TECHNICAL MEMORANDUM 505-2

Texas Transportation Institute
Texas A&M Research Foundation

TOR-SHOK ENERGY ABSORBING PROTECTIVE BARRIER

A Tentative Progress Memorandum on Contract No. CPR-11-5851, U. S. Dept. of Transportation, Federal Highway Administration, Bureau of Public Roads

by

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INTRODUCTION

From November 14, 1967 to January 10, 1968, the Texas Transportation Institute conducted four full-scale vehicle crash tests on the TOR-SHOK energy absorbing highway protective system which was developed by Aerospace Research Associates (ARA), Inc., of 2017 West Garvey Avenue, West Covina, California. This Technical Memorandum is being written to provide some of the technical information and crash performance of this vehicle impact attenuation system.

Included are photographs of the vehicle and barrier before and after each of the four crash tests. Also included is a summary of the high speed motion picture film data taken of the tests, giving the vehicle impact velocity, average deceleration, peak deceleration, stopping distance, etc. (see Appendix B). In addition, a summary of the electromechanical instrumentation data which was collected during the tests is included (see Appendix B).

BARRIER DESCRIPTION

The TOR-SHOK energy absorbing barrier was developed by ARA, Inc. under a contract with the Bureau of Public Roads. The barrier was fabricated, delivered, and installed by ARA, and the vehicle crash tests were conducted by personnel of the Texas Transportation Institute. This highway protective system (see Figure 1) is constructed of high strength, lightweight steel tubes which are supported from the fixed object by a number of TOR-SHOK attenuators (detailed description given in Appendix A). At impact, the protective barrier tubes transmit the impact forces axially to the cylindrical TOR-SHOK arms which contain a large number of stainless steel "torus" elements that are squeezed between two cylindrical tubes. At impact these "torus" elements absorb the energy by rolling between the cylinders. Eight of the twelve TOR-SHOK arms are acting in tension while four others are acting in compression. These TOR-SHOK arms exert a stopping force on the vehicle as the barrier deforms under the vehicle collision.

Supplementary data on the TOR-SHOK energy absorbing system is presented in Appendix A. This information was provided by ARA, Inc. Drawings B1450 and B1449 in Appendix A show the dimensions and configuration of the barrier tested. Table 1 in Appendix A gives a summary of the characteristics of the TOR-SHOK barrier. The barrier tested by TTI had a nose angle of 15°, a nose radius of 31 in., and the weight of the tubular nose was 845 lbs.

TEST PROGRAM

A brief description of the four crash tests conducted is given in Table 1. Test 2A was a head-on impact with a 4600 lb vehicle going at a relatively slow speed, 34 mph. Tests 2B and 2C were both head-on impacts at relatively high speeds, 54 mph and 60 mph, respectively. In Test 2B, a lightweight vehicle weighing 2520 lbs was used, while in Test 2C a heavy vehicle weighing 4940 lbs was used. Test 2D was impacted at an angle of 30° with the longitudinal axis of the barrier with a heavy vehicle weighing 5000 lbs and traveling at a speed of 50 mph.

TEST 2A RESULTS

Figures 1 through 4 show the vehicle and barrier before and after impact for Test 2A. Figure 5 shows an idealized stopping force which the TOR-SHOKs will exert on the impacting vehicle during a head-on collision for various barrier deformations. This force-deformation curve was developed using data presented in Appendix A. Table 2 presents a brief summary of the test results for the head-on impact. It can be seen that the 4600 lb vehicle in Test 2A deformed the barrier 4.48 ft. The maximum TOR-SHOK stopping force was thus approximately 48 kips. From Table 2, it can be seen that the TOR-SHOKs absorbed 163 kip-ft of the vehicle kinetic energy (approximately 91%). The average deceleration during this impact was 6.6 g's, and the maximum significant deceleration was approximately 13 to 14 g's. This average deceleration was obtained from an analysis of the high speed movies. A more complete summary of the crash test data gathered from the high speed film and electromechanical devices is presented in Appendix B, Table 1B.

An analysis of the crash test results and the photographs presented in Figures 1 through 4 indicate the following conclusions concerning Test 2A:

1. The ARA TOR-SHOK barrier performed as designed.
2. The vehicle damage was relatively minor.
3. The barrier damage was relatively minor. Minor maintenance was required; however, the barrier nose and TOR-SHOKs were reusable.
4. The deceleration level was considered moderate.

Table 3 presents a comparison of the ARA TOR-SHOK impact performance with a "rigid" barrier impact. If the 4600 lb vehicle used in Test 2A had struck a "rigid" wall, the estimated maximum deceleration would have been 30.8 g's; and the estimated average deceleration, 19.6 g's. Using these maximum and average decelerations of a "rigid" barrier impact, the maximum and average decelerations from the ARA TOR-SHOK impact can be compared by taking a ratio which will be defined as Attenuation Index (AI). From Table 3, it can be seen that the Attenuation Index for Test 2A ranged from 0.34 to 0.44 for the average and maximum deceleration, respectively. This Attenuation Index is presented

TABLE 1.

BRIEF DESCRIPTION OF TEST PROGRAM

ON ARA TORSHOK BARRIER

Test Number	2A	2B	2C	2D
Angle of Attack	Head-on	Head-on	Head-on	30°
Vehicle Weight (w)	4600 lb.	2520 lb.	4940 lb.	5000 lb.
Speed (V)	34.1 mph	53.5 mph	59.4 mph	49.9 mph
Kinetic Energy of Vehicle (K.E.)	179 Kip-ft	242 Kip-ft	582* Kip-ft	418 Kip-ft

*Note: The ARA Torshok Barrier was designed to stop a 4000 lb vehicle traveling at 60 mph (88 fps). The max. design kinetic energy was thus 482 Kip-ft. The vehicle in test 2C exceeded this design energy by 21%.

for comparative purposes only. It in no way indicates whether the vehicle crash was survivable or would inflict minor or severe injuries to the occupants of the vehicle. This Index indicates that this collision was about 34 to 44% as severe as a rigid barrier impact.

TEST 2B RESULTS

Figures 6 through 9 show the TOR-SHOK barrier and 2520 lb vehicle before and after the 53.5 mph collision. The test results presented in Table 2 show that the barrier deformed 5.33 ft. Referring to Figure 5, it can be seen that the maximum TOR-SHOK stopping force exerted on the vehicle was 69.6 kips. The total energy absorbed by the TOR-SHOKs was approximately 210 kip-ft (87% of the vehicle kinetic energy). The average deceleration during this impact was 12.3 g's. The maximum significant deceleration on the vehicle was 26 to 27 g's as shown in Table 2.

The conclusions which can be drawn from this test are as follows:

1. The ARA TOR-SHOK barrier performed as designed.
2. The vehicle damage was severe (note Figures 7 and 9).
3. The barrier damage was minor, and the nose element and TOR-SHOKs were reusable.
4. The deceleration level produced on this lightweight vehicle was considered severe.

Referring to Table 3, we can compare this ARA TOR-SHOK impact performance with a rigid barrier impact. If the vehicle in Test 2B had hit a rigid barrier, the maximum deceleration would have been about 48.5 g's, and the average deceleration about 31.0 g's. Comparing

TABLE 2. BRIEF SUMMARY OF TEST RESULTS

TEST NUMBER	2A	2B	2C	2D
Angle of Attack	Head-on	Head-on	Head-on	30° Angle of Impact
Vehicle Weight (W)	4600 lb	2520 lb	4940 lb	5000 lb
Vehicle Velocity (V)	50.0 fps	78.8 fps	87.1 fps	73.3 fps
Vehicle Deformation	1.42 ft	1.88 ft	1.75 ft	1.83 ft
Barrier Deformation	4.48 ft	5.33 ft	11.12 ft	12.13 ft
Max. TOR-SHOK Stopping Force (F)	48 kips	69.6 kips	69.6 kips	--
Energy Absorbed by Torshoks	163 kip-ft (91%)	210 kip-ft (87%)	361 kip-ft (62%)	--
Max. Significant Deceleration	13 to 14 g's	26 to 27 g's	20 to 21 g's	28 to 30 g's
Avg. Deceleration (film) ($\Delta V \div Tg$)	6.6 g's	12.3 g's	9.9 g's	8.1 g's
Remarks: 1.	Performed as Designed	Performed as Designed	Performed as Designed	Unsatisfactory Performance
2.	Vehicle Damage Minor	Vehicle Damage Severe	Vehicle Damage Moderate	Vehicle Damage Severe
3.	Barrier Damage Minor, Reusable	Barrier Damage Minor, Reusable	Barrier Damage Severe, Most Torshoks not Reusable, Major Repairs Required	Barrier Damage Severe, Almost Total Loss
4.	Deceleration Level Moderate	Deceleration Level Severe	Deceleration Level Moderate	Deceleration Level Severe

TABLE 3. COMPARISON OF ARA TORSHOK IMPACT PERFORMANCE WITH RIGID BARRIER IMPACT

Test Number	2A	2B	2C	2D
Vehicle Weight	4600 lb	2520 lb	4940 lb	5000 lb
Vehicle Velocity	34.1 mph	53.5 mph	59.4 mph	49.9 mph
Comparative Rigid Barrier Impact				
Estimated Maximum Deceleration* (G_{max})	30.8 g's	48.5 g's	53.5 g's	44.8 g's
Estimated Average Deceleration* (G_{avg})	19.6 g's	31.0 g's	34.1 g's	30.6 g's
Attenuation Index				
$AI_{max} = \frac{G\ max\ Torshoks}{G\ max\ Rigid}$	.44	.55	.38	.65
$AI_{avg} = \frac{G\ avg\ Torshoks}{G\ avg\ Rigid}$	.34	.40	.29	.27

*Estimated Maximum Deceleration = 0.9 V

Estimated Average Deceleration = 0.574 V,
where V is in mph.

Reference: Emori, Richard I., "Analytical Approach to Automotive Collisions," SAE Paper 680016, Auto. Engr. Congress, Detroit, January 8, 1968.

these figures with those obtained in Test 2B yield an Attenuation Index of 0.55 considering the maximum g forces, and an Attenuation Index of 0.40 considering the average g forces. This comparison shown in Table 3 indicates that the impact forces in Test 2B were from 40 to 55% as severe as those that would have been obtained if the vehicle had struck a rigid barrier.

TEST 2C RESULTS

Test 2C was a head-on collision by a 4940 lb vehicle which was traveling at 59.4 mph. In this test, the vehicle kinetic energy exceeded the design energy of the ARA TOR-SHOK barrier by 21% (see Table 1). Since the kinetic energy of the vehicle in Test 2C was 580 kip-ft, it was anticipated that the energy absorbing capacity of the TOR-SHOK arms (361 kip-ft) would be used up; and consequently the arms would be broken or buckled, and the vehicle would penetrate far into the barrier. Figures 10 through 13 show the TOR-SHOK barrier and vehicle before and after the collision.

From Table 2C, it can be seen that the barrier deformed 11.12 ft. The maximum TOR-SHOK stopping force was 69.6 kips. The energy absorbed by the TOR-SHOKs was 361 kip-ft (about 62% of the vehicle kinetic energy). The additional energy of the vehicle was absorbed by breaking and buckling the TOR-SHOK arms and by the vehicle deformation during the collision. The maximum significant vehicle deceleration was approximately 20 to 21 g's. The average vehicle deceleration was 9.9 g's.

In summary, the following conclusions can be drawn concerning this test:

1. The barrier performed as designed.
2. The vehicle damage was moderate (see Figures 11 and 13).
3. Damage to the TOR-SHOK barrier was considered severe. Most of the TOR-SHOKs were buckled and bent, and consequently not reusable. Major repairs and replacement of components were required.
4. The deceleration level was considered moderate.

To compare this ARA TOR-SHOK impact performance with a rigid barrier impact, refer once again to Table 3. If the vehicle used in Test 2C had struck a rigid barrier, it can be seen that the estimated maximum deceleration would have been 53.5 g's, and the average deceleration 35.1 g's. Computing the Attenuation Index yield 0.38 and 0.29, respectively. This indicates that the severity of the TOR-SHOK barrier impact was from 29 to 38% as severe as that which would have resulted from striking a rigid barrier.

DISCUSSION OF HEAD-ON TESTS

To further analyze the head-on impact performance of the ARA TOR-SHOK barrier, Figure 14 presents a comparison of the Attenuation Index with the vehicle weight. From Figure 14, it can be seen that for heavy vehicles around 5000 lbs the Attenuation Index varies from about 0.29 to 0.38. For a 2500 lb vehicle, a lightweight car, the Attenuation Index is seen to vary from about 0.40 to 0.55. This comparison indicates that the TOR-SHOK barrier is more effective as an impact attenuator for heavy vehicles than it is for lightweight or compact vehicles.

TEST 2D RESULTS

In Test 2D, a 5000 lb vehicle struck the ARA TOR-SHOK barrier at an angle of 30° from the longitudinal axis at a speed of 49.9 mph. Figures 15 through 19 show the vehicle and TOR-SHOK barrier before and after the collision. Under this collision, the nose of the TOR-SHOK barrier rotated from the path of the vehicle and allowed the vehicle to strike the rigid post. The TOR-SHOK arms were not activated properly, and consequently they absorbed very little of the vehicle kinetic energy. The impact with the backup post was extremely severe. The maximum deceleration was approximately 28 to 30 g's (from the vehicle accelerometer data, Appendix B). The average deceleration, on the other hand, was approximately 8.1 g's. The vehicle traveled 12.13 ft after striking the nose angle before coming to a complete stop against the vertical backup post.

The following conclusions can be drawn from the results of this test:

1. The barrier did not perform in a satisfactory manner under this 30° angle of impact.
2. The vehicle damage was very severe (see Figures 16, 18, and 19).
3. Damage to the TOR-SHOK barrier was quite severe. Most all the TOR-SHOKs were damaged beyond repair and were not reusable. The TOR-SHOK nose piece was almost totally destroyed.
4. The deceleration level was quite severe.

Table 3 compares the rigid barrier maximum deceleration of 44.8 g's to the approximately 29 g's obtained in Test 2D. It can be seen that the Attenuation Index is about 0.65 when the maximum values are compared. The Attenuation Index based on the average g's is seen to be about 0.27. This average g Attenuation Index may be misleading since an analysis of the high speed film data shows that the vehicle was still traveling at about 40 mph when the nose angle and vehicle bottomed out and collided with the vertical backup post. This severe impact near the end of the crash is what caused most of the damage to the vehicle and was very severe (about 65% as severe as a rigid barrier collision).

SUMMARY AND CONCLUSIONS

The following general conclusions can be drawn from these four vehicle crash tests:

Head-On Collisions

(1) For head-on collisions, the ARA TOR-SHOK barrier performed as anticipated by the design. (2) Reasonable impact attenuation can be realized when the barrier is struck by heavy vehicles (say 4000 lb or more in weight). (3) Quite severe deceleration levels will be obtained when the barrier is struck by lighter weight and compact vehicles. (4) When the kinetic energy of the vehicle exceeds about 425,000 ft-lb, considerable damage to the barrier and TOR-SHOKs can be anticipated.

Angle Collisions

(1) For the angle collision used in these tests, the performance of the TOR-SHOK barrier was unsatisfactory. Modification of the barrier design to minimize or correct this deficiency is being made by the designers. Angle impact tests on the modified design are anticipated in the near future.

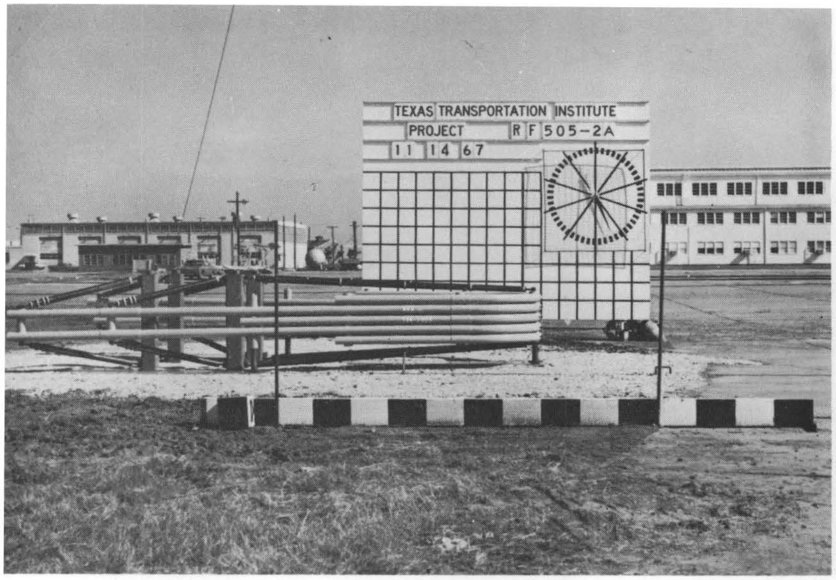


FIGURE 1. TORSHOK BEFORE COLLISION.
TEST 2A.

