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16. Abstract

Four full-scale crash tests were conducted on inertia barriers using scrap tires as containers for the sand mass. The first barrier utilized additional tires with empty beverage cans in the annular space and banded together for a support base. The bases of scrap tires collected under the front of the impacting vehicle and caused it to ramp upward. The second scrap tire-sand barrier was tested in which the modules were supported by a 14 gage welded wire cage. This inertia barrier performed satisfactorily. The ramping of the vehicle was eliminated and the vehicle was stopped smoothly. In the third and fourth tests the supports were fabricated from used 55 gal paint drums. When the chimes and tops and bottoms were removed and a series of vertical cuts made in the drum, the barrier performed satisfactorily. There was a slight tendency toward vertical ramping, but the vehicle was stopped smoothly.

17. Key Words Vehicle impact attenuation, scrap tires, sand, inertia barrier	18. Distribution Statement

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FULL SCALE CRASH TESTS
OF A
TIRE-SAND INERTIA BARRIER

by

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Research Report 146-12
Studies of Field Adaptation of Impact
Attenuation Systems

Research Study Number 2-10-68-146

Sponsored by
The Texas Highway Department
in cooperation with
The United States Department of Transportation
Federal Highway Administration

March 1975

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

LIST OF TABLES

DISCLAIMER

ABSTRACT

Four full-scale crash tests were conducted on inertia barriers using scrap tires as containers for the sand mass. The first barrier utilized additional tires with empty beverage cans in the annular space and banded together for a support base. The bases of scrap tires collected under the front of the impacting vehicle and caused it to ramp upward. The second scrap tire-sand barrier was tested in which the modules were supported by a 14 gage welded wire cage. This inertia barrier performed satisfactorily. The ramping of the vehicle was eliminated and the vehicle was stopped smoothly. In the third and fourth tests the supports were fabricated from used 55 gal paint drums. When the chimes and tops and bottoms were removed and a series of vertical cuts made in the drum, the barrier performed satisfactorily. There was a slight tendency toward vertical ramping, but the vehicle was stopped smoothly.

Key Words: Vehicle impact attenuation, scrap tires, sand, inertia barrier

ACKNOWLEDGEMENTS

This study was conducted under a cooperative program between the Texas Transportation Institute and the Texas Highway Department. It was sponsored by the Texas Highway Department and the Federal Highway Administration. Liaison was maintained through Mr. John F. Nixon of the Texas Highway Department and Mr. Edward V. Kristaponis of the Federal Highway Administration.

The wire cage to support the various modules was conceived of and designed by Monroe C. White, Assistant Research Engineer with the Texas Transportation Institute. The use of used paint drums for supports of the modules was conceived by personnel of District 15 of the Texas Highway Department and refined by Researchers from the Texas Transportation Institute. The crash tests and evaluation were carried out by personnel of the Highway Safety Research Center of the Texas Transportation Institute.

IMPLEMENTATION STATEMENT

A vehicle impact attenuator utilizing scrap automobile tires filled with sand has been successfully tested. The tire units are stacked on 3/8" plywood discs supported by wire cages fabricated from 14 ga. 1" x 2" galvanized welded wire fabric or supported by portions of used 55 gal paint drums. The wire cage support insures that no upward force component is produced on impact and that an orderly vehicle attenuation is achieved.

In three series of tests with light and heavy vehicles, the sand-tire attenuator system, weighing approximately 9,600 pounds, smoothly stopped vehicles traveling at 60 mph. The decelerations produced in these tests were all tolerable to the unrestrained occupants. Re-installation of the attenuator could proceed rapidly since no additional site preparation was required, all of the tires were reusable, and much of the sand salvable.

The estimated cost of this sytem is approximately $850, which includes labor and materials for fabrication of the wire cages and installation of the units filled with sand. This economical attenuator is an ideal system for protecting motorists from the low incident off-the-road hazard sites where tire and sand scatter will not be a secondary hazard to other vehicles.

A seven-minute film and 35 mm slides illustrating these tests and plan sheets detailing its construction are available from The Texas Highway Department, Planning and Research Division, D-10, Austin, Texas.

INTRODUCTION

There are many rigid obstacles on our nation's highways which cannot be removed or made breakaway and consequently are hazardous to the motoring public. Vehicle impact attenuators have been developed to protect the motoring public from impacting these obstacles directly. In general, most of these attenuators are expensive and some obstacles remain unprotected since available funds are directed to protecting more "cost effective" locations. This study was undertaken to develop an inexpensive and effective barrier which could be employed to protect motorists from many hazards located near our highways.

Two previous studies had been made (1, 2) to show that a vehicle impact attenuator composed of scrap tires filled with sand was effective and feasible. The conclusions expressed in both reports were that the tire-sand inertia barrier was both effective and economical for selective locations. Also the bases should be constructed so that they will not "build-up" under the impacting vehicle and cause ramping. Three base designs meeting this criterion were considered. First, the base would be stiff, light and an integral part of the module and thus be knocked out of the way during impact. Second, the base and sand container would be frangible so that it would fragment on impact. Third, the base would collapse on impact and slide under the impacting vehicle without causing ramping.

Bases composed of scrap tires with the annular space filled with empty metal beverage cans, bases composed of welded wire mesh and bases composed of portions of used 55 gal paint drums were investigated in this study.

DESIGN OF THE TIRE-SAND INERTIA BARRIER

The design of an inertia barrier is based on the conservation of momentum and has been documented by Hirsch (1) and Marquis et al. (2). In addition, Hirsch has discussed the principle extensively in various publications and presentations (3, 4). D. Leon Hawkins of the Texas Highway Department, Bridge Division, first conceived of the idea of using scrap or salvage tires filled with sand as a vehicle impact attenuator in December 1965. At that time, Mr. Hawkins proposed using modules around high level lighting standards and proposed this in a sketch (11).

Development of Design Equations

The concept of the conservation of momentum is illustrated in Figure 1. The momenta before impact are equal to the momenta after impact. For rigid body plastic impact (i.e. the coefficient of restitution is zero).

$$V_o M = V_1 \ (M + M_1)$$

where

V_o = the velocity of the vehicle before impact,

V_1 = the velocity of the vehicle and first mass after impact,

M = the mass of the impacting vehicle W/g,

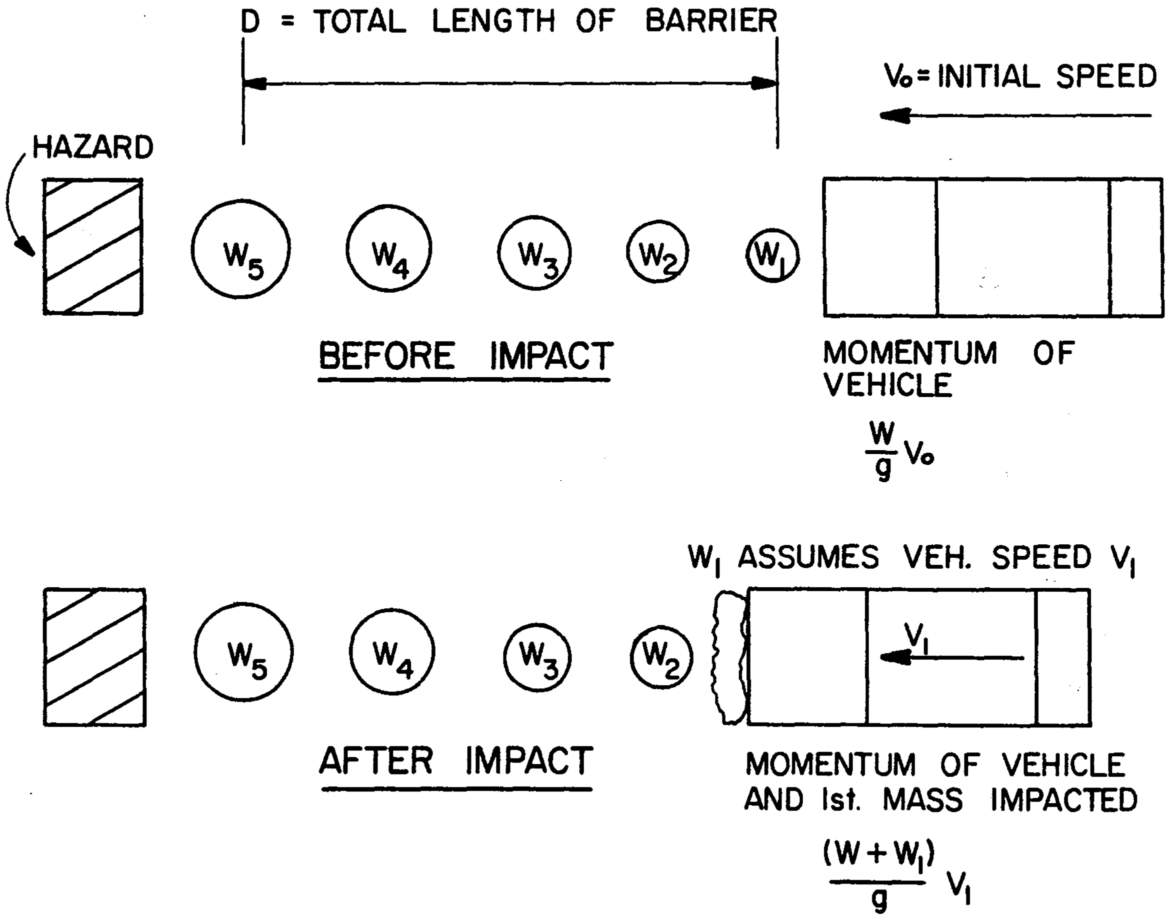
M_1 = the mass of the impacted module W_1/g, and

g = acceleration due to gravity.

Multiplying both sides of the equation by g and solving for V_1 gives

$$V_1 = V_o \quad \frac{W}{W + W_1}$$

Assuming that the first mass impacted (W_1) remains independent of the vehicle.



MOMENTA BEFORE IMPACT = MOMENTA AFTER IMPACT

$$W V_o = (W + W_1) V_1$$

$$V_1 = V_o \left(\frac{W}{W+W_1} \right)$$

FIGURE 1 PRINCIPLE OF TRANSFERRING VEHICLE MOMENTUM TO EXPENDABLE MASSES-ASSUMING PLASTIC RIGID BODY IMPACT.

The vehicle speed after second mass impact is

$$V_2 = V_1 \left(\frac{W}{W + W_2}\right)$$

The vehicle speed after the ith mass impact is

$$V_i = V_{i-1} \left(\frac{W}{W + W_i}\right) \tag{1}$$

If "s" is defined as the distance between the expendable mass centers the average deceleration between the masses is

$$G = \frac{v_{i-1}^{2} - v_i^{2}}{2gs} \tag{2}$$

For design purposes, the above equation may be solved for v_i as the minimum velocity to maintain an average specified deceleration G for spacing "s" giving.

$$v_i = \sqrt{v_{i-1}^2 - 2Ggs} \tag{3}$$

The weight of the module can be obtained by solving for W_i by

$$W_i = \frac{W\ (V_{i-1} - V_i)}{V_i} \tag{4}$$

It is apparent that theoretically the vehicle cannot be stopped completely by this principle. Practically, however, it is usually adequate to design the Inertia Barrier to reduce the vehicle speed to about 10 mph.

The remaining energy is dissipated by "ploughing" action (1, 2, 10) from sand and additional modules placed in the vehicle path.

Development of Statistical Data and Standard Modules

Since scrap automobile tires vary in size and weight, statistical data were needed for design purposes. Hirsch (1) collected one hundred twenty-four (124) 14 in. and 15 in. used automobile tires from a disposal area in Brazos County in order to determine their average weight, diameter, weight and height filled with sand. The average weight of the tires was 18.5 lbs and the standard deviation 3.8 lbs. The outside diameters of the tire ranged from 25.5 in. to 27.5 in. with an average of 26.25 in. being adequate for design purposes. After determining the above data, the tires were filled with sand and weighed. The procedure was to fill a tire, weigh it, and measure the thickness. A second tire was placed on the first filled with sand and the combination weighed and measured. The process was repeated until the stack was four tires high. The process was continued until 108 tires were processed. The average total weight of the tires filled with sand was 228 lbs (230 lbs was used for design) with a standard deviation of 23.54 lbs. The average height for tires filled with sand was 7.5 in. The average height for empty tires was 5.5 in.

These data led to the development of standard modules as shown in Figure 2. The lightest module - 150 to 230 lbs - is used on the nose of the barrier. This is the only module in which the average weight will vary. The variation may be accomplished easily using a 1 cu-ft container

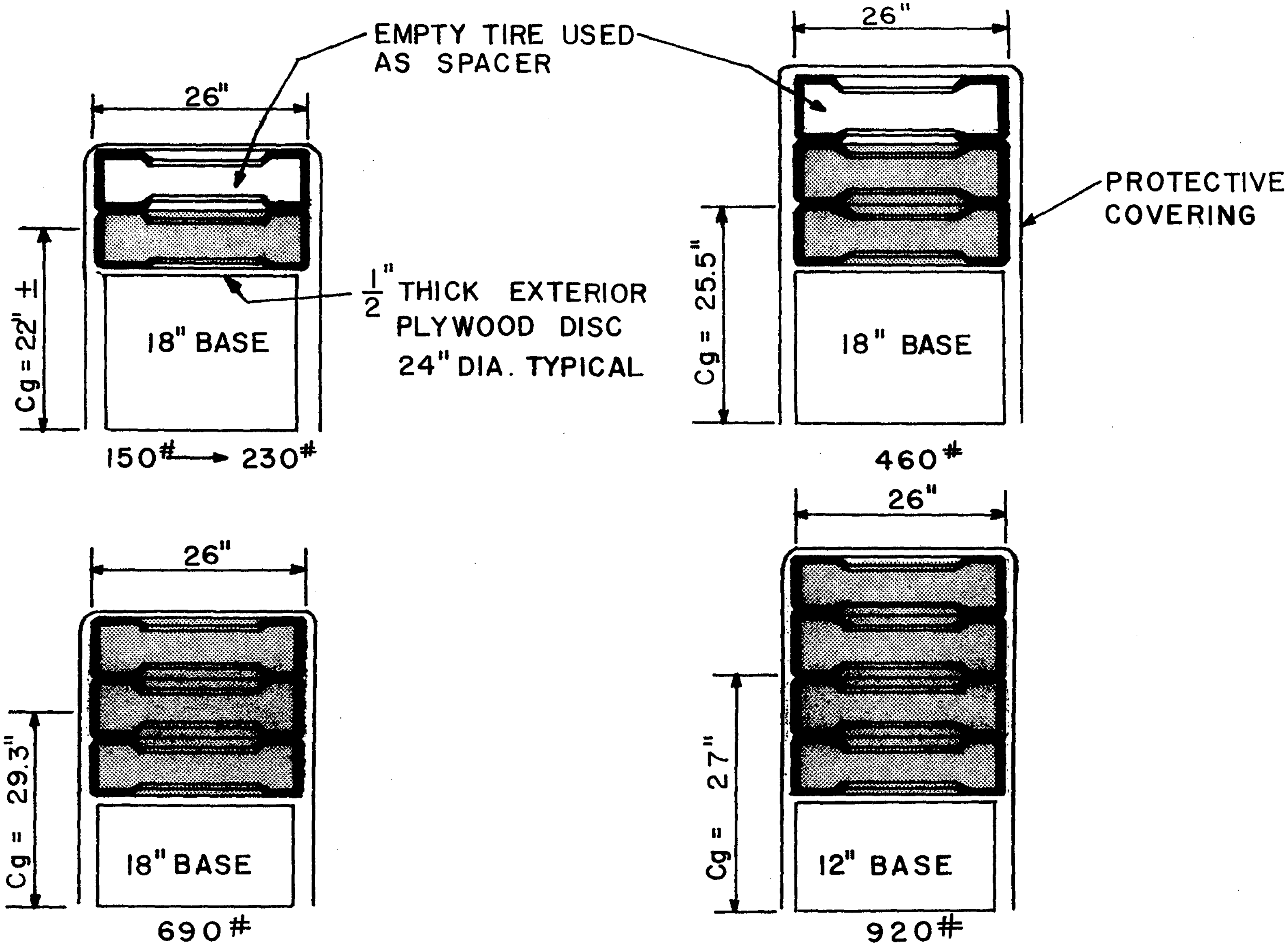


FIGURE 2 DESIGN MODULES TIRE-SAND INERTIA BARRIER

to measure the sand. The other three modules are progressively heavier up to a limit of four tires filled with sand, an average weight of 920 lbs. These modules may be used singly in each row or in multiples of 2 or 3 per row.

Design of a Typical Barrier

The design of an inertia barrier is divided into two steps. The first step is to use conservation of momentum equations to slow the vehicle to 10 mph or less. The second step is to place enough "soft" mass or additional modules ahead of the vehicle to completely stop it by ploughing action.

In order to accomplish step 1, it is first necessary to determine the level of force to be allowed on the vehicle c.g. The Federal Highway Administration has established criteria for the design of vehicle impact attenuators. They are (5):

"Vehicle weight range - 2000 to 4500 pounds

Vehicle speed - 60 miles per hour

Impact angle - 0 degrees to 25 degrees as measured from the direction of the roadway

Average permissible vehicle deceleration - 12 g's maximum while preventing actual impacting or penetrating of the roadside hazard"

FHWA further states in the same memorandum that the maximum average deceleration should be further reduced where space and funds permit. The 12 g average is considered to be a reasonable value for vehicle occupants restrained by lap belts. An average deceleration of 6 or 7 g's is considered reasonable (12) for unrestrained occupants. Therefore, a 6 g average is recommended for design where possible.

An investigation of equations 1 through 4 will reveal that it is possible to design a perfectly rectangular deceleration block. This would require weighing each tire and determining the quantity of sand in the module to the nearest pound. This is seldom practical. Except for the nose modules which may be partially filled with sand, the recommended practice is to use a modular weight of 230 lb per tire as discussed in the paragraphs, "Development of Statistical Data and Standard Modules". In this manner the barriers can be designed so that they can be constructed simply by placing as much sand as possible into passenger vehicle tires from 14 in. and 15 in. rims.

The module selection is accomplished by using equations 1 through 4. Using FHWA criteria and a 6 g deceleration

Velocity = 60 mph or 88 fps head-on

S = cc spacing of rows = 30 in.

g = acceleration due to gravity 32.2 ft/sec^2

G = $^A/g$

W = weight of the vehicle = 2,000 lb

substituting these values in equation 3, we solve for the vehicle velocity after impacting the first module.

$$V_1 = \sqrt{88^2 - 2 \times 6 \times 32.2 \times 2.5} = 82.3 \text{ fps}$$

or 56.1 mph

Now substitute in Equation 4, the theoretical weight of the nose module is determined as

$$W_1 = \frac{2000\ (88-82.3)}{82.3} = 139 \text{ lb}$$

This weight can be used, but it is not a standard. The designer used 150 lbs for the nose module necessitating solving for the theoretical velocity after impact and average deceleration during the impact using Equations 1 and 2. The theoretical velocity is

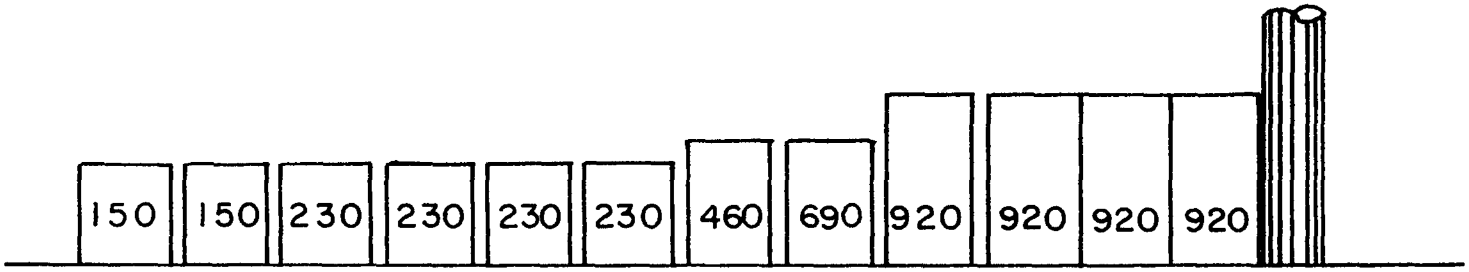
$$V_i = 88 \ \frac{2000}{2000 + 150} = 81.86 \text{ fps}$$

or 55.8 mph and the average deceleration is

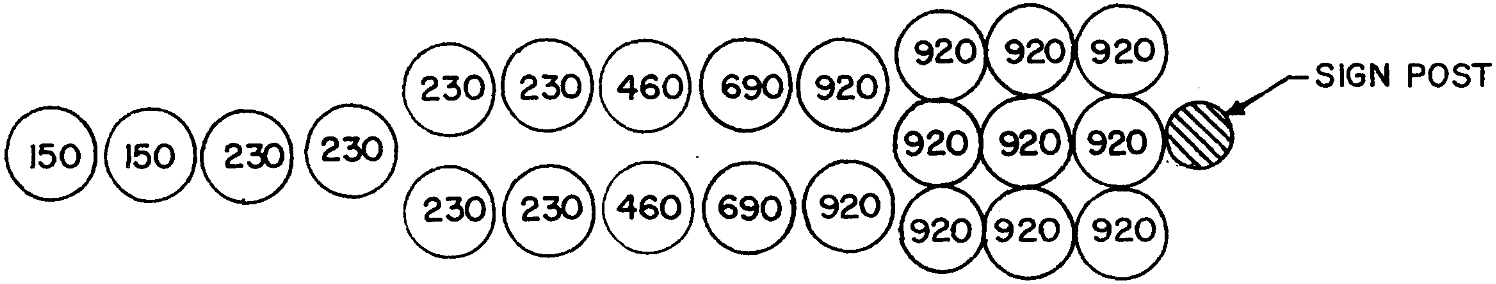
$$G = \frac{\overline{88}^2 - \overline{81.86}^2}{2 \times 32.2 \times 2.5} = 6.48 \approx 6.5 \text{ g's}$$

This process is continued for the 2000 lb vehicle until $V_i \leq 10$ mph. The results of the design for a typical tire sand inertia barrier are shown in Figure 3. Note that after impacting 9 rows, the vehicle was slowed to a theoretical 5.8 mph, and the average deceleration was 5.6 g's.

