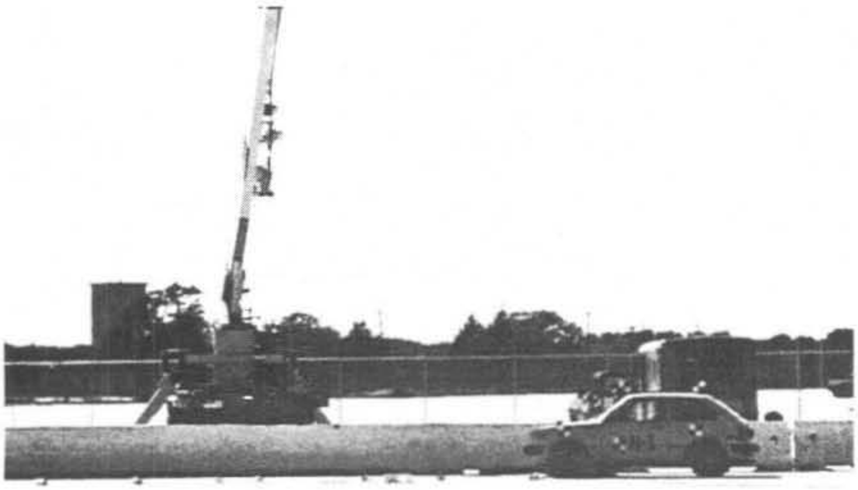
FULL-SCALE VEHICLE CRASH TEST ON NEBRASKA BRIDGE RAIL BARRIER WITH A MODIFIED NEW JERSEY SHAPE



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ABSTRACT

The New Jersey Shape Barrier is one of the most popular shaped concrete barriers implemented today on American highways. Previous tests using this barrier have shown that it is worthy of being a standard for bridge rail barriers on an international level. This investigation was an attempt to modify the New Jersey Shape Barrier by increasing the 3 inch initial step to 4 1/2 inches. This extra 1 1/2 inches would allow more of an exposed vertical face which is beneficial in applying future deck overlays. To determine whether or not this modification was acceptable, a full-scale crash test was performed on the modified barrier shape using an 1800 lb., 1982 Honda Civic at an impact speed of 60 mph and an impact angle of 20 degrees. The test results showed that a minicompact sedan, such as the 1982 Honda Civic, would likely roll under these test conditions and barrier modifications.

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INTRODUCTION

A. Problem Statement

Over the years, concrete safety shaped barriers have become more and more familiar on American highways due to its satisfactory performance in redirecting a vehicle; the most popular being the New Jersey Shaped Barrier (NJ Barrier). The Nebraska Department of Roads (NDOR) has designed a bridge rail that uses the general shape of the NJ Barrier face; however, one modification was made to the barrier face. NDOR has increased the 3-in. initial step to 4 1/2-in. The modification stemmed from a desire to increase the initial step of the barrier since the step provides a complementary edge for future deck overlays.

The problem with increasing the initial step is that the slope break point of the barrier face is also raised 1 1/2-in. to a height of 14 1/2-in. above the road surface. The slope break point is the point of intersection between the two sloped surfaces of the barrier face and has been found to be the key parameter in vehicle rollover potential. One purpose of the lower sloped surface of any safety shaped barrier is to lift the vehicle just enough to reduce the friction between the tires of the vehicle and the road surface. This allows easier redirection of the vehicle by the barrier. However, too much lift of the vehicle can cause a hazard in vehicle rollover potential. Thus, keeping the slope break point to a minimum height is imperative.

This problem has also been a concern of others such as the Department of the Environment (DOE) or of the Department of Transport (DOT) in Crowthorn, Berkshire; England. The Transport and Road Research Laboratory (TRRL) has already conducted a test for the DOE and DOT in England on a barrier similar to the NJ Barrier, but having a 6-in. initial step instead of a 3-in. step which raised the slope break point of the barrier to a height of 16-in. above the road surface (1). The test conducted by TRRL was unsatisfactory because of vehicle rollover. Because of the unsatisfactory performance of the barrier in Europe, the Federal Highway Administration (FHWA) and NDOR were concerned about the vehicle rollover potential of the NDOR Bridge Rail Barrier due to the 14 1/2-in. height of the slope break point.

B. Objective

The primary objective of this study was to test the modification of increasing the height of the slope break point on the NJ Barrier face to 14 1/2-in. and to evaluate the results. Testing procedures and evaluation of the results were to be in accordance with the saftey performance criteria inferred from the "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances" by the National Cooperative Highway Research Program Report 230 (NCHRP 230) (2), and the "Standard Specifications for Highway Bridges" by the American Association of State Highway and Transportation Officials (AASHTO) (3).

C. Goals

Goals for this test are (1) that the vehicle should be smoothly redirected, (2) that the vehicle shall remain upright throughout the collision, and (3) its after-collision trajectory should not present undue hazard to other traffic.

As stated in NCHRP 230 and AASHTO, "Keeping vehicles upright during all crash tests is a worthy goal as occupant risks are generally more severe and less predictable in vehicle rollover."

TECHNICAL DISCUSSION

A. Test Conditions

A.1 Test Facility

The test site facility where the full-scale vehicle crash testing is conducted is located approximately 7 miles northwest from the University at the Lincoln Municipal Airport on the northwest end of the west apron. Appendix A explains the facility in greater detail and shows the guidance and towing methods used.

A.2 Test Article

It was decided by NDOR and the FHWA that since the barrier to be tested was similar to the New Jersey Safety Shape, that 10 ft. precast sections of temporary New Jersey Concrete Barrier, shown in Figure 1, could be used as a surrogate for the NDOR Bridge Rail Barrier as long as certain requirements were met. The first requirement was that the dimensions of the face for the precast barrier sections be made identical to that of NDOR's bridge barrier shown in Figure 2. This only called for elevating the precast barrier sections 1 1/2-in. above the road surface so that the initial step of the barrier would be 4 1/2-in. instead of 3-in. No other change in the dimensions of the precast barrier sections were necessary since elevating

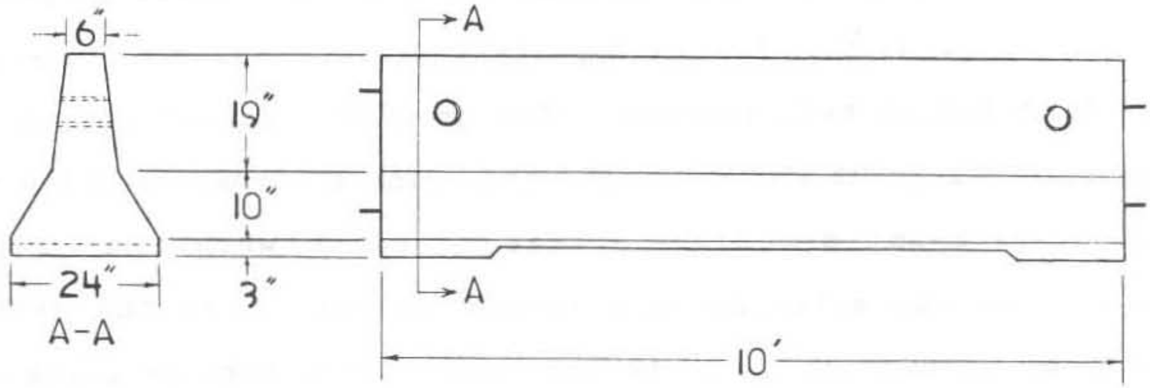


FIGURE 1. 10 ft. Precast New Jersey Concrete Barrier Section

them 1 1/2-in. made all face dimensions between the precast section barriers and the NDOR Bridge Rail Barrier identical. The second requirement was that the precast barrier sections be reinforced on the opposite side of impact with a rigid steel frame backup system to provide lateral support for the barrier. This was imperative so that the section barriers would not deflect in any way, simulating the NDOR Bridge Rail Barrier. Figure 3 shows the reinforcement details used in making the precast barrier sections rigid while Figure 4 shows the rigid steel frame backup system in place behind the precasted barriers.

Using the 10 ft: precasted sections of barrier instead of constructing an actual bridge rail barrier, as well as the bridge deck, was a significant savings in conducting the full-scale crash test. The barrier was 100 ft. long (ten 10 ft. precasted barrier sections) and was elevated to the desired height by setting the barrier sections on constructed wooden pallets that were 1 1/2-in. thick. Three vertical joints between the 10 ft.

barrier sections were grouted near the point of impact to provide a smooth transition for an impacting vehicle, as would be with the NDOR Bridge Rail Barrier. The grouted vertical joints were the vertical joint upstream from the point of impact and the next two downstream; all other vertical joints were not grouted because of the anticipated duration of time that the vehicle would be in contact with the barrier. The barrier system was also grouted underneath the precast barriers at impact to give a uniform initial step near the area of impact. Photographs of the grouted surrogate NDOR Bridge Rail Barrier are shown in Figure 5.

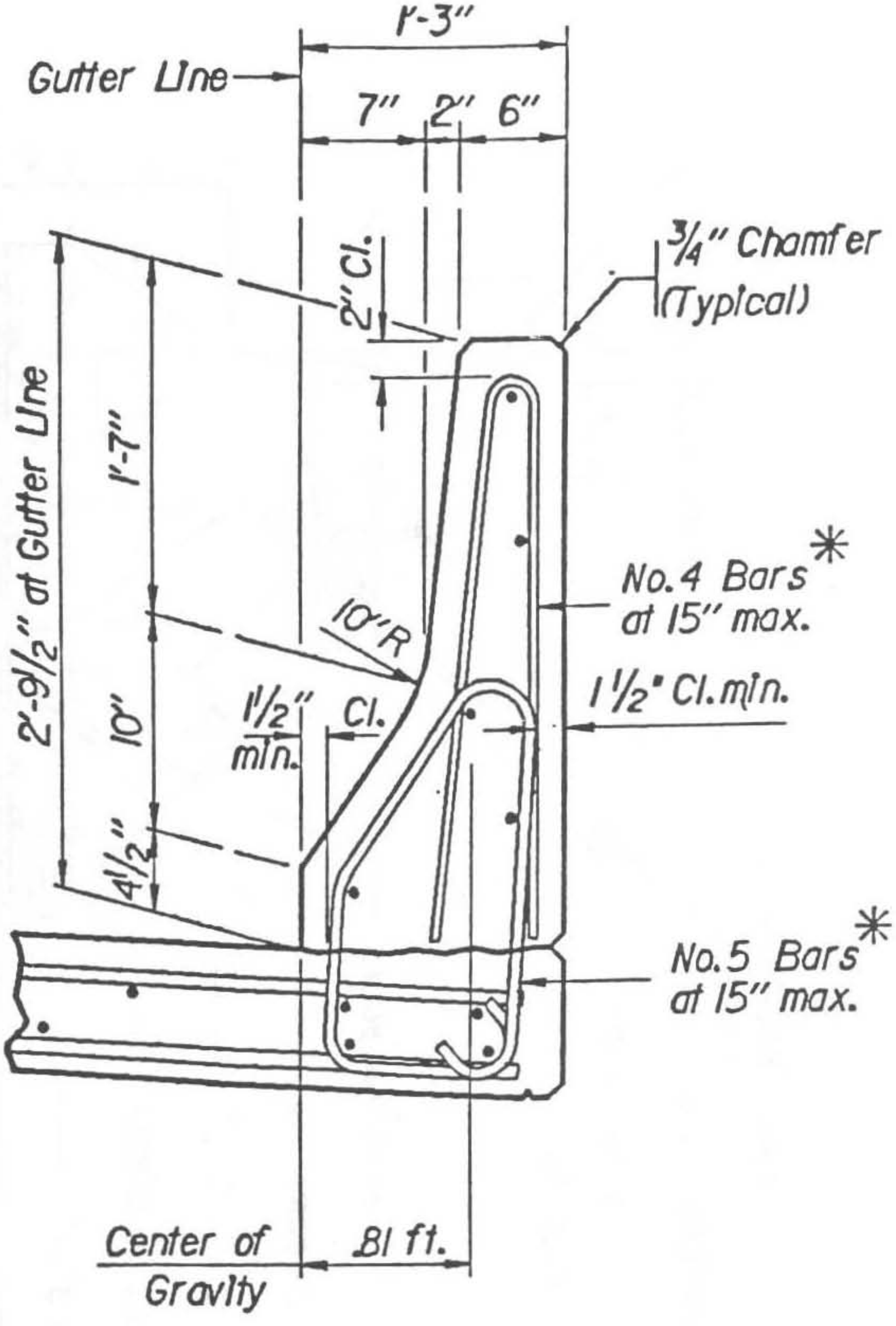


FIGURE 2. NDOR Bridge Rail Barrier

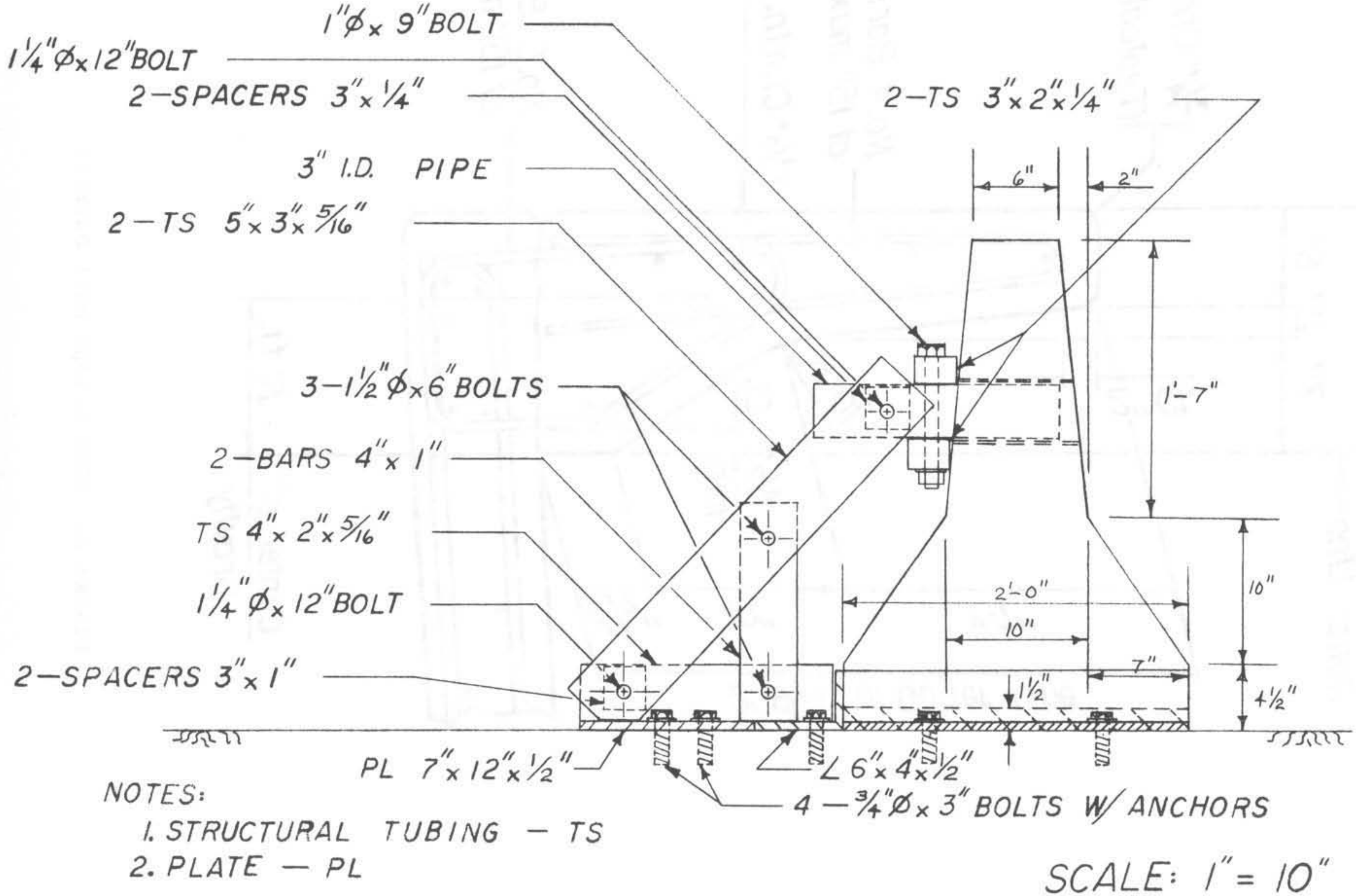
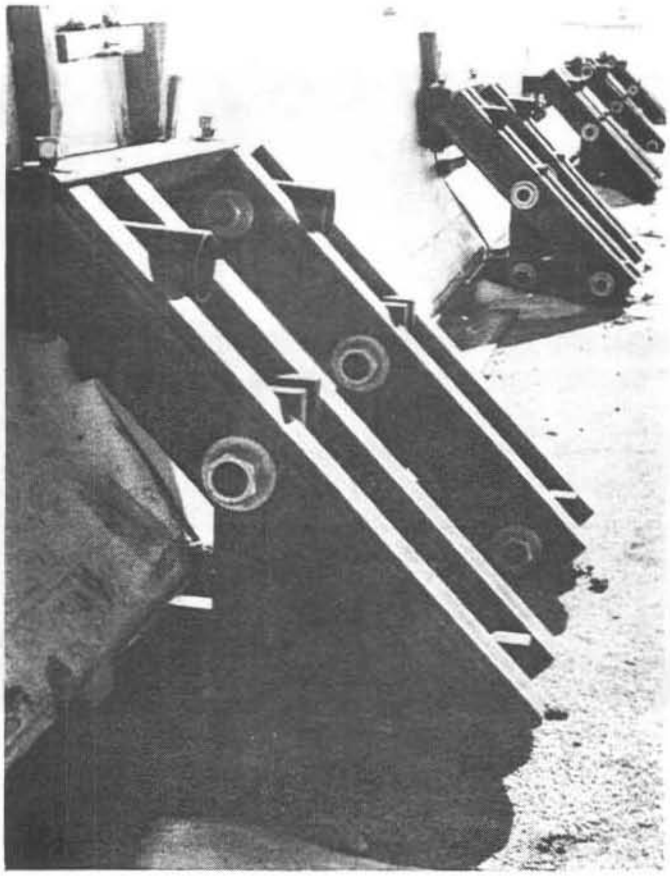


FIGURE 3. Schematic of Rigid Steel Frame Backup System



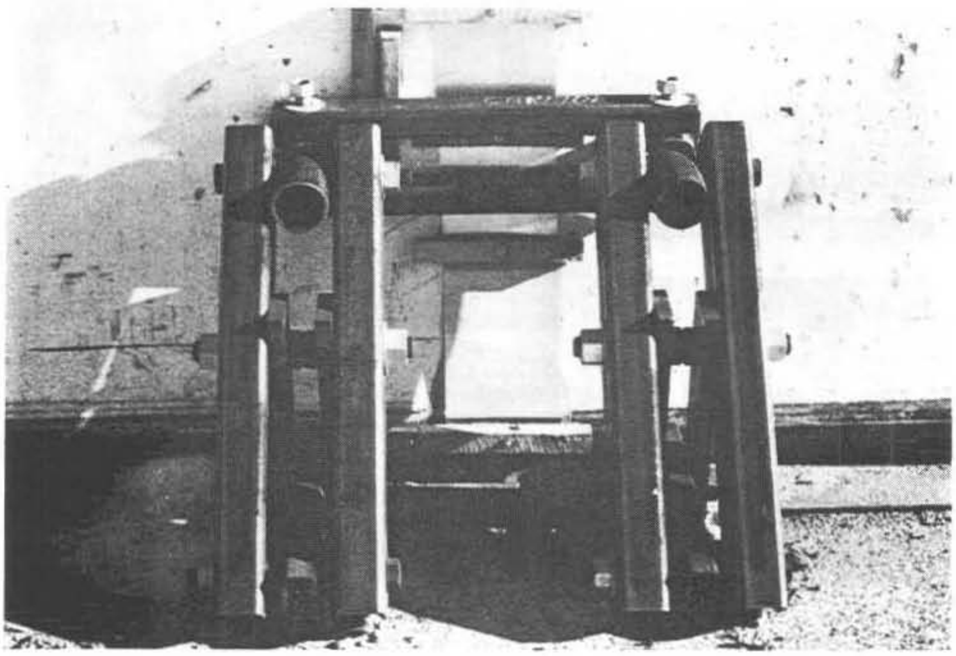
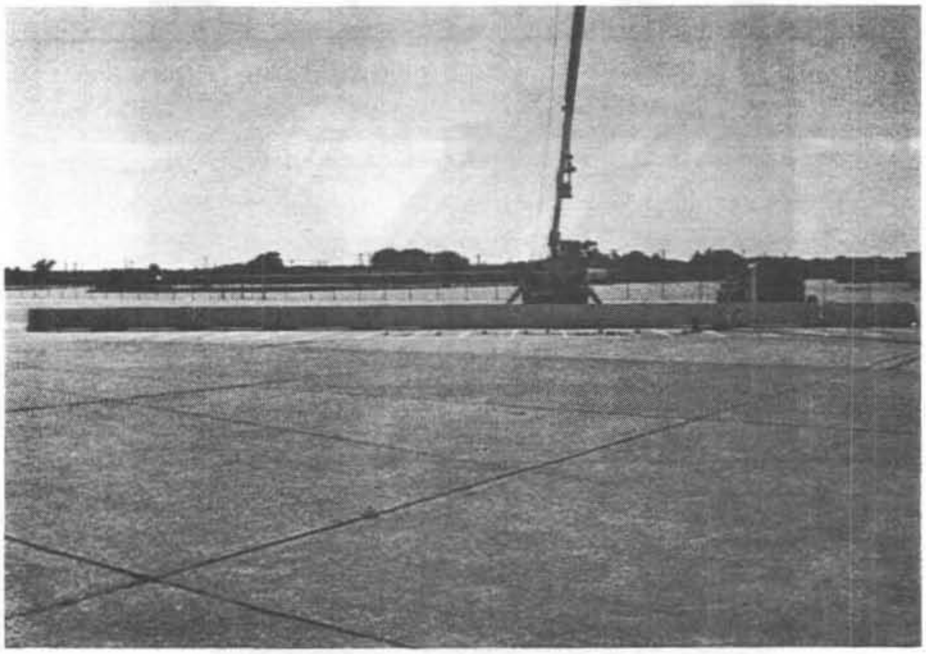