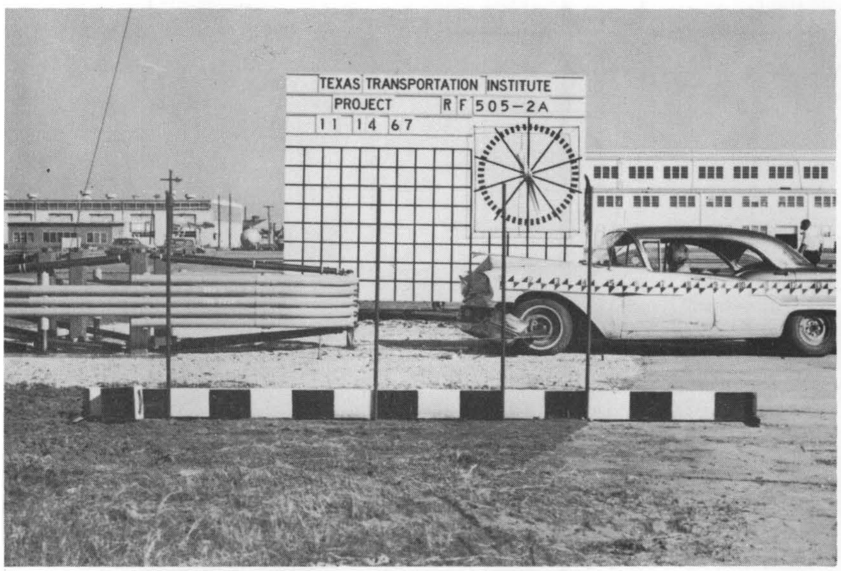


FIGURE 2. TORSHOK AND VEHICLE AFTER COLLISION.
INITIAL VEHICLE VELOCITY 34.1 MPH,
STOPPING DISTANCE 5.90 FT., AVERAGE
VEHICLE DECELERATION 6.6 G'S.
TEST 2A, HEAD-ON IMPACT.

FIGURE 3. VEHICLE BEFORE COLLISION. TEST 2A.
1957 OLDS, WEIGHT 4600 LB.

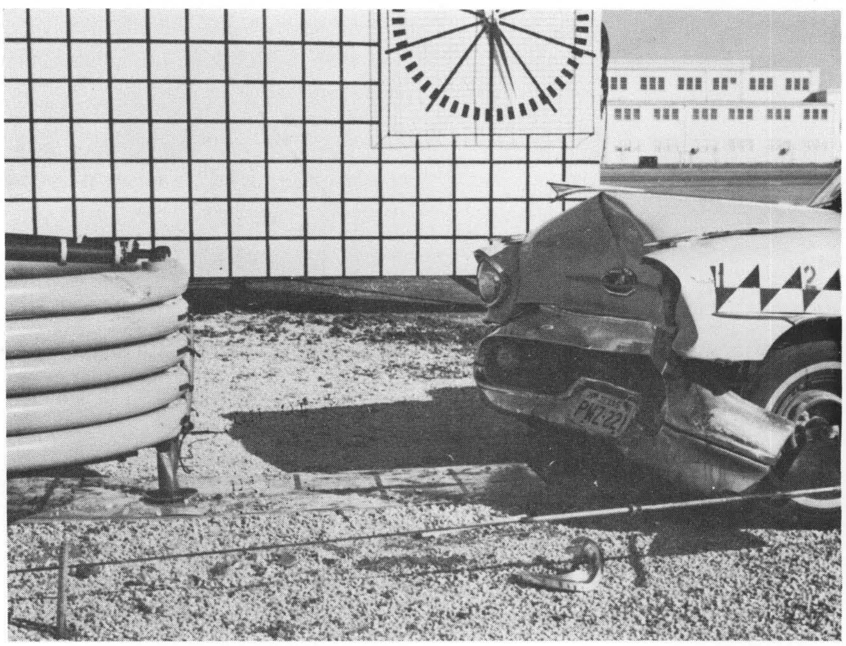


FIGURE 4. VEHICLE DAMAGE. TEST 2A.
VEHICLE DEFORMATION 1.42 FT.,
BARRIER DEFORMATION 4.48 FT.

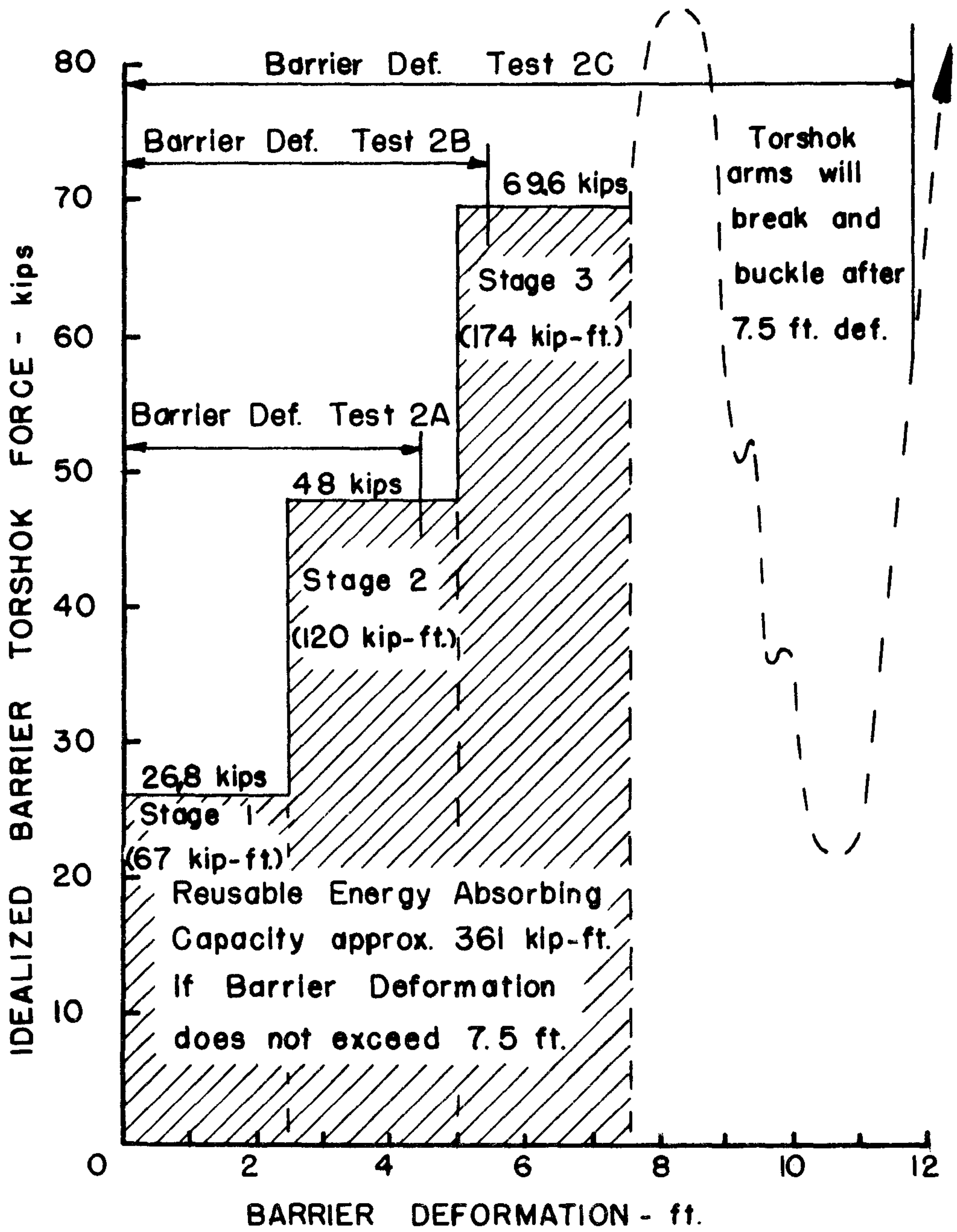


FIGURE 5. IDEALIZED ARA BARRIER TORSHOK FORCE-DEFORMATION CURVE FOR HEAD-ON VEHICLE IMPACT

(Skid friction forces and inertia forces are not included. Curve developed from data presented in Appendix A.)

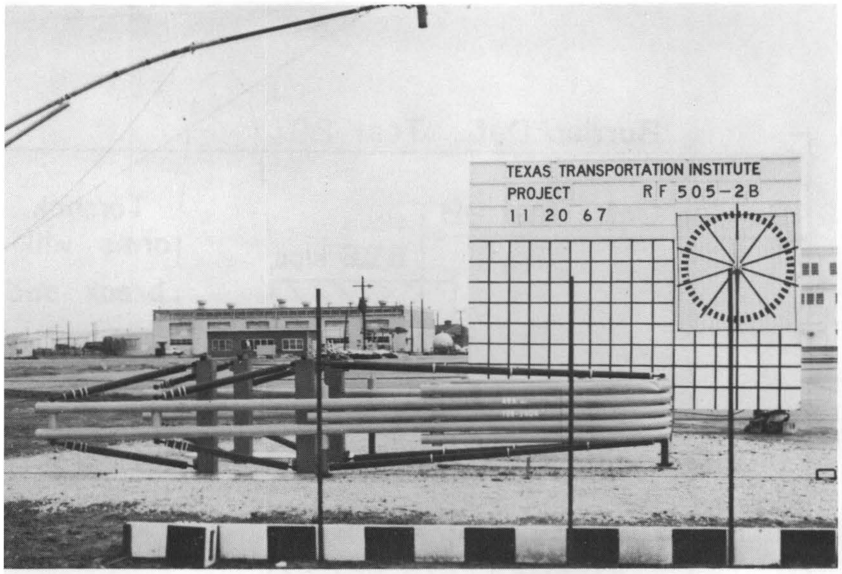


FIGURE 6. TORSHOK BEFORE COLLISION.
TEST 2B.

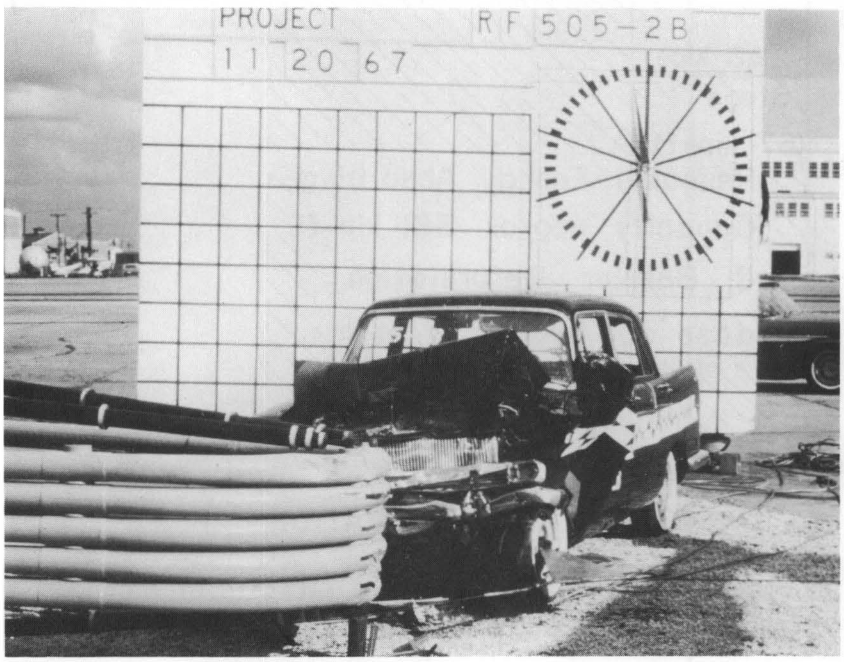


FIGURE 7. TORSHOK AND VEHICLE AFTER COLLISION.
INITIAL VEHICLE VELOCITY 53.5 MPH.,
STOPPING DISTANCE 7.21 FT., AVERAGE
VEHICLE DECELERATION 12.3 G'S.
TEST 2B, HEAD-ON IMPACT.

FIGURE 8. VEHICLE BEFORE COLLISION.
TEST 2B, 1957 AUSTIN,
WEIGHT 2520 LB.

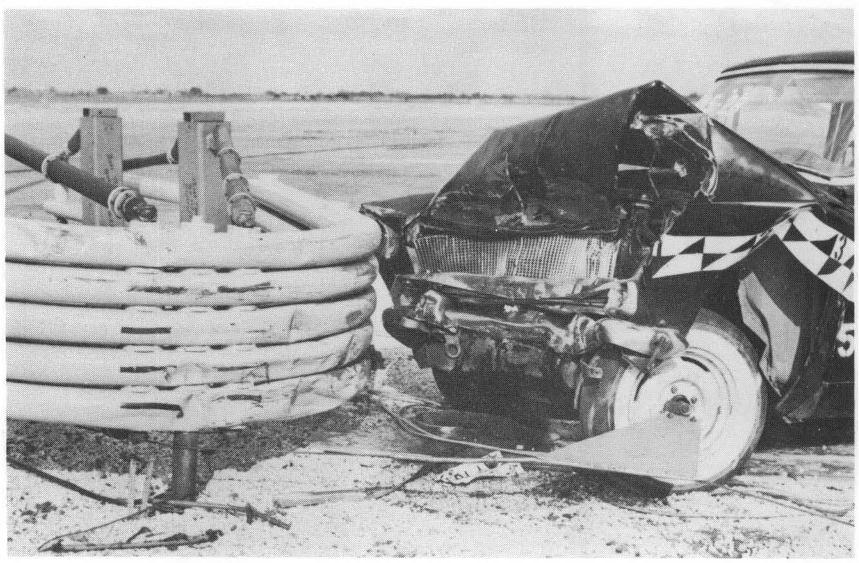


FIGURE 9. VEHICLE DAMAGE.
VEHICLE DEFORMATION 1.88 FT.,
BARRIER DEFORMATION 5.33 FT.
TEST 2B.

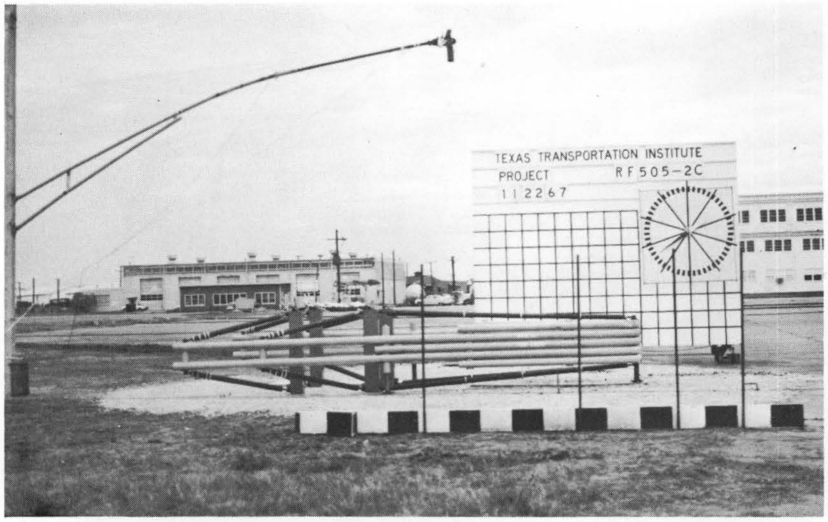


FIGURE 10. TORSHOK BEFORE COLLISION.
TEST 2C.

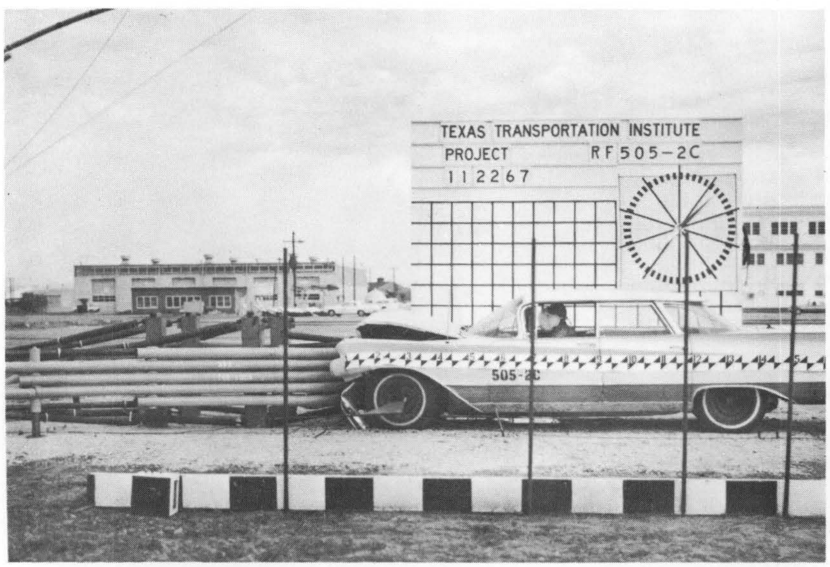


FIGURE 11. TORSHOK AND VEHICLE AFTER COLLISION.
INITIAL VEHICLE VELOCITY 59.4 MPH,
STOPPING DISTANCE 12.87 FT., AVERAGE
VEHICLE DECELERATION 9.9 G'S.
TEST 2C, HEAD-ON IMPACT.