FHWA requires that the range of vehicles be from 2000 lb to 4500 lb. It is usually adequate to design for the extreme conditions. Therefore, the barrier designed for the 2000 lb vehicle should be reviewed for the 4500 lb vehicle using Equations 1 and 2. Toward the front of the barrier the average decelerations are higher for the lighter vehicle, but toward the rear of the barrier these decelerations



ELEVATION



PLAN VEIW

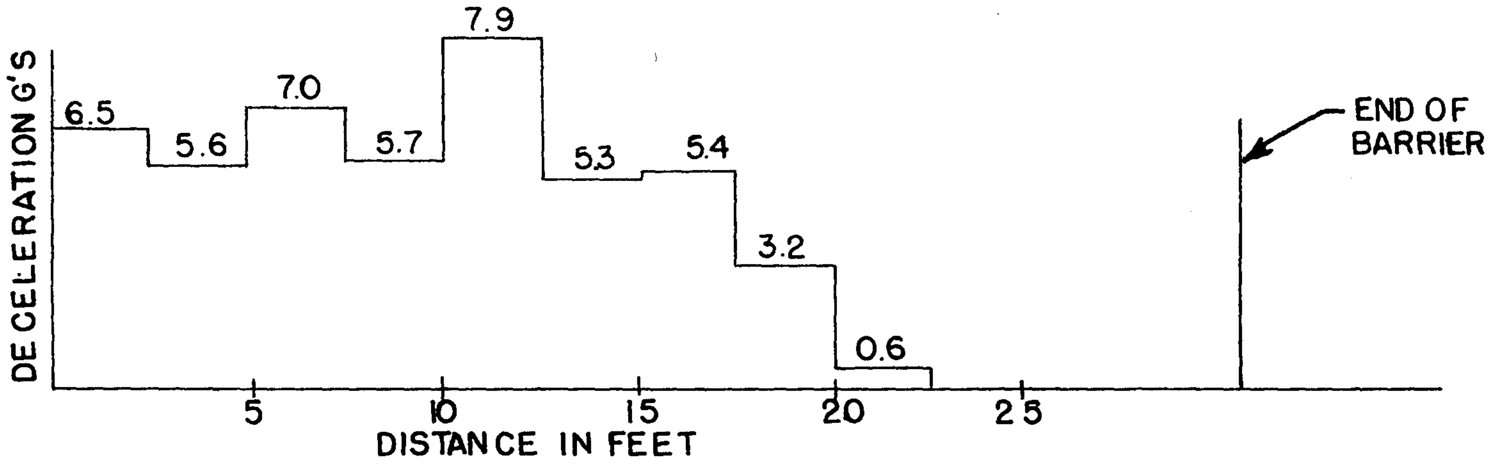
2000 #	G_{avg}	6.5	5.6	7.0	5.7	7.9	5.3	5.4	3.2	0.6			Avg = 5.6g
Vehicle	V_i mph	55.8	51.9	46.6	41.8	34.0	27.6	18.9	11.1	5.8			
4500 #	G_{avg}	3.2	2.7	4.0	3.8	6.1	5.1	7.3	6.6	4.7	2.9	1.1	Avg = 4.0g
Vehicle	V_i mph	58.0	56.2	53.5	50.8	46.1	41.8	34.7	26.6	18.9	11.7	7.3	

FIGURE 3 DESIGN OF A TYPICAL LAYOUT OF A TIRE-SAND INERTIA BARRIER

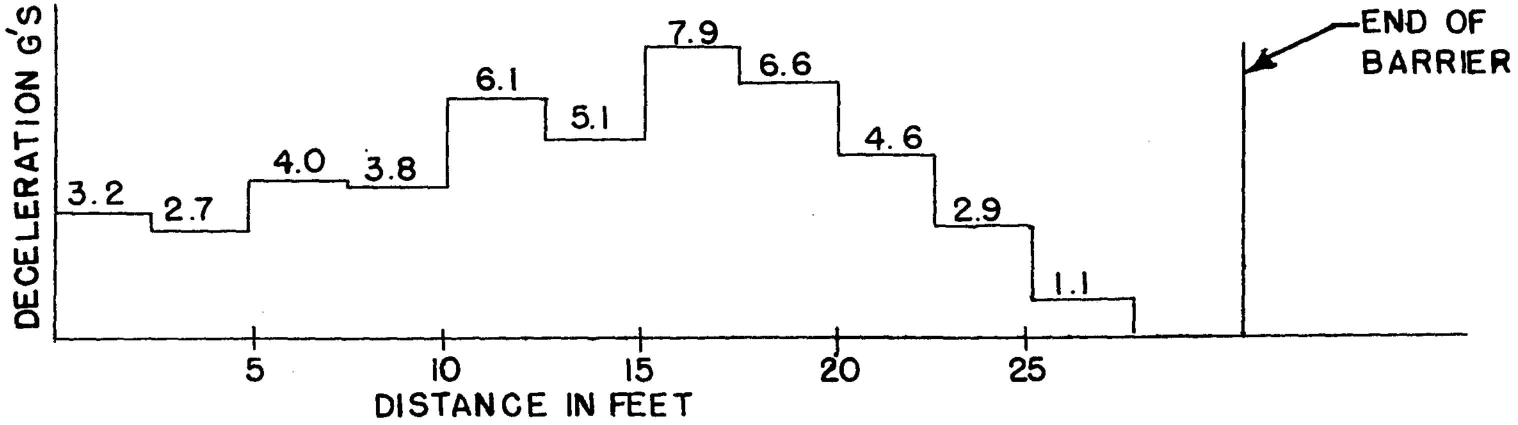
are significantly larger for the heavier vehicle since the velocity of the heavier vehicle is much higher when it impacts these modules. Nine rows were required to slow the 2000 lb vehicle to less then 10 mph and at that time, the 4500 lb vehicle will be traveling in excess of 18 mph (Figure 3). Two more rows were required to reduce the velocity to less than 10 mph. Figure 4 shows a graphic comparison of the calculated deceleration values. The calculated values for displacement were compared to actual displacement values for full-scale tests (1, 2) and found to agree within 8%. The calculated values were conservative.

A large mass of tires and sand were added to the end of the barrier to completely stop the vehicle by ploughing. The barriers constructed under previous programs (1, 2) were not particularly pleasing in appearance and several coverings were investigated. The first and probably most satisfactory were plastic tire sleeves made of polyethelene sheet similar to those used by automobile service stations when used to advertise a tire sale. Another satisfactory material investigated for a covering was polyvinyl floor covering. This was purchased in rolls and fabricated at the job site. These coverings are discussed in the write up of the respective tests.

Two successful supports were tested. The first was a wire cage that collapsed when impacted. The wire cage was constructed of 14 gage galvanized welded wire fabric with 1 in. by 2 in. openings. Details of construction are shown in Figure 5. The details of the second successful support is shown in Figure 6. This support is made of 55 gal steel drums with the stiffening tops and bottoms removed then cut



2000 VEHICLE, IMPACT VELOCITY 60 MPH



4500 VEHICLE, IMPACT VELOCITY 60 MPH

FIGURE 4 CALCULATED AVG. G'S FOR A TYPICAL TIRE SAND INERTIA BARRIER

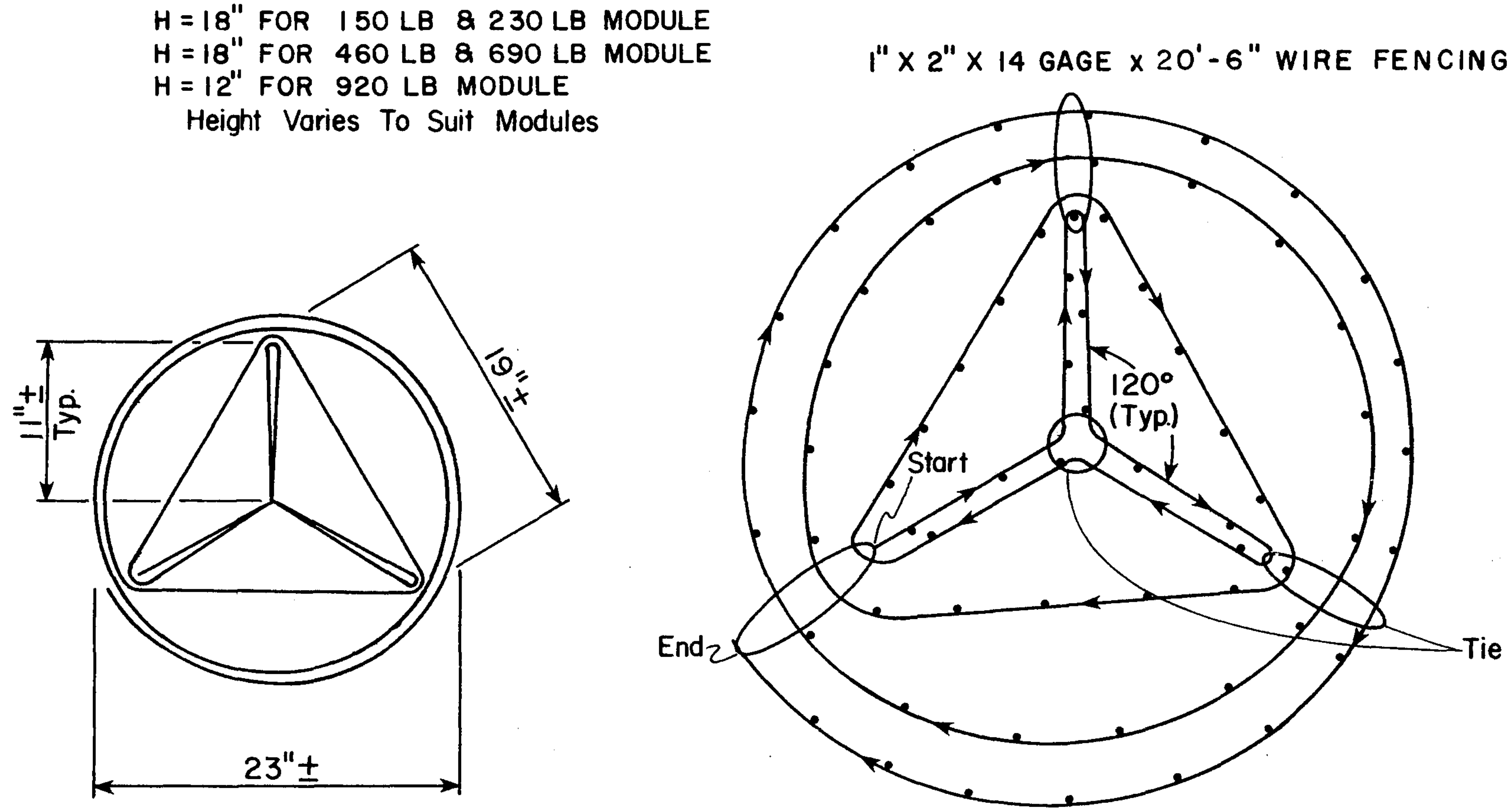
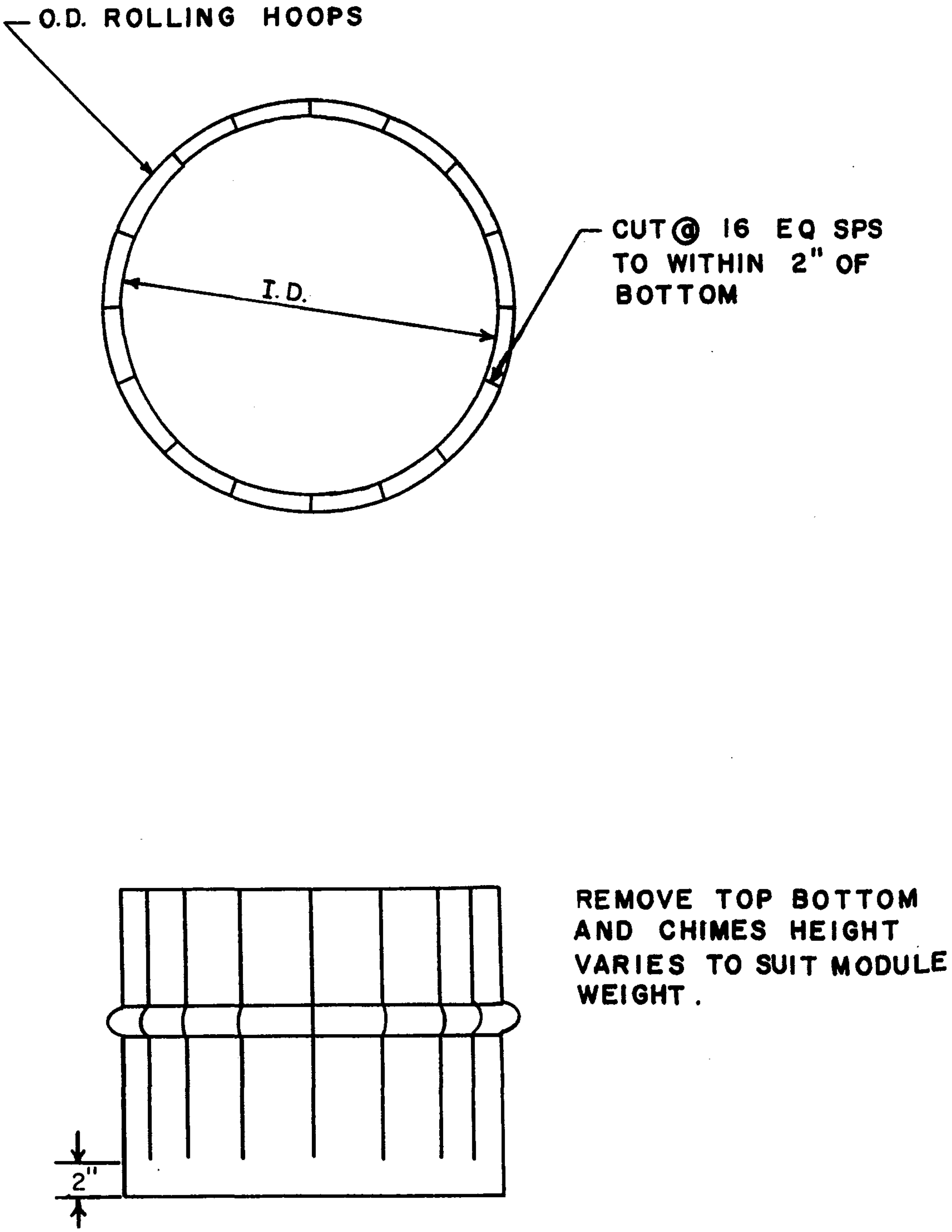


FIGURE 5 WIRE CAGE SUPPORT DETAILS

H = 18" FOR 150 lb. & 230 lb. Modules
H = 18" FOR 460 lb. & 690 lb. Modules
H = 12" FOR 920 lb. Module
Height Varies to Suit Modules



CUT @ 16 EQ SPS TO WITHIN 2" OF BOTTOM

REMOVE TOP BOTTOM AND CHIMES HEIGHT VARIES TO SUIT MODULE WEIGHT.

FIGURE 6 STEEL DRUM SUPPORT DETAILS

vertically at 16th points. These cuts make the support weak laterally while still retaining sufficient strength vertically to support the heaviest module. One 18 in. high support was tested in a universal static testing machine. A compressive load of 2300 lb was slowly applied, held for several minutes and released. The support was undamaged and at no time did it exhibit any tendency toward instability. From this test, it was concluded that there was no strength problem. This was born out in erecting the test installation.

A series of graphs have been developed to aid in the design of inertia barriers. These graphs based on the number of tires at a 30 in. spacing and module or row weights for 30 in. and 36 in. spacing are shown in Figures 7 through 12.

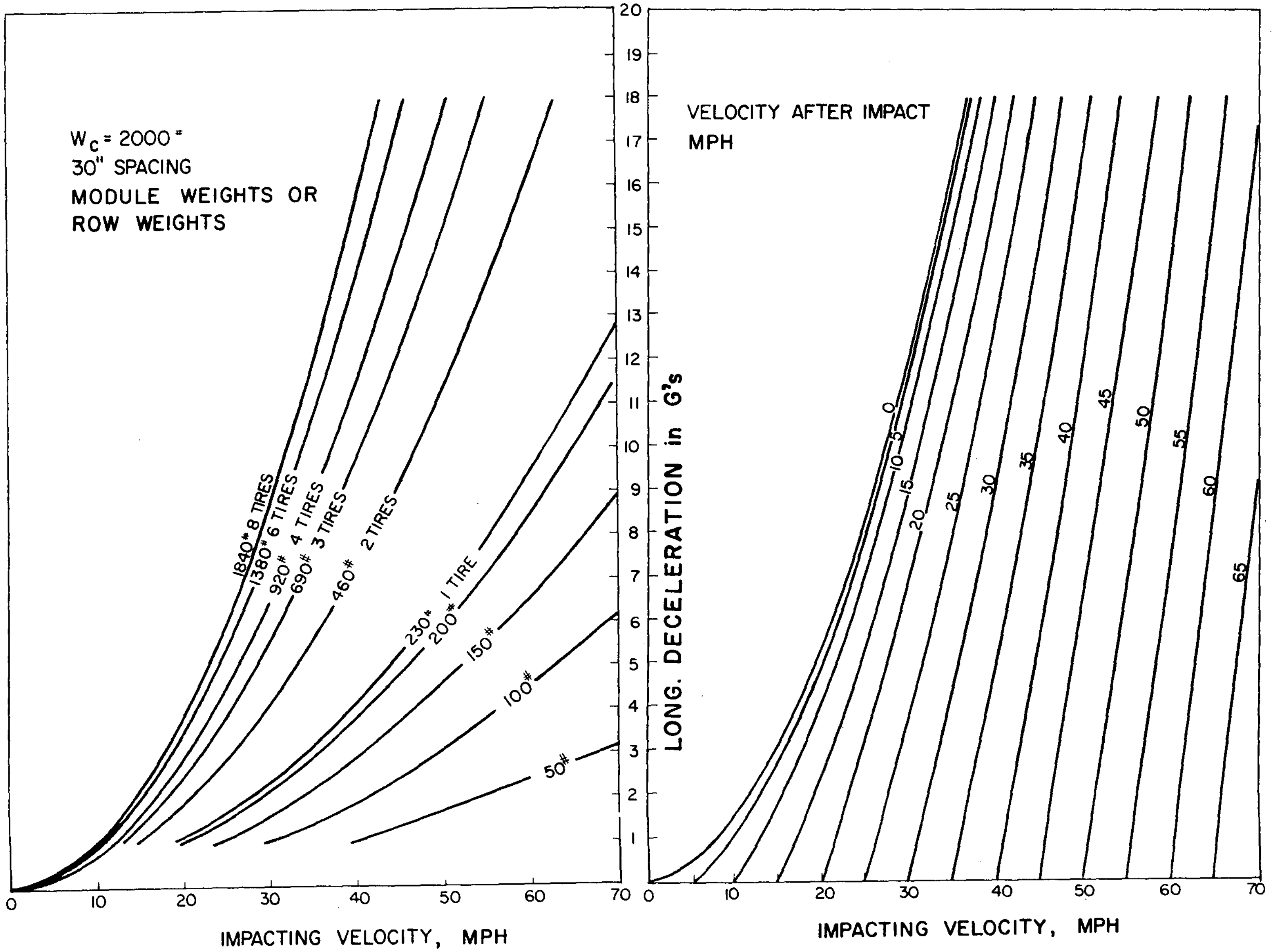
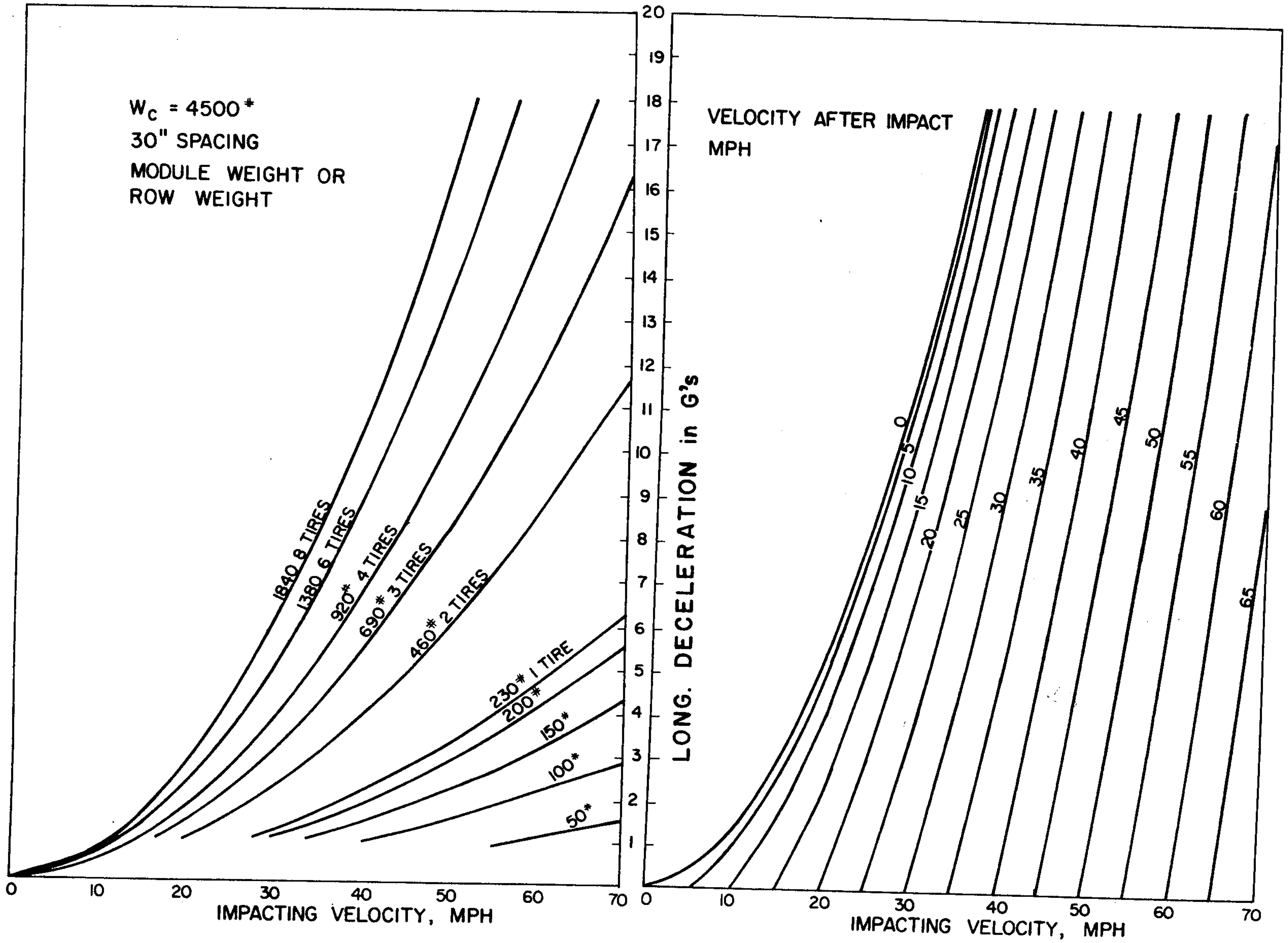


FIGURE 7 SAND-TIRE INERTIA BARRIER DESIGN CURVES 2000# VEHICLE


W_C = 4500*
30" SPACING
MODULE WEIGHT OR
ROW WEIGHT
1840 8 TIRES
1380 6 TIRES
920* 4 TIRES
690* 3 TIRES
460* 2 TIRES
230* 1 TIRE
200*
150*
100*
50*
0
10
20
30
40
50
60
70
IMPACTING VELOCITY, MPH
LONG. DECELERATION in G's
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
VELOCITY AFTER IMPACT
MPH
0
5
10
15
20
25
30
35
40
45
50
55
60
65
0
10
20
30
40
50
60
70
IMPACTING VELOCITY, MPH