FIGURE 4. Photographs of the Rigid Steel Frame Backup System



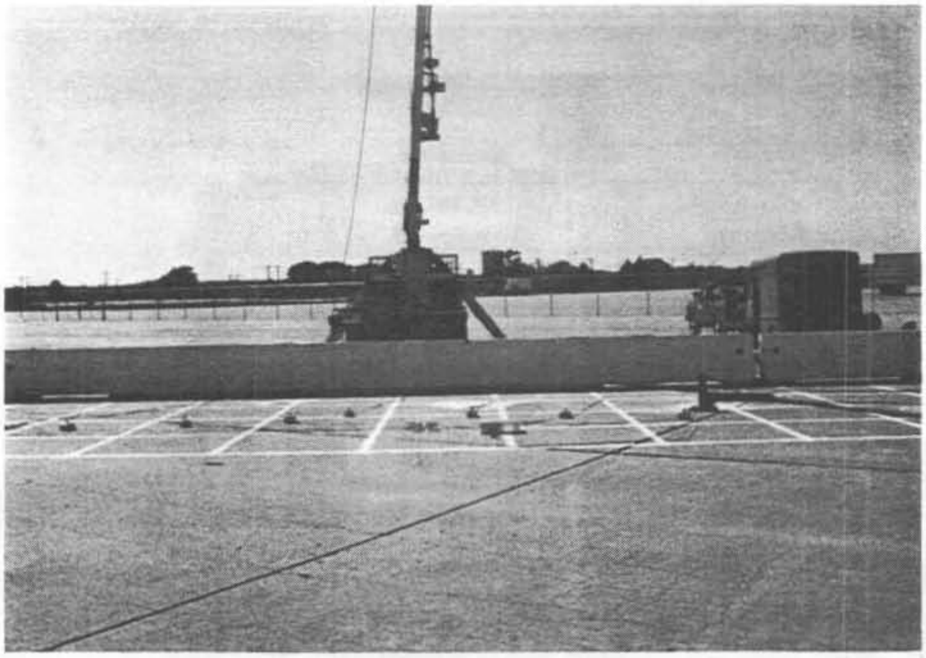
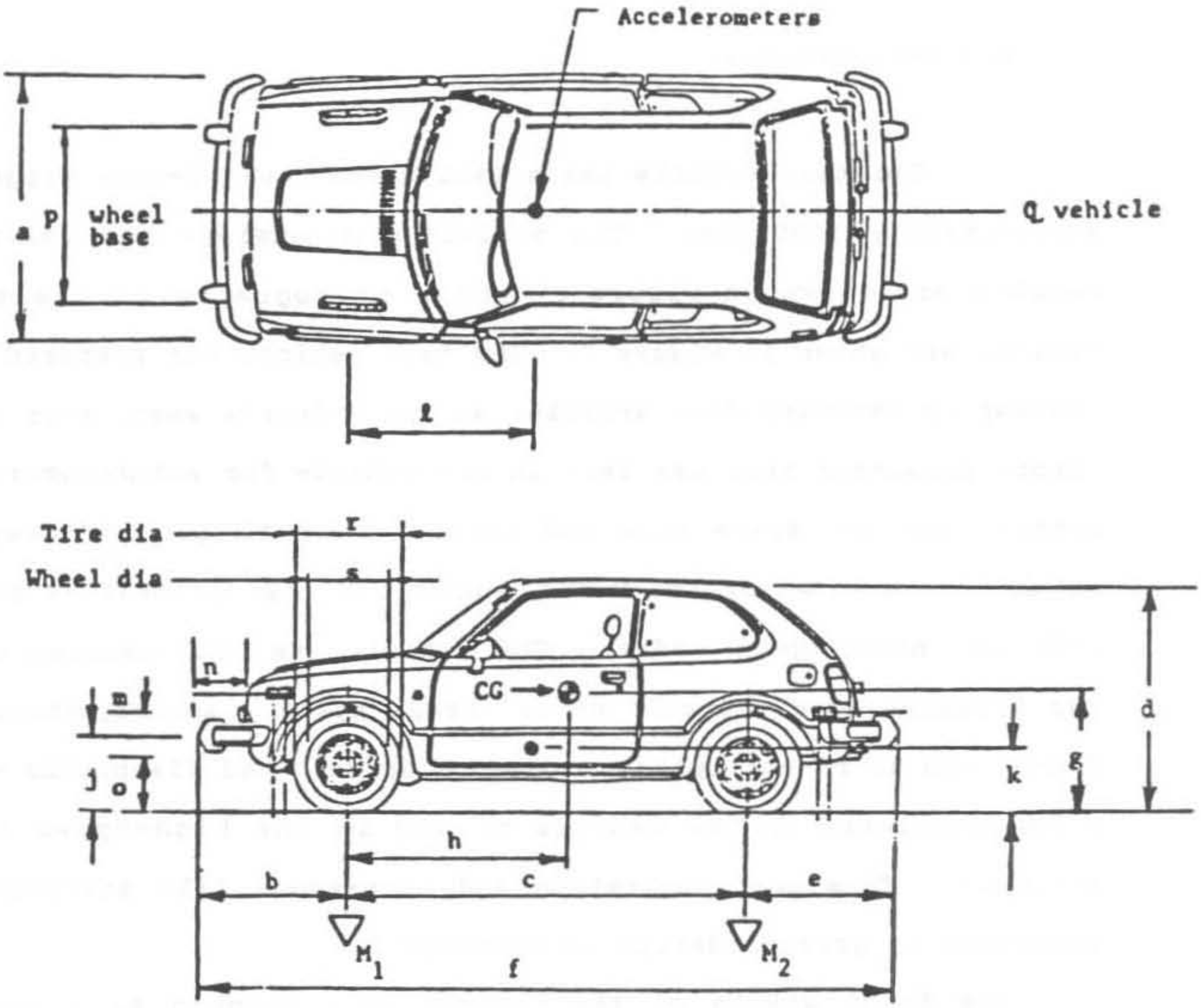


FIGURE 5. Surrogate NDOR Bridge Rail Barrier

A.3 Test Vehicle

The test vehicle was a 1982 Honda Civic 3-door weighing approximately 1800 lbs. The vehicle's dimensions and relative weights are shown in Figure 6, while photographs of the test vehicle are shown in Figure 7. The test vehicle was prepared for testing by removing such articles as the driver's seat, rear seat (front passenger seat was left in the vehicle for anthropomorphic dummy), and the spare tire and rim in order to get the desired weight recommended by the NCHRP Report 230 (2) guidelines for a 1800 lb. minicompact sedan. The vehicle was instrumented with two triaxial accelerometer units, brake system, anthropormorphic dummy, and an FM multiplexer. Camera targets and flashbulbs were also positioned on the vehicle to aid in the high-speed film analysis. This instrumentation and high-speed film analysis is explained in greater detail in Appendix B.

The front wheels of the vehicle were aligned to a toe-in value of zero-zero so that the vehicle would track properly along the guide cable.



Geometry - (in.)

a.	62.2	d.	53.2	g.	21.5	l.	33.0	p.	53.5
b.	29.5	e.	28.0	j.	18.0	n.	4.5	r.	14.2
c.	88.6	f.	148.4	k.	21.5	o.	10.0	s.	22.6

Mass - lb.	Test Inertial *	Gross Static **
M_1	1150	______
M_2	650	______
M_T	1800	1965
h - (in.)	33.0	______
g - (in.)	21.5	______

* Ready for test but excludes passenger/cargo payload
** Gross ready for test including passenger/cargo payload

FIGURE 6. Test Vehicle Weights and Dimensions

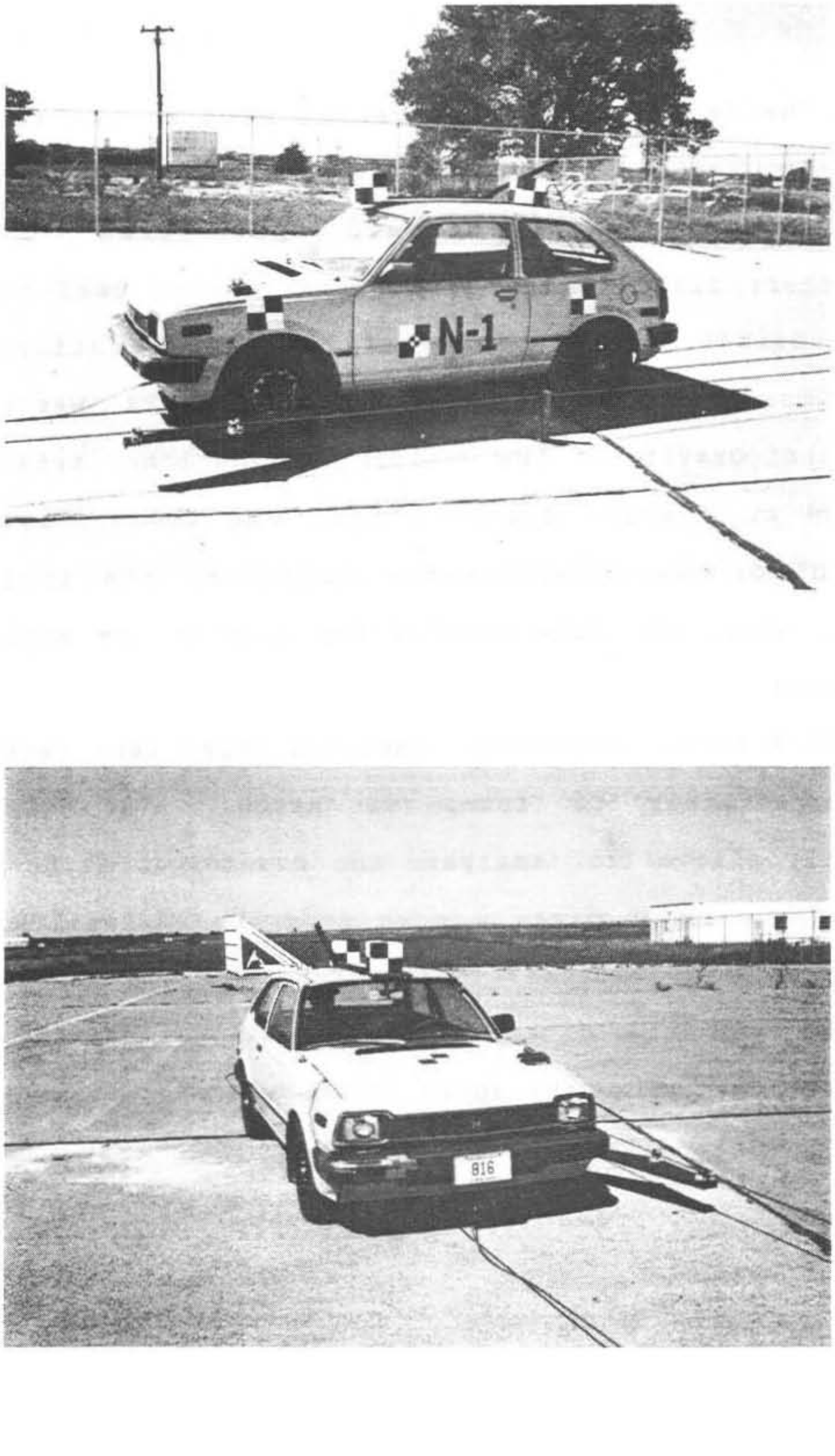


FIGURE 7. Photographs of Test Vehicle

A.4 Data Acquisition Systems

The data acquisition systems used in the full-scale crash testing includes piezoresistive accelerometers, high-speed photography, and an electronic speed trap. The six accelerometers placed in the test vehicle were used to measure the longitudinal, lateral, and vertical accelerations of the vehicle. One triaxial unit (three accelerometers) was placed at the center of gravity of the vehicle and the other triaxial unit was placed at a known distance from the C.G. Figures and photographs of the accelerometer positions are included in Appendix B where the data acquisition systems are explained in greater detail.

The high-speed photography included three 16mm cameras that ran at approximately 500 frames per second. The cameras were strategically placed for analysis and documentation of the test results. Appendix B gives a more in-depth explanation of the camera positions as well as a schematic of the camera layouts.

A speed trap made of tape pressure switches was also used as one source to determine the speed of the vehicle before and after impact. Appendix B also explains the speed trap in greater detail.

A.5 Test Parameters

The full-scale crash test was conducted on the Nebraska Department of Roads Bridge Rail Barrier with a Modified New Jersey Shape as mentioned in part A.2 of the Technical Discussion. An 1800 lb. 1982 Honda Civic 3-Door impacted the barrier at a target impact speed of 60 mph and a target impact angle of 20 degrees.

The location of impact on the barrier was at a point 35 ft. from the upstream end of the constructed barrier. Since the main concern of this test was the roll motion of the vehicle after impact due to the critical inertial properties of the vehicle, the vehicle was impacted at the center of one of these 10 ft. barrier sections. This insured that the vehicle trajectory was caused solely by the interaction of the vehicle and the barrier face; not by barrier deflection or vehicle snagging.

A.6 Performance Evaluation Criteria

The safety performance objective of a highway appurtenance is to minimize the consequences of a vehicle leaving the roadway to create an off-road incident. The safety goal is satisfactory when the appurtenance smoothly redirects the vehicle away from another hazardous situation without subjecting the vehicle occupants to forces which may produce major injury.

Because test conditions are sometimes difficult to control, a composite tolerance limit, called the impact severity (IS), is presented in the NCHRP Report 230 (2). The IS values, both target and actual, are given in Table 1. The formula used to calculate impact severity is given as follows:

$$IS = \tfrac{1}{2}m(v\sin\Theta)^2$$

where, m = vehicle test inertial mass (slugs)

v = impact velocity (fps)

Θ = impact angle (degrees)

Safety performance of a highway appurtenance cannot be measured directly, but can be evaluated by three major factors which are defined and explained by both NCHRP 230 (2) and AASHTO (3). The factors are: (1) structural adequacy, (2) occupant risk, and (3) vehicle trajectory. A matrix of these factors for both NCHRP 230 and ASSHTO are shown in Tables 2 and 3 in the Conclusion of this report (pp. 26 and 27).

B. <u>Test Results</u>

A matrix of the crash test conditions is given in Table 1, while a summary of the full-scale crash test is presented in Figure 8.

Immediately after impact, the vehicle started to climb up the face of the barrier, as shown from the tire marks in Figure 9, and became completely "air-born" at a time of approximately 0.142 seconds. A point marked on the rear part of the vehicle and at the C.G. height of 21 1/2-in., showed that at that point, the vehicle's maximum distance from the ground surface was approximately 54 inches. After losing contact with the barrier, the vehicle started a looping trajectory path back toward the extended centerline of the barrier. Figure 10 shows a schematic of the vehicle's trajectory as well as a photograph of the vehicle's final stopping position which was 203 ft. downstream from the point of impact. The vehicle started to roll at a time of 1.82 seconds and was rolled over onto its roof at a time of 3.08 seconds when the brakes were applied in the vehicle.

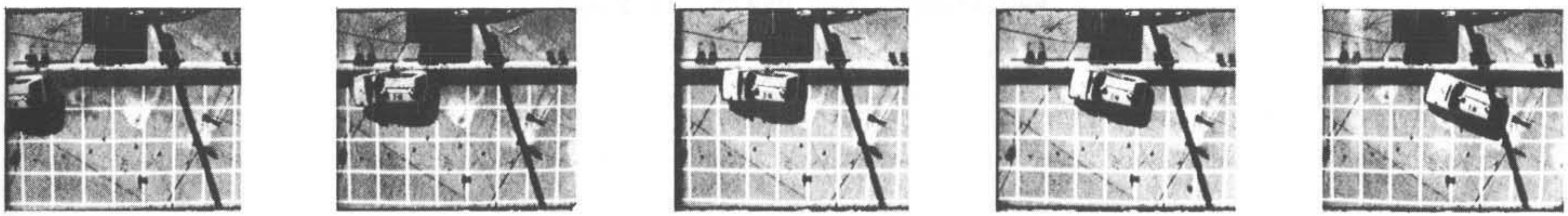
Sequential photographs during the time when the vehicle was in contact with the barrier are shown Figure 8. At a time of 0.074 seconds, the anthropomorphic dummy in the vehicle breaks the passenger door window. At 0.110 seconds, the damaged right front end of the vehicle loses contact with the barrier and at 0.162 seconds, the vehicle is parallel with the barrier. Finally, at 0.270 seconds, the rear part of the vehicle loses contact with the barrier.

Longitudinal and lateral accelerometer traces for the test may be found in Appendix C. The accelerometer traces show the deceleration of the vehicle, the vehicle change in velocity, and the occupant displacement for both triaxial units. From this data, one can find the occupant impact velocity and the average 10 millisecond occupant ridedown acceleration as presented in Figure 8.

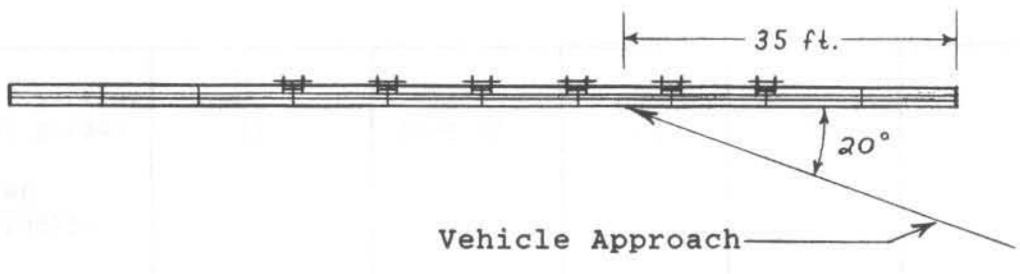
Photographs of the vehicle damage are shown in Figure 11, while Figure 12 shows the roll, pitch, and yaw of the test vehicle after impact. The damage of the vehicle was classified according to the Traffic Accident Data (TAD) scale (4), and the Vehicle Damage Index (VDI) scale (5). Classifications of the vehicle damage are also presented in Figure 8.

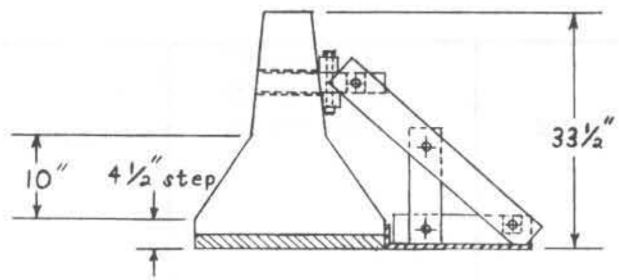
APPURTENANCE	TEST DESIGNATION	VEHICLE TYPE	TARGET IMPACT SPEED (mph)	TARGET IMPACT ANGLE (deg)	TARGET IMPACT SEVERITY (ft-kips)	IMPACT POINT	EVALUATION CRITERIA (NCHRP 230)
Longitudinal Barrier NDOR Bridge Rail Barrier	S13	1800 lb. ±50	60	20	$25^{-2,+4}$	35 ft. from upstream end of barrier	A,D,E,F,H,I

TABLE 1. Crash Test Conditions



0.270 s 0.162 s 0.110 s 0.074 s Impact





TEST NO. NDR-1
DATE 9-20-88
INSTALLATION .... MODIFIED NEW JERSEY SECTION
BARRIER LENGTH .... 100 ft.
VEHICLE
- MODEL .... 1982 HONDA CIVIC
- WEIGHT -
  - TEST INERTIAL ...... 1800 lb.
  - DUMMY .... 165 lb.
  - GROSS .... 1965 lb.