FIGURE 12. VEHICLE BEFORE COLLISION.
TEST 2C, 1960 BUICK,
WEIGHT 4940 LB.

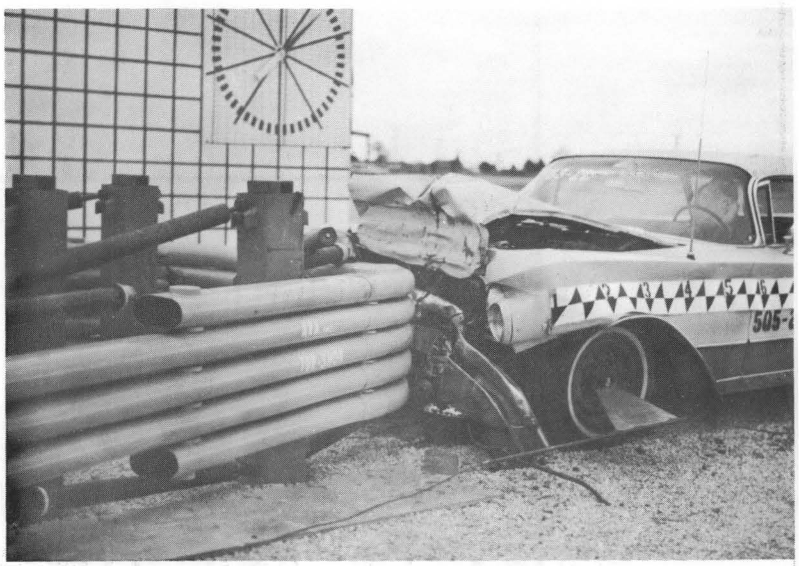


FIGURE 13. VEHICLE DAMAGE. VEHICLE
DEFORMATION 1.75 FT.,
BARRIER DEFORMATION 11.12 FT.
TEST 2C.

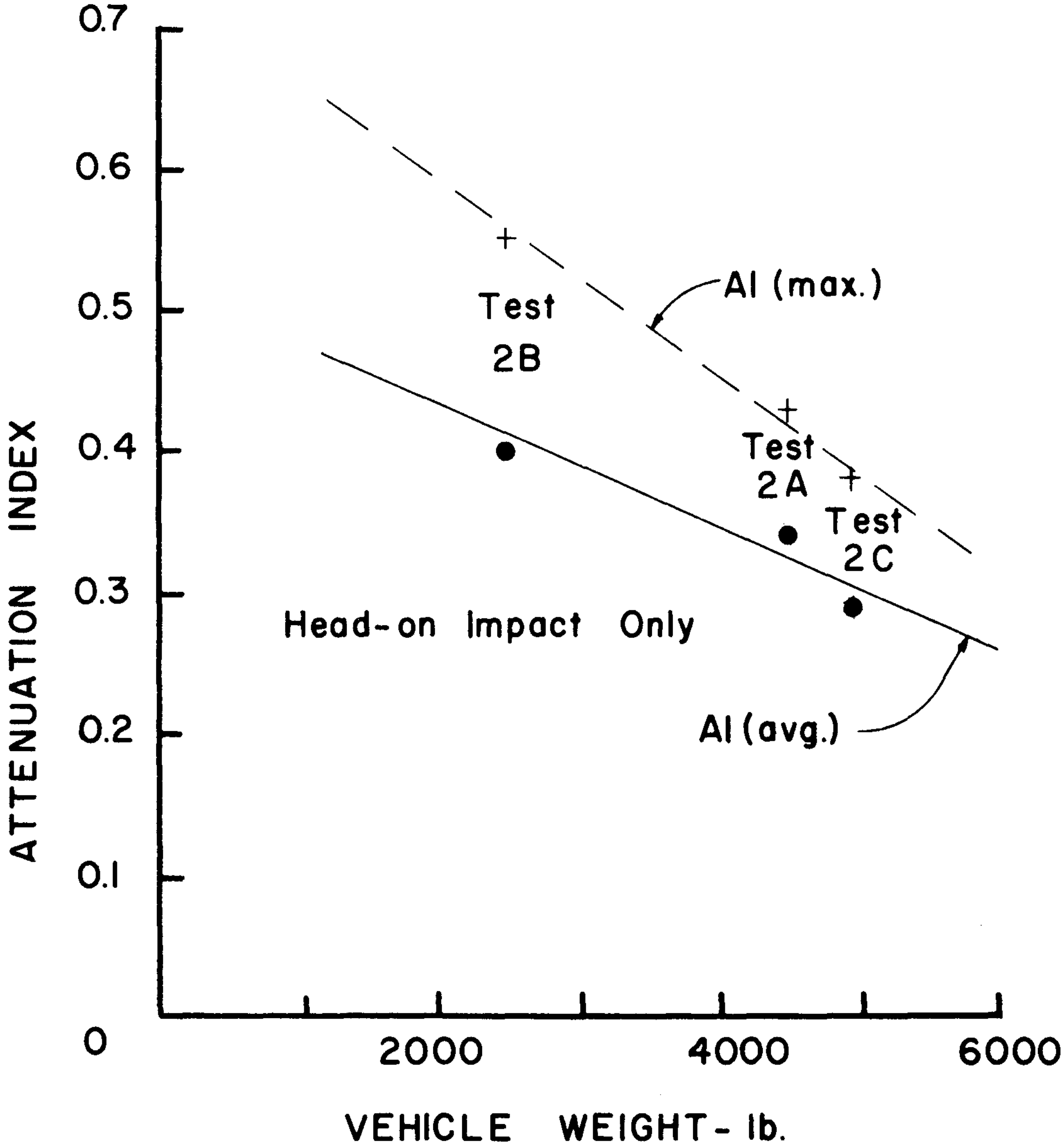


FIGURE 14. COMPARISON OF ATTENUATION INDEX OF ARA TORSHOK BARRIER WITH VEHICLE WEIGHT.

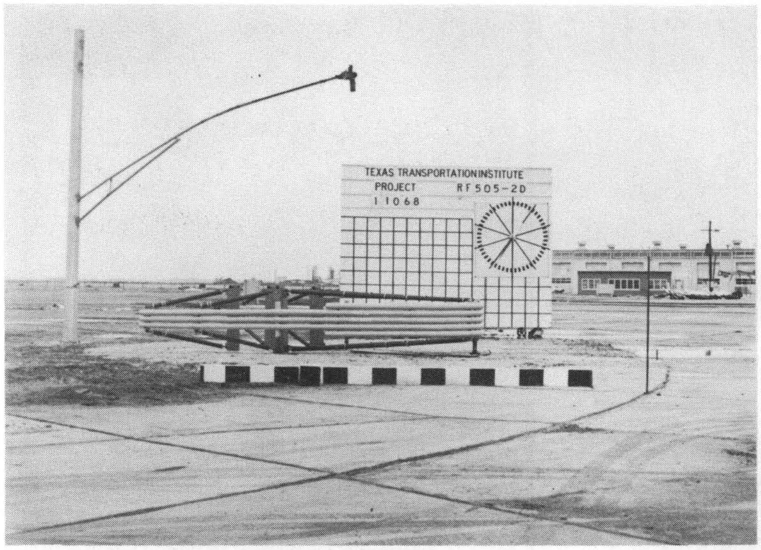


FIGURE 15. TORSHOK BEFORE COLLISION.
TEST 2D.

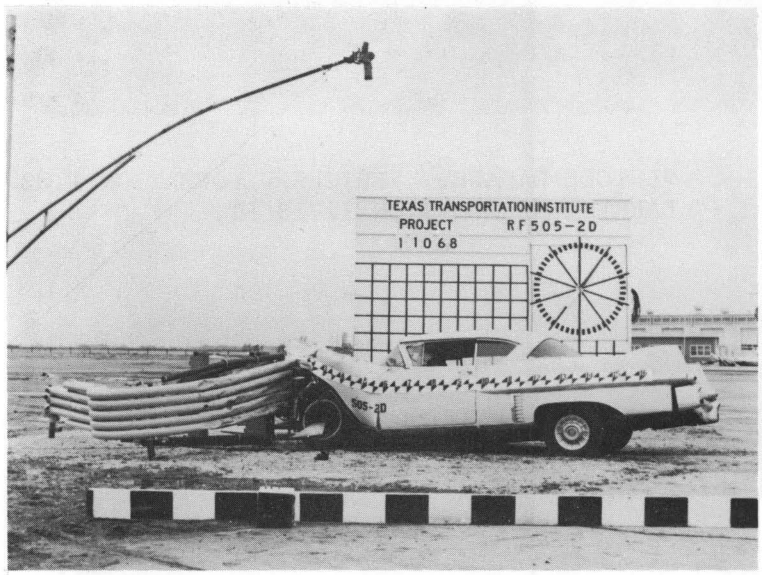


FIGURE 16. TORSHOK AND VEHICLE AFTER COLLISION.
INITIAL VEHICLE VELOCITY 49.9 MPH,
STOPPING DISTANCE 13.96 FT.,
AVERAGE VEHICLE DECELERATION 8.1 G'S.
TEST 2D, 30° ANGLE IMPACT.

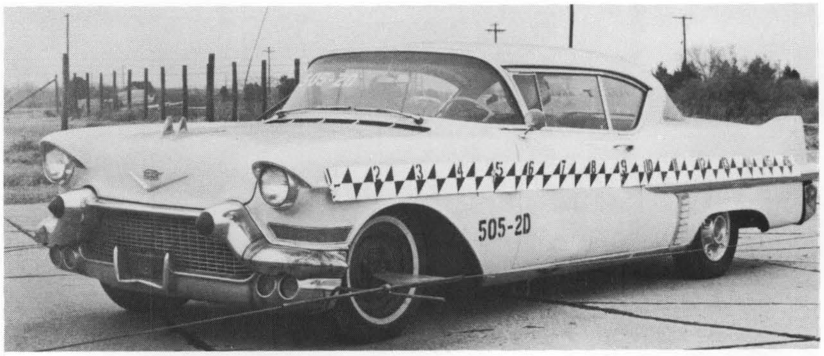


FIGURE 17. VEHICLE BEFORE COLLISION.
TEST 2D. 1957 CAD.,
WEIGHT 5000 LB.

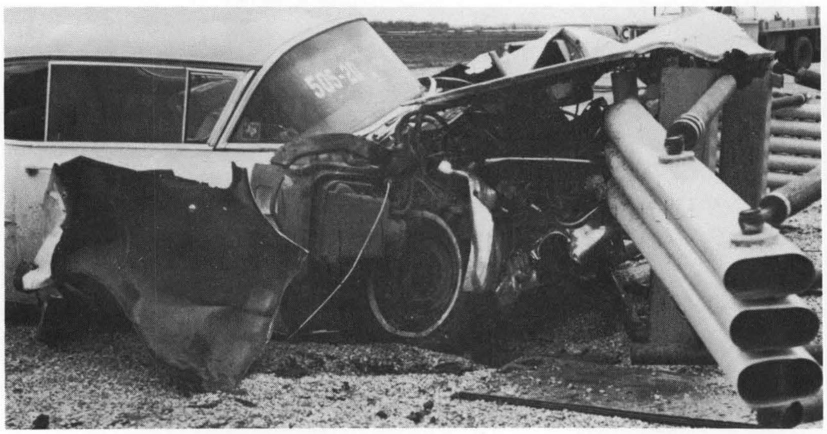


FIGURE 18. VEHICLE DAMAGE. VEHICLE DEFORMATION 1.83 FT.,
BARRIER DEFORMATION 12.13 FT.

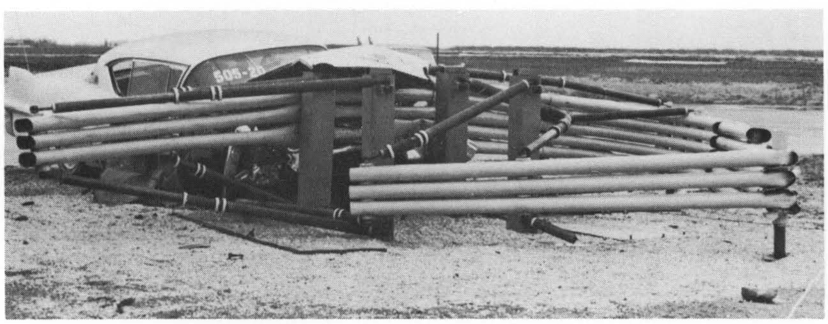


FIGURE 19. BARRIER DAMAGE. BARRIER DEFORMATION 12.13 FT., BARRIER ALMOST
TOTAL LOSS.
TEST 2D, 30° ANGLE IMPACT.

APPENDIX A

Supplementary Data on TOR-SHOK
Reusable Energy Absorbing
Highway Protective System

Recently, ARA, Inc. has designed, fabricated, and crash tested an improved TOR-SHOK barrier for the Bureau of Public Roads. In addition, a systematic parametric variation of TOR-SHOK dimensions to meet fixed object abutment dimensions was also made. The purpose of this brief brochure is to provide you with the results of this valuable study.

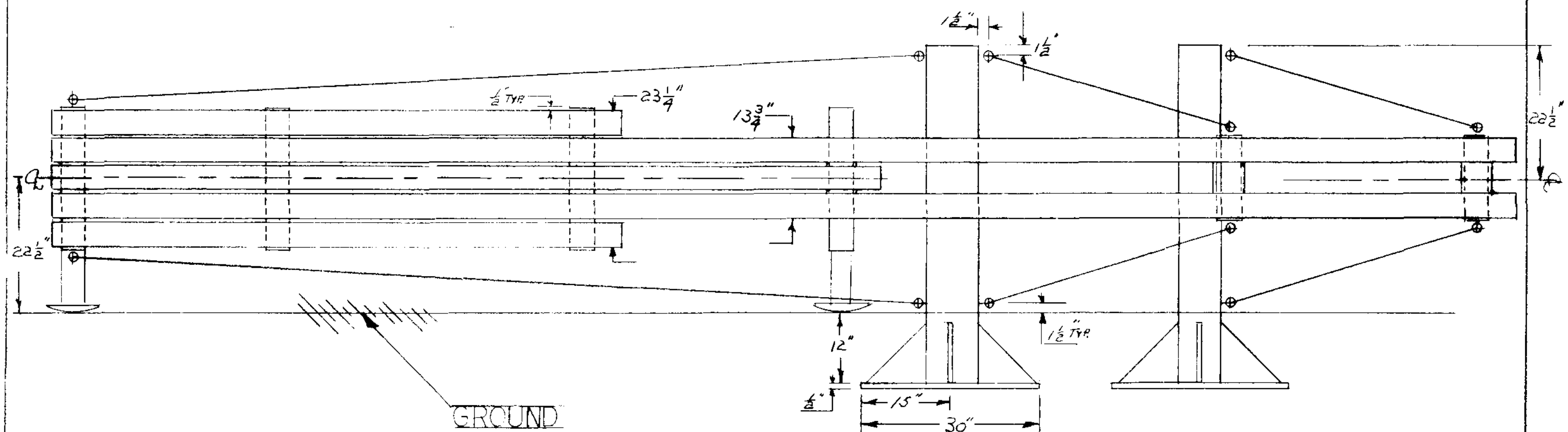
GENERAL DESCRIPTION OF TOR-SHOK BARRIER

A detailed design drawing of a typical TOR-SHOK barrier which has recently been tested successfully at Texas A & M University is provided in Figures 1 and 2. Basically, the barrier consists of a series of elliptical tubing (4" x 7") with a wall thickness of .065". The barrier is connected with 4" round tubing which, as vertical members, transmit the loads from the elliptical tubing to a set of TOR-SHOKs that provide the principal source of energy absorption. For the configuration shown in Figures 1 and 2, twelve TOR-SHOKs are used. Four are used in front (in compression) and eight are used in the rear (in tension). This arrangement has been found to be desirable for reducing the bending moments in the elliptical guard-rail tubing as well as providing rotational stability of the barrier when the impact is not head-on. Each TOR-SHOK consists of four telescoping tubes which provide three different but successive loading conditions. The lowest load experiences initial movement and strokes until the stage is completely bottomed out at which time the next stage initiates its stroke; finally, the barrier displaces until all three stages are completely bottomed out.

In order to provide a smooth planing surface, the barrier is supported by three skids as shown in Figures 1 and 2. These skids also make use of the TOR-SHOK principle such that for relatively rough surfaces, the barrier strokes downward on the skids rather than destroying the skids due to excessive bending moments caused by the large coefficients of friction between the skid and the ground surface.

Although in Figures 1 and 2, use is made of four posts to simulate the fixed abutment, the abutment itself can be used to react against the twelve TOR-SHOKs. The location of the four posts consequently represent the critical dimensions of the abutment for determining the compatability of the TOR-SHOK barrier geometry.

