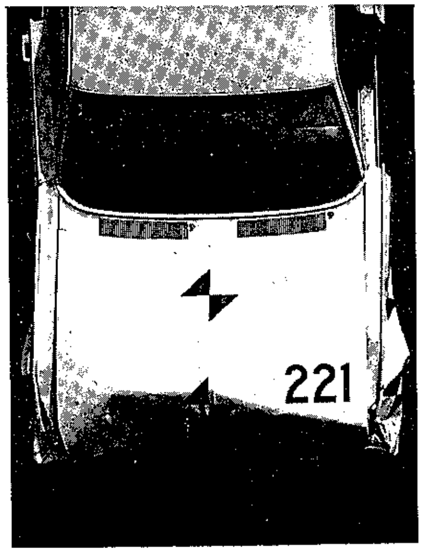
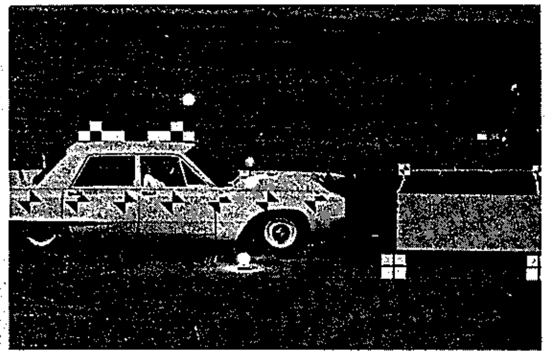


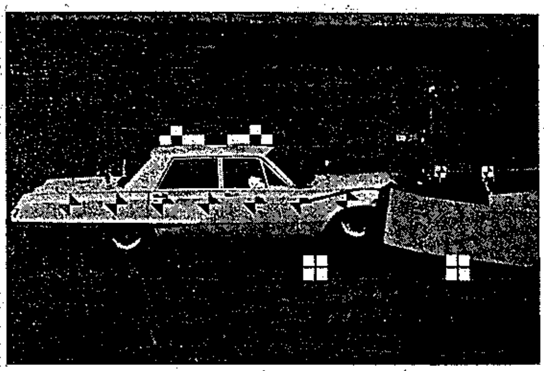
FIGURE 7

All the drums in the barrier were deformed (see Figures 8 and 9). The cables were slack but undamaged. The plywood fender panels were badly cracked and splintered but remained attached to the barrier as it was deformed around the nose of the bridge approach guardrail. The drums crushed one row at a time, in successive order, as had been assumed in the design procedure. See Plate 3 (following page) for additional test data.

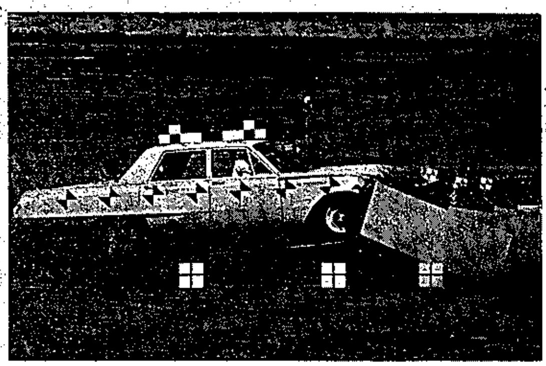
PLATE 3



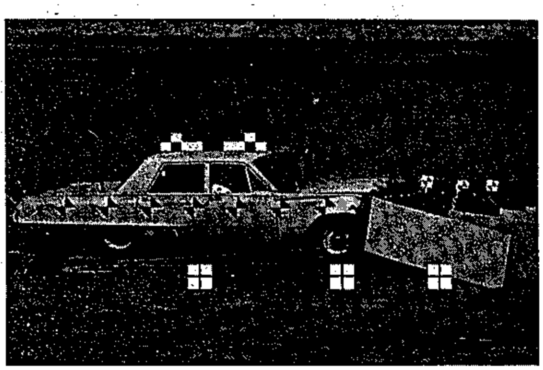
Impact + 0.04 Sec.



I + 0.13 Sec.



I + 0.50 Sec.



I + 3.10 Sec.

Barrier Depth	19.6 Ft.
No. of Drums	41
Permanent Displacement of Barrier Nose	10.7 Ft.
Deceleration Distance-Passenger Compartment	16.5 Ft.
Maximum Vehicular Deformation	16.5 In.
Steering Column Collapse[1]	3.4 In.
Passenger Compartment Deceleration (Highest 50 ms avg.)	10.3 G's
Vehicle Average Deceleration-Calculated	8.4 G's

Test No.	221
Date	9-11-69
Vehicle	1968 Dodge[2]
Vehicle Weight (W/Dummy and Instrumentation)	4690 Lbs.
Impact Velocity	64.2 MPH
Impact Angle	Head-On
Dummy Restraint	Lap Belt

[1] Energy Absorbing Steering Column - 1500 lb. design axial force required to initiate collapse.

[2] Left front door removed.

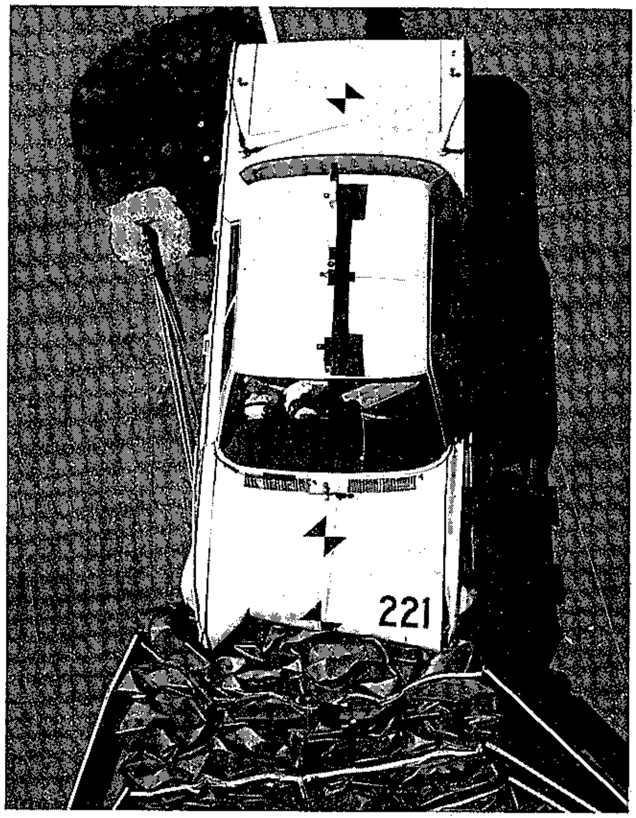


FIGURE 8

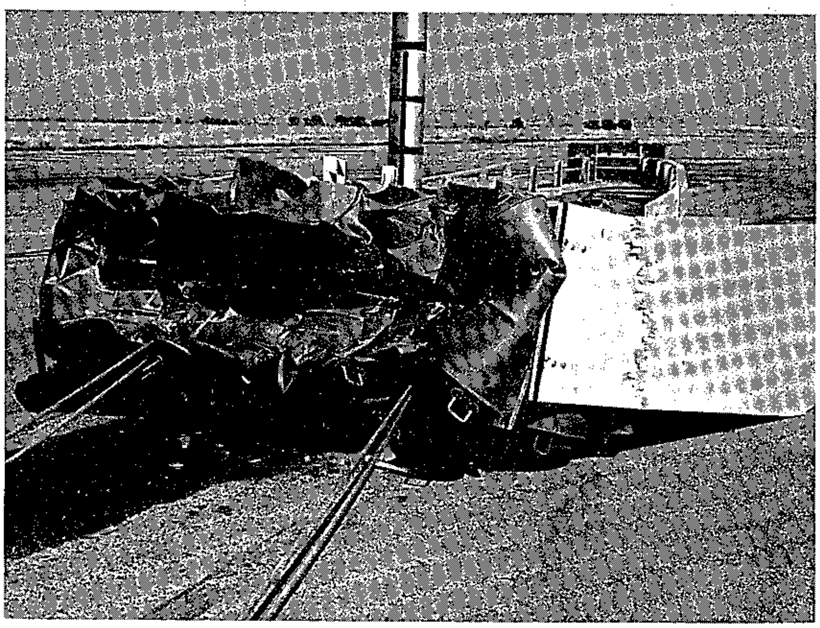


FIGURE 9

Test 222

The barrier used for this test was identical to that used for the first test with the following exceptions: (1) the length of the fender panels was decreased to minimize contact of the bottom corner of the trailing edge of these panels with the ground surface (this required a proportionate increase in the number of diaphragms used) and (2) the drum-to-drum bolted connections were made at the rolling hoops to eliminate the need for wood spacers and make it easier to tighten the lower bolts from the top of the barrier.

The 4760 pound 1968 Dodge sedan impacted the left side of the barrier 10.2 feet in front of the bridge approach guardrail at a speed of 59.8 mph and an angle of 11 degrees with the barrier (see Figure 10, below, for approximate location at impact). The vehicle was redirected but minimal redirectional forces were provided by the drums. The vehicle axis was displaced 12 inches laterally from its location at impact before any redirection began (i.e., crabbing occurred). At this time, solid contact with the bridge approach guardrail had been established.

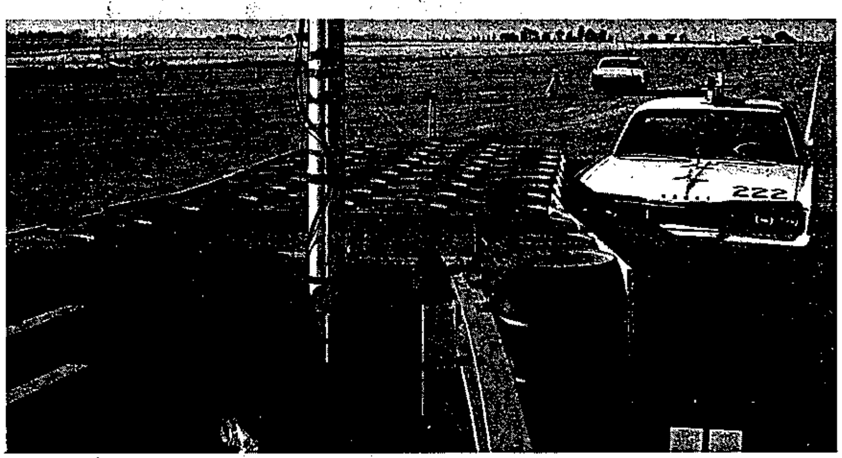


FIGURE 10

The force of the impact caused a clamping action to take place between the rear drums and the bridge approach guardrail, thus preventing drum ejection (see Figure 11).

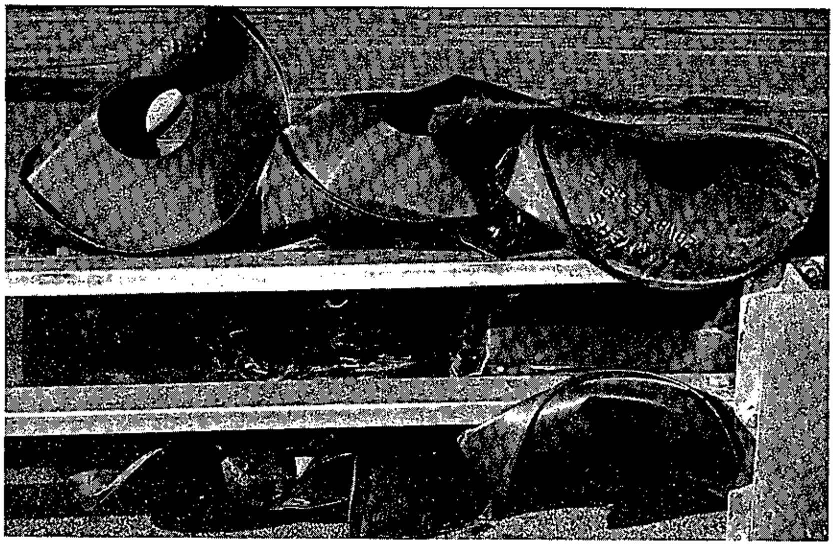


FIGURE 11

Additional barrier damage consisted of crushing of the outside drums in the back half of the barrier on the impacted side. All the fender panels beyond the point of impact were torn off the barrier. There were some failures at hinge pins; the ends of the last few diaphragms were broken off on the impact side. There was an unacceptable amount of debris deposited in what would be the adjacent traveled way. Some of the fender panel fragments were thrown 155± feet from the point of impact (see Figures 12 and 13).

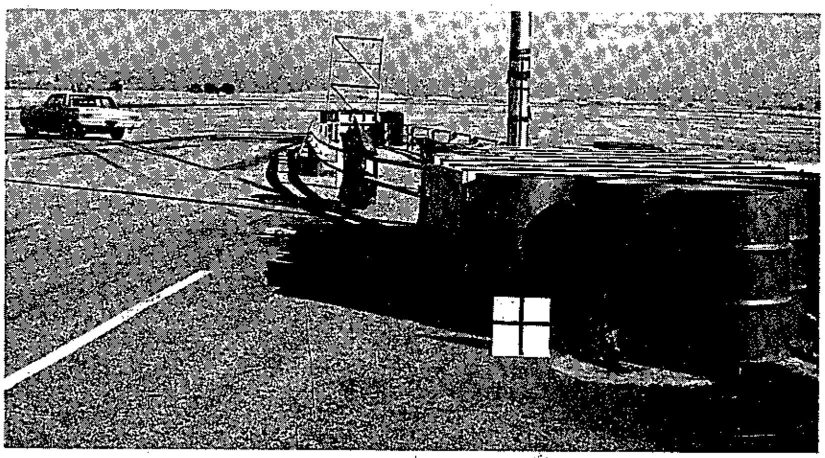


FIGURE 12

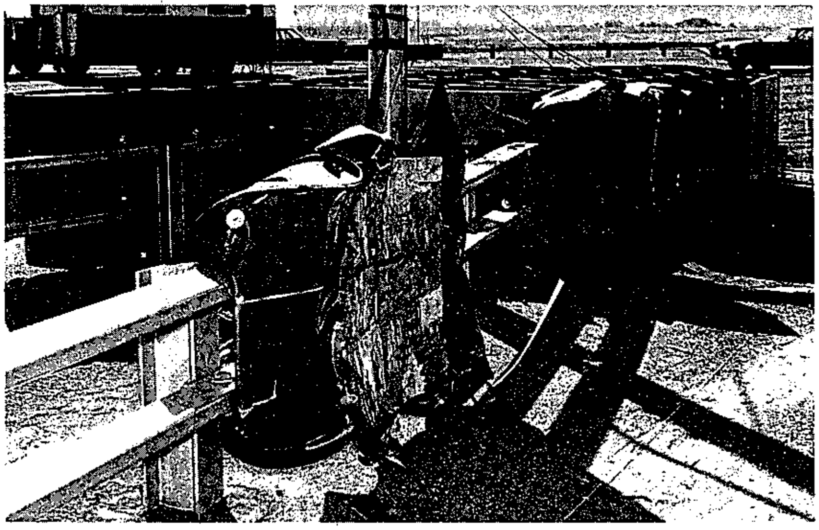


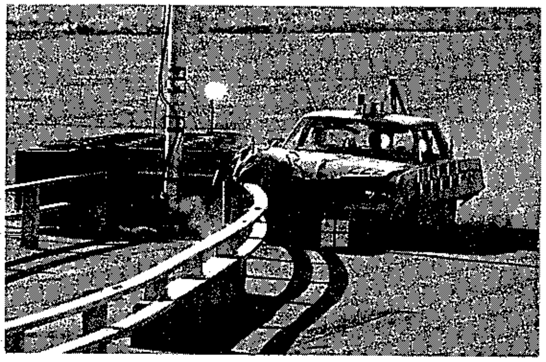
FIGURE 13

The maximum 50 ms average vehicular passenger compartment decelerations recorded were 5.3 G's lateral and 6.6 G's longitudinal. Thus, unrestrained occupants would probably have sustained moderate injuries (see Discussion, pages 26 to 30). Although the lateral deceleration was slightly in excess of the tolerance limits for lap belt restrained occupants, little or no injury would probably occur in most collisions of this severity if any occupant restraints were in use at the time of the collision.