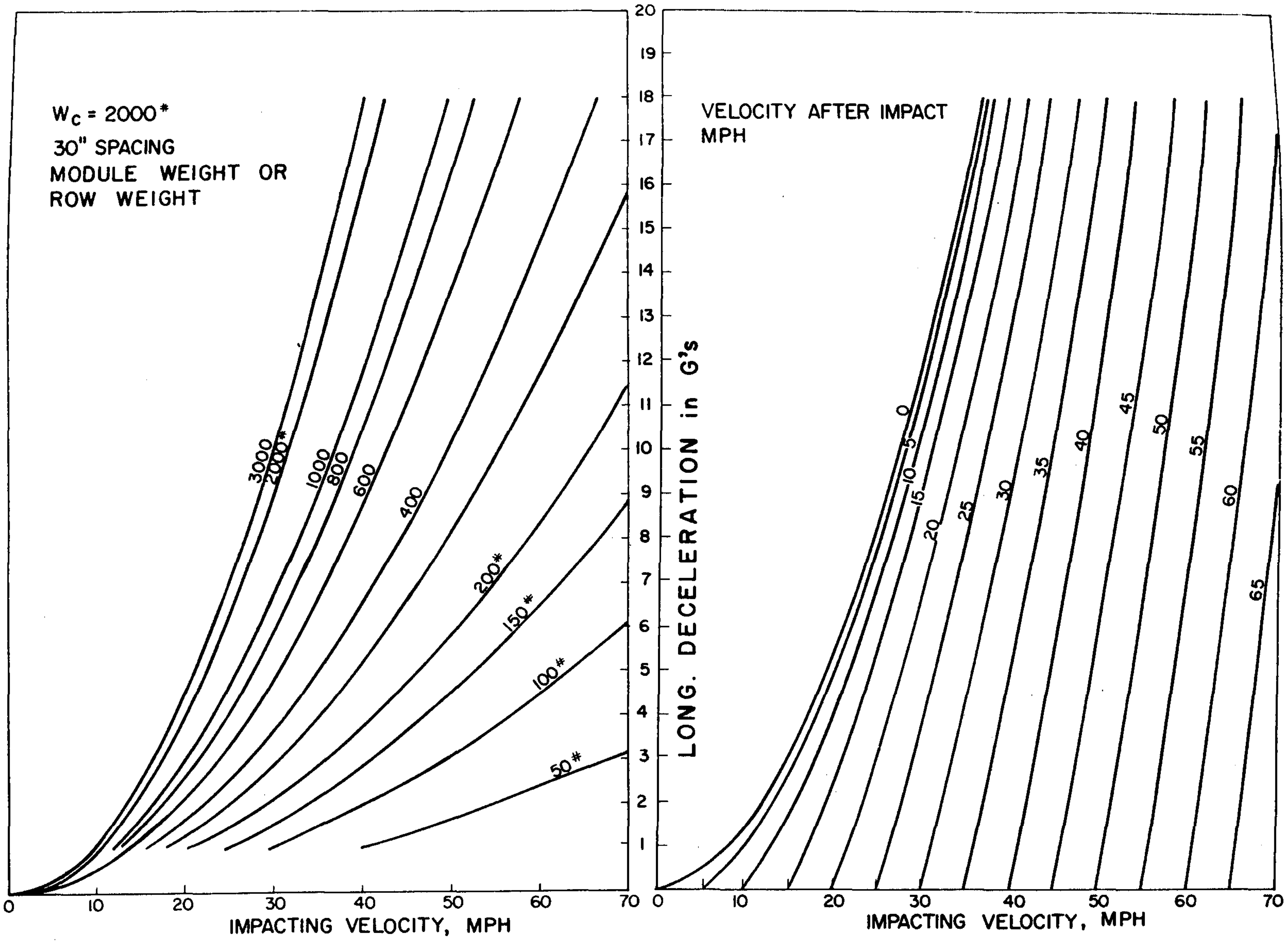


FIGURE 9 SAND-TIRE INERTIA BARRIER 30" ROW SPACING 2000# VEHICLE

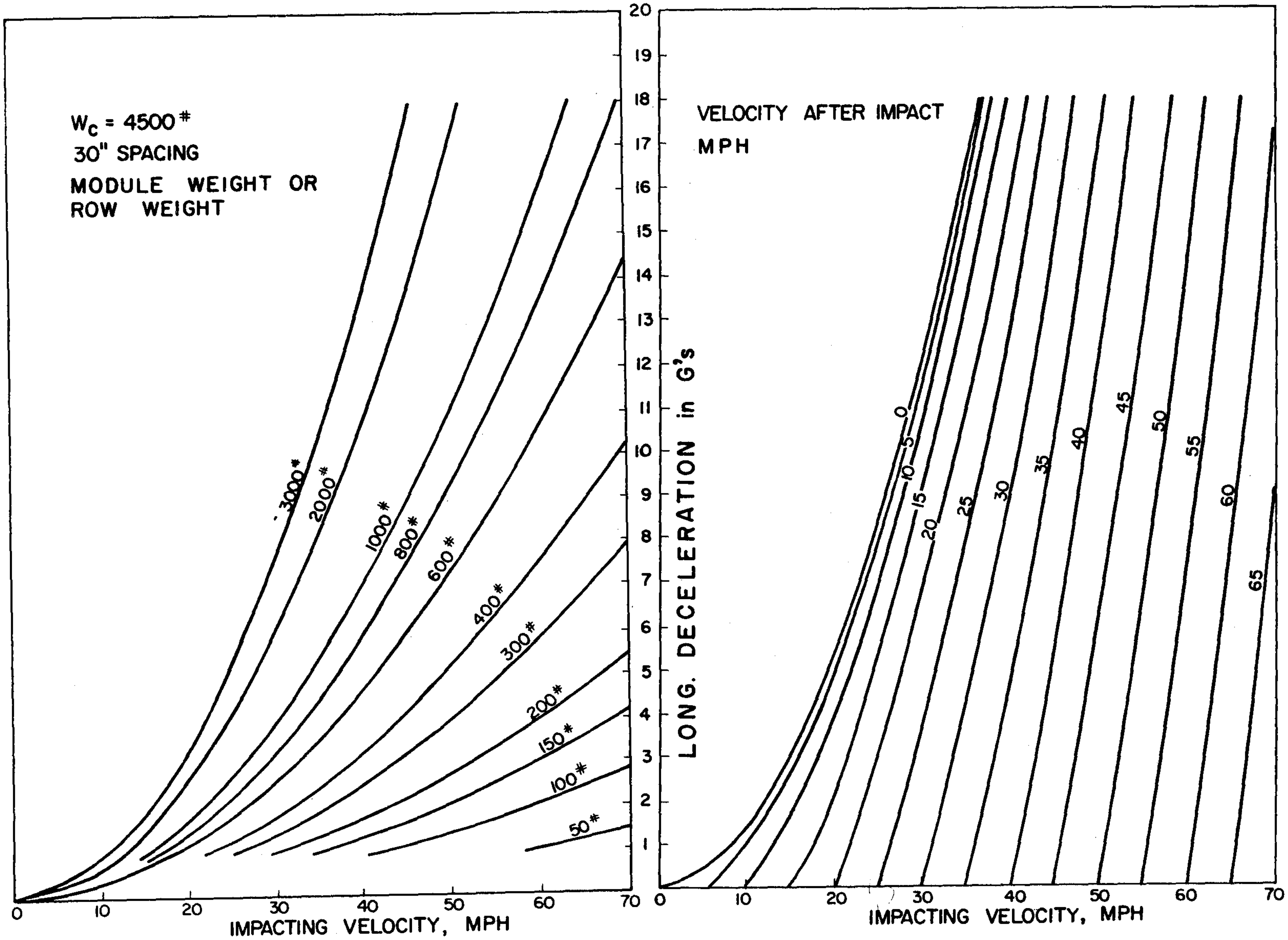


FIGURE 10 SAND-TIRE INERTIA BARRIER 30"ROW SPACING 4500# VEHICLE

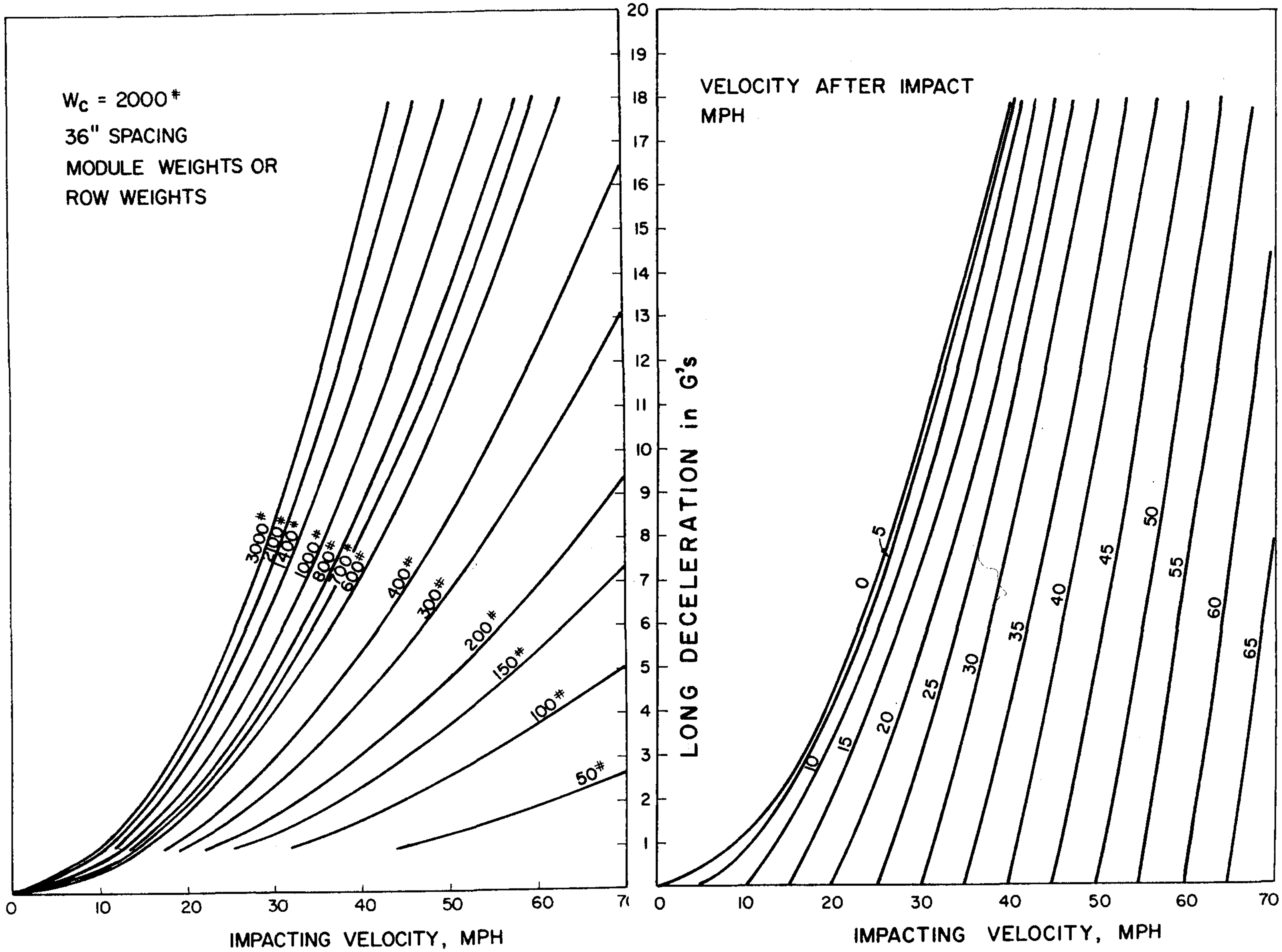
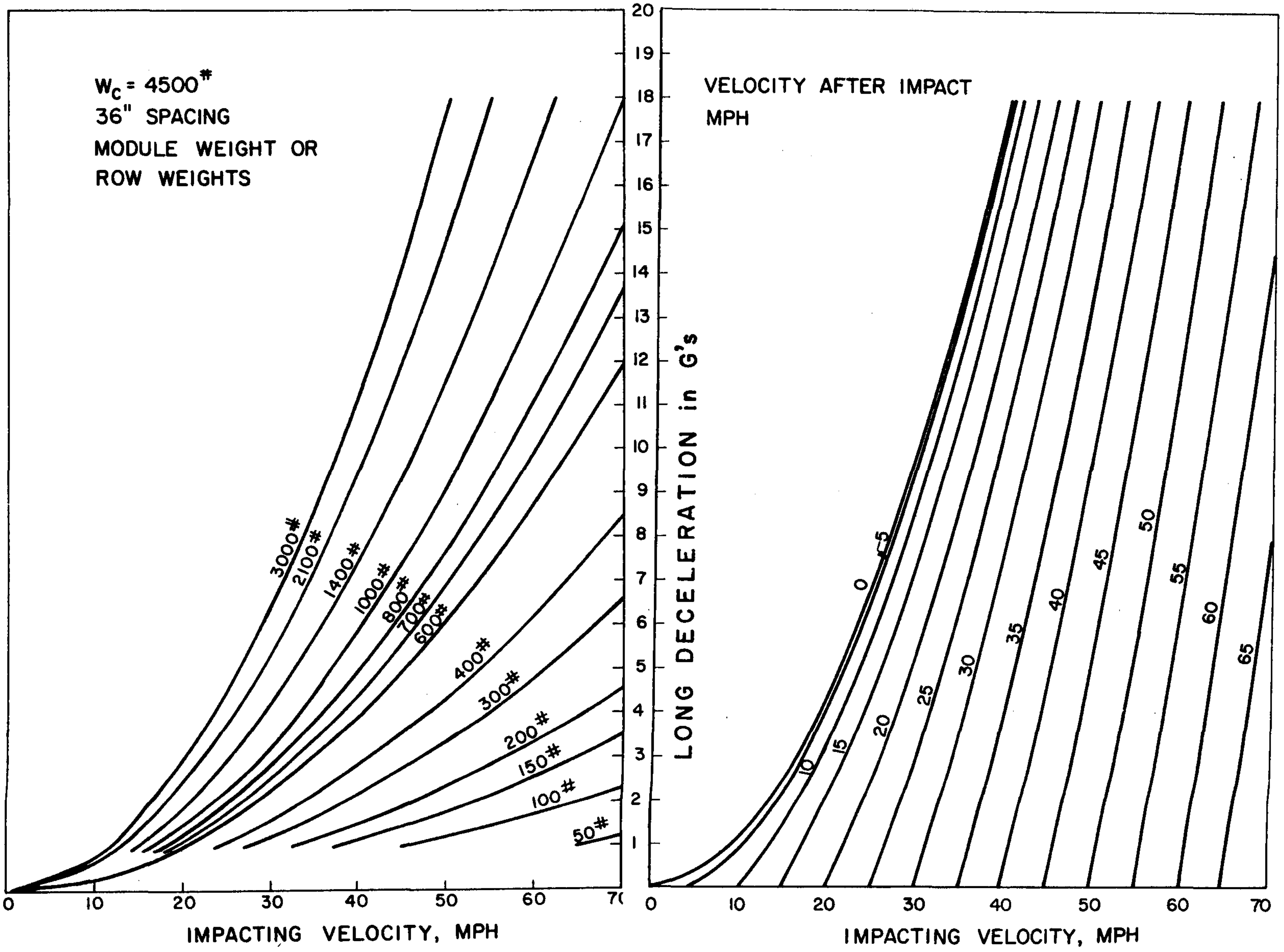


FIGURE 11 SAND-TIRE INERTIA BARRIER 36"ROW SPACING 2000# VEHICLE


W_C = 4500#
36" SPACING
MODULE WEIGHT OR
ROW WEIGHTS
3000#
2100#
1400#
1000#
800#
700#
600#
400#
300#
200#
150#
100#
50#
IMPACTING VELOCITY, MPH
0
10
20
30
40
50
60
70
LONG DECELERATION in G's
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
VELOCITY AFTER IMPACT
MPH
0
5
10
15
20
25
30
35
40
45
50
55
60
65
IMPACTING VELOCITY, MPH
0
10
20
30
40
50
60
70

VEHICLE CRASH TESTS

Test 2146-I-4

The vehicle used for this test was a 1967 Dodge Monaco with a gross weight of 4290 lbs. Figure 13 shows the vehicle prior to the test. No accelerometers were installed.

Photography included documentary motion pictures and high speed (200 frames per second) films with timing marks. The high speed film is used to develop time-displacement data for the vehicle. The data camera was located perpendicular to the vehicle path. A flash bulb was located on the target at the center of the vehicle and was actuated at the time of impact by a tape switch on the front bumper.

The barrier, Figure 14, was not located near any rigid backup. Also, the bases used were wire cages which were designed to collapse on impact and not produce an uplift force on the vehicle as they rolled under the vehicle. The vehicle was towed into the barrier at an impact angle of 0 degrees using the reverse tow mechanism described in Reference (6).

The vehicle impacted the center of the barrier. The speed was 64.0 mph. The vehicle behaved as anticipated during impact. However, the majority of the mass was displaced to a place well ahead of the vehicle and the vehicle stopped approximately 18 ft after it passed the original end of the barrier. Figure 15 shows sequence photographs of the tests and Figure 16 shows the vehicle and barrier after the test. Time-displacement data and the table of events are in the appendix.

FIGURE 13 TEST 1-4 VEHICLE BEFORE IMPACT

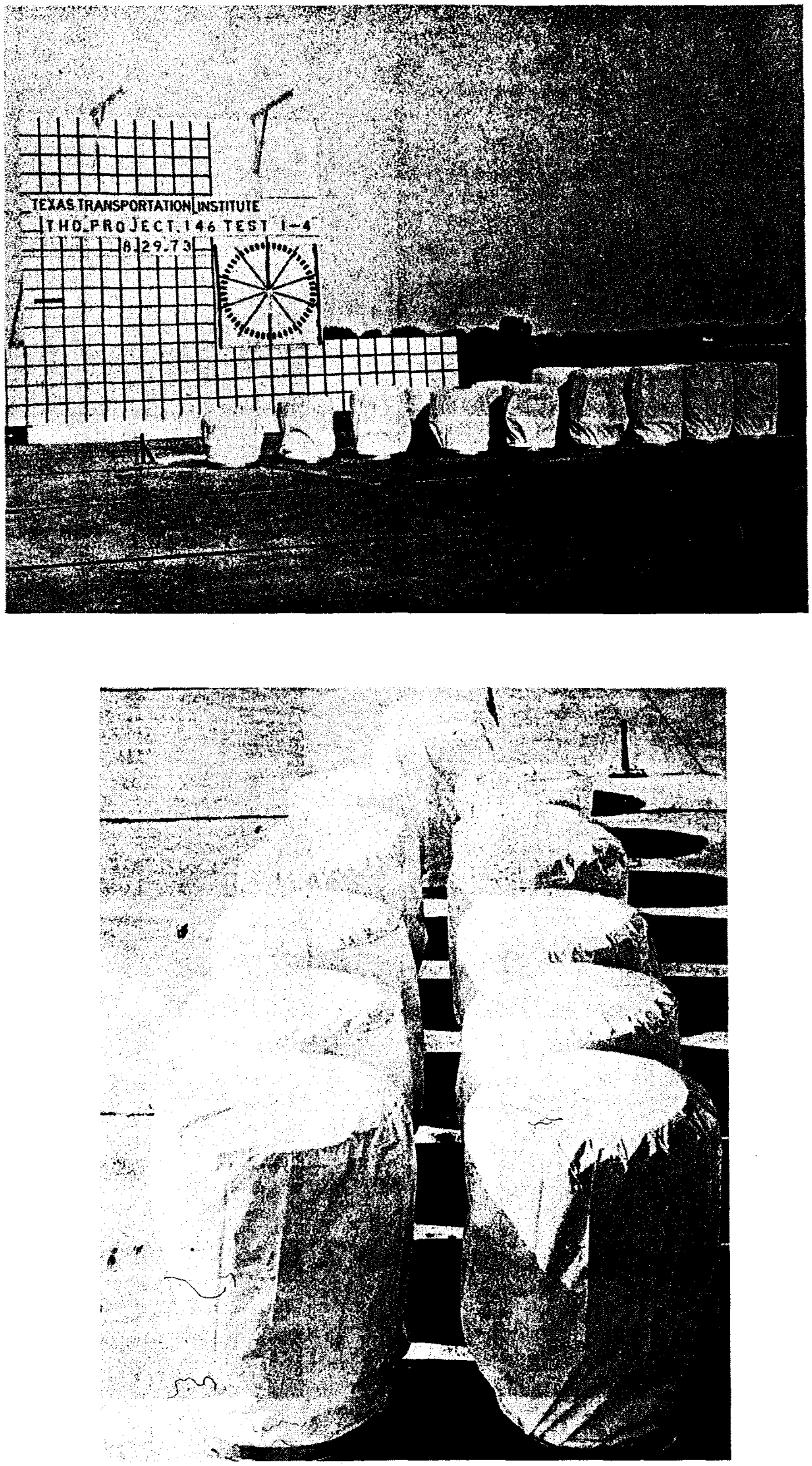
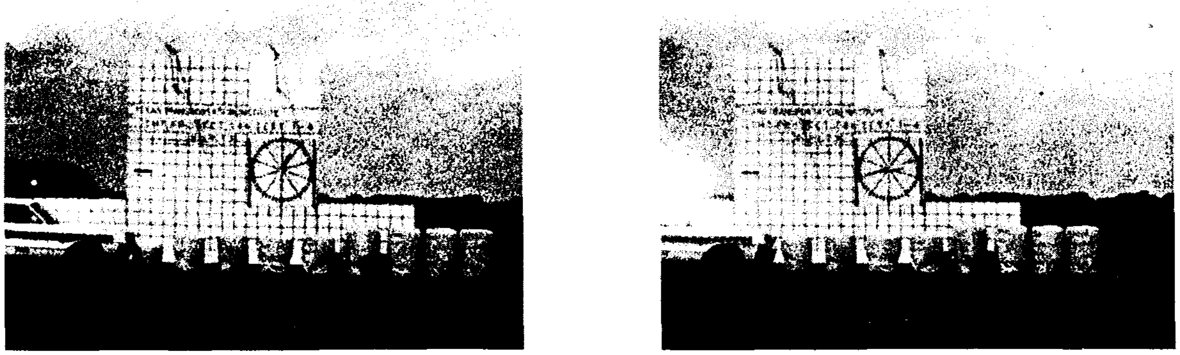


FIGURE 14 TEST 1-4 BARRIER BEFORE IMPACT



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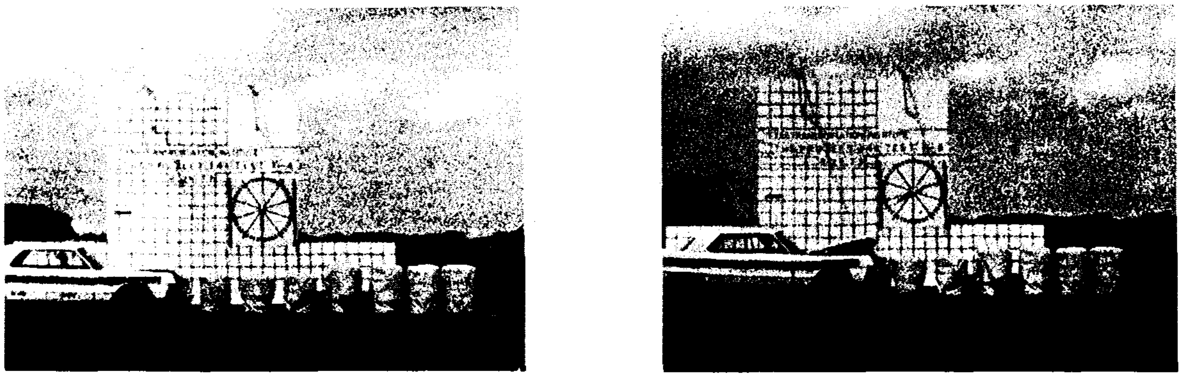