The main parameter of the abutment appears to be its width since its height and length can invariably be accommodated by an adapter frame which must be required to transmit the loads from the TOR-SHOK's "ball joint" fittings to the fixed abutment. Consequently, a detailed parameter analysis of TOR-SHOK barrier



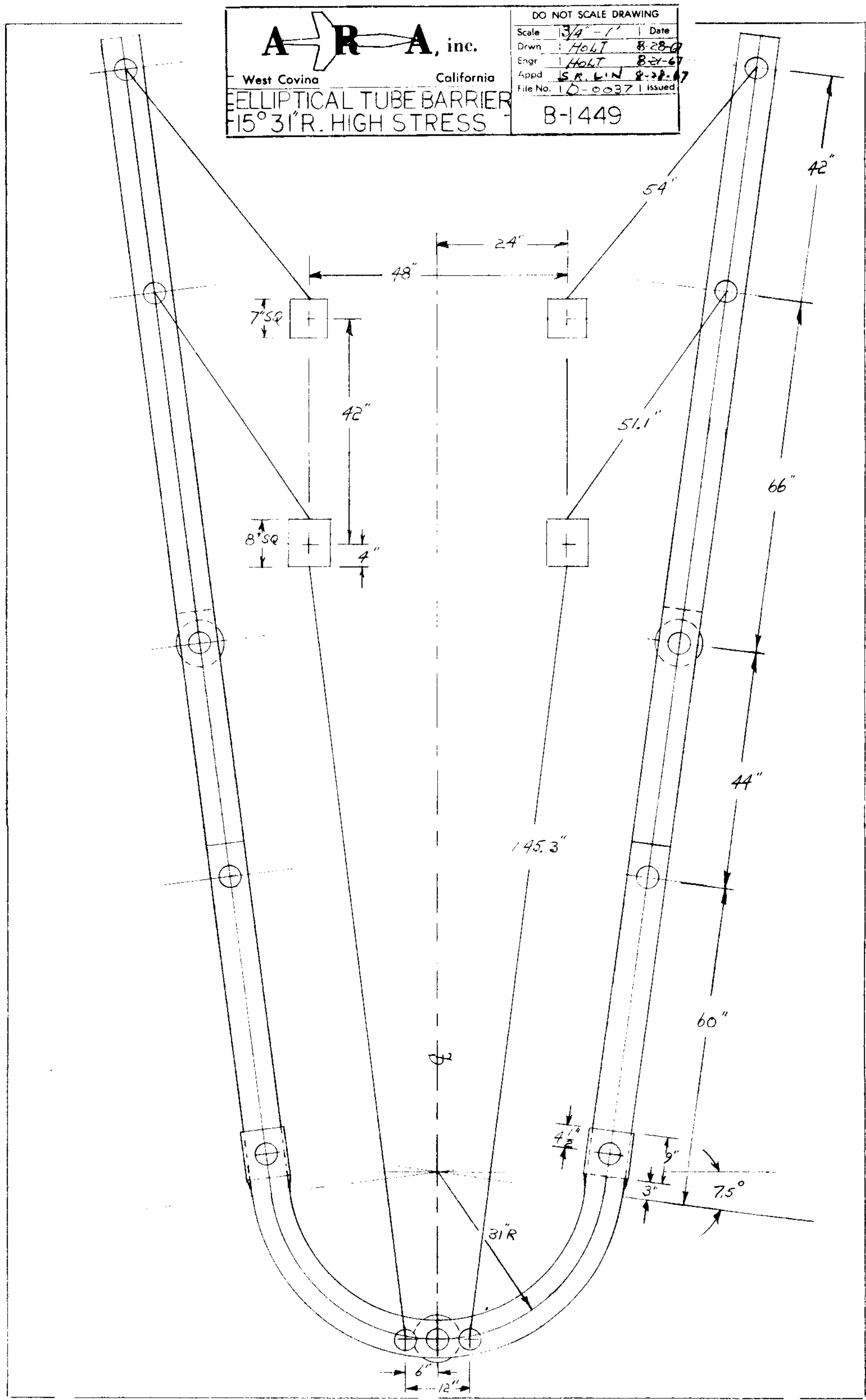
SIDE VIEW

A R A, inc.
West Covina California

ELLIPTICAL TUBE BARRIER
15°31"R HIGH STRESS

DO NOT SCALE DRAWING		
Scale	3/4" = 1'	Date
Drwn	HOLT	8-28-67
Engr	HOLT	8-28-67
Appd	S.R. LIN	8-28-67
File No.	D-0037	Issued

B-1450

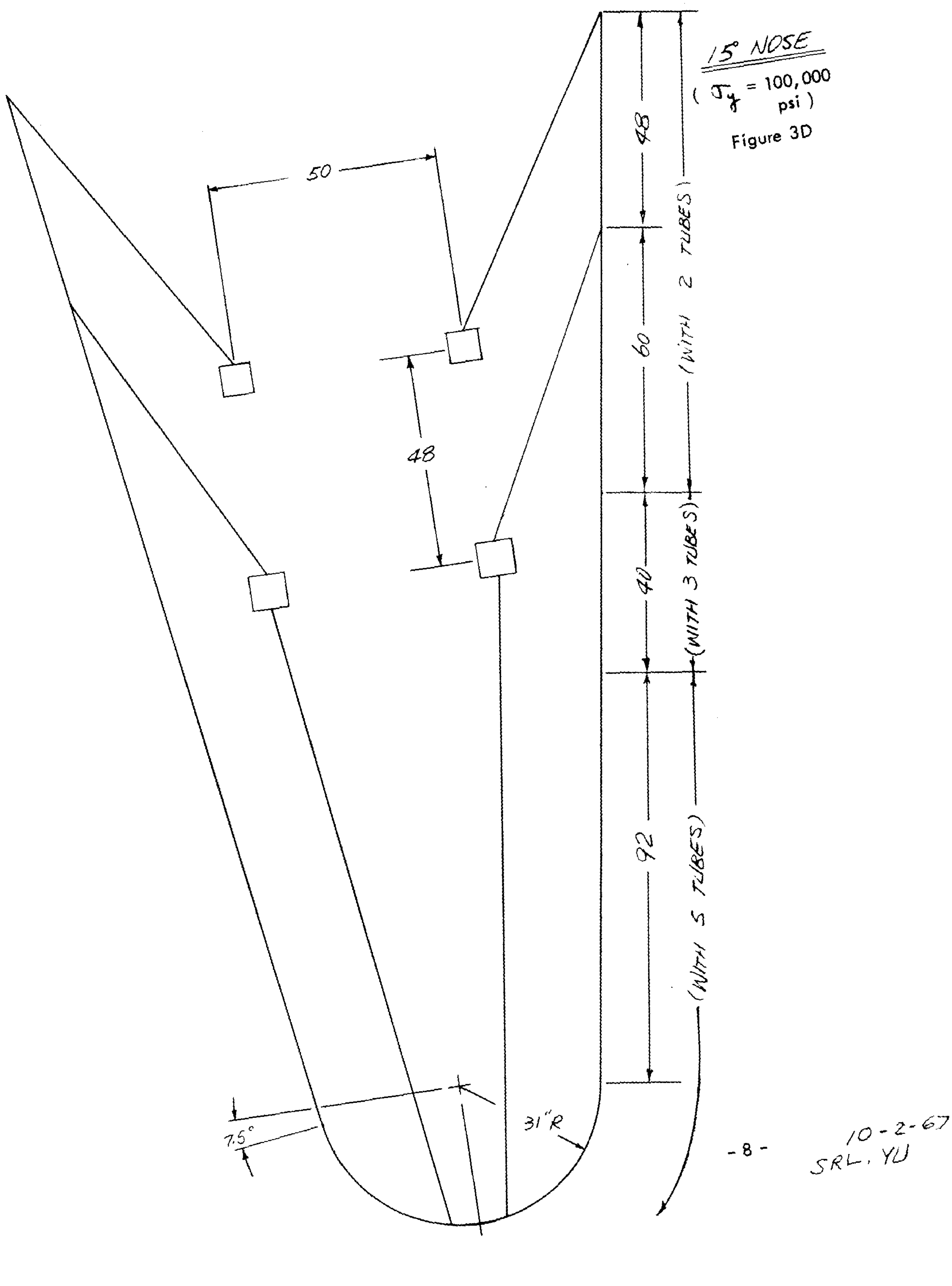


DO NOT SCALE DRAWING
Scale 3/4" - 1'
Date
Drwn HOLT 8-28-67
Engr HOLT 8-21-67
Appd S.R. LIN 8-28-67
File No. 10-0037
Issued
A R A, inc.
West Covina California
ELLIPTICAL TUBE BARRIER
15° 31"R. HIGH STRESS
B-1449
42"
54"
24"
48"
7"SQ
42"
51.1"
66"
8"SQ
4"
44"
145.3"
60"
4 1/2"
9"
3"
7.5°
31"R
6"
12"

configurations was made as a function of fixed abutment width for a given attachment distance of 48" from the front of the fixed abutment.

PARAMETRIC DESIGN DATA FOR TOR-SHOK BARRIER

The configuration studies for the TOR-SHOK barrier were made based on using elliptical type tubing having a minimum yield strength of 100,000 psi. This material is available at low cost and provides for a light-weight TOR-SHOK barrier. Since it is difficult to establish the types of abutments that are most applicable, ARA, Inc. has taken it upon itself to develop a detailed parametric analysis of the TOR-SHOK barrier over a range of nose angles which would be acceptable not only from a configuration standpoint, but also from a manufacturing point of view. All of the calculations for the preliminary analysis were based on a 31" nose radius which can be manufactured readily and satisfies most configuration requirements. The details of the calculations are not provided herein, but their results are clearly shown in Figures 3A through 3F, inclusive, wherein nose angle variations were made from 0^{o} to 25^{o}. For all of the cases considered, the number of tubes were varied from the nose to the rear section of the guard-rail (as shown in the figures) to accommodate the variation in bending moment such that the stresses remain reasonably constant. From an analysis of the results shown in Figures 3A to 3F, it is clear that there are many factors to be considered in selecting the optimum design or the optimum configuration for a particular application. In order to provide additional details of the performance characteristics of the TOR-SHOK barrier, TABLE I was prepared. The calculations are made on the basis that the input energy is equivalent to arresting a 4,000 pound vehicle impacting at 60 mph. It must also be understood that for this condition a certain amount of energy will be absorbed by the vehicle since it cannot remain completely intact during the impact. Based on the crash tests conducted under CPR-11-4629, the barrier absorbed approximately 72% of the energy. The results of TABLE I indicate that variations in abutment width can best be accommodated by varying the nose angle for a given nose radius of 31 inches. It is also clear that the energy absorption remains fairly constant over the range of nose angles from 0^{o} to 25^{o}. However, the weight of the barrier has a definite tendency to increase as the nose angle is increased beyond 10^{o} to 15^{o}. The primary reason for this requirement, is that as the nose angle is increased, the inertia loading becomes greater in a direction to cause severe bending moments in the nose section of the barrier which must be accommodated by increasing the structural capability of the barrier tubes and consequently the weight of the barrier. Review of TABLE I also indicates that the loading in each of the TOR-SHOK attenuators are consistent for the front, middle, and rear attenuators, as well as for the first, second and third stages. Note, however, that as the nose angle increases the length of the TOR-SHOKs for the middle and the rear become quite large in order to retain reasonable stresses in the nose section of the elliptical tubes. The additional cost due to an increase in TOR-SHOK lengths is far less than the cost for higher yield strength elliptical barrier tubes.


15° NOSE
(σ_y = 100,000 psi)
Figure 3D
50
48
48
60
40
92
(WITH 2 TUBES)
(WITH 3 TUBES)
(WITH 5 TUBES)
7.5°
31"R
10-2-67
SRL, YU

In order to illustrate the significant results of the detailed information given in TABLE I, Figure 4 was prepared to summarize the results of the parametric study involving the total weight of the barrier, its relative cost, and the energy absorption capability of the barrier. The results are shown in Figure 4 for the case of an elliptical tubing with a yield strength of 100,000 psi, as well as for comparison purposes, barrier tubes with a yield strength of 150,000 psi. (For the preliminary design shown in Figures 1 and 2, the configuration is noted to be a high-stress nose section which for this case corresponds to the yield stress of 150,000 psi.) Examination of Figure 4 indicates that in general, the energy absorption capability of the barrier remains fairly constant; however, the relative cost tends to increase slightly up to approximately a 20° nose angle. Beyond this nose angle, the weight and the relative cost start to increase rather rapidly. If the weight is a problem beyond 25°, it is recommended that in order to keep the weight below a prescribed value, say 800 pounds, then a high-stress material for the barrier tubes must be used. To illustrate this effect, a weight comparison is shown in Figure 4 at approximately 15° and 25° nose angles for the two yield strength barriers selected. Although the advantages of a high yield stress are obvious, the addendant increase in cost is also obvious as shown in Figure 4. Thus, it appears that up to 25° of nose angle, it is recommended that unless unusual circumstances are warranted, the TOR-SHOK barriers can be designed adequately with elliptical type tubing having a yield stress of approximately 100,000 psi.

TABLE I A

SUMMARY OF PERFORMANCE CHARACTERISTICS
FOR TOR-SHOK BARRIER (NOSE SECTION)
FOR 4000 LB. VEHICLE AT 60 MPH

(σ_y = 100,000 psi)

						SYSTEM TESTED		
NOSE ANGLE (DEGREE)			0	5	10	15	20	25
ABUTMENT WIDTH (INCHES)			24	36	46	50	52	54
INITIAL LENGTH (INCHES)		Front	144.25	143.75	141.25	141.25	140.75	140.75
		Middle	51.50	52.125	52.50	76.00	91.875	92.875
		Rear	52.00	53.25	55.00	78.00	94.375	95.25
ATTENUATOR FORCE, LB.	FIRST STAGE	Front	1600	1600	1500	1500	1500	1500
		Middle	2600	2600	2500	2600	2500	2500
		Rear	2600	2600	2500	2600	2500	2500
	SECOND STAGE	Front	2600	2600	2500	2600	2500	2500
		Middle	4200	4400	4800	4700	4000	4500
		Rear	4200	4400	4800	4700	4000	4500
	THIRD STAGE	Front	4200	4400	4800	4700	4000	4500
		Middle	5900	6700	7400	6350	6450	6800
		Rear	5900	6700	7400	6350	6450	6800
STROKE IN.	FIRST STAGE	Front	33.00	32.00	32.00	31.00	30.00	30.00
		Middle	31.00	28.625	31.125	29.75	28.75	27.75
		Rear	31.25	29.50	30.125	29.25	28.375	27.50
	SECOND STAGE	Front	32.00	32.00	32.00	31.00	31.00	31.00
		Middle	31.50	32.50	30.75	29.875	28.875	25.375
		Rear	31.50	31.50	29.625	29.375	27.875	24.375
	THIRD STAGE	Front	30.50	31.00	28.125	30.50	31.00	31.00
		Middle	29.375	31.00	29.625	31.875	32.875	35.375
		Rear	29.25	30.75	29.75	31.875	32.875	35.375
STAGE LENGTH, IN.	FIRST STAGE	Front	111.25	111.75	109.25	110.25	110.75	110.75
		Middle	82.50	80.75	83.625	105.75	120.625	120.625
		Rear	83.25	82.75	85.125	107.25	122.75	122.75
	SECOND STAGE	Front	79.25	79.75	77.25	79.25	79.75	79.75
		Middle	114.00	113.25	114.375	135.625	149.50	146.00
		Rear	114.75	114.25	114.75	136.625	150.625	147.125
	THIRD STAGE	Front	48.75	48.75	48.75	48.75	48.75	48.75
		Middle	143.375	144.25	144.00	167.50	182.375	181.375
		Rear	144.00	145.00	144.50	168.50	183.50	182.50
ENERGY ABSORPTION (%)			72.9	77.2	79	76.6	76.5	76.5
TOTAL WEIGHT (LB.)			798	794	794	845	897	1122

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Fig. (4) Parametric Study of TOR-SHOK Barrier (Nose Section) for 4000 lb. Vehicle at 60 mph

