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THE RELATION OF SIDE SLOPE DESIGN TO HIGHWAY SAFETY

FINAL REPORT ON TASK ORDER 2/1

Project 20-7

Highway Safety as it Relates to
Specific Highway Design Aspects

a report from the Texas A&M RESEARCH FOUNDATION
College Station, Texas

Prepared for
Highway Research Board
National Cooperative Highway Research Program
National Academy of Sciences

by

Texas Transportation Institute
Texas A&M University
College Station, Texas 77843

Project RF-626A

March 1972

THE RELATION OF SIDE SLOPE DESIGN TO HIGHWAY SAFETY

by

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TEXAS A&M RESEARCH FOUNDATION

TEXAS TRANSPORTATION INSTITUTE

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FOREWORD

This report, "The Relation of Side Slope Design to Highway Safety," represents the final report on Task Order No. 2/1 of the NCHRP 20-7 Program entitled, "Highway Safety as it Relates to Specific Design Aspects," initiated by the AASHO Planning and Design Policies Committee, administered by the National Cooperative Highway Research Program, and conducted by the Texas Transportation Institute.

The mission of the NCHRP 20-7 Program is to employ a multidisciplinary team approach to identify deficiencies in existing technology, and to develop new technology, thereby establishing the factual framework required by the AASHO Planning and Design Policies Committee in creating effective policy decision.

DISCLAIMER

The opinions and conclusions expressed or implied in this report are those of the authors. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Federal Highway Administration, or the American Association of State Highway Officials.

ACKNOWLEDGMENTS

The work reported herein was conducted at College Station, Texas by personnel of the Texas Transportation Institute. Charles J. Keese, Director, represented the Institute as principal investigator. The development of the test procedures and studies related to them were under the supervision of Graeme D. Weaver, Assistant Research Engineer. Analysis of the test data and correlation with the HVOSM simulation model were conducted by Eugene L. Marquis, Assistant Research Engineer and Alvin R. Luedecke, Jr., Research Assistant.

The authors wish to acknowledge the assistance and cooperation of the following individuals: J. G. Hanover, W. J. Byford, J. O'Connell, and J. H. Young, all of the Texas Highway Department (District 17, Bryan); H. S. Cherry, Allan Construction Company, Incorporated; J. Lacy, L. H. Lacy Company; and Sgt. P. L. Allen, the Texas Department of Public Safety.

The work by the persons behind the scenes, the secretaries, technicians, and support groups, is gratefully acknowledged. No project of this scope could be completed without their dedication and skills.

D. L. Loutzenheiser, of the AASHO Planning and Policies Committee, and James R. Novak, of the Highway Research Board, have contributed significantly to this work through their guidance and interest.

TENTATIVE DESIGN RECOMMENDATIONS

FOR

ROADSIDE SLOPES

DISCUSSION OF FIGURE S-1

Figure S-1 presents tentative recommendations for the design of roadside slope combinations to permit vehicle traversal at speeds up to 60 mph and encroachment angles up to 25 degrees. The curves are based on evaluation of the Task Order 2/1 full-scale tests on the V-ditches, the Task Order 3 berm tests, and engineering judgment and experience. Development of Figure S-1 is discussed in Section VI.

The example shown in Figure S-1 illustrates the maximum and desirable back slope that can be used with a given 6:1 side slope. (3:1 and 4:1 respectively as shown by the dashed lines)

TENTATIVE DESIGN RECOMMENDATIONS FOR ROADSIDE SLOPES

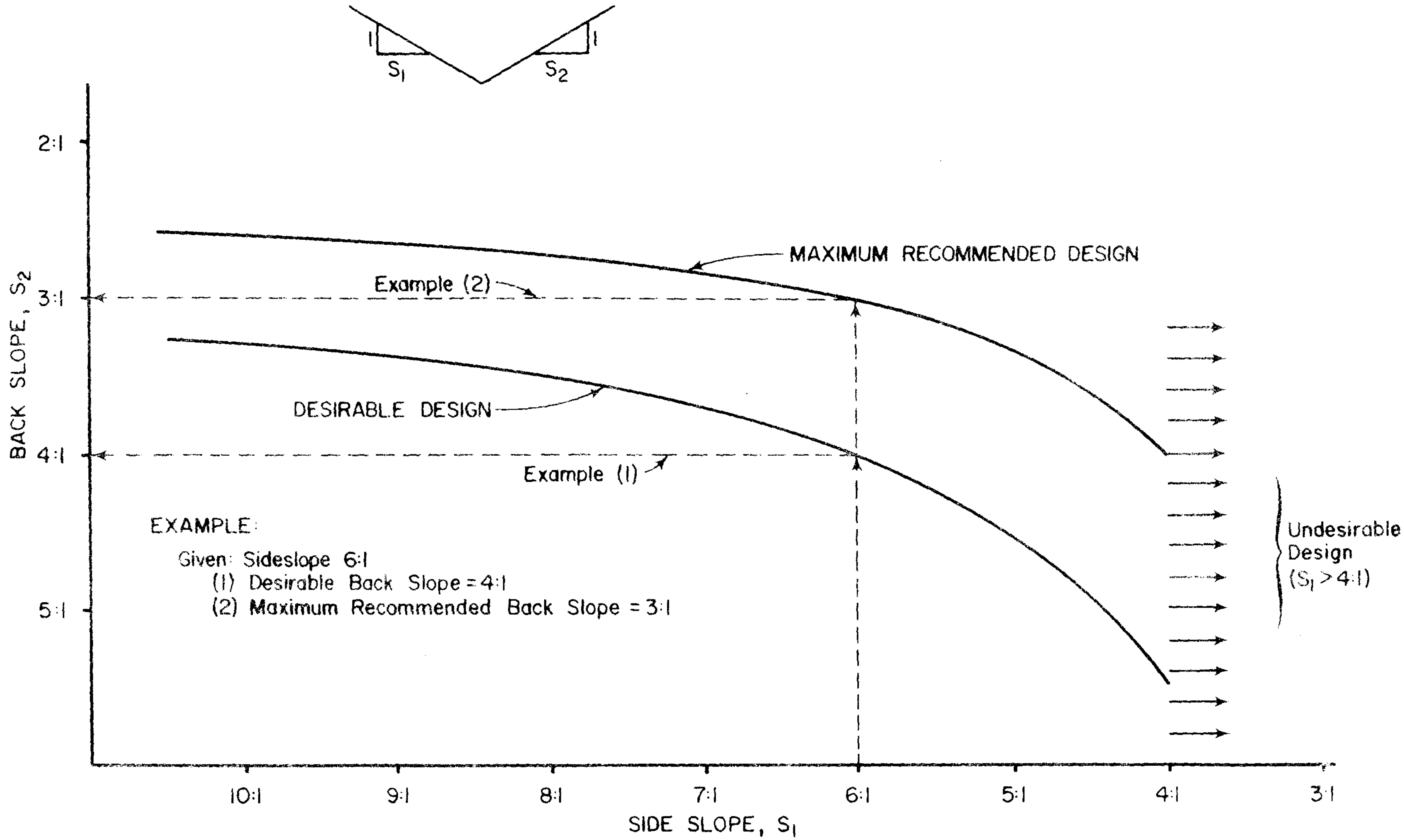

Figure S-1

SUMMARY OF RESEARCH

The American Association of State Highway Officials (AASHO) Standing Committee on Engineering Policies is continually called upon to rule on planning and design policies as a guide for state highway departments to follow. The committee requested a continuing research project geared to its needs and wishes in the development of planning and design guides, standards, policies, and other AASHO activities. The committee further determined that the most expeditious means of obtaining the desired research output was by establishing a continuing research capability with the Texas Transportation Institute, thus permitting TTI to retain capable research staff specialists on a permanent basis.

The work includes a continuing series of research tasks specified by the committee and conducted by TTI to obtain practical and usable data required by the committee to fulfill its responsibilities. Of the six research tasks undertaken by TTI at the request of the committee, four have been completed, two are in progress. The study reported here (Task Order 2/1) concerns full-scale vehicle tests on roadside slopes and ditch configurations conducted as a continuation of the original Task Order 2 roadside slope study.

ORIGINAL TASK ORDER 2 RESEARCH

As originally worded, the problem statement with regard to side slope was: "...to conduct run-down-the-slope trials by typical passenger cars and trucks to establish combinations of slope-height-rounding that are *safe* in that the vehicle did not turn over or could be guided as by a driver."

The dynamic response of a vehicle when traversing a roadside terrain feature is dependent on many vehicle and roadway parameters. Of primary importance are such factors as the speed and angle at which the vehicle leaves the roadway; the single and/or combined effects of the side and back slope steepness; the shape of ditch contour forming the transition from side to back slope and other related geometric factors. Dynamic response is further affected by vehicle properties such as body dimensions, weight distribution through the suspension system and attitude of the vehicle prior to leaving the roadway. Passenger response is greatly affected by the degree of body restraint existing throughout the maneuver. It is readily apparent that a large number of parameters exert individual influences on vehicle response, and that the complexity of the problem is grossly compounded by their interaction.

Due to the many variables involved in a study of this scope, the Texas Transportation Institute proposed the use of computer simulation to study the problem. Use of a computer simulation model would facilitate investigation of a variety of terrain features within the constraints of time and budget. TTI further proposed that full-scale tests be conducted to validate the model and provide confidence in its ability to analytically investigate the many variables. The panel directed that to reduce project costs of the study, full-scale tests conducted under Task Order 3 on the earth berm be used to validate the model for the side slopes as well.

Under the guidelines, a TTI modification of the Highway-Vehicle-Object-Simulation Model (HVOSM), formerly referred to as the Cornell Aeronautical Laboratory Single Vehicle Accident Simulation (CALSVA), was used to determine the dynamic forces on a vehicle as it traversed various roadside configurations. Certain criteria for tolerable forces were selected based on a literature review. Lateral, longitudinal, and vertical accelerations were determined for traversal (60 mph at 25-degree encroachment angle) of each of four ditch contours and twelve combinations of side and back slope (48 situations). The four ditch configurations were evaluated with respect to suggested limits of human tolerance to accelerations. Combinations of side and back slope, and ditch contours through which traversal is considered tolerable were recommended. (7) Table S-1 presents a summary of the criteria upon which the roadside configurations were evaluated.

Vehicle accelerations predicted by the model were compared to those obtained in five full-scale tests conducted under Task Order 3 on the earth berm. The tests were conducted on an extremely steep back slope (1.2:1), and at only one encroachment angle, 15 degrees. Unfortunately, the limited number of tests did not adequately verify the HVOSM as desired. Although reasonably close agreement was obtained between peak vertical accelerations predicted by the model and those actually experienced, other factors such as vehicle stability and redirection did not compare adequately.

TABLE S-1

SUMMARY OF TASK ORDER 2 RESEARCH

SLOPE COMBINATIONS AND DITCH SHAPE

The study included investigation of traversals at 60 mph and 25-degree encroachment angle for all combinations of:

Side Slope: 3:1, 4:1, 6:1

Back Slope: 3:1, 4:1, 5:1, 6:1

Four ditch configurations were evaluated:

Profile 1 - V-ditch

Profile 2 - Round Bottom Ditch

Profile 3 - Trapezoidal Ditch

Profile 4 - Trapezoidal Ditch with Rounded Corners

SUGGESTED TOLERANCE LEVELS

	Maximum Acceleration (G's)		
Degree of Occupant Restraint	Lateral	Longitudinal	Vertical
Unrestrained Occupant	5	7	6
Lap Belt Restraint	9	12	10
Lap Belt & Shoulder Harness Restraint	15	20	17

Three "zones" of tolerable vertical accelerations were established for the above restraint conditions:

Zone 1 - <6 G's

Zone 2 - 6-10 G's

Zone 3 - 10-17 G's

The four ditch configurations were evaluated on the basis of these zones.

Summary of Task Order 2 Results

The results of the Task Order 2 study are summarized:

Ditch configurations in which 3:1 side slopes were used, resulted in vertical accelerations in or above Zone 3 for all back slope combinations in all profiles. It was recommended that 3:1 side slopes be used only when flatter slopes are not feasible.

The 4:1 side slope represented an apparent division point in terms of performance level. This was considered to be one of the most significant findings of the study. With only one exception, vertical G's were reduced from Zone 3 to Zones 2 or 1 when the side slope was flattened from 3:1 to 4:1. In view of the safety benefits by this substitution, it was recommended that side slopes of 4:1 or flatter be used whenever possible.

With the exception of the V-ditch, flattening the side slope from 4:1 to 6:1 did not result in an appreciable reduction of vertical G's for a particular configuration. Although slope combinations having 6:1 side slopes generally produced somewhat smaller vertical accelerations, the degree of improvement appeared to be minor.

When used with the trapezoidal ditch configuration, back slopes of 4:1 or flatter steepness were little, if any, more hazardous than flat back slopes (such as where the side slope in a fill section intersects level ground).

For unequal side and back slopes, higher vertical accelerations were generally observed when the side slope was steeper than the back slope. It was recommended that, when conditions prohibit the use of equal slopes, the steeper slope should be located on the back slope.

The trapezoidal ditch (and the Profile 4 modification) produced vertical accelerations that were well within Zone 1 for side slopes of 4:1 and 6:1 and all combinations of back slope. Although the vertical accelerations were slightly higher than those of Profile 4, the trapezoidal ditch (Profile 3) with side slopes of 4:1 or flatter, represented the most favorable choice of the four alternatives.

TASK ORDER 2/1 RESEARCH

Since the slopes recommended in the Task Order 2 final report (7) were not validated by full-scale tests, Task Order 2/1 was initiated at the Committee's request to evaluate, through correlation with full-scale vehicle test data, the effectiveness of the HVOSM model in predicting vehicle response during traversal of roadside slopes and ditches. The results of the model validation would provide a confidence level in the potential use of the model as a design tool to investigate vehicle behavior during traversal of a variety of terrain features in addition to substantiating or refuting the original Task Order 2 findings.

To obtain a variety of data for input to the HVOSM model, 24 full-scale vehicle tests were conducted; 8 tests were run at each of three sites selected on a newly constructed divided highway near College Station, Texas. At each site, the 8 tests comprised a 30, 40, 50, and 60-mph traversal through both a round and a V-ditch. A 25-degree encroachment angle was used for all tests. Site geometry is summarized in Table S-2.

The test vehicle was driven by a professional test driver in sixteen of the twenty-four tests. The test vehicle was towed and released through the eight tests at the most severe site (Site 3, 7:1 side slope, 3:1 back slope).

Each full-scale test was simulated using, as initial values in the model, the site geometry, and the vehicle speed, encroachment angle, and point of departure measured from the test data. The predicted vertical, lateral, and longitudinal vehicle accelerations were

TABLE S-2

GEOMETRICS OF STUDY SITES

Site No.	Side Slope Steepness	Back Slope Steepness	Height of Back Slope (ft)	Displacement of Ditch Centerline From Pavement (ft)
1	6.5 to 1	4.9 to 1	11	18
2	7.2 to 1	4.2 to 1	15	20
3	7.0 to 1	3.3 to 1	17	18

NOTE

The above values represent an average steepness in the ditch-contact region of the study site.

compared to the accelerometer measurements obtained from the full-scale tests.

Summary of Task Order 2/1 Results

The HVOSM model predicted, with remarkable consistency, the vehicle response resulting from traversal of the ditch/slope configurations. Extremely close correlation was obtained between predicted and actual resultant average accelerations. From the correlation obtained in this study, the HVOSM simulation model appears to be a very powerful design tool with which to analytically investigate vehicle behavior on various terrain features. It offers a very cost-effective method to investigate all combinations of roadside slopes at various vehicle speeds and angles of attack or selected configurations of interest to the designer.

The 16 tests on the 4:1 and 5:1 back slopes with a side slope of approximately 7:1 revealed that these combinations could be safely negotiated at speeds up to 60 mph with no rollover hazard and only moderate discomfort if the driver was adequately restrained. The 3:1 back slope (7:1 side slope) appeared quite formidable to the researchers and to the professional test driver. Since this slope combination was not driven, the effect on an occupant can only be estimated. However, based on vehicle damage sustained during the Site 3 tests and the peak g's measured, slopes of this steepness are not considered desirable design.

The ditch/slope combinations investigated in the original Task Order 2 study were evaluated on the basis of *peak g's*. Since the

Task Order 2 report was written, it has become the accepted practice by the Federal Highway Administration to use average g's as a criterion (8). Therefore, average g's were used as the criterion in the Task Order 2/1 study. The two sets of results are not directly comparable. Also, the steepest side slope that could be used economically in the full-scale tests was approximately 6:1. However, the close agreement between predicted and measured response lends substantial credence to the recommendations presented in the Task Order 2 study.

Other specific Task Order 2/1 findings are summarized:

The test driver experienced considerable difficulty in achieving the 25-degree exit angle at speeds of 50 and 60 mph due to rear wheel drift yet he had a 42-ft wide pavement in which to negotiate the turn. A 25-degree encroachment angle at these speeds can be executed by a professional driver under certain conditions, but probably is too severe for design purposes.

Vertical accelerations comprise the dominant accelerations in ditch traversal and consequently contribute most significantly to the resultant acceleration. This substantiates the criteria assumed in the Task Order 2 study. Lateral and longitudinal accelerations can be considered to be virtually negligible in round ditch traversals and in V-ditch traversals at speeds less than 50 mph.

The HVOSM predicted accelerations generally were slightly higher than the measured values. This can be attributed to vehicle suspension and inertia characteristics used in the model which influence the predicted response. It is extremely important that compatible vehicle characteristics are used for comparison purposes.

The HVOSM performs admirably in predicting vehicle path, and points of loss of contact between wheels and terrain.

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I. INTRODUCTION

DESCRIPTION OF THE PROBLEM

The dynamic response of a vehicle when traversing a roadside terrain feature is dependent on many roadway and vehicle parameters. Of primary importance are such factors as the speed and angle at which the vehicle leaves the roadway; the single or combined effects of the side and back slope steepness; the shape of the ditch forming the transition from side to back slope, and other related geometric and operational features. Dynamic response is further affected by vehicle properties such as body dimensions, weight distribution through the suspension system, and the vehicle attitude prior to leaving the roadway. Passenger response is greatly affected by the degree of body restraint existing throughout the maneuver. It is readily apparent that a large number of parameters exert individual influences on vehicle response, and that the complexity of the problem is grossly compounded by their interaction.

Unlike many aspects of highway design in which comprehensive criteria and specifications exist, the design engineer has been handicapped by the lack of objective criteria in the area of selecting safe combinations of slopes for roadway design. To enable him to evaluate alternatives and thus achieve optimum safety in his design, objective criteria must be made available to him.

It is the intent of NCHRP 20-7 Program, Task Orders 2 and 2/1 to develop criteria for safe roadside design which will assist the AASHO

Planning and Policy Design Committee in establishing design standards and guidelines.

TASK ORDER 2 RESEARCH (7)

In a previous study (7), a Texas Transportation Institute modification of the Highway-Vehicle-Object Simulation Model (HVOSM), formerly referred to as the Cornell Aeronautical Laboratories Single Vehicle Accident Simulation (CALSVA), was used to determine the dynamic forces on a vehicle as it traversed various roadside configurations. (7) Certain criteria for tolerable forces were selected based on a literature review. Lateral, longitudinal, and vertical accelerations were determined for traversal (60 mph at 25-degree encroachment angle) of each of four ditch contours and twelve combinations of side and back slope (48 situations). The four ditch configurations were evaluated with respect to suggested limits of human tolerance to acceleration. Combinations of side and back slope, and ditch contours through which traversal is considered tolerable were recommended.

TASK ORDER 2/1 RESEARCH

Since the slopes recommended in the Task Order 2 final report (7) were not tested, Task Order 2/1 was initiated at the Committee's request to evaluate through correlation with full-scale vehicle test data, the effectiveness of the HVOSM model in predicting vehicle response during traversal of roadside slopes and ditches. The results of the model validation would provide a confidence level in the potential use of the model as a design tool to investigate vehicle behavior during traversal of a variety of terrain features in addition to substantiating or refuting the original Task Order 2 findings. The conduct and results of the full-scale tests under the requirements of Task Order 2/1 are described in this report.

To obtain a variety of data for input to the HVOSM model, 24 full-scale vehicle tests were conducted; 8 tests were run at each of three sites selected on a newly constructed divided highway near College Station, Texas. At each site, the 8 tests comprised a 30, 40, 50 and 60-mph traversal through both a round and a V-ditch. A 25-degree encroachment angle was used for all tests.

The side slope - back slope combinations at the respective sites were: Site 1, 6.5:1 - 4.9:1; Site 2, 7.2:1 - 4.2:1; and Site 3, 7:1 - 3.3:1. The test vehicle was driven by a professional test driver in the sixteen tests at Sites 1 and 2. The vehicle was towed and released through the eight tests at Site 3, the most severe slope combination.

Each full-scale test was simulated using, as initial values to the model, the site geometry, and the vehicle speed, encroachment angle, and point of departure measured from the test data. The predicted vertical, lateral, and longitudinal vehicle accelerations were compared to the accelerometer measurements obtained from the full-scale tests.

Included in the individual chapters of the report are descriptions of the HVOSM model, the full-scale test methodology and a discussion of the results obtained. The research findings are summarized and tentative recommended maximum slope design criteria based on evaluation of the test data and other related studies are presented in Chapter VI. Sample data from test equipment and from the HVOSM model are presented in the Appendix.

II. HVOSM---HIGHWAY VEHICLE AND OBJECT SIMULATION MODEL

The computer simulation* employs a highly sophisticated dynamic model of a passenger vehicle which was developed at Cornell Aeronautical Laboratories (1) and modified at the Texas Transportation Institute (2). It is capable of simulating the response of a vehicle traversing a given three-dimensional terrain configuration. The vehicle is assumed to be composed of four rigid masses, viz, sprung mass, unsprung masses of the left and right independent suspensions of the front wheels, and an unsprung mass representing a solid rear axle assembly (1). A conceptual representation of the simulated vehicle is shown in Figure 1.