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0.092 sec

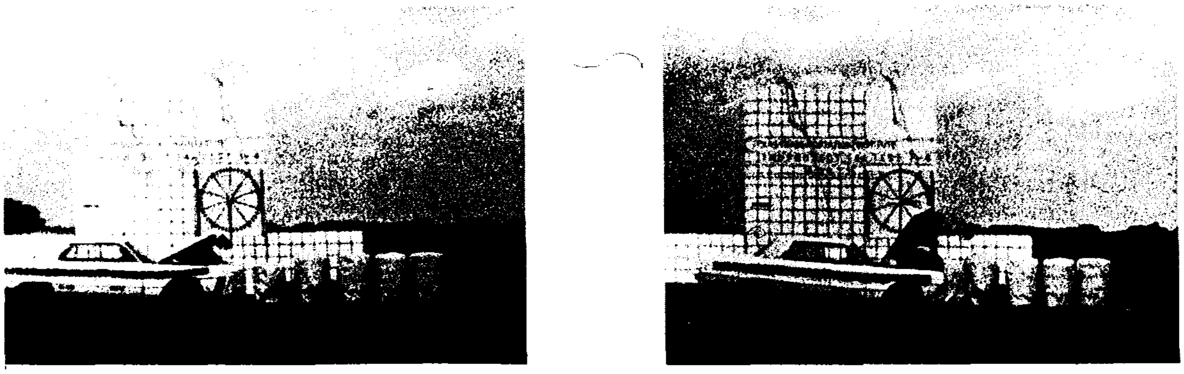

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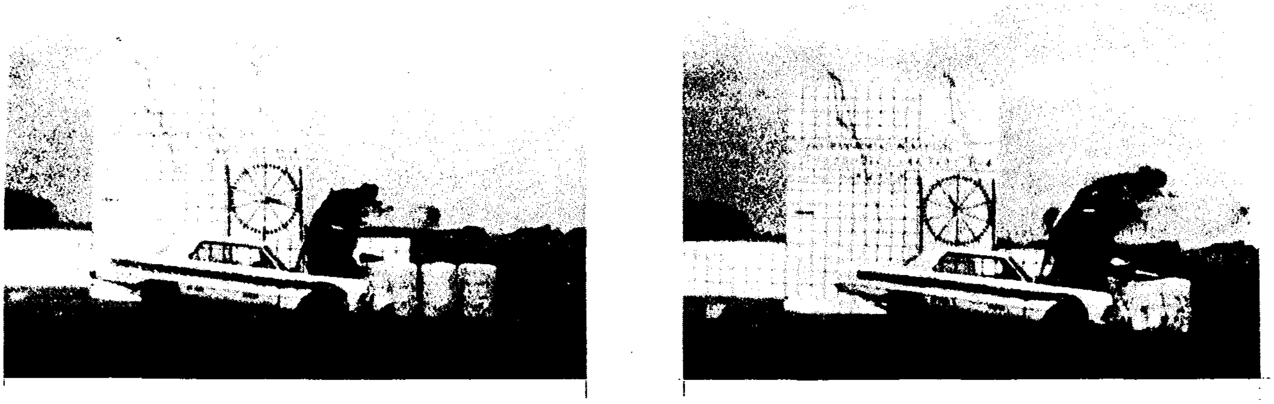
Figure 15 Seqence Photographs of Test I-4
4290 lb vehicle - 64.0 mph



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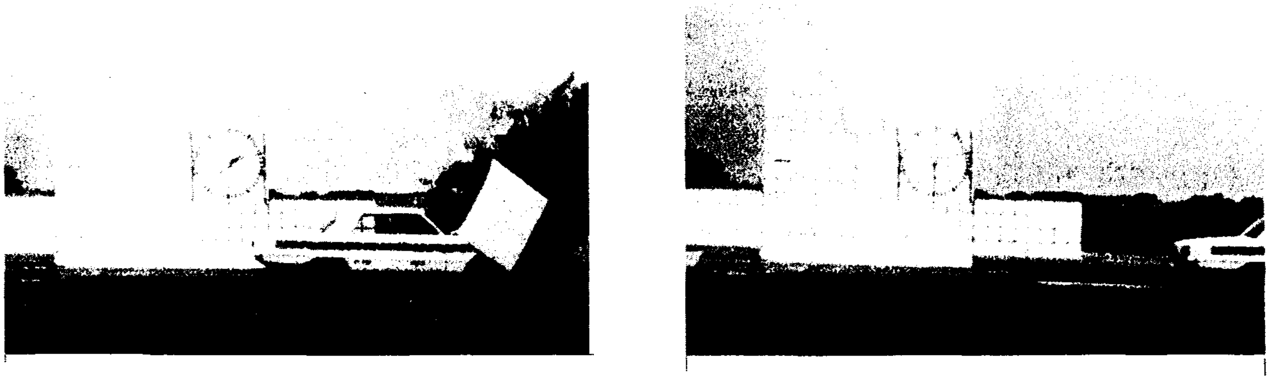

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Figure 15a Sequence Photographs of Test I-4 (continued)
4290 lb vehicle - 64.0 mph

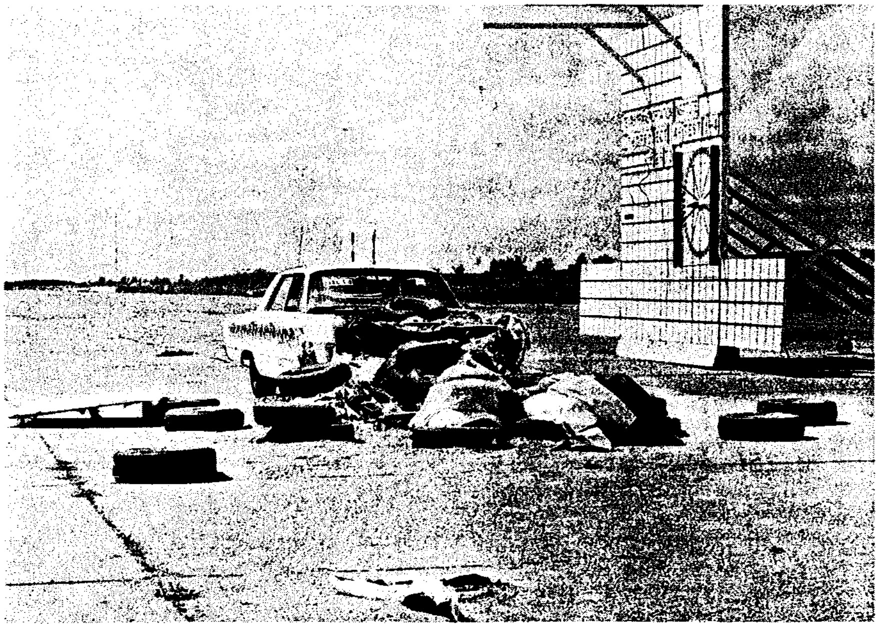


FIGURE 16 TEST 1-4 VEHICLE & BARRIER AFTER IMPACT

Two tires were hurled more than 100 feet during impact, "however 95% were within 10 feet of the rear of the attenuator." This occurred in previous tests (1, 2) with the tire-sand barrier.

The protective coverings used in this were the polyethelene tire sleeves of 4 mil thickness previously discussed. One module was erected and left in place to determine the effects of weathering. During a six-month period the sleeve was removed at least three times to examine the module. Each time the sleeve was handled, it was damaged. At the end of the six-month period, the covering was no longer usable. The original recommendation by the manufacturer was for a 6 mil thickness and several installations were subsequently made with the 6 mil sleeve which also deteriorated in about 6 months.

Test 2146-I-6

The vehicle used for this test was a 1968 Chevrolet. The gross weight was 4000 lbs which included a 165 lb anthropometric dummy. Figure 17 shows the vehicle before and after the test.

Longitudinal and lateral accelerometers were mounted on each of the longitudinal frame members to sense vehicle accelerations. The dummy was secured in the driver's seat with a lap belt anchored through a load cell which indicated the lap belt force through the telemetry system. A flash bulb and an event mark on the electronic data were actuated by a tape-switch on the front bumper. This allows the electronic data to be synchronized with the high speed film. All electronic data were transmitted by telemetry to a ground station (6) where the electronic data were recorded on magnetic tape and displayed in analog form on a strip chart.

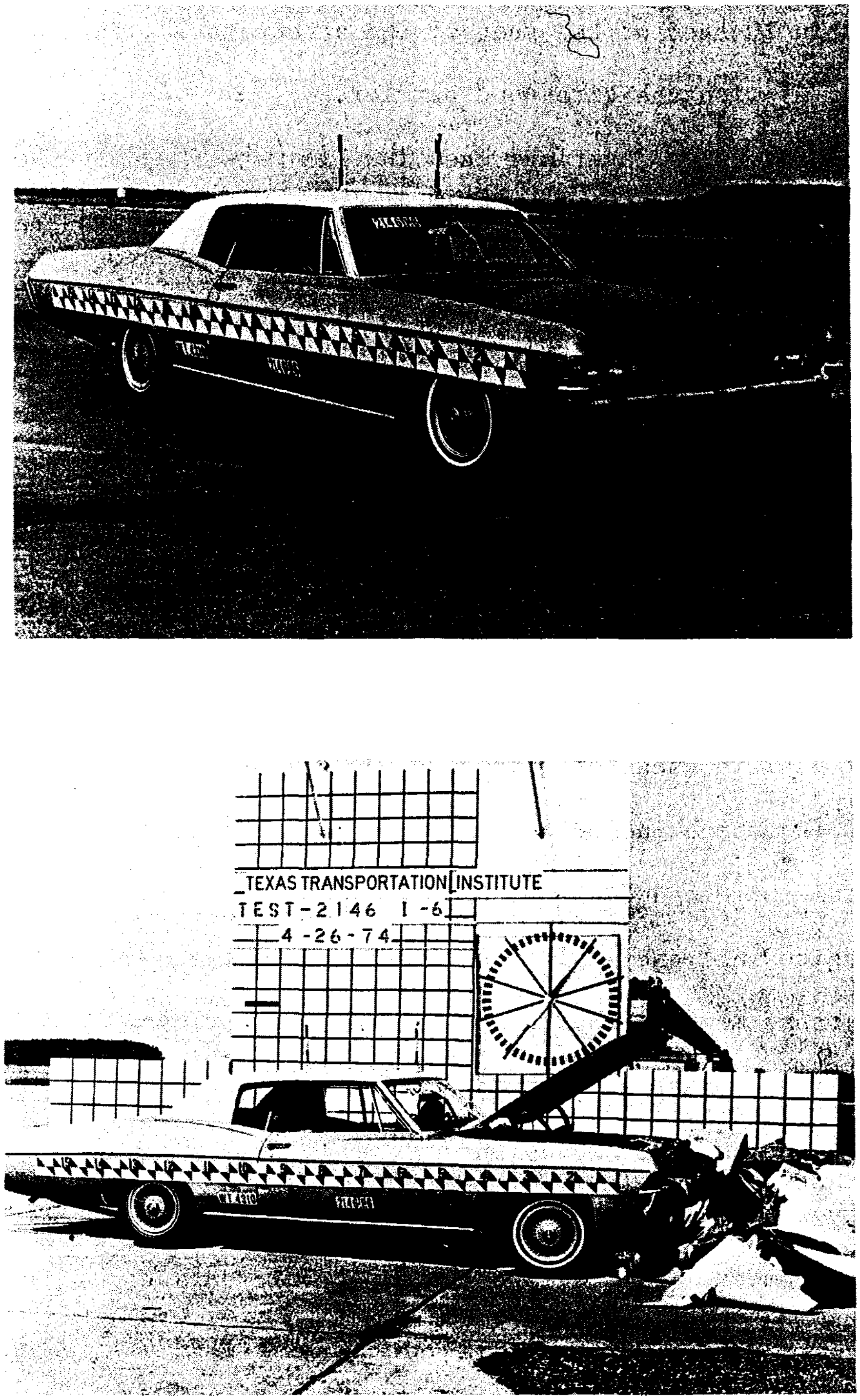
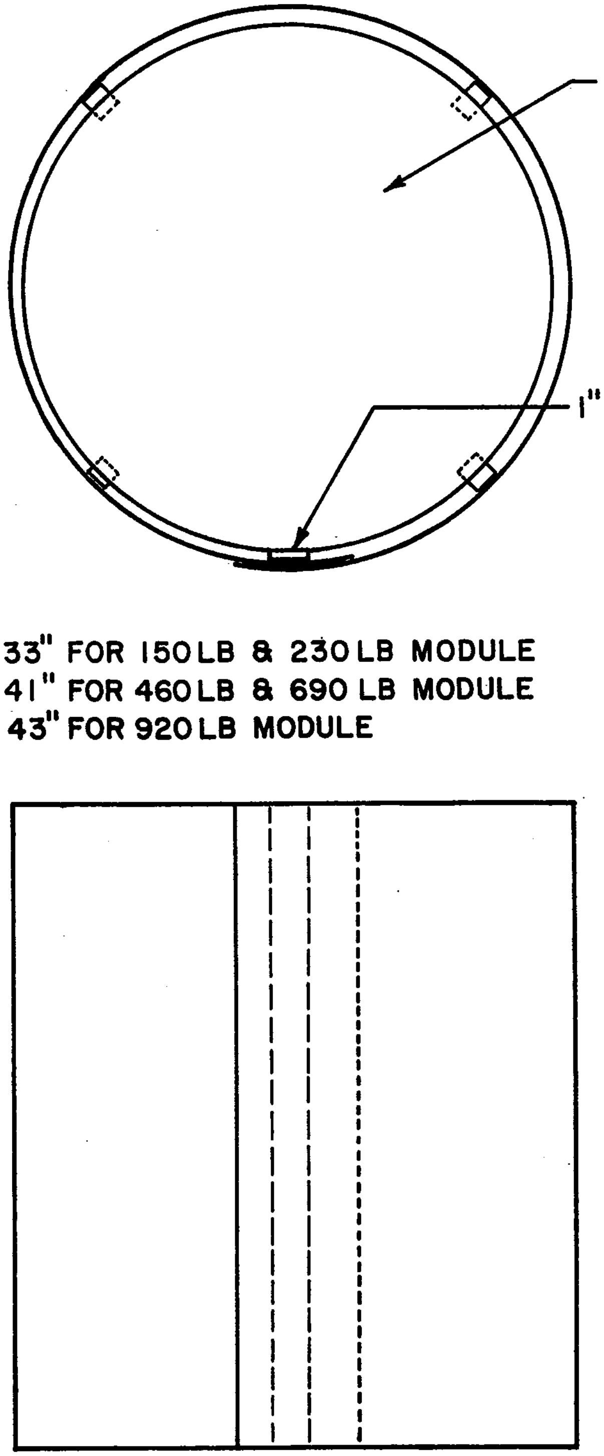


FIGURE 17 TEST 1-6 VEHICLE BEFORE AND AFTER IMPACT



COVER 27" DIA. LINOLEUM WITH 4 TABS STAPLED TO CYLINDER.

1" X 2" WOOD SLAT

H = 33" FOR 150 LB & 230 LB MODULE
H = 41" FOR 460 LB & 690 LB MODULE
H = 43" FOR 920 LB MODULE

MODULE CYLINDER COVER-HEIGHT AS REQUIRED, DIAMETER = 28" — ARMSTRONG DECOLON VINYL RUGS (LINOLEUM) UNCOILED LENGTH 9'-0" STAPLE END TO WOOD SLAT (1/4"X 2" X MODULE HEIGHT)

FIGURE 18 MODULE CYLINDER COVER DETAILS FOR TESTS 2146-16

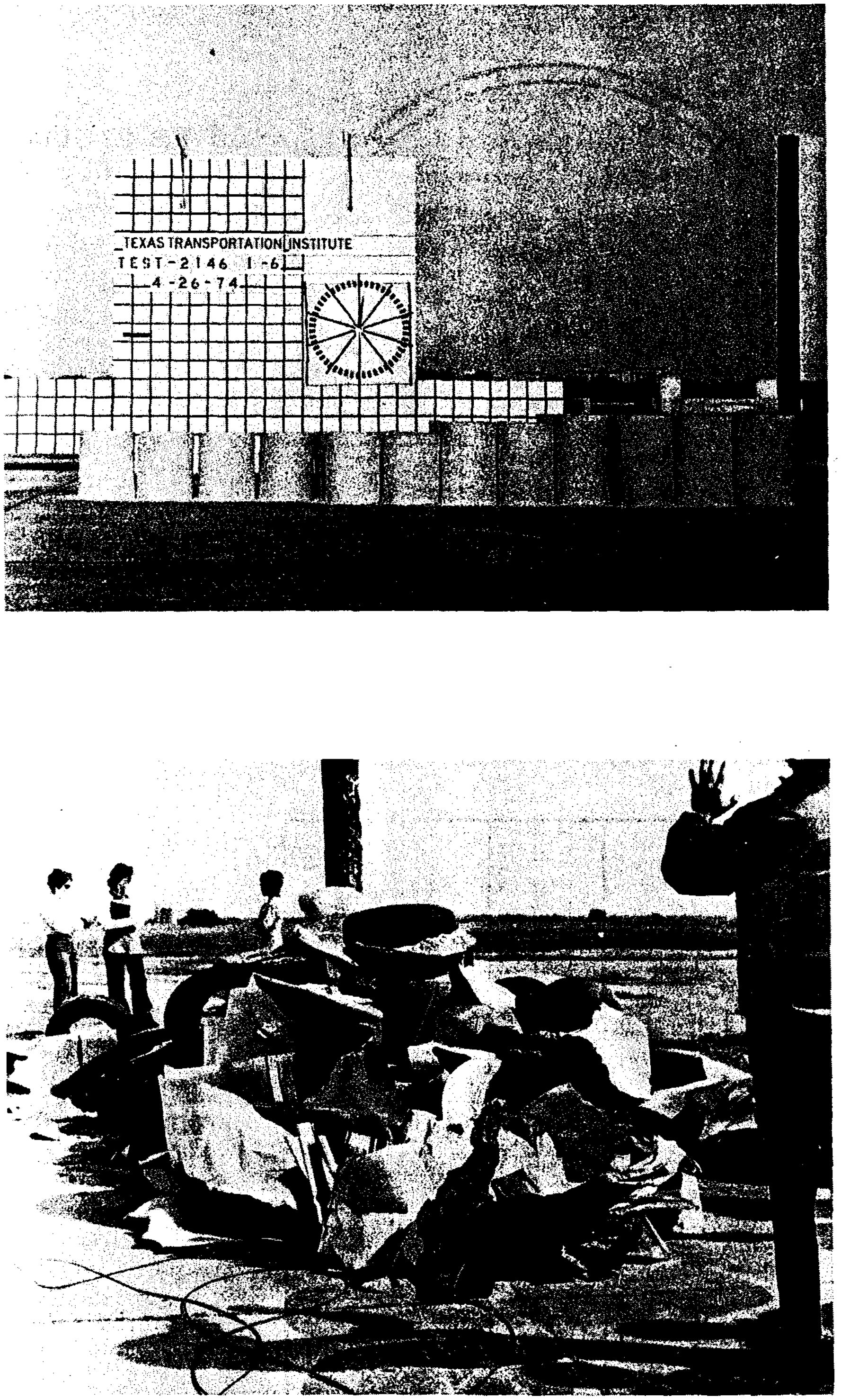
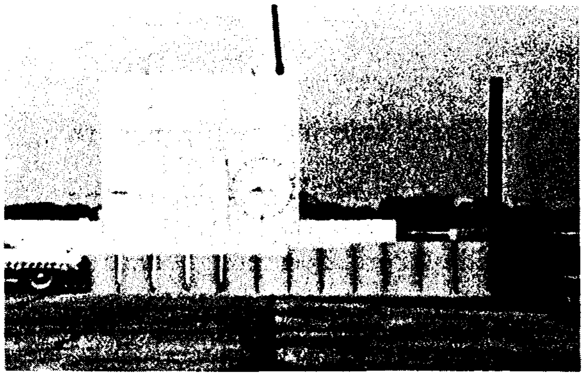


FIGURE 19 TEST 1-6 BARRIER BEFORE AND AFTER IMPACT

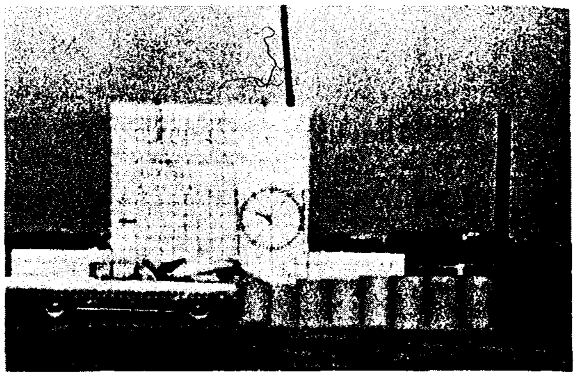
The barrier tested was the typical barrier designed and shown in Figure 3. The supports were made from steel drums designed according to Figure 6. The protective covering was made from Armstrong Decolon vinyl rugs (linoleum) at a cost of approximately $.11 per sq ft. The details are shown in Figure 18.

The barrier was located in front of a simulated luminaire standard as shown in the top half of Figure 19. The vehicle impacted the center of the barrier at 43.1 mph. The vehicle performed as predicted except that there was a slight tendency to ramp evidenced toward the end of impact. Figure 20 shows a sequence of photographs of the test. The hood remained intact during the test as shown in Figure 16.

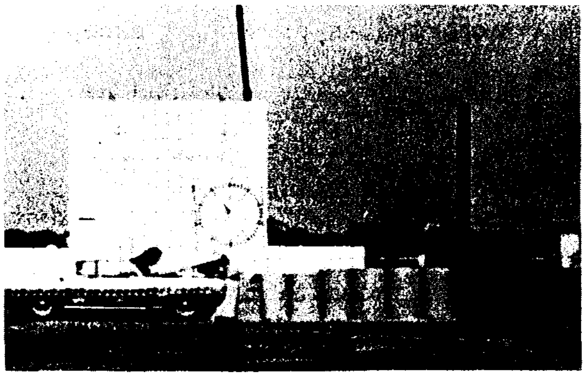
Accelerometer data, time displacement data and a table of events are in the appendix.