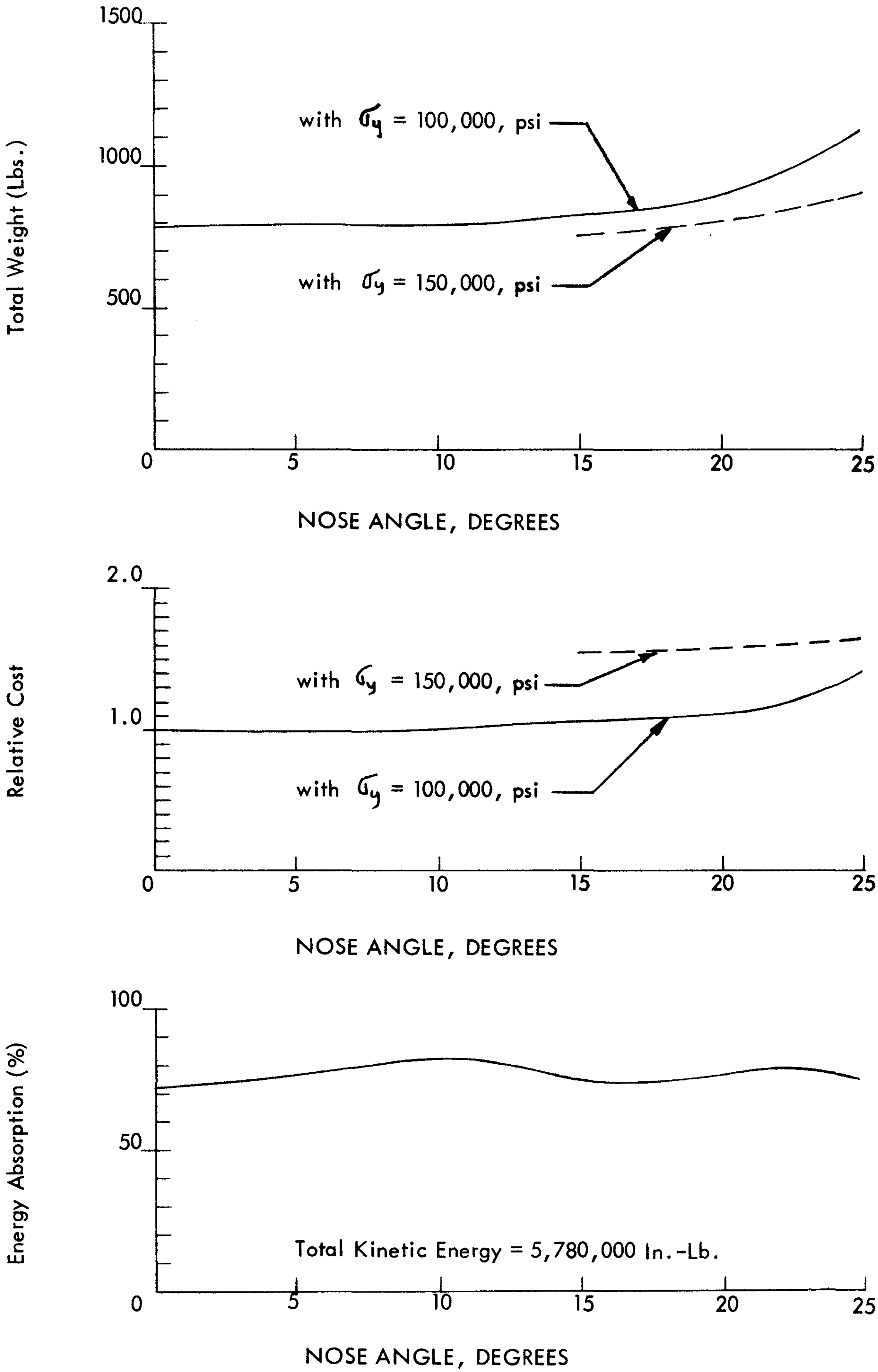
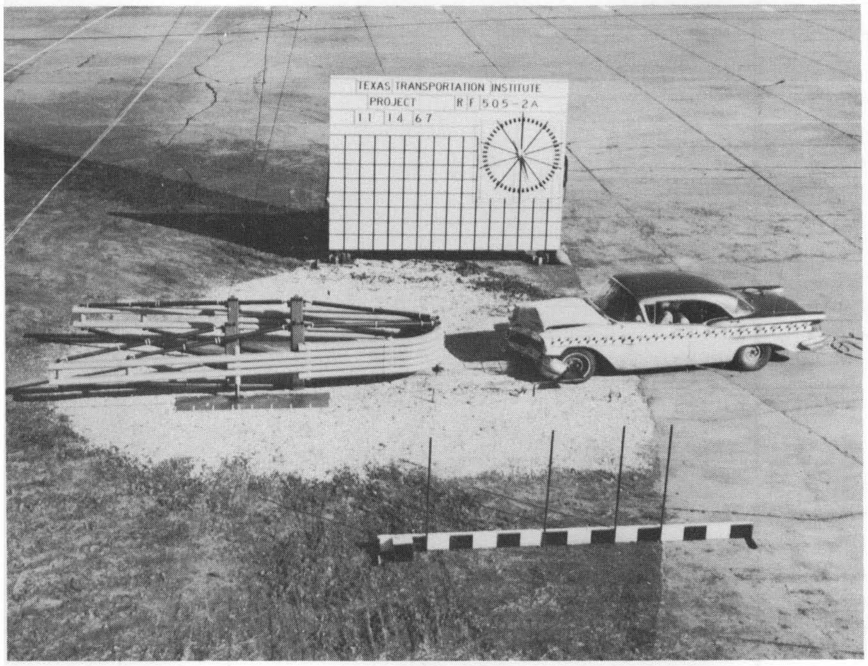


TABLE 1B.- SUMMARY OF CRASH TEST DATA FROM HIGH-SPEED FILM AND ELECTROMECHANICAL DEVICES FOR ARA TORSHOK BARRIERS, RF505-2A, 2B, 2C, and 2D.

TEST NUMBER	A	B	C	D
VEHICLE	1957 Olds. 4dr. Sed., 4600 lbs.	1957 Austin 4dr. Sed., 2520 lbs.	1960 Buick 4dr. Sed., 4940 lbs.	1957 Cad. 2 dr. Hdtp., 5000 lbs.
ANGLE OF IMPACT	0°	0°	0°	30°
FILM DATA				
Velocity (mph)	34.1	53.5	59.4	49.9
Velocity (fps)	50.0	78.8	87.1	73.3
Velocity Change (mph)	37.1	53.5	59.4	49.9
Velocity Change (fps)	54.4	78.5	87.1	73.3
Average Deceleration (g's)	6.6	12.3	9.9	8.1
Peak Deceleration (g's)	29.4	42.1	30.3	60.7
Duration of Impact (sec.)	0.237	0.198	0.273	0.280
Stopping Distance (ft.)	5.90	7.21	12.87	13.96
ELECTROMECHANICAL DATA				
Peak Deceleration (g's)				
Frame Accelerometer	13-14 (long.)	26-27 (long.)	20-21 (long.)	28-30 (long.)
Dummy Accelerometer	12-13 (long.)	33 (long.)	20 (long.)	28-30 (long.)
	11-12 (vert.)	10 (vert.)	19 (vert.)	8 (vert.)
	2-3 (trans.)	4-6 (trans.)	4-6 (trans.)	14-16 (trans.)
Peak Seatbelt Force (lbs.)	No Data	2000	1400	No Data
Duration of Impact (sec.)	0.257	0.242	0.343	0.300
OBSERVATIONS				
Vehicle Deformation (ft.)	1.42	1.88	1.75	1.83
Barrier Deformation (ft.)	4.48	5.33	11.12	12.13
Vehicle Damage	Minor	Severe	Moderate	Severe
TORSHOK Damage	Re-usable	Re-usable	Severe	Severe



CONDITIONS AFTER TEST (VEHICLE STRUCK BARRIER HEAD-ON)

TABLE 2B.
Summary of High-speed Film Crash Test Data

Test 505-2A ARA Torshok Barrier 15° Nose Angle

Vehicle Weight = 4600 lb. (1957 Olds, 4 dr. Hdtp.)

Vehicle Velocity = 34.1 mph or 50 fps

Change in Velocity = 37.1 mph or 54.4 fps

Average Deceleration = 6.6 g's

Peak Deceleration = 29.4 g's (7.28 msec.)

Duration of Impact = 0.237 sec.

Stopping Distance = 5.90 ft.

Remarks: Minor Damage to Vehicle, behavior was very good.

Vehicle Deformation 1.42 ft. Barrier Deformation 4.48 ft.

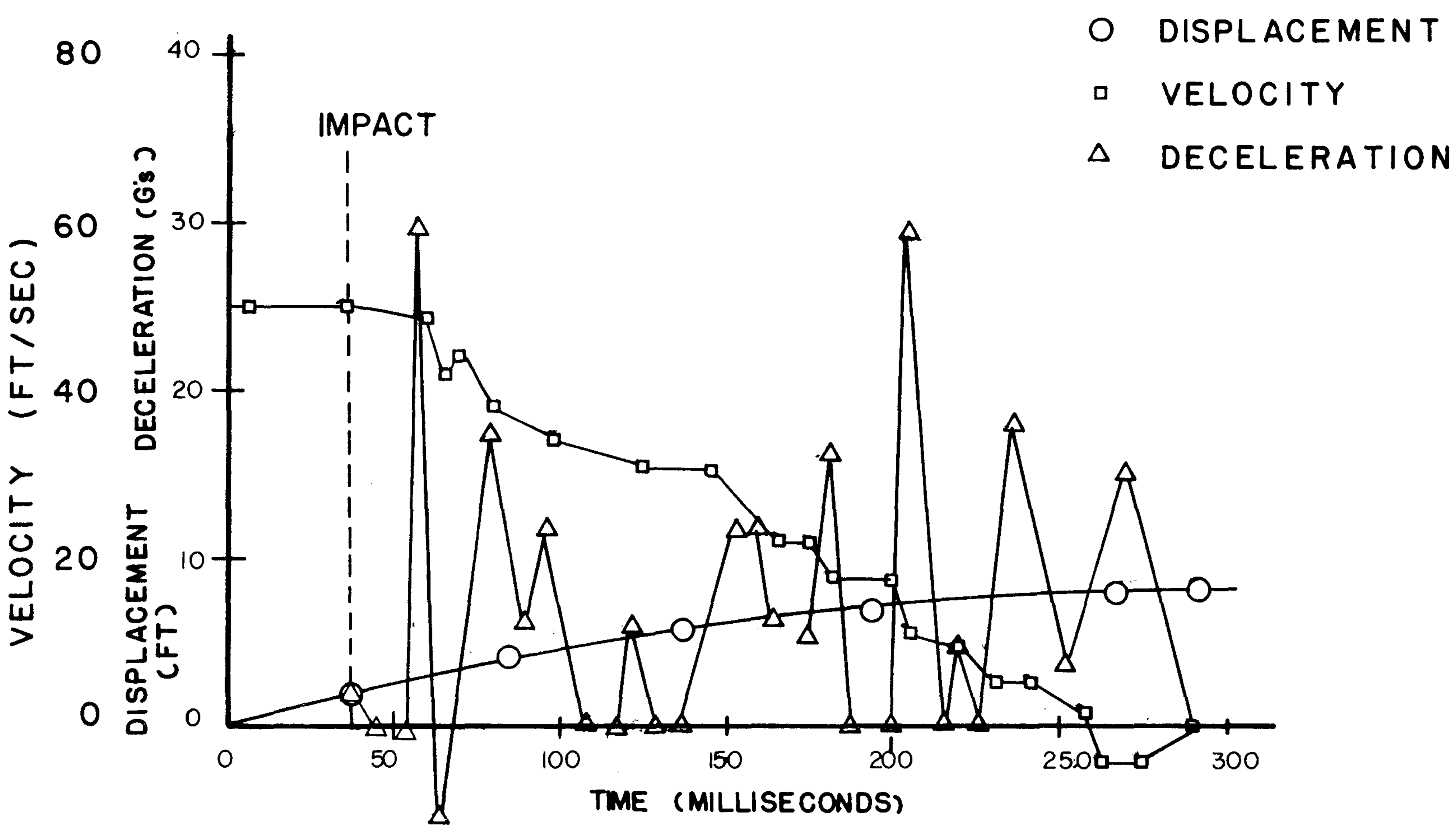


FIGURE IB. DISPLACEMENT, VELOCITY, AND DECELERATION VS. TIME CURVES FOR TEST 505-2A

TABLE 3B.

TEST RF 505-2A

ARA TORSHOK BARRIER 15° NOSE ANGLE

1957 OLDS., 4 DOOR HARDTOP, 4600 LB.

HIGH SPEED FILM DATA

Time Milliseconds	Displacement ft	Velocity ft/sec	Deceleration ft/sec^2	Deceleration g's
0	0		0	0
		49.5		
7.28	0.36		0	0
		49.5		
14.56	0.72		0	0
		49.5		
21.84	1.08	50.0 avg.	0	0
		50.8		
36.40 Impact	1.82		69	2.1
		49.5		
43.68	2.18		0	0
		49.5		
50.96	2.54		0	0
		49.5		
58.24	2.90		948	29.4
		42.6		
65.52	3.21		-179	-5.6
		43.9		
72.80	3.53		179	5.6
		42.6		
80.08	3.84		563	17.5
		38.5		
87.36	4.12		192	6.0
		37.1		
94.64	4.39		385	12.0
		34.3		
101.92	4.64		179	5.6
		33.0		
109.20	4.88		0	0
		33.0		
116.48	5.12		0	0
		33.0		
123.76	5.36		192	6.0
		31.6		
131.04	5.59		0	0
		31.6		
138.32	5.82		0	0
		31.6		
145.60	6.05		192	6.0
		30.2		
152.88	6.27		371	11.5
		27.5		

(continued on next page)

TABLE 3B.

TEST RF 505-2A (continued)

Time Milliseconds	Displacement ft	Velocity ft/sec	Deceleration ft/sec^2	g's
160.16	6.47		385	12.0
		24.7		
167.44	6.65		192	6.0
		23.3		
174.72	6.82		179	5.6
		22.0		
182.00	6.98		563	17.5
		17.9		
189.28	7.11		0	0
		17.9		
196.56	7.24		0	0
		17.9		
203.84	7.37		948	29.4
		11.0		
211.12	7.45		0	0
		11.0		
218.40	7.53		134	4.2
		9.9		
227.50	7.62		0	0
		9.9		
236.60	7.71		604	18.8
		4.4		
245.70	7.75		361	11.2
		1.1		
254.80	7.76		121	3.8
		0		
263.90	7.76		483	15.1
		-4.4		
273.00	7.72		0	0
		-4.4		
282.10	7.68		0	0