The model includes eleven degrees of freedom, ten in which inertial couplings exist between the sprung and unsprung masses, and a front wheel steering degree of freedom for which inertial interactions are neglected. The unsprung masses in an actual automobile are constrained to move along paths that are fixed relative to the sprung mass. It was assumed in the model that the centers of gravity of the front unsprung masses move along straight-line paths that are parallel to the sprung mass Z-axis. The center of gravity of the rear unsprung mass is assumed to be constrained to motions in a plane that is perpendicular to the sprung mass X-axis and, additionally, to remain a fixed distance from the rear axle "roll center". The rear axle "roll center" is assumed to be limited to straight-line motions in a direction parallel to the sprung mass Z-axis. (3)

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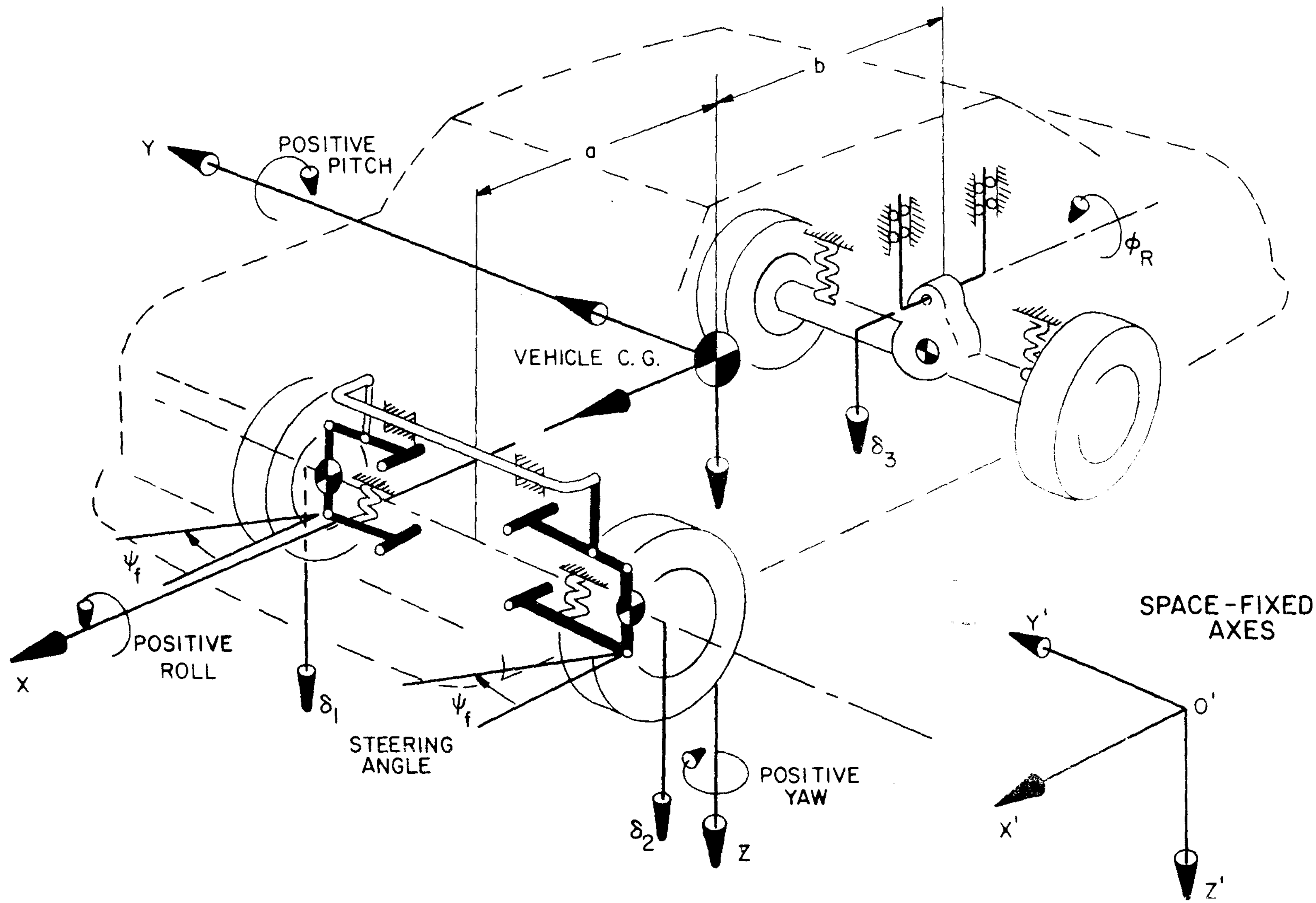
*This computer simulation, formerly known as CALSVA, is referred to as "HVOSM" throughout this report. The basic model is available from the Federal Highway Administration, Washington, D. C.



Conceptual Representation of Simulated Vehicle (3)

Figure 1

The steer angle, ψ_f, is assumed to be equal for both front wheels, and may optionally be entered either as a control input (tabular function of time) or as a degree of freedom which is responsive to external forces.

Several modifications to the HVOSM program were made at the Texas Transportation Institute to facilitate its use in operational conditions.

1. The terrain input method was improved by incorporation of a "template" system in which the terrain is analytically described by lateral, longitudinal and elevation coordinates from a reference origin. Each template is, in essence, a cross section of the terrain in the lateral (Y-axis) direction perpendicular to the X-axis of the space fixed system. Each template may include a maximum of 20 elevation and lateral displacement coordinates, and a maximum of 20 templates may be used along the longitudinal axis.
2. The original program made allowance only for contact of the tires with the terrain. Consequently, the computer model of the vehicle was modified to provide twenty vehicle/terrain monitoring points. These monitoring points indicated terrain contact and vehicle forces were computed for load input at the contact points resulting from terrain contact.

3. The number of input data cards was considerably decreased by specifying in a subroutine, constant vehicle characteristics and other associated constants for a 1963 Ford Galaxie Police Special. The program includes an "over-ride" capability whereby constants for other vehicles may be introduced. Certain vehicle constants were modified in this study to adapt the simulation program to the test vehicle.

4. Output data format was also modified, primarily to include generation of CALCOMP plots with each data group. Nineteen plots were generated for each ditch traversal, including:

    a. accelerations in the tri-axes with lateral displacement and time as a base;

    b. roll, pitch, yaw, and steering angle on a time base;

    c. vehicle vertical (Z-axes) acceleration versus longitudinal (X-axes) displacement; and

    d. position of all four wheels on an X-Y coordinate system to indicate the plan view of wheel-tracking throughout each maneuver under study.

The program generates a considerable amount of vehicle response data. Data printed out at 0.01-second intervals of real time included roll, pitch, and yaw angles; acceleration at the center of gravity of the sprung mass in the longitudinal, lateral, and vertical axes; coordinates in the X-, Y-, and Z-axes of the vehicle center of gravity and each wheel; circumferential, side and horizontal tire forces; and depths of body contact point penetrations in the terrain. Loss of contact between a wheel and the terrain was indicated. Other vehicle response characteristics were also computed but were not used in this study.

VEHICLE

Two 1963 Ford Galaxie vehicles were used for test conduct: a four-door sedan weighing 3820 pounds, and a 2-door hardtop weighing 3830 pounds. Most of the tests were conducted using the 2-door vehicle. The 4-door sedan was used when the primary test vehicle was being repaired and during the final test sequence after the 2-door vehicle had sustained considerable alignment damage from repeated tests.

The test vehicles differed in weight and certain inertia, suspension, and dynamic properties from the Police Special Vehicle simulated in the main program. Therefore, to simulate the test vehicle as closely as possible, the over-ride feature in the subroutine was used to incorporate the following test vehicle constants: (4)

front spring constant	= 100.0 #/in.
rear spring constant	= 105.0 #/in.
coulomb damping front	= 30.0 #
coulomb damping rear	= 45.0 #
roll moment of inertia	= 6,200 #in/sec^2
pitch moment of inertia	=34,400 #in/sec^2
yaw moment of inertia	=36,000 #in/sec^2

When exact information was unavailable (such as the distribution of vehicle mass), the distributions were estimated according to recommended procedures (5). The total weight of the 4-door test vehicle was 3820 pounds with estimated distribution as follows:

Wuf (front unsprung mass) = 0.04 Wt + 60 = 212.8# = 0.5507# sec^2/in

Wur (rear unsprung mass) = 0.067 Wt + 90= 345.9# = 0.8952# sec^2/in

Ws (sprung mass) =3261.3# = 8.4402# sec^2/in

3820.0#

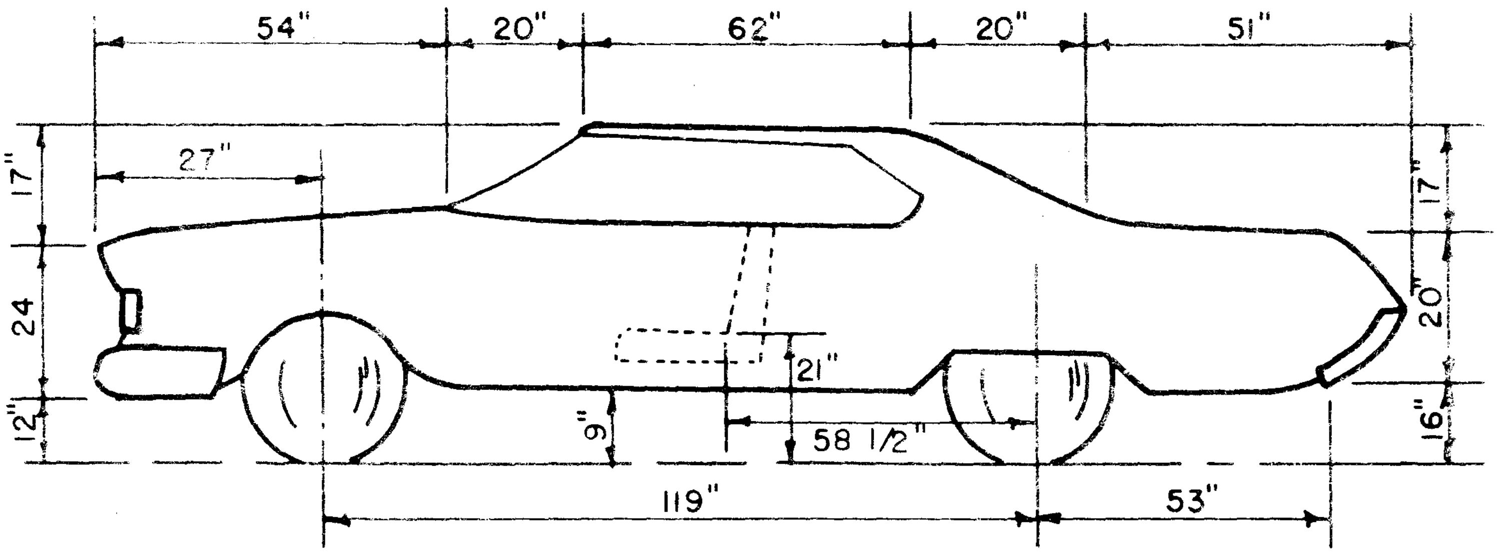
The above distribution was assumed for both test vehicles. All other simulated vehicle constants are presented in reference (2). Test vehicle dimensions are shown in Figures 2 and 3.

TIRE AND VEHICLE GROUND-CONTACT

Tire and vehicle body ground-contact forces are dependent upon several factors including soil stiffness and damping characteristics, coefficients of friction, the speed and attitude of the vehicle at impact, and other variables. To simulate soil normal forces, ground stiffness was assumed to be 4000 lb per in. with a soil damping constant of 0.001 seconds per inch. A coefficient of friction of 0.25 was assumed at vehicle body ground-contact monitoring points. The coefficient of friction between the tires and ground was 0.8 in all simulated tests. Vehicle ground-contact was monitored at the locations shown in Figure 4.

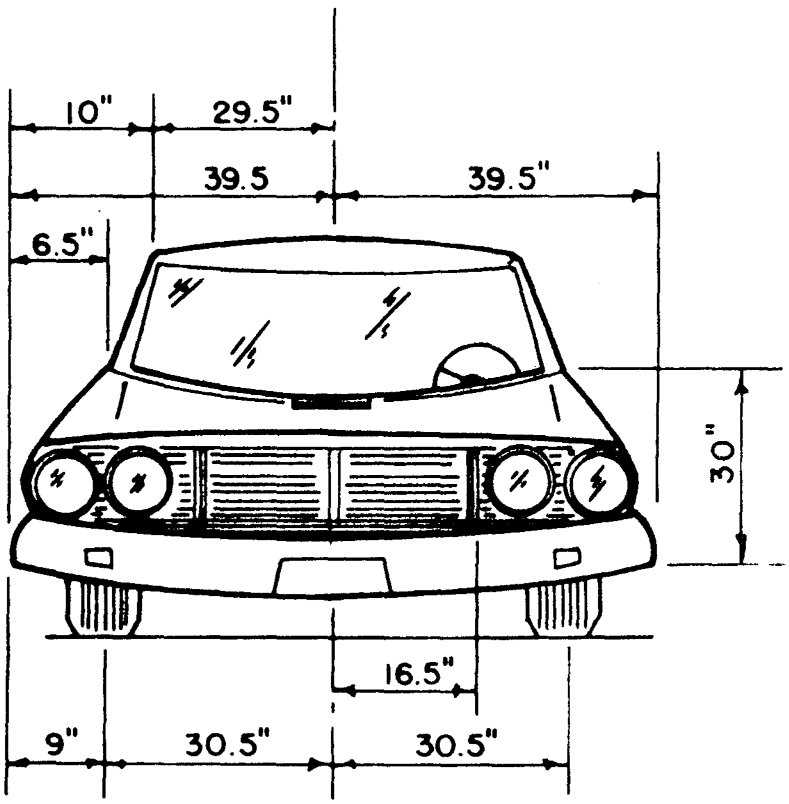
STEERING MODE

The "no-steer" mode was used in all simulated traversals. The vehicle was oriented in the 25-degree encroachment path in the left lane



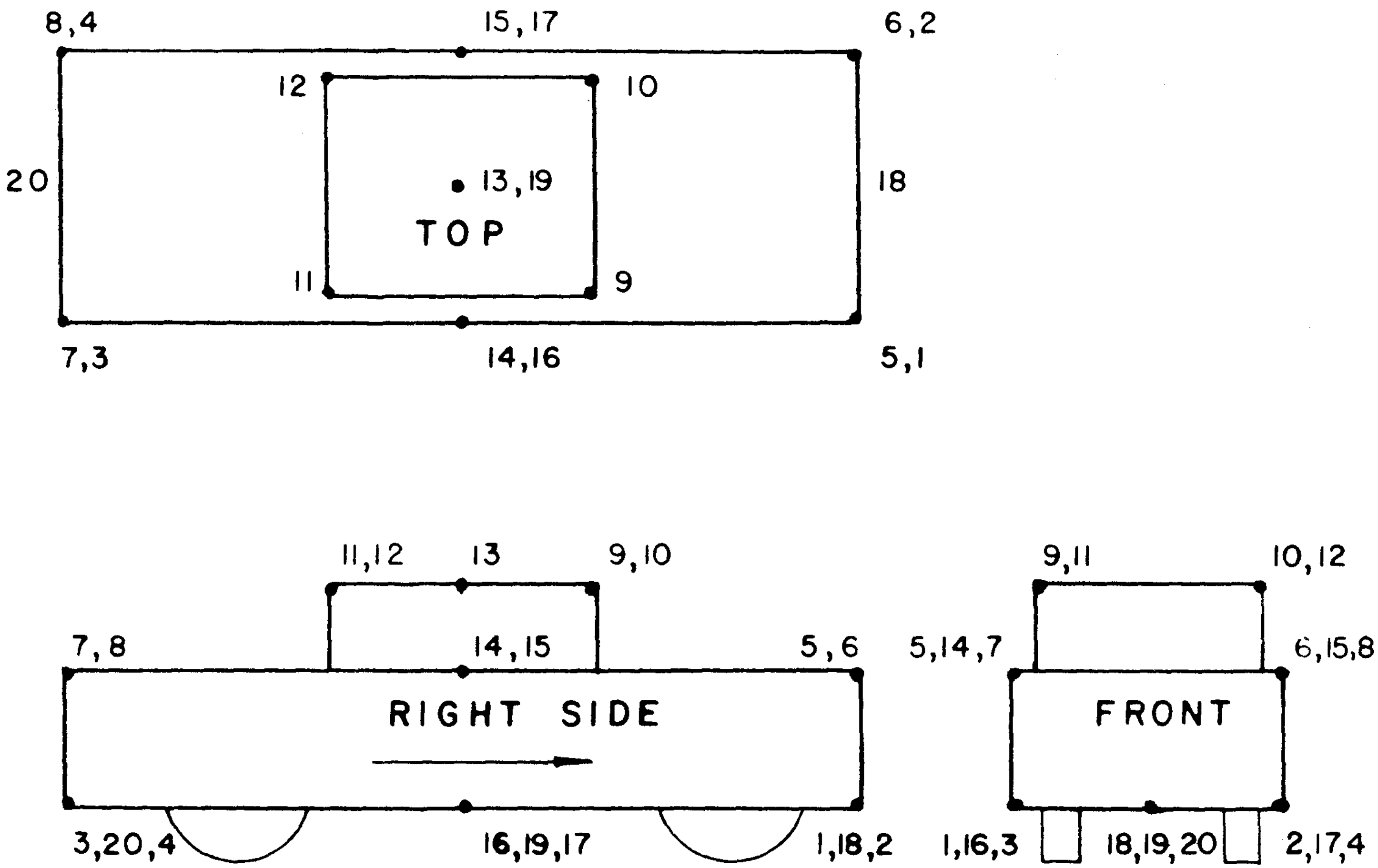
Approximate Longitudinal Body Dimensions of the 1963 Ford (1)

Figure 2



Approximate Lateral Body Dimensions
of the 1963 Ford (1)

Figure 3



Location of Vehicle Ground-Contact Monitoring Points (1)

Figure 4

of the highway as initial coordinates for each simulated test. The vehicle then traveled in a free-wheeling mode across the roadway through the ditch area and up the back slope. Its path was dictated by the forces exerted on the wheels (or other point of contact) by the terrain.

III. FULL-SCALE VEHICLE TESTS

To obtain a variety of data for input to the HVOSM model, twenty-four full-scale vehicle tests were conducted. Two series of four tests were run at each of three study sites on the East Bypass at Bryan/College Station, Texas. Each site contained a different combination of side and back slope. Each test series comprised four traversals, one each at speeds of 30, 40, 50, and 60 mph. A circular ditch and a V-ditch were investigated at each site.

The test vehicle was driven by a professional test driver during the first four series of tests (16 situations). The test vehicle was towed and released during the eight tests at the third site. In all tests, the desired encroachment angle was 25 degrees.

Vertical, lateral, and longitudinal accelerations were measured by accelerometers located at the center of gravity of the vehicle. A tri-axes recording impactograph was mounted on the vehicle flour close to the center of gravity to provide back-up measurements. Vehicle speed, path through the ditch, and other characteristics were obtained from high-speed film coverage, and on-site measurements.

A detailed description of the study sites, test vehicles and equipment, and test procedure is presented in this section.

SELECTION AND DESCRIPTION OF STUDY SITES

Three study sites were selected on the Bryan/College Station East Bypass (Texas State Highway 6), a four-lane median- divided facility currently under construction. Existing roadside slopes on the bypass, mostly through cut sections, range from 8:1 to approximately 3:1 steepness with varying heights and displacement from the travel lanes. All test sites were located in cut sections; thus, the slopes were extremely well compacted, having been constructed to final grade for many months. The slopes are watered frequently and support a complete coverage of natural vegetation.

Several factors influenced the selection of the sites. The primary consideration in the use of the bypass was its proximity to the research center. Funding constraints prohibited construction of the many combinations of side and back slopes that could possibly be found throughout the country, nor could the test vehicles, equipment and personnel be economically transported to test locations that were too far from Texas A&M University. Consequently, the bypass represented the most cost-effective test location.

The travel lanes, shoulders, and service roads had been surfaced with approximately four inches of asphaltic concrete ("black base") in preparation for the 8-inch continuously reinforced concrete surface. The asphaltic concrete surface provided a 42-foot wide area in which the required 25-degree departure angle could be negotiated. Since the highway was not open to traffic, the entire width of travel lane and shoulders could be used without necessitating lane closure or traffic detouring. Also, the bypass is being constructed in a semi-rural environment. Therefore, should the test vehicle travel beyond the service road, property damage would be minimized.

The three sites were selected to provide the greatest variety of side and back slope combinations. Also considered in site selection were the height of the back slope, the distance from the edge of pavement to the ditch center line, and available recovery distance beyond the back slope (a service road was located atop the back slope at all sites) in case the test vehicle could not be stopped on the slope. Although these additional characteristics influenced the choice of sites, the prime objective was the selection of three sites having progressively steeper back slopes within the range of approximately 6:1 to 3:1. The flattest back slope that afforded adequate height and recovery distance for test purposes was approximately 5:1 (Site 1). The steepest back slope on the bypass was located at Site 3 (3.3 to 1). At this location the service road was placed closer to the travel lanes to bypass a cemetery. The adjacent point on the travel lane was the point of departure for an exit ramp. This design produced a steep cut slope between the travel lane and the service road.

The slopes at each site were graded to produce a fairly smooth surface for a 200-ft length parallel to the travel lane. Only prominent irregularities in the slope face were removed, and erosion cuts were filled and conpacted. A majority of the grading was so shallow that the natural vegetation was not substantially removed. A hard plane surface was desired to simulate as closely as possible the HVOSM model idealized plane surfaces.