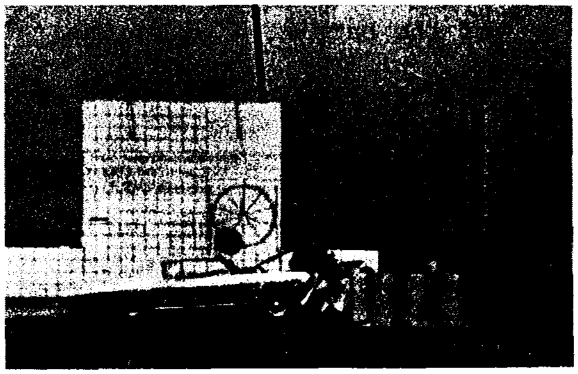
T = 0.0 sec



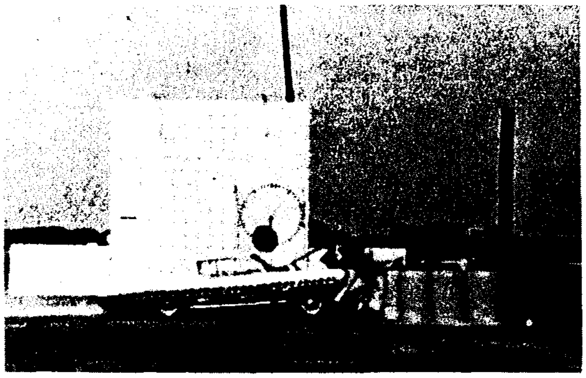
T = 0.180 sec



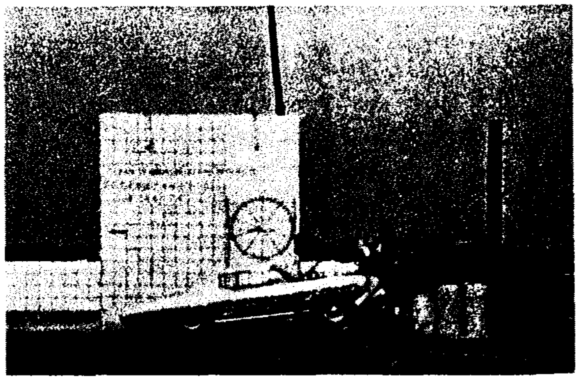
T = 0.213 sec



T = 0.360 sec

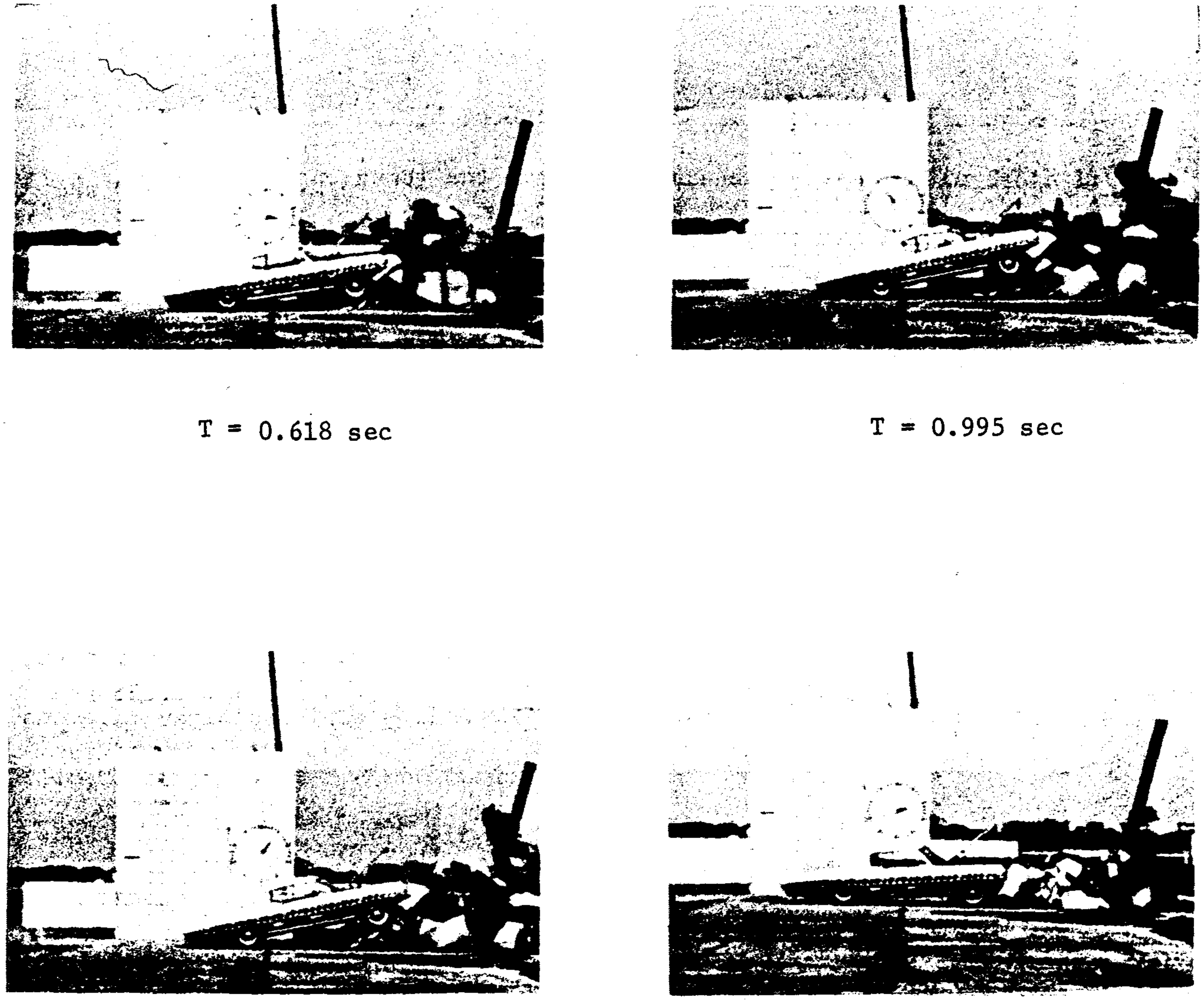


T = 0.380 sec



T = 0.490 sec

FIGURE 20 SEQUENCE PHOTOGRAPHS OF TEST I-4
4000 lb vehicle - 43.1 mph



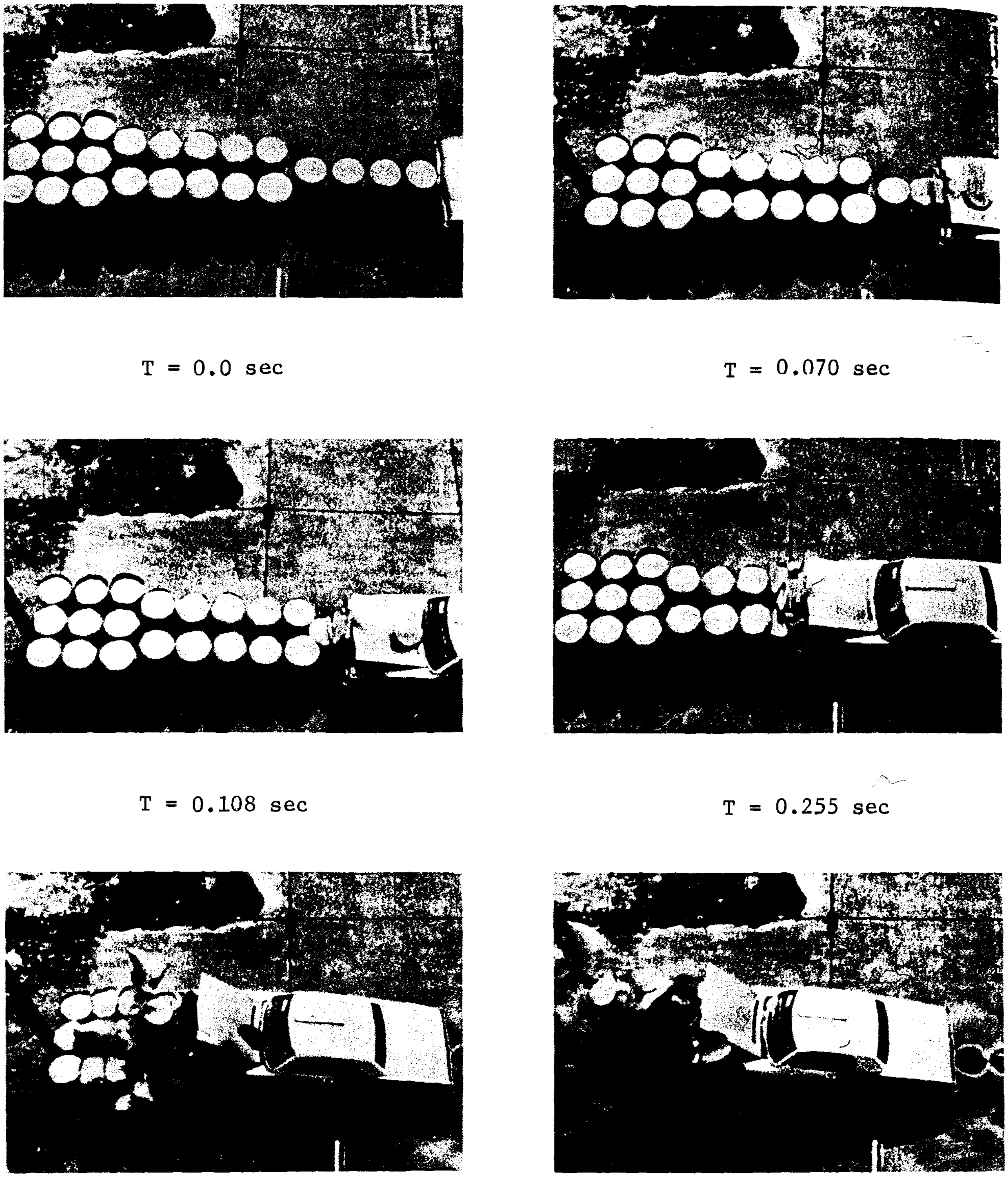
T = 0.618 sec

T = 0.995 sec

T = 1.165 sec

T = 2.378 sec

FIGURE 20 SEQUENCE PHOTOGRAPHS OF TEST I-4 (continued)
4000 lb vehicle - 43.1 mph



T = 0.0 sec

T = 0.070 sec

T = 0.108 sec

T = 0.255 sec

T = 0.450 sec

T = 0.608 sec

FIGURE 21 OVERHEAD SEQUENCE PHOTOGRAPHS OF TEST I-4

DISCUSSION OF TESTS

Four full-scale tests were conducted on tire-sand inertia barriers using bases of four different designs. Tests 3 and 5 were less than successful and are described in detail in the appendix. Pertinent data from high speed photography and accelerometers are presented in Table 1. The stopping characteristics of the barriers were as predicted by the equations until the vehicle vaulted as in Test I-3 or penetrated the barrier as in Tests I-4 or I-5.

The base for the modules used in Test I-3 were tires banded together as described in the appendix. The vehicle in Test I-3 had traveled approximately 5 ft when the first tires were dragged underneath the vehicle. The base of each module was crushed and friction resistance with the ground caused the tires to move at a lesser speed than the vehicle. This pulled the tires underneath the vehicle. The tires holding the sand were tied to the bases and were pulled under the vehicle. The result was that at about 0.172 seconds, or after the vehicle had traveled 10-12 ft, it began to climb up the modules. This chain of events caused the vehicle to end up with the front of the vehicle undercarriage resting on top of the concrete backup wall. The rear end of the vehicle was dragging the ground when it came to rest. There was little scatter of the modules or individual tires as was the case in all previous tests (1, 2).

TABLE 1

TEST DATA

Vehicle	Test I-3	Test I-4	Test I-5	Test I-6
Make	Ford	Dodge	Chevrolet	Chevrolet
Year	1964	1967	1961	1968
Weight, lb	4500	4290	4090	4000
Impact Angle, degrees	0	0	15	0
Film Data				
Initial speed, fps	91.2	93.0	90.7	63.2+
mph	62.2	64.0	61.9	43.1
Final Speed, mph	0	0	28.7	0
fps	0	0	19.5	0
Maximum forward motion, ft	Vehicle Ramped	43.9		
time, sec		2.25		
When last row started to move				
time, sec		0.35		
vehicle dis., ft		20.60		
speed, fps		24.00		
mph		16.30		
**average deceleration		6.10		
Accelerometer Data		*		
Peak - long. (g's)	11.6		6.3	4.9
Trans -	2.2		3.9	1.0
Average deceleration				
long.	5.0		3.4	2.6
over-time, sec	0.2		0.4	0.5
Maximum seat-belt force, lb	1395		460.0	290.0

* No accelerometer was obtained in Test I-4

**

$$a = \frac{V_o^2 - V_f^2}{2gs}$$

\+ Tow cable broke before desired speed obtained

The wire cage used to support the sand mass in Test 2146-I-4 collapsed on impact and rolled underneath the vehicle as intended. There was no tendency for the vehicle to ramp during this test. The vehicle behaved essentially according to the mathematical predictions until after the last module had been impacted. Since there was no backup wall to stop tires or the sand mass they were moved ahead for a considerable distance. The vehicle ploughing action into the debris (which is necessary to completely stop the vehicle) eventually brought the vehicle to a complete stop 43.9 ft from the initial impact point 18.9 ft from the rear of the barrier. The majority of the tire-sand debris was located in the space 15-20 ft in front of the vehicle. This would require a clear space of about 60-65 ft to stop a vehicle with no rigid hazard immediately behind the barrier. This distance can be greatly reduced by adding a few much heavier modules at the rear of the barrier. This would reduce the required distance for ploughing action and also the space to collect debris since the heavier modules would help stop the bulk of the sand and tires from going beyond the back of the barrier. Regardless of the design some additional space must be supplied behind the barrier for penetration and collection of debris if no rigid obstacle or backup wall is present.

The hood was forced open in Test I-3. The hinges of the hood on the vehicle used in Test I-4 were broken causing the hood to fall off (Figure 14, 0.350 and 0.749 sec). Similar incidents have occurred in three previous tests on other projects.

Two of these hoods were torn from their hinges. In a series of tests using the Fitch Inertia barrier, the California Division of Highways (9) noted that "Immediately after impact, the hood flew open." This was observed in two of their three tests. Also pictures presented in the sales literature of Fibco (10) show that it appears to be a common occurrence for the hood to fly open when a vehicle impacts an inertia barrier. In all of the tests reported, the hood was a conventional type with about 6 in. of cowling between the end of the hood and the windshield.

Recent model American-made vehicles have been designed without the intermediate cowl between the hood and windshield. Researchers were concerned about the possibility of these hoods breaking loose from their hinges and penetrating the windshield. The two final tests were conducted using vehicles without the intermediate cowling. In both tests the hoods flew open on impact, but the hinges held and the hoods remained with the vehicle. The hinges comply with the latest Federal Motor Vehicle Safety Standards and are adequate to withstand the impact intensities without allowing the hinges to fracture.

The base used in Test I-5, reported on in the appendix, was fabricated from used 55 gal steel paint drums similar to the base shown in Figure 6. The major difference from Figure 6 was that the end chime and bottom of the drum were utilized as support for possible soft soil. These bases proved to be too stiff and caused vehicle ramping as the vehicle crossed through the barrier on a 15 degree impact angle.

The cover used in this test was 0.030 in. aluminum, the thinest available. It was too stiff to be of practical benefit.

The base used in Test I-6 was fabricated as shown in Figure 6 from used 55 gal paint drums. The chimes and top and bottoms were removed and these modified drums were not as stiff laterally as were the bases used in Test I-5. They were still somwhat stiffer than would be desirable. However, they are satisfactory as bases.

The protective cover, Figure 18, used in this test is inexpensive and satisfactory. The linoleum should last several months in the weather and appears to contain the tires so that the missile problem is reduced. Special care should be exercised to attach the top of the covering so that rain or atmospheric moisture will not penetrate the sand and change the impact characteristics of the modules.

The top speed of the vehicle was only 43.1 mph and the deceleration values were low. By designing for a relatively flat deceleration curve, Figure 4, the longitudinal deceleration and the seat belt pull were both much smoother for this test and Test I-5 than were curves for previous tests which had a much harder nose, that is Tests I-1 and I-2 (2) and I-3 and I-4 presented here.

SUMMARY AND CONCLUSIONS

Scrap tires filled with sand will make an effective inertia type vehicle impact attenuator for selected locations. The sand filled tires used in each module need to be supported on friable bases such as treated cardboard cartons (2), wire cages developed on this project, Figure 5, or bases fabricated from used 55 gal paint drums, Figure 6.

The center of gravity of vehicles on the road generally varies from a low of 18 in. to a high of 23 in. (8). The average height of the c.g. is about 20 in. The collapsible bases as shown in Figure 2 have been sized to raise the c.g. of the module to 23 in. or more except for the first module impacted to overcome the slight ramping tendency.

In addition, the following conclusions have been reaffirmed.

1. The theory of conservation of momentum will provide satisfactory design method for the tire-sand inertia barrier.
2. The state of the art of inertia barriers is sufficiently advanced so that the tire-sand inertia barrier can be considered for selected use.
3. Tire-sand inertia barriers should be installed only in locations where the effects of flying or rolling tires, flying or loose sand and other debris associated with the barrier would not become a secondary hazard to other traffic.

In all high speed impacts to date a considerable amount of sand has accumulated on the engine which could make it temporarily inoperative; however, this same sand could minimize the probability of fire.

Additional research is recommended to determine the effectiveness of the tire-sand barrier in protecting guardrail ends.

This research indicates that the tire-sand inertia barrier would be an economical and effective crash cushion for use in front of rigid obstacles along the roadside where the scattered sand and tires are not likely to fall on the paved travelway. The estimated total installed cost of the tire-sand inertia barrier is approximately $850 when installed by state employees.

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3. Hirsch, T. J., "Use of Mathematical Simulations to Develop Safer Highway Design Criteria," paper presented at the North Carolina Symposium on Highway Safety, Spring 1973, April 12, 1973.

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11. D. Leon Hawkins (deceased) from his personal papers.

12. Weaver, G. D. and Marquis, E. L., "The Relation of Side Slope Design to Highway Safety (Combinations of Slopes)," Report 626B NCHRP 20-7 Task Order 2/2, Texas Transportation Institute, Texas A&M University, October 1973.

APPENDIX

ADDITIONAL VEHICLE CRASH TESTS

Test 2146-I-3

The vehicle used for this test was a 1964 Ford Galaxie 500. The gross weight was 4500 lb which included a 165 lb anthropometric dummy. Figure A-1 shows the vehicle prior to the test.

Longitudinal and lateral accelerometers were mounted on each longitudinal frame member to sense vehicle accelerations. The dummy was secured in the driver's seat with a lap belt anchored through a load cell which indicated the lap belt force through the telemetry system. A flash bulb and an event mark on the electronic data were actuated by a tape-switch on the front bumper. This allows the electronic data to be synchronized with the high speed film. All electronic data were transmitted by telemetry to a ground station (6) where the electronic data were recorded on magnetic tape and displayed in analog form on a strip chart.

Photography included documentary motion pictures and high speed (200 frames per second) films with timing marks. The high speed film is used to develop time-displacement data for the vehicle. The data camera was located perpendicular to the vehicle path.

The barrier, Figure A-2, was located in front of a rigid backup. The vehicle was towed into the barrier at an impact angle of 0 degrees using the reverse tow mechanism described in Reference (6).

The vehicle impacted the barrier in the center at 62.2 mph and during the first part of the impact performed as mathematically predicted. As the sand escaped the individual modules, they became limber and tended to act as

FIGURE A-1 TEST 1-3 VEHICLE BEFORE IMPACT

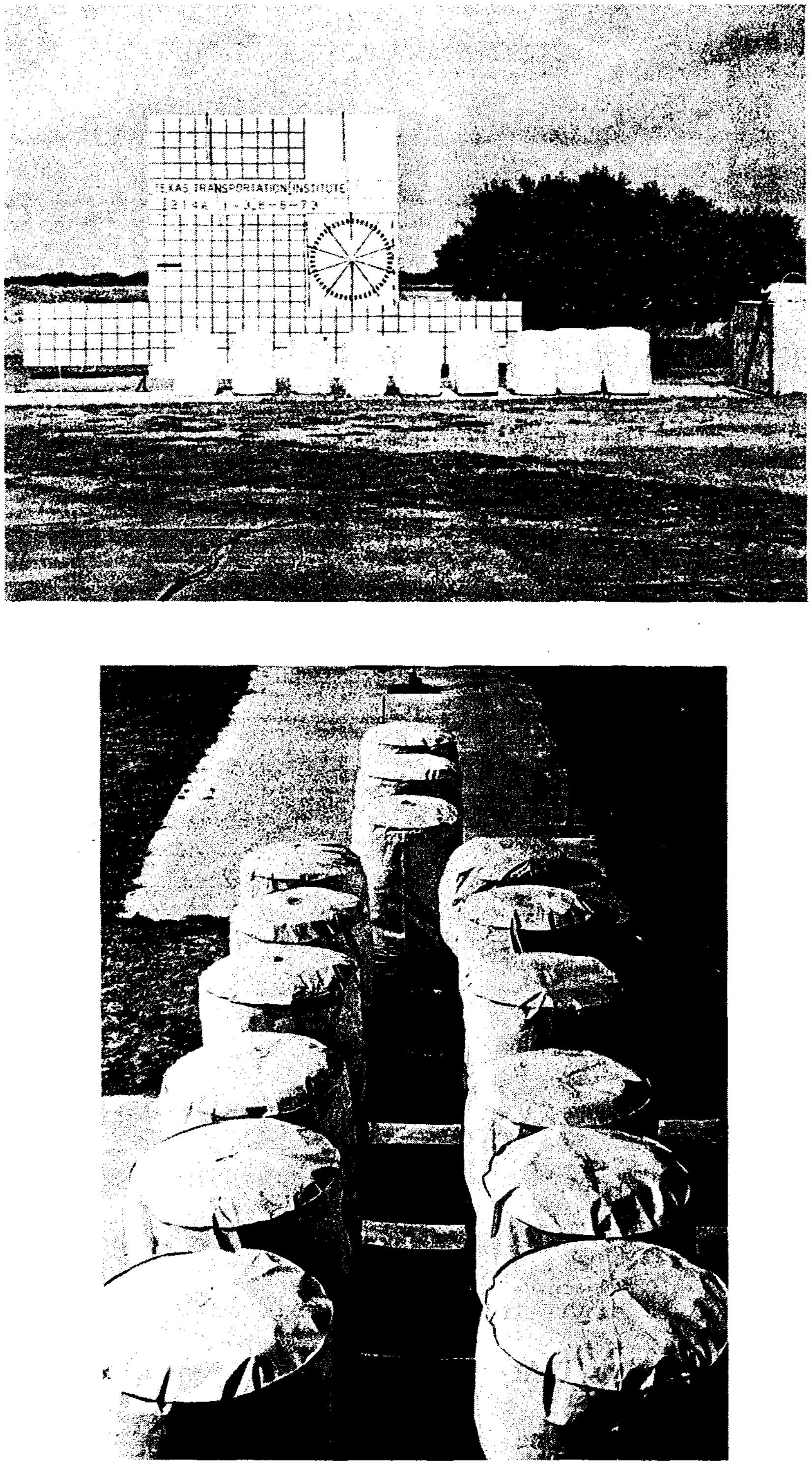


FIGURE A-2 TEST 1-3 BARRIER BEFORE IMPACT individual tires. The bases and tires built up under the vehicle and the vehicle ramped. Figure A-3 shows a sequence of ten photographs of the test. The sequence was taken from the high speed film. Time t = 0 sec was the time of impact. Figure A-4 shows a close-up view of the vehicle and barrier after impact. As can be seen, the vehicle ramped.

Accelerometer traces, time-displacement data and the table of events are elsewhere in the appendix.