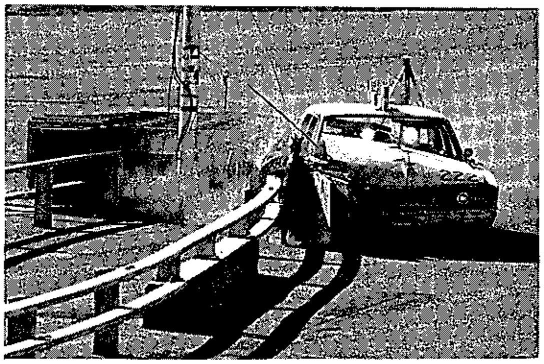
Vehicle damage included severe crushing of the right front quarter panel, jamming of the right front door, scars on the right doors and right rear panel, and displacement of the radiator to the point of touching one fan blade (see Figure 14, below). See Plate 4 (following page) for additional test data.

FIGURE 14

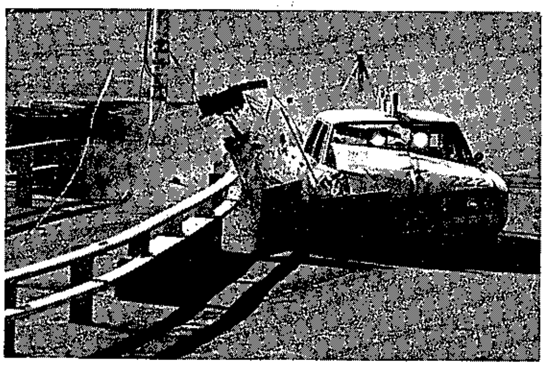
PLATE 4



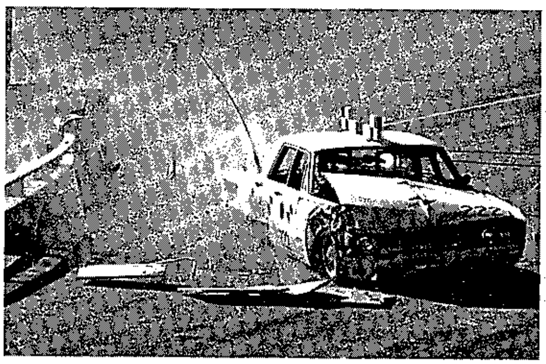
Impact + 0.14 Sec.



I + 0.32 Sec.



I + 0.50 Sec.



I + 1.05 Sec.

Barrier Depth	19.6 Ft.
No. of Drums	41
Permanent Displacement of Barrier Nose	None
Deceleration Distance-Passenger Compartment	Redirected
Maximum Vehicular Deformation	27 In.
Steering Column Collapse[1]	None
Passenger Compartment Deceleration (Highest 50 ms avg.)	6.6 G's Long. 5.3 G's Lat.
Vehicle Average Deceleration-Calculated	-

Test No.	222
Date	11-21-69
Vehicle	1968 Dodge
Vehicle Weight (W/Dummy and Instrumentation)	4760 Lbs.
Impact Velocity	59.8 MPH
Impact Angle	11^o (Side)
Dummy Restraint	Lap Belt

[1] Energy Absorbing Steering Column - 1500 lb. design axial force required to initiate collapse.

Test 223. This test consisted of a 4740 pound 1968 Dodge sedan impacting the same barrier design used for the previous test. The vehicle impacted the left corner of the barrier nose at a speed of 53.6 mph and an angle of 9 degrees. At impact, the center of the front of the vehicle was offset 3.5 feet from the barrier axis. Significant elastic lateral deflection of the barrier took place as the vehicle penetrated 13.2 feet, rotated clockwise, and then rebounded 2.5 feet. The maximum 50 ms average vehicular passenger compartment deceleration, based on accelerometer data, was 10.9 G's (in the longitudinal direction). The average passenger compartment longitudinal deceleration was 7.2 G's. (The vehicular rotation was neglected because the longitudinal velocity was approximately zero before rotation began.) Deceleration of this magnitude would probably result in moderate to severe injury for an unrestrained occupant, minor to moderate injury for an occupant restrained by a lap belt, and little or no injury for an occupant using both a lap belt and a diagonal shoulder harness. The position of the vehicle after the collision was such that it would have been a hazard to adjacent traffic (see Figure 15, below).

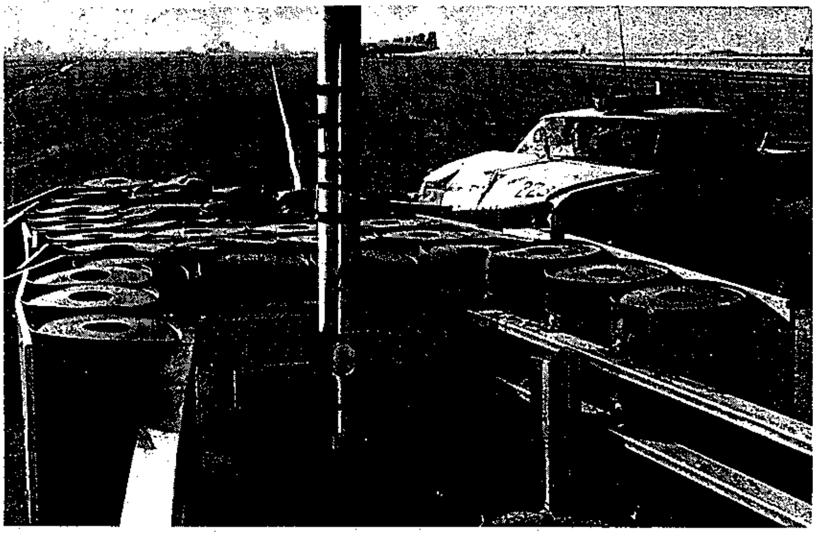


FIGURE 15

Vehicle damage consisted of a crimp in the roof on the passenger side, extensive hood deformation, slight displacement of the left front quarter panel, and 3.6 inches of (energy absorbing) steering column collapse (see Figures 16 and 17). There was a slash high on the cheek of the dummy driver and the windshield was broken in front of the dummy passenger. The dummy passenger was badly cut on the tip of the bridge of his nose, over his right eye and on his forehead, and on the right side of his face and cheek. This dummy's lower legs were removed before the crash; this may have contributed to some excessive movement of his upper body during the collision.

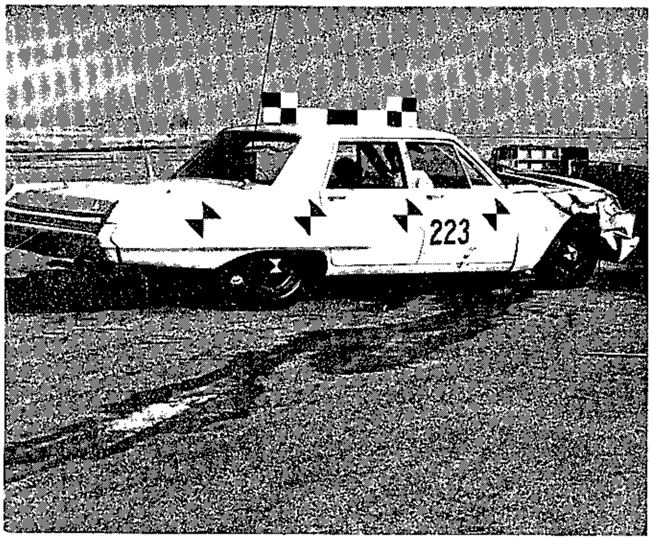


FIGURE 16

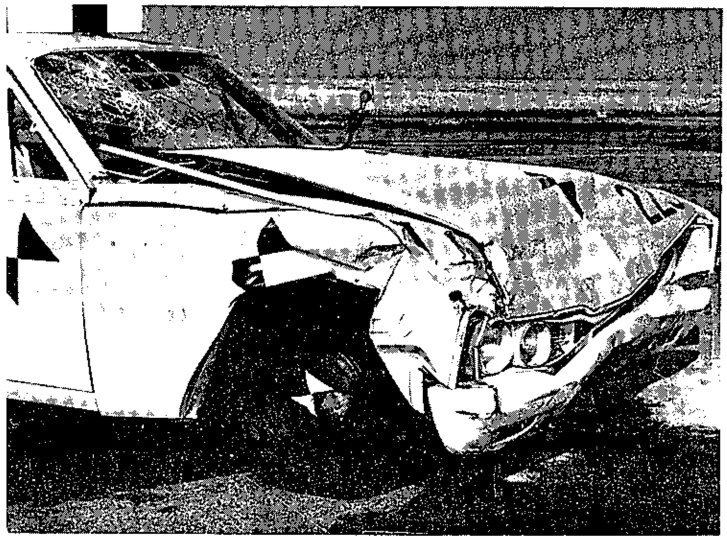


FIGURE 17

All but two drums were damaged. The left front and the right rear plywood fender panels were the only ones damaged. It appeared that the impact force was transmitted somewhat diagonally from the left front to the right rear of the barrier (see Figure 18, below). The left front portion of the barrier was crushed much more than the right front side. The film record shows the drums crushing one row at a time in successive order with the exception of the back row, which was deformed soon after impact. This was very similar to the dynamic barrier compression sequence observed during Test 221 and again verified the design assumptions. From a maintenance standpoint, all the drums would have required replacement.

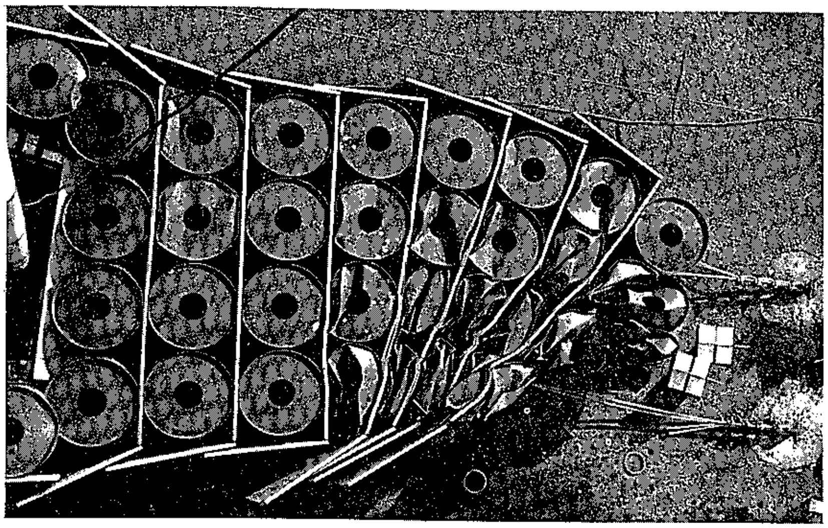
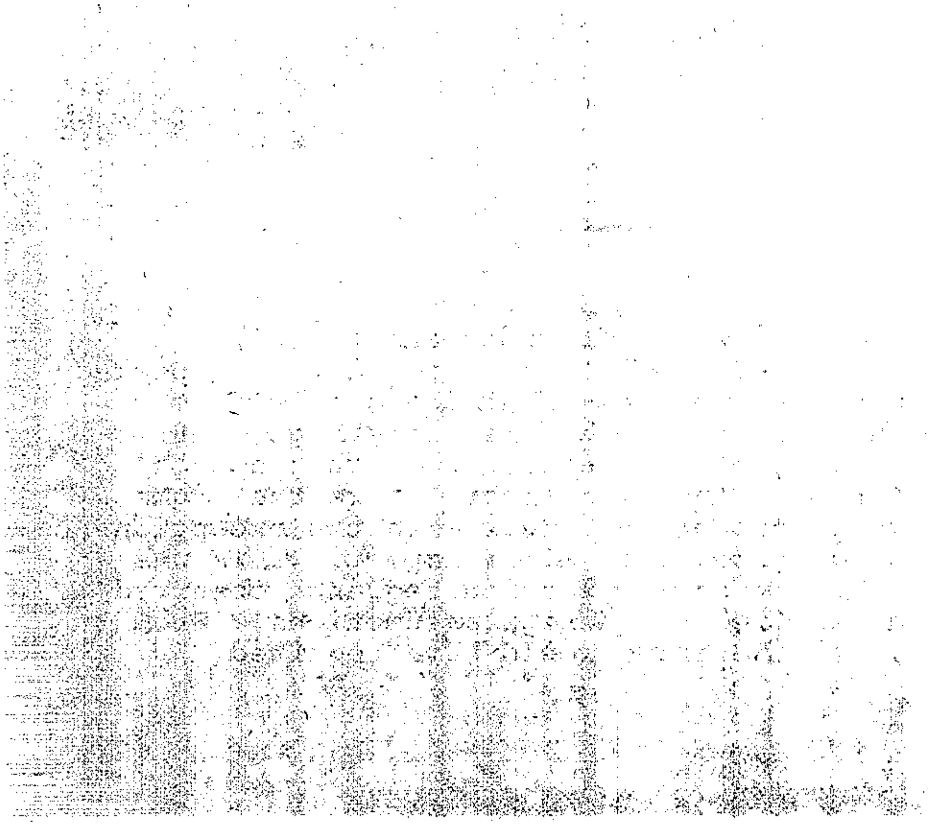


FIGURE 18

The movies showed the car being ejected outward from the barrier due to the elastic energy stored within the barrier. The clockwise rotation of the car was probably caused by a moment couple consisting of the vehicular momentum, acting through the vehicle CG, and this "elastic" energy, acting through the centroid of the vehicle-barrier contact interface. See Plate 5 (following page) for additional test data.



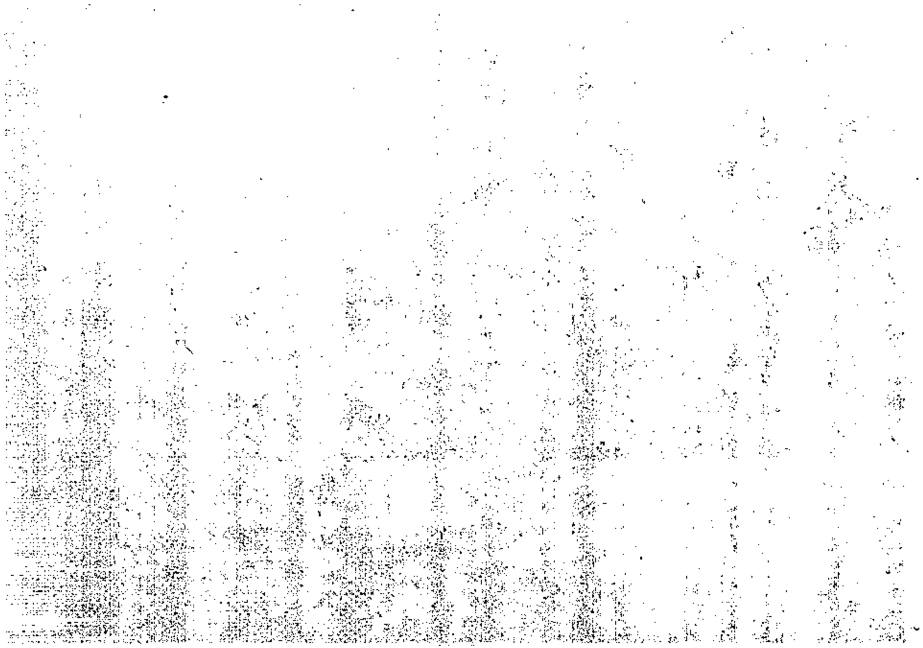
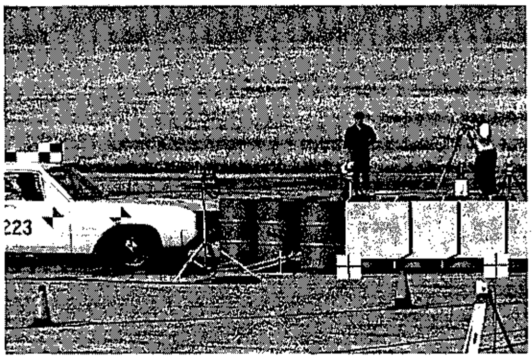
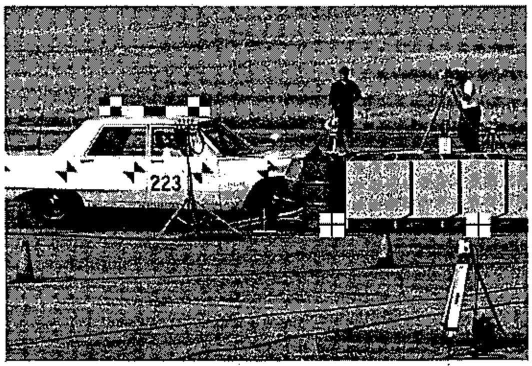


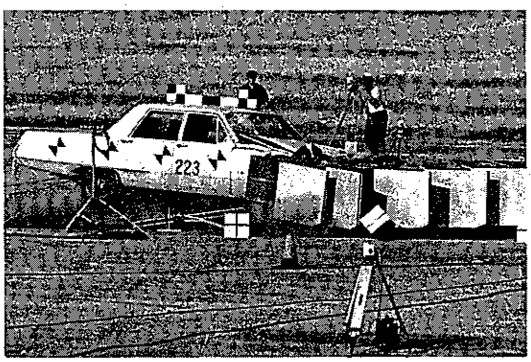
PLATE 5



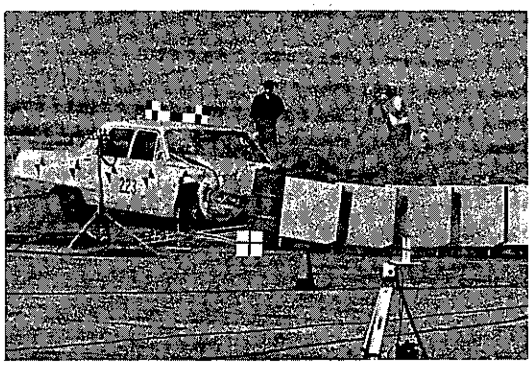
Impact



I + 0.09 Sec.