The study slopes, in their existing state, were extremely hard. Tire imprints from a vehicle driven on the slope were practically invisible. Therefore, to permit measurement of the vehicle path from tire imprints, the slopes and ditch were surfaced with a thin layer of sand.

Figures 5 through 7 show details of the study sites before and after site preparation and present views of the ditch configurations used at each site. Geometric features of the sites are shown in Table 1.

TEST VEHICLES

Two test vehicles were used. A 1963 Ford Galaxie 4-door sedan was equipped for the cable-tow system (Figure 8) and the turning guidance mechanism (Figure 9). A 1963 Ford Galaxie 2-door hardtop was used during the driven tests.

The objective of the program was specifically to obtain field data from actual vehicle tests for correlation with the HVOSM predictions. The HVOSM model contains vehicle dimensions, and physical and dynamic characteristics of the 1963 Ford Galaxie. To date, the 1963 Ford has been used for all correlation with the model and actual tests. Obviously the 1963 Ford sedan is not typical of all passenger vehicles. It is, however, representative of the 3500-4000 pound passenger automobile (having similar distribution of mass, and dimensions such as wheel-base, length, width, etc.).

The test vehicles were modified from stock configuration only to the degree necessary to install recording equipment and protect the driver and equipment. Rear seats and the front passenger seat were

TABLE 1

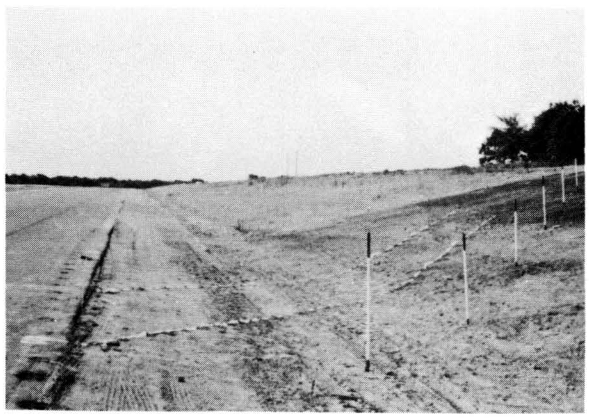
GEOMETRICS OF STUDY SITES

Site No.	Side Slope Steepness	Back Slope Steepness	Height of Back Slope (ft)	Displacement of Ditch Centerline From Pavement (ft)
1	6.5 to 1	4.9 to 1	11	18
2	7.2 to 1	4.2 to 1	15	20
3	7.0 to 1	3.3 to 1	17	18

Note

The above values represent an average steepness in the ditch-contact region of the study site.

(a) Original Condition of Site

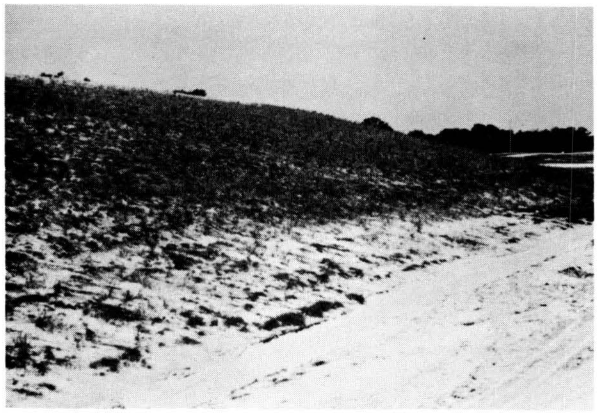


(b) Round Ditch Test Configuration

(c) V-Ditch Test Configuration

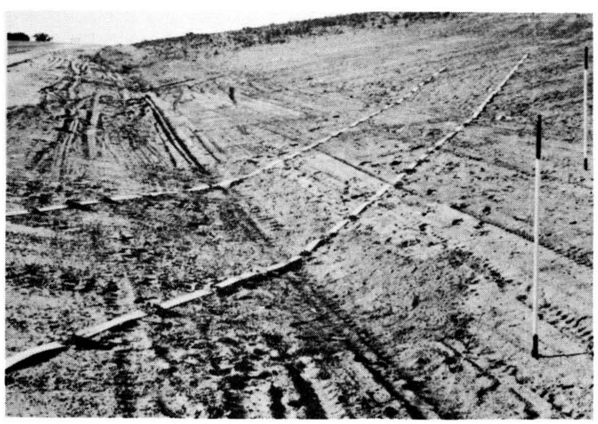
Site No. 1 (5:1 Back Slope)

Figure 5



(a) Original Condition of Site

(b) Round Ditch Test Configuration

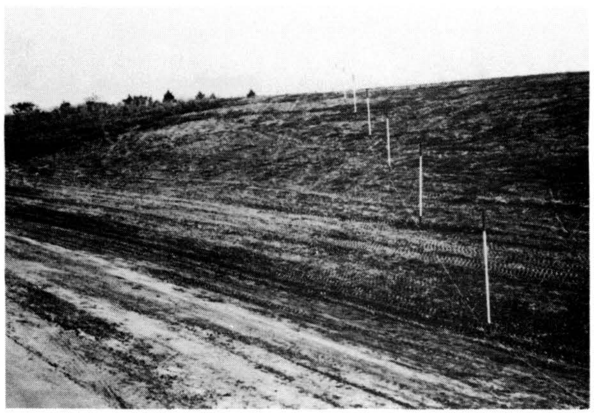


(c) V-Ditch Test Configuration

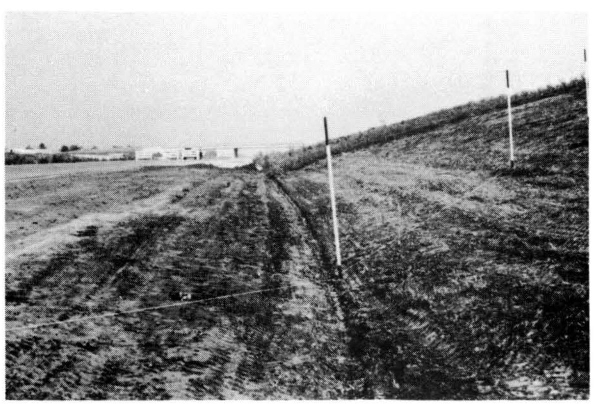
Site No. 2 (4:1 Back Slope)

Figure 6

(a) Original Condition of Site



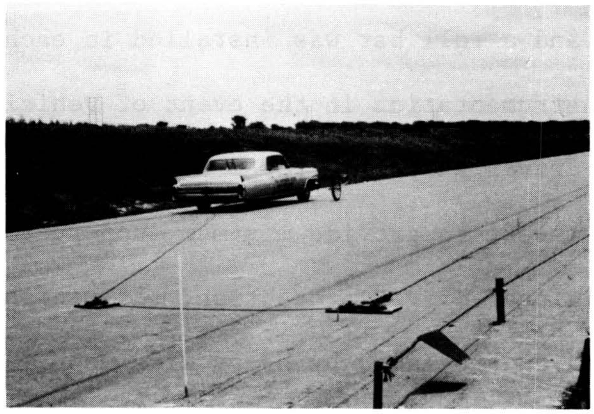
(b) Round Ditch Test Configuration



(c) V-Ditch Test Configuration

Site No. 3 (3:1 Back Slope)

Figure 7



Tow-Cable and Guidance System

Figure 8

Test Vehicle Remote Turning System

Figure 9

removed from both vehicles to permit installation of recording instrumentation, and a roll bar was installed in each to protect the driver and instrumentation in the event of vehicle rollover. The conventional driver's seat in the 2-door was replaced by a racing type bucket seat to provide maximum support for the test driver. For additional driver protection, the windshield and side glass were removed and replaced by heavy wire mesh.

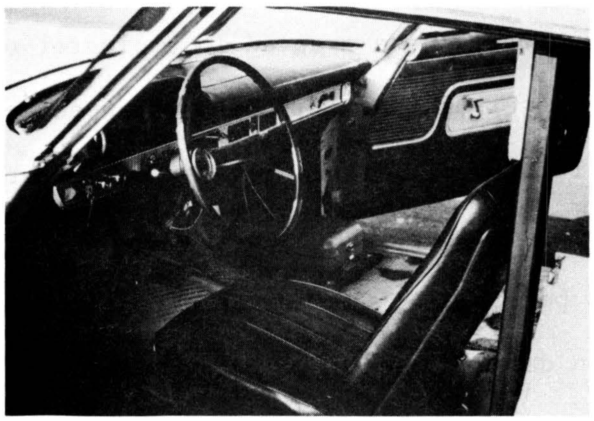
Both vehicles were completely operable. The steering mechanism, suspension, and front end alignment were in good repair and were inspected after each test.

After modification and installation of the instrumentation equipment, the vehicles were weighed and the center of gravity was determined for accelerometer positioning. The weight of the 2-door and 4-door vehicles was 3830 and 3820 pounds respectively including all test equipment.

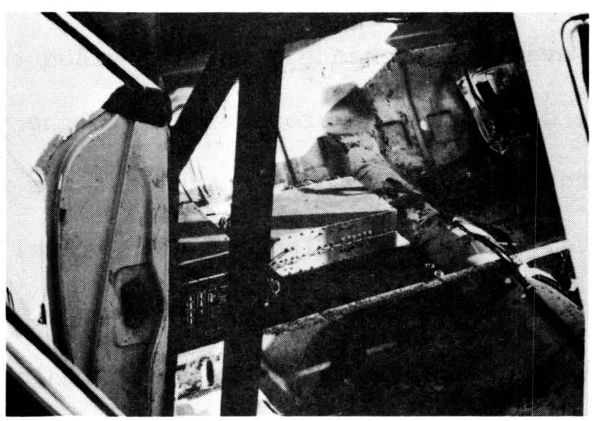
VEHICLE INSTRUMENTATION

The measurement and data acquisition system consisted of selected force and event sensors, properly signal conditioned, and thence applied for transmission through an Inter Range Instrumentation Group (IRIG) Standard proportional bandwidth telemetry data system. Each force measurement channel was provided with individual discrete force level calibrations. In addition, each IRIG subcarrier was subject to standard high and low band edge calibration voltages and resultant frequencies. Band edge calibrations were supplied by an

(a) Stadia Markings on Test Vehicle No. 1



(b) Modifications for Driven Tests



(c) Instrumentation in Rear Passenger Compartment

Test Vehicle No. 1

Figure 10

"in-flight" calibrator, an integral module of the IRIG transmitter system.

All data were acquired on-site using the TTI Mobile Telemetry Station. Data were processed and stored on magnetic tape in real-time. In addition, real-time meter displays in the mobile unit provided qualitative functional analysis as the tests were in progress.

Three force measurement transducers measuring longitudinal, lateral and vertical forces were mounted in a cluster equidistant from the vehicle static center of gravity. Each force sensor was dynamically calibrated using a factory-calibrated reference accelerometer. A tri-axis recording Impactograph was also installed on the vehicle floor as closely as possible to the center of gravity to provide back-up acceleration data in case of primary equipment failure.

Average velocity over the last ten feet before leaving the roadway was determined by impulses from a tape switch mounted on the front bumper as two upright wooden dowels were impacted. Two separate, yet closely related event data channels were provided to record this and to produce pulse data directly proportional to the vehicle wheel velocity. A pulse-to-distance ratio over the last ten feet of roadway travel was determined. Vehicle decelerations in traveling up the slope could be approximated from pulse data; however, the pulse-instrumented wheel (left front) was not always in contact with the ground after leaving the roadway.

Figures 11 and 12 show details of the vehicle instrumentation equipment and the mobile telemetry station.

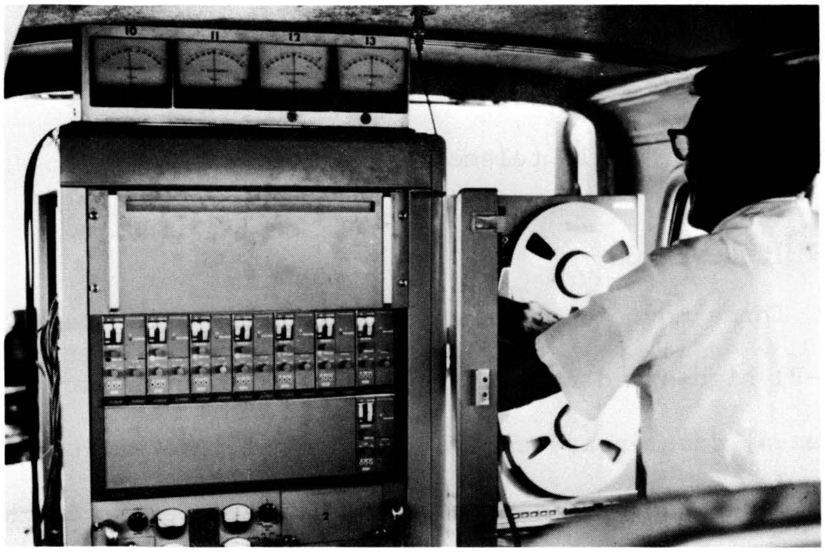
PHOTOGRAPHIC COVERAGE

Three movie cameras were used during each test - two Photosonic (Model 1-P) high-speed cameras for data acquisition purposes, and a Bolex (Rex-4) documentary camera for general information film coverage.

One high-speed camera was positioned in the ditch region; the other at the top of the backslope with the fields of view of the two cameras overlapping to provide a common reference point for triangulation purposes. The lower camera was used primarily to investigate vehicle behavior during the turning maneuver and as it traveled through the ditch region. Vehicle behavior on the back slope was studied from the upper camera film. The upper camera was panned to follow the test vehicle throughout its entire path, the lower camera remained stationary.

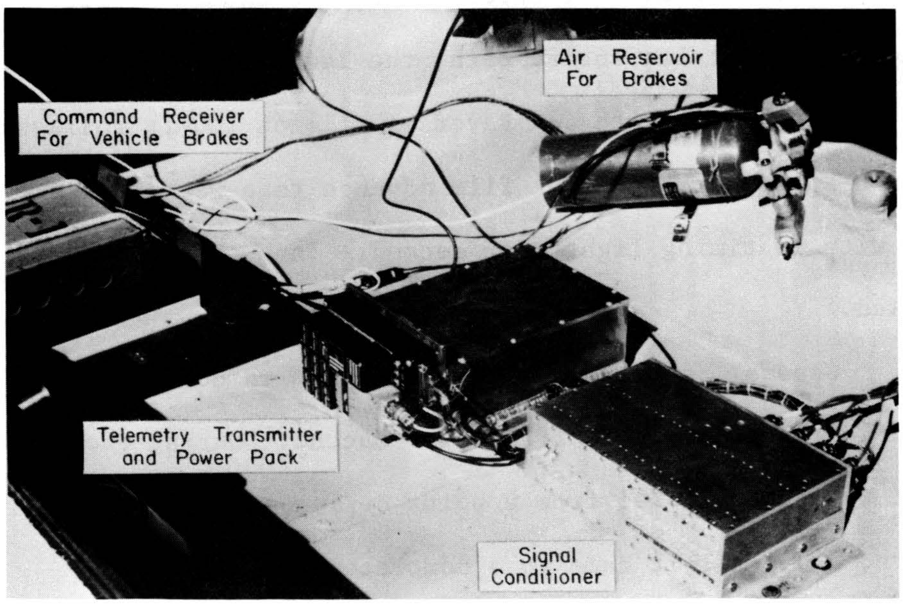
Black and white 4-X Reversal film on 100-ft rolls was used in both high-speed cameras. The film advance rate was 100 frames per second with 10 timing lights per second. In both cameras, 25-mm lenses were used.

General documentary film was taken in color using ECO color film in 100-ft rolls at 24 frames per second. During each test, the vehicle was photographed from a point during acceleration, through the turn, and until it came to a complete stop.



TTI Mobile Telemetry Station

Figure 11



Telemetry Equipment in Trunk of Test Vehicle

Figure 12

TEST PROCEDURE

The instrumented test vehicle was driven, or towed and released, through the slope and ditch configuration. Longitudinal, lateral, and vertical accelerations at the vehicle center of gravity were measured for each traversal. The intended angle of departure from the roadway was 25 degrees for all tests. Speed was varied from 30 to 60 mph in 10-mph increments at each site and ditch configuration.

TEST SEQUENCE

A test sequence of increasing severity was established to minimize the hazard to driver and equipment. The tests on the steepest slopes were scheduled last to permit maximum data acquisition by "working up" through the less severe slope combinations. This procedure provided the test driver an indicator or relative scale on which to base his tolerance limit.

Four traversals (30, 40, 50, and 60 mph) were conducted on the rounded ditch at Site 1, the site having the flattest back slope. The rounded ditch was then converted to a V-ditch by extending the side and back slope at their existing steepness until a vee was formed at their intersection. A test was conducted at each of the four speeds through the V-ditch. This test sequence was repeated at Site 2 and finally at Site 3, the site having the steepest back slope.

DRIVER CONTROL

In the sixteen tests conducted at Sites 1 and 2, the vehicle was driven by a professional test driver. Several advantages were realized by using a driven rather than a towed vehicle. The encroachment angle could be achieved more accurately because the driver could make minor steering adjustments during the turn to compensate for drift. This was particularly useful during the afternoon tests when the asphalt was extremely hot and frictional capability was reduced. Also, the delay between successive tests was decreased. The driver's most important contribution was his personal evaluation of the severity of the test, and immediate "after-the-fact" discussion of the sensations experienced through the turning maneuver and the ditch.

All tests were conducted in a "hands-off" steering mode. Since the "no-steer" mode was used in the HVOSM simulation, complete lack of steering control was required in the full-scale tests. Therefore, the driver accelerated to desired speed along the main travel lane, negotiated the turn to the 25-degree departure line, then removed his hands from the steering wheel immediately prior to leaving the pavement. Manual steering control was not regained until the vehicle had traveled through the ditch and well up the back slope, and only then if it became apparent that the vehicle would travel over the top of the slope and incur undercarriage damage. Vehicle path, therefore, was dependent only upon the wheel forces induced by the terrain.

TOW-CABLE, GUIDANCE AND TURNING SYSTEM

Approximately 1000 feet of acceleration distance was required to attain the 50 and 60-mph exit speeds. Right-of-way and pavement width constraints prohibited use of a direct tow and release system into the ditch region at 25 degrees. Therefore, acceleration to the desired speed was accomplished along the travel lane by a conventional reverse-tow system. Upon release from the tow and guidance cable, a vehicle-mounted mechanism provided the necessary steering input to turn the vehicle toward the ditch.

Release from the tow and guidance cable activated a mechanism connected to the steering wheel which turned the vehicle to the right in an arc toward the side slope. This turning force was maintained until released by a second mechanism, activated by a timing switch, which applied a left-turning force to the steering wheel to return the front wheels to a straight-forward direction. The complete maneuver was accomplished within the 42-ft pavement width so that the vehicle was traveling in a free-wheeling condition along a straight line as it left the roadway.

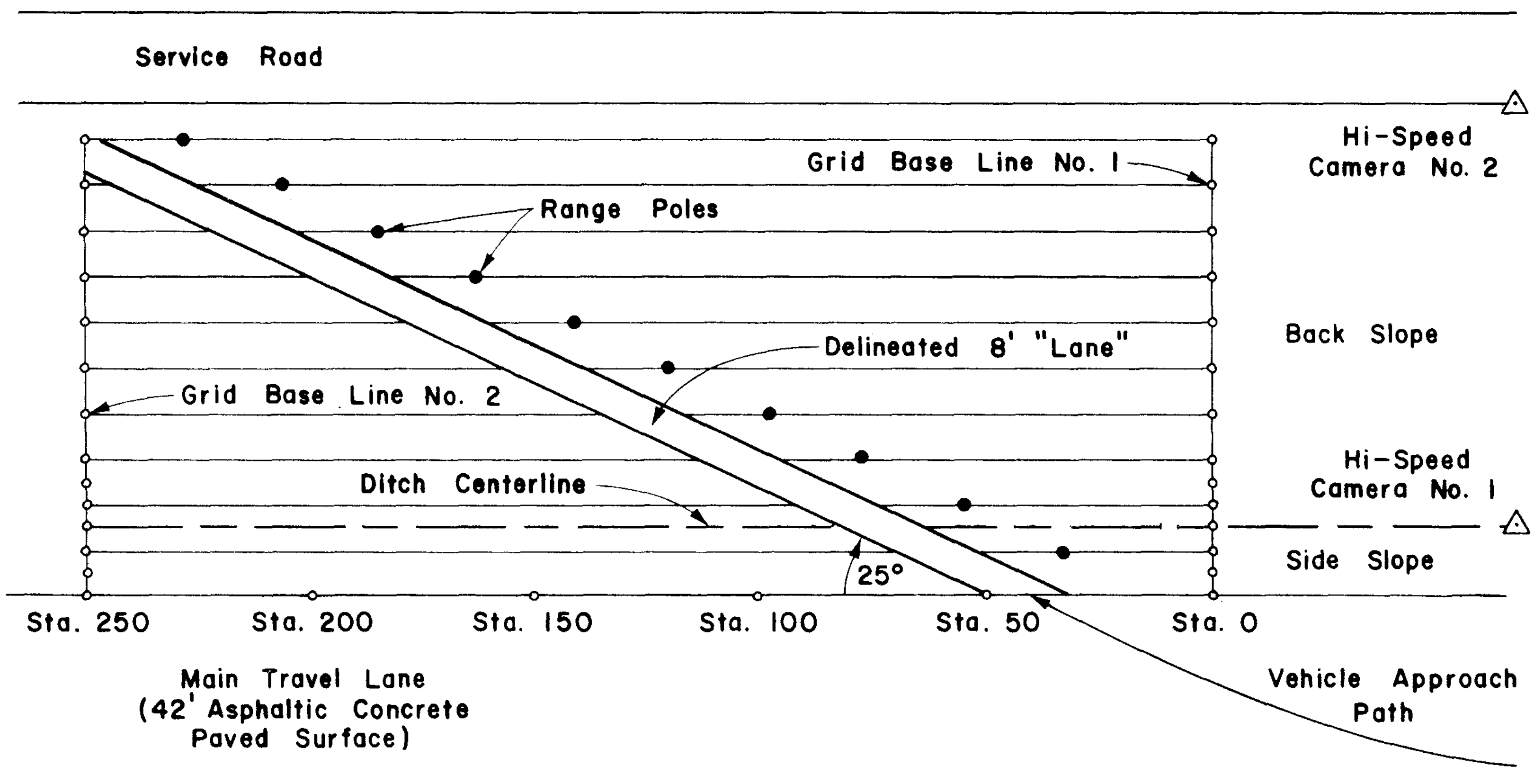
The amount of right-steer angle and subsequent left correction was determined by repeated trial and adjustment. Calibration at the study sites prior to actual test conduct was unfeasible because of insufficient lateral recovery distance. Therefore, the system was tested and calibrated on the concrete runways at the Texas A&M Research Annex. The required 25-degree departure angle could be negotiated within one or two degrees in the available 42-foot pavement width. However, the friction characteristics of the concrete runway differed considerably from the asphaltic concrete pavement at the test sites. Therefore, it was obvious that adjustments would be required to obtain the desired exit angle under actual test conditions.