SPEED (mph)
- IMPACT .... 60.0, (88.0 fps)
- EXIT .... 53.4, (78.4 fps)

VEHICLE REBOUND DISTANCE .... 15.0 ft.
ANGLE (degrees)
- IMPACT.............................. 20.9
- EXIT .... < 1.0

OCCUPANT IMPACT VELOCITY (fps)
- LONGITUDINAL 17.2
- LATERAL 17.2

OCCUPANT RIDEDOWN ACCELERATION (g's)
(maximum 10 millisecond average)
- LONGITUDINAL 5.0
- LATERAL 11.0

VEHICLE DAMAGE
- TAD .... 1-RFQ-5, 1-LFQ-3, 1-R&T-1
- VDI 01RFAO1

FIGURE 8. Test Results and Sequential Photographs

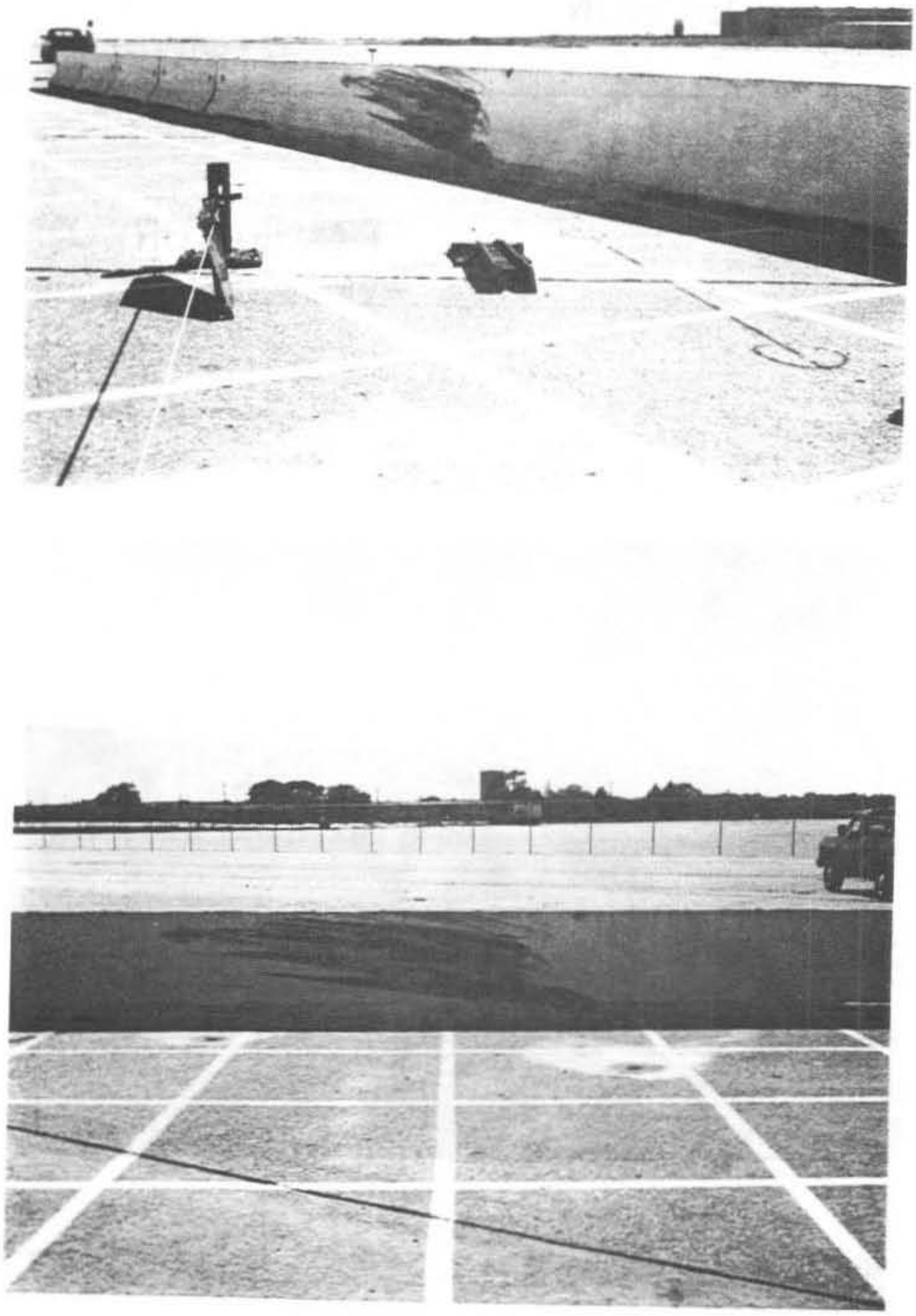


FIGURE 9. Photographs of Barrier Damage

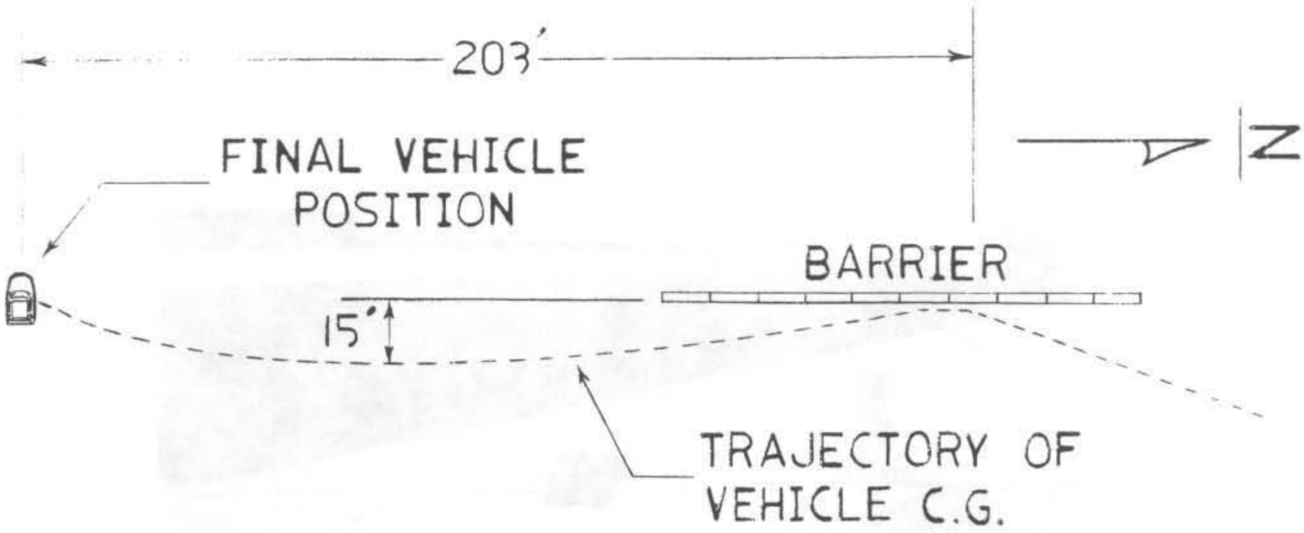


FIGURE 10. Vehicle Trajectory and Final Stopping Position

FIGURE 11. Photographs of Test Vehicle Damage

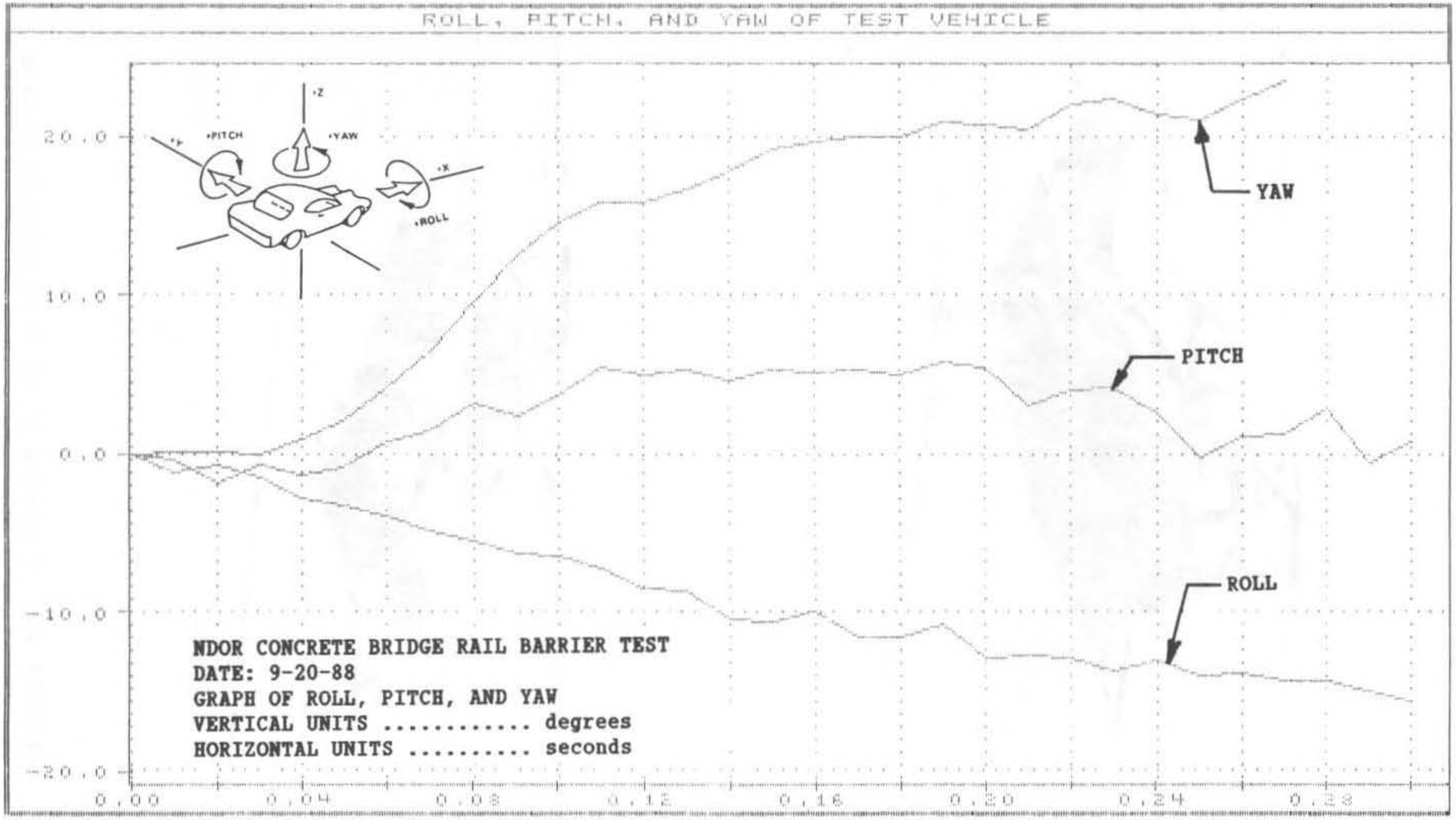


FIGURE 12. Roll, Pitch, and Yaw of Test Vehicle

CONCLUSIONS

A summary of the safety evaluation guidelines, as provided by NCHRP 230 (2) and AASHTO (3) for longitudinal barriers, is given in Tables 2 and 3.

There was no barrier deflection or vehicle snagging during the test and the impact severity was within the allowable limits. Therefore, the results from this test with the constructed surrogate barrier for the Nebraska Bridge Rail Barrier were considered valid. Results of the full-scale crash test revealed the following:

1. Though the change to the New Jersey Barrier face seemed small, raising the slope break point from the standard 13-in. to 14 1/2-in. proved to be unsatisfactory as far as keeping the vehicle upright is concerned. The barrier redirected the vehicle at an exit angle which was satisfactory; however, the lift of the vehicle was excessive. The vehicle lift, along with the roll and yaw motions of the vehicle, caused the vehicle to roll.
2. The occupant impact velocities and occupant ridedown accelerations were satisfactory as well as the all of the evaluation criteria, except the vehicle rollover specifications. This suggests that if the vehicle would have remained upright, it may have been deemed an acceptable bridge rail barrier.

3. The after-impact trajectory of the vehicle showed the vehicle's lateral rebound distance to be 15 ft. The rebound distance was measured from the impact face of the barrier to the side of the vehicle closest to the barrier. This distance of 15 ft. was acceptable according to the AASHTO performance criteria, but was marginal according NCHRP 230.

In summary, it is believed that the increased height of the slope break point was the cause of the rollover motion of the test vehicle. As previous tests have shown, the dynamics of a vehicle impacting a bridge barrier gradually change once the initial step of the barrier exceeds 3-in. The higher the initial step, the more drastic the change and therefore, the less predictable is the vehicle's performance. It is the belief of the University of Nebraska Civil Engineering Department that had the slope break point for the Nebraska Bridge Rail Barrier been designed at the standard height of 13-in., the barrier may have passed. This may have been achieved by decreasing the slope of the lower sloped surface of the barrier face. The University of Nebraska Civil Engineering Department realizes that this suggestion is purely speculative and cannot be proven without confirmation from a full-scale crash test.

Based upon the results of this test, the Nebraska Bridge Rail Barrier with a Modified New Jersey Shape is deemed unacceptable according to NCHRP 230 and AASHTO safety performance guidelines.

Evaluation Criteria	NDOR Test
Part A: Test article shall smoothly redirect the vehicle; the vehicle shall not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.	Satisfactory
Part D: Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	Satisfactory
Part E: The vehicle shall remain upright during and after collision although moderate roll, pitching, and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.	Unsatisfactory
Part F: Impact velocity of hypothetical front seat passenger against vehicle interior, calculated from vehicle accelerations and 24 in. forward and 12 in. lateral displacement, shall be less than: Occupant Impact Velocity - fps Longitudinal / Lateral 30 / 20 and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger impact should be less than: Occupant Ridedown Accelerations - g's Longitudinal / Lateral 15 / 15	Satisfactory
Part H: After collision, vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.	Marginal
Part I: In test where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mph and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device.	Satisfactory

Table 2. NCHRP 230 Criteria For Evaluating Bridge Rail Crash Tests

Evaluation Criteria	NDOR Test
A: The test article shall contain the vehicle; neither the vehicle nor its cargo shall penetrate or go over the installation. Controlled lateral deflection of the test article is acceptable.	Satisfactory
B: Detached elements, fragments, or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	Satisfactory
C: Integrity of the passenger compartment must be maintained with no intrusion and essentially no deformation.	Satisfactory
D: The vehicle shall remain upright during and after collision.	Unsatisfactory
E: The test article shall smoothly redirect the vehicle. A redirection is deemed smooth if the rear of the vehicle does not yaw more than 5 degrees away from the railing from time of impact until the vehicle separates from the railing.	Satisfactory
F: The smoothness of the vehicle-railing interaction is further assessed by the effective coefficient of friction μ; where $\mu = (\cos\theta - V_p/V)/\sin\theta$. μ — Assessment 0.0 - 0.25 — Good 0.26 - 0.35 — Fair > 0.35 — Marginal	Satisfactory 1 μ=0.09
G: The impact velocity of a hypothetical front-seat passenger against the vehicle interior, calculated from vehicle accelerations and 2.0 ft. longitudnal and 1.0 ft. lateral displacements, shall be less than: Occupant Impact Velocity - fps Longitudinal: 30 — Lateral: 25 and for the vehicle highest 10-ms average accelerations subsequent to the instant of hypothetical passenger impact should be less than: Occupant Ridedown Accelerations - g's Longitudinal: 15 — Lateral: 15	Satisfactory
H: Vehicle exit angle from the barrier shall not be more than 12 degrees. Within 100 ft. plus the length of the test vehicle from the point of initial impact with the railing, the railing side of the vehicle shall move no more than 20 ft. from the line of the traffic face of the railing.	Satisfactory

Table 3. ASSHTO Criteria For Evaluating Bridge Rail Crash Tests

REFERENCES

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4. "Vehicle Damage Scale for Traffic Accident Investigators," Traffic Accident Data Project Technical Bulletin No. 1, National Safety Council, Chicago, Ill., 1971.

5. "Collision Deformation Classification, Recommended Practice J224 Mar 80," SAE Handbook Vol. 4, Society of Automotive Engineers, Warrendale, Penn., 1985.

6. Hinch, J., Yang, T-L, and Owings, R., "Guidance Systems for Vehicle Testing," ENSCO, Inc., Springfield, VA, 1986.

APPENDICES

Appendix A. Test Facility

1. Test Site

The location of the test site, with respect to the Lincoln Municipal Airport is shown in Figure A1. An 8 ft. high chain-linked fence surrounds the facility to ensure security for the test article and any test equipment that is setup and left on the facility grounds.

2. Vehicle Tow System

A reverse cable tow system, with a 1:2 mechanical advantage, was used to propel the test vehicle. Using this tow system allows the tow vehicle to travel half the distance at half the speed than that of the test vehicle. A sketch of the cable tow system is shown in Figure A2. The test vehicle was released from the tow cable approximately 10 ft. before impact with the Nebraska Bridge Rail Barrier. Photographs of the tow vehicle and the attached fifth-wheel are shown in Figure A3. The fifth-wheel, built by Nucleus Corporation, was used for accurately towing the test vehicle at the required target speed with the aid of a digital speedometer in the tow vehicle.

3. Vehicle Guidance System

A vehicle guidance system, developed by Hinch (6), was used to steer the test vehicle. A sketch of the guidance system is shown in Figure A2, while photographs of the guidance system before and after impact are shown in Figure A4. The guide flag was attached to the front left wheel of the test vehicle and was sheared off (at the distances stated above) before impact with the Nebraska Barrier. The 3/8 in. diameter cable was tensioned to 3,000 lbs., and was supported laterally and vertically every 100 ft. by hinged stanchions which stood upright while holding up the guide cable. When the vehicle passed, the guide flag struck each stanchion and knocked it to the ground. The vehicle guidance system was approximately 1,000 ft. in length.