I + 0.46 Sec.



I + 1.69 Sec.

Barrier Depth	19.6 Ft.	Test No.	223
No. of Drums	41	Date	12-5-69
Permanent Displacement of Barrier Nose	5.5 Ft.	Vehicle	1968 Dodge[3]
Deceleration Distance-Passenger Compartment	13.2 Ft.	Vehicle Weight (W/Dummy and Instrumentation)	4740 Lbs.[3]
Maximum Vehicular Deformation	14.5 In.	Impact Velocity	53.6 MPH
Steering Column Collapse[1]	3.6 In.	Impact Angle	9° (Nose)
Passenger Compartment Deceleration (Highest 50 ms avg.)	10.9 G's Long.	Dummy Restraint	Lap Belt
Vehicle Average Deceleration-Calculated	7.2 G's[2]		

[1] Energy Absorbing Steering Column - 1500 lb. design axial force required to initiate collapse.

[2] Lateral components of deceleration not included.

[3] Lower legs removed from dummy placed in passenger location to facilitate handling of dummy.

Discussion

In addition to studying accident records, it is necessary to investigate the various aspects of human and vehicle tolerance to deceleration before an energy absorbing barrier can be designed effectively. Numerous research studies have been conducted on this subject; some of the more pertinent findings will be outlined below.

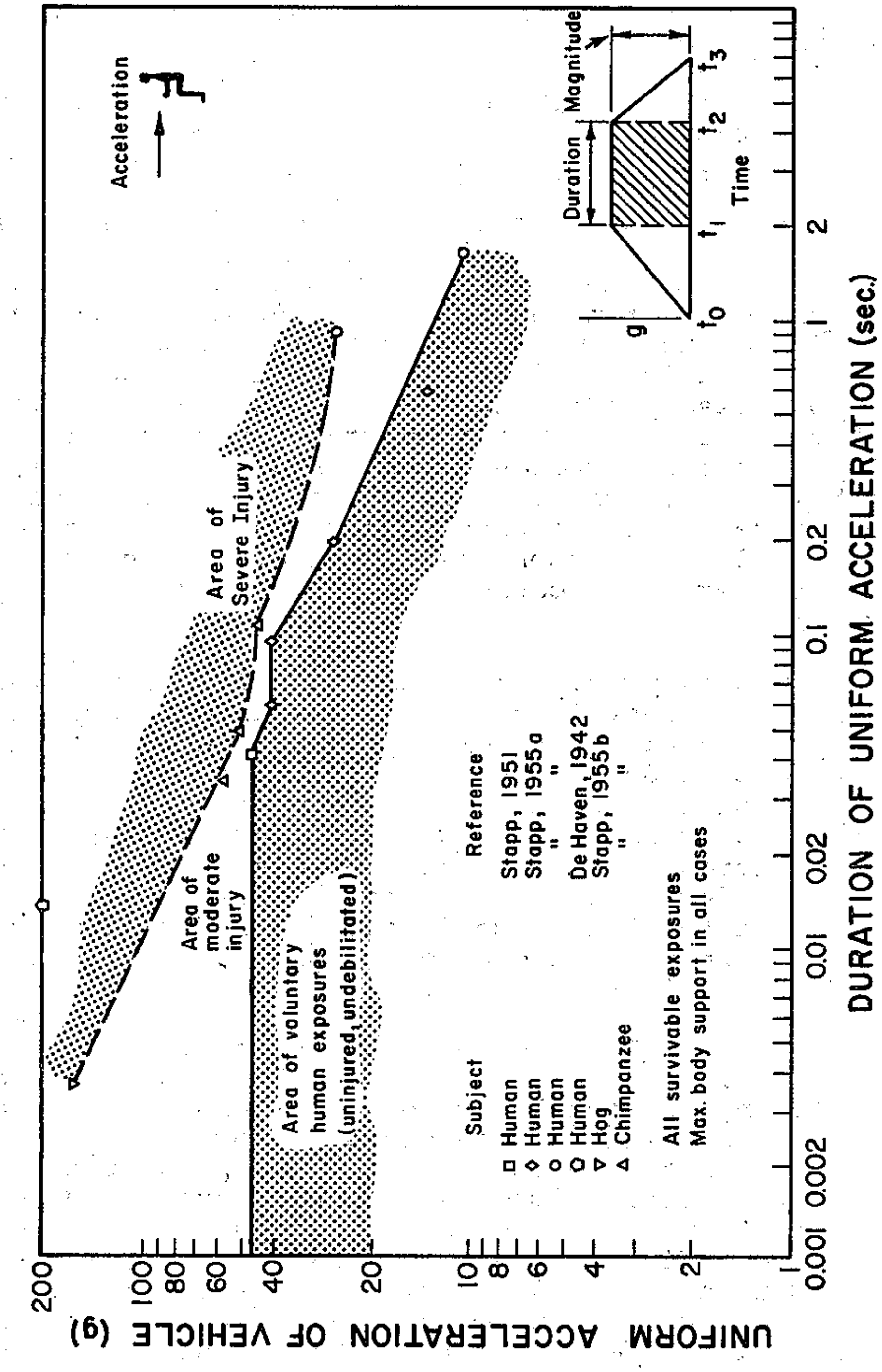
It is useful to determine some general upper limits of deceleration tolerance. If a vehicle occupant is restrained with a lap belt and shoulder harness, then his body will decelerate at about the same rate as the car. Longitudinal decelerations as high as 40 G's have been tolerated by fully restrained healthy young male volunteers for up to 100 milliseconds with no ill effects[8] (see Plate 6, following page). Acceleration above this level caused extreme chest pain, difficulty in breathing, and visual malfunctions such as blurred vision, pain, headache, and retinal hemorrhage.

The deceleration of a 160 lbs. driver in a headon rigid barrier crash at 22 mph is about 25 G's[9]. The same reference reported that few serious injuries occurred in vehicle collisions at 20 mph. This would indicate that a tolerable occupant longitudinal deceleration of 25 G's would be appropriate. This does not appear to be compatible with the 12 G maximum deceleration permitted for devices classified as satisfactory when evaluated under the 4S program of the Federal Highway Administration. However, these 4S criteria are intended to provide a survivable environment and, as such, apply to the decelerations sustained by the passenger compartments of 2000 to 4500 pound vehicles.[14] The 12 G average deceleration limit corresponds to a 10 ft. stopping distance for a 60 mph impact. These criteria were based on tentative tolerable limits of deceleration proposed by the Cornell Aeronautical Laboratory in 1961.[10] These Cornell limits, shown in Table 2 below, are for a duration of impact less than 200 milliseconds and a rate of onset less than 500 G's per second.

TABLE NO. 2

Occupant Restraint	Maximum Decleration (G's)		
	Lateral	Longitudinal	Total
Unrestrained	3	5	6
Lap Belt	5	10	12
Lap Belt & Shoulder Harness	15	25	25

Plate 6


Acceleration
Area of Severe Injury
Area of moderate injury
Area of voluntary human exposures (uninjured, undebilitated)
Subject
Reference
□ Human
Stapp, 1951
◇ Human
Stapp, 1955a
○ Human
"
⬡ Human
De Haven, 1942
▽ Hog
Stapp, 1955b
△ Chimpanzee
"
All survivable exposures
Max. body support in all cases
Duration
Magnitude
g
Time
t_0 t_1 t_2 t_3
UNIFORM ACCELERATION OF VEHICLE (g)
DURATION OF UNIFORM ACCELERATION (sec.)
200
100
80
60
40
20
10
8
6
4
2
1
0.001
0.002
0.01
0.02
0.1
0.2
1
2

The above table, although helpful as a rough guide for vehicle decelerations, does not define completely the shape of the deceleration pulse, which can vary considerably and still satisfy the 12 G average limitation.

A small study has been completed in which average longitudinal vehicular deceleration was related to the proportion of those vehicles in which unrestrained occupants sustained injuries[11]. This study indicated that a 12 G vehicular deceleration will result in occupant injuries in the majority of cases. When this study is tied to one regarding general use of seat belts[12] one can conclude that, even with energy absorbing barriers designed for maximum vehicle decelerations of 12 G's (60 mph impact velocity), the 65-70% of the public who disdain the use of seat belts will probably be injured in a major collision with these barriers.[14] The results of these studies involving actual automobile accidents indicate that the 12 "G" limit is anything but conservative. Consequently, for the purposes of this study, the deceleration limits established by Cornell (Table 2 above) were applied to the maximum average vehicle passenger compartment deceleration measured over a 50 millisecond (ms) period. It is acknowledged that higher decelerations could be safely tolerated for shorter time intervals.

An even more complex problem regarding deceleration tolerance is that of measuring and evaluating the impacts of occupants with the interior of the vehicle. Any given vehicle deceleration can result in a wide range of body decelerations depending on which body part is being investigated, whether seat belts are worn, whether a steering wheel, windshield or dashboard are impacted, and what the energy absorbing properties of each of these items is. Even when the actual values of deceleration are known, there is still very little information about the tolerance levels of different parts of the body, especially when consideration is given to differences in size, age, physical condition and so on.

An injury study by UCLA indicated that impact into the steering wheel and column is the most common and also most dangerous cause of injuries during non-fatal accidents. Therefore, it would be well to adjust the design of the energy absorbing barrier with due consideration given to the energy absorbing properties of steering columns in current vehicle models. A paper from a GM Seminar[5] includes information on energy absorption in steering columns. This type of column was first installed in 1967 in cars made by General Motors, American Motors, and Chrysler. This column was designed to collapse a maximum of 8-1/4" under loads no greater than 1,000 to 1,500 lbs. (The Federal Motor Vehicle Safety Standards limit the impact force of a simulated body traveling at a relative velocity of 15 mph to 2,500 lbs. when impacting the steering control system[13]). Accident statistics from 257 cases involving the steering column in 1967 model cars traveling at speeds of 10-125 mph show that the column collapsed more than 5 inches in only 6 cases. A more detailed study of 88 headon accidents out of the total of 257 cases revealed two fatalities. This study also indicated that, at 60 mph, the maximum column compression for all 88 cases was slightly less than 8 inches and the average compression was about 3-1/2 inches. There were numerous cases of steering column compression with closure speeds of 50-60 mph which resulted in no injury to the chest.

The main conclusions that can be drawn from this limited review of the effect of energy absorbing steering columns is that recent improvements to the steering column are probably reducing fatalities and serious injuries. The severity of those chest injuries being sustained will decrease even more if the vehicular passenger compartment longitudinal deceleration is decreased. (This conclusion is based on the assumption that no occupant ejection occurs.) The steering column collapse of 3.4 inches for Test #221 and 3.6 inches for Test #223 indicates that there would be a good possibility of little or no chest injuries being sustained during 60 mph headon or nearly headon collisions with the drum type energy attenuator. This correlates well with the predicted severity based on passenger compartment decelerations.

The Federal Motor Vehicle Safety Standards[13] now require lap belts in all permanent passenger positions and shoulder belts in the outboard, front seat positions. Lap belt anchorages must resist a 5000 lb. load applied in a dynamic test with a body block, and shoulder-lap anchorage combinations must resist a 3000 lb. load applied to the pelvic body block together with a 3000 lb. load on the upper torso body trunk. When the lap belt is securely fastened below the top of the pelvic structure, it can withstand a load of 5000 lbs.[12] It has been reported that occupants of vehicles impacting a rigid barrier at 30 mph can impart a 5000-6000 lb. load on seat belt systems[12]. The tests reported in this reference gave total harness loads of 4000-5000 lbs. for 30 mph impacts and lap-shoulder restraint systems. The peak vehicle decelerations were over 30 G's. In these tests, "submarining" occurred, a phenomenon mentioned in other references. (Submarining is the sliding under the lap-belt by a passenger during impact.) This tendency is increased with a lap-shoulder combination system. If the lap belt slips above the pelvic structure, then the passenger is much more vulnerable to abdominal injuries or possible spinal injuries. The strength of the chest and encased organs is less well defined; none of the references studied mentioned a maximum safe load that could be applied by a shoulder strap during impacts. Other variables mentioned by various references were the location of harness anchorages which can affect the chance of neck, shoulder, chest, abdominal injuries, etc., and the amount of slack in the harness system due to belt stretch, belt tightness, anchorage slip and so on.

A small but detailed accident study has been conducted at Cornell University to determine the benefits of lap belts other than to prevent ejection[12]. The study showed no significant reduction in the severity of injuries due to the wearing of lap belts. They did determine that the type of injury varied; viz, whereas unbelted occupants impacted the windshield, belted occupants jacknifed toward and hit the steering wheel or instrument panel and received head injuries in a slightly different manner.

The above data suggests that loads from seat belt transducers, if under 5000 lb. for the total loop load, would indicate no injury to passengers due to the belts assuming the belts were properly secured and that no contact with the dashboard occurred. On the other hand, deceleration of the vehicle by the protective barrier may need to be almost as low for lap belted passengers as for unrestrained passengers in order to minimize head injuries during a collision in which ejection would be quite unlikely even if no restraint was used. The lap belt maximum force measured during Test #221 (only test so instrumented) was 525 lbs. This low magnitude indicated that the measurement may well have been erroneous so the collision severity conclusions were not based on it.

Implementation

As a result of the tests reported herein, an experimental energy attenuator incorporating empty 55 gallon drums is now planned for a gore at a freeway intersection in the Los Angeles area. The installation of a remotely triggered camera to document any impacts into this barrier is also being considered.

VII. REFERENCES

1. Nordlin, E. F., Ames, W. H., Hackett, R. P., and Folsom, J. J., "Dynamic Tests of Type 9 Bridge Barrier Rail and Type 8 Bridge Approach Guardrail", Series XVII, California Division of Highways, June, 1969.

2. Michie, J. D., Calcote, L. R., and Bronstad, M. E., "Guardrail Performance and Design", NCHRP Final Report, Project No. 15-1(2), Southwest Research Institute, January, 1970.

3. Hirsch, T. J., and Ivey, D. L., "Vehicle Impact Attenuation by Modular Crash Cushion", Research Report 146-1, Texas Transportation Institute of Texas A & M University, June, 1969.

4. Nordlin, E. F., Woodstrom, J. W., and Doty, R. N., "Dynamic Tests of an Energy Absorbing Barrier Employing Water-Filled Cells", Series XXI, California Division of Highways, November, 1970.

5. "Proceedings, General Motors Corporation Automotive Safety Seminar", General Motors Safety Research and Development Laboratory, July 11-17, 1968.