Since the point of cable release was fixed, corrections were made by adjusting one or a combination of the right-turning force, the left-turning force, or the time interval between application of the two. Necessary adjustments for the higher speed tests were based on the vehicle behavior during the lower speed runs.

DETERMINATION OF VEHICLE PATH

Two independent methods were used to determine the vehicle path after departure from the travel lane. The edges of an 8-ft. wide lane along the 25-degree line were delineated with 3-inch white tape at Sites 1 and 2. Thus, the proper exit angle was highly visible to the driver as he negotiated the turn. A row of range poles was located parallel to the 25-degree "lane" and offset 8 feet. The position of the range poles with respect to a grid system on the ground and to the two high-speed camera positions was known. The coordinates of the test vehicle with respect to the grid could then be computed from the film analysis using triangulation techniques and the vehicle path plotted.

A thin layer of sand was spread over the slopes in which tire imprints were clearly visible. The vehicle path was measured from the grid system base lines after each run. The slopes were then raked to remove the tire imprints. The path was plotted on a large scale plan view of the test site from which exit angles could be verified. A typical site grid system is shown schematically in Figure 13.



Typical On-Site Grid System and Reference Markers

Figure 13

DETERMINATION OF VEHICLE SPEED

An immediate indication of vehicle speed was determined from tape switches mounted on the front bumper. The tape switches were activated by successive contact with two ½-inch upright wooden dowels placed 10 feet apart at the edge of the pavement on the 25-degree line. Precise speed was determined from the high speed film.

IV. ANALYSIS OF TEST DATA

FILM ANALYSIS

The study film was analyzed on a Vanguard Motion Analyzer. This device is a film reader used to evaluate photographic data. Its principle components are a projection head and a ground glass screen that permit precise observation and measurement of distance, angles, and time from 16-mm film. Film may be viewed a single frame at a time or at variable speeds up to 30 frames per second. Displacement or rotation with respect to time may be determined since the original film advance speed is known.

The ground glass screen contains an X-Y grid system (0.001-inch measurement capability) on which the image is projected. These movable crosshairs, in conjunction with a fixed reference line in the plane of the screen, allow determination of the object displacement between successive frames.

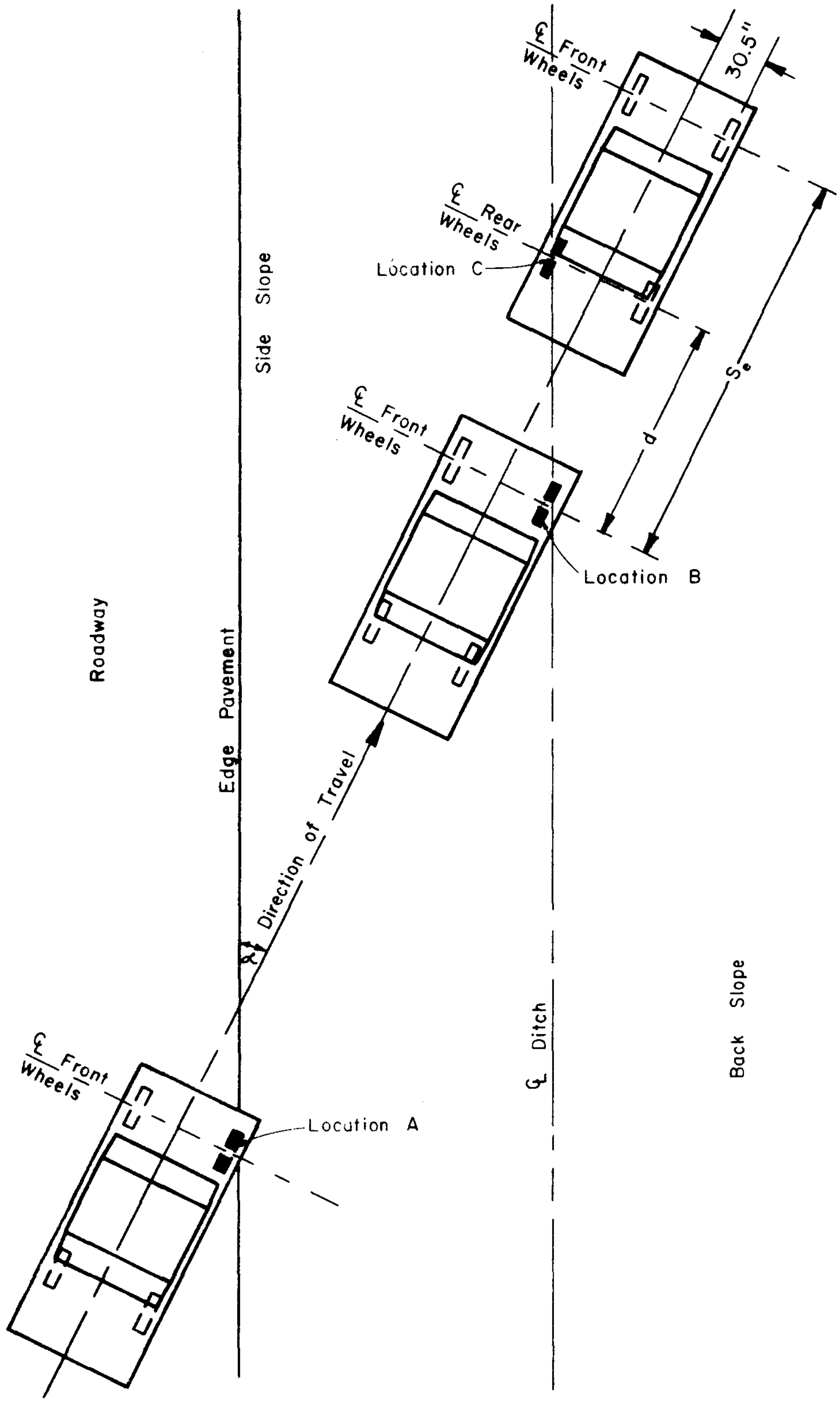
VEHICLE SPEED

The high-speed film was used primarily to determine vehicle speed at various positions along the path. Also it was possible from the film coverage to determine the points at which vehicle wheels were airborne, when bumper contact occurred and a qualitative evaluation of the severity of the ditch traversal. Although it was not used to determine vehicle position, the coordinates of the vehicle throughout its entire path could be obtained from film analysis using triangulation techniques. Vehicle path up the back slope was more easily obtained by measurements of the tire imprints after each test.

Vehicle speed could be determined more accurately from the high-speed film than from wheel-pulse telemetered data or from the tape switch data. At Sites 1 and 2, initial speed at the right edge of the pavement just prior to encroachment on the side slope was determined from the three sources: tape switch activation, wheel-pulse telemetered data, and high-speed film analysis. With the exception of test 5, Site 1, all speed determinations agreed with ±0.5 percent (0.5 frames at 100 frames per second film advance). The tape switch dowel at Site 3 was located at the end of cable guidance system rather than at the pavement edge. Therefore, only film analysis and wheel pulse data were used to determine the initial speed for all tests at Site 3.

After the front wheels left the pavement, the accuracy of speed determination from the wheel impulse data decreased significantly because the instrumented front wheels became airborne. Therefore, all speed determinations for calculation purposes were obtained from the film analysis.

In all tests, vehicle speed was determined at three locations: the point of right front wheel departure from the pavement, the point at which the right front wheel crossed the ditch centerline, and the point at which the left rear wheel crossed the ditch centerline. The speed at these locations are designated thoughout this report as *initial speed, entering speed,* and *exit-speed* respectively. Figure 14 illustrates the wheel positions at each location. The speed at Location A was used in the simulation model as initial speed. Changes in vehicle speed in traversing the ditch were determined from the



Determination of Event Time from Vehicle Path

Figure 14

speed measurements at Locations B and C. In a few instances, speed could not be determined at Location C because dust obscured the vehicle stadia marks. The vehicle speeds are shown in Table 2.

EVENT TIME

In this report, event time, T_e, is defined as the time during which the test vehicle travels from Location B to Location C (distance S_e) as shown in Figure 14. The distance, S_e, is dependent on vehicle speed, V_e, and encroachment angle, α. The following procedure was used to determine the event time for each ditch traversal:

$$T_e = \frac{S_e}{V_e}$$

where T_e = event time, seconds

S_e = 119 + d, inches (Reference Figure 14)

d = 61.0 cot α

V = average of entering and exit-speed, feet per second

Table 3 presents a summary of event times for each test.

The time duration over which the acceleration forces were experienced differed for each test since the speed differed and the encroachment angle, although desirably constant, varied between tests. Four separate acceleration "spikes" were evidenced during each traversal as the individual wheels passed through the bottom of the ditch. Therefore, average accelerations were determined with respect to the

TABLE 2

TEST VEHICLE SPEEDS

Test Reference No.	Desired Speed (mph)	Initial Speed (mph)	Entering Speed (mph)	Exit Speed (mph)
SITE NO. 1				
1	30	28.9	32	31
2	40	38.2	40	38
3	50	45.2	46	43
5	60	53.4	56	57
6	30	29.0	31	28
7	40	38.3	40	38
8	50	47.5	50	47
9	60	55.9	57	50
SITE NO. 2				
2	30	34.3	34	34
3	40	41.7	44	41
4	50	48.8	51	40
5(a)	60	62.0	65	--*
6	30	29.8	31	30
7	40	41.7	44	42
8	50	50.6	52	44
9	60	62.2	65	56
SITE NO. 3				
1	30	33.7	32	28
2	40	45.9	42	36
4	50	42.6	45	42
5	60	47.6	53	50
7	40	47.2	46	37
8	50	53.6	48	46
10	30	35.6	34	27
11	60	56.9	50	47

*Vehicle stadia marks could not be seen because of dust. Film analysis was not possible.

TABLE 3

EVENT TIMES

Test Reference No.	Entering Speed (fps)	Exit Speed (fps)	Average Speed (fps)	Average Speed (in./sec)	Distance S_e (in.)	Event Time, T_e (sec)
SITE NO. 1						
1	47	46	46.5	558	230	0.41
2	58	55	56.5	628	205	0.32
3	68	63	65.5	786	244	0.31
5	83	84	83.5	1002	249	0.25
6	46	42	44.0	528	213	0.40
7	58	56	57.0	684	254	0.37
8	73	69	71.0	852	254	0.30
9	83	73	78.0	936	251	0.27
SITE NO. 2						
2	50	50	50.0	600	242	0.40
3	64	60	62.0	744	257	0.37
4	75	59	67.0	804	231	0.25
5	97	--	----	1164	249	0.21
6	45	44	44.5	534	255	0.40
7	64	62	63.0	----	242	0.35
8	76	64	70.0	----	256	0.30
9	95	82	88.5	1062	231	0.21
SITE NO. 3						
1	47	40	43.5	522	236	0.40
2	61	52	56.5	678	192	0.30
4	66	72	69.0	828	224	0.30
5	78	73	75.5	906	234	0.25
7	63	55	59.0	708	216	0.30
8	71	67	69.0	828	264	0.25
10	49	45	47.0	564	217	0.35
11	73	69	71.0	852	214	0.25

appropriate event time for that traversal rather than with respect to a constant event time for all speeds. Average accelerations on the basis of a constant event time would produce disproportionate results if the significant g's for a 30-mph traversal were computed on the same time base as a 60-mph traversal.

VISICORDER ANALYSIS

Acceleration data recorded on magnetic tape in the mobile telemetry station were transferred through a visicorder to paper tape displays of acceleration versus real-time. Pulse data were simultaneously recorded on the acceleration traces. All acceleration data were filtered (80-hz filter) prior to tape display, and were printed on a constant 6.67 g-per-inch ordinate. The real-time scale varied between tests from 80 msec to 160 msec.

Peak accelerations were measured on the visicorder tape. Average significant accelerations for each event were determined by ratioing the applicable area under the acceleration/time curve to the event time.

Presented in Appendix A are visicorder vertical acceleration traces of the critical event areas for the 60-mph tests on the round and V-ditch configurations for all sites. The visicorder traces were replotted to the same scales as the CALCOMP plots to facilitate comparison between test and simulated results. Accelerations measured during test and those predicted by the simulation model are discussed in detail in Section V of the report.

AVERAGE SIGNIFICANT ACCELERATIONS

Lateral, longitudinal, and vertical average accelerations were determined for each test. The average acceleration is defined herein as the ratio of the area under the acceleration/time relationship to the event time,

$$\text{Average Significant Acceleration} = \frac{\Sigma \text{ Area}}{T_e}$$

The vertical acceleration spikes, being more prominent than either the lateral or longitudinal spikes in all tests, were used to establish the beginning of the critical event through the ditch region. The calculated event times (Figure 14) agreed closely with the visicorder data and the HVOSM data. Therefore, the time point at which the critical event began was determined from the HVOSM data. This acceleration spike occurred when the right front wheel impacted the ditch.

The beginning point was located on the visicorder tape and the appropriate event time was scaled from this point along the time axis. The area under the acceleration curve between these two time points was obtained using a compensating polar planimeter from which the average significant accelerations were calculated.

HVOSM INPUT

One of the primary objectives of the study was the validation of the HVOSM simulation model for traversal of ditches and flatter slope configurations. To allow comparison between predicted vehicle response and that measured during the full-scale tests, it was necessary to simulate as closely as possible the actual test conditions.

Each test site was surveyed prior to test conduct. Cross-sectional profiles of the slopes were obtained at 50-ft stations along the pavement throughout the departure area and for a distance of 100 ft beyond each end of the prepared test section. The profiles comprised the terrain templates in the simulation model.

The test vehicle path was determined with respect to the on-site grid system (Figure 13) by measurement of the tire imprints in the layer of sand covering the test site. The coordinates of each tire were plotted on a large-scale drawing of the grid system from which were determined the point of departure from the pavement, the angle of departure, and the vehicle path throughout the maneuver. The departure coordinates, encroachment angle and initial speed obtained from test data were used as initial input values in the simulation model.

V. CORRELATION OF TEST RESULTS WITH HVOSM

Simulated results generally agreed very favorably with the test results, particularly for Sites 1 and 2. Several factors contributed to the close agreement between results on the first two sites. Most importantly, vehicle speed and encroachment angle could be much more accurately controlled at Sites 1 and 2 because the test driver was able to adjust speed and steering throughout the turning maneuver up until the point of side slope encroachment.

Speed and angle corrections could not be accomplished in the tests at Site 3 with the two-cable system and turning mechanism. Vehicle control, with the exception of remote braking, could be exercised only while the test vehicle was approaching the release point under tow. The turning maneuver was initiated by activation of the mechanism upon release from the guidance cable. The turning mechanism was calibrated by trial-and-error on a concrete pavement surface prior to test conduct. However, friction characteristics of the asphalt concrete at Site 3 differed considerably from the concrete surface. Since the turning mechanism could not be re-calibrated at Site 3 within the available recovery distance, the mechanism adjustment was estimated prior to each successive test. Therefore, the deviation from the required 25-degree encroachment angle was appreciable in several tests.

The departure point influenced the test data appreciably at Site 3. The departure point differed for each successive test as speed was increased. The tow system and guidance cable were anchored in the roadway, thus the point at which the turning maneuver was initiated remained fixed. For each 10-mph speed increase between successive tests, the point of departure from the roadway shifted approximately 50 ft. Since the entry point was shifted upstream for each speed increment, the test vehicle traveled over a different section of the test site during each test. This introduced another variable at Site 3 because the back slope steepness was not constant throughout the entire length. The back slope decreased in steepness near the region traversed by the test vehicle during the higher speed tests.

The adverse effects of a varied departure point were not experienced during the tests at Sites 1 and 2 because the driver was able to steer the vehicle through the turn and leave the roadway at approximately the same point for all tests. Marker cones were located upstream from the required departure point to identify the beginning of the turning maneuver. After one or two trial runs, the driver was able to negotiate the proper turning maneuver to enter the ditch region at the required angle within the delineated 8-ft "lane." The point of departure varied less than 2 ft during all tests at Sites 1 and 2.

The manner in which the turning maneuver was accomplished at Site 3 introduced another very important variable unique to this site. Whereas the driver was able to negotiate the turn at Sites 1 and 2 with only a minimum of vehicle rear tire lateral drift, the mechanical turning system introduced the right-turning force very rapidly, and four wheel drift was evidenced during the 50 and 60-mph tests. Therefore, the test vehicle was in a side-slipping attitude when it left the pavement. A significant roll angle was developed as the test vehicle skidded through the turn. The roll attitude will amplify or dampen the resulting vehicle accelerations, depending on the vehicle orientation at the time of impact. Side slip and vehicle draft can be accommodated in HVOSM provided the initial conditions (vehicle attitude, path, etc.) are determined and used as model input data. However, these data were not determined during the tests; a straight-line exit path was used as HVOSM initial condition input. Therefore, the predicted vehicle behavior did not simulate the test conditions in the Site 3 tests as precisely as in the Sites 1 and 2 tests.

With the exception of the four-wheel draft, the variabilities discussed above between tests at Site 3 and those at Sites 1 and 2 did not directly affect a comparison between test data and simulated results, because the test conditions (speed, angle, site geometry, etc.) were used as initial input to the simulation model. Therefore, on a test-by-test basis, the test and simulated results could be compared on a common base.

CORRELATION BASIS

Test vehicle accelerations were quantitatively compared to the vehicle accelerations predicted by the model. Comparisons included maximum and average accelerations at the vehicle center of gravity in the lateral, longitudinal and vertical axes. Identical event times were used to determine average accelerations for both test and simulated results. The area under the acceleration curve was determined by planimetering the visicorder trace for the test data. Average acceleration for simulation data were calculated from the printout data.

Resultant vehicle accelerations representing the vector sum of the tri-axes accelerations were determined for all tests. Table 4 presents a summary of the measured peak and calculated average vehicle accelerations in the lateral, longitudinal, and vertical axes plus the resultant acceleration. Simulated accelerations are shown for comparison.

DISCUSSION OF RESULTS -- SITE 1

Full-scale test resultant accelerations and their simulated counterparts are shown in Figure 15 for both ditch configurations at Site 1. Neglecting the small deviation in encroachment angle and point of departure between tests, a comparison on the basis of speed is rational. The significant points illustrated in Figure 15 are discussed below.

Accelerations predicted by the model agreed extremely well with those measured in the eight tests. In general, the predicted accelerations were slightly higher than those experienced in the tests; the 53.4-mph test being the only one in which the measured accelerations exceeded the prediction. The disparity between test and simulation ranged from 0.03 to 0.29 g's (Ref. Table 4) with an average of approximately 0.14 g's.