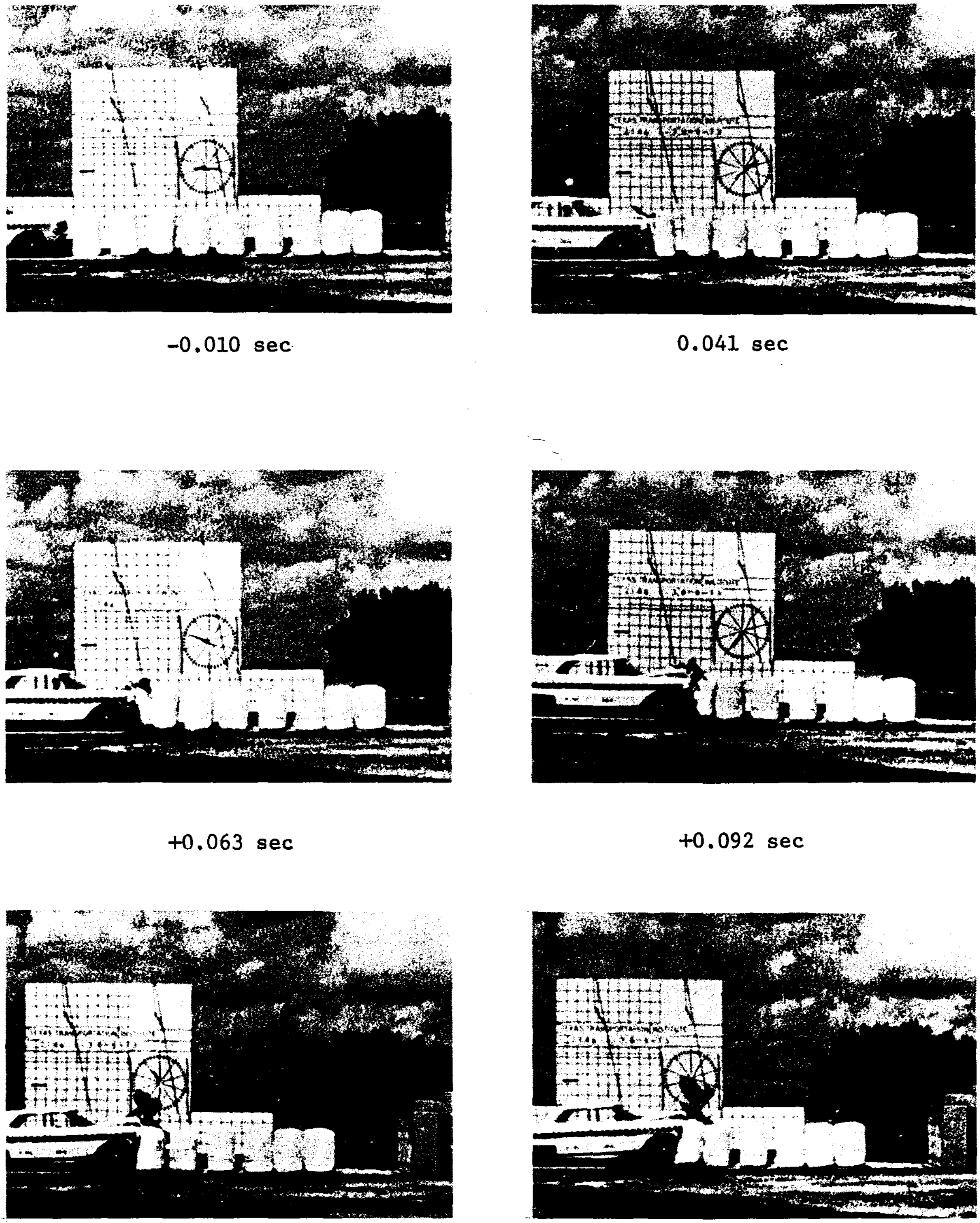
Test 2146-I-5

The vehicle used for this test was a 1961 Chevrolet. The gross weight was 4090 lb which included a 165 lb anthropometric dummy. Figure A-5 shows the vehicle prior to and following the test. The hood extends from the grill to the windshield without intermediate cowling.

Instrumentation and photography were the same as for Test I-5 except that an overhead camera was also used.

The impact angle of the test was 15 degrees from the longitudinal axis of the barrier.

The vehicle impacted the barrier, shown in Figure A-6, in the center at 61.9 mph and performed as mathematically predicted until the vehicle penetrated the barrier. The lower chimes of the cut-off drums and bottoms made the bases very stiff; they tended to build up under the vehicle and the vehicle ramped. Figure A-7 shows a sequence of photographs of the test. Figure A-8 shows an overhead sequence. The sequence was taken from the highspeed film. Time t = 0 sec was the time of impact. Figure A-9 shows a close-up view of the vehicle and barrier after impact.



-0.010 sec

0.041 sec

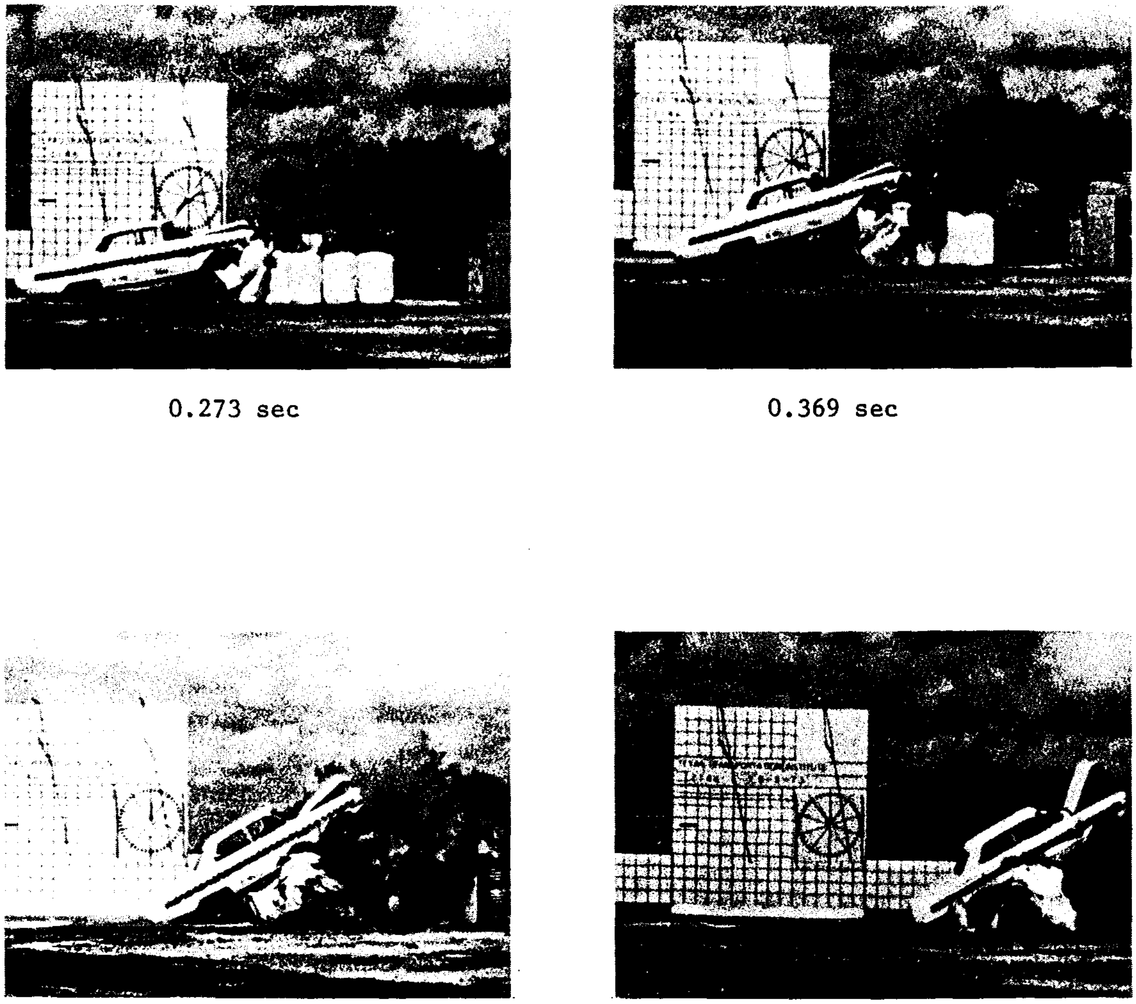
+0.063 sec

+0.092 sec

0.140 sec

0.163 sec

Figure A-3 Sequence Photographs of Test I-3
4250 lb vehicle - 62.2 mph



0.273 sec

0.369 sec

0.609 sec

0.820 sec

Figure A-3a Sequence Photographs of Test I-3 (continued)
4250 lb vehicle - 62.2 mph

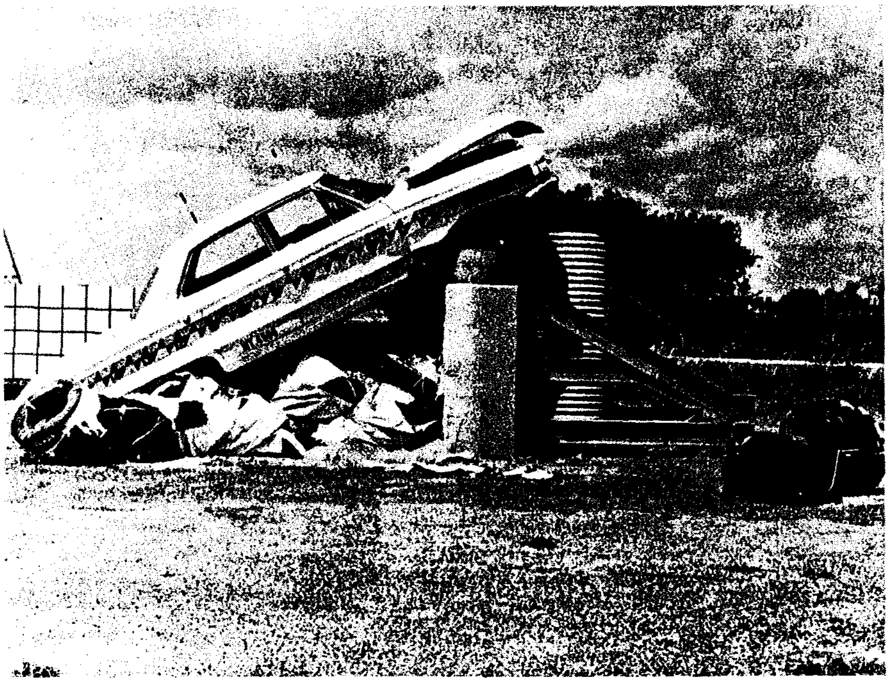


FIGURE A-4 TEST 1-3 VEHICLE & BARRIER AFTER IMPACT

FIGURE A-5 TEST 1-5 VEHICLE BEFORE AND AFTER IMPACT

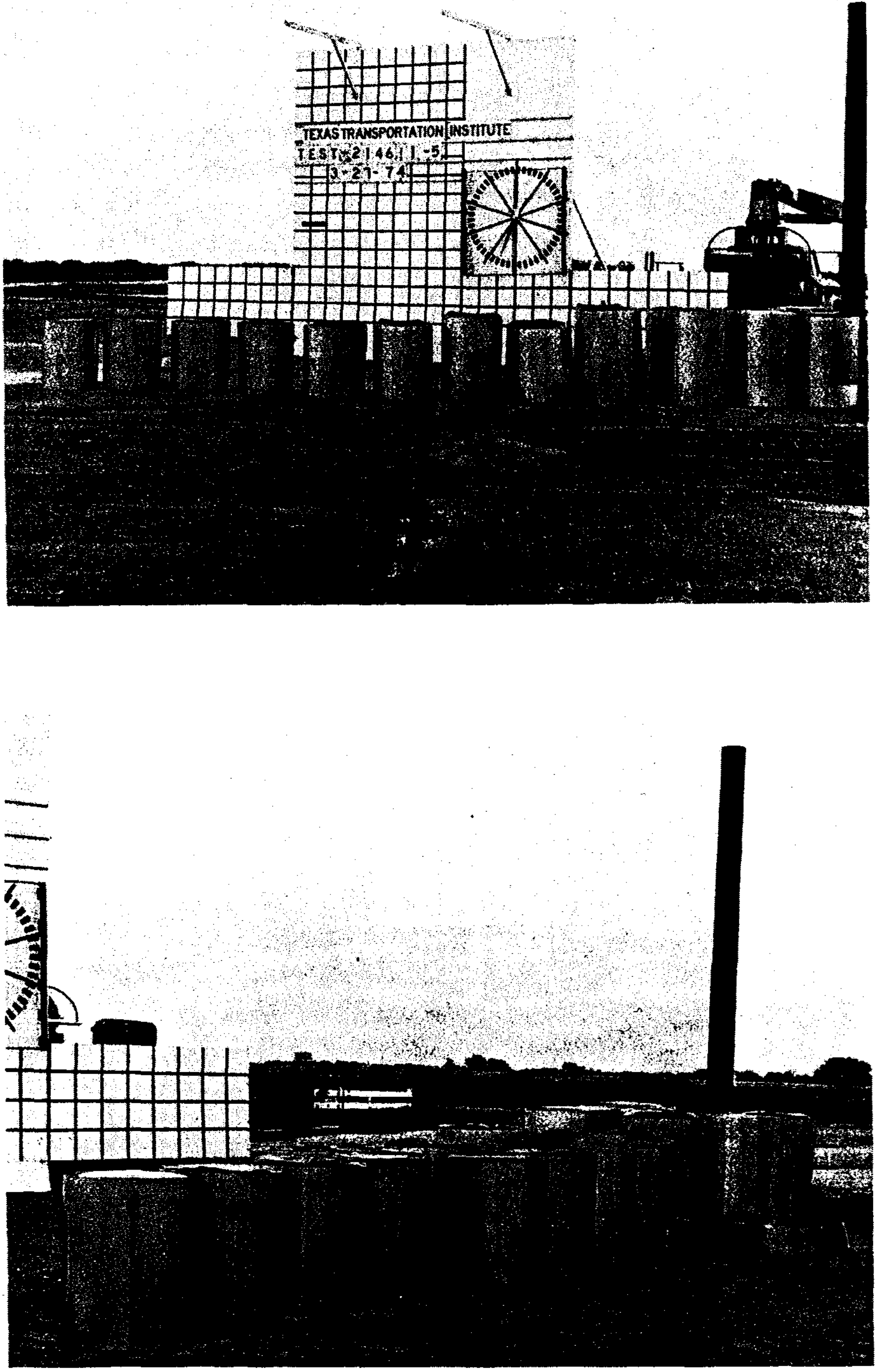
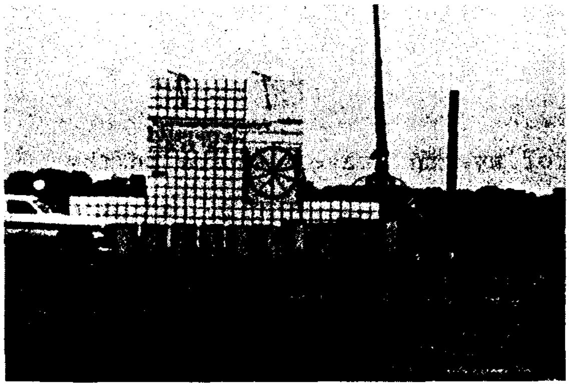
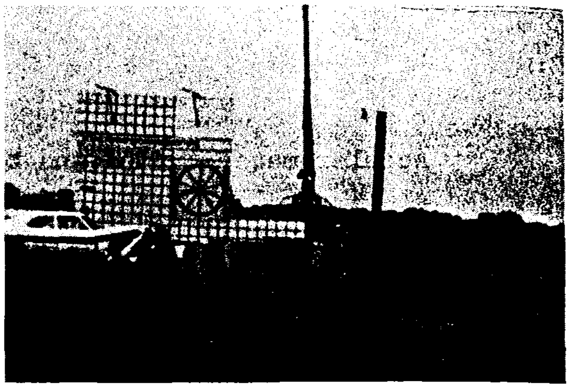


FIGURE A-6 TEST I-5 BARRIER BEFORE IMPACT

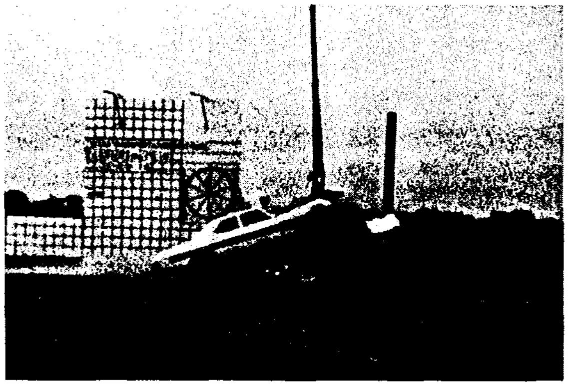
Accelerometer traces and the table of events are elsewhere in the appendix.



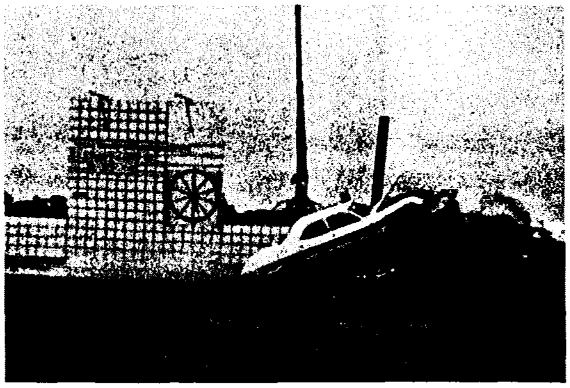
T = 0.0 sec



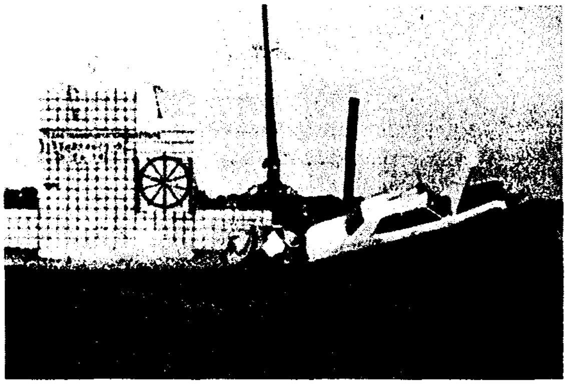
T = 0.128 sec



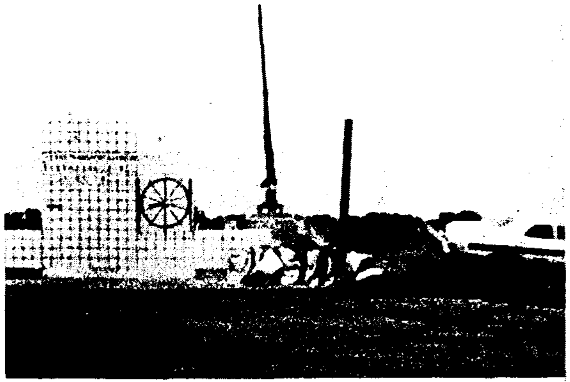
T = 0.226 sec



T = 0.715 sec

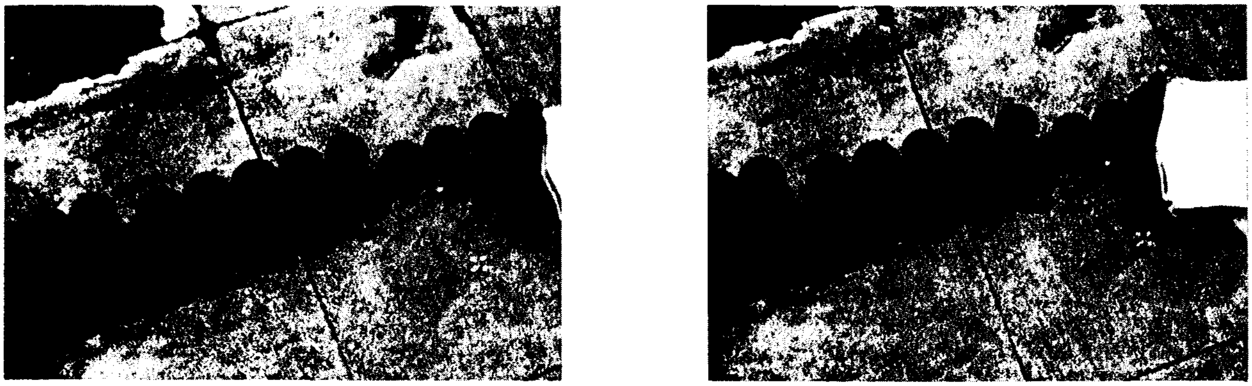


T = 0.960 sec



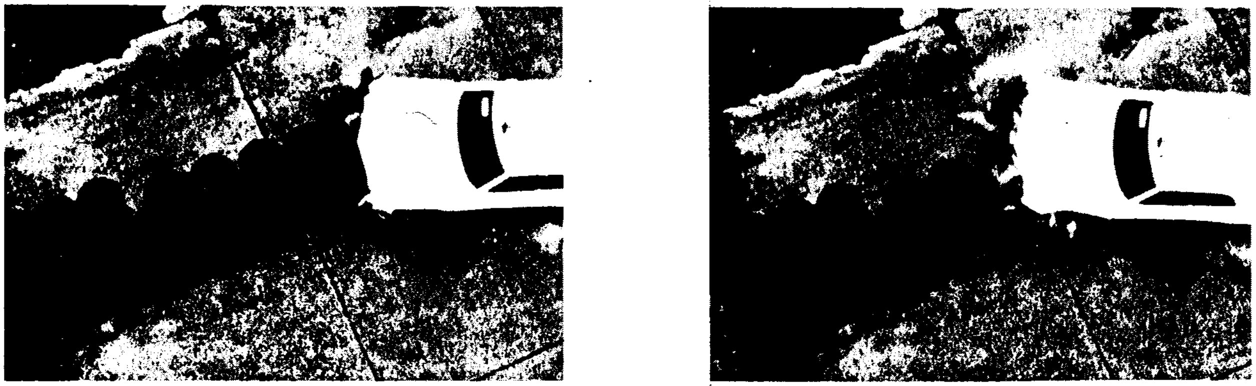
T = 1.998 sec

FIGURE A-7 SEQUENCE PHOTOGRAPHS OF TEST I-5
4090 lb VEHICLE



T = 0.0 sec

T = 0.038 sec



T = 0.136 sec

T = 0.205 sec

T = 0.453 sec

T = 0.715 sec

FIGURE A-8 OVERHEAD SEQUENCE OF PHOTOGRAPHS
TEST I-5

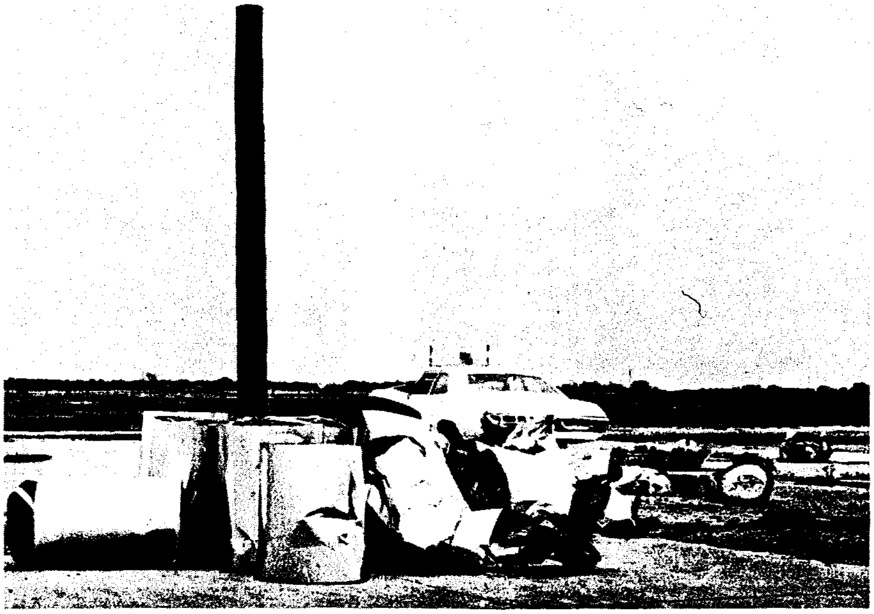


FIGURE A-9 TEST 1-5 VEHICLE AND BARRIER AFTER IMPACT

TABLE A-1

TIME DISPLACEMENT DATA

Test 2146 I-3

TIME (sec)	DISPLACEMENT (ft)	TIME (sec)	DISPLACEMENT (ft)
-0.060	-5.46	0.052	4.48
-0.052	-4.75	0.060	5.05
-0.045	-4.08	0.067	5.59
-0.037	-3.40	0.075	6.11
-0.030	-2.73	0.082	6.64
-0.022	-2.04	0.090	7.16
-0.015	-1.37	0.097	7.63
-0.008	-0.68	0.105	8.11
0	0	0.112	8.56
0.007	0.68	0.119	9.04
0.015	1.33	0.127	9.49
0.022	2.00	0.134	9.94
0.030	2.65	0.142	10.36
0.037	3.27	0.149	10.74
0.045	3.88	0.157	11.15