6. Nordlin, E. F., Ames, W. H., and Hackett, R. P., "Dynamic Tests of the California Type 20 Bridge Barrier Rail", Series XXIII, California Division of Highways, September, 1970.

7. Nordlin, E. F., Ames, W. H., Kubel, L. G., and Chow, W., "Evaluation of a Telementry System for use in Vehicle-Barrier Impact Tests", California Division of Highways, July, 1969.

8. Damon, A., Stoudt, H. W., and MacFarland, R. A., "The Human Body in Equipment Design", Harvard University Press, 1966.

9. Vanderstempel, T. M., "A Device to Lessen Injuries in Fixed Object Collisions", Traffic Engineering, November, 1966.

10. "Highway Barrier Analysis and Test Program", Summary Report for period July, 1960 - July, 1961, Cornell Aeronautical Laboratory Report No. VJ-1472-V-3, July, 1969.

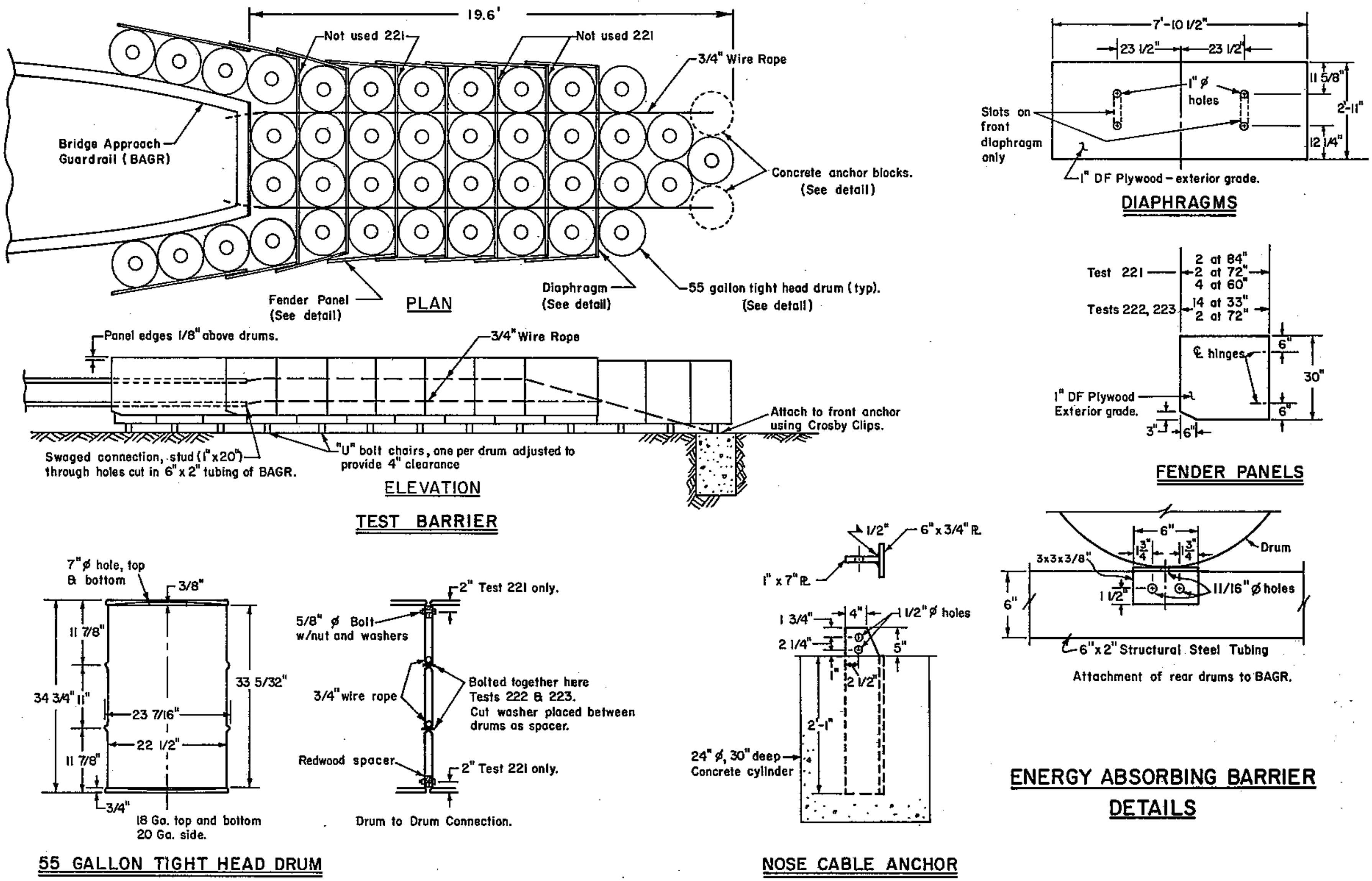
11. Olson, R. M., Post, E. R., and MacFarland, W. F., "Tentative Service Requirements for Bridge Rail Systems", NCHRP Report 12-8, February, 1969.

12. "The Seventh Stapp Car Crash Conference Proceedings", Derwyn M. Severy, editor, Charles S. Thomas, publisher.

13. "Federal Motor Vehicle Safety Standards", National Safety Bureau, U. S. Department of Transportation, with amendments and interpretations through August 6, 1968.

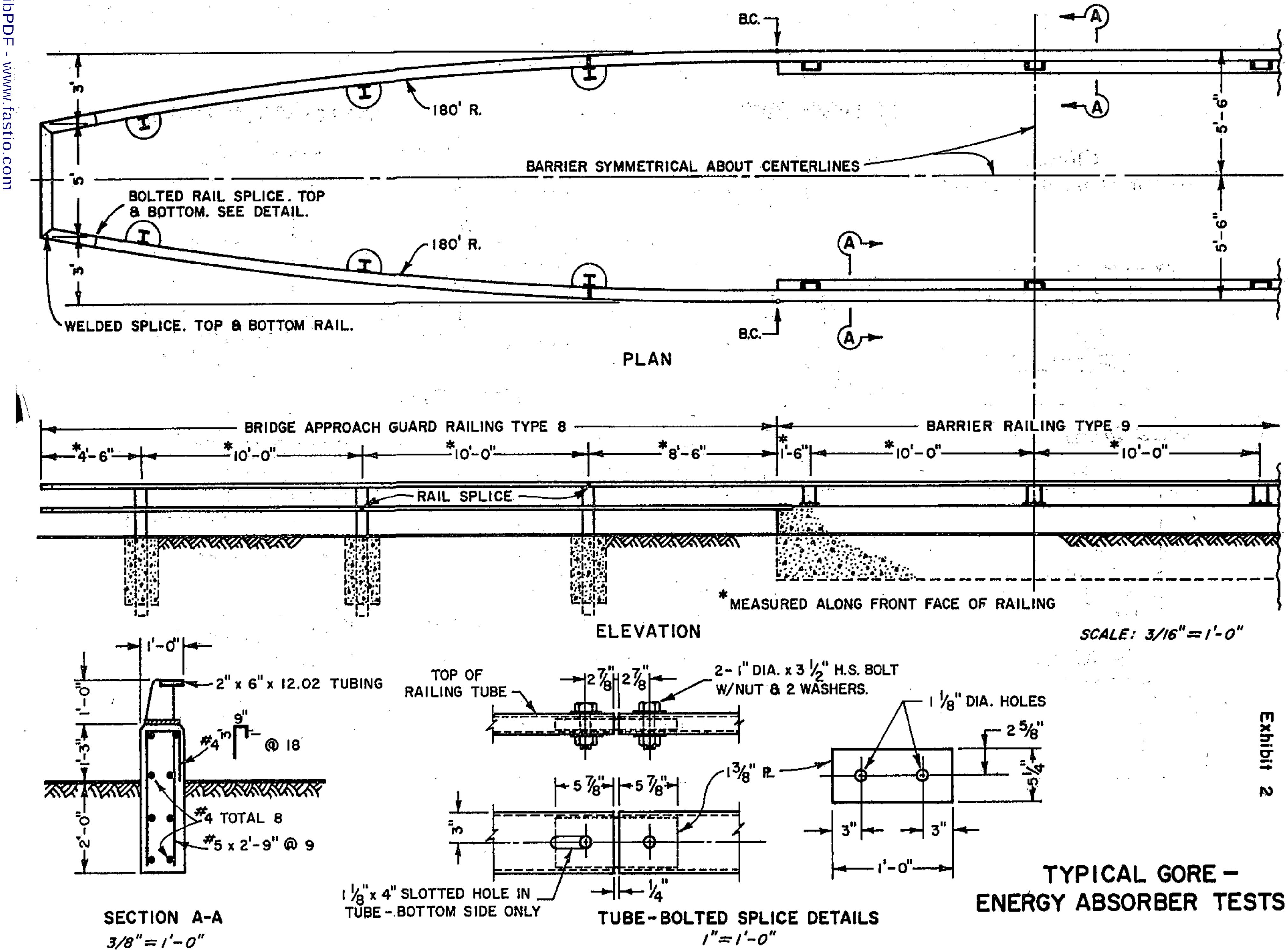
14. Tamanini, F. J. and Viner, J. G., "Structural Systems in Support of Highway Safety", Office of Research and Development of the Bureau of Public Roads (now Federal Highway Administration); paper presented at the ASCE National Meeting on Transportation Engineering, Washington, D. C., July 21-25, 1969.

EXHIBIT 1



19.6'
Not used 221
Not used 221
3/4" Wire Rope
Bridge Approach Guardrail (BAGR)
Concrete anchor blocks. (See detail)
Fender Panel (See detail)
PLAN
Diaphragm (See detail)
55 gallon tight head drum (typ). (See detail)
Panel edges 1/8" above drums.
3/4" Wire Rope
Attach to front anchor using Crosby Clips.
Swaged connection, stud (1"x20") through holes cut in 6" x 2" tubing of BAGR.
"U" bolt chairs, one per drum adjusted to provide 4" clearance
ELEVATION
TEST BARRIER
7" ø hole, top & bottom
3/8"
11 7/8"
34 3/4"
11"
23 7/16"
22 1/2"
33 5/32"
11 7/8"
3/4"
18 Ga. top and bottom
20 Ga. side.
55 GALLON TIGHT HEAD DRUM
5/8" ø Bolt w/nut and washers
2" Test 221 only.
3/4" wire rope
Bolted together here Tests 222 & 223. Cut washer placed between drums as spacer.
Redwood spacer
2" Test 221 only.
Drum to Drum Connection.
1/2"
6" x 3/4" ℞
1" x 7" ℞
1 3/4"
4"
1 1/2" ø holes
2 1/4"
5"
1"
2 1/2"
2'-1"
24" ø, 30" deep Concrete cylinder
NOSE CABLE ANCHOR
7'-10 1/2"
23 1/2"
23 1/2"
1" ø holes
11 5/8"
2'-11"
12 1/4"
Slots on front diaphragm only
1" DF Plywood - exterior grade.
DIAPHRAGMS
Test 221
2 at 84"
2 at 72"
4 at 60"
Tests 222, 223
14 at 33"
2 at 72"
℄ hinges
6"
30"
6"
1" DF Plywood Exterior grade.
3"
6"
FENDER PANELS
6"
1 3/4
1 3/4
Drum
3x3x3/8"
1 1/2"
11/16" ø holes
6"
6"x2" Structural Steel Tubing
Attachment of rear drums to BAGR.
ENERGY ABSORBING BARRIER
DETAILS

Exhibit 2



TYPICAL GORE – ENERGY ABSORBER TESTS

APPENDIX A - BARRIER DESIGN CALCULATIONS

The test barrier was designed using the procedures outlined in Reference 3. The following conditions were either given or assumed.

Impact velocity (Vi) = 60 mph = 88 fps
Impact angle (θ) = 0° (headon)
Weight of the vehicle at impact (W) = 4690 lbs.
Maximum average deceleration (G avg) = 10 G's
Average deformation of each crushed drum = 0.75 dia. = 18"

The 55 gallon drums chosen for the barrier were approximately 24" in diameter and weighed 38 lbs. The force required to crush each drum was reduced by cutting 7" diameter holes in the 18 gage top and bottom of each drum. The side of each drum was fabricated using 20 gage steel. This particular drum was chosen because it was the lightest standard 55 gallon drum and appeared to have characteristics compatible with those outlined in TTI's research reports.

Calculations

f_s - Static force required to crush a single drum -

No static test data was reported by TTI on this particular combination of drum gage and hole arrangement. Consequently, the static crush force f_s was calculated as follows. Assume that the average load for 18" of deformation is equal to the average load for 20 inches of deformation that was reported by TTI. TTI static tests 10 and 13 were conducted using 18/18 and 18/20 gage drums, respectively, with identical cutout patterns (not single 7" Ø holes). The ratio of the average crush forces, for 20" of deformation, of the 18/20 to the 18/18 drums was $\frac{5688 \text{ lbs.}}{6884 \text{ lbs.}}$ (Reference 3 - Table 6) or 0.825. The average crush force for the 18/18 gage drum with 1-7" Ø hole, top and bottom, was 11,642 lbs. (Reference 3, Table 5, Test 18). Consequently, the calculated average static crush force for the 18/20 combination with 1-7" Ø hole, top and bottom, is (0.825) (11.6) = 9.6 kips. The energy (e_s) consumed during the crushing of this drum to 0.25 of its original 24" diameter is then 9.6 kips x 1.5 ft. = 14.4 kip-feet. However, the energy consumed by the barriers during the full scale tests at TTI was 50% higher than the cumulative static energy absorption capacity of the drums in each barrier. The dynamic energy absorption capacity of each drum, e_d was thus 14.4 x 1.5 = 21.6 kip-feet. Thus the average dynamic crush force, f_d, equals $e_d/0.75d$ = 14.4 kips. The barrier was then designed using the following nomenclature:

KE = kinetic energy of the impacting vehicle = $1/2 \frac{W}{G} Vi^2$ = 565 kip-ft.

N_b - number of drums required = $\frac{KE}{e_d}$ = 26.2 drums say 27

Ls = minimum stopping distance = $\frac{Vi^2}{2g\ G\ avg}$ = 12 feet

L = total barrier length = $\frac{Ls}{0.75}$ = 16 feet

Nr = number of rows of drums = $\frac{Ls}{2\ ft}$ = 8

Nw = number of drums per row for rectangular array = $\frac{Nb}{Nr}$ = 3.38, say 4

Thus, a rectangular array 4 drums wide by 8 drums long should be satisfactory. However, the value used for the static drum crush strength, f_s, was based on calculations rather than test results. Also, it is desirable to decrease the amount of decelerating force applied by the barrier nose to adjust for the smaller vehicle. The barrier design chosen was thus a rectangular array of 8 rows of 4 drums each, preceded by a row of two drums and one "nose" drum. Three additional drums were placed along each side of the bridge approach guardrail to soften any impacts in this area and provide some support for the outside, rear drums. A plywood fendering system was also incorporated in the design. This provided an overall barrier length of 19.6 feet and a theoretical stopping distance of 14.7 feet. Using the procedures outlined in TTI's report, the theoretical decelerating force was calculated (see Plate A-1, next page).

The deceleration data for Test 221 indicated that the barrier had "bottomed out" whereas the calculations indicated there should have been some reserve energy absorption capability available. Also, the actual stopping force curve, as calculated from the vehicular deceleration data (see Plate A-1) indicated that the theoretical energy absorption capacity was not realized. Thus, static crush tests were performed on two drums with 20 gage bodies and one 7 inch diameter hole in their 18 gage tops and bottoms. A plot of force versus deformation was integrated to determine an average value for f_s of 6.7 kips. This produced a value for e_d of 15 kip-ft. and f_d of 10.0 kips for a 1.5 ft. deformation of the drum, significantly less than the 21.6 kip-ft. and 14.4 kip values that had been assumed for the original design.