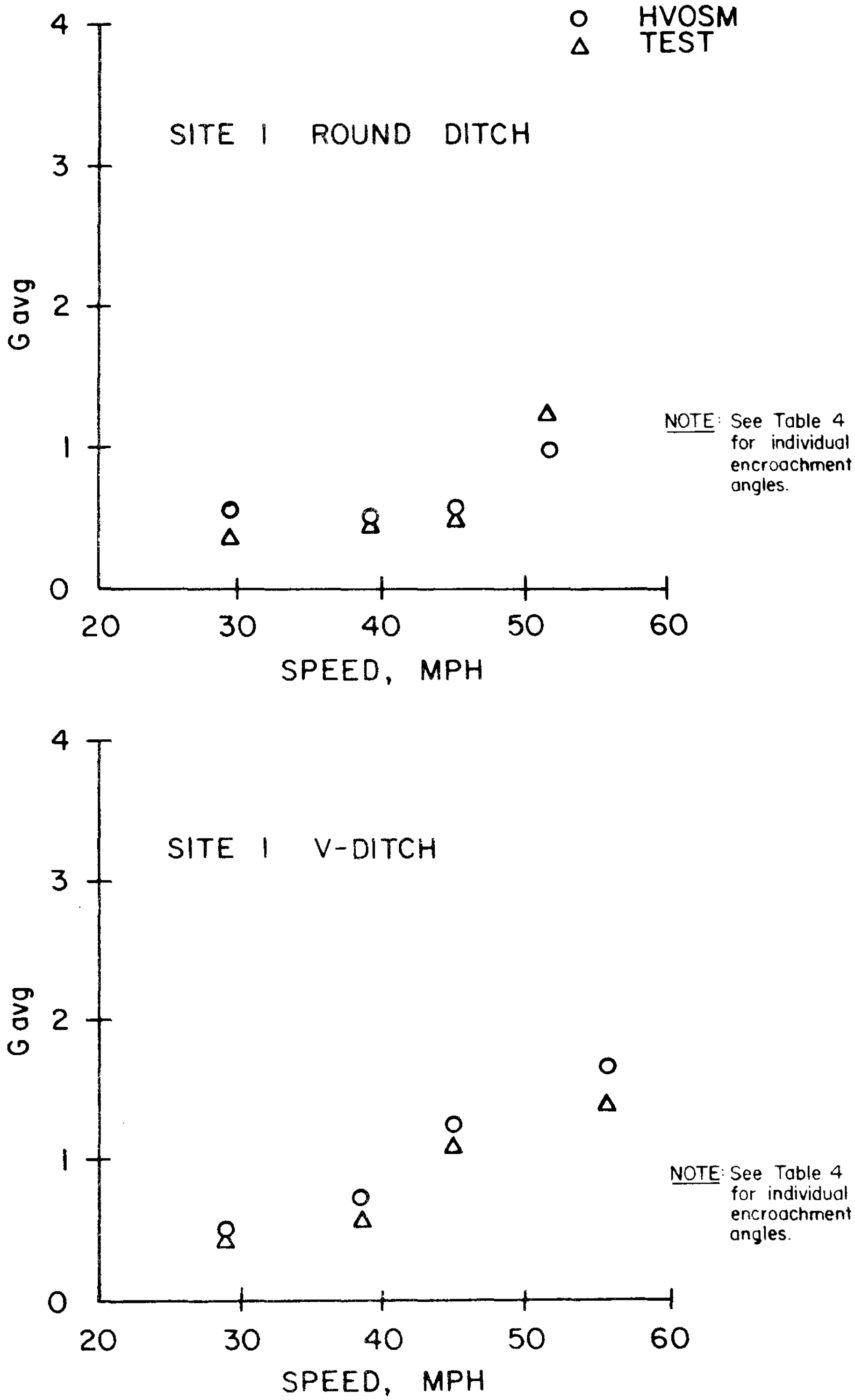
Also of significance is the apparent sudden increase in the upward trend of acceleration with increased speed. Intuitive reasoning would predict a general increase in acceleration, particularly in the vertical direction, in proportion to speed. A rapid increase in g's is

TABLE 4 SUMMARY OF VEHICLE ACCELERATIONS

TEST REF. NO.	DITCH SHAPE	INITIAL SPEED (MPH) DESIRED	INITIAL SPEED (MPH) TEST	INITIAL ENCROACHMENT ANGLE (DEGREES) DESIRED	INITIAL ENCROACHMENT ANGLE (DEGREES) TEST	TIME OF EVENT (SEC)	LATERAL ACCELERATION (G's) PEAK HVOSM	LATERAL PEAK TEST	LATERAL AVERAGE HVOSM	LATERAL AVERAGE TEST	LONGITUDINAL ACCELERATION (G's) PEAK HVOSM	LONGITUDINAL PEAK TEST	LONGITUDINAL AVERAGE HVOSM	LONGITUDINAL AVERAGE TEST	VERTICAL ACCELERATION (G's) PEAK HVOSM	VERTICAL PEAK TEST	VERTICAL AVERAGE HVOSM	VERTICAL AVERAGE TEST	TOTAL ACCELERATION (G's) PEAK HVOSM	TOTAL PEAK TEST	TOTAL AVERAGE HVOSM	TOTAL AVERAGE TEST
SITE 1	6.5:1 SIDE SLOPE, 4.9:1 BACK SLOPE																					
1	ROUND	30	28.9	25	28.8	0.40	1.18	—	0.37	—	0.87	—	0.20	—	3.14	1.21	0.37	0.30	3.47	1.21	0.56	0.37
2	ROUND	40	38.2	25	24.9	0.32	0.500	0.40	0.17	—	0.09	0.35	0.06	—	1.30	1.63	0.48	0.43	1.55	1.71	0.51	0.48
3	ROUND	50	45.2	25	24.2	0.31	.25	0.50	0.14	—	0.08	0.65	0.04	—	1.70	1.60	0.56	0.50	1.72	1.90	0.58	0.50
5	ROUND	60	53.4	25	26.5	0.25	0.93	0.74	0.20	0.62	0.75	1.07	0.18	0.05	3.37	2.60	0.94	1.07	3.52	2.91	0.97	1.24
6	VEE	30	29.0	25	24.5	0.40	1.02	—	0.20	—	0.87	—	0.32	—	2.13	1.50	0.33	0.40	2.44	1.50	0.50	0.40
7	VEE	40	38.3	25	26.0	0.37	1.19	1.40	0.25	0.174	0.94	0.63	0.39	0.08	3.73	4.06	0.58	0.66	4.02	4.34	0.74	0.69
8	VEE	50	47.5	25	24.3	0.30	1.05	1.36	0.16	0.196	2.00	1.17	0.72	0.09	3.79	5.55	1.02	1.06	4.03	5.83	1.25	1.08
9	VEE	60	55.9	25	26.5	0.27	1.99	1.83	0.44	0.60	1.58	1.50	0.65	0.10	6.40	6.60	1.47	1.24	6.53	7.01	1.67	1.38
SITE 2	7.2:1 SIDE SLOPE, 4.2:1 BACK SLOPE																					
2	ROUND	30	34.3	25	25.1	0.40	1.69	1.50	0.39	—	0.76	—	0.11	—	2.94	1.50	0.63	0.70	3.30	2.50	0.75	0.70
3	ROUND	40	41.7	25	23.9	0.37	1.97	1.85	0.16	0.10	1.36	1.01	0.29	0.10	5.28	4.54	1.00	1.00	5.35	5.00	1.06	1.01
4	ROUND	50	48.8	25	28.6	0.25	3.02	2.00	0.55	0.55	2.29	1.35	0.42	0.35	10.38	5.75	2.10	1.99	10.42	6.24	2.22	2.09
5	ROUND	60	62.0	25	25.1	0.21	7.69	4.63	1.33	1.00	5.64	2.05	1.68	0.77	12.17	9.52	2.56	3.03	12.41	10.94	3.34	3.28
6	VEE	30	29.8	25	24.1	0.40	2.55	—	0.40	—	1.50	—	0.64	—	2.76	2.41	0.46	0.88	4.04	2.41	0.89	0.88
7	VEE	40	41.7	25	26.3	0.35	1.76	1.70	0.62	0.86	1.37	1.34	0.72	0.31	3.24	4.48	1.29	1.27	3.38	4.98	1.60	1.56
8	VEE	50	50.6	25	24.0	0.30	2.54	3.21	0.75	1.11	1.90	1.47	0.86	0.40	5.02	5.22	1.95	1.89	5.07	6.30	2.26	2.23
9	VEE	60	62.2	25	27.5	0.21	10.0	4.50	1.43	1.52	7.13	1.65	1.98	0.50	13.12	6.61	3.24	2.70	18.13	8.16	4.06	3.14
SITE 3	7.0:1 SIDE SLOPE, 3.3:1 BACK SLOPE																					
1	ROUND	30	33.7	25	27.5	0.40	0.221	1.00	0.12	—	0.13	—	0.06	—	1.03	2.54	0.52	0.60	1.05	2.73	0.54	0.60
2	ROUND	40	45.9	25	39.8	0.30	1.06	1.15	0.51	—	1.45	1.29	0.40	—	4.02	3.34	1.62	1.32	4.14	3.76	1.74	1.32
4	ROUND	50	42.6	25	30.2	0.30	0.75	1.35	0.13	0.55	0.55	1.35	0.13	0.34	2.12	3.34	1.25	1.32	2.32	3.85	1.27	1.47
5	ROUND	60	47.6	25	27.9	0.25	0.71	2.00	0.15	—	0.66	1.27	0.14	—	2.67	5.55	1.21	1.82	2.82	6.03	1.23	1.82
7	VEE	40	47.2	25	32.4	0.30	2.57	2.55	0.41	0.09	2.39	3.45	0.77	0.79	7.23	6.02	1.77	1.41	7.96	7.39	1.97	1.62
8	VEE	50	53.6	25	22.9	0.25	2.39	2.00	0.47	0.35	2.08	2.15	0.69	0.41	7.25	4.20	1.45	1.59	7.87	5.12	1.67	1.68
10	VEE	30	35.6	25	32.0	0.35	2.17	2.80	0.34	0.41	1.56	2.35	0.73	0.31	3.40	4.45	0.76	0.62	4.32	5.76	1.11	0.81
11	VEE	60	56.9	25	32.8	0.25	4.43	1.41	1.03	0.18	3.59	10.80	1.06	2.06	10.88	15.40	2.88	2.18	11.67	16.04	3.23	3.00

NOTES:

1. ACCELERATIONS MEASURED AT VEHICLE CENTER OF GRAVITY.



Average Resultant Accelerations (Site 1)

Figure 15

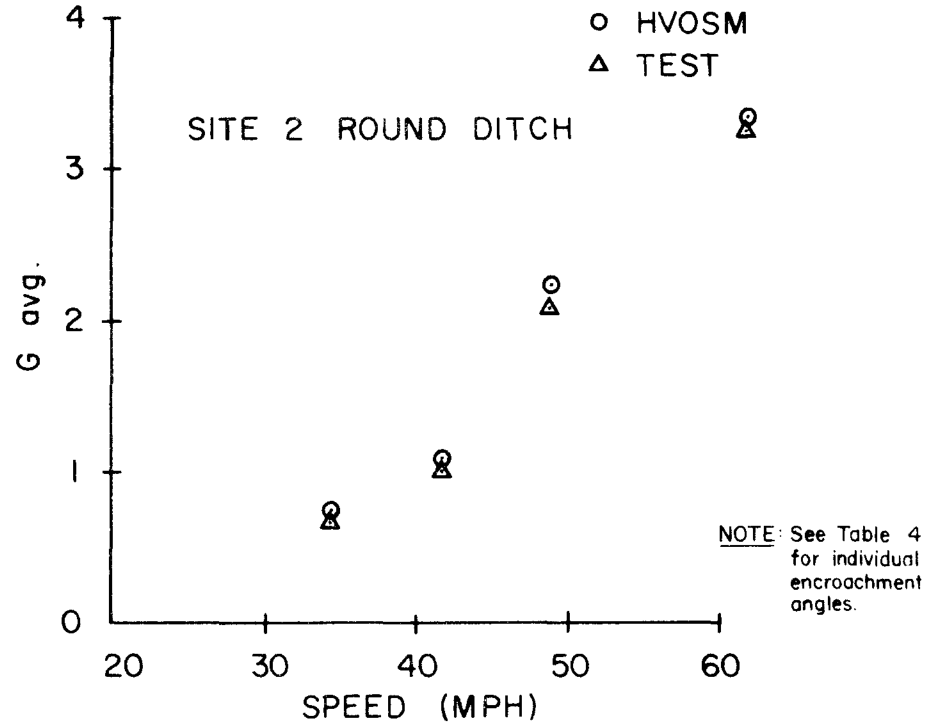
apparent at speeds of approximately 50 mph in the round ditch configuration. The increase occurs at approximately 40 mph in the V-ditch. Review of the high-speed film indicated that bumper contact and rear overhang drag occurred at and above these speeds in the two test series. Vehicle body/ground contact was minor or nonexistent at the lower speeds. Also, there was no evidence of the vehicle wheels becoming airborne when leaving the pavement during the low speed tests. Certain wheels became airborne as the test vehicle left the pavement during all tests above 40 mph and during some 40-mph tests. The model predicted that wheels would become airborne in leaving the pavement.

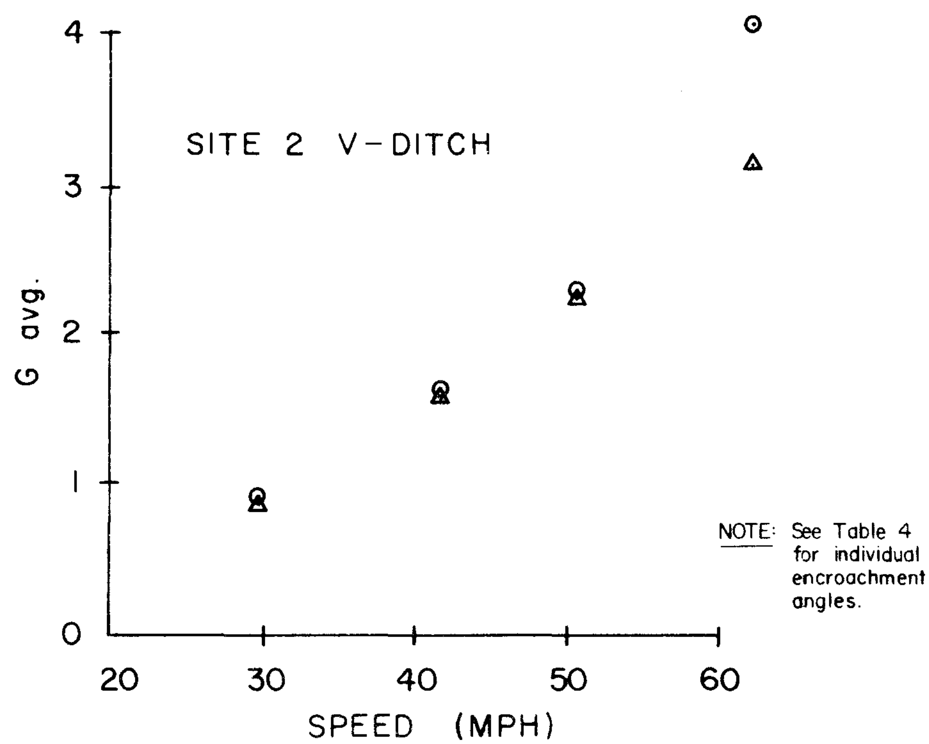
Higher vehicle accelerations were observed for the V-ditch tests throughout the speed range. This phenomenon was also observed in the simulated tests. The higher g's were particularly evident in the higher speed tests. This may be attributed to the severe bumper contact that occurred in these tests.

DISCUSSION OF RESULTS - SITE 2

Figure 16 illustrates the measured and predicted vehicle accelerations for the tests at Site 2. With the exception of the 62.2-mph V-ditch test, correlation between test and simulation was excellent.

The general trends observed in the Site 1 tests are repeated in the Site 2 data. The predicted accelerations were slightly higher in every test, with a disparity range of 0.01 to 0.13 g's excluding the 0.92-g difference at the 62.2-mph test. The





Average Resultant Accelerations (Site 2)

Figure 16

measured and predicted accelerations were higher than those in Site 1 as would be expected with the slightly steeper back slope. Again, the V-ditch produced more severe accelerations than the round ditch.

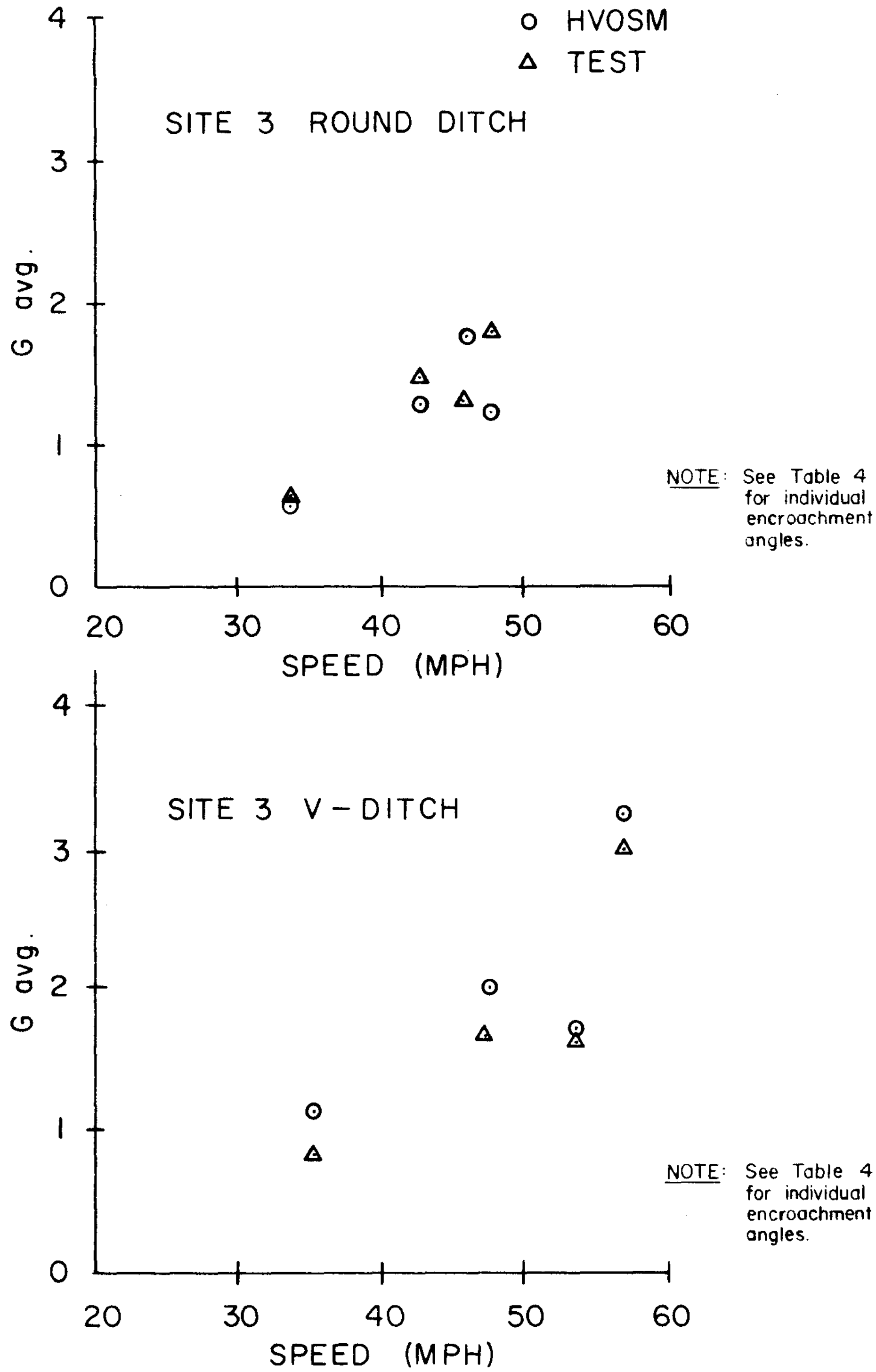
The 0.92-g difference between the test data and the simulation data represented the greatest disparity observed in the 24 tests. Since such close agreement had been observed between test and simulation results through the first fifteen tests, it appeared that the disparity was caused by either a faulty accelerometer measurement or an erroneous simulation input. The accelerometer measurement was corroborated by the Impactograph measurement. Additional traversals were simulated to detect systems errors. None were observed and the acceleration value could be substantiated by bracketing the speed and angle input values.

The high-speed film was critically reviewed to detect evidence of "fish-tailing" or other characteristics by which the phenomenon could be explained. The film analysis revealed that the test vehicle was completely airborne upon leaving the pavement. The right front wheel touched down just prior to entering the ditch, and entered a left-roll while partially airborne, but impacted the back slope approximately one wheel diameter beyond the ditch centerline. Therefore, the accelerations produced by the sudden reversal at the ditch centerline were not actually experienced. Instead, the net effect was a reduced vector change and a decreased vertical acceleration. The simulated vehicle became airborne, but regained wheel contact approximately 0.01 sec. prior to crossing the ditch centerline. Therefore, the accelerations resulting from the slope reversal were computed.

DISCUSSION OF RESULTS -- SITE 3

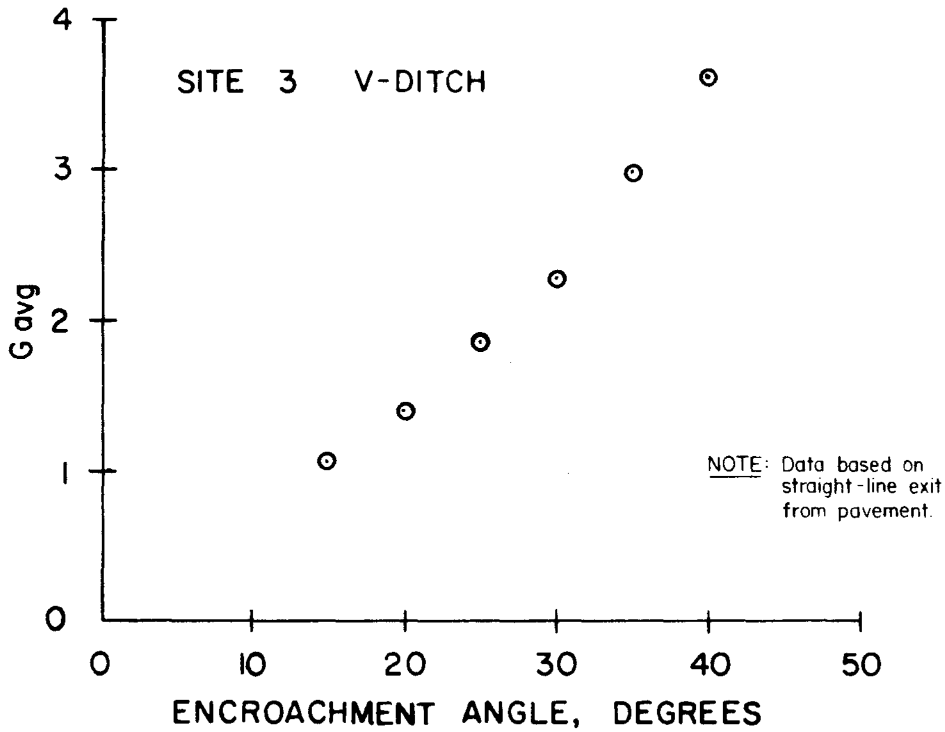
The measured and predicted accelerations for tests at Site 3 are presented in Figure 17. On a test-by-test comparison basis, the predicted accelerations agreed quite well. The disparity range between test and simulation was 0.01 to 0.59 g's with an average of 0.27 g's. (Ref. Table 4). Plotting acceleration on a speed base as shown in Figure 17 does not constitute a representative comparison because the encroachment angle varied from 22.9 to 39.8 degrees. However, the results were presented in this manner to maintain uniformity in data display. The significant point is that the accelerations predicted by the model using test values of the speed, angle, and site geometry as program input agreed quite closely. It is felt that the sliding attitude of the test vehicle in leaving the roadway contributed to the disparity between results at the higher speeds.