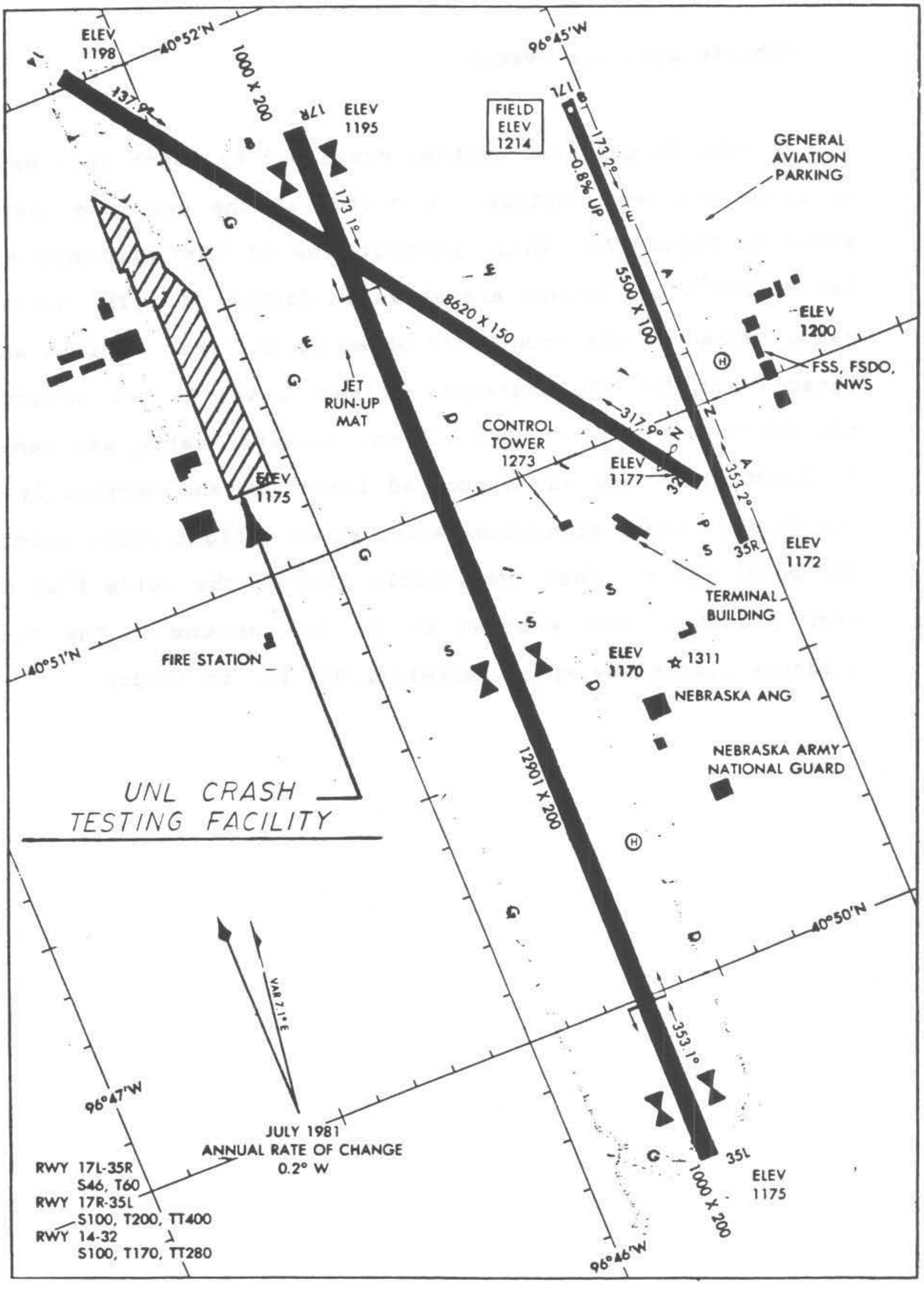


FIGURE A1. Full-Scale Vehicle Crash Testing Facility

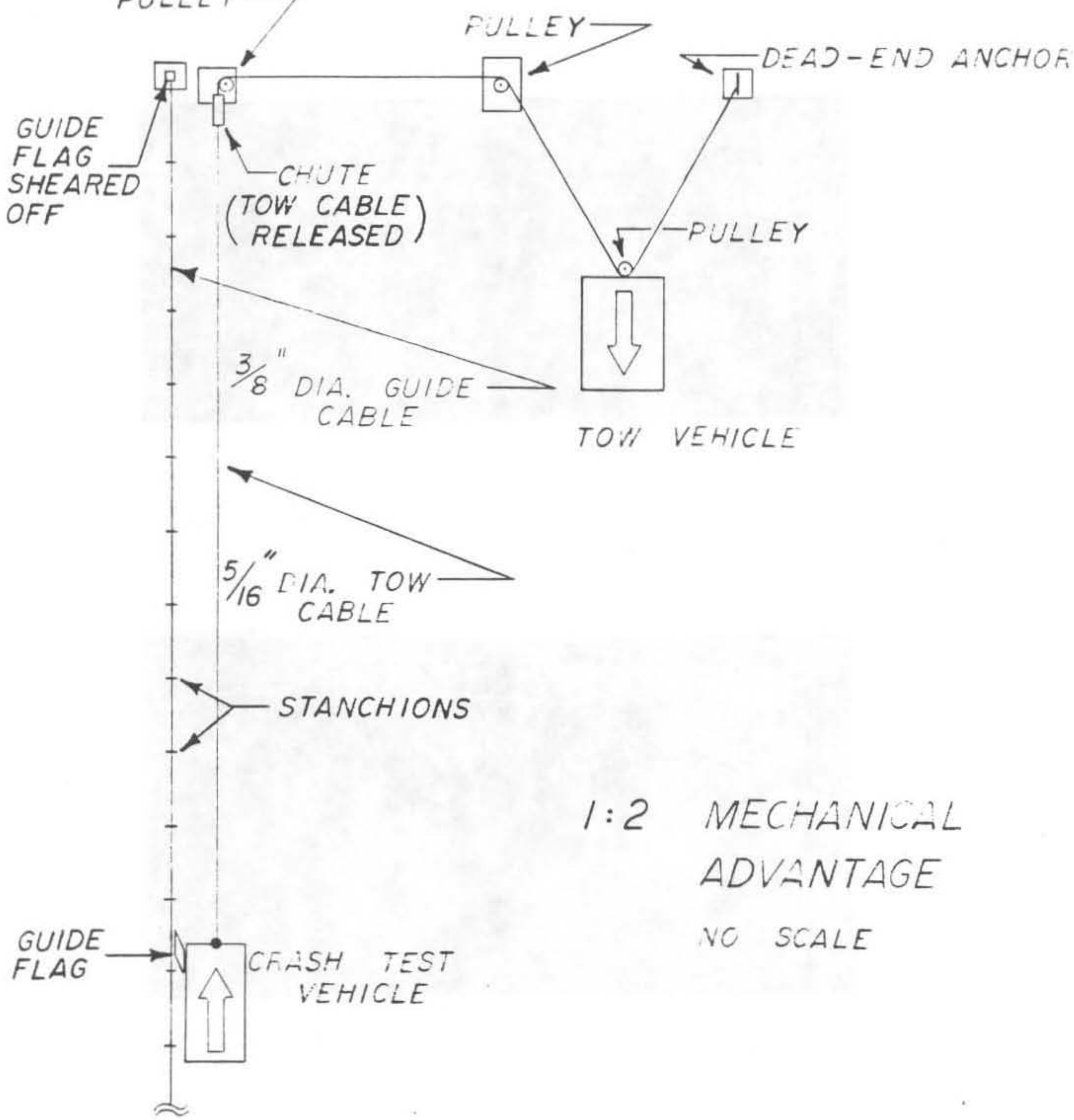


FIGURE A2. Sketch of Tow and Guidance Systems

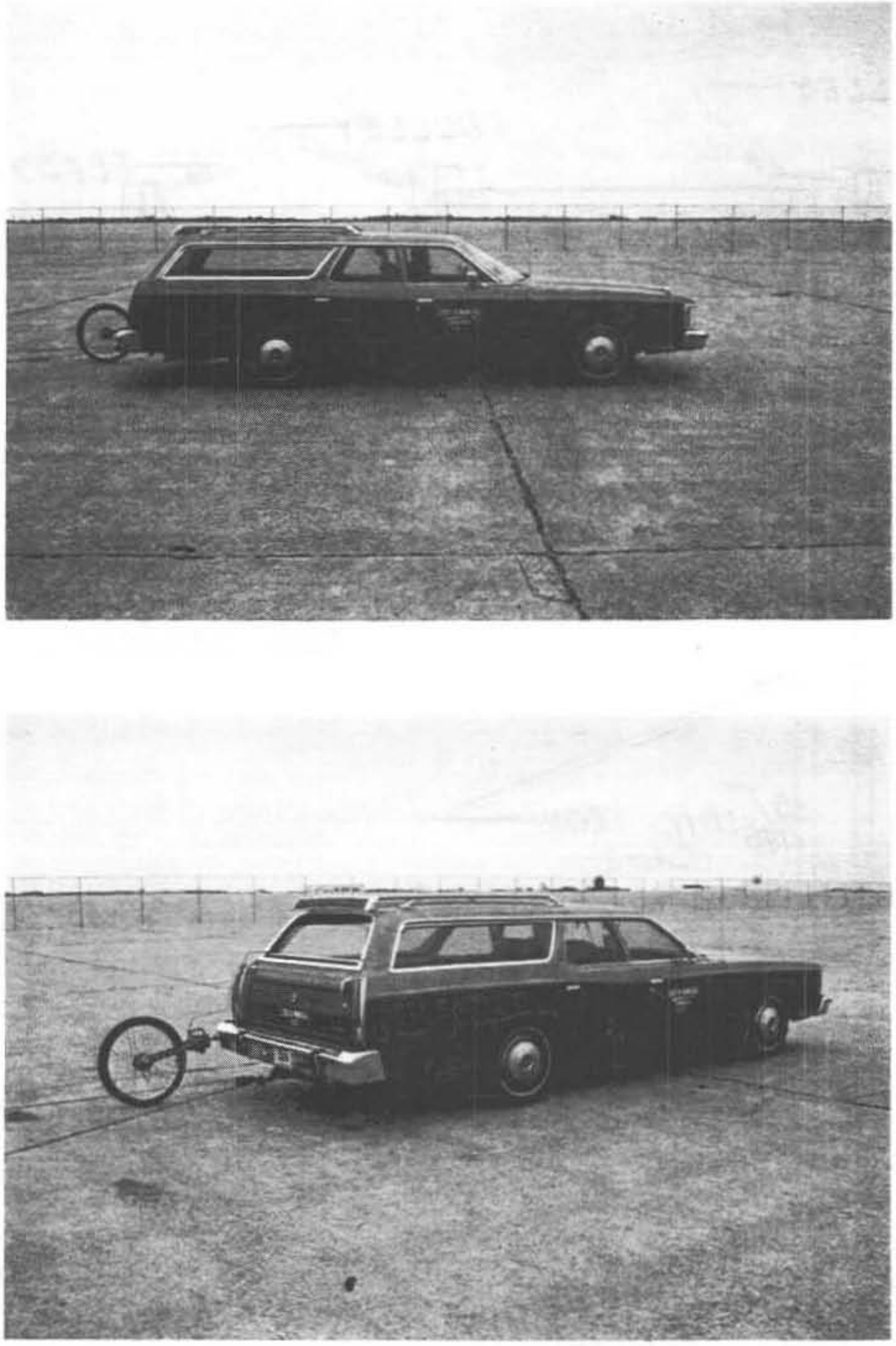
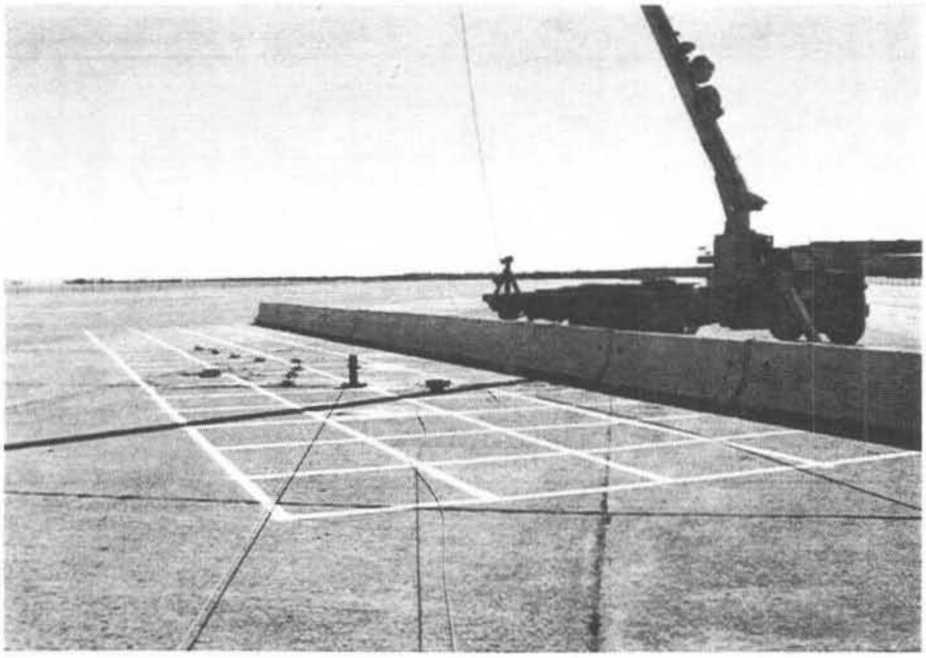


FIGURE A3. Photographs of Tow Vehicle with Fifth-Wheel



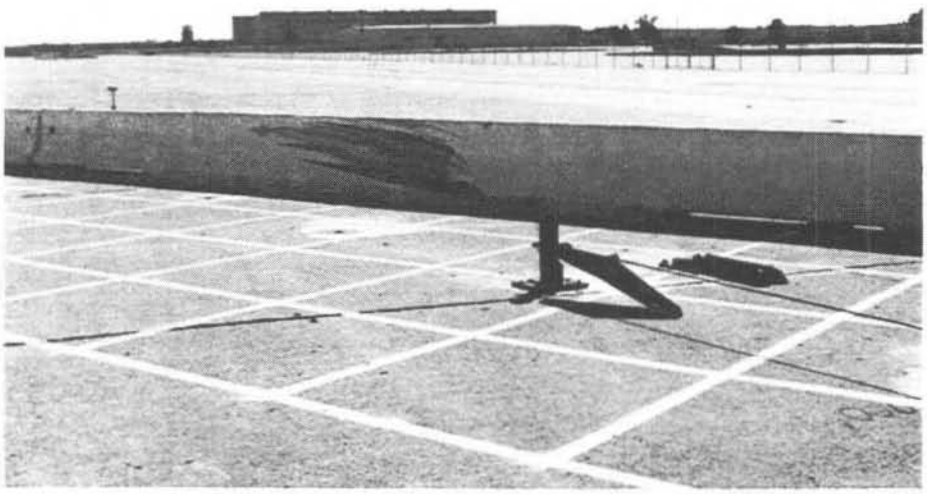


FIGURE A4. Photographs of Vehicle Guidance System

Appendix B. Data Acquisition Systems

1. Accelerometers

Endevco triaxial piezoresistive accelerometers (Model 7264) with a range of 200 g's were used to measure the accelerations in the longitudinal, lateral, and vertical directions of the test vehicle. The accelerometers were rigidly attached to metal blocks mounted at the center of mass and at the rear of the test vehicle. A photograph of the accelerometers mounted in the test vehicle is shown at the top of Figure B1, while Figure B2 shows a schematic of the accelerometer locations. The signals from the accelerometers were received and conditioned by an onboard vehicle Metraplex unit shown at the bottom of Figure B1. The multiplexed signal was then sent through a single coaxial cable to the Honeywell (101) Analog Tape Recorder in the central control van. Photographs of the system located in the centrally controlled step-van are shown in Figures B3 and B4, and a flowchart of the accelerometer data aquisition system is shown in Figure B5. The latest state-of-the-art computer software, 'Computerscope' and 'DSP' was used to analyze and plot the accelerometer data on a Cyclone 386/AT, which uses a very high speed data aquisition board.

2. High-Speed Photography

Three high-speed 16mm cameras were used to film the crash tests. The cameras ran at approximately 500 frames per second. The overhead camera was a Red Lake Locam with a wide angle 12.5 millimeter lens. It was placed 50 ft. above the concrete apron over the point of impact. The perpendicular camera was a Photec IV with a 55 millimeter lens and was located 165 ft. from the vehicle point of impact. The parallel upstream camera was also a Photec IV with a 80 millimeter lens. It was located 185 ft. upstream from the point of impact and was in line with the barriers front face. A schematic of the camera layouts is shown in Figure B6.

A 100 ft. long by 20 ft. wide grid layout was painted on the concrete slab in front of the barrier. The white grid was incremented with 5 ft. divisions to produce a visible reference system which could be used in the analysis of the overhead high-speed film.

3. Speed Trap Switches

Eight tape pressure switches spaced at 5 ft. intervals were used to determine the speed of the vehicle before and after impact. Each tape switch fired a blue 5B flashbulb located near each switch on the concrete slab as the left front tire of the test vehicle passed over it. The average speed of the test vehicle between the tape switches was determined by knowing the distance between the tape switches, the calibrated camera speed, and the number of frames, from the high-speed film, between flashes. In addition, the average speed was determined from electronic timing mark data recorded on the oscilloscope software used with the 386/AT computer as the test vehicle passed over each tape switch.

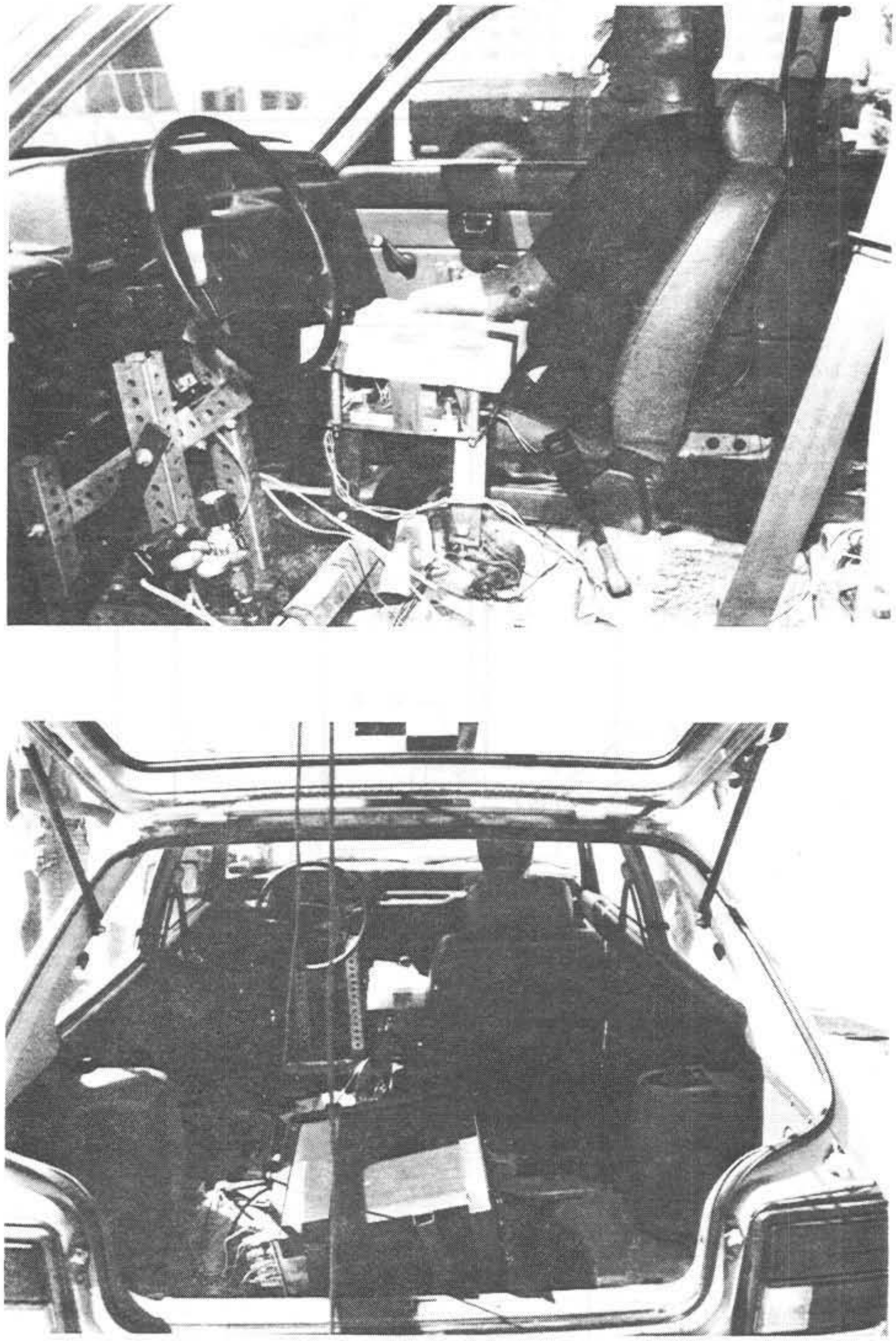


FIGURE B1. Photographs of Onboard Data Acquisition System

Accel. No.	Serial No.	Calibr. Factor
No. 1	AE46	3.217 mV/g
No. 2	BP24H	2.125 mV/g
No. 3	AM44	2.640 mV/g
No. 4	BR47H	2.224 mV/g
No. 5	BJ62H	2.438 mV/g
No. 6	BF57H	2.546 mV/g

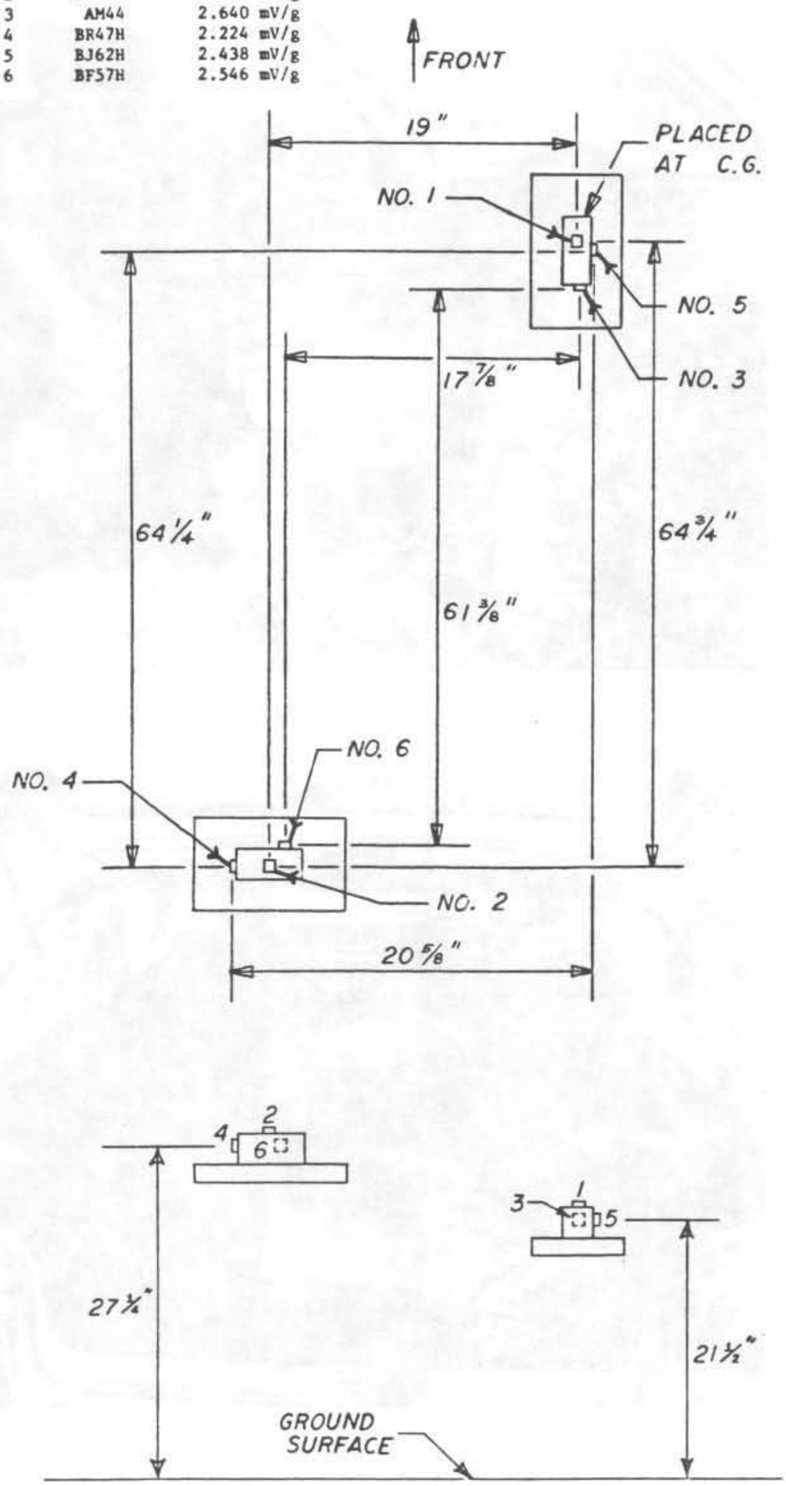
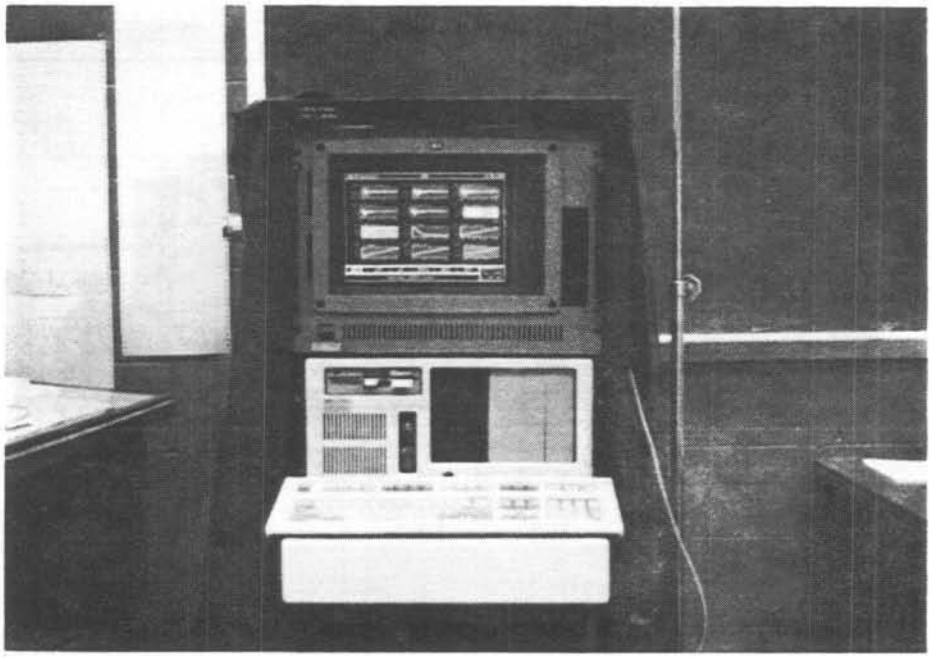