The required barrier length for Test 221 was then recomputed, taking into account the actual impact velocity of 64 mph (not 60 mph as assumed before the test) with the following results:

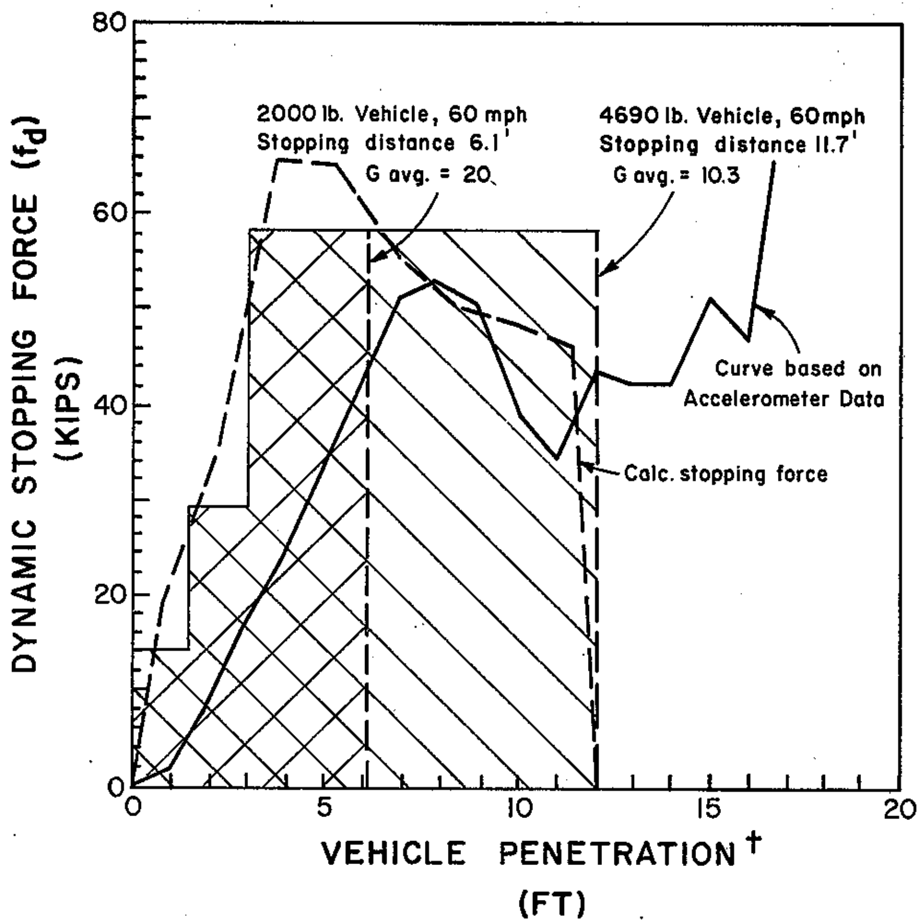
$$KE = \frac{1}{2}\ \frac{(4690)}{(32.2)}\ (94)^2 = 644\ \text{kip-ft.}$$

PLATE A-1

DECELERATING FORCE VS PENETRATION

(Energy Analysis)

55 gallon drum, 18 ga. top & bottom, 20 ga. side, 1 – 7" φ hole in top and bottom. Assume 14.4 Kips/drum decelerating force.



† ASSUMES 18" OF CRUSH PER 24" (nominal) DIAMETER DRUM.

$N_b = \frac{KE}{e_d} = \frac{644}{15} = 42.9$ drums (We had 35 in front of the bridge approach guardrail.)

$$L_s = \frac{V^2}{2g \ G_{avg}} = \frac{(94)^2}{2(32.2)\ (10)} = 13.7 \text{ ft.}$$

$L_t = \frac{13.7}{0.75} = 18'\text{-}3''$ (Our length was 19'-6" in front of the guardrail.

These figures indicate the test barrier, although of sufficient length, did not have an energy absorption capacity equivalent to the kinetic energy of the impacting vehicle. "Bottoming out" would therefore be expected.

APPENDIX B - DATA ACQUISITION, PROCESSING, AND INTERPRETATION

Data from instrumentation on the crash vehicle, dummies and test barrier was transmitted by the Wyle FM Telemetry system or by a hard-wire (umbilical cord) system to a magnetic tape recorder during the crash test. After the test, the data on the tape was played back through a visicorder which produced an oscillographic trace (line) on paper. The visicorder paper also contained the trace of a 100 millisecond time cycle to relate acceleration data to time. In addition, it contained event traces which marked the times when the front and rear wheels passed over tape switches a measured distance from the front of the barrier. With this information, the time of impact could be located on the data traces.

The raw data recorded with the FM telemetry system contained many high frequency spikes. These spikes may have been due to high frequency vibrations in the car body and/or interference by the radio waves generated with the telemetry transmitters located in the test vehicle and are typical of those being reported by many other researchers now active in barrier testing. The reasons for this interference were never firmly established. In an effort to remove the noise, the data were filtered at 20 Hz (20 cycles per second) or 100 Hz. The filtered data was then reproduced on visicorder paper. Plates B1 and B2 (following pages) illustrate the effects of filtering the raw data at 100 Hz and at 20 Hz.

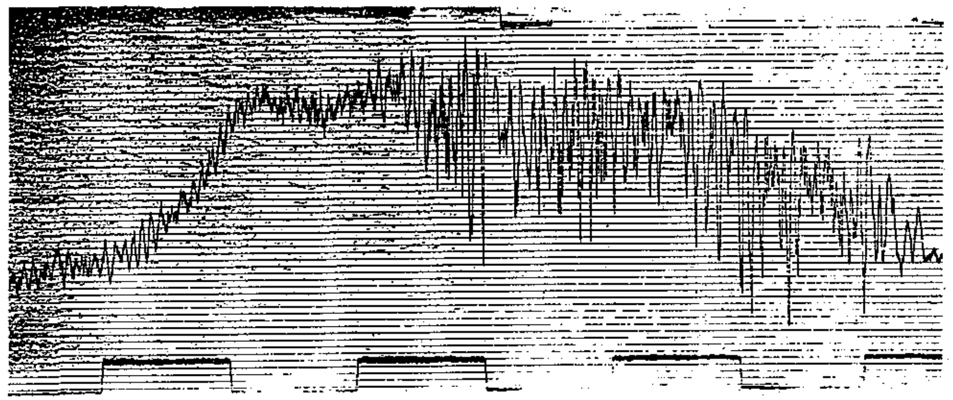
There was no significant difference in the quality of the data transmitted by telemetry and that transmitted by hardwire. Only the filtered traces were used to determine the effectiveness of the barriers tested as it was assumed that no significant data were removed during the filtration process. The choice of the filtration rate required to remove only noise is open to question, however. A discussion of filtering is included in the appendix of reference 6.

There was some lack of confidence in using either the raw data or the filtered data. In using the raw data, it was necessary to fair in a curve through the high frequency spikes before transferring the data to graph paper. A slight vertical shift of this faired in curve (0.1 inch in one case) was enough to alter the total change in velocity significantly (10 feet/sec.). The filtered data showed some spikes of questionable validity on some visicorder traces. It was observed that some of the high frequency ringing that was evident on the unfiltered traces as high thin spikes was unsymmetrical about the zero reference line. Therefore, during filtering, which is an integration process, high peaks of acceleration were produced which did not actually describe the true motion of the car.

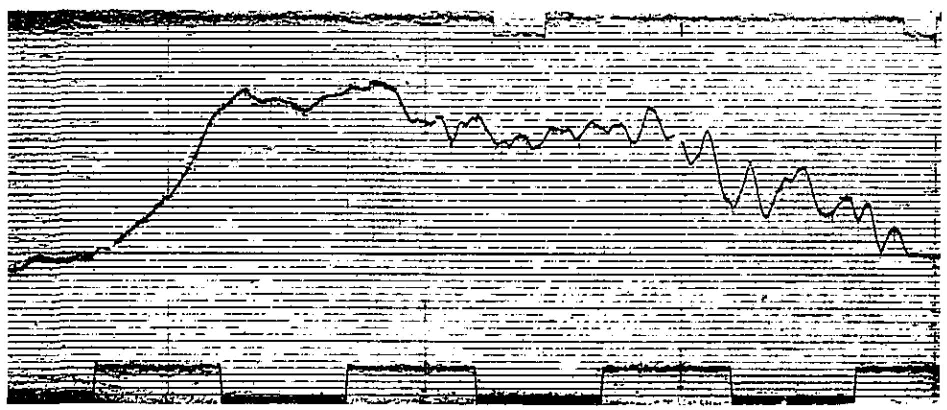
An attempt was made to compare the data from the instrumentation system with that from the film to verify the accuracy of the electronic data. Therefore, the trace of acceleration data was replotted on graph paper to the same scale as that used for the

PLATE B-I

ACCELEROMETER DATA FILTRATION
(100 Hertz)



Unfiltered



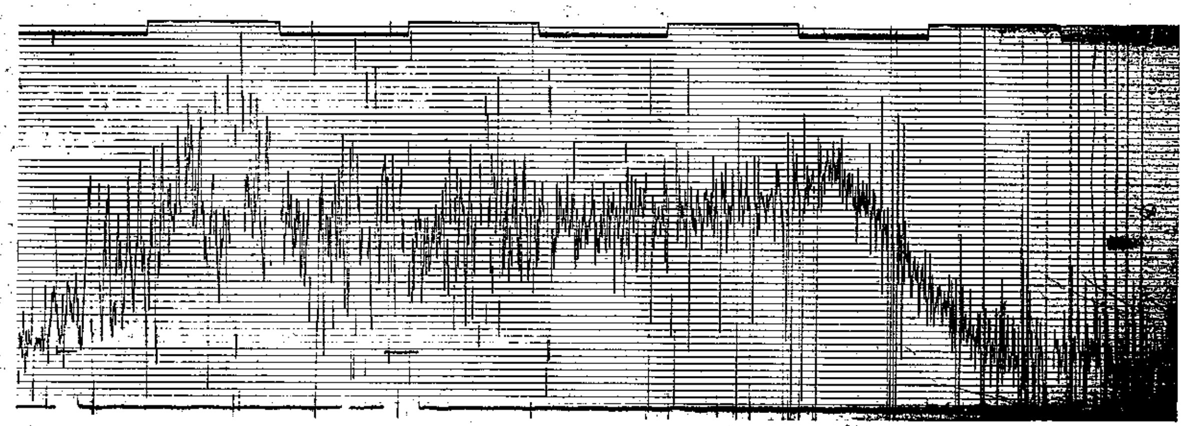
Filtered at 100 Hertz

TEST 223 VEHICLE PASSENGER COMPARTMENT HARDWIRE

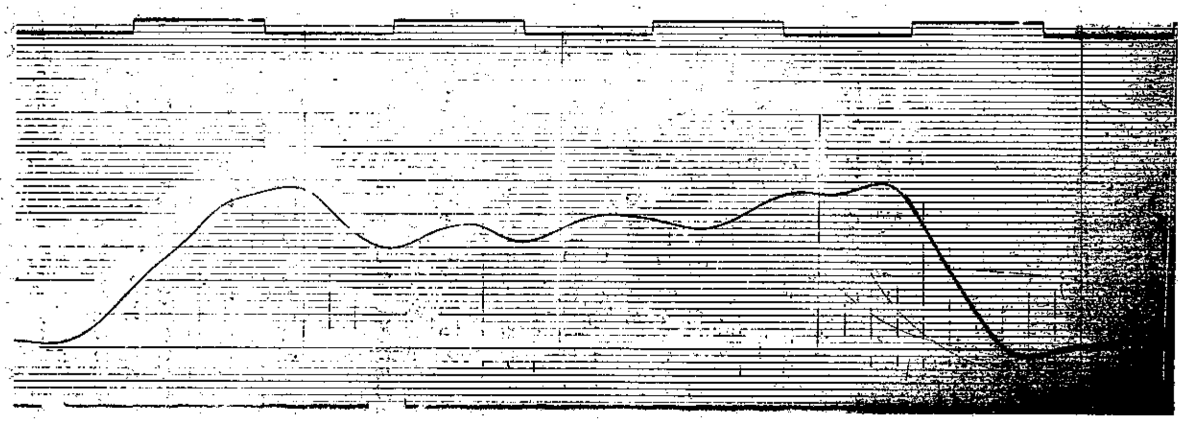
(Longitudinal)

PLATE B-2

ACCELEROMETER DATA FILTRATION
(20 Hertz)



Unfiltered



Filtered at 20 Hertz

TEST 221 VEHICLE PASSENGER COMPARTMENT FM TELEMENTRY

(Longitudinal)

film data. It was found that a 10 millisecond (ms) time interval (5 ms for some traces in Tests 222 and 223) gave a good reproduction of the visicorder trace. This was also about the same interval as that used to plot the photographic data. The relatively good agreement of the electronic and photographic data for Test 221 is described below.

The photographic data (time-displacement) was differentiated to determine velocity and acceleration, a tenuous procedure at best. A more satisfactory procedure is the double integration of the electronic data and subsequent comparison with the photographic time displacement data. This also was attempted but with unsatisfactory results. Due to the time and effort that would have been required, the development and refinement of the double integration procedures was not pursued.

Test 221: Curves of longitudinal acceleration were plotted from the filtered data of two accelerometers and from film data (Plates B3 and B4). The two curves from instrumentation data were very similar initially. However, halfway through impact one of the traces shifted and indicated consistently higher values of acceleration (1-1/2 - 2 G's higher) for the remainder of the event. This resulted in velocity plots that diverged (see Plate B5). The plot of acceleration showed a peak value of about 10 G's at 90 ms after impact, followed by a decrease to approximately 8 G's until the final "bottoming" out peak value of slightly above 10 G's was measured at impact plus 320 ms. The film data (Plate B4) indicated similar but slightly higher accelerations, hovering around 10 G's ± 2 G's from 40 to 300 ms after impact. (The acceleration plot from film data was made with conservatively rounded numbers.) The velocity curves from both the electronic and the photographic data indicated a relatively constant drop in velocity (because of the constant acceleration value). In other words, the barrier appears to have crushed at a constant rate, as assumed in the design procedure (Appendix A).

The accelerometer traces from the dummy (restrained by a lap belt) have a maximum first peak which occurred less than 50 milliseconds after the peak from the vehicle (see Plate B6). The second peak occurred about the same time as that for the vehicle, thus indicating that the "second collision" had taken place. The dummies were then sustaining approximately the same decelerations as the vehicle. The peak acceleration varied between 15 and 20 G's but was of relatively short duration. This was, however, considerably greater than the vehicle deceleration and serves to illustrate the independence of occupant and vehicular decelerations if full restraints are not in use.

Test 222: This test proved interesting in that the comparison of four "lateral" vehicle accelerometer traces was possible (Plate B7). Two accelerometers were located at each of two locations on the floor of the passenger compartment. Data was transmitted by both FM telemetry and hardwire systems. The traces were all very similar except that those transmitted by FM telemetry had a few random spikes during the last 100 ms that were probably a result of telemetry transmission rather than actual deceleration. Also, the values obtained at the vehicle center of gravity (location A) were slightly higher. Traces from three longitudinally directed accelerometers provided similar results in that the traces were somewhat similar and the telemetry data contained some spikes attributed to noise (Plate B8). The traces of the accelerometers in the dummy (restrained by a lap belt) showed very high peaks of 20-35 G's (telemetry transmission) which occurred when the vehicle was redirected by the bridge approach guardrail (Plate B9). These peaks occurred slightly after the peak vehicular decelerations.

Test 223: The longitudinal accelerometer trace from the vehicle shows a fairly uniform deceleration hovering around 9-11 G's (see Plate B10). The peak decelerations measured in the dummy (lap belt restraint) in the longitudinal direction were slightly in excess of 20 G's (Plate B11). The vehicle and dummy traces for Test 223 are quite similar to those for Test 221 with respect to peak values and shapes except that the deceleration pulses decay sooner in Test 223. This is probably due to the lower initial velocity of 54 mph for Test 223 versus 64 mph for Test 221.

Table B1 (following page) shows the loads sustained by the cable system and back-up bridge approach guardrail. The results indicate that all members absorbed a portion of the load, i.e., that the loads were not concentrated within the barrier; no members appeared to be sustaining dangerously high loads; and that the size of barrier members were not overly conservative. High loads might have been expected on the cables in Test 222; however, it appeared as though the vehicle impacted the barrier far enough to the rear so that the main lateral resistance came from the bridge approach guardrail. The cable loads in Test 223 were high, as would be expected, due to the angle impact on the nose of the barrier.