TABLE A-2

TIME DISPLACEMENT ANGLE

Test 2146 I-3

TIME (sec)	EVENT (Angle) (degrees)
0.117	1-1/2
0.143	2-3/4
0.168	3-3/4
0.194	4-3/4
0.219	6-3/4
0.245	8-3/4
0.270	10-3/4
0.295	12-3/4
0.321	15
0.346	16-1/4
0.372	17-1/2
0.397	18-3/4
0.423	20
0.448	21
0.474	22-1/4
0.499	23-3/4
0.525	25
0.550	26-1/4
0.576	27-3/4
0.601	28-3/4
0.627	29-1/2
0.652	30-1/4
0.678	30-1/4
1.307	25

TABLE A-3

TABLE OF EVENTS

Test 2146 I-3

Time (sec)	Event
0	Impact with 1st tire set
0.007	Bottom tire in stack remaining at rest, upper tires moving; front of car beginning to buckle
0.012	Hood beginning to rise; bottom tire still at rest; tire stack deformed to about 1/2 of its original thickness; plastic bag bursting
0.015	Bottom tire beginning to tilt up at the left edge, hood rising
0.017	Dummy just beginning to move forward
0.030	First tire stack now hitting second tire stack, hood rising, dummy moving forward
0.042	Second plastic bag now rupturing at top
0.062	Second bag hitting third bag; dummy moving forward, hood up approximately 6 inches; front end buckling; tires from first and second stacks are buckled and some are underneath car
0.090	3rd bag hitting 4th bag; hood up about 12 inches; dummy's face about 4 inches from top of steering wheel; tires piling up under front of car; sand coming from 2nd bag
0.095	Impact of dummy's face and top of steering wheel
0.100	Front of car beginning to rise
0.122	Impact of car with rows of stacks; 1st three stacks now between the rows of stacks
0.140	Dummy's face still in contact with steering wheel; tires from 3rd stack knocked between the row of stacks
0.143	Right front wheel leaving the ground
0.155	First bag in second row hitting 2nd bag
0.172	Car beginning to climb up the rows of stacks
0.176	Car climbing the rows; stacks in rows falling over
0.199	Sand scattering; 2nd row hitting 3rd row; dummy still in contact with steering wheel

TABLE A-3 (cont'd)

TABLE OF EVENTS

Test 2146 I-3

Time (sec)	Event
0.308	Rear bumper dragging the ground; stacks are compressing together and stacking up beneath car; sand scattering; dummy still in contact with wheel
0.405	Front of car completely on top of tire stacks; sand exploding everywhere; bumper still dragging

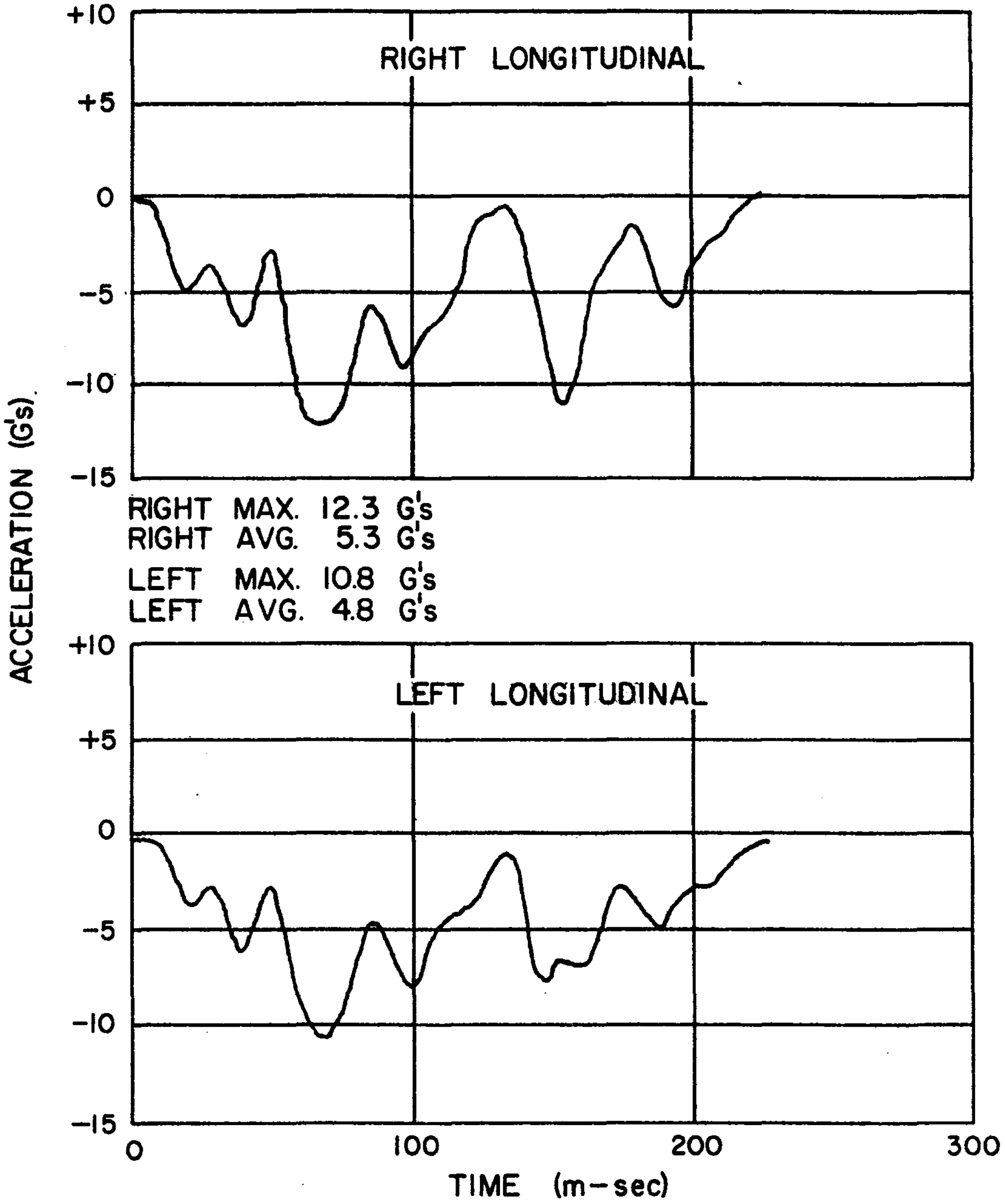
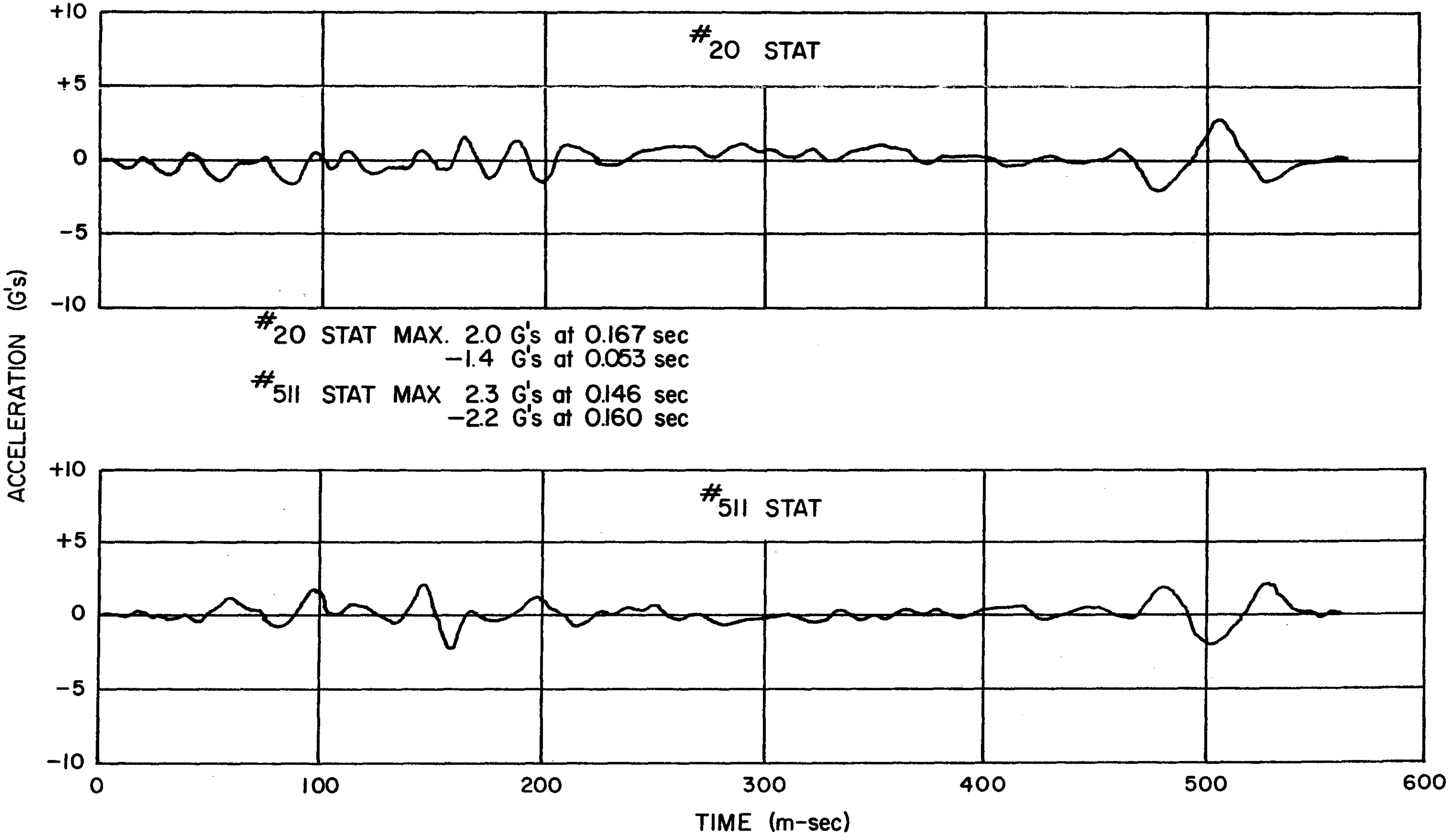


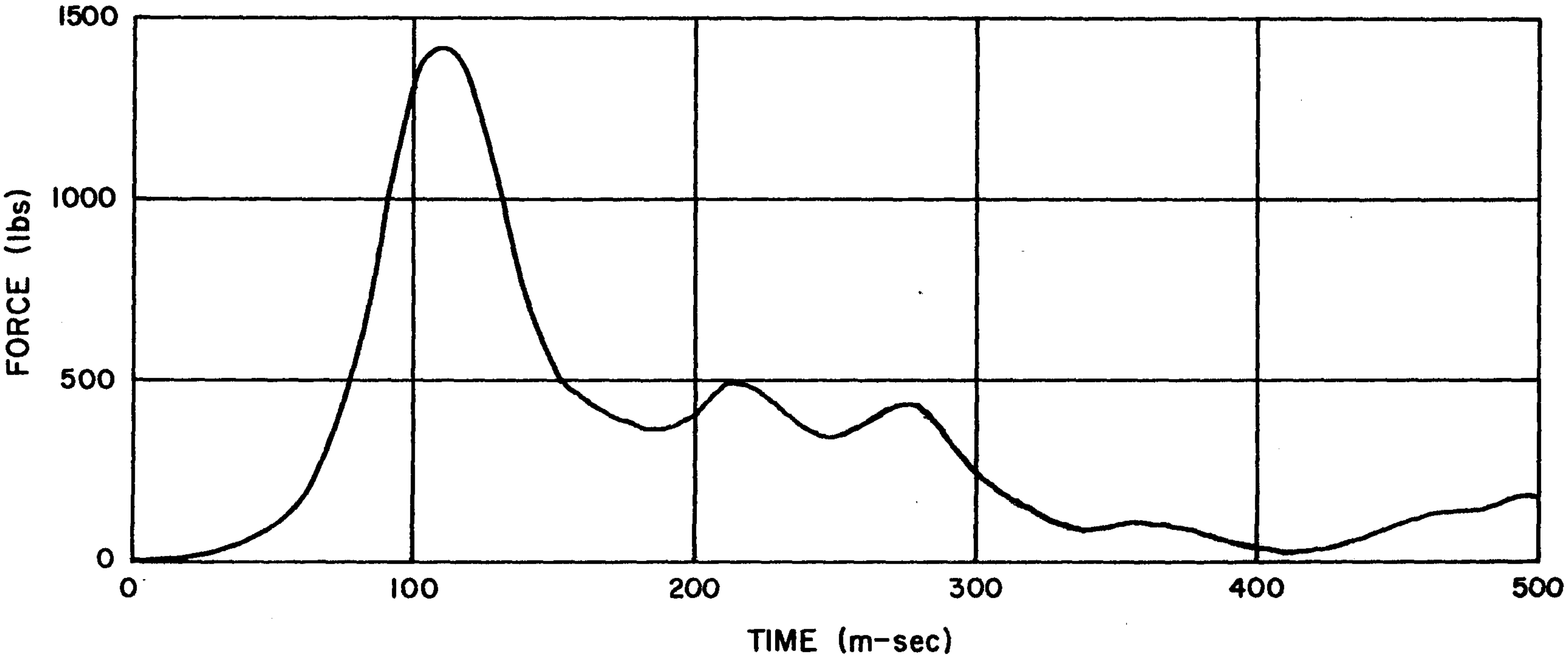
FIGURE A-10 LONGITUDINAL ACCELERATION DATA
TEST 2146 I-3



#20 STAT MAX. 2.0 G's at 0.167 sec
−1.4 G's at 0.053 sec

#511 STAT MAX 2.3 G's at 0.146 sec
−2.2 G's at 0.160 sec

FIGURE A-11 TRANSVERSE ACCELERATION DATA TEST 2146 I−3



MAXIMUM FORCE = 1395 lbs

FIGURE A-12 SEAT BELT STRAIN GAGE DATA TEST 2146 I-3

TABLE A-4
Time-Displacement Data
Test 2146 I-4

Time (sec)	Disp. (ft)	Time (sec)	Disp. (ft)	Time (sec)	Disp. (ft)
-0.052	-4.89	0.112	9.47	0.261	17.74
-0.045	-4.18	0.119	10.01	0.269	18.03
-0.037	-3.50	0.127	10.54	0.276	18.30
-0.030	-2.79	0.134	11.06	0.284	18.57
-0.022	-2.10	0.142	11.54	0.291	18.89
-0.015	-1.40	0.149	12.01	0.299	19.12
-0.008	-0.70	0.157	12.48	0.306	19.37
0	0	0.164	12.94	0.314	19.62
0.007	0.70	0.172	13.37	0.321	19.85
0.022	2.06	0.179	12.80	0.329	20.11
0.030	2.75	0.187	14.22	0.336	20.33
0.037	3.42	0.194	14.62	0.336	20.33
0.045	4.08	0.202	15.01	0.344	20.54
0.060	5.36	0.209	15.38	0.351	20.74
0.067	5.98	0.217	15.75	0.359	20.96
0.075	6.58	0.224	16.12	0.366	21.17
0.082	7.19	0.232	16.45	0.373	21.37
0.090	7.78	0.239	16.80	0.381	21.59
0.097	8.34	0.246	17.11	0.388	21.77
0.105	8.91	0.254	17.42	0.396	21.96

TABLE A-4 Continued
Time-Displacement Data
Test 2146 I-4

Time (sec)	Disp. (ft)	Time (sec)	Disp. (ft)	Time (sec)	Disp. (ft)
0.403	22.19	0.788	30.52	1.647	41.18
0.411	22.32	0.818	31.12	1.749	41.91
0.418	22.52	0.849	31.66	1.852	42.60
0.426	22.71	0.880	32.17	1.954	43.10
0.433	22.88	0.910	32.77	2.056	43.44
0.441	23.05	0.941	33.21	2.158	43.75
0.448	23.22	0.972	33.72	2.261	43.93
0.471	23.65	1.002	34.20		
0.491	24.08	1.033	34.64		
0.511	24.50	1.084	35.45		
0.532	25.05	1.135	36.16		
0.552	25.49	1.187	36.73		
0.573	25.91	1.238	37.30		
0.593	26.40	1.289	37.87		
0.614	26.83	1.340	38.41		
0.634	27.27	1.391	39.05		
0.665	28.01	1.442	39.43		
0.696	28.64	1.494	39.92		
0.726	29.21	1.544	40.40		
0.757	29.90	1.596	40.81		

TABLE A-5
Table of Events
Test 2146 I-4

Event	Time (sec)
Impact, top edge of bumper impacts 1st row at lower portion of top tire. Front hood was already open slightly prior to impact	0
Front row has moved slightly	0.010
About 1/2 width of row has penetrated vehicle front end, row tilting downwards and backwards	0.023
Rt front door and fender are starting to separate	0.026
1st row contacts 2nd row, most of 1st row penetrated vehicle	0.033
2nd row has moved	0.043
Top coming off 2nd row	0.051
Plastic on middle, back part of 2nd row is ripping, hood is lifted higher, door and fender separating more	0.054
2nd row impacts 3rd, right front door and fender are separated more, hood higher	0.064
Most of 2nd row has penetrated vehicle front end	0.077
3rd row has moved. Right end of car up, front end of car up	0.082
4th row contacted by 3rd, Tires are in engine compartment, dummy is falling forward	0.092
Almost all of 3rd row has penetrated the vehicle	0.110
Dummy's chest hits steering wheel, 4th row has moved	0.123
4th row impacts 5th row, some sand flying out from vehicle hood	0.136

TABLE A-5 Continued
Table of Events
Test 2146 I-4

Event	Time (sec)
Most of 4th row has penetrated vehicle, rear end - 4 1/4°	0.164
5th row has moved	0.166
5th row contacts 6th, ft hood is flying off	0.179
Dummy's forehead close to windshield	0.184
6th row has moved. Rear end - 6 1/4°	0.210
6th row contacts 7th. Rear end - 6 1/4°	0.223
7th row has moved. A tire is flying out from car hood	0.256
7th row contacts 8th	0.263
Last row has moved, Rear end - 6 3/4°	0.350
Rear End - 1 1/2°	0.749
End of forward motion	2.253

TEST 2146 I-5 - TABLE A-6

TIME DISPLACEMENT DATA

TIME (sec)	DISPLACEMENT	TIME (sec)	DISPLACEMENT
-0.122	-11.44	-0.009	-0.76
-0.117	-10.64	-0.005	-0.46
-0.112	-10.30	0	0
-0.108	- 9.76	0.002	0.14
-0.103	- 9.36	0.005	0.39
-0.098	- 8.93	0.007	0.60
-0.094	- 8.54	0.010	0.73
-0.089	- 8.01	0.012	0.90
-0.084	- 7.68	0.015	1.15
-0.078	- 7.25	0.017	1.44
-0.075	- 6.89	0.020	1.73
-0.070	- 5.99	0.022	1.89
-0.066	- 5.66	0.025	2.09
-0.061	- 5.56	0.027	2.23
-0.056	- 5.13	0.029	2.43
-0.051	- 4.68	0.032	2.65
-0.047	- 4.32	0.034	2.81
-0.042	- 3.92	0.037	3.10
-0.037	- 3.46	0.039	3.31
-0.033	- 2.97	0.042	3.43
-0.028	- 2.40	0.044	3.70
-0.023	- 1.93	0.047	3.91
-0.019	- 1.92	0.049	4.12
-0.014	- 1.14	0.052	4.38

V_i = 91 fps
62 mph

V_2 = 84 fps
57 mph

TEST 2146 I-5 - TABLE A-6

Continued

TIME (sec)	DISPLACEMENT
0.054	4.51
0.056	4.73
0.059	4.96
0.061	5.11
0.064	5.37
0.069	5.84
0.076	6.25
0.079	6.63
0.084	7.00
0.088	7.43
0.093	7.83
0.098	8.15
0.103	8.52
0.108	8.92
0.113	9.23
0.118	9.58
0.123	9.89
0.128	10.22
0.133	10.57
0.138	10.90