FIGURE B2. Schematic of Accelerometer Locations in Vehicle

FIGURE B3. Photographs of Central Control Van



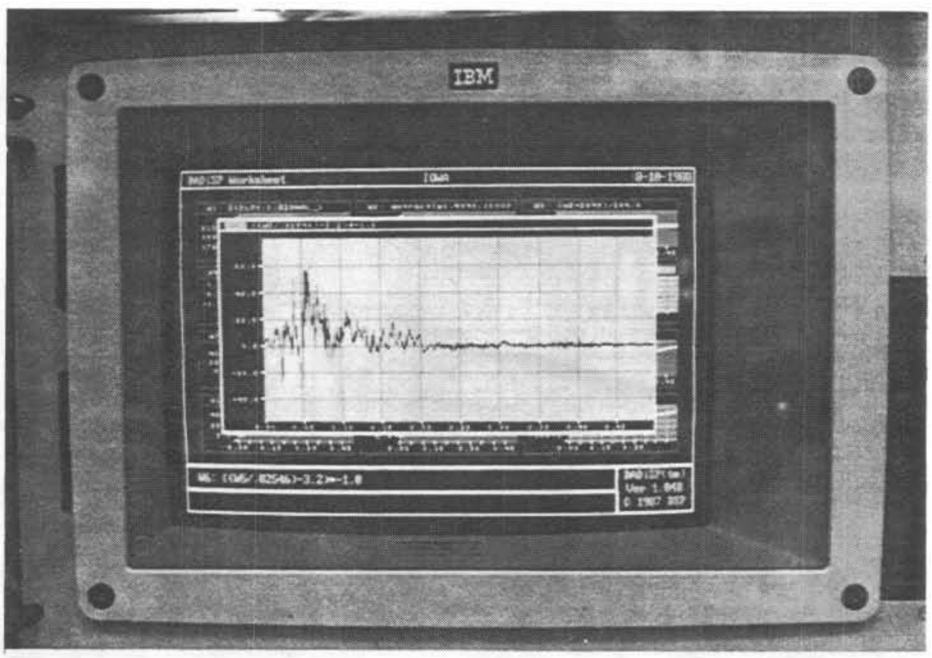


FIGURE B4. Photographs of 386/AT Computer and Computer Software

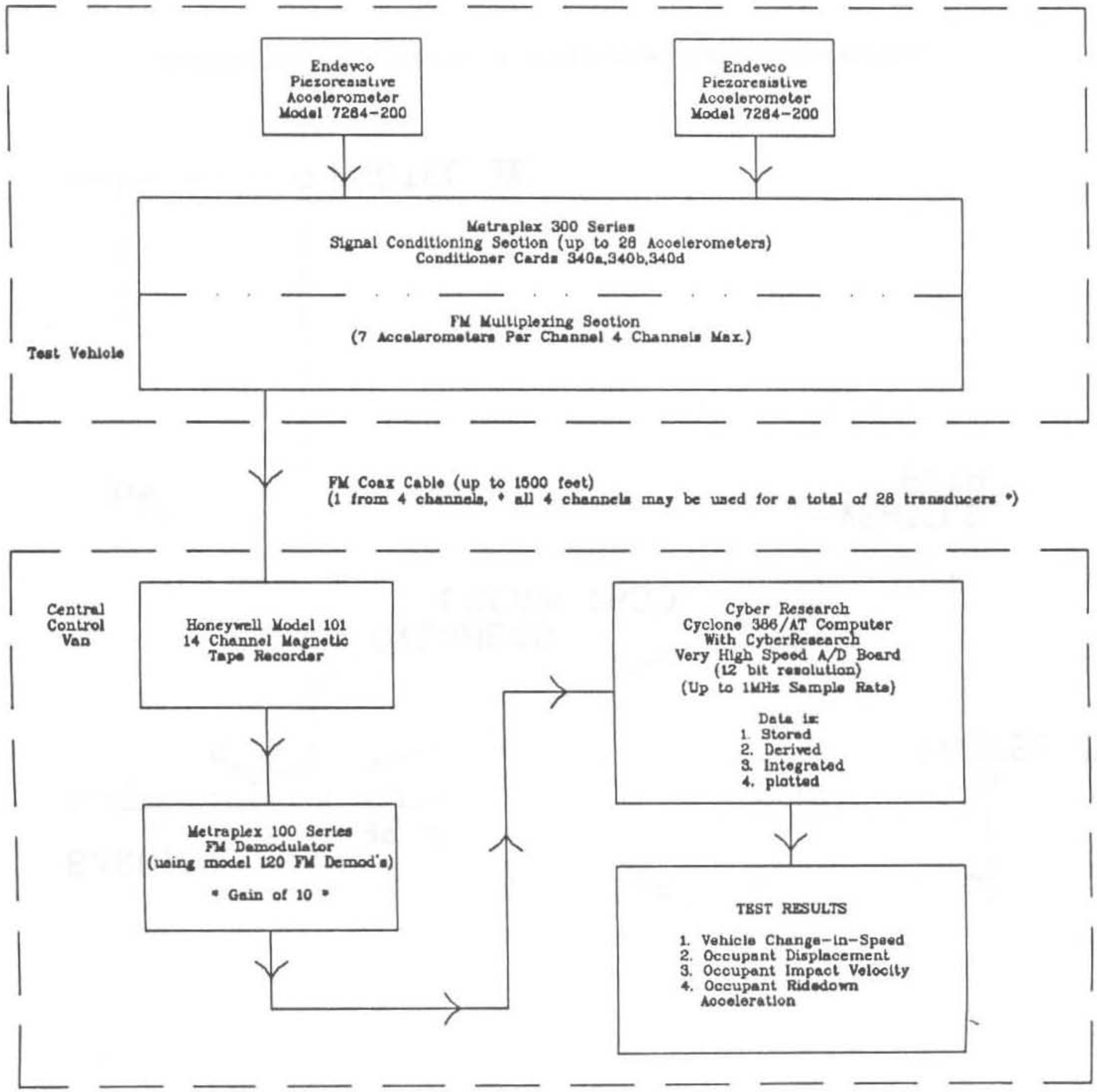


FIGURE B5. Flowchart of Accelerometer Data Acuisition System

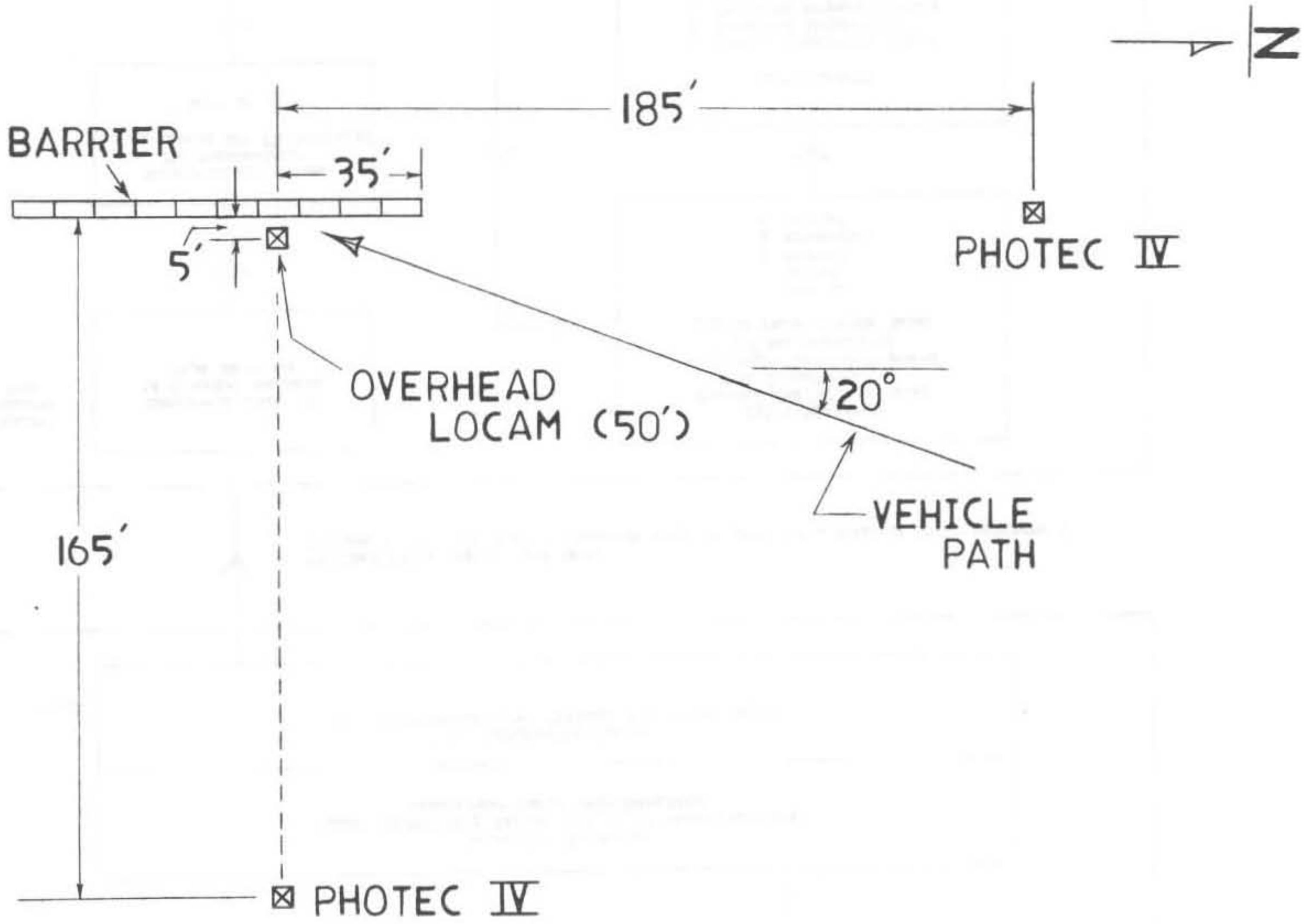
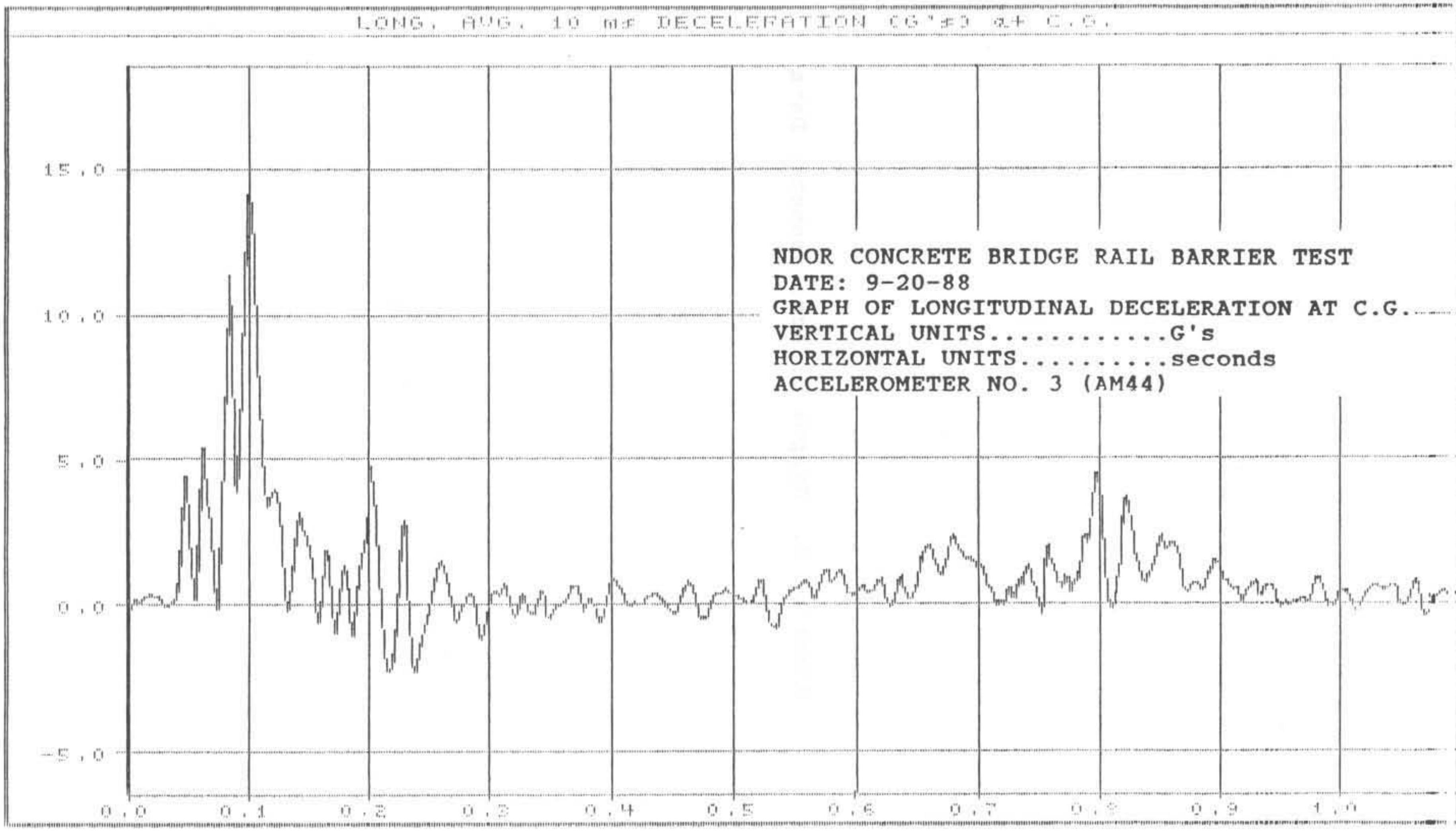
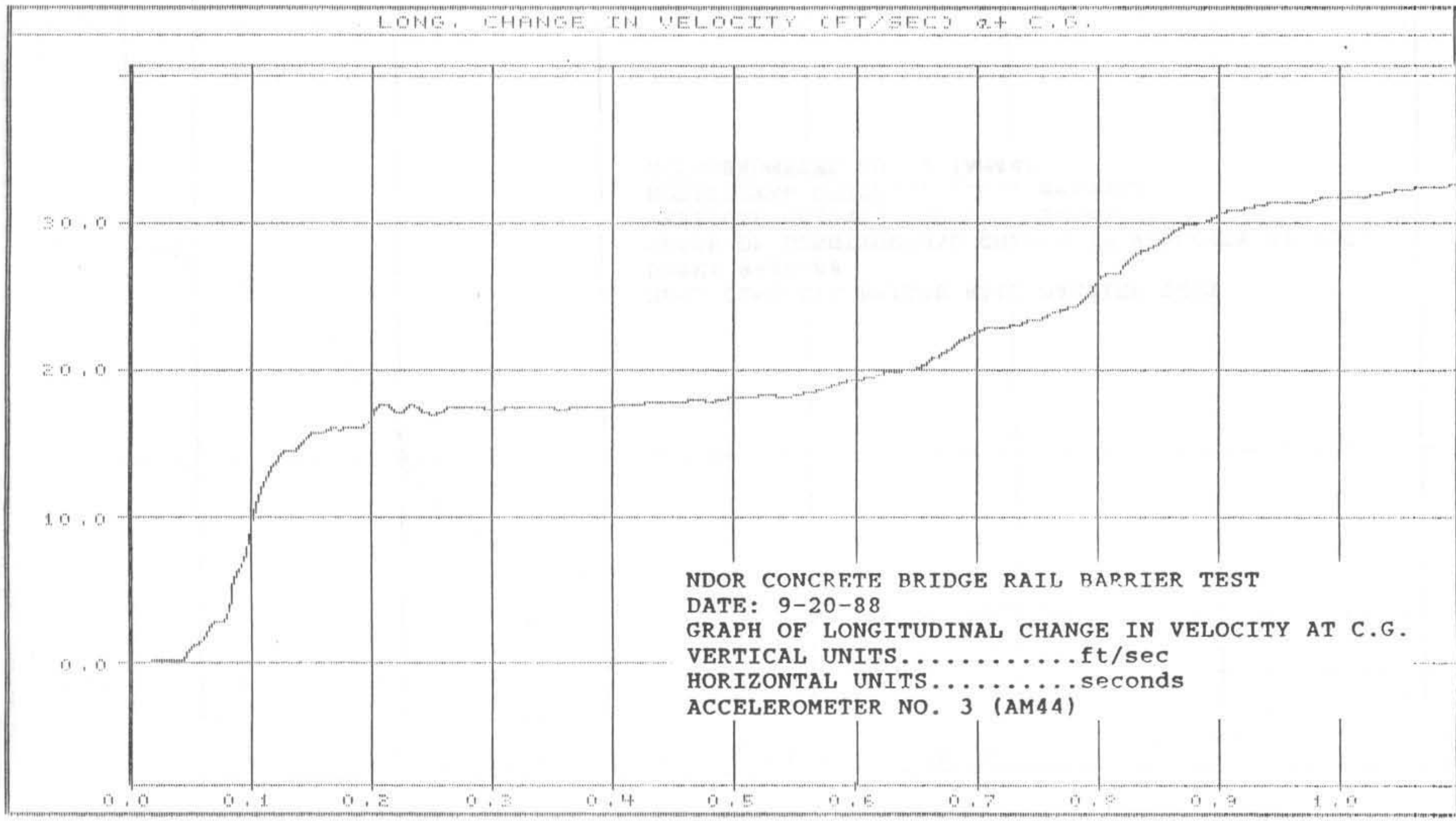


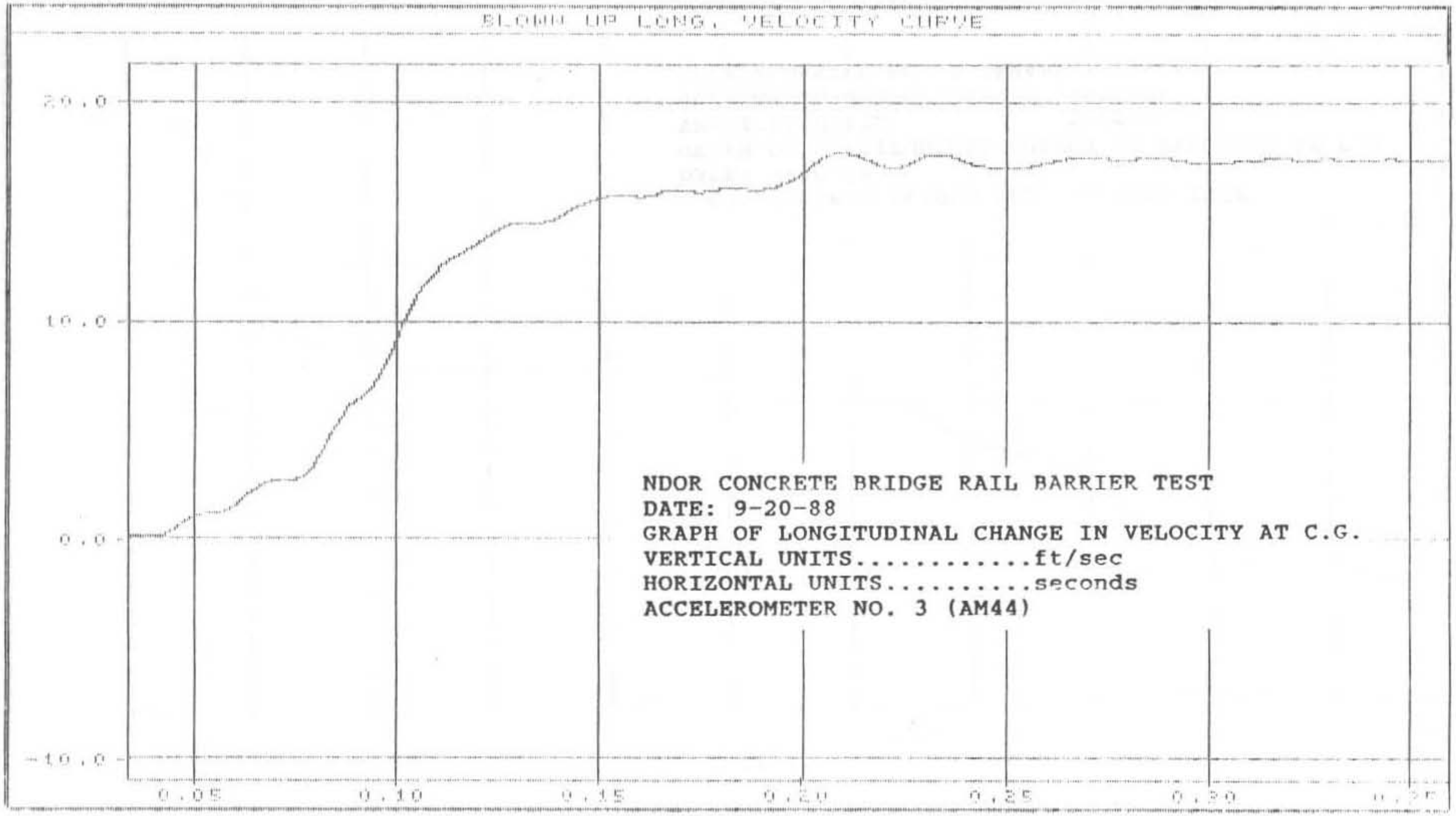
FIGURE B6. Schematic of High-Speed Camera Locations

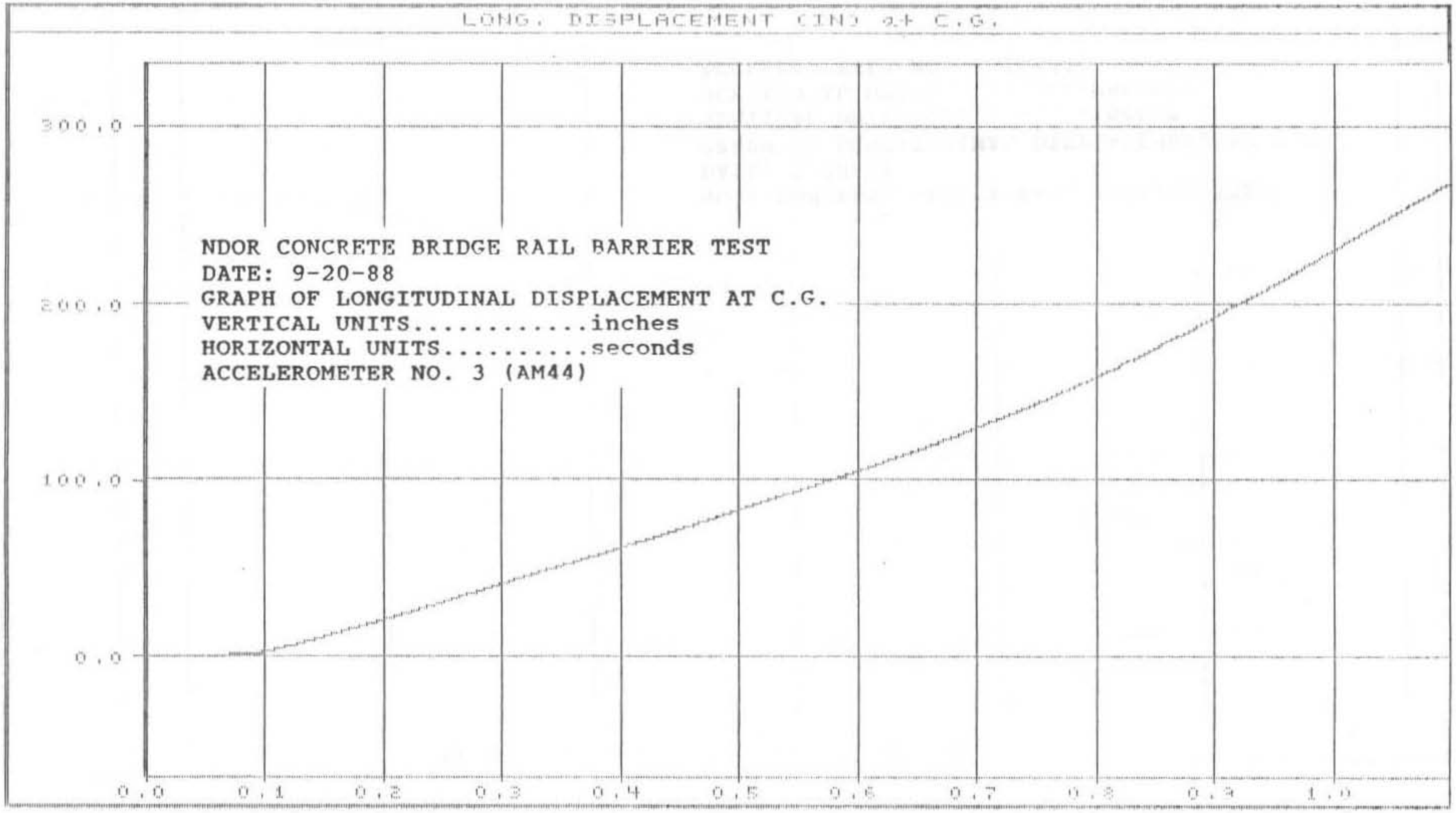
Appendix C. Graphs of Accelerometer Data