The seat belt load was so low it appeared to be of questionable validity. The seat belt transducer was used in only one test so there was no basis for comparison.

Plates B12-14 contain traces from the Impact-O-Graph for Tests 221, 222 and 223. They are much less descriptive than the accelerometer traces. They do, however, give a general idea of the relative shape and magnitude of deceleration pulses. As was the case with the electronic data, the peaks for the dummy are considerably higher than those for the vehicle.

TABLE NO. B-1

INSTRUMENTATION RESULTS

	Load Cell-Cable* (lb.)	% Distrib.	Strain-Gage** Bridge Approach Guardrail (psi)	% Distrib.
Test #221				
Top-Left	3510	13%	4950 C,T	15%
Top-Right	5010	18	12300 T	37
Bottom-Left	7460	27	6600 T	20
Bottom-Right	11500	42	9600 C	28
Totals	27480	100%		100%
Test #222				
Top-Left	1460	15%	5400 C	26%
Top-Right	2330	23	6900 T	34
Bottom-Left	1630	16	3480 C	17
Bottom-Right	4520	46	4710 T	23
Totals	9940	100%		100%
Test #223				
Top-Left	20800	29%	8400 T	22%
Top-Right	No Load Cell	(Assume 25%)	15300 T	40
Bottom-Left	18200	25	6300 T	16
Bottom-Right	15100	21	8650 T	22
Totals	54100 (3 cables)	100%		100%

* Includes 500# pre-load in Tests #221 and #222, and 1000# pre-load in Test #223.

** C = Compression, T = Tension

Seat Belt - Test #221 - Stan - 525# load

Poor Data - Accelerometers - Barrier Panels - Test #221
Strain Gages - Barrier Panels - Test #222

PLATE B-3

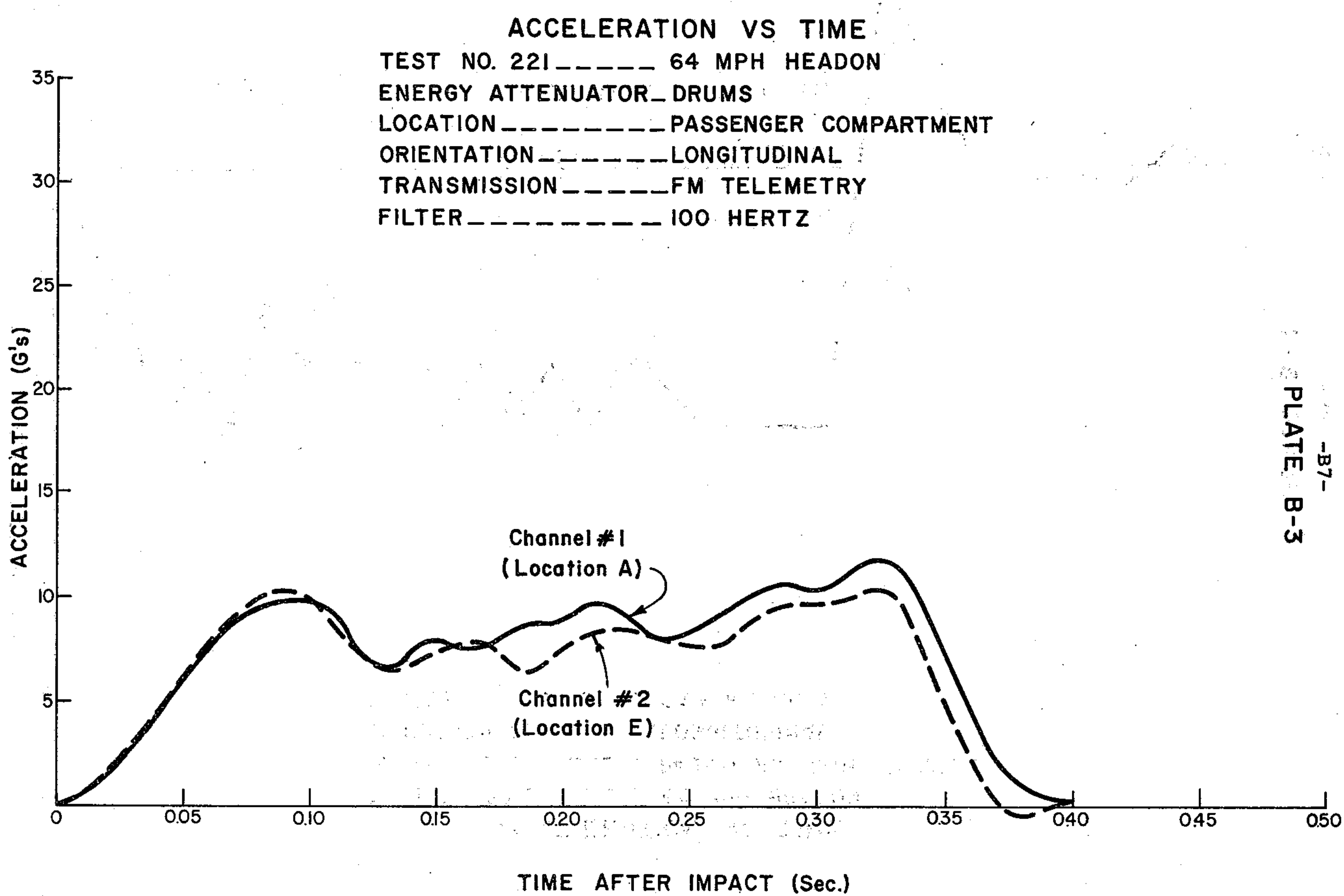

ACCELERATION VS TIME
TEST NO. 221 ______ 64 MPH HEADON
ENERGY ATTENUATOR _ DRUMS
LOCATION __________ PASSENGER COMPARTMENT
ORIENTATION ________ LONGITUDINAL
TRANSMISSION ______ FM TELEMETRY
FILTER __________ 100 HERTZ
ACCELERATION (G's)
35
30
25
20
15
10
5
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Channel #1 (Location A)
Channel #2 (Location E)
TIME AFTER IMPACT (Sec.)

PLATE B-4

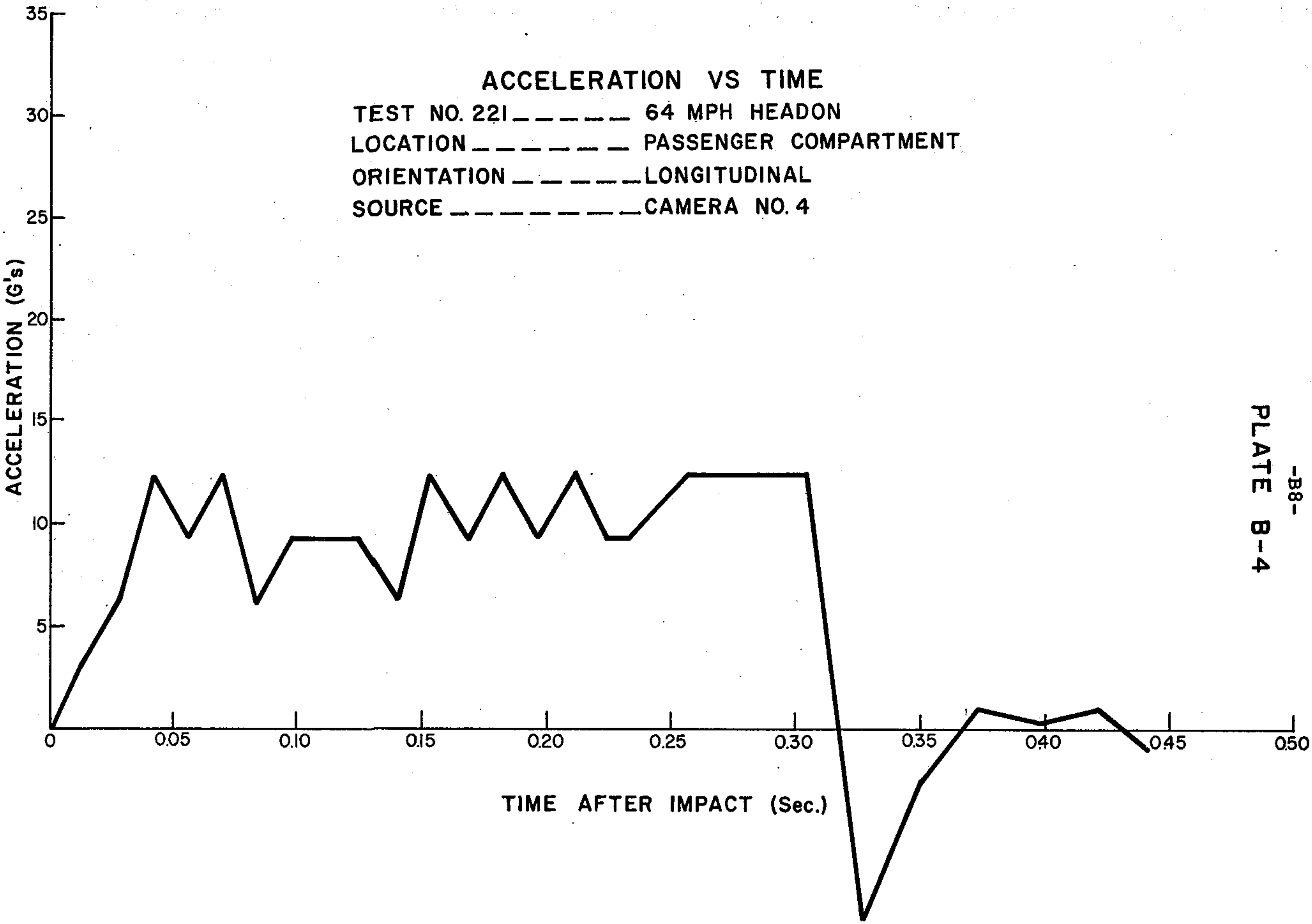

ACCELERATION VS TIME
TEST NO. 221 — 64 MPH HEADON
LOCATION — PASSENGER COMPARTMENT
ORIENTATION — LONGITUDINAL
SOURCE — CAMERA NO. 4
ACCELERATION (G's)
35
30
25
20
15
10
5
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
TIME AFTER IMPACT (Sec.)

PLATE B-5

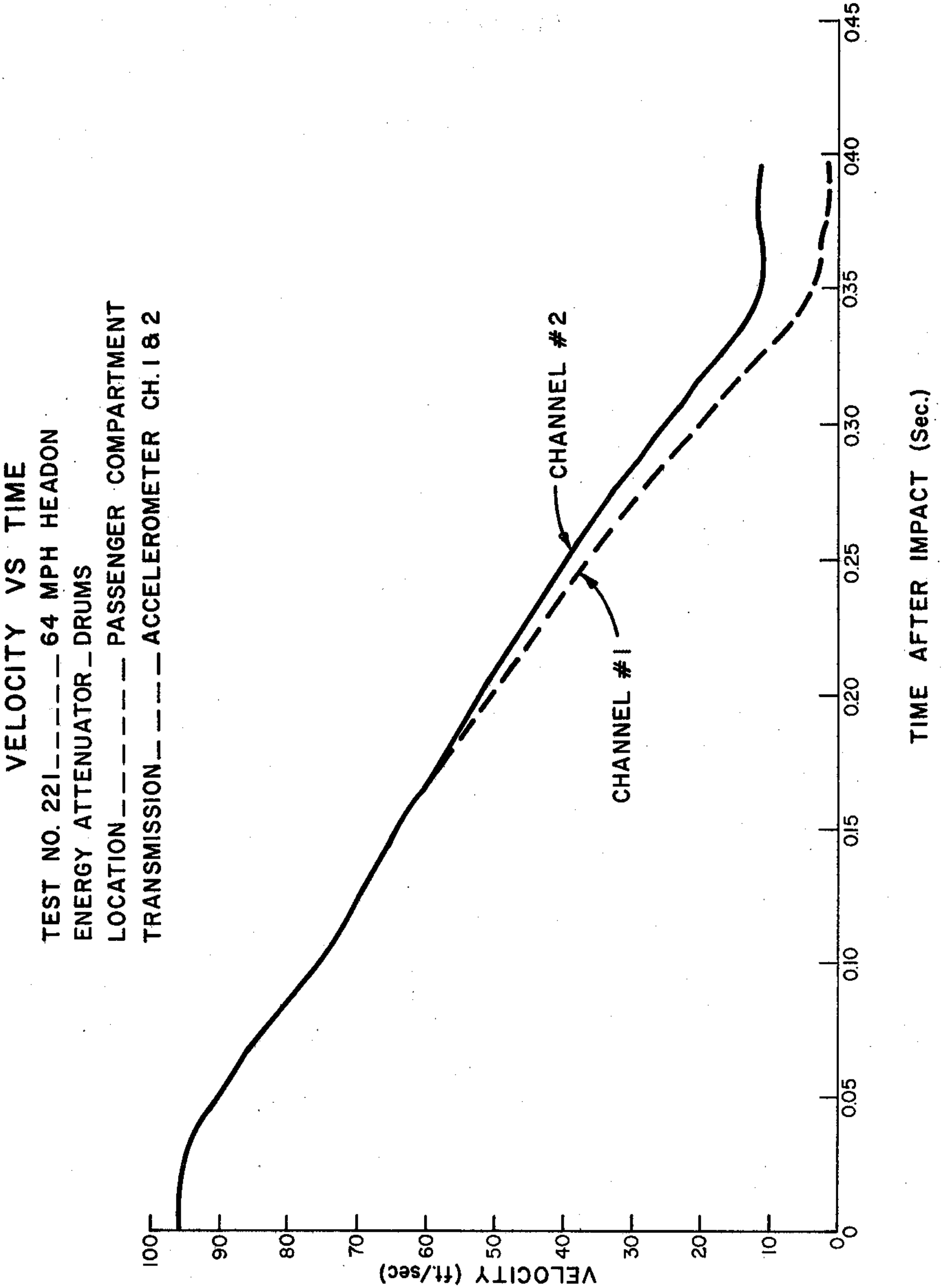

VELOCITY VS TIME
TEST NO. 221______64 MPH HEADON
ENERGY ATTENUATOR_DRUMS
LOCATION________PASSENGER COMPARTMENT
TRANSMISSION______ACCELEROMETER CH. 1 & 2
CHANNEL #2
CHANNEL #1
VELOCITY (ft./sec)
100
90
80
70
60
50
40
30
20
10
0
TIME AFTER IMPACT (Sec.)
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45