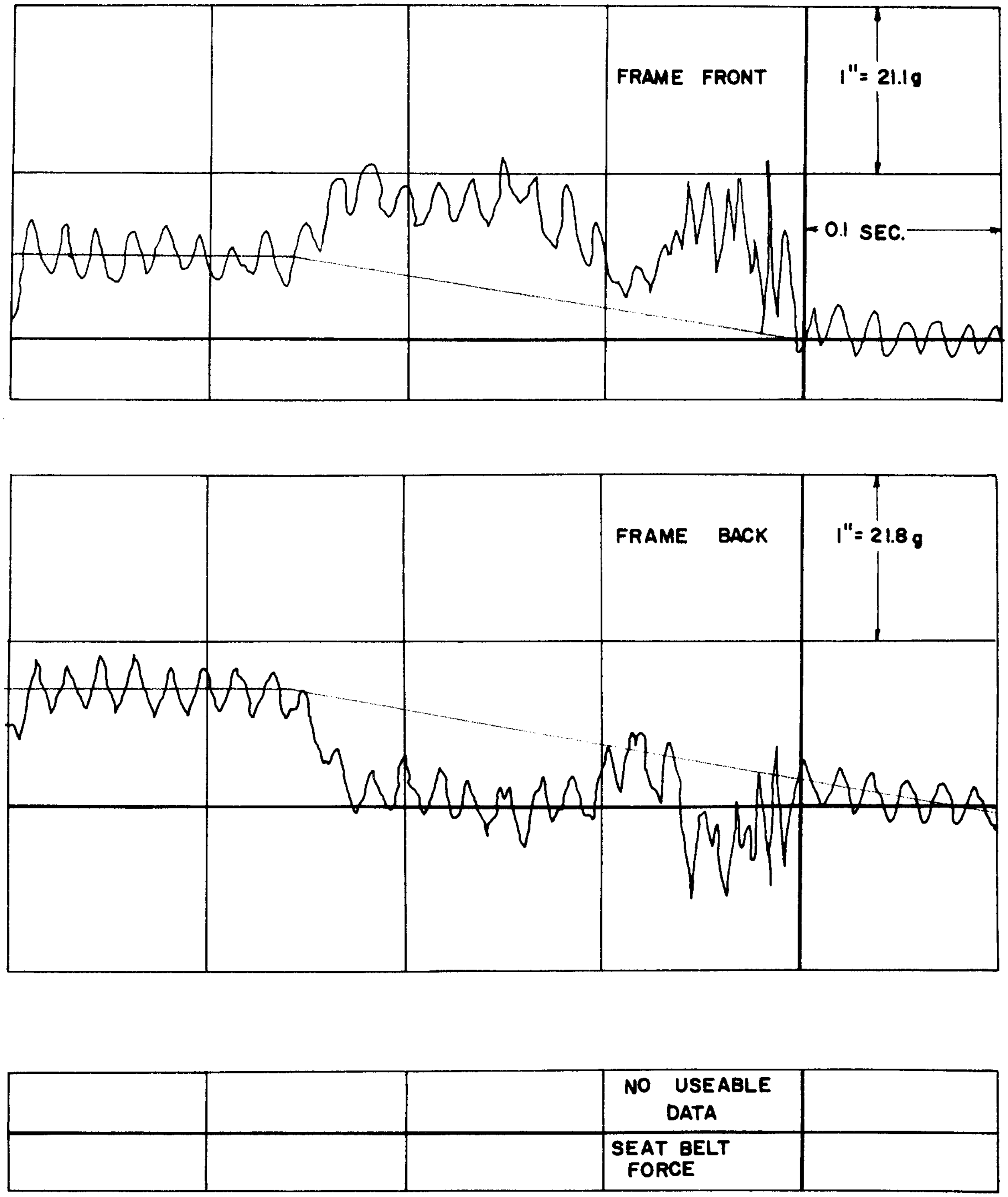


FIGURE 2B. TEST 505 2A FRAME ACCELEROMETER DATA & SEAT BELT FORCE

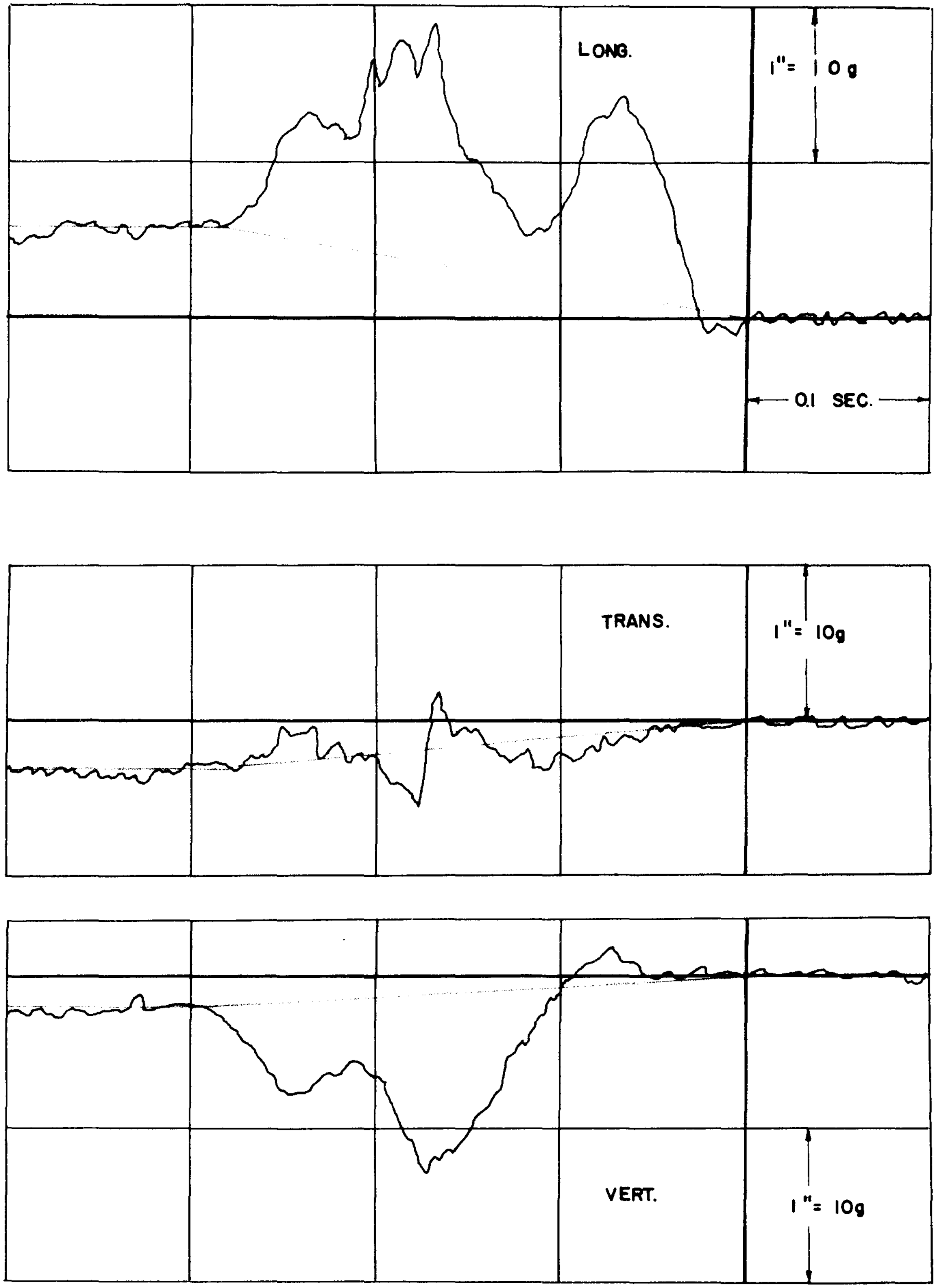


FIGURE 3B. TEST 505 2A DUMMY ACCELEROMETER DATA

CONDITIONS AFTER TEST (VEHICLE STRUCK BARRIER HEAD-ON)

TABLE 4B.
Summary of High-speed Film Crash Test Data

Test 505-2B ARA Torshok Barrier 15^{o} Nose Angle

Vehicle Weight = 2520 lb. (1960, Austin, 4-Door Sedan)

Vehicle Velocity = 53.5 mph or 78.5 fps

Change in Velocity = 53.5 mph or 78.5 fps

Average Deceleration = 12.3 g's

Peak Deceleration = 42.1 g's (9 msec.)

Duration of Impact = 0.198 sec.

Stopping Distance = 7.21 ft.

Remarks: Damage to Vehicle Severe. Vehicle Deformation 1.88 ft.

Barrier Deformation 5.33 ft.

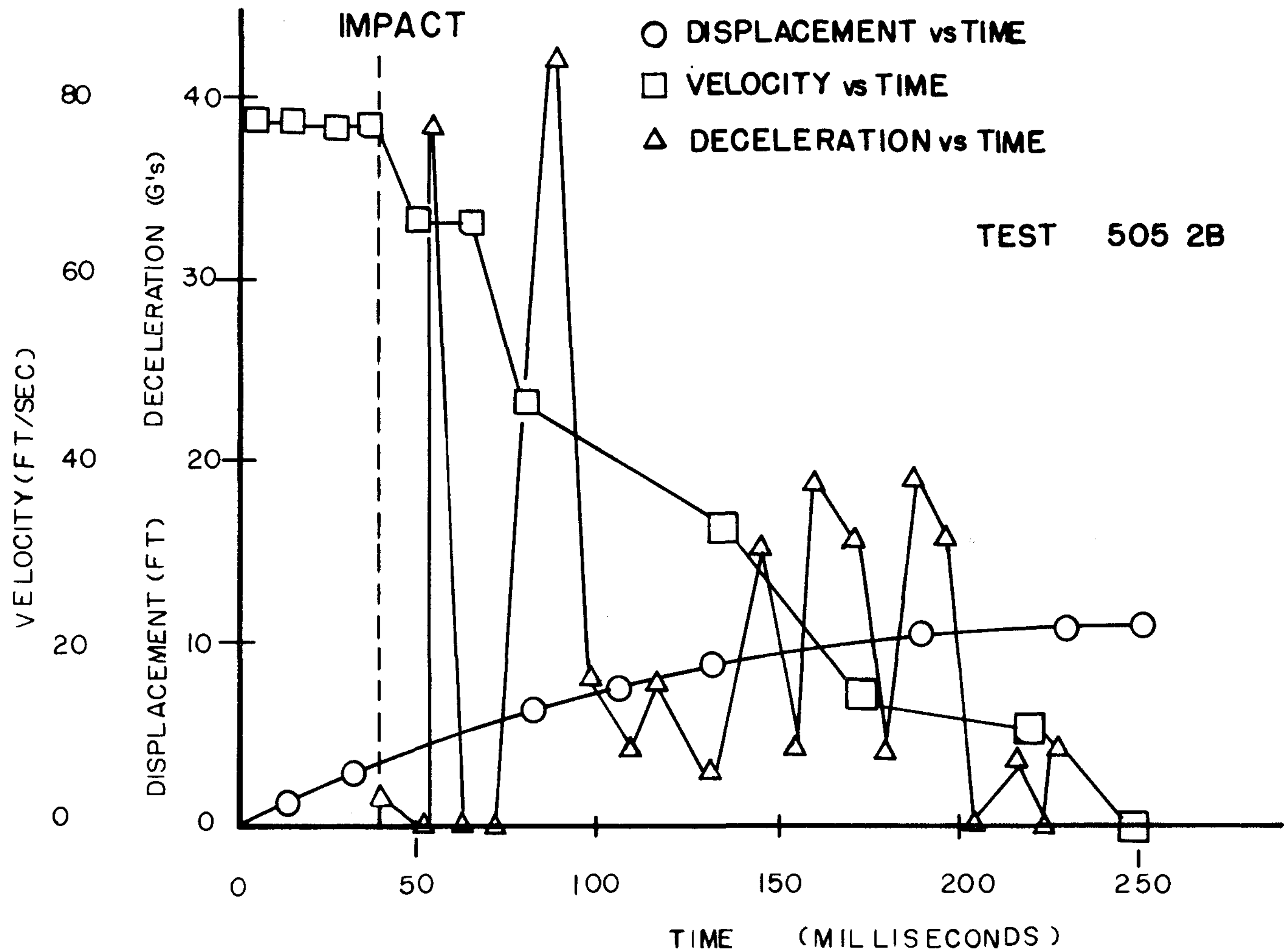


FIGURE 4B. DISPLACEMENT, VELOCITY, AND DECELERATION VS. TIME FOR TEST 505-2B

TABLE 5B.

TEST RF 505-2B

ARA TORSHOK BARRIER 15° NOSE ANGLE

1960 AUSTIN, 4 DOOR SEDAN, 2520 LB.

HIGH SPEED FILM DATA

Time Milliseconds	Displacement ft	Velocity ft/sec	Deceleration ft/sec^2	g's
0	0		0	0
		78.9		
9.0	.71		0	0
		78.9		
18.0	1.42	78.5 avg.	0	0
		77.8		
27.0	2.12		0	0
		78.9		
36.0	2.83		0	0
		77.8		
45.0 Impact	3.53		78	2.4
		77.8		
54.0	4.23		1232	38.3
		66.7		
63.0	4.83		0	0
		66.7		
72.0	5.43		0	0
		66.7		
81.0	6.03		867	26.9
		58.9		
90.0	6.56		1355	42.1
		46.7		
99.0	6.98		256	8.0
		44.4		
108.0	7.38		122	3.8
		43.3		
117.0	7.77		245	7.6
		41.1		
126.0	8.14		122	3.8
		40.0		
135.0	8.50		122	3.8
		38.9		
144.0	8.85		489	15.2
		34.5		
153.0	9.16		133	4.1
		33.3		
162.0	9.46		612	19.0
		27.8		
171.0	9.71		500	15.5
		23.3		
180.0	9.92		122	3.8
		22.2		
189.0	10.12		612	19.0
		16.7		
198.0	10.27		500	15.5
		12.2		

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TABLE 5B.

TEST RF 505-2B (continued)

Time Milliseconds	Displacement ft	Velocity ft/sec	Deceleration ft/sec^2	Deceleration g's
207.0	10.38		0	0
		12.2		
216.0	10.49		122	3.8
		11.1		
225.0	10.59		0	0
		11.1		
234.0	10.69		612	19.0
		5.6		
243.0	10.74		622	19.3
		0		
252.0	10.74		0	0