Since the encroachment angle varied to such a degree, six Site 3 traversals were simulated to investigate the sensitivity of acceleration to encroachment angle. The speed was held constant at 60 mph and the encroachment angle was varied in 5-mph increments from 15 to 40 degrees. Actual Site 3 geometry comprised the program templates and the departure point remained fixed so that the vehicle traveled through the same ditch area for each run. The resultant accelerations from these simulated traversals, shown in Figure 18,



Average Resultant Accelerations (Site 3)

Figure 17



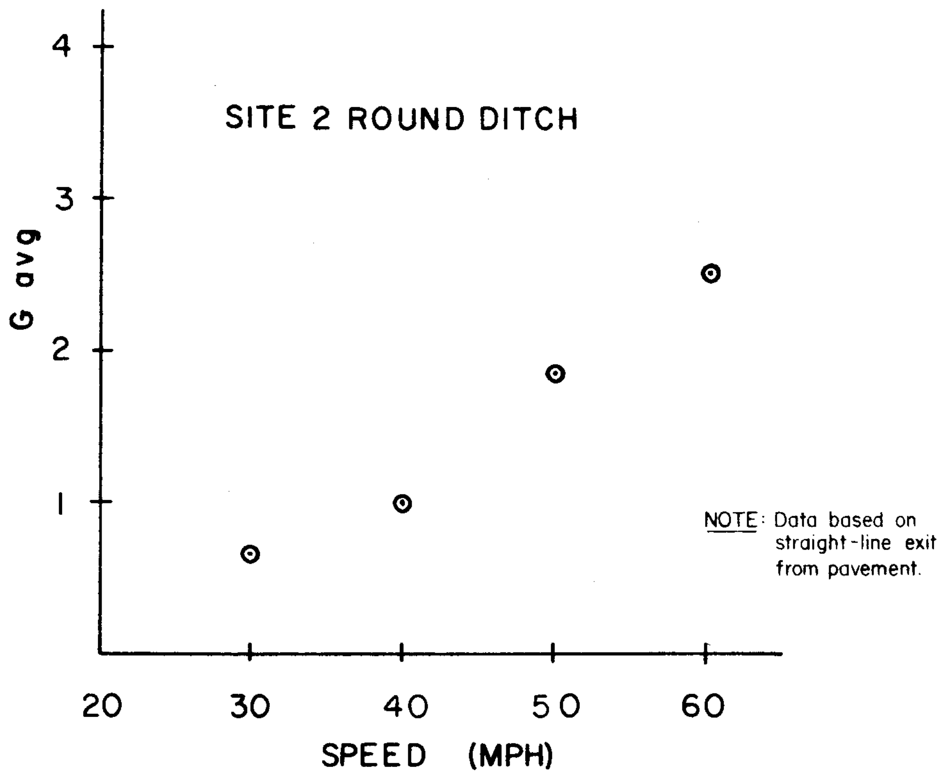
Sensitivity of Acceleration to Encroachment Angle
(HVOSM Simulation, constant 60-mph speed)

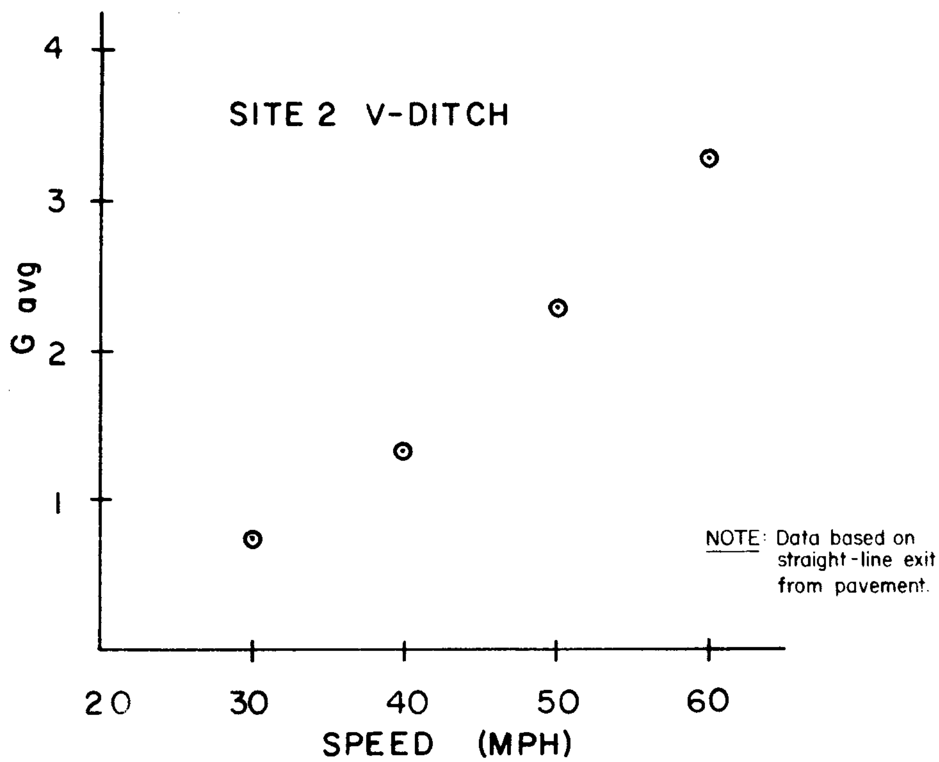
Figure 18

reveal that vehicle acceleration is strongly dependent upon encroachment angle.

To investigate the effect of speed on vehicle acceleration, traversals at a constant departure point and 25-degree encroachment angle were simulated at the three sites. Figure 19 presents a typical relationship between resultant average acceleration and speed under these conditions. It is evident that speed is an influential parameter.

The data obtained from the V-ditch tests contained less scatter than the round ditch data because the desired speed was attained more precisely and the encroachment angle was fairly constant. The accelerations from the 53.6-mph V-ditch test appear unreasonably low in Figure 17. However, the encroachment angle was 22.9° whereas the angles were approximately 32 degrees for the other three tests. The estimated acceleration for a 32-degree encroachment angle from Figure 18 would be approximately 2.5 g's. This value would agree closely with the acceleration trend shown in Figure 17.





Sensitivity of Acceleration to Speed
(HVOSM Simulation, constant 25-degree encroachment angle)

Figure 19

VI. SUMMARY OF FINDINGS

The objective of this research project was two-fold:

1. to evaluate, through correlation with full-scale vehicle test data, the effectiveness of the HVOSM model in predicting vehicle response during traversal of roadside slopes and ditches, and
2. to recommend maximum slope criteria based on best judgment of the test data evaluation and other related studies.

The research findings are summarized below and recommended maximum slope design curves are presented in Figure 20.

The HVOSM model predicted, with remarkable consistency, the vehicle response resulting from traversal of the ditch/slope configurations. Extremely close correlation was obtained between predicted and actual resultant average accelerations. From the correlation obtained in this study, the HVOSM simulation model appears to be a very powerful design tool with which to analytically investigate vehicle behavior on various terrain features. It offers a very cost effective method to investigate all combinations of roadside slopes at various vehicle speeds and angles of attack or selected configurations of interest to the designer.

The 16 tests on the 4:1 and 5:1 back slopes with a side slope of approximately 7:1 revealed that these combinations could be safely negotiated at speeds up to 60 mph with no rollover hazard and only moderate discomfort if the driver was adequately restrained. The 3:1 back slope (7:1 side slope) appeared quite formidable to the researchers and to the professional test driver. Since this slope combination was not driven, the effect on an occupant can only be estimated. However, based on vehicle damage sustained during the Site 3 tests and the peak g's measured, slopes of this steepness are not considered desirable design.

The test driver experienced considerable difficulty in achieving the 25-degree exit angle at speeds of 50 and 60 mph due to rear wheel drift yet he had a 42-ft wide pavement in which to negotiate the turn. A 25-degree encroachment angle at these speeds can be executed by a professional driver under certain conditions, but probably is too severe for design purposes.

Vertical accelerations comprise the dominant accelerations in ditch traversal and consequently contribute most significantly to the resultant acceleration. This substantiates the criteria assumed in the Task Order 2 study. Lateral and longitudinal accelerations can be considered to be virtually negligible in round ditch traversals and in V-ditch traversals at speeds less than 50 mph. Although relatively high acceleration "spikes" may be experienced, their time duration is so short that they do not appreciably affect the average acceleration.

The HVOSM predicted accelerations generally were slightly higher than the measured values. This can be attributed to vehicle suspension and inertia characteristics used in the model which influence the predicted response. It is extremely important that compatible vehicle characteristics are used for comparison purposes. This was emphasized by the results obtained from several preliminary simulated traversals using model constants pertaining to the Police Special Sedan rather than the "softer sprung" conventional Ford sedan used in the tests.

Response is influenced appreciably by the speed and angle at which the vehicle enters the ditch region. At the 25-degree encroachment angle, bumper contact and rear overhang drag were observed in all tests above 40 mph.

The HVOSM performed admirably in predicting the points at which wheels would be airborne. Even on the rather flat side slopes (7:1 average), loss of contact between wheels and the ground was observed at speeds of 40 mph and greater. This was predicted in the simulation data. At 60 mph, the test vehicle was completely airborne until just before entering the ditch.

When no steering or braking control was applied, the path followed by the test vehicle throughout the maneuver agreed, on a qualitative basis, with the predicted path. In general, very little redirection was observed as the vehicle passed through the ditch.

Although the resultant accelerations observed at each site were higher for the V-ditch than the corresponding round ditch, the V-ditch did not appear to be significantly more severe. The driver considered the V-ditch to be less severe than the round at the higher speeds whereas the reverse was observed for the low-speed tests. It is felt that the rate of loading imparted to the suspension system contributed to the effect experienced by the driver. At the high speeds, the significant loading resulted from short duration impact whereas at low speeds, the suspension system was allowed to "unwind" imparting a secondary vehicle acceleration over a longer duration. The overall effect may have been partly psychological because the measured response was not significantly different between the two configurations. This would indicate that design based on a V-ditch slope would not be appreciably unconservative.

TENTATIVE DESIGN RECOMMENDATIONS

Figure 20 presents tentative recommendations for the design of roadside slope combinations to permit vehicle traversal at speeds up to 60 mph and encroachment angles up to 25 degrees. The curves are based on evaluation of the Task Order 2/1 full-scale tests on the V-ditches, the Task Order 3 berm tests (6), and engineering judgment and experience. Table 5 shows the rationale on which Figure 20 is based.

In developing feasible combinations of side and back slope, various degrees of steepness were paired and then accepted or rejected on the basis of full-scale test experience in this study, Task Order 3 (6), HVOSM data, or engineering judgment. It can be seen in Table 5 that the exterior angle subtended by the side and back slope, Δ, becomes an indicator of expected severity. It is noted that for maximum combinations considered traversable, the angle Δ was equal to or less than 28.0 degrees. Similarly, the angle Δ was 23.5 degrees or less for the desirable recommended combinations. Since the resultant maximum and/or average acceleration is dependent primarily on the angle Δ, for a constant speed and encroachment angle, the angle Δ can be used as a "rule of thumb" indicator of expected severity. Using these criteria, slope combinations were calculated to produce the curves on Figure 20.

It is pointed out that the maximum recommended design curve lies in the upper region of Zone 2 (Ref. pg. xi), and the desirable design curve lies in the lower region of Zone 2 as presented in the Task Order 2 final report (7).

TENTATIVE DESIGN RECOMMENDATIONS FOR ROADSIDE SLOPES

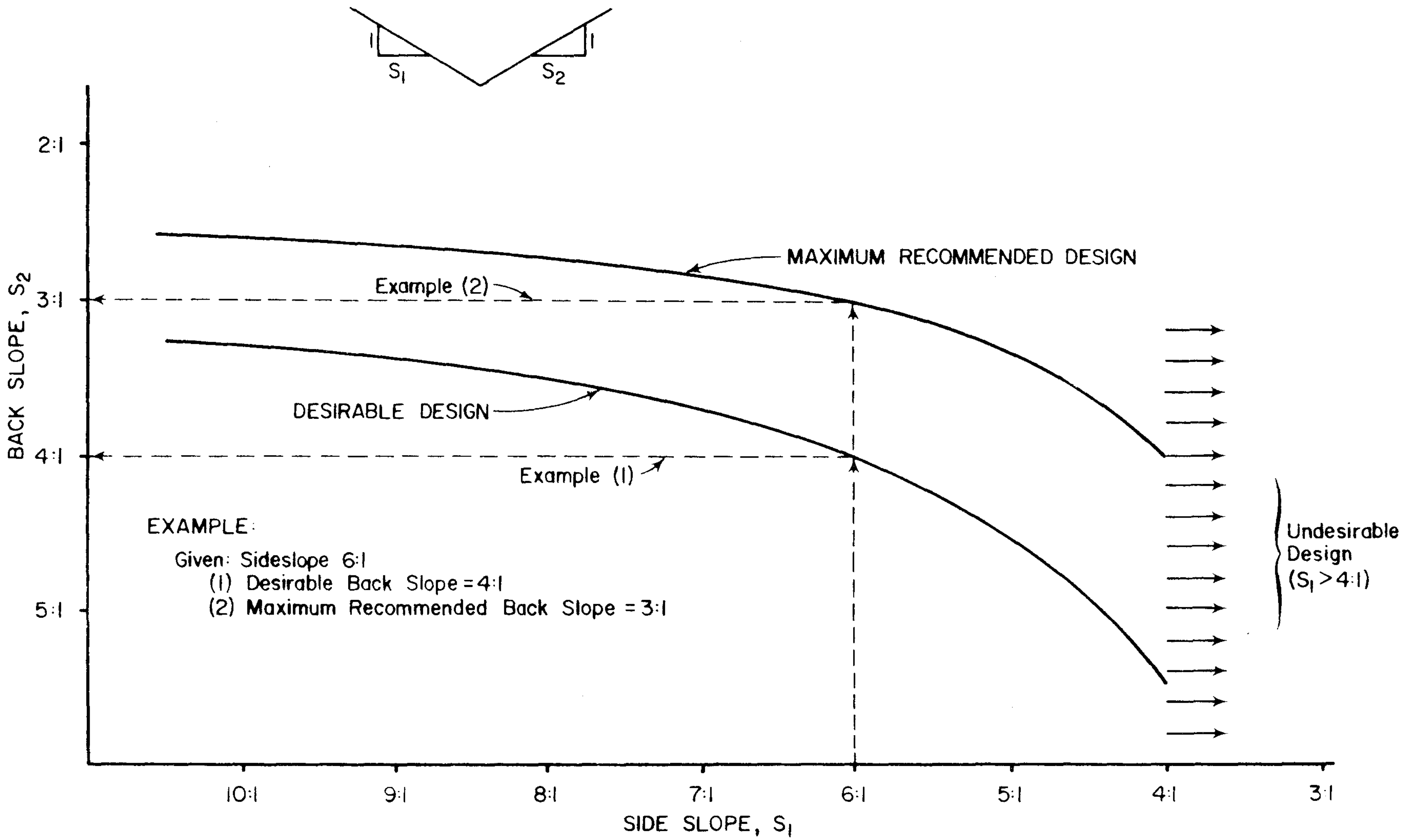
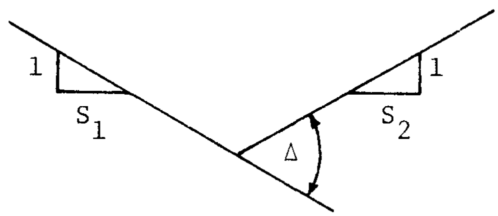


Figure 20

TABLE 5

TENTATIVE CRITERIA FOR ROADSIDE SLOPE DESIGN
(60 mph, 25-degree Encroachment Angle)



Rule of Thumb

Desirable Combination: $\Delta \leq 23.5°$

Maximum Recommended Combination: $\Delta \leq 28.0°$

Side Slope, S_1	Back Slope, S_2			
Nominal Steepness	Desirable Maximum (Nominal)	Δ (degrees)	Absolute Maximum (Nominal)	Δ (degrees)
4:1 (1)	5:1	25.3	4:1	28.0
5:1 (1)	5:1	22.6	4:1	25.3
6:1	4:1	23.5	3:1 (2)	27.9
7:1	4:1	22.1	3:1 (2)	26.5
8:1	4:1	21.1	3:1	25.5
10:1	4:1	19.7	3:1	24.1
Flat	3:1	18.4	2:1 (1) (3)	26.6

Notes:

(1) Slopes of this steepness are considered severe, and are recommended only where flatter slopes are not economically feasible.
(2) Substantiated by full-scale tests, Task Order 2/1.
(3) Substantiated by full-scale tests, Task Order 3 (6).
(4) The values in the above table represent "engineering judgments" based on observation of full-scale tests and HVOSM data from Task Orders 2, 2/1, and 3.

An example is shown in Figure 20 to illustrate its use. The curves in Figure 20 can be entered with a known side slope to select a safe back slope or vice versa. The example given in Figure 20 illustrates that for a given 6:1 side slope, the maximum recommended back slope and desirable back slope would be 3:1 and 4:1 respectively as shown by the dashed lines.

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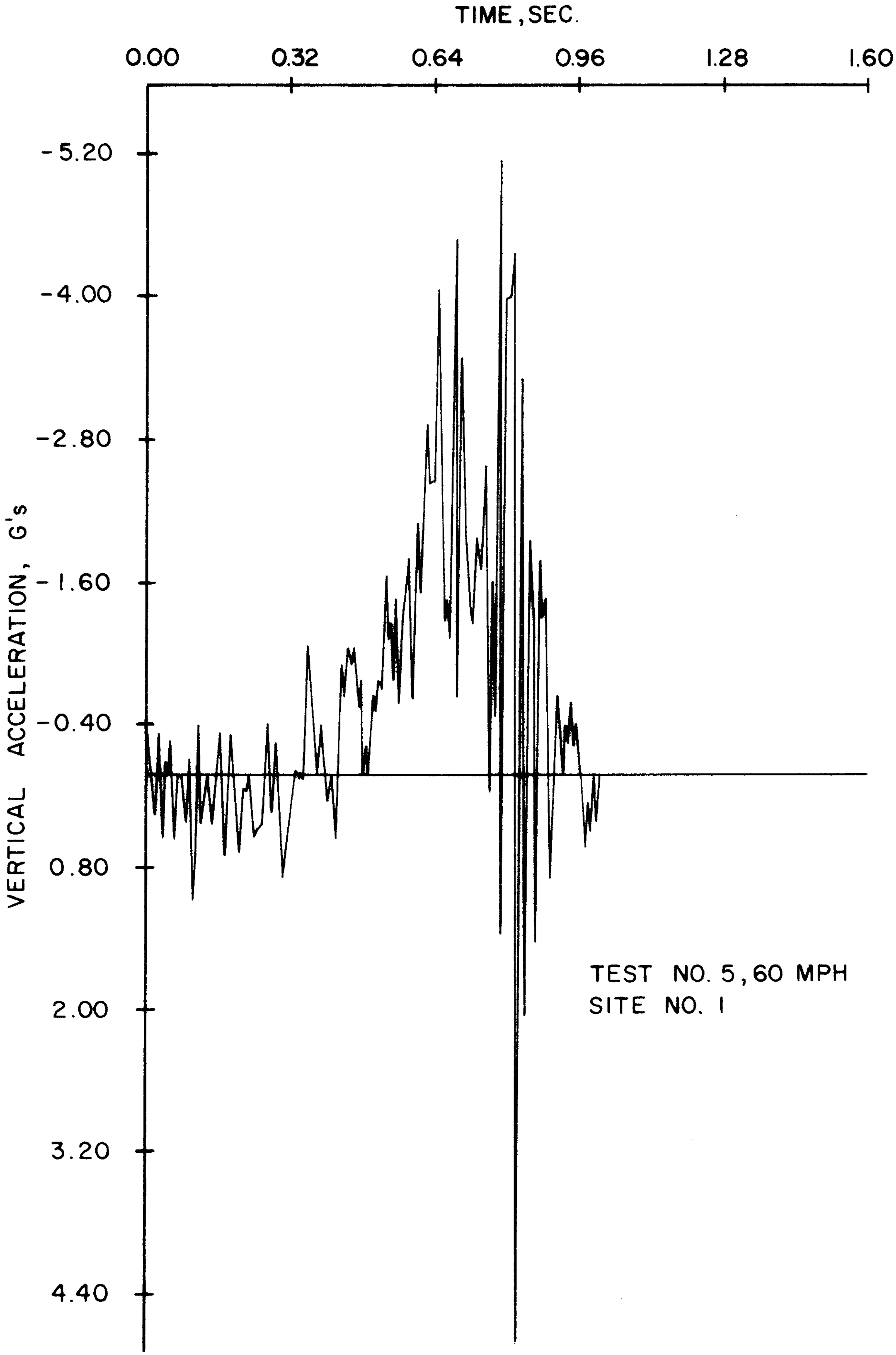
APPENDIX "A"