TEST 2146 I-5 - TABLE A-7

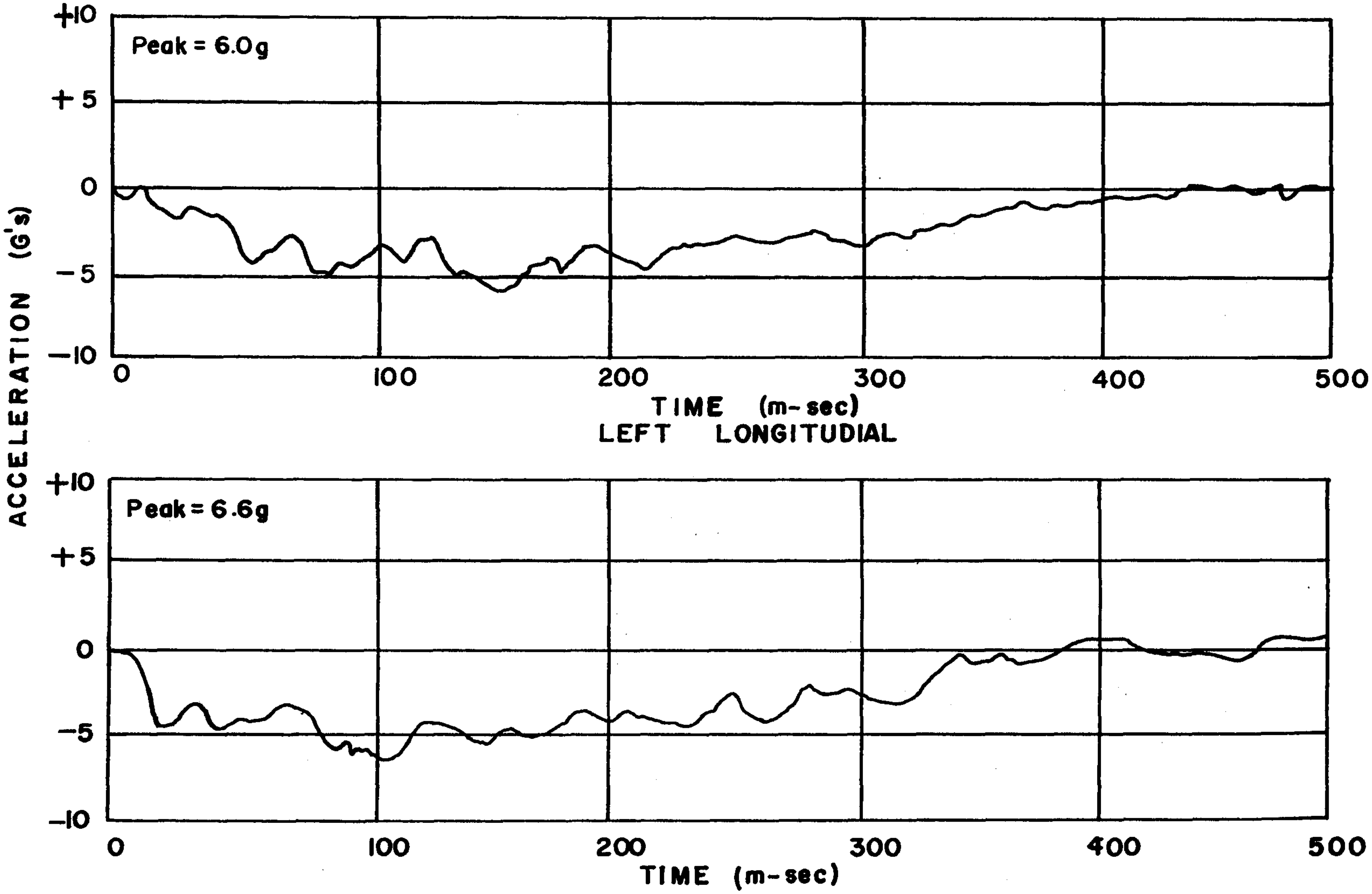
TIME DISPLACEMENT ANGLE

TIME (sec)	EVENT ANGLE (degrees)
0.211	6
0.241	8
0.310	11-1/2
0.354	14
0.388	15-1/2
0.415	17-1/4
0.442	18-1/2
0.457	19
0.477	20-1/2
0.515	21
0.545	22
0.565	22-1/4
0.590	22-1/4
0.592	23-1/4
0.638	22-1/2
0.671	22-1/2

TEST 2146 I-5 - TABLE A-8

TABLE OF EVENTS

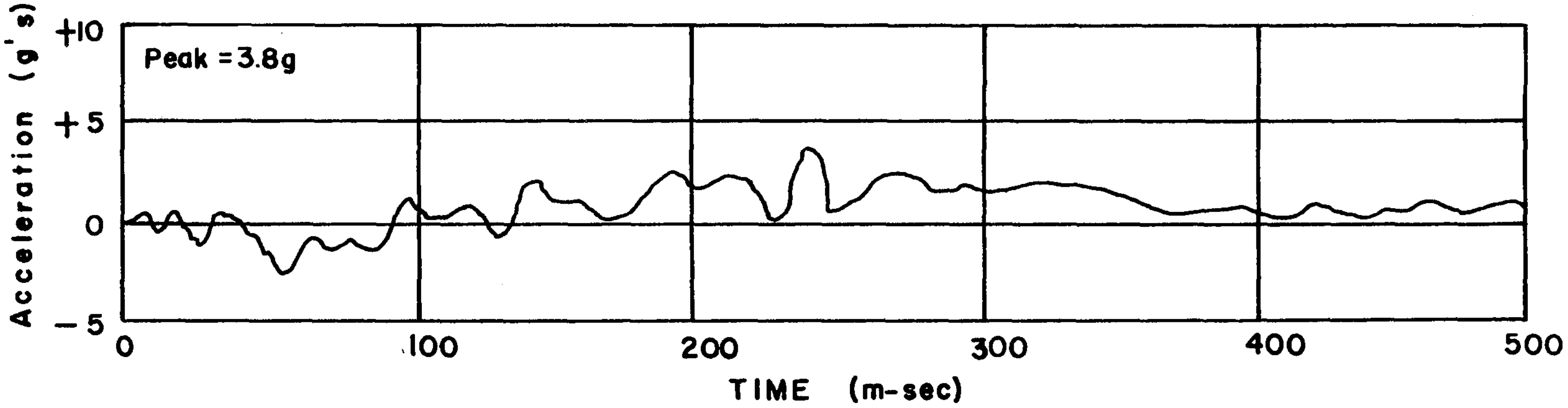
EVENT	TIME (sec)
Impact, rt ft bumper with 1st stack	0
Impact with 2nd stack	0.038
Impact with 3rd stack	0.056
Impact with 4th stack	0.095
Impact with 5th row of stacks	0.128
Impact with 6th row of stacks	0.136
Car beginning to ramp	0.138
Impact with 7th row, sand spraying	0.205
Car hood beginning to open	0.211
Car still ramping, climbing up tires and sand, Impact with 8th row	0.266
9th row stacks pushed into 10th row	0.453
Car ramping	0.594
Hood open, tires being thrown free	0.715
Car coming down, tilted to right, hood open 45°	0.960
Car looks as though might rollover	1.023
Car settling down	1.998



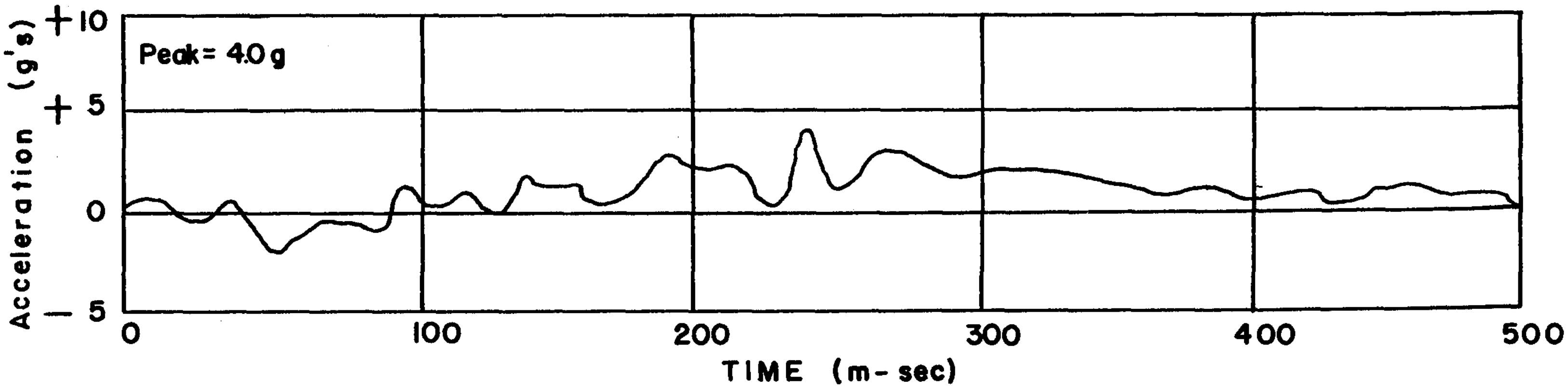
LEFT LONGITUDIAL

RIGHT LONGITUDIAL

FIGURE A-13 LONGITUDINAL ACCELERATION DATA TEST 2146 I-5



LEFT TRANSVERSE



RIGHT TRANSVERSE

FIGURE A-14 TRANSVERSE ACCELERATION DATA TEST 2146 I-5

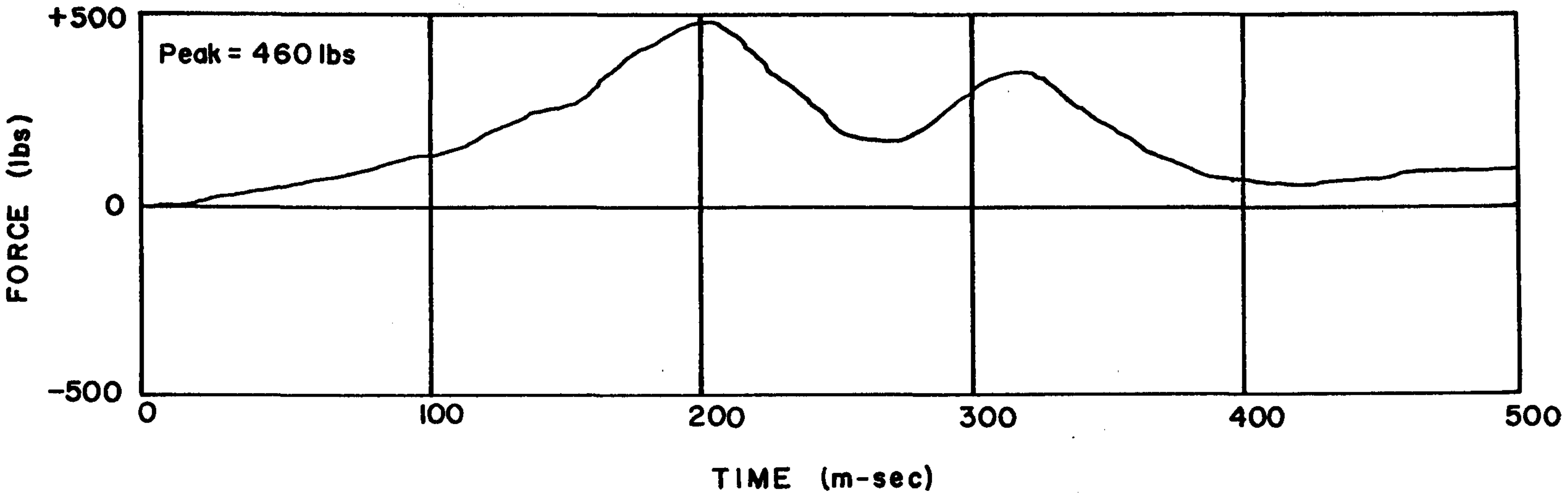
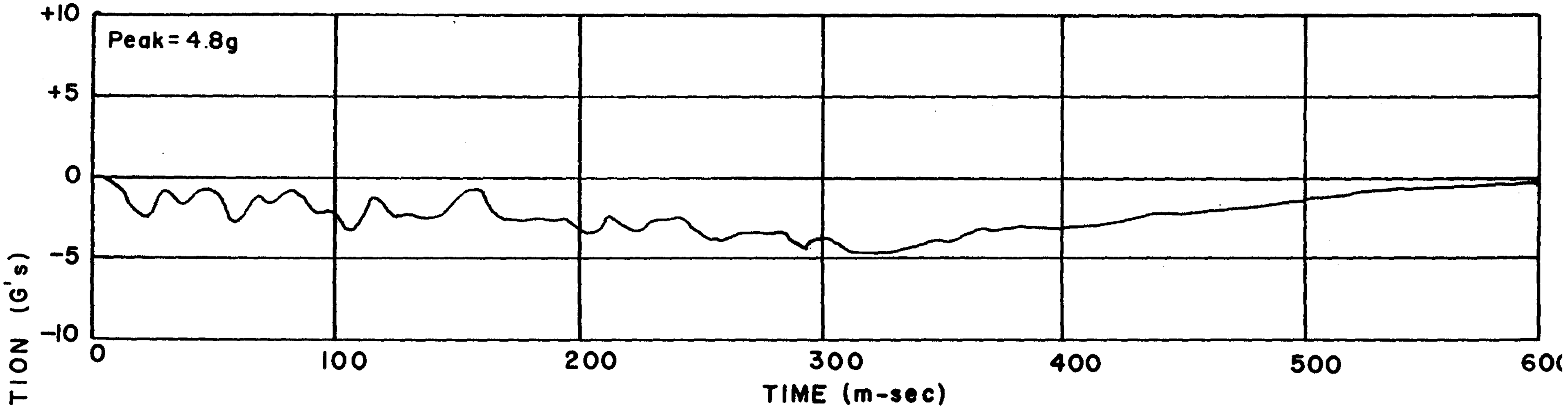


FIGURE A-15 SEAT BELT STRAIN GAGE DATA TEST 2146 I-5

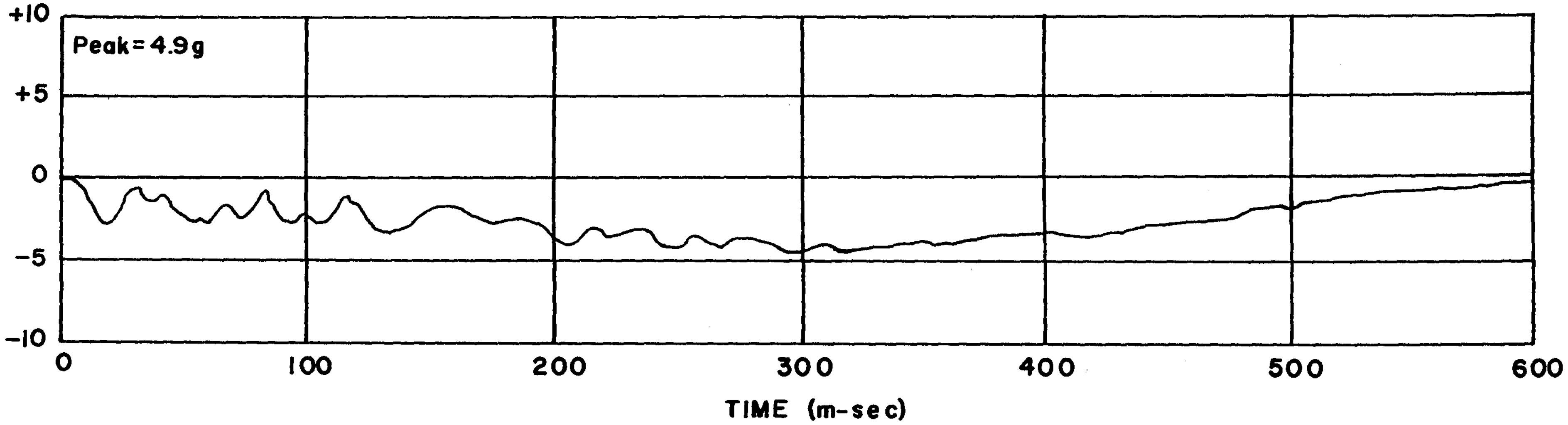
TEST 2146 I-6 - TABLE A-9

TABLE OF EVENTS

	Seconds
Impact, front center bumper with 1st stack	0.000
Left side of hood beginning to open	0.018
Impact with 2nd stack, lid from 1st stack on hood	0.035
Hood open	0.045
Dummy moving forward toward dash, car exhibiting negative pitch	0.053
Impact with 3rd stack	0.070
Sand is beginning to spray	0.078
Impact with 4th stack, hood open 6°, lid approaching windshield	0.108
Impact with 5th row of stacks, lid hit windshield, dummy leaning half-way between seat and dash, hood up 15°	0.180
Car body horizontal	0.185
6th row of stacks hit 7th row of stacks	0.203
Dummy hit dash, car exhibiting positive pitch	0.213
Left front tire beginning to climb the tire, sand, linoleum barrier	0.225
7th row of stacks hit 8th row of stacks	0.255
8th row of stacks hit 9th row of stacks	0.268
Rows 9, 10, 11 & 12 appear to be moving in mass	0.302
Painted circle from 1st stack can be seen at the rear of the car, hood at 23°	0.310
Front of car is beginning to mount the barrier	0.360
Loose tires are becoming noticeable and are moving toward the pole, hood at 26°, 10th row of stacks beginning to show deformation, car is moving laterally to its right	0.370
Hood at 27°, front tires off the pavement	0.380
11th row of stacks showing deformation	0.420
12th row of stacks showing deformation, complete paint circle from 1st stack can be seen at the rear of the car	0.450
Pole beginning to lean	0.490
Complete paint circle from 2nd stack can be seen at the rear of the car	0.608
Pole at 12°, car has a pitch of 9°	0.618
Car reached maximum pitch, 12°	0.995
Point of maximum forward movement, car has 11.5° pitch	1.165
Car beginning to move backward	1.718
Front tires back on pavement, hood at 34°, pitch - 3.25°	2.378
Car body leveled off	2.585

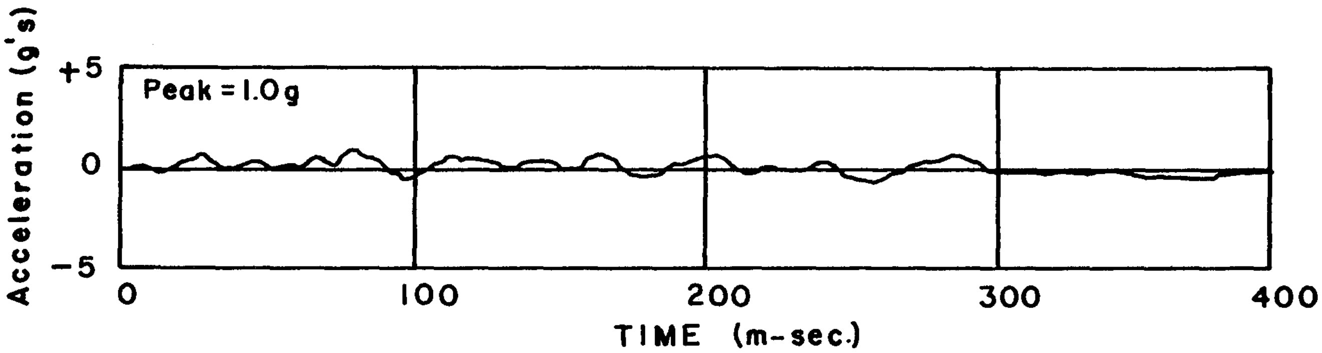


RIGHT LONGITUDINAL

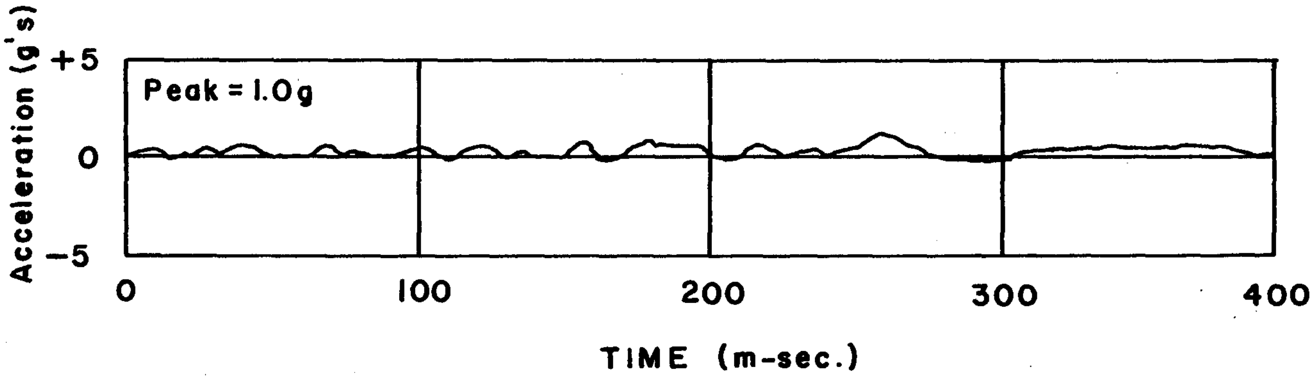


LEFT LONGITUDINAL

FIGURE A-16 LONGITUDINAL ACCELERATION DATA TEST 2146 I-6



RIGHT TRANSVERSE



LEFT TRANSVERSE

FIGURE A-17 TRANSVERSE ACCELERATION DATA TEST 2146 I-6

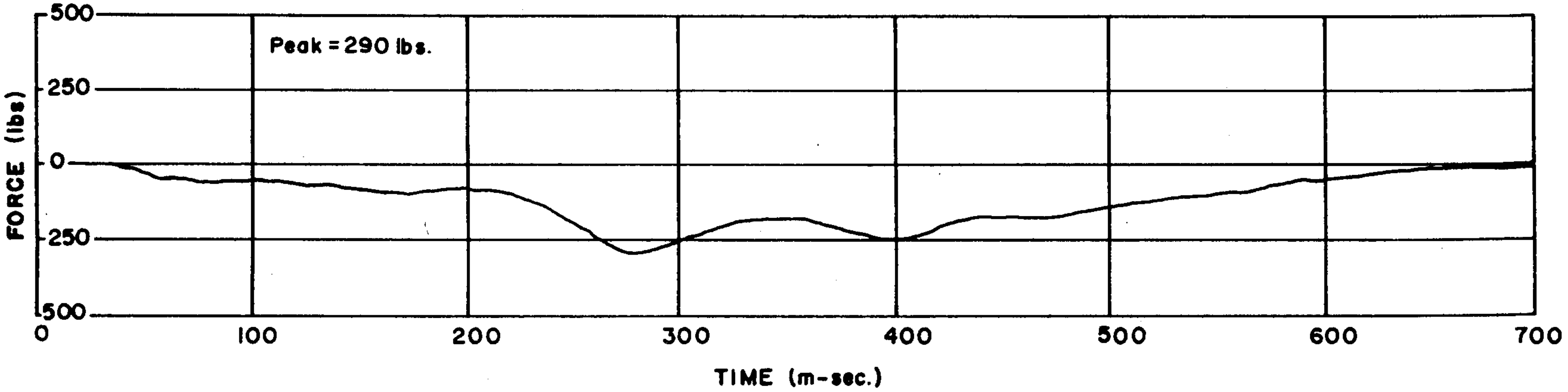


FIGURE A-18 SEAT BELT STRAIN GAGE DATA TEST 2146 I-6

PREVIOUS RESEARCH REPORTS OF STUDY

Research Report 146-1. "Vehicle Impact Attenuation by Modular Crash Cushion," by T. J. Hirsch and Don L. Ivey.

Research Report 146-2. "In-Service Experience on Installations of Texas Modular Crash Cushions," by Monroe C. White, Don L. Ivey, and T. J. Hirsch.

Research Report 146-3. "Flexbeam Redirectional System for the Modular Crash Cushion," by Gordon G. Hayes, Don L. Ivey, and T. J. Hirsch.

Research Report 146-4. "Vehicle Crash Test and Evaluation of Median Barriers for Texas Highways," by T. J. Hirsch, Edward R. Post, and Gordon G. Hayes.

Research Report 146-5. "Evaluation of Breakaway Lightpoles for Use in Highway Medians," by N. E. Walton, T. J. Hirsch, and N. J. Rowan.

Research Report 146-6. "Texas Crash Cushion Trailer to Protect Highway Maintenance Vehicles," by E. L. Marquis and T. J. Hirsch.

Research Report 146-7. "Truck Tests on Texas Concrete Median Barrier," by T. J. Hirsch and E. R. Post.

Research Report 146-8. "Crash Test of Mile Post Marker," by T. J. Hirsch and Eugene Buth.

Research Report 146-9. "Pendulum Tests on Transformer Bases for Luminaire Supports," by Eugene Buth, T. J. Hirsch, E. L. Marquis, and J. W. Button.

Research Report 146-10. "Chain Link Fence Vehicle Arresting System," by E. L. Marquis, G. G. Hayes, and T. J. Hirsch.

Research Report 146-11. "Full Scale Crash Tests of a Tire-Sand Inertia Barrier," by E. L. Marquis and T. J. Hirsch.