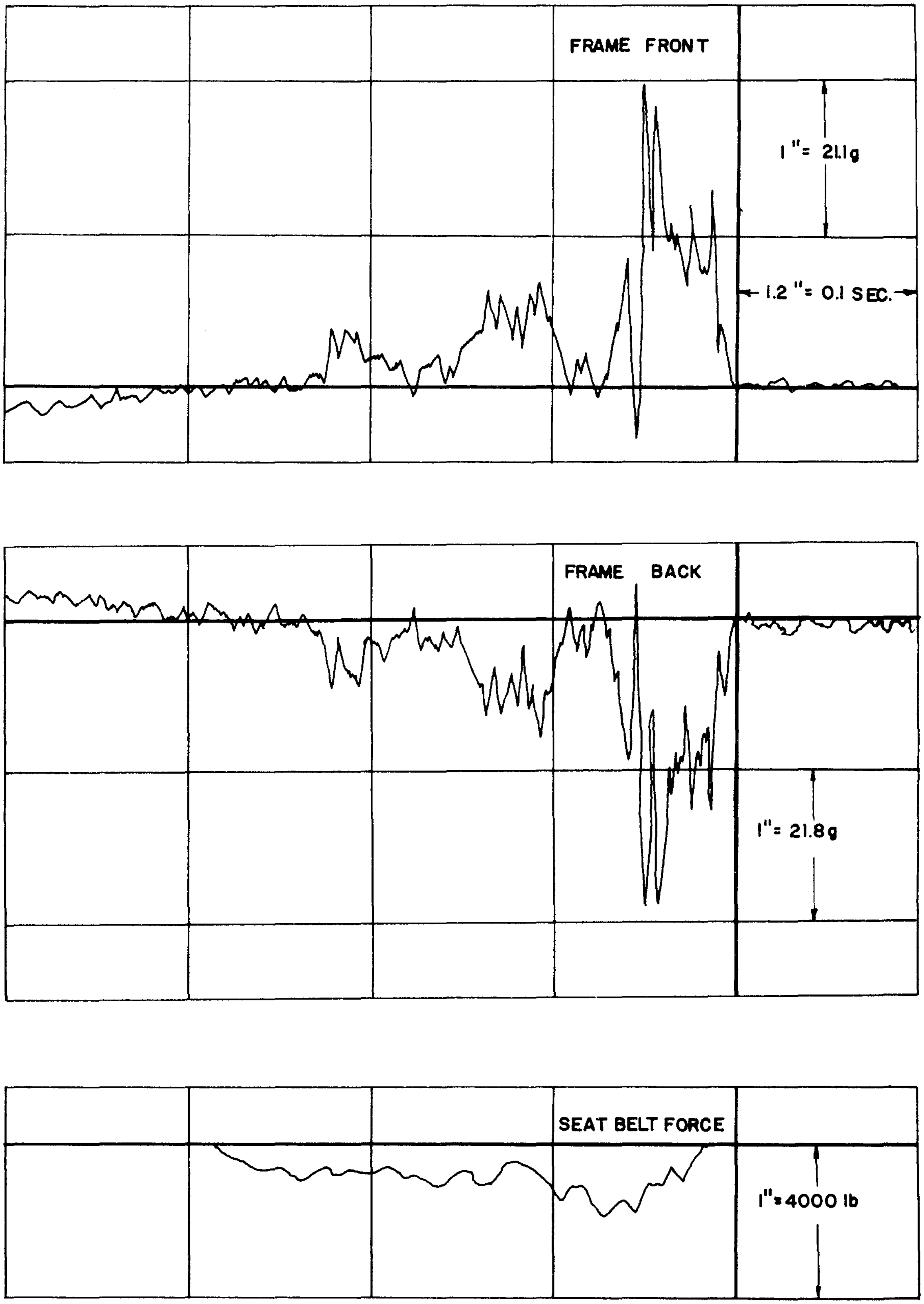


FIGURE 5B. TEST 505 2B FRAME ACCELEROMETER DATA & SEAT BELT FORCE

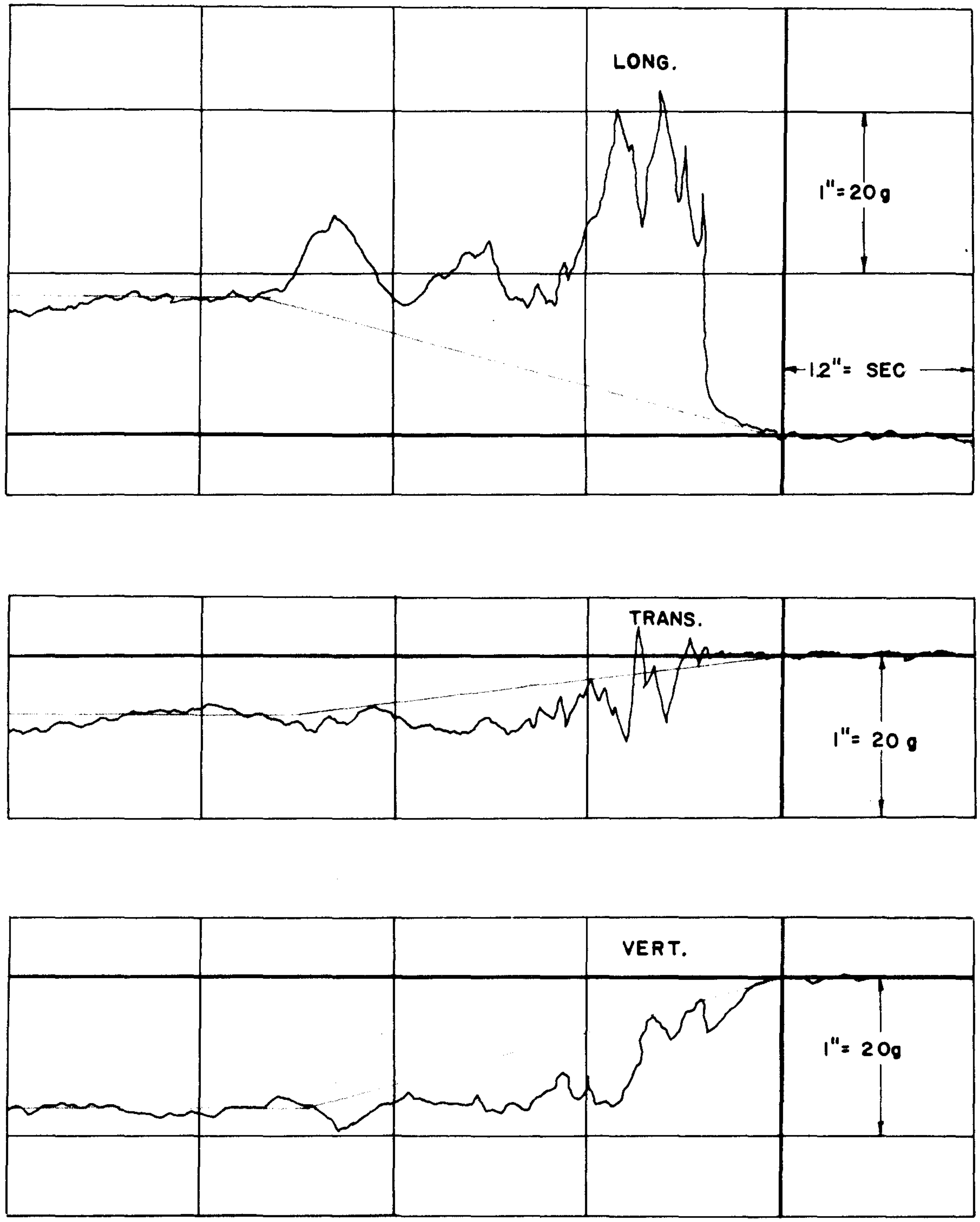
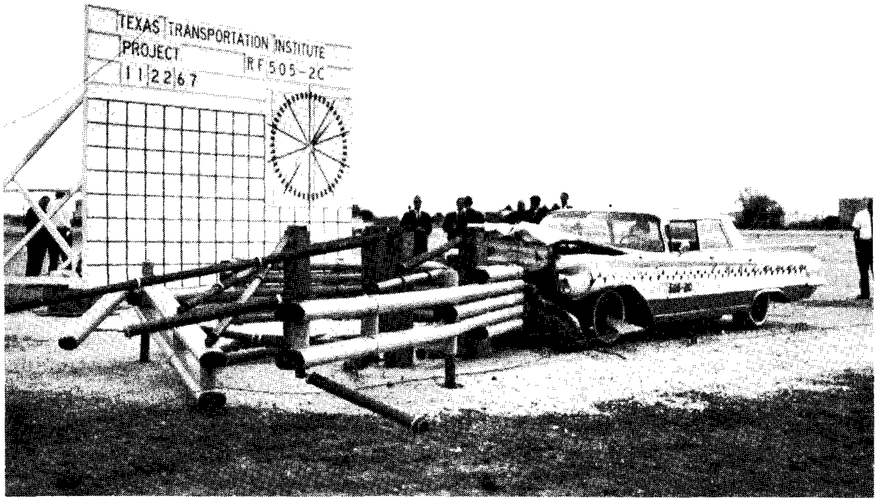


FIGURE 6B. TEST 505 2B DUMMY ACCELEROMETER DATA



CONDITIONS AFTER TEST (VEHICLE STRUCK BARRIER HEAD-ON)

TABLE 6 B.
Summary of High-speed Film Crash Test Data

<u>Test 505-2C</u> ARA Torshok Barrier 15° Nose Angle

Vehicle Weight = 4940 lb. (1960 Buick, 4-Door Sedan)

Vehicle Velocity = 59.4 mph or 87.1 fps

Change in Velocity = 59.4 mph or 87.1 fps

Average Deceleration = 9.9 g's

Peak Deceleration = 30.3 g's (12.4 msec.)

Duration of Impact = 0.273 sec.

Stopping Distance = 12.87 ft.

Remarks: Damage to Vehicle Moderate. Vehicle Deformation 1.75 ft.
Barrier Deformation 11.12 ft. Barrier Severely Damaged.

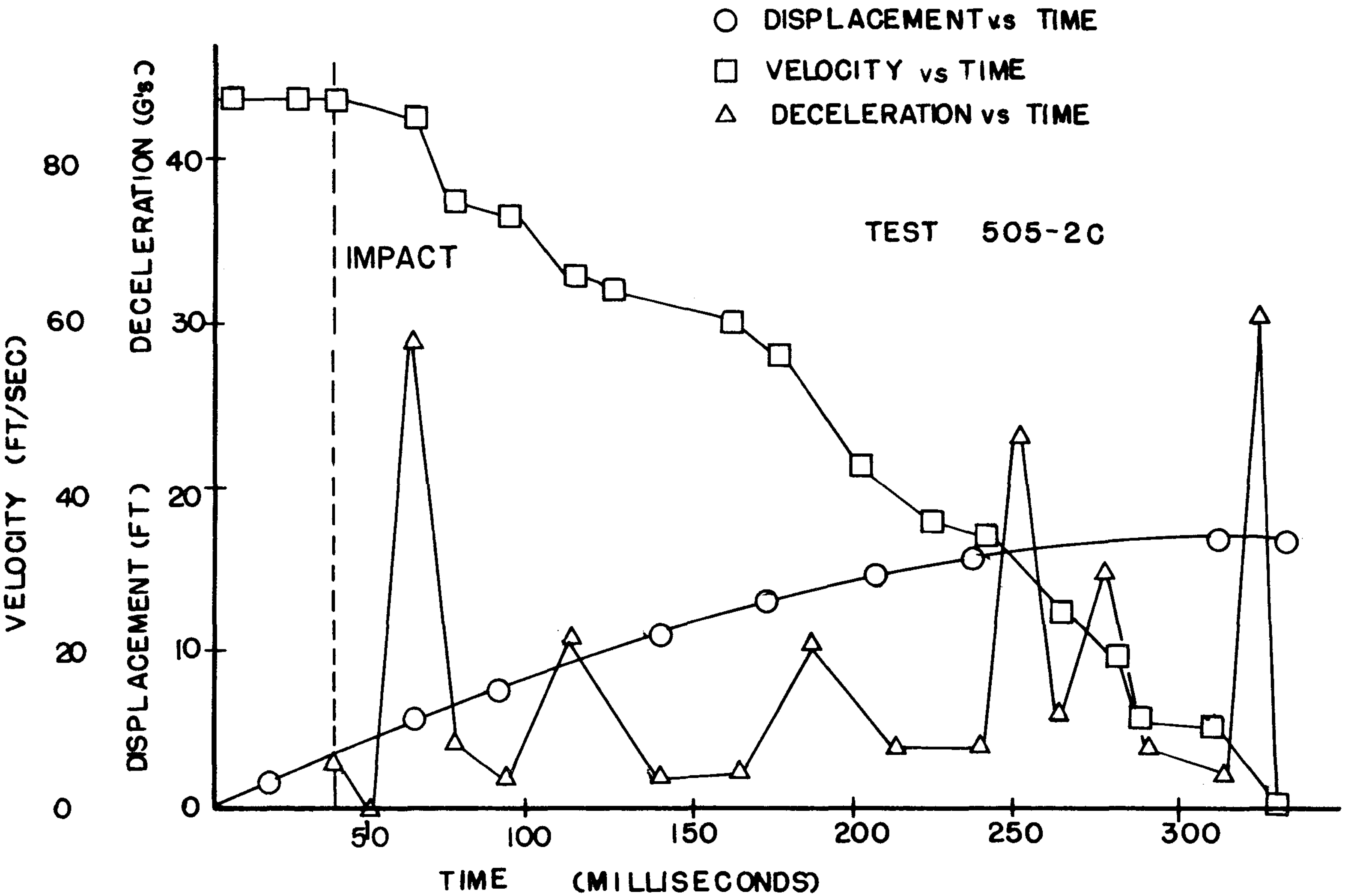


FIGURE 7B. DISPLACEMENT, VELOCITY, AND DECELERATION VS. TIME FOR TEST 505-2C

TABLE 7 B.

TEST RF 505-2C

ARA TORSHOK BARRIER 15° NOSE ANGLE

1960 BUICK, 4 DOOR SEDAN, 4940 LB.

HIGH SPEED FILM DATA

Time Milliseconds	Displacement ft	Velocity ft/sec	Deceleration ft/sec^2	g's
0	0		0	0
		87.1		
12.4	1.08		0	0
		87.1		
24.8	2.16		9	0
		87.1		
37.2 Impact	3.24		137	4.3
		85.4		
49.6	4.30		0	0
		85.4		
62.0	5.30		902	28.0
		74.2		
74.4	6.28		129	4.0
		72.6		
86.8	7.18		65	2.0
		71.8		
99.2	8.07		177	5.5
		68.6		
111.6	8.92		331	10.3
		64.5		
124.0	9.72		258	8.0
		61.3		
136.4	10.48		65	2.0
		60.5		
148.8	11.23		387	12.0
		55.7		
161.20	11.92		73	2.3
		54.8		
173.60	12.60		226	7.0
		42.0		
186.0	13.12		331	10.3
		37.9		
198.4	13.59		194	6.0
		35.5		
210.8	14.03		129	4.0
		33.9		
223.2	14.45		129	4.0
		32.3		
235.6	14.85		653	20.3
		24.2		
248.0	15.15		194	6.0
		21.8		
260.4	15.42		460	14.3
		16.1		
272.8	15.62		129	4.0

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TABLE 7B.

TEST RF 505-2C (continued)

Time Milliseconds	Displacement ft	Velocity ft/sec	Deceleration ft/sec^2	Deceleration g's
		14.5		
285.2	15.80		129	4.0
		12.9		
297.6	15.96		65	2.0
		12.1		
310.0	16.11		975	30.3
		0		
322.4	16.11		0	0
		0		
334.8	16.11		0	0

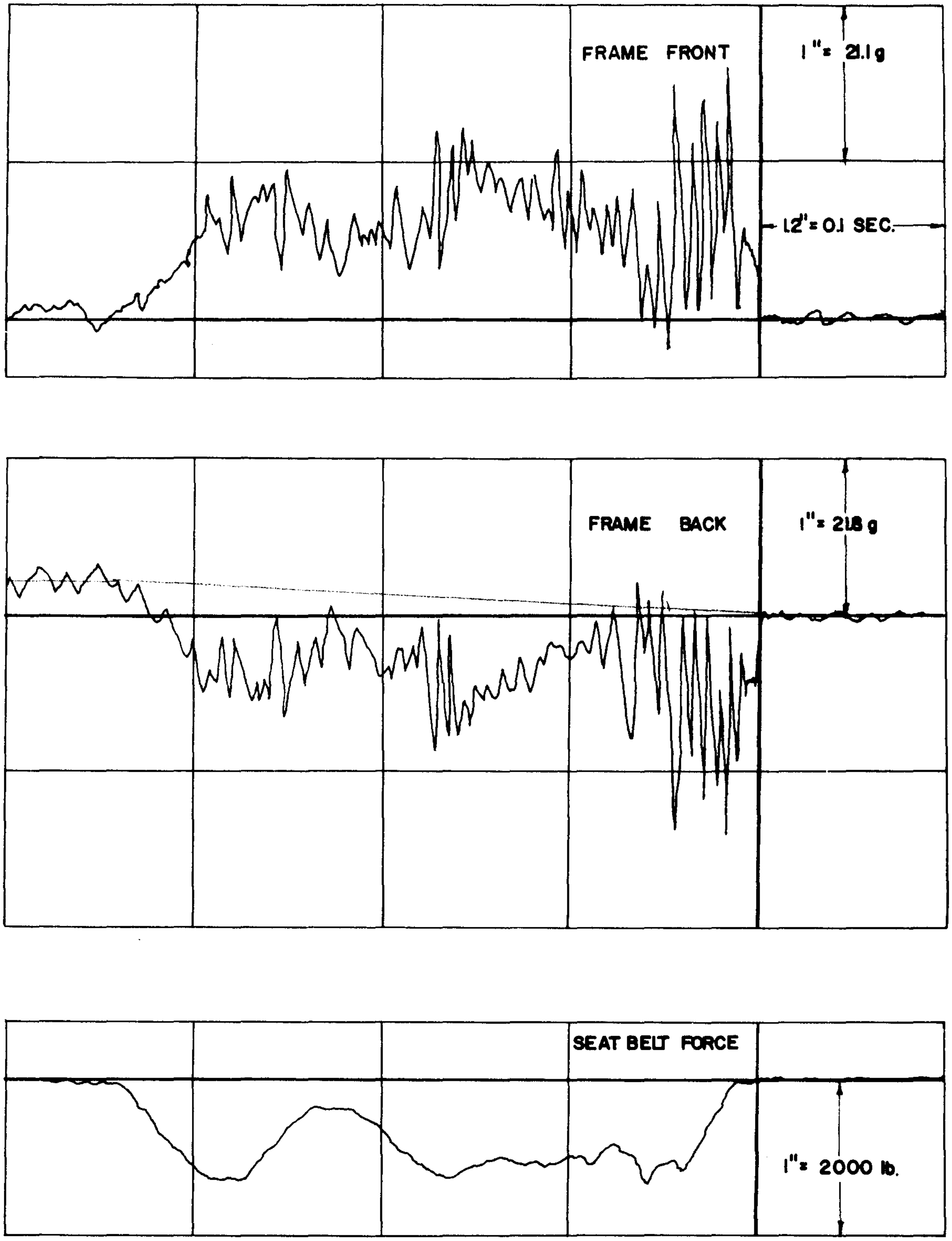


FIGURE 8B. TEST 505 2C FRAME ACCELEROMETER & SEAT BELT FORCE

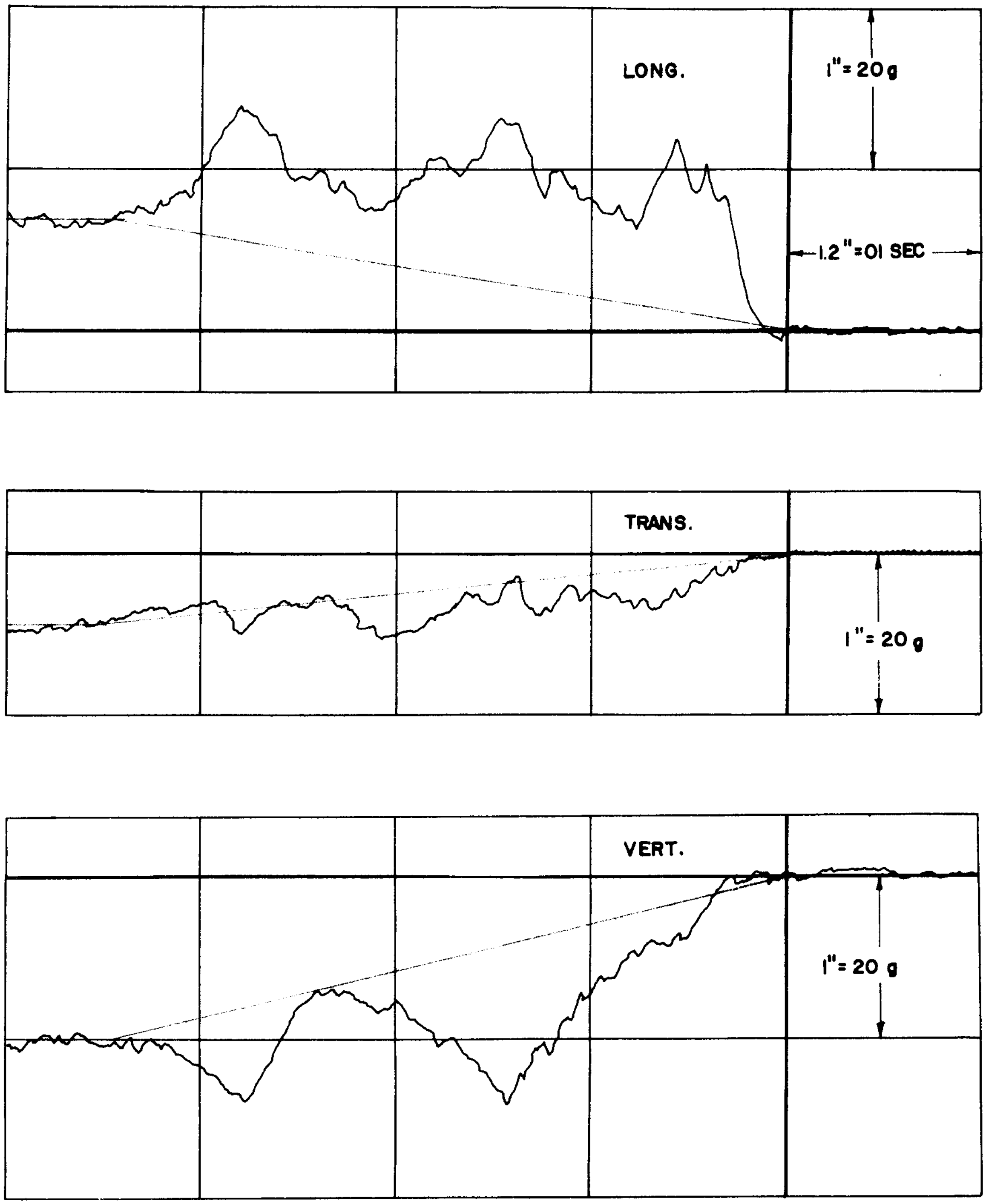
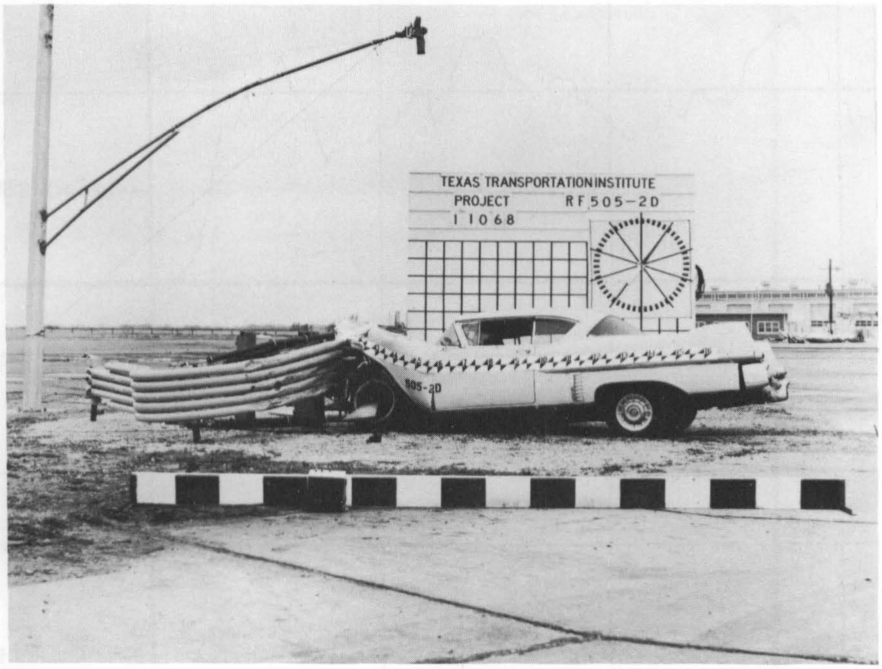