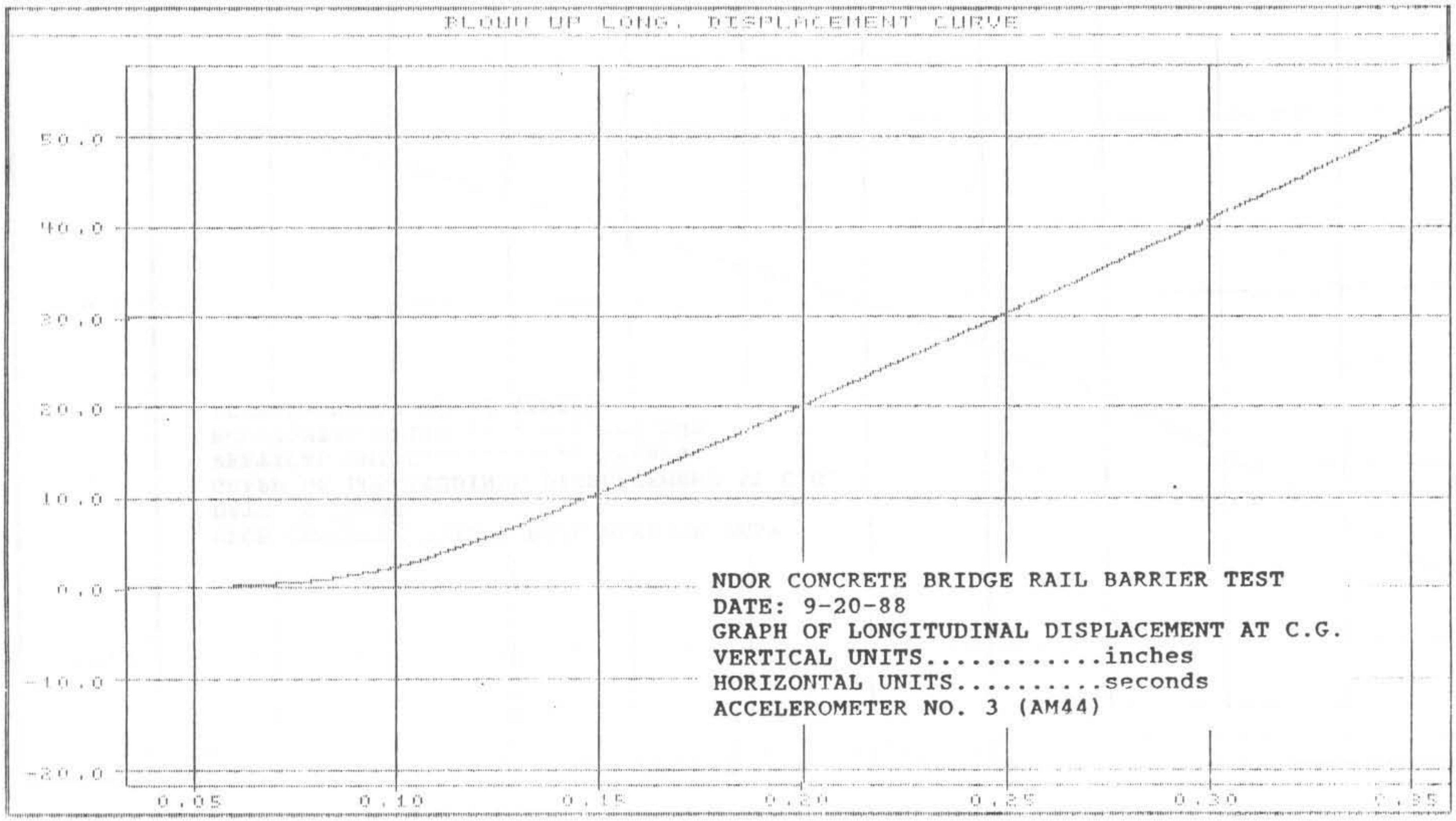


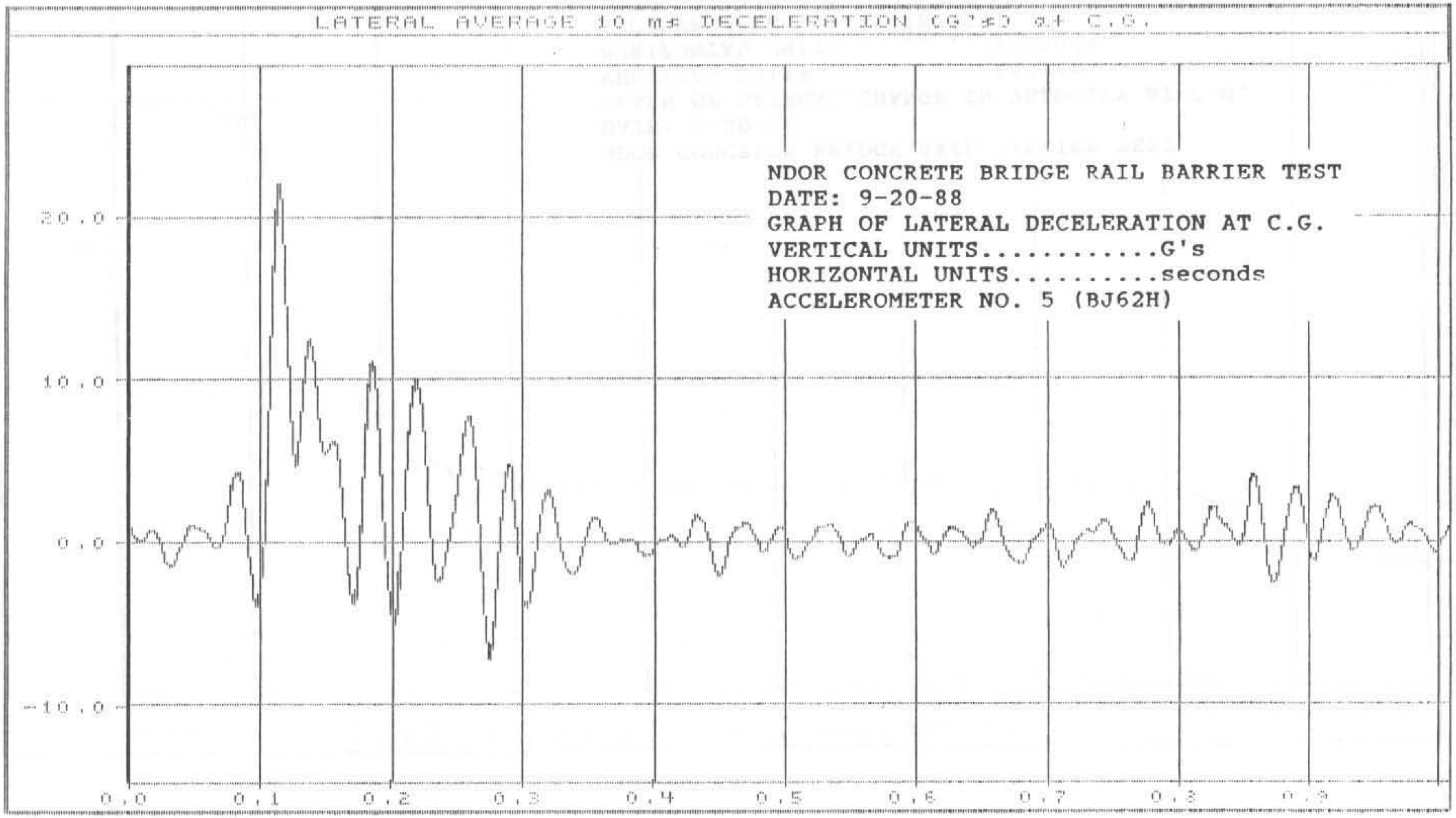
LONG. AVG. 10 ms DECELERATION (G's) at C.G.
15.0
10.0
5.0
0.0
-5.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL DECELERATION AT C.G.
VERTICAL UNITS............G's
HORIZONTAL UNITS.........seconds
ACCELEROMETER NO. 3 (AM44)

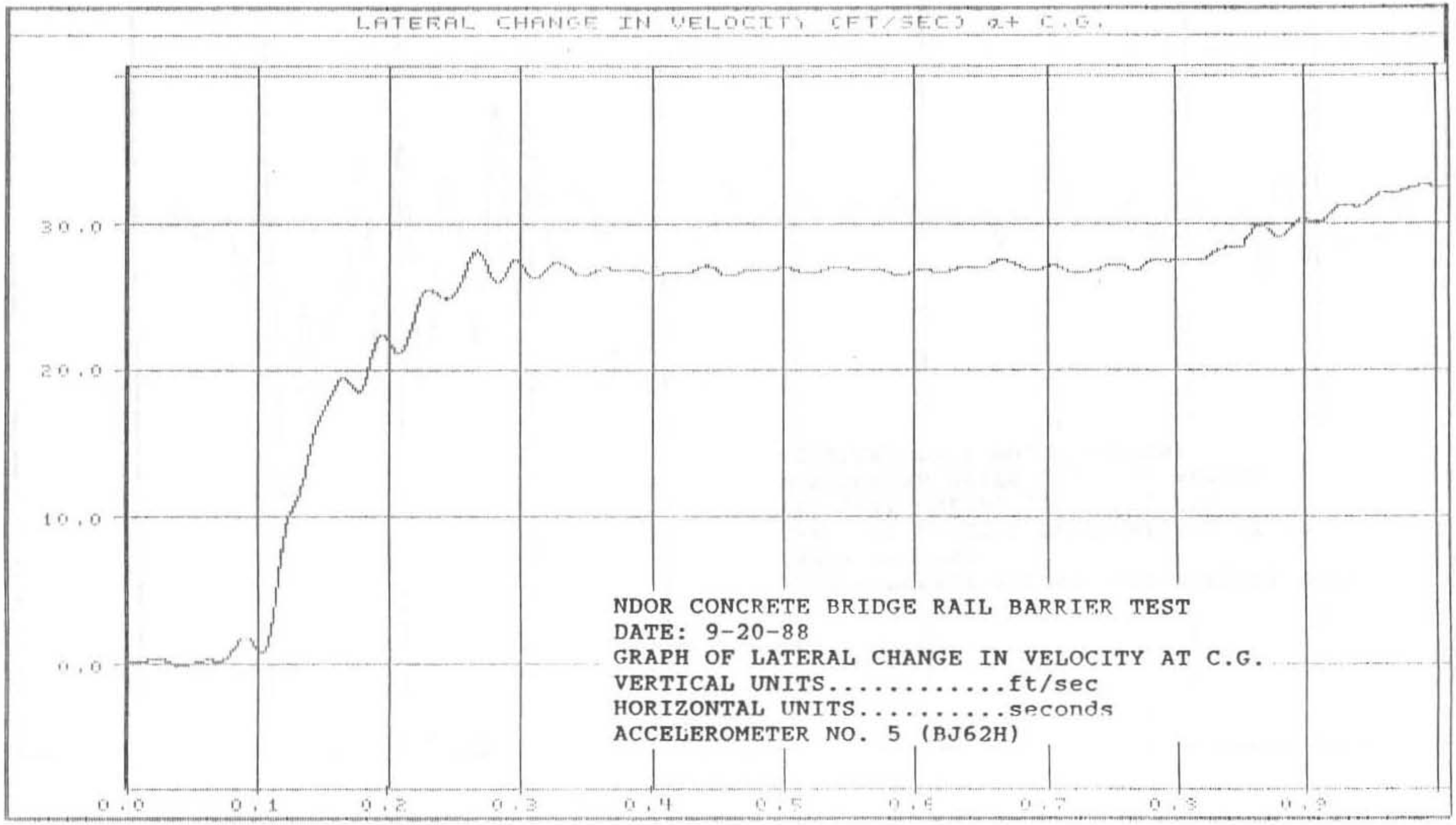

LONG. CHANGE IN VELOCITY (FT/SEC) at C.G.
30.0
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL CHANGE IN VELOCITY AT C.G.
VERTICAL UNITS............ft/sec
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 3 (AM44)

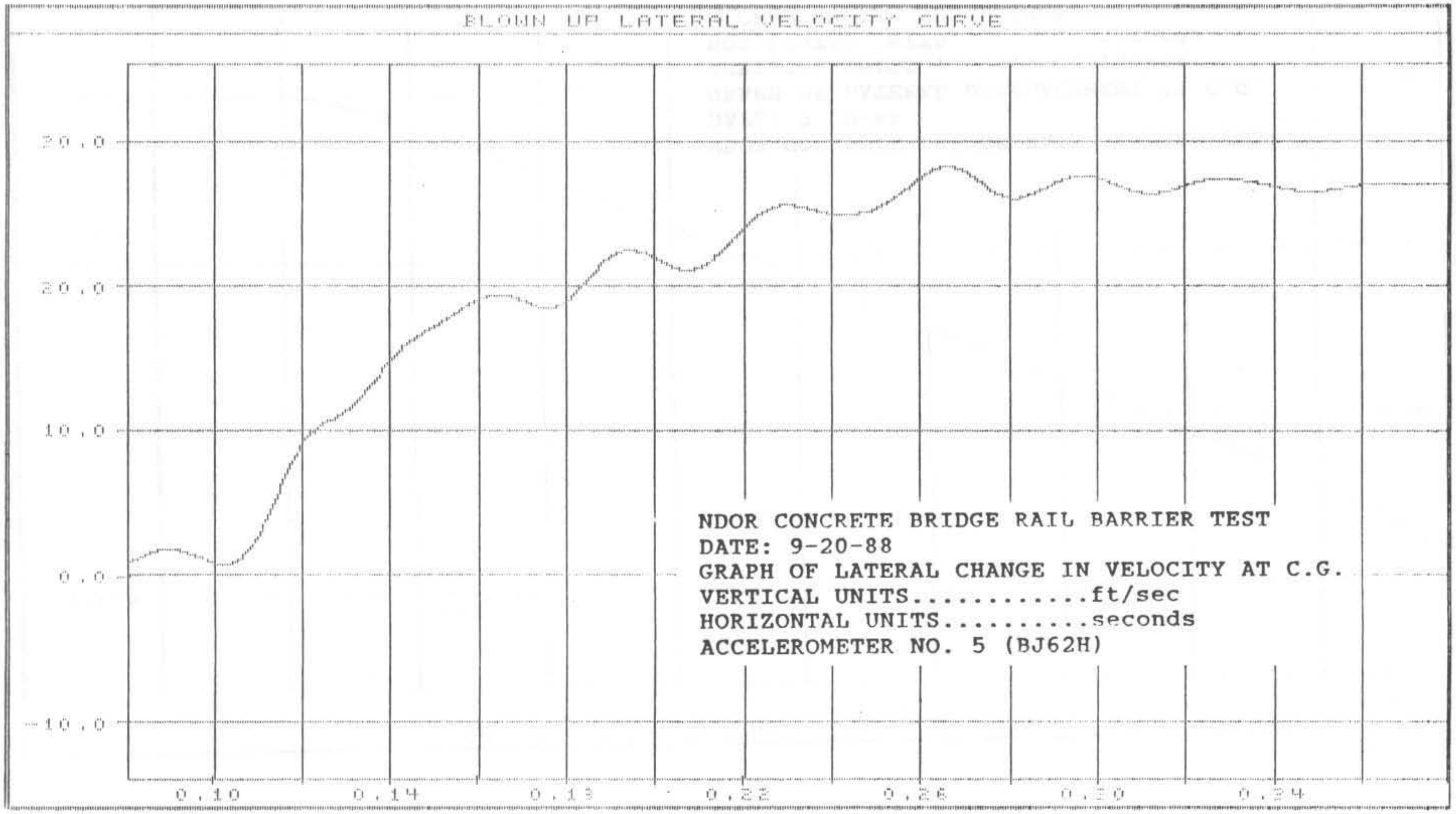

BLOWN UP LONG. VELOCITY CURVE
20.0
10.0
0.0
-10.0
0.05
0.10
0.15
0.20
0.25
0.30
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL CHANGE IN VELOCITY AT C.G.
VERTICAL UNITS............ft/sec
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 3 (AM44)

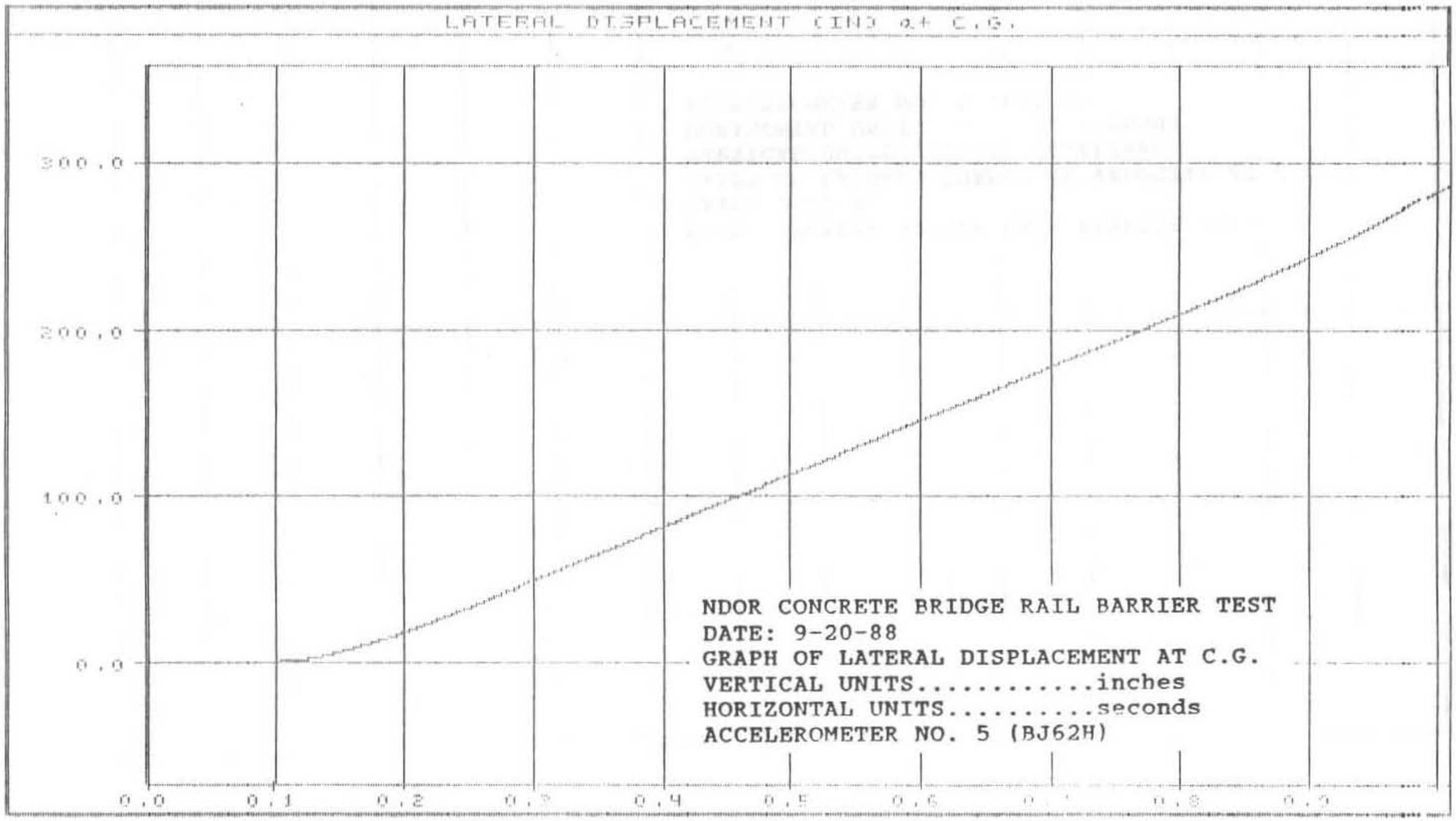

LONG. DISPLACEMENT (IN) at C.G.
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL DISPLACEMENT AT C.G.
VERTICAL UNITS............inches
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 3 (AM44)
300.0
200.0
100.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


BLOWN UP LONG. DISPLACEMENT CURVE
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL DISPLACEMENT AT C.G.
VERTICAL UNITS...........inches
HORIZONTAL UNITS.........seconds
ACCELEROMETER NO. 3 (AM44)