PLATE B-6

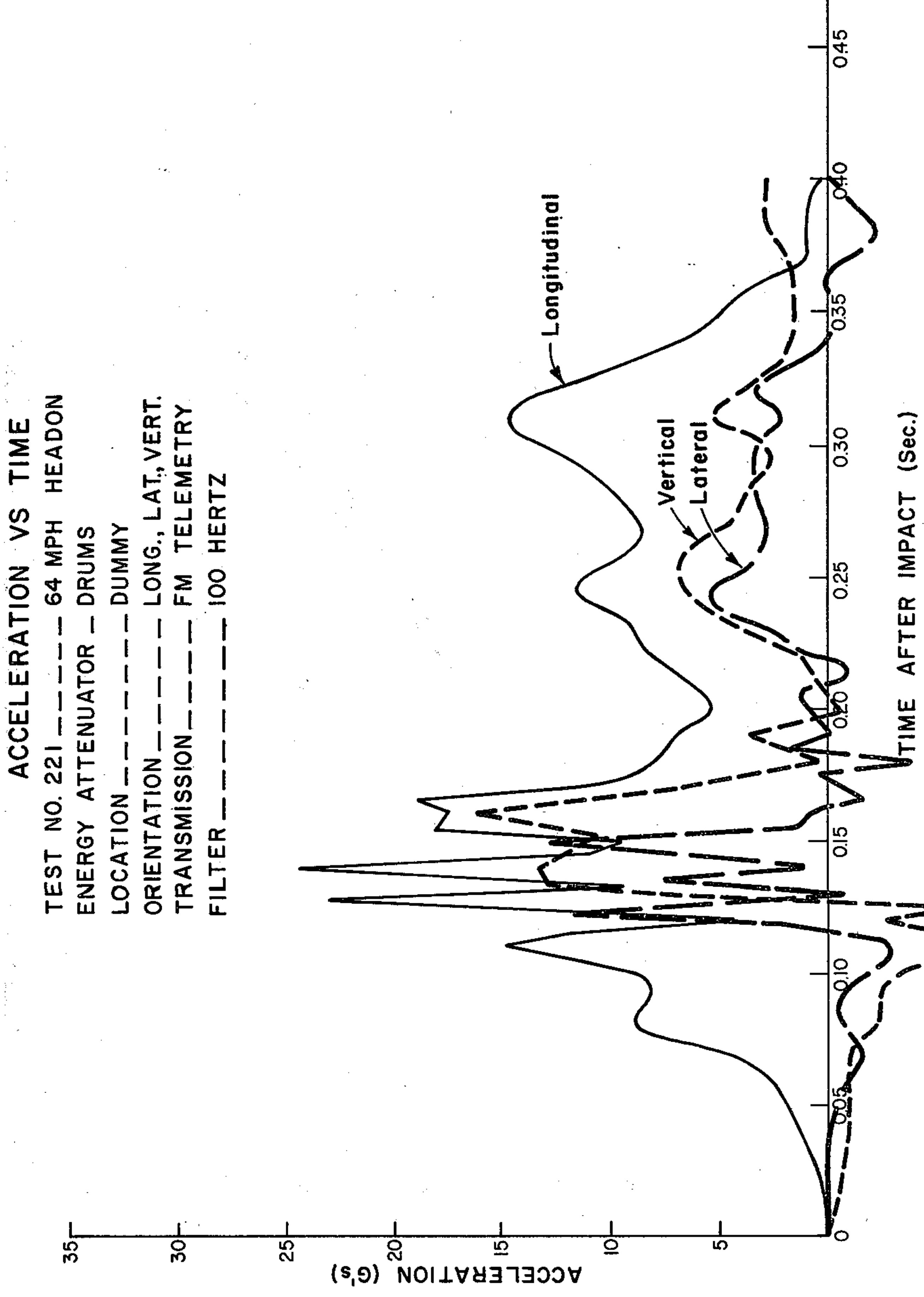

ACCELERATION VS TIME
TEST NO. 221 ———— 64 MPH HEADON
ENERGY ATTENUATOR — DRUMS
LOCATION ———— DUMMY
ORIENTATION ———— LONG., LAT., VERT.
TRANSMISSION ———— FM TELEMETRY
FILTER ———— 100 HERTZ
Longitudinal
Vertical
Lateral
TIME AFTER IMPACT (Sec.)
ACCELERATION (G's)
0
5
10
15
20
25
30
35
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45

PLATE B-7

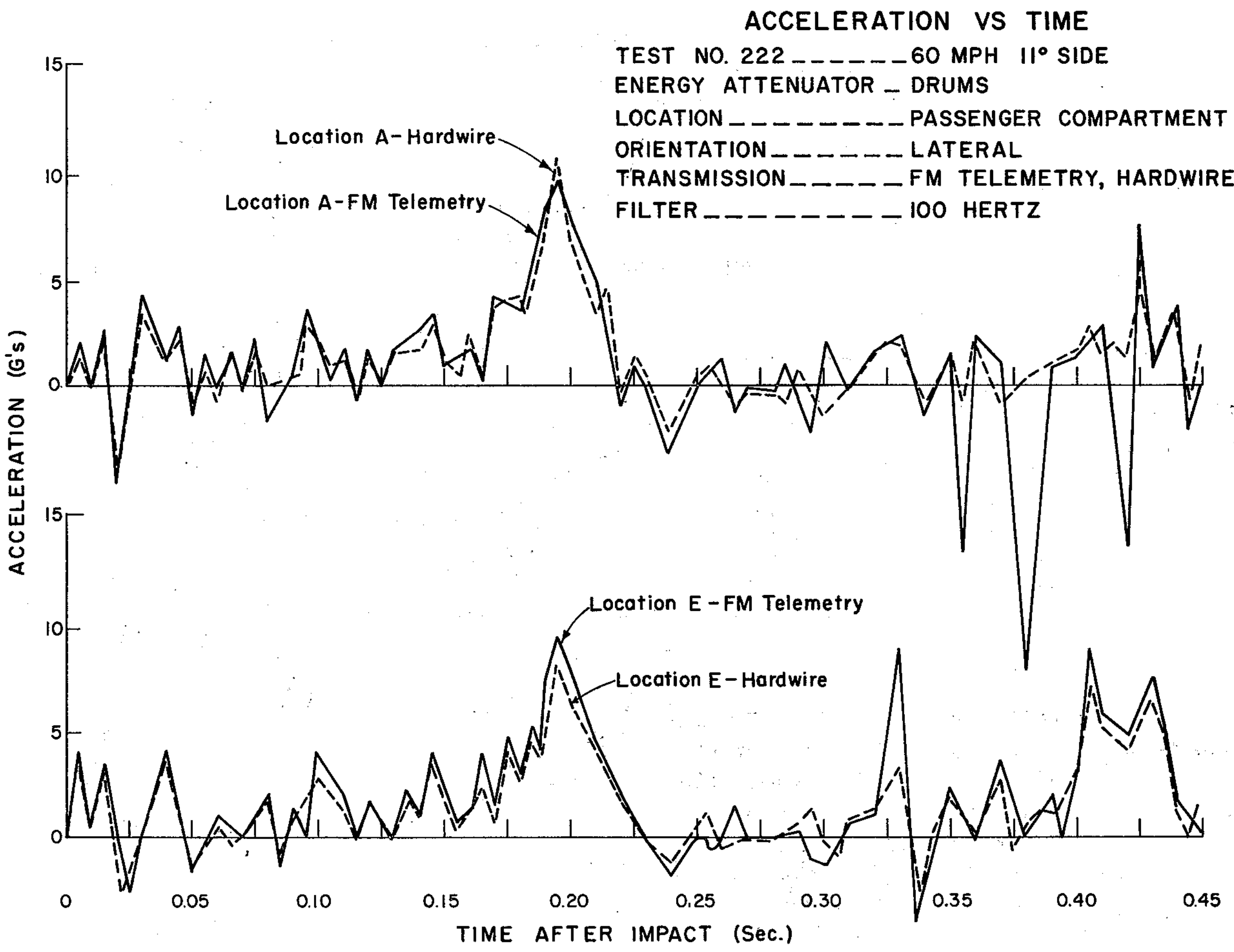
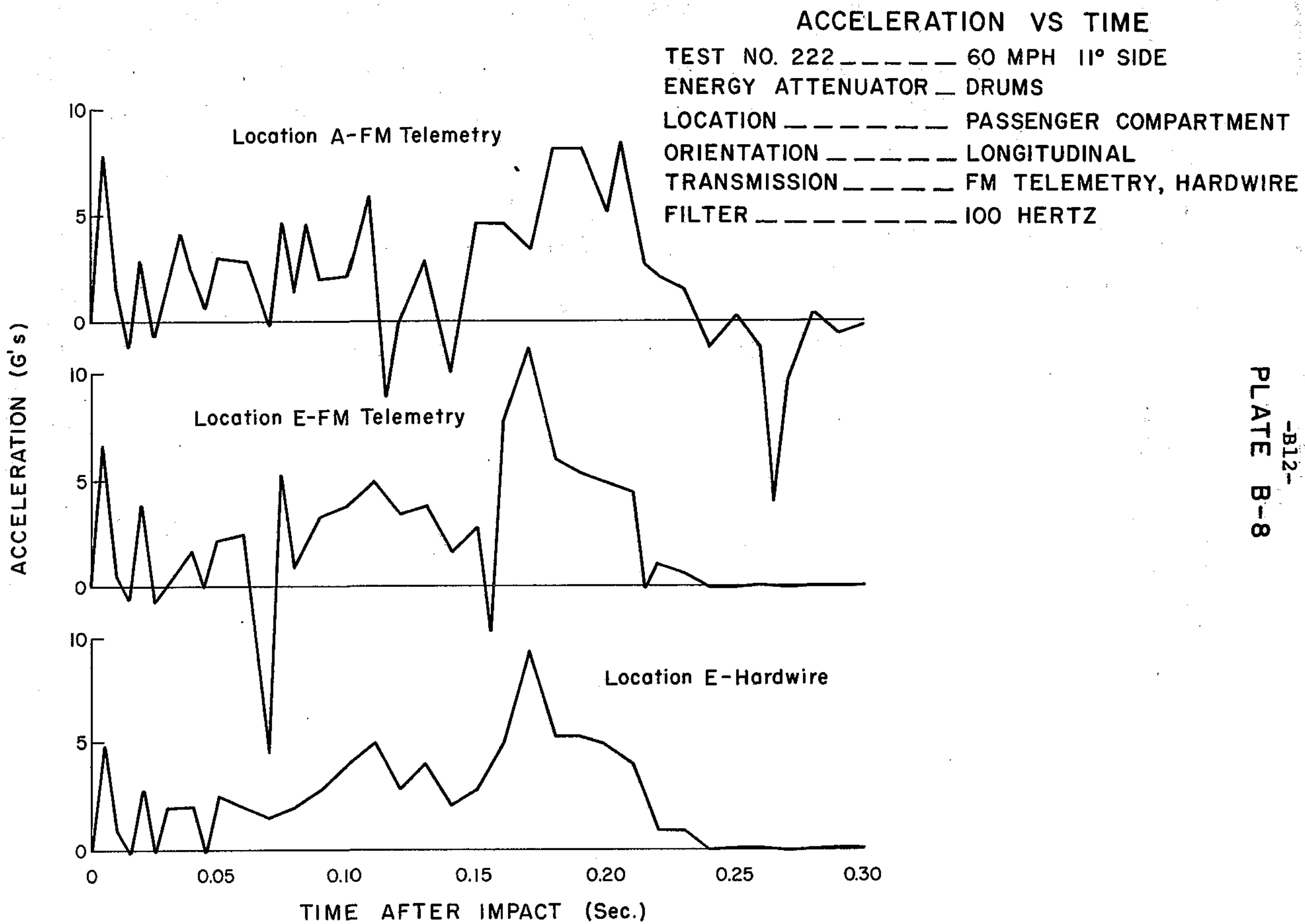

ACCELERATION VS TIME
TEST NO. 222 — — — — — — 60 MPH 11° SIDE
ENERGY ATTENUATOR — DRUMS
LOCATION — — — — — — — — — PASSENGER COMPARTMENT
ORIENTATION — — — — — — — LATERAL
TRANSMISSION — — — — — — FM TELEMETRY, HARDWIRE
FILTER — — — — — — — — — — 100 HERTZ
Location A-Hardwire
Location A-FM Telemetry
Location E-FM Telemetry
Location E-Hardwire
ACCELERATION (G's)
15
10
5
0
15
10
5
0
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
TIME AFTER IMPACT (Sec.)

PLATE B-8



ACCELERATION VS TIME
TEST NO. 222 ______ 60 MPH 11° SIDE
ENERGY ATTENUATOR _ DRUMS
LOCATION ________ PASSENGER COMPARTMENT
ORIENTATION ______ LONGITUDINAL
TRANSMISSION _____ FM TELEMETRY, HARDWIRE
FILTER __________ 100 HERTZ
Location A-FM Telemetry
Location E-FM Telemetry
Location E-Hardwire
ACCELERATION (G's)
10
5
0
0
0.05
0.10
0.15
0.20
0.25
0.30
TIME AFTER IMPACT (Sec.)

PLATE B-9

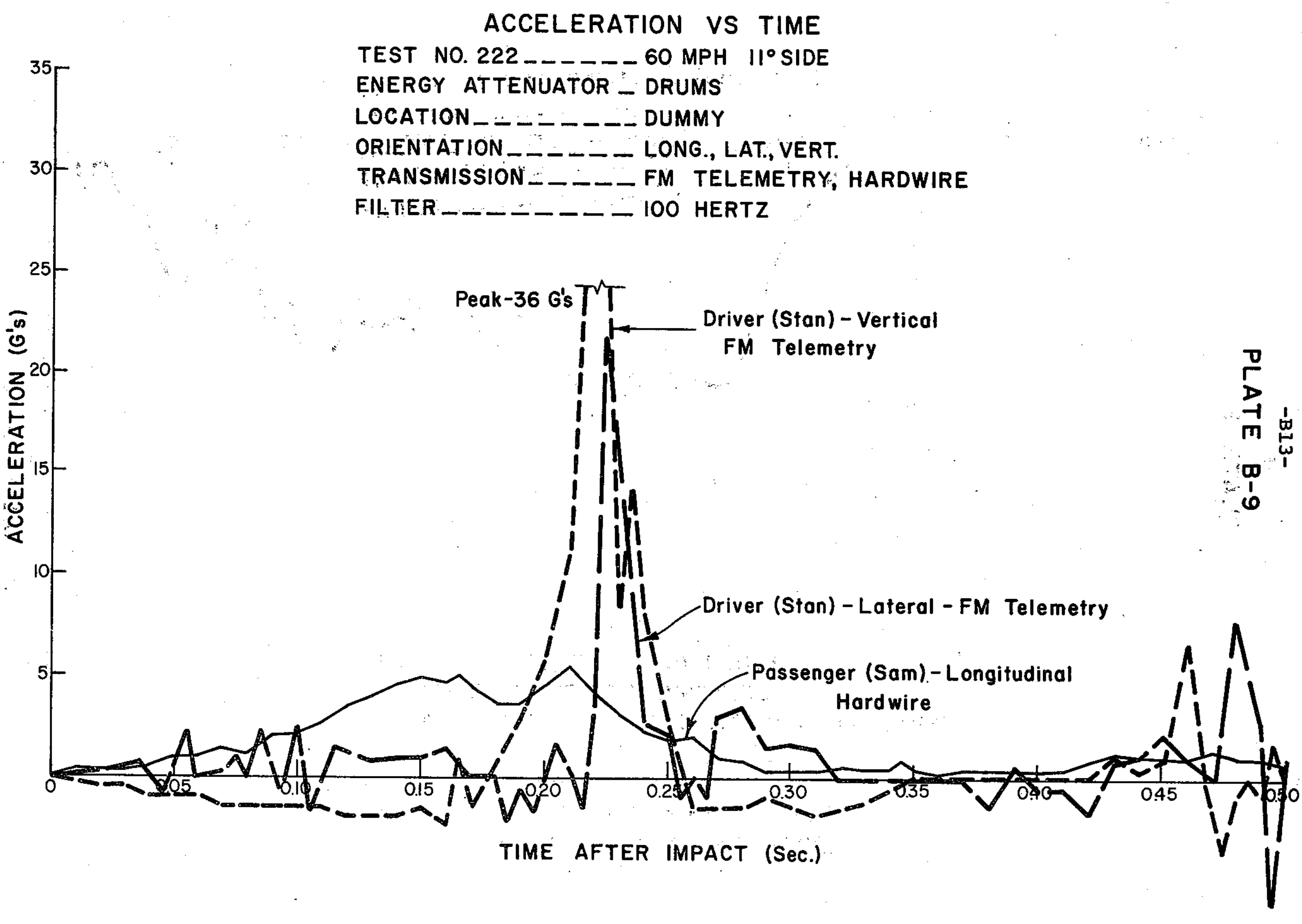

ACCELERATION VS TIME
TEST NO. 222 ------ 60 MPH 11° SIDE
ENERGY ATTENUATOR _ DRUMS
LOCATION --------- DUMMY
ORIENTATION ------- LONG., LAT., VERT.
TRANSMISSION ------ FM TELEMETRY, HARDWIRE
FILTER ---------- 100 HERTZ
Peak-36 G's
Driver (Stan) - Vertical
FM Telemetry
Driver (Stan) - Lateral - FM Telemetry
Passenger (Sam) - Longitudinal
Hardwire
ACCELERATION (G's)
35
30
25
20
15
10
5
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
TIME AFTER IMPACT (Sec.)