APPENDIX A

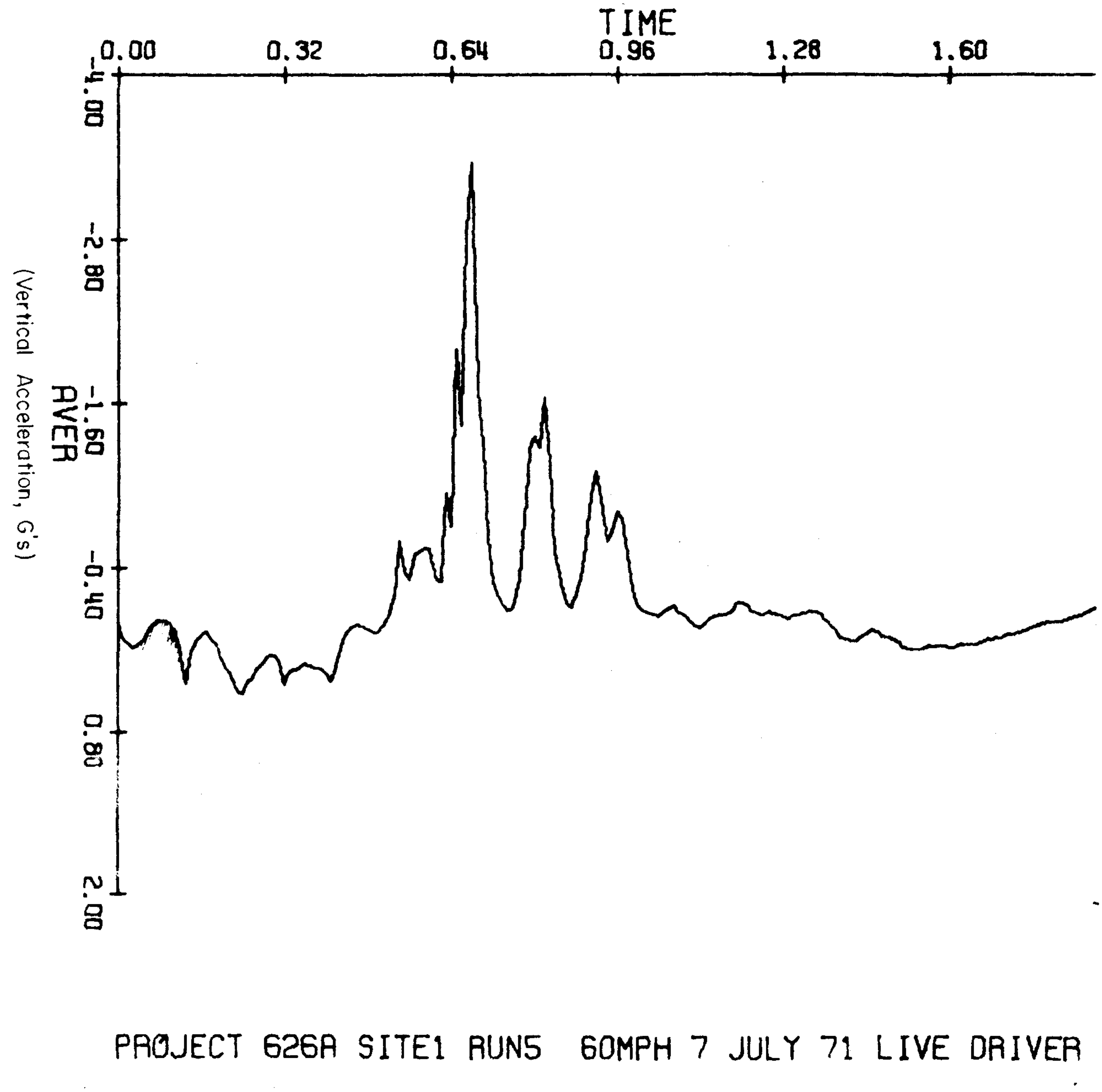
Presented in this Appendix are Visicorder acceleration traces and corresponding CALCOMP acceleration plots for the nominal 60-mph round and V-ditch traversals at each site. Visicorder traces have been replotted to the scale of their respective CALCOMP plot obtained from the model to facilitate comparison.

The event times and general characteristics of the simulation data and the respective test data agree favorably. The most significant difference between respective traces is the occurrence of a relatively large positive acceleration "spike" on the Visicorder trace and its conspicuous absence on the CALCOMP trace. Two explanations for this are possible. A 0.005-sec increment was used for calculation purposes in the HVOSM model with the data printout and CALCOMP plot increment being 0.01 sec. Since the time duration of the positive "spike" is extremely short, it is possible that the model did not calculate it. Also, the positive "spike" could be attributed to vehicle vibration. The model does not simulate vibration-caused accelerations. The model is developed on rigid body principles and calculates only acceleration forces which affect the vehicle orientation and speed.



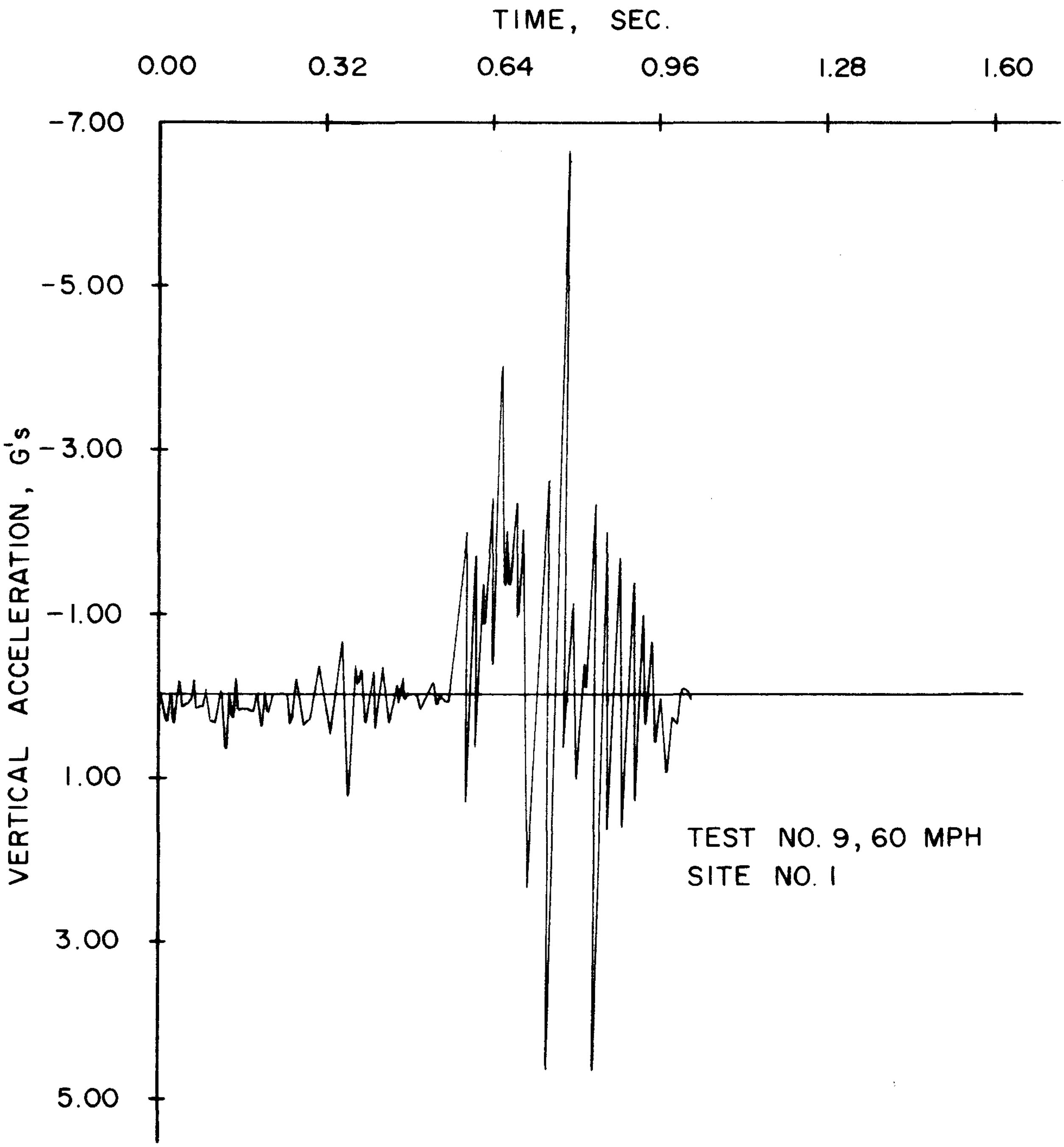
Vertical Acceleration Data from Visicorder (Round Ditch)

Figure A-1



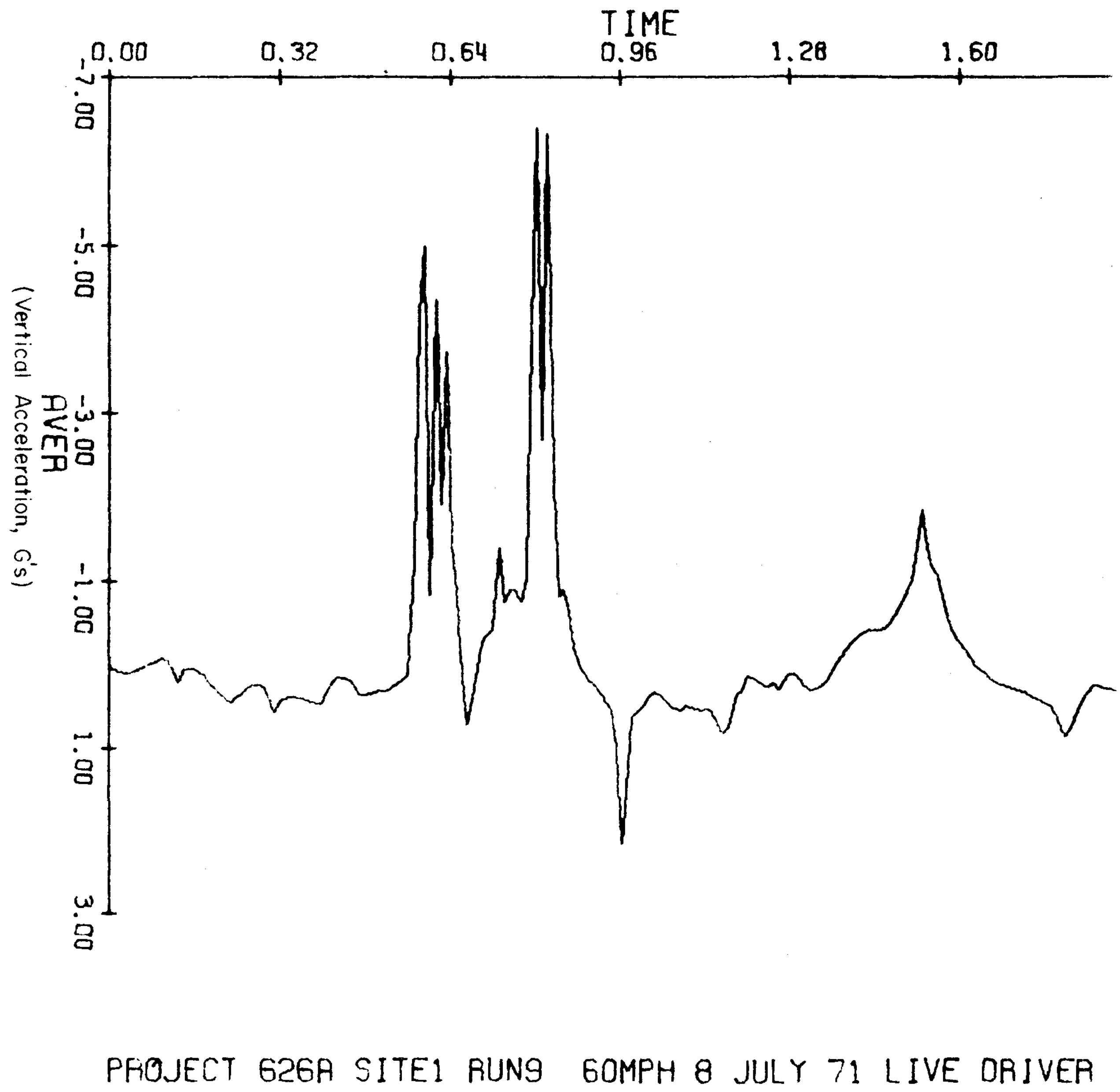
Vertical Acceleration Data from HVOSM (Round Ditch)

Figure A-2



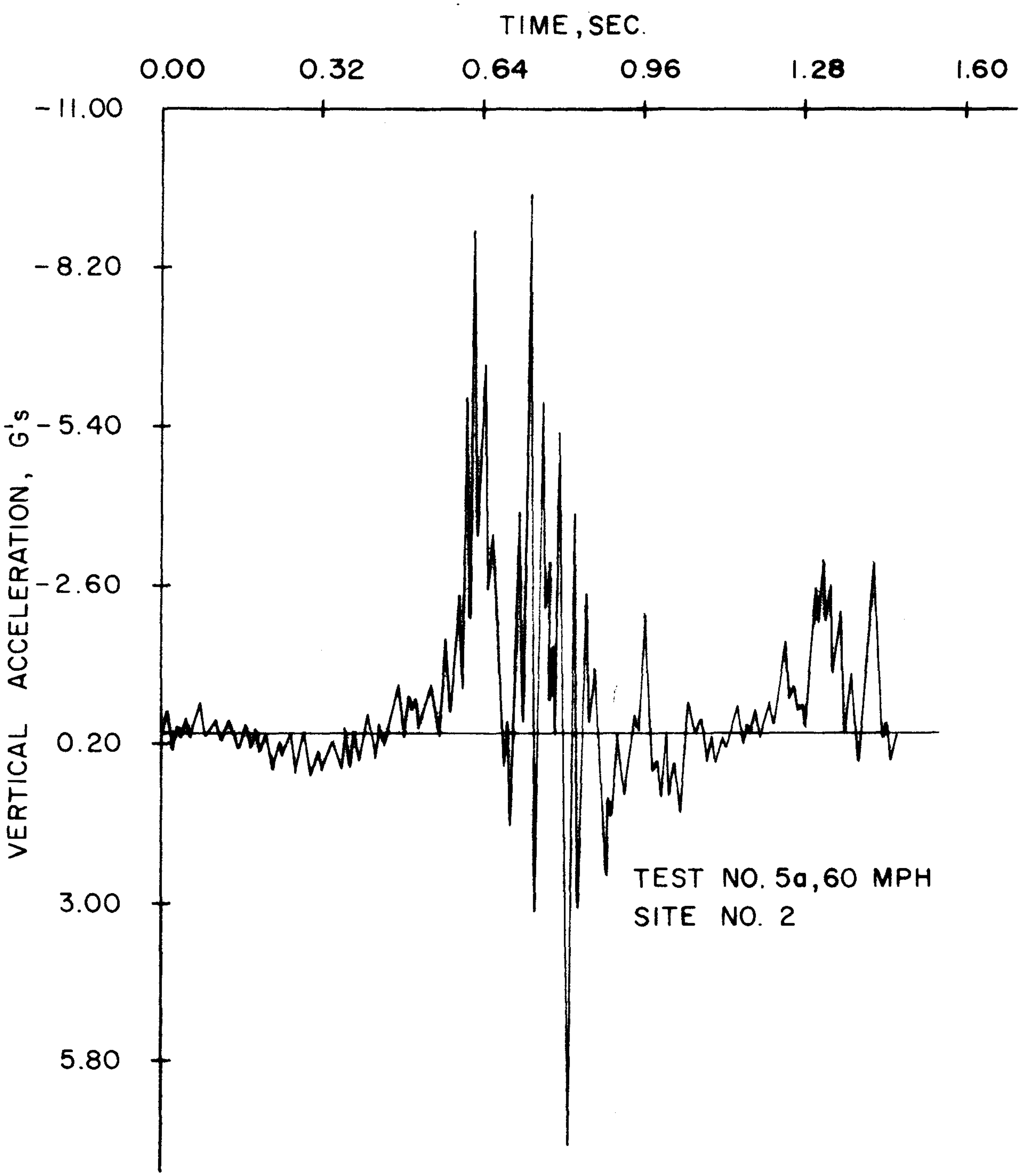
Vertical Acceleration Data from Visicorder (V-Ditch)

Figure A-3



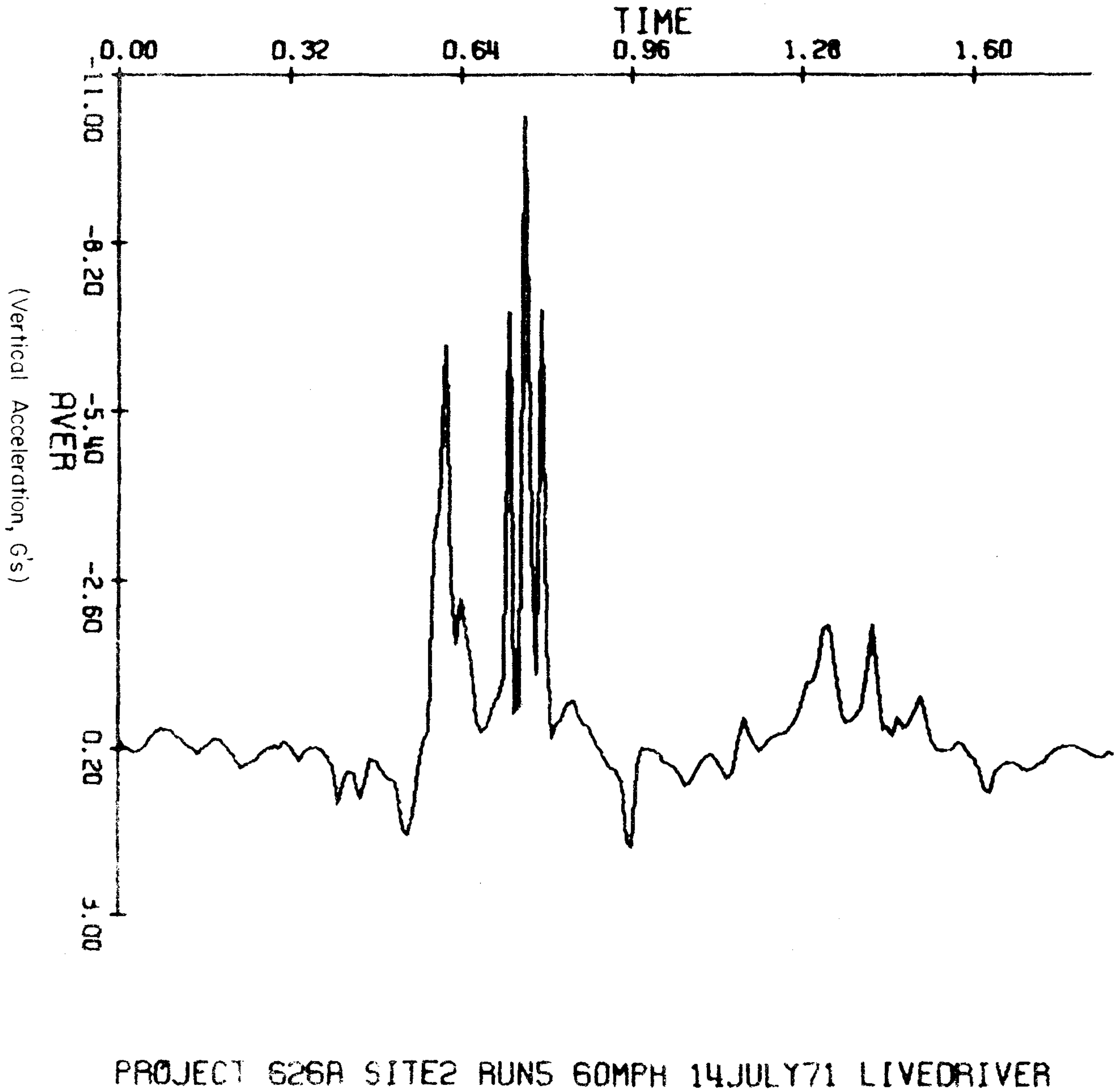
Vertical Acceleration Data from HVOSM (V-Ditch)