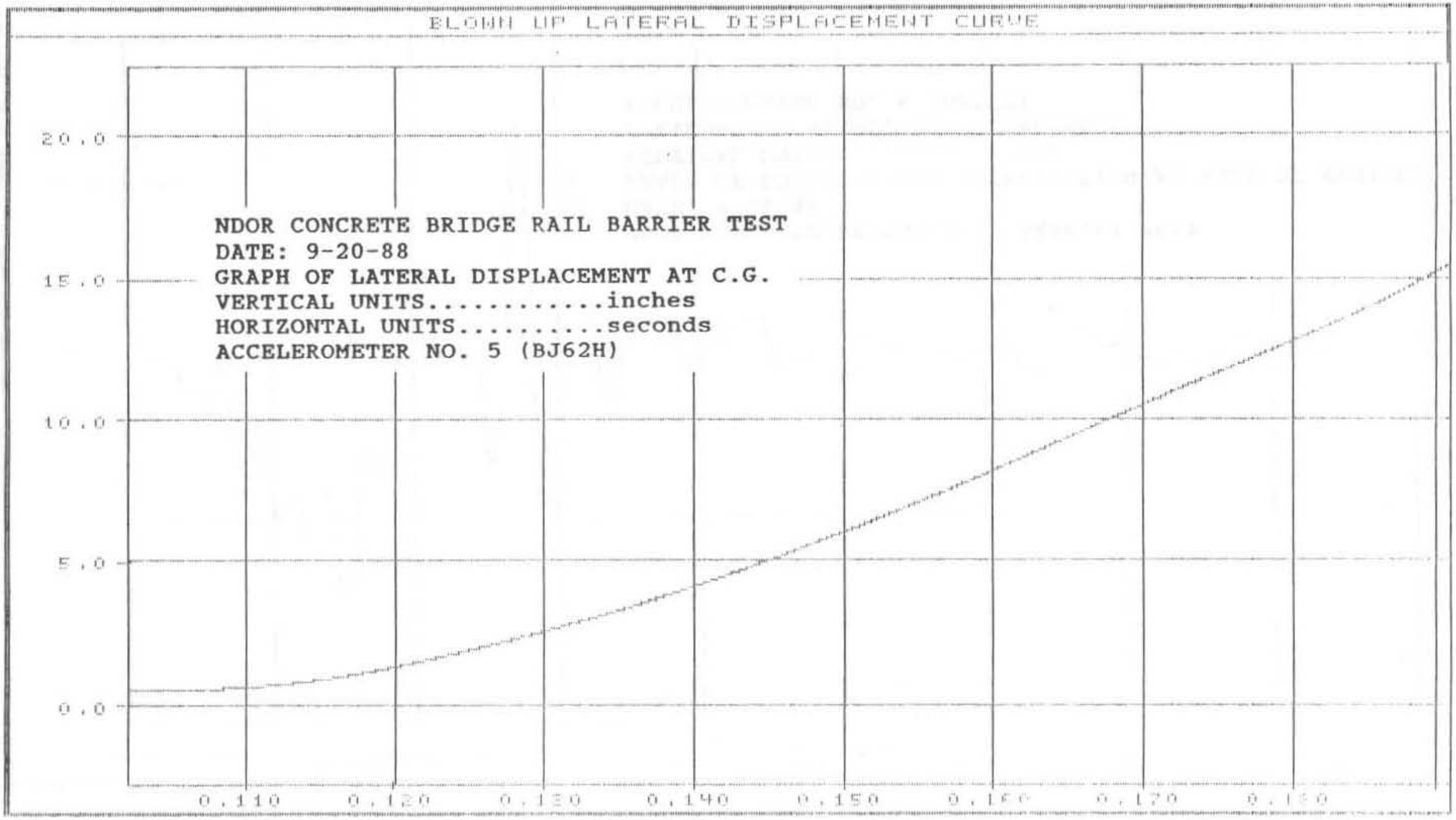

LATERAL AVERAGE 10 ms DECELERATION (G's) at C.G.
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL DECELERATION AT C.G.
VERTICAL UNITS............G's
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 5 (BJ62H)
20.0
10.0
0.0
-10.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

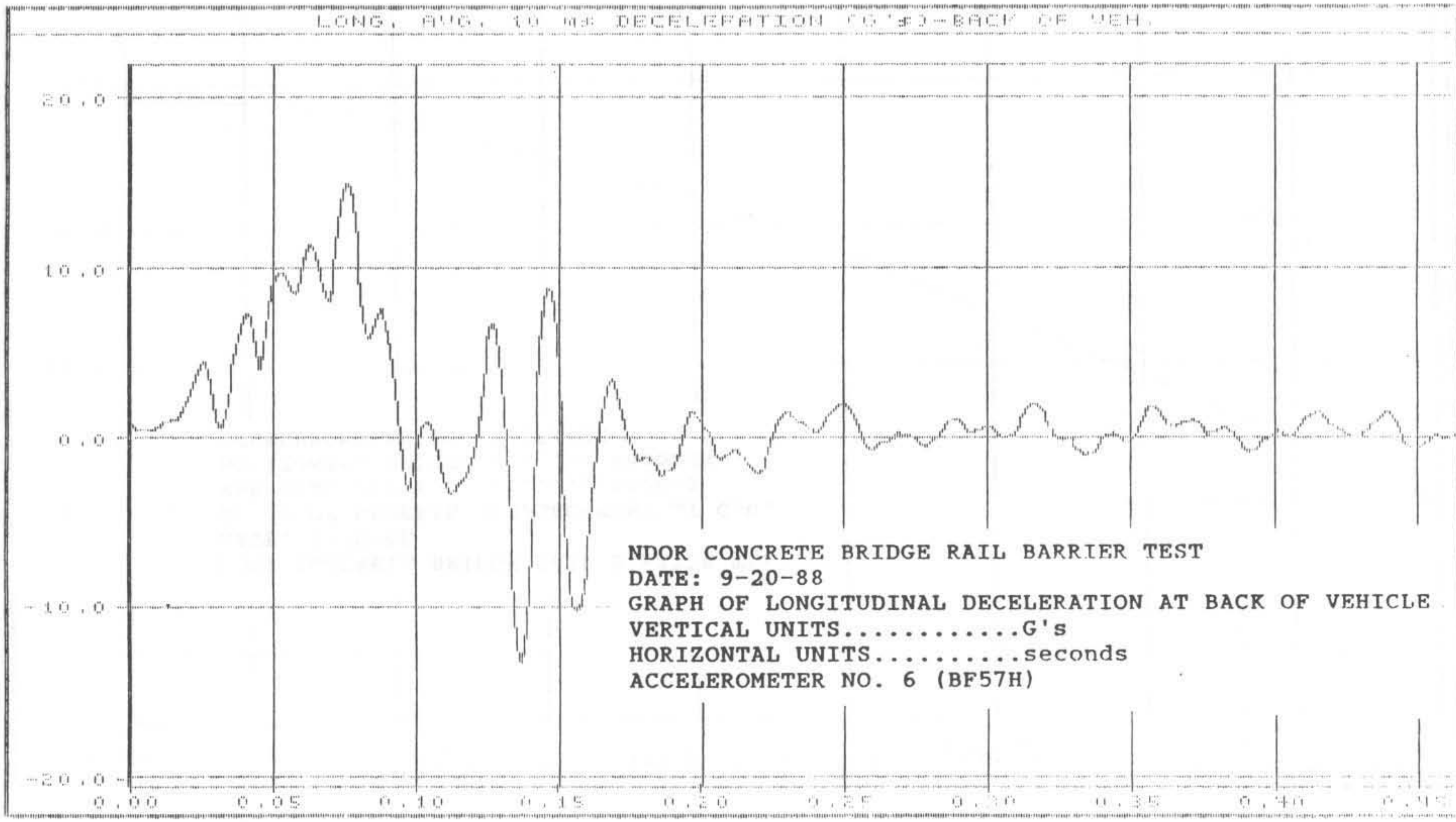

LATERAL CHANGE IN VELOCITY (FT/SEC) at C.G.
30.0
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL CHANGE IN VELOCITY AT C.G.
VERTICAL UNITS...........ft/sec
HORIZONTAL UNITS.........seconds
ACCELEROMETER NO. 5 (BJ62H)

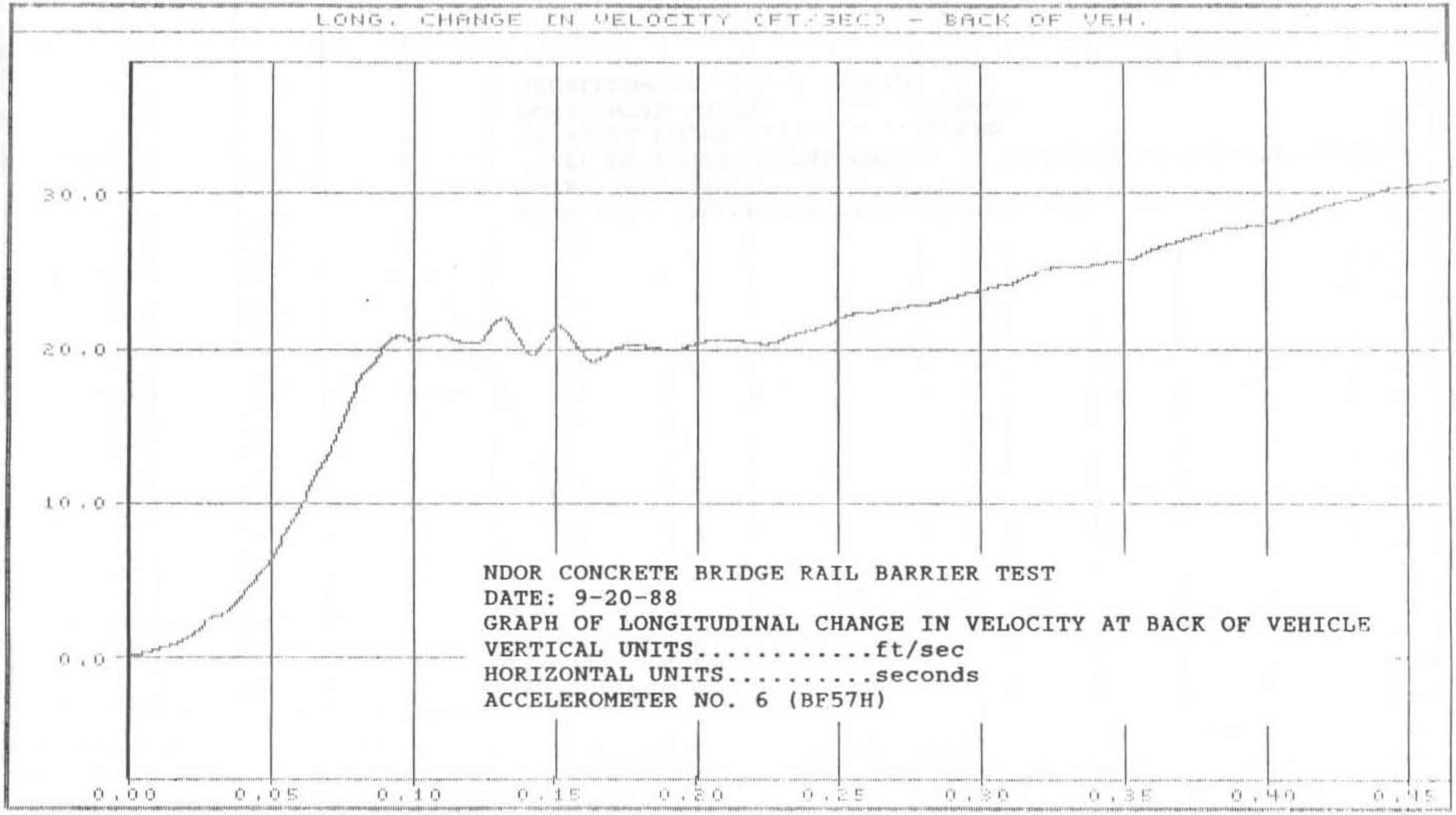

BLOWN UP LATERAL VELOCITY CURVE
30.0
20.0
10.0
0.0
-10.0
0.10
0.14
0.18
0.22
0.26
0.30
0.34
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL CHANGE IN VELOCITY AT C.G.
VERTICAL UNITS...........ft/sec
HORIZONTAL UNITS.........seconds
ACCELEROMETER NO. 5 (BJ62H)

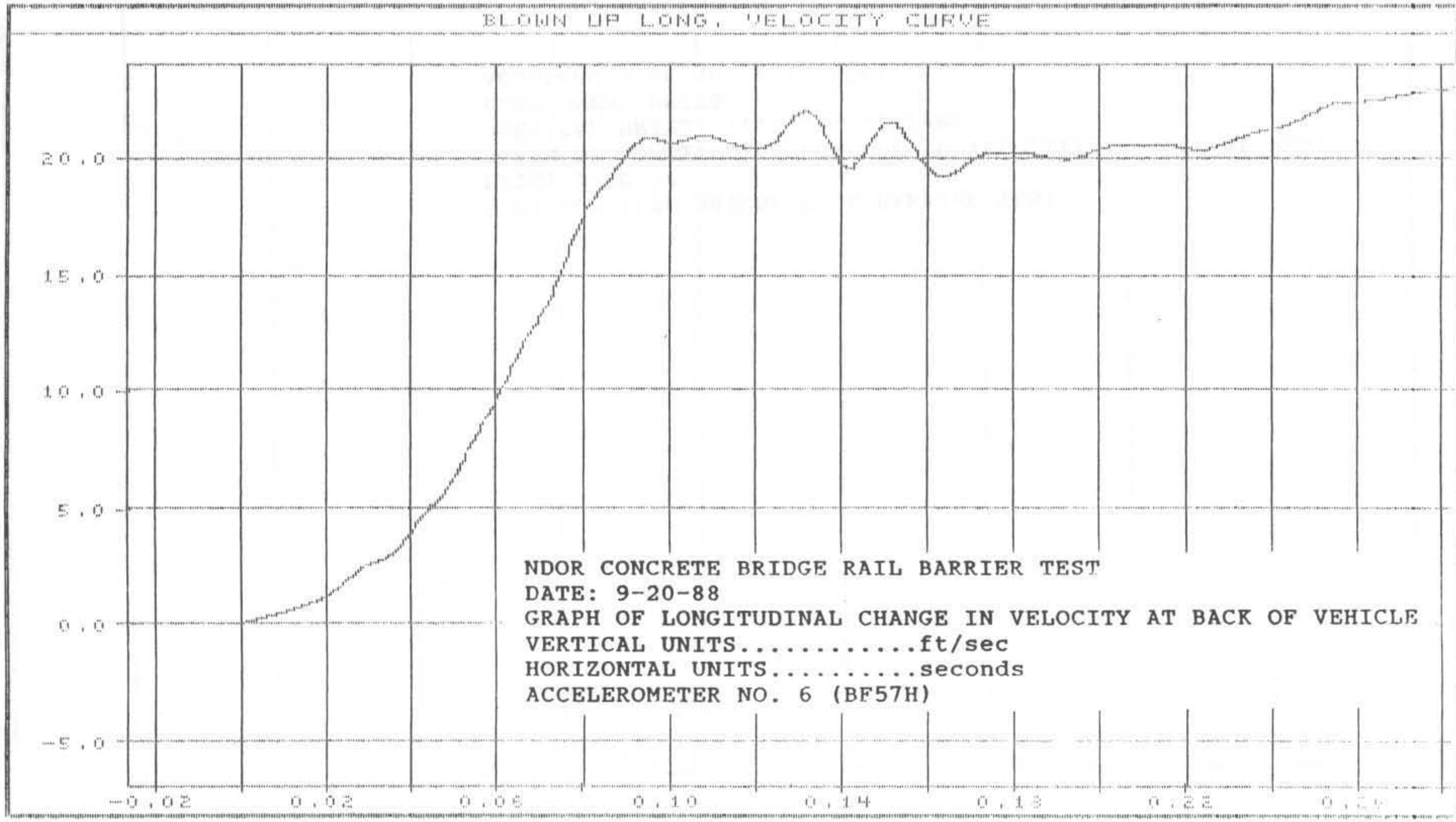


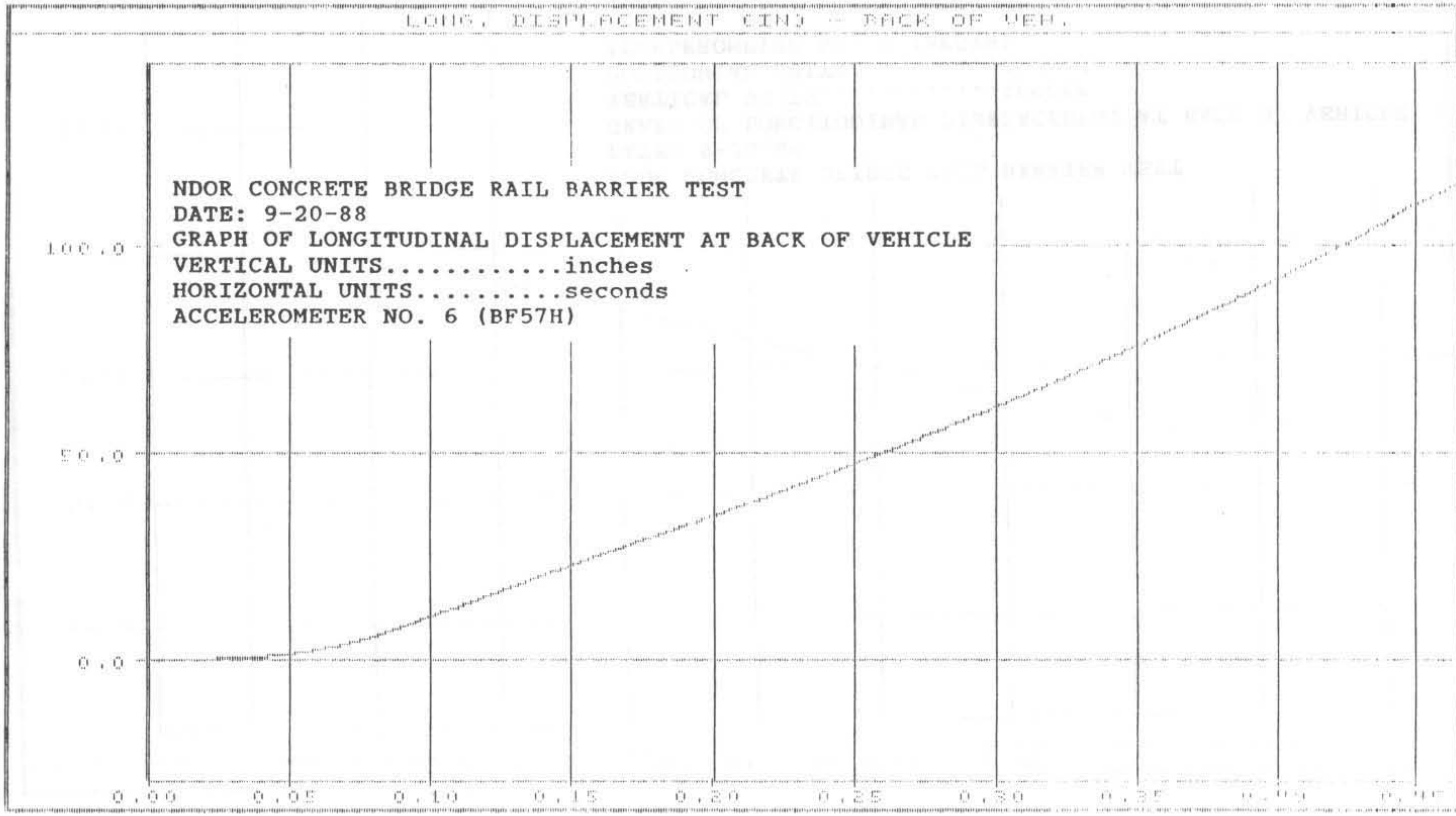
LATERAL DISPLACEMENT (IN) at C.G.
300.0
200.0
100.0
0.0
0.0
0.1
0.2
0.4
0.5
0.6
0.8
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL DISPLACEMENT AT C.G.
VERTICAL UNITS............inches
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 5 (BJ62H)

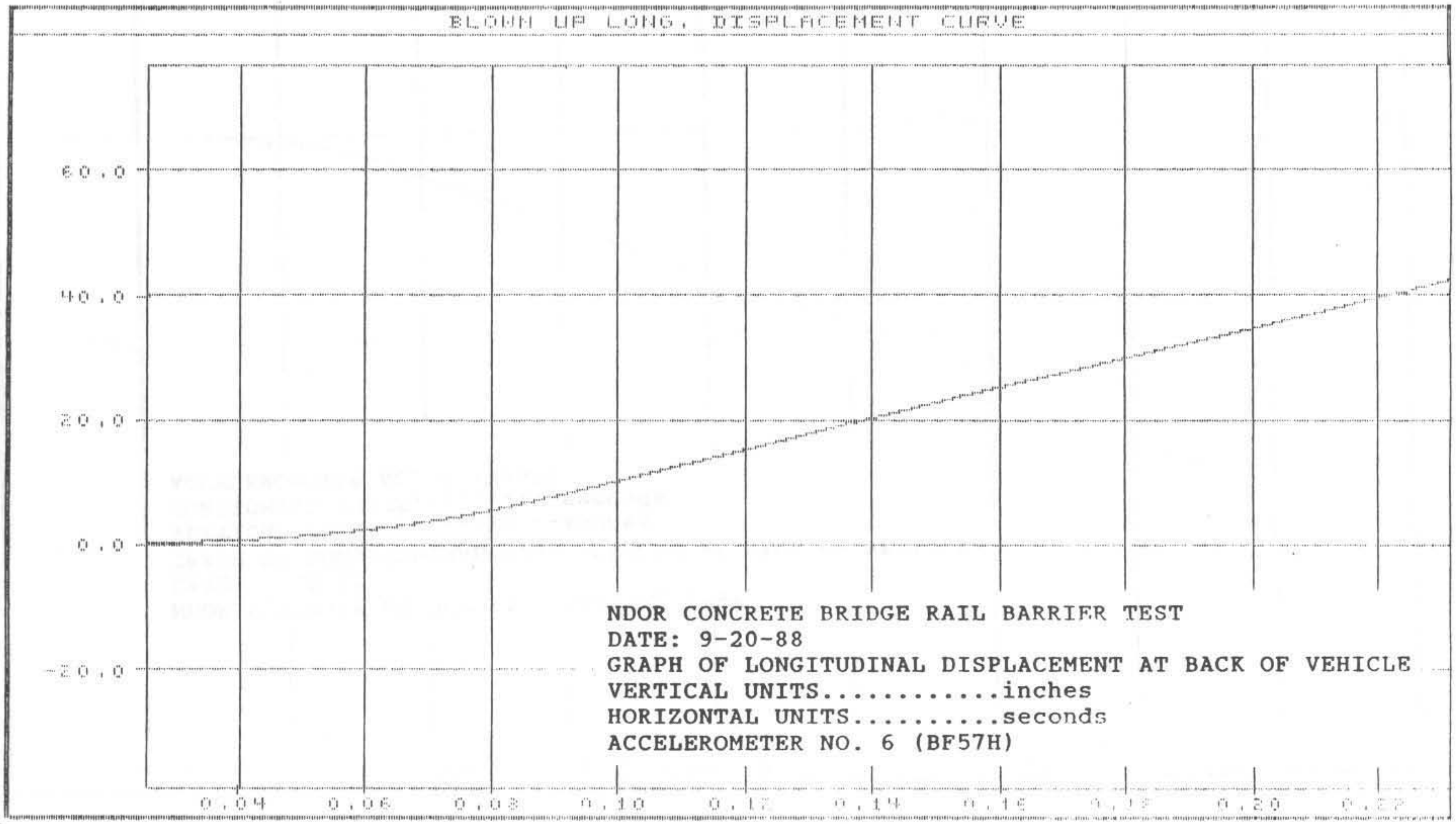

BLOWN UP LATERAL DISPLACEMENT CURVE
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL DISPLACEMENT AT C.G.
VERTICAL UNITS............inches
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 5 (BJ62H)
20.0
15.0
10.0
5.0
0.0
0.110
0.120
0.130
0.140
0.150
0.160
0.170
0.180