PLATE B-10

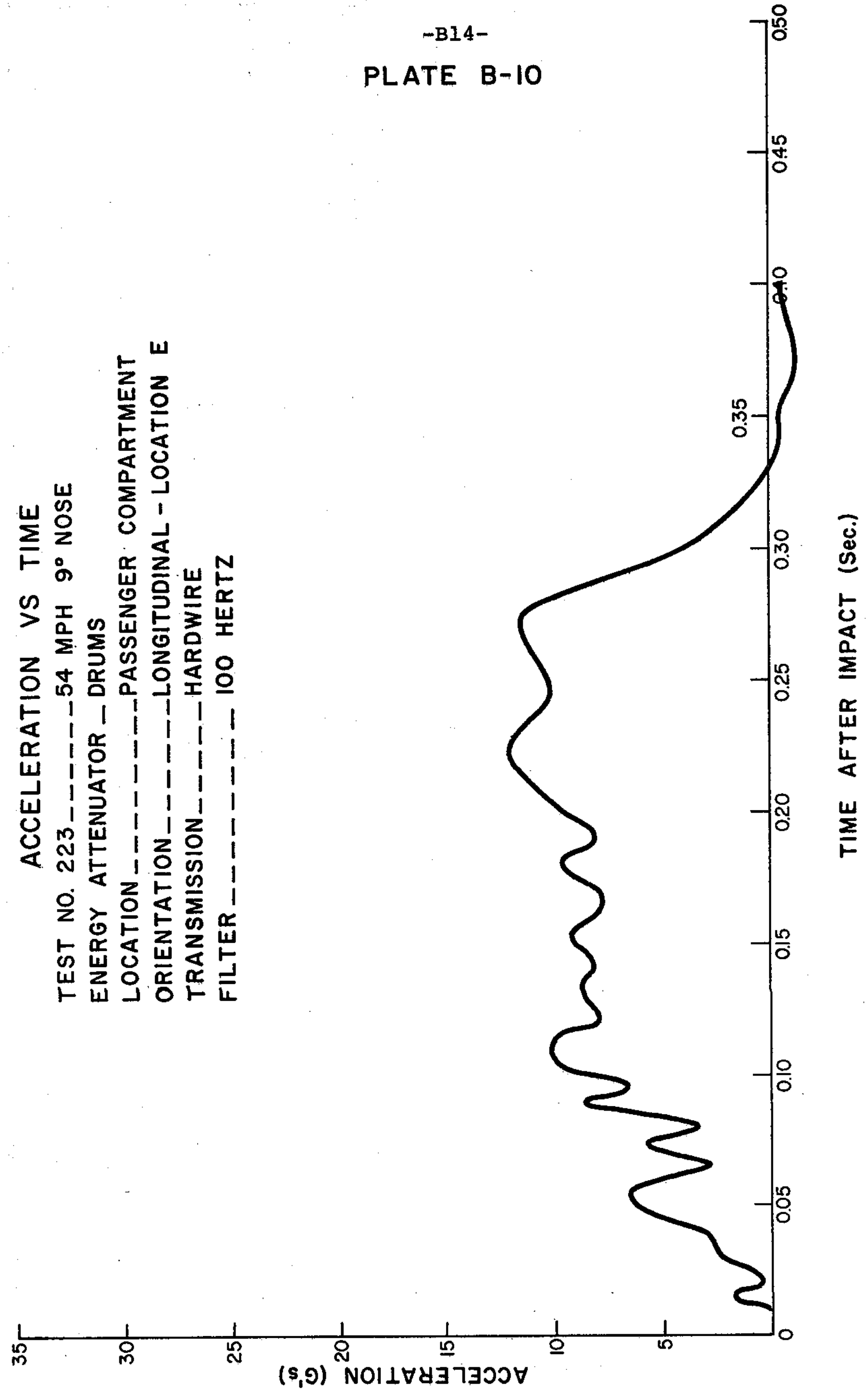

ACCELERATION VS TIME
TEST NO. 223 - - - - - - - 54 MPH 9° NOSE
ENERGY ATTENUATOR _ DRUMS
LOCATION - - - - - - - - - PASSENGER COMPARTMENT
ORIENTATION - - - - - - - LONGITUDINAL - LOCATION E
TRANSMISSION - - - - - - HARDWIRE
FILTER - - - - - - - - - - - 100 HERTZ
ACCELERATION (G's)
35
30
25
20
15
10
5
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
TIME AFTER IMPACT (Sec.)

PLATE B-11

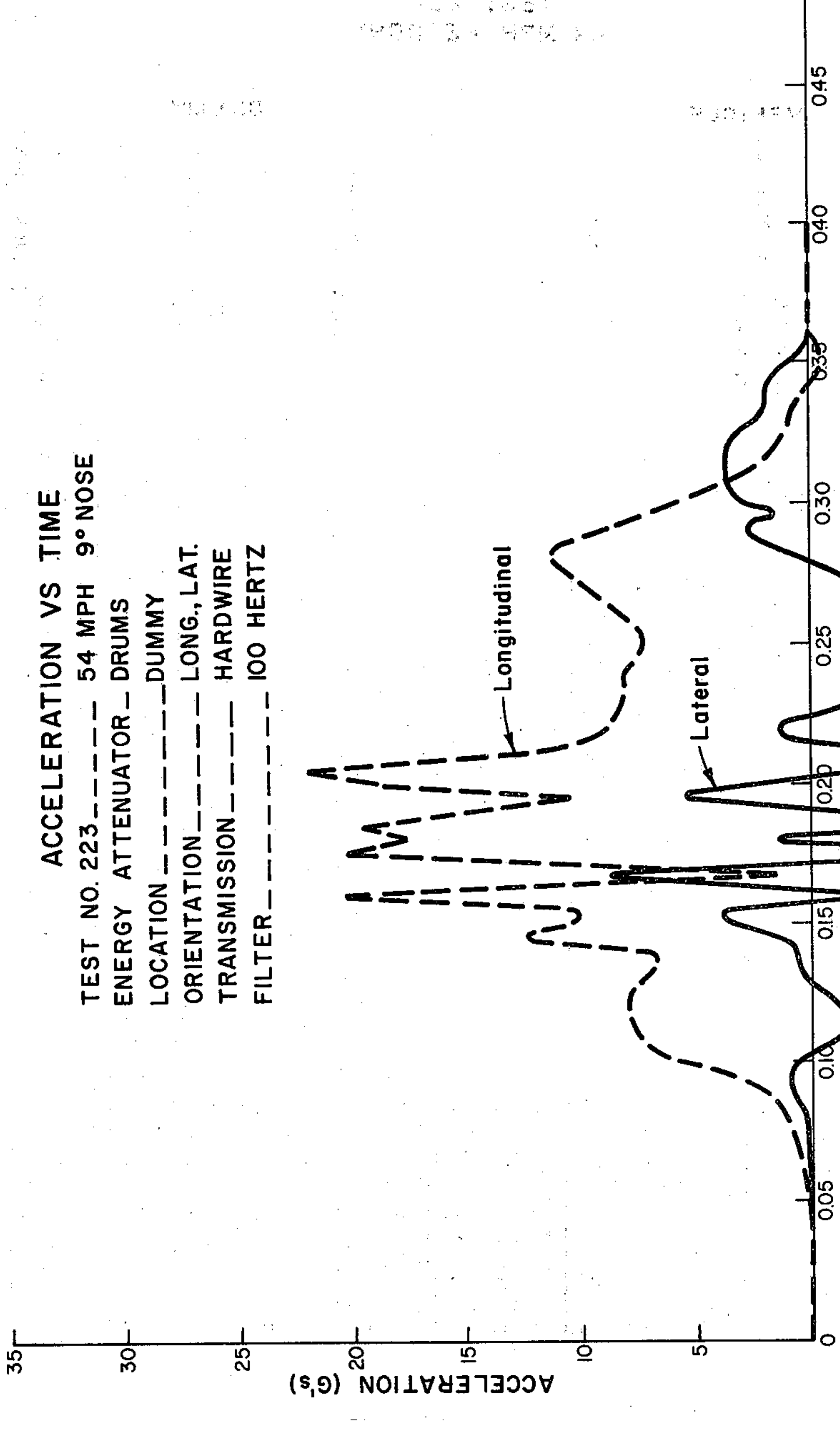

ACCELERATION VS TIME
TEST NO. 223 ------ 54 MPH 9° NOSE
ENERGY ATTENUATOR_ DRUMS
LOCATION ---------- DUMMY
ORIENTATION ------- LONG., LAT.
TRANSMISSION ------ HARDWIRE
FILTER ------------ 100 HERTZ
Longitudinal
Lateral
ACCELERATION (G's)
0
5
10
15
20
25
30
35
TIME AFTER IMPACT (Sec.)
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50

PLATE B-12
TEST 221
(64 MPH HEADON)

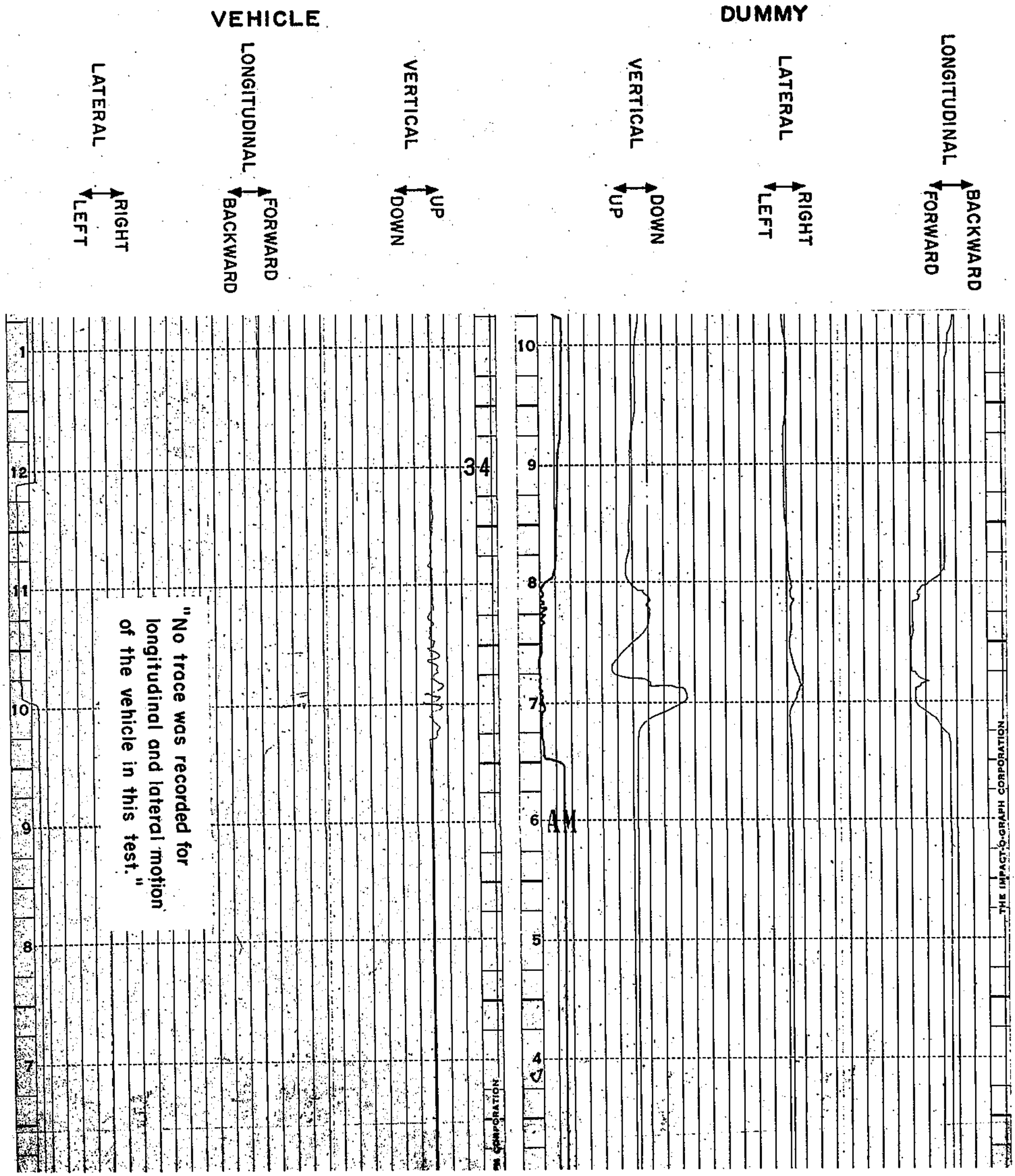


PLATE B-13
TEST 222
(60 MPH 11° SIDE)

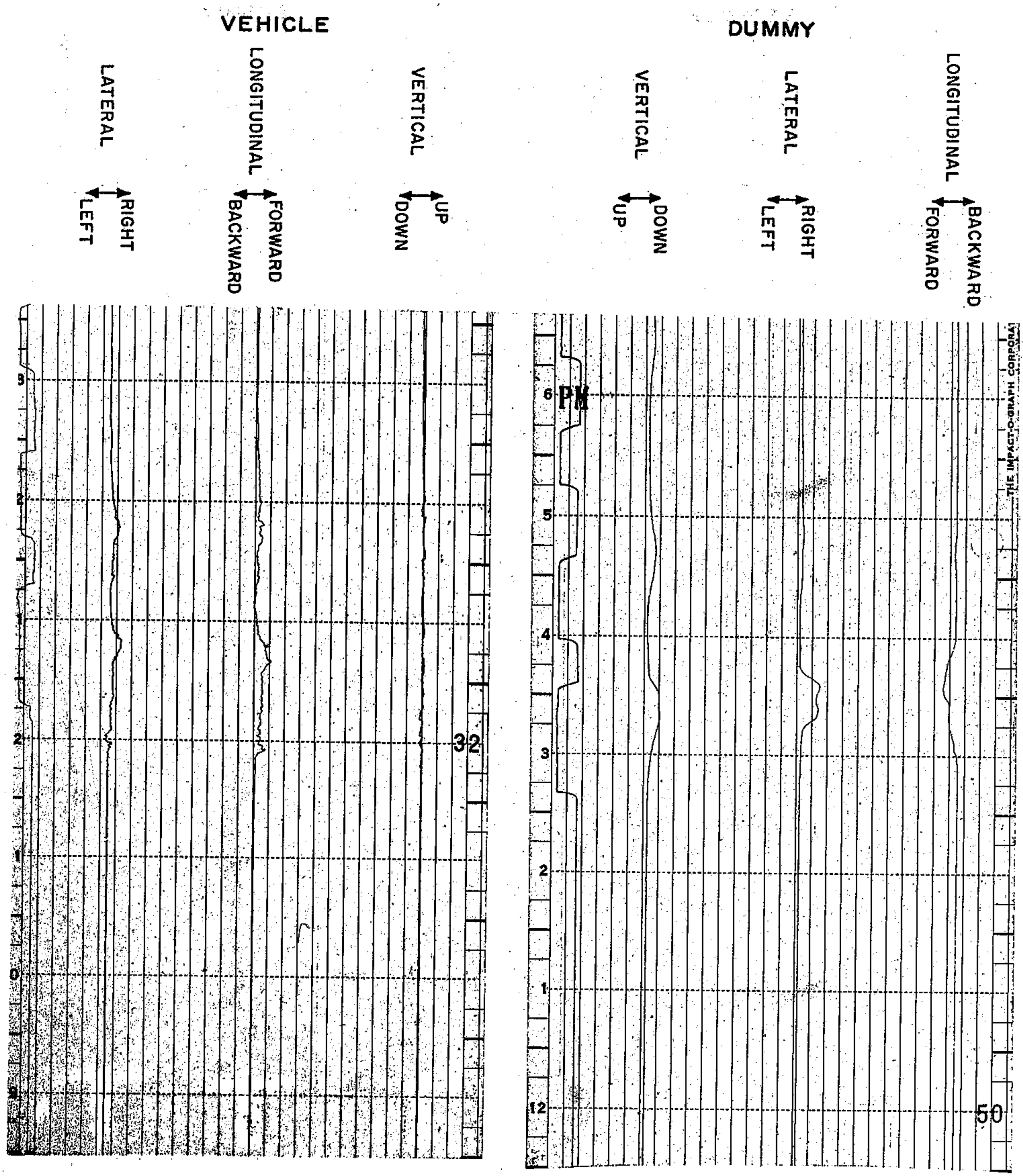


PLATE B-14
TEST 223
(54 MPH 9° NOSE)