FIGURE 9B. TEST 505 2C DUMMY ACCELEROMETER DATA



CONDITIONS AFTER TEST (ANGLE OF IMPACT = 30°)

Table 8B.
Summary of High-speed Film Crash Test Data
Test 505-2D ARA Torshok Barrier 15° Nose Angle

Vehicle Weight = 5000 lb. (1957 Cadillac, 2 door hardtop)

Vehicle Velocity = 73.3 fps or 49.9 mph

Change in Velocity = 73.3 fps or 49.9 mph

Average Deceleration = 8.1 g's

Peak Deceleration = 60.7 g's (9.35 msec.)

Duration of Impact = 0.280 sec.

Stopping Distance = 13.96 ft. (Longitudinal movement of vehicle)

Remarks: Damage to Vehicle Severe. Vehicle Deformation 1.83 ft.

Barrier Deformation 12.13 ft. Barrier Almost Total Loss.

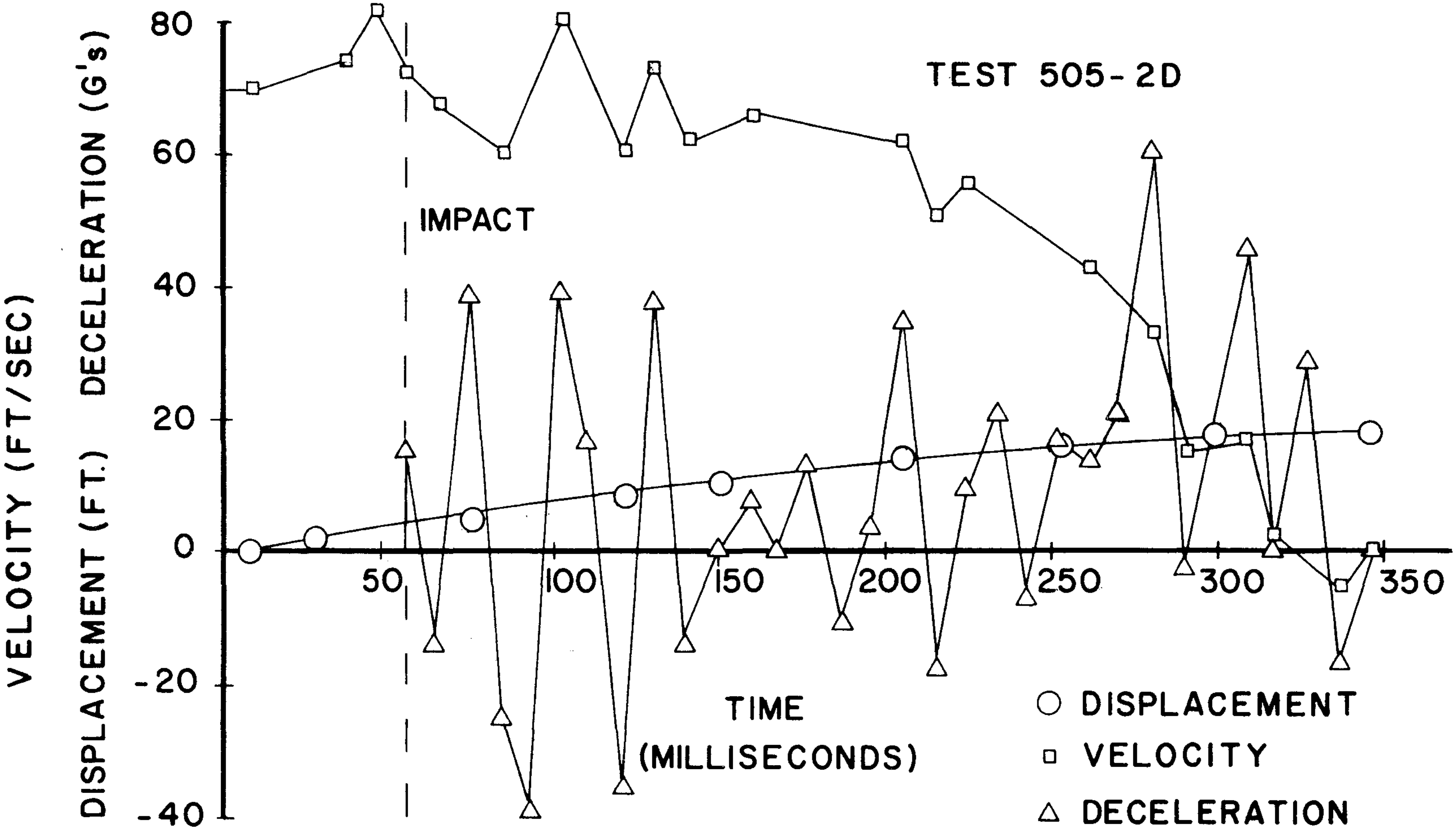


FIGURE 10B. DISPLACEMENT, VELOCITY, AND DECELERATION VS. TIME FOR TEST 505-2D

TABLE 9B.

TEST RF 505-2D

ARA TORSHOK BARRIER 15° NOSE ANGLE

1957 CADILLAC, 2-DOOR HARDTOP, 5000 LB.

HIGH SPEED FILM DATA

Time Milliseconds	Displacement ft	Velocity ft/sec		Deceleration ft/sec^2	g's
		70.6			
9.35	0.66				
		69.5			
18.70	1.31				
		69.5			
28.05	1.96		73.3		
		74.9	Avg.		
37.40	2.66				
		82.5			
46.75	3.43			0	0
		72.8			
56.10 Impact	4.11			514	16.0
		68.5			
65.45	4.75			-460	-14.3
		72.8			
74.80	5.43			1273	39.6
		60.9			
84.15	6.00			-814	-25.3
		68.5			
93.50	6.64			-1262	-39.2
		80.3			
102.85	7.39			1262	39.2
		68.5			
112.20	8.03			568	17.6
		63.2			
121.55	8.62			-1134	-36.2
		73.8			
130.90	9.31			1250	38.9
		62.1			
140.25	9.89			-460	-14.3
		66.4			
149.60	10.51			0	0
		66.4			
158.95	11.13			235	7.3
		64.2			
168.30	11.73			0	0
		64.2			
177.65	12.33			460	14.3
		59.9			

(continued on next page)

TABLE 9B.

TEST RF 505-2D
(Continued)

Time Milliseconds	Displacement ft	Velocity ft/sec	Deceleration ft/sec^2	g's
187.00	12.89		-353	-11.0
		63.2		
196.35	13.48		128	4.0
		62.0		
205.70	14.06		1145	35.6
		51.3		
215.05	14.54		-578	-17.9
		56.7		
224.40	15.07		342	10.6
		53.5		
233.75	15.57		685	21.3
		47.1		
243.10	16.01		-225	- 7.0
		49.2		
252.45	16.47		578	17.9
		43.8		
261.80	16.88		450	14.0
		39.6		
271.15	17.25		685	21.3
		33.2		
280.50	17.56		1950	60.7
		15.0		
289.85	17.70		-107	-3.3
		16.0		
299.20	17.85		-129	-4.0
		17.2		
308.55	18.01		1500	46.6
		3.2		
317.90	18.04		0	0
		3.2		
327.25	18.07		910	28.3
		-5.3		
336.60	18.02		-568	-17.6
		0.0		
345.95	18.02		0	0
		0.0		
355.30	18.02		0	0

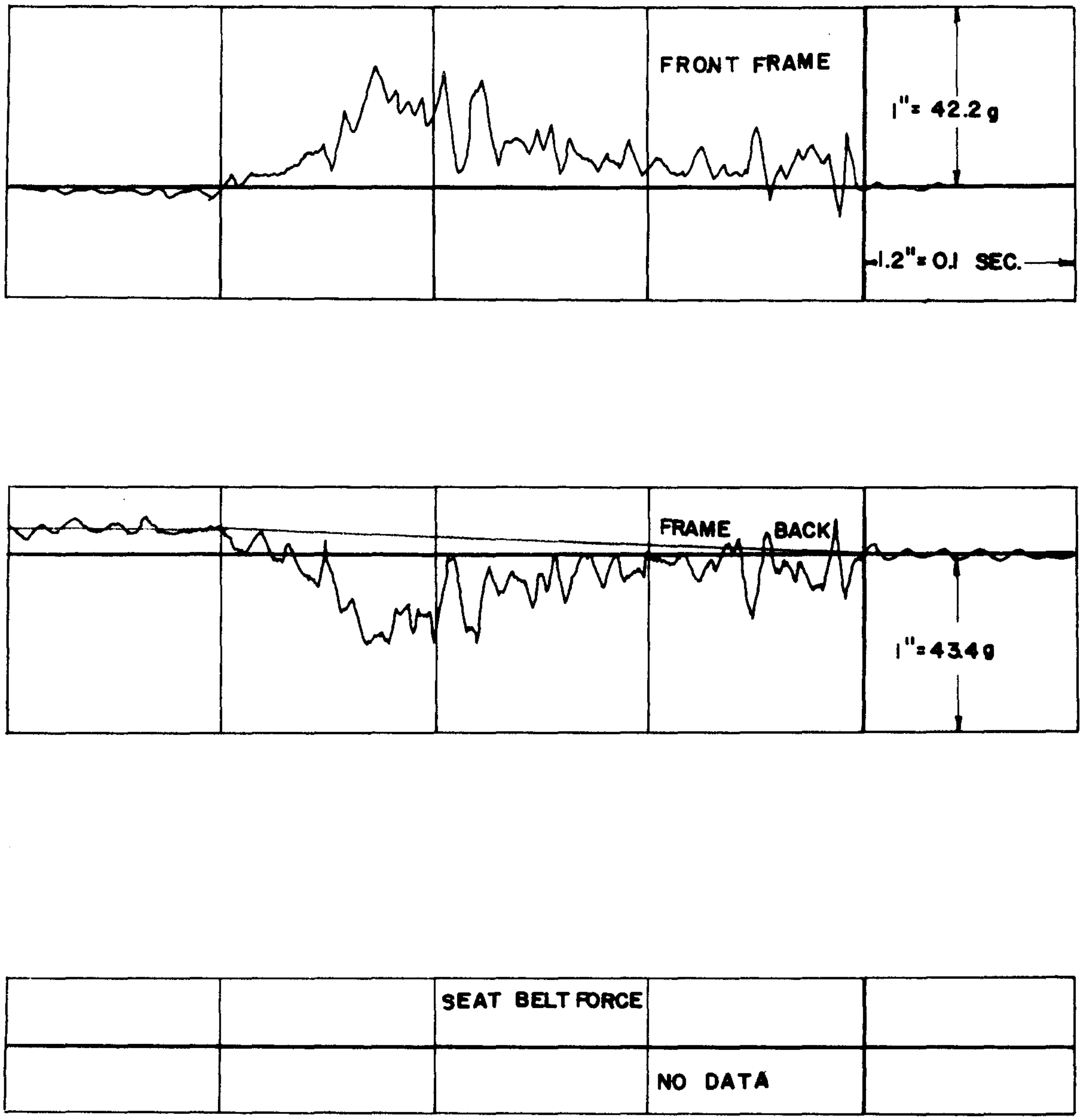


FIGURE 11B. TEST 505 2D FRAME ACCELEROMETER DATA & SEAT BELT FORCE

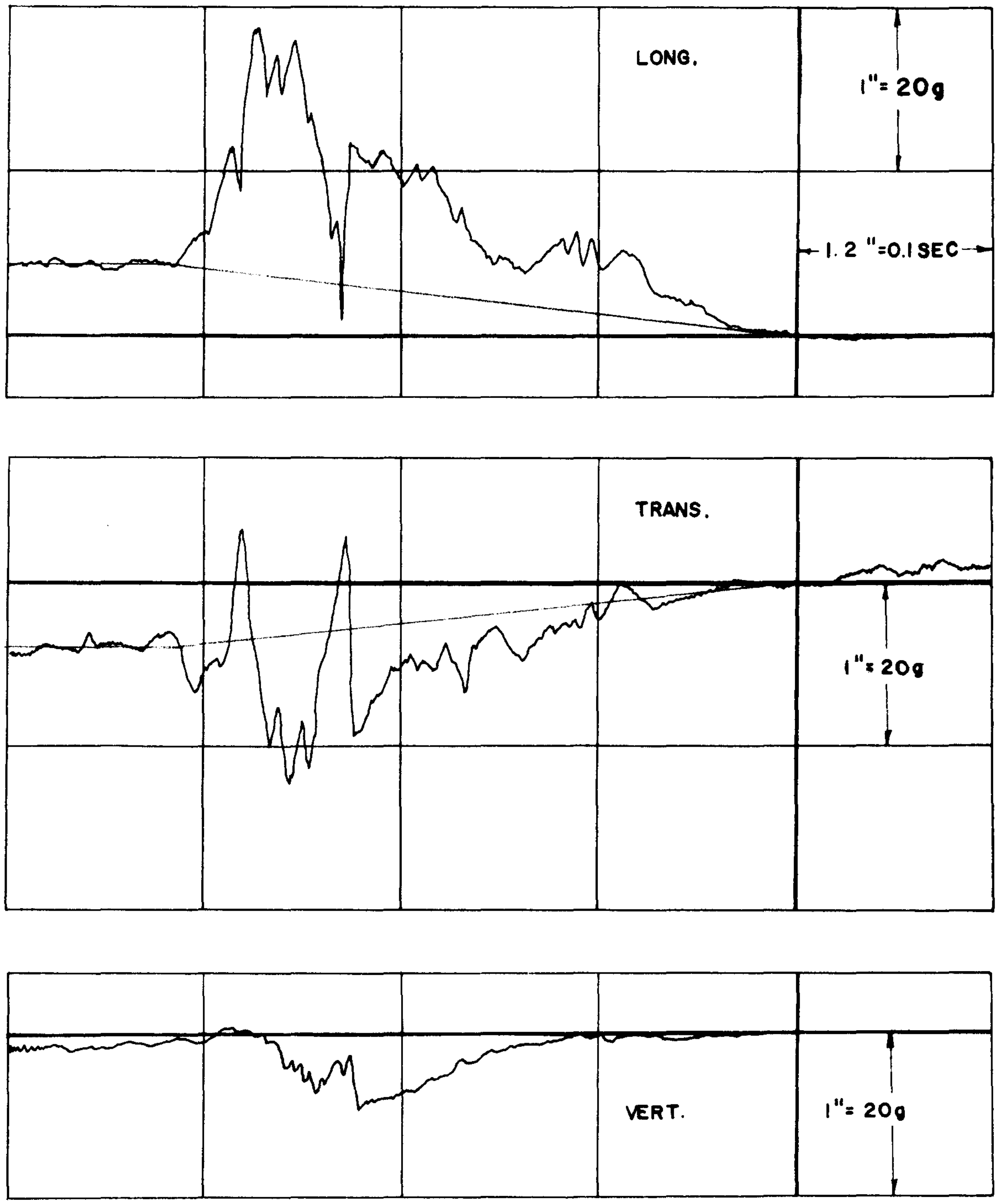


FIGURE 12B. TEST 505 2D DUMMY
ACCELEROMETER DATA