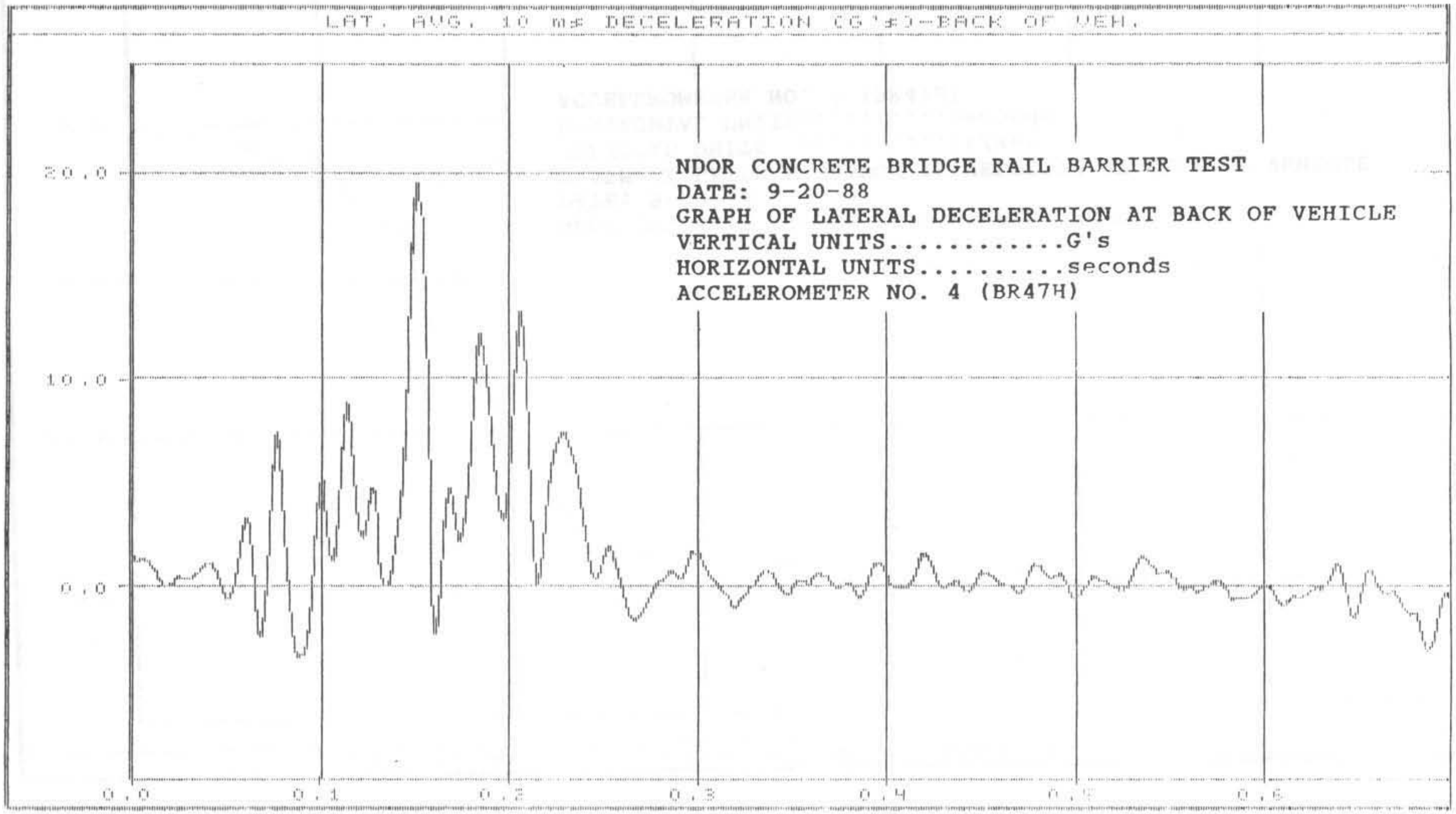

LONG. AVG. 10 ms DECELERATION (G's)-BACK OF VEH.
20.0
10.0
0.0
-10.0
-20.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL DECELERATION AT BACK OF VEHICLE
VERTICAL UNITS............G's
HORIZONTAL UNITS.........seconds
ACCELEROMETER NO. 6 (BF57H)

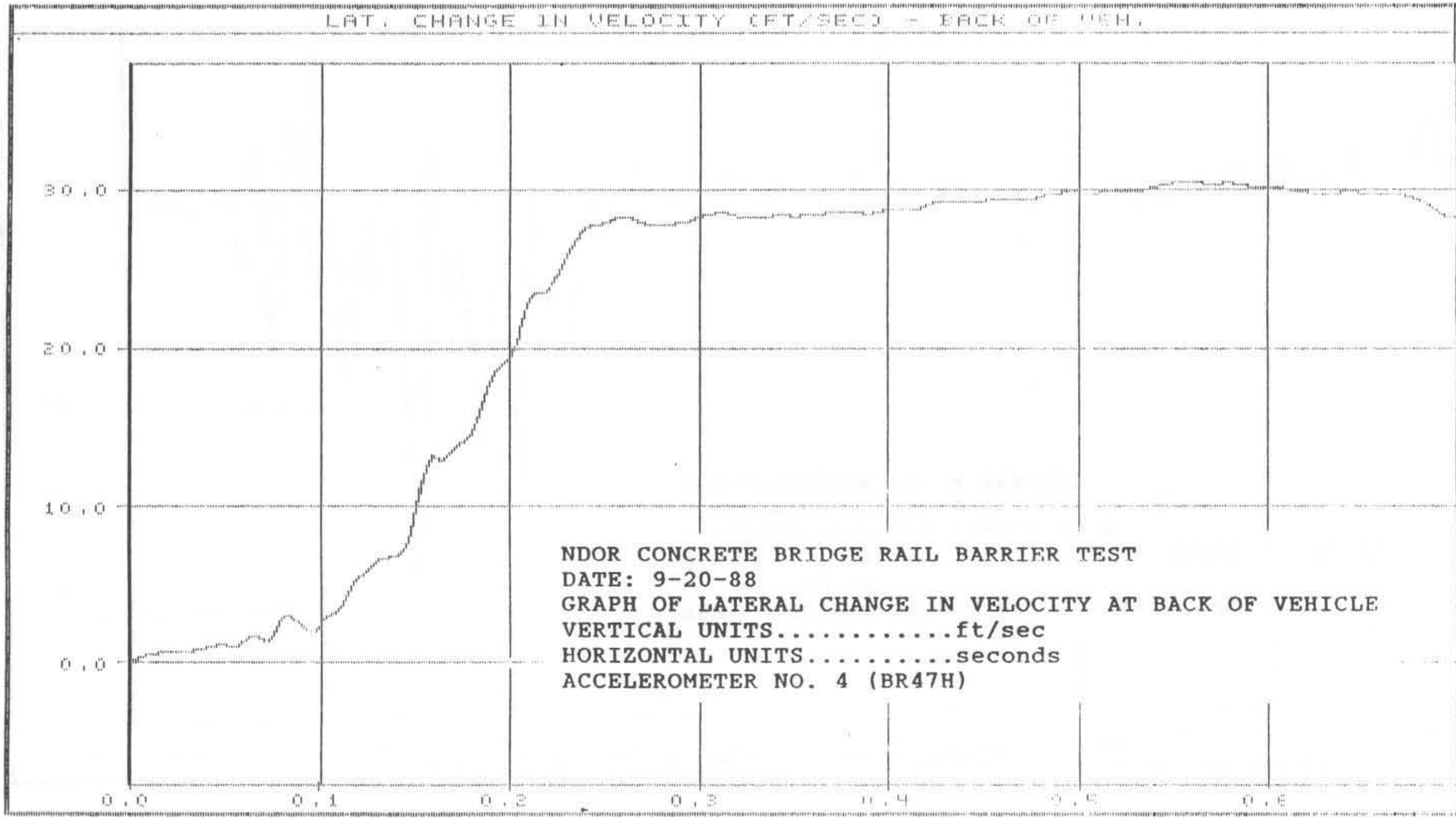

LONG. CHANGE IN VELOCITY (FT/SEC) - BACK OF VEH.
30.0
20.0
10.0
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL CHANGE IN VELOCITY AT BACK OF VEHICLE
VERTICAL UNITS............ft/sec
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 6 (BF57H)

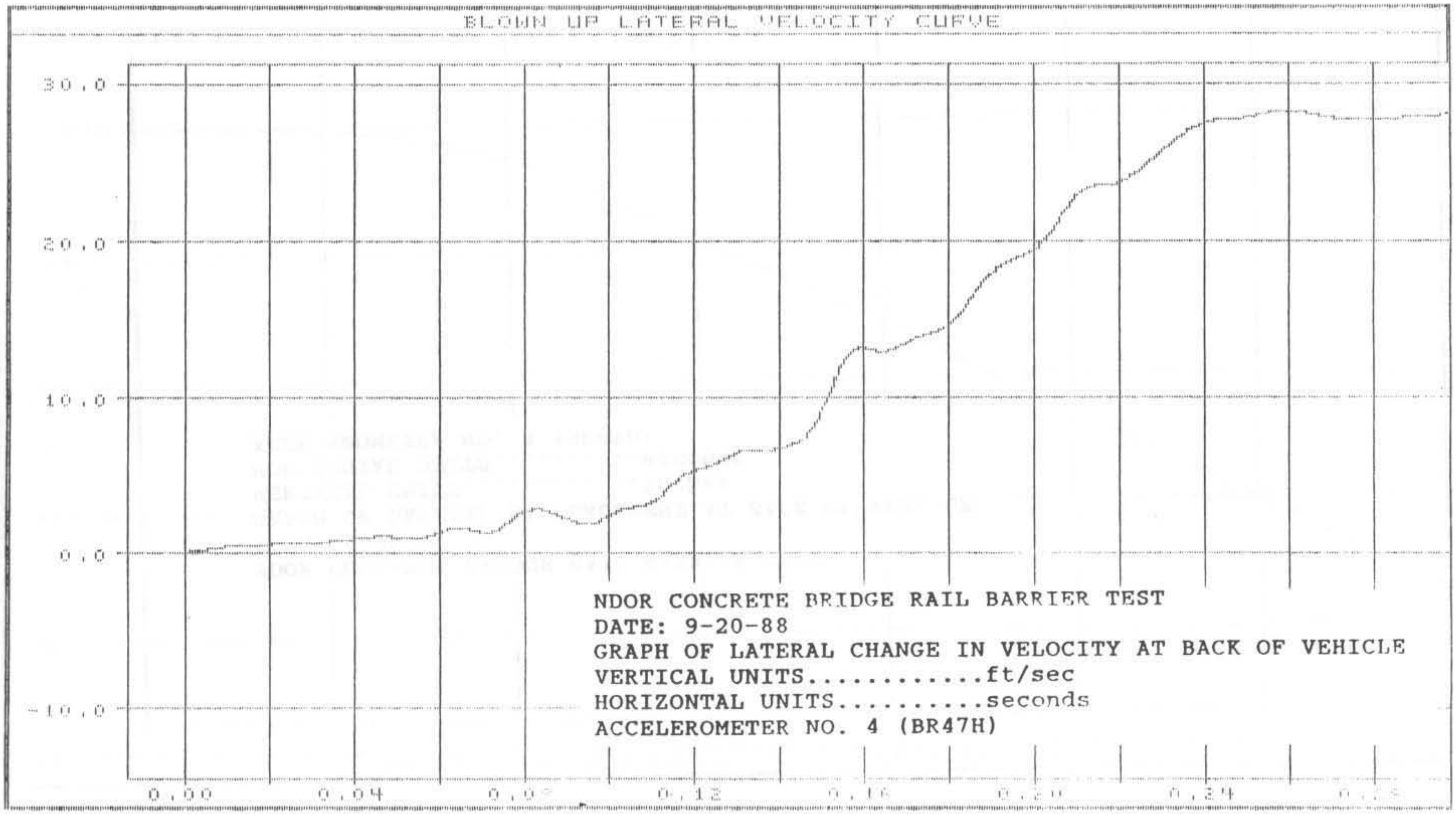

BLOWN UP LONG. VELOCITY CURVE
20.0
15.0
10.0
5.0
0.0
-5.0
-0.02
0.02
0.06
0.10
0.14
0.18
0.22
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL CHANGE IN VELOCITY AT BACK OF VEHICLE
VERTICAL UNITS............ft/sec
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 6 (BF57H)

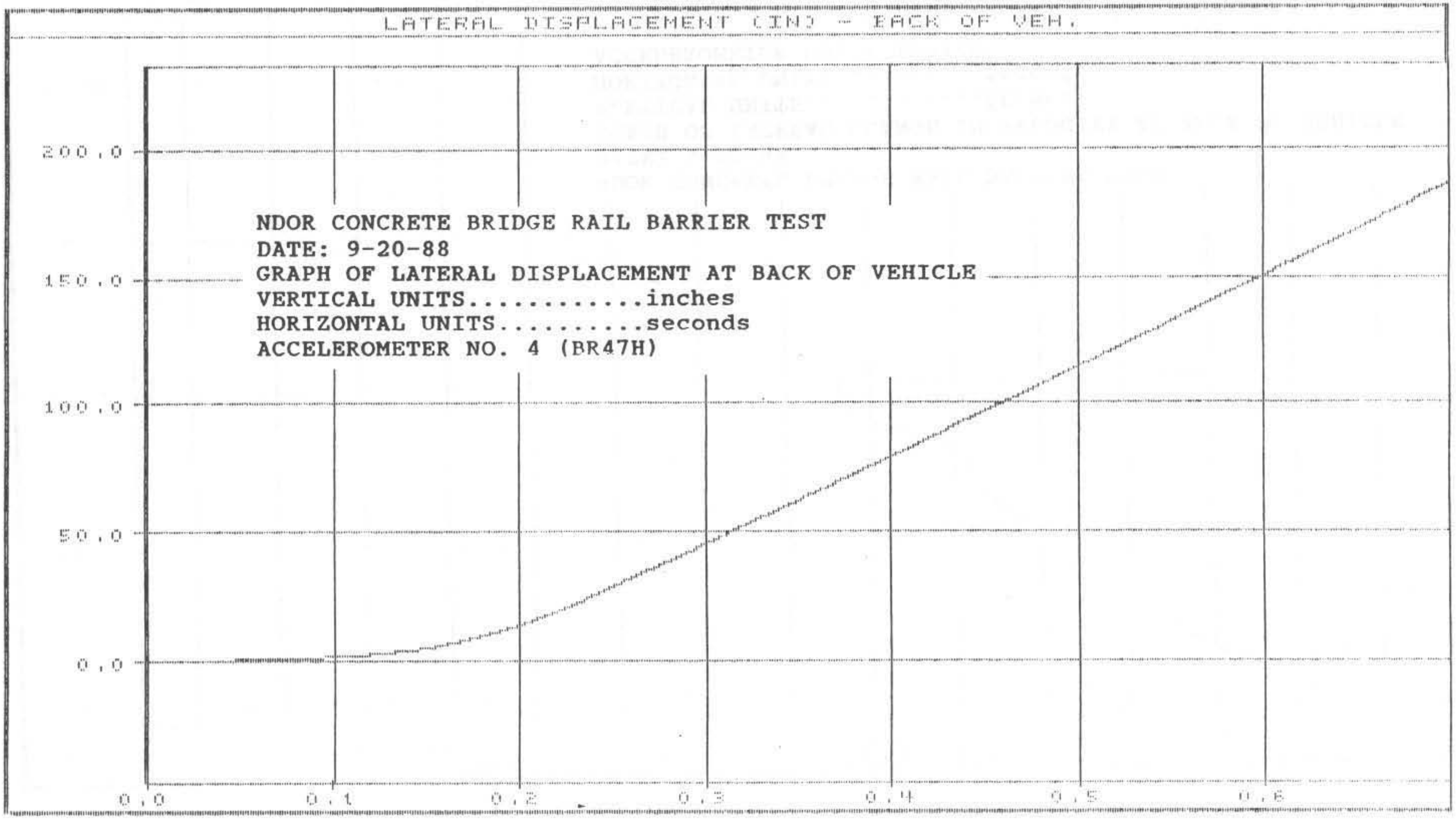

LONG. DISPLACEMENT (IN) - BACK OF VEH.
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL DISPLACEMENT AT BACK OF VEHICLE
VERTICAL UNITS............inches
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 6 (BF57H)
100.0
50.0
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30

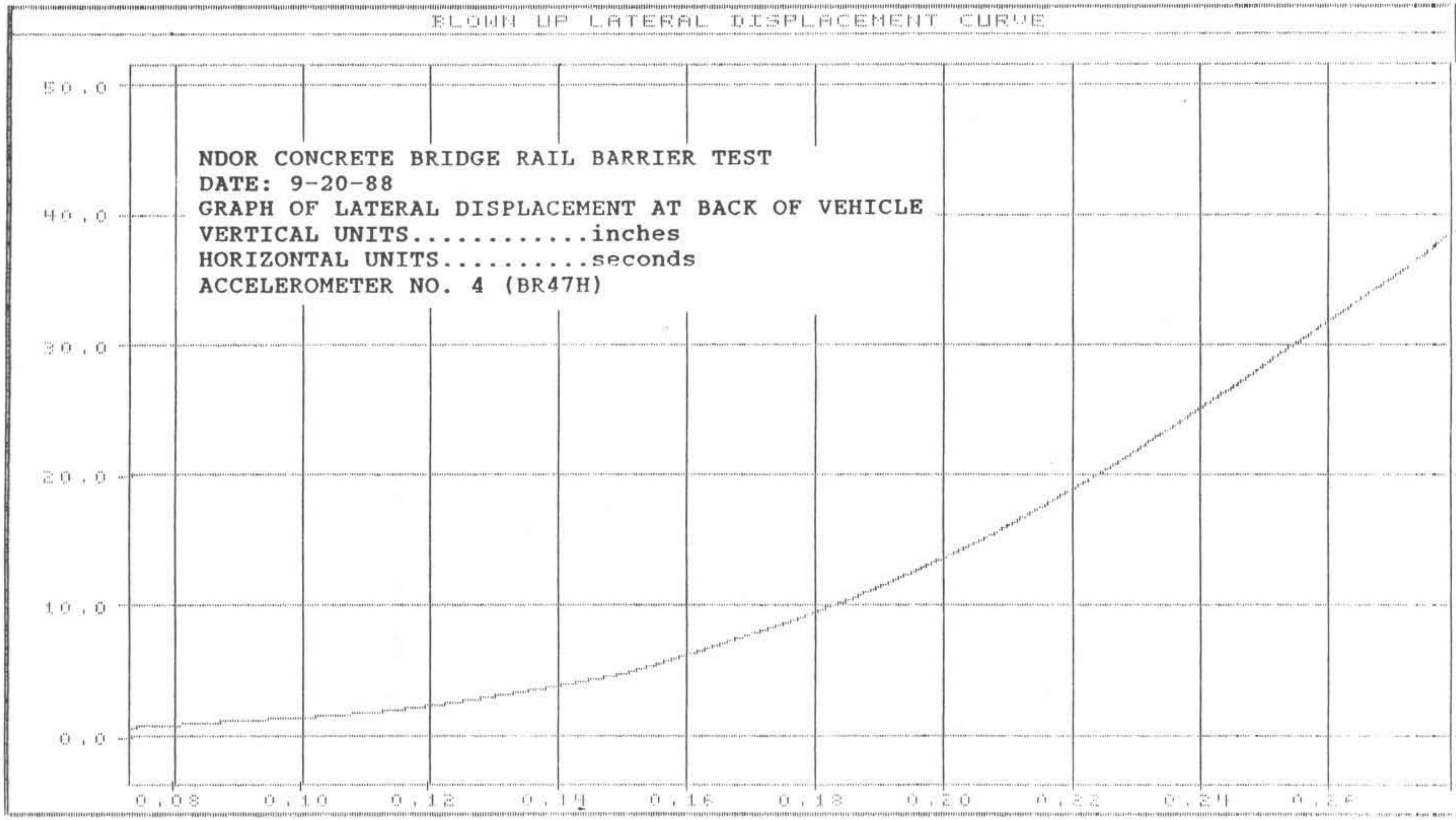

BLOWN UP LONG. DISPLACEMENT CURVE
60.0
40.0
20.0
0.0
-20.0
0.04
0.06
0.08
0.10
0.14
0.20
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LONGITUDINAL DISPLACEMENT AT BACK OF VEHICLE
VERTICAL UNITS............inches
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 6 (BF57H)


LAT. AVG. 10 ms DECELERATION (G's)-BACK OF VEH.
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL DECELERATION AT BACK OF VEHICLE
VERTICAL UNITS............G's
HORIZONTAL UNITS.........seconds
ACCELEROMETER NO. 4 (BR47H)
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6


LAT. CHANGE IN VELOCITY (FT/SEC) - BACK OF VEH.
30.0
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL CHANGE IN VELOCITY AT BACK OF VEHICLE
VERTICAL UNITS............ft/sec
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 4 (BR47H)


BLOWN UP LATERAL VELOCITY CURVE
30.0
20.0
10.0
0.0
-10.0
0.00
0.04
0.12
0.16
0.20
0.24
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL CHANGE IN VELOCITY AT BACK OF VEHICLE
VERTICAL UNITS............ft/sec
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 4 (BR47H)


LATERAL DISPLACEMENT (IN) - BACK OF VEH.
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL DISPLACEMENT AT BACK OF VEHICLE
VERTICAL UNITS............inches
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 4 (BR47H)
200.0
150.0
100.0
50.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6



BLOWN UP LATERAL DISPLACEMENT CURVE
NDOR CONCRETE BRIDGE RAIL BARRIER TEST
DATE: 9-20-88
GRAPH OF LATERAL DISPLACEMENT AT BACK OF VEHICLE
VERTICAL UNITS............inches
HORIZONTAL UNITS..........seconds
ACCELEROMETER NO. 4 (BR47H)
50.0
40.0
30.0
20.0
10.0
0.0
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26