Figure A-4



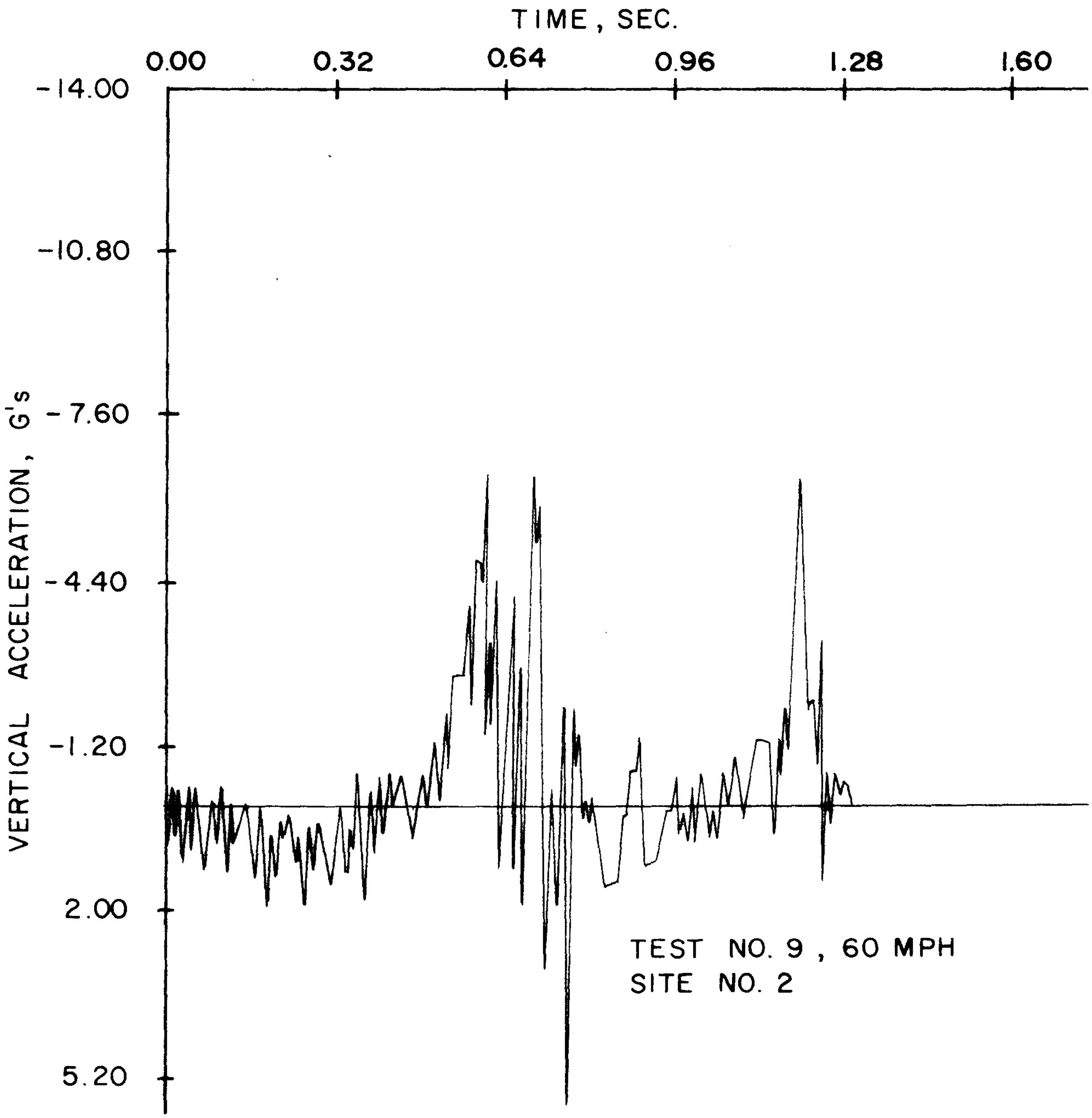
Vertical Acceleration Data from Visicorder (Round Ditch)

Figure A-5



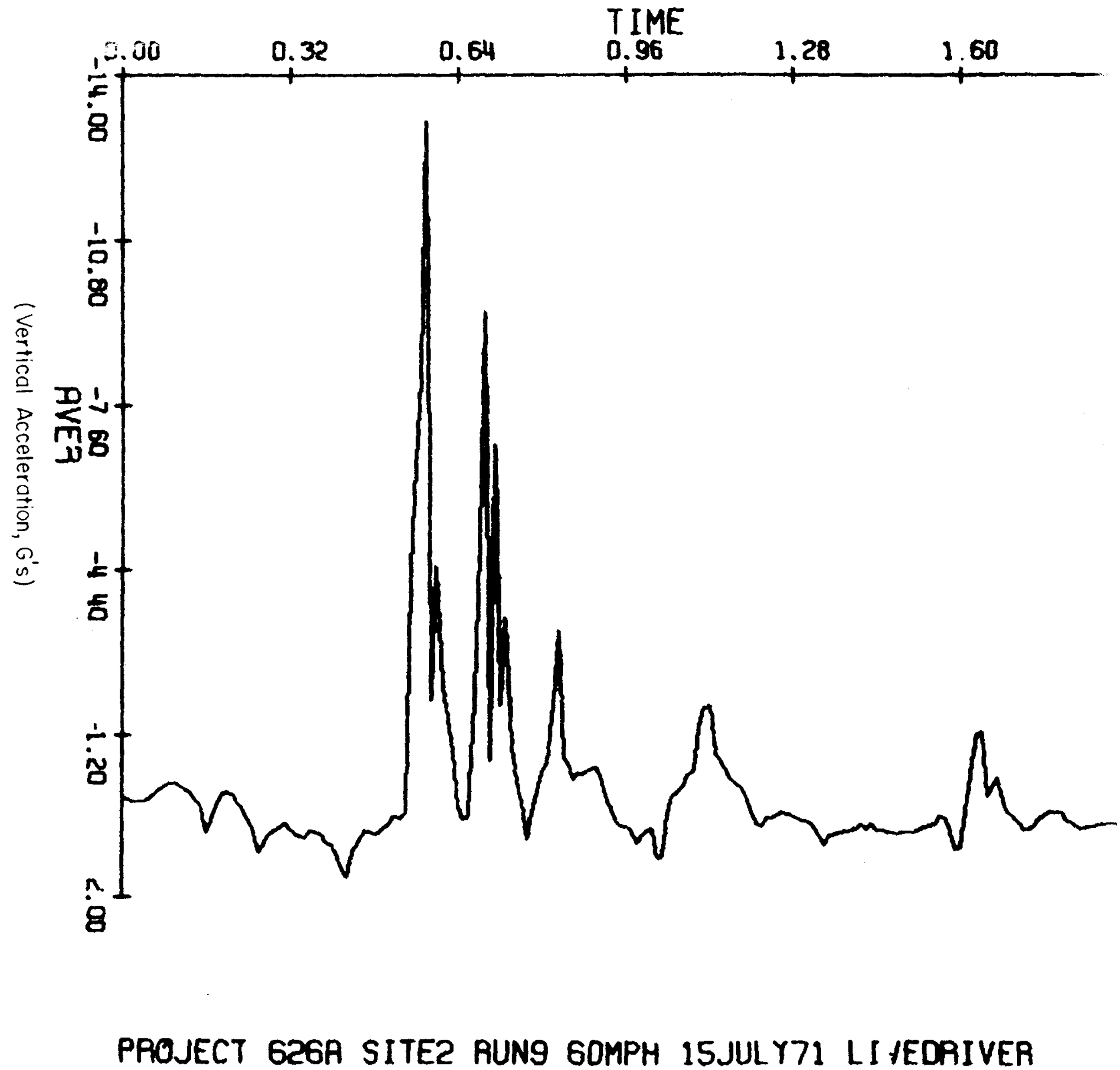
Vertical Acceleration Data from HVOSM (Round Ditch)

Figure A-6



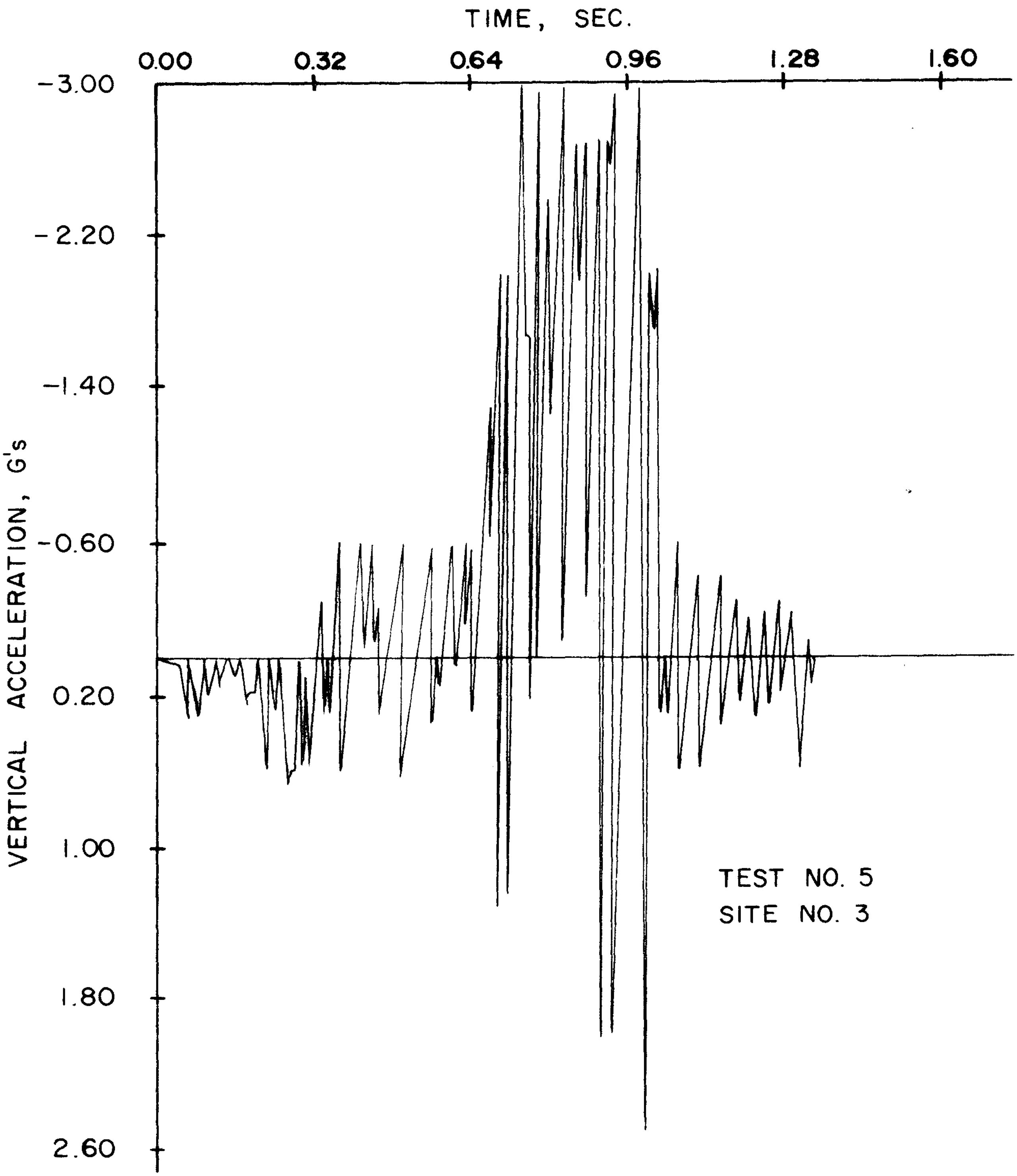
Vertical Acceleration Data from Visicorder (V-Ditch)

Figure A-7



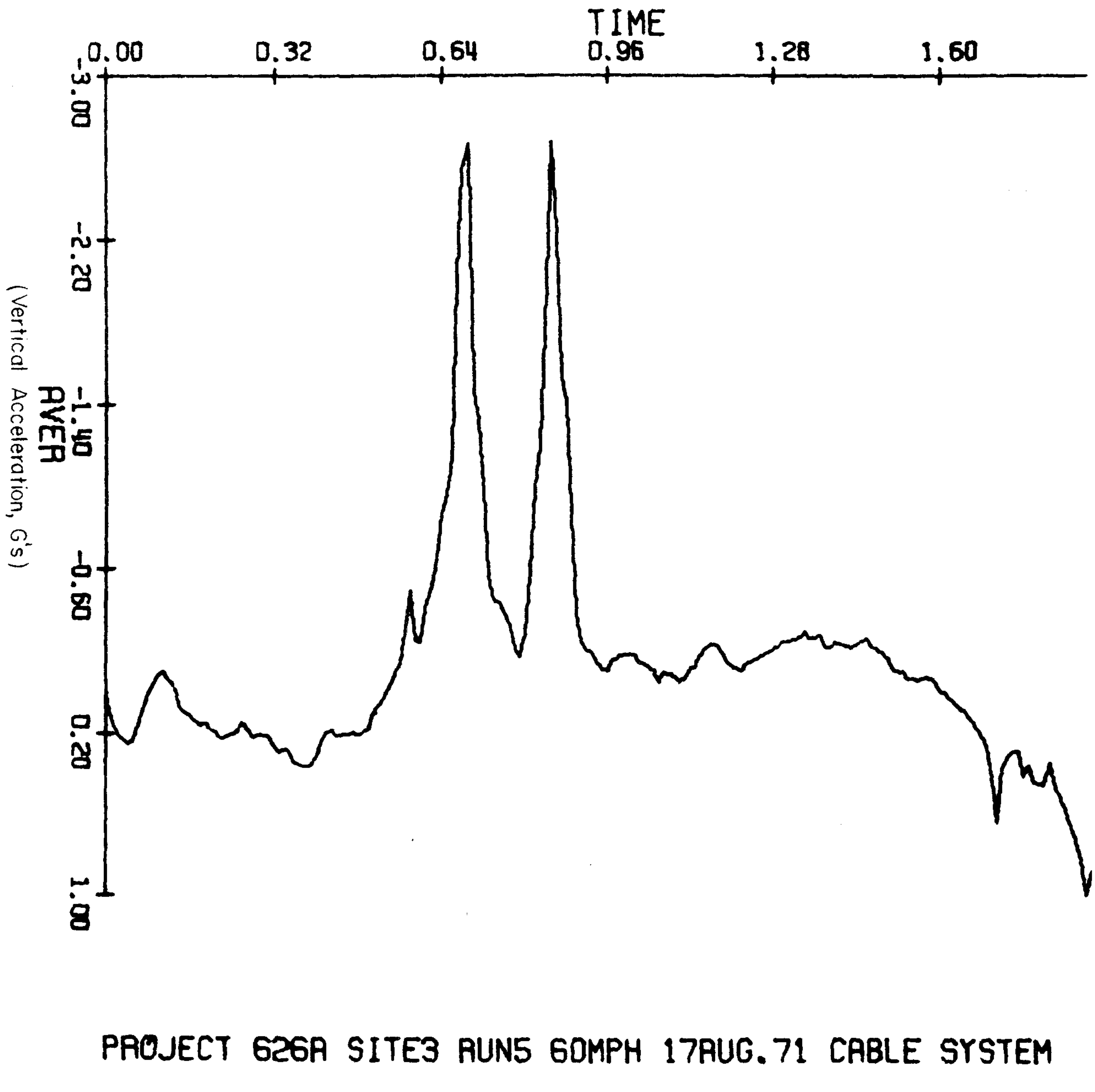
Vertical Acceleration Data from HVOSM (V-Ditch)

Figure A-8



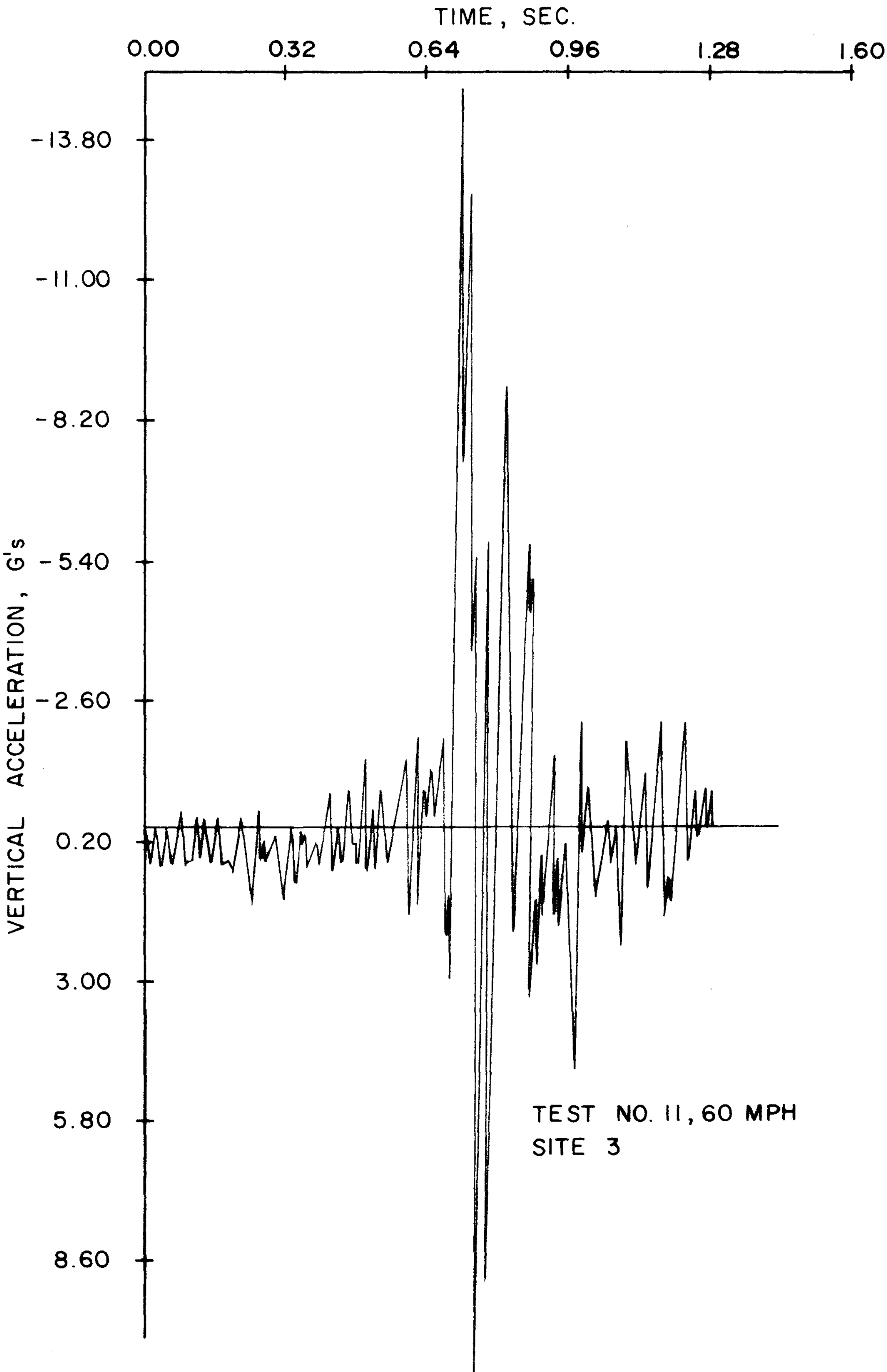
Vertical Acceleration Data from Visicorder (Round Ditch)

Figure A-9



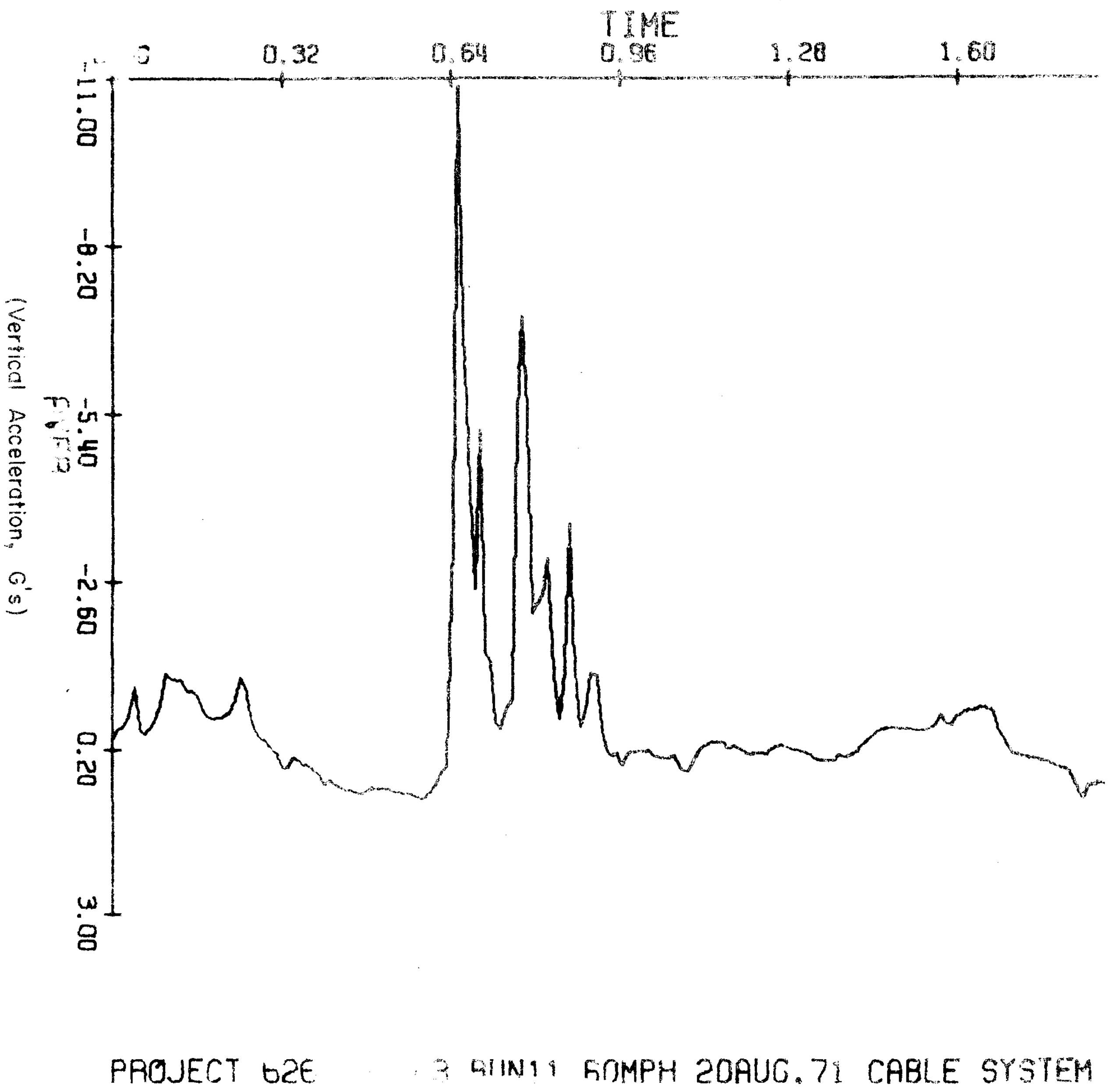
Vertical Acceleration Data from HVOSM (Round Ditch)

Figure A-10



Vertical Acceleration Data from Visicorder (V-Ditch)

Figure A-11



Vertical Acceleration Data from HVOSM (V-Ditch)

Figure A-12