ABSTRACT

This thesis investigates the use of nondestructive bridge load testing utilizing strain sensing equipment. Nondestructive bridge load testing has not been used extensively due to lack of expertise and perceived high cost. It can, however, play a key role when an existing bridge needs to be evaluated. Since most evaluation techniques tend to be conservative, the results from such an evaluation may not represent the real properties of the structural members. The true properties of an existing bridge can be identified using the results from nondestructive static and dynamic load testing. The procedures used to identify a structure with the potential to be used for load testing and the execution of a dynamic load test are outlined.

This thesis also presents the findings of a field study on a through-girder railroad bridge. The study was conducted on the NJ Transit's UG 7.96 Boonton Line over Broadway in Newark, New Jersey. This bridge consists of three simply supported spans, of varying length, and carries two ballasted tracks on continuously welded rail. Static and dynamic tests were performed involving controlled and in-service traffic conditions. The study demonstrates how load testing can be done effectively for a low cost and in a short period of time.

NONDESTRUCTIVE DYNAMIC LOAD TESTING OF BRIDGES USING STRAIN SENSORS

by
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A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Civil Engineering

Department of Civil and Environmental Engineering

January 1996

APPROVAL PAGE

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This thesis is dedicated to
my husband, Tom

ACKNOWLEDGMENT

I wish to express my sincere gratitude to my advisor, Prof. Edward Dauenheimer, for his valuable help, guidance and patience throughout the writing of this thesis.

I would also like to thank Dr. William Spillers and Prof. Walter Konon for serving as members of the committee and for their review.

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CHAPTER 1

INTRODUCTION

1.1 General Information

The condition of the infrastructure in the industrial world is deteriorating and, thus, the need to evaluate older bridges is growing. However, identifying the existing properties and making reliable judgments of the structure's safety is not easy. One approach is to use inexpensive strength testing, which is performed in the laboratory. This method requires samples of the existing structure, such as cores. Unfortunately, obtaining these samples may compromise the integrity of the structure. Another approach is to use in-place nondestructive load testing. This method uses instrumentation that attaches to the structural elements without disturbing them and measures responses to static and/or dynamic loading.

Current evaluation and rating techniques emphasize bridge conditions and member dimensions and then allowable loads and stresses are specified from this limited information. Actual bridge loads or member performance under loading is rarely found. Recent studies have shown that the codes are usually conservative and, thus, do not present an accurate rendering of the bridges response. Procedures have been outlined for consolidating nondestructive testing data and guidelines to incorporate the data into bridge ratings have been established.

Nondestructive load testing is a valuable tool. Bridge closure or posted load/speed limits may be avoided if the testing proves the structure to be competent.

These outcomes demonstrate the economic feasibility of testing a bridge. However, even if the only outcome is increased reliability and a better understanding of the structure's mechanisms, nondestructive load testing is still a valuable resource.

1.2 Background

Switzerland has the most standardized and longest running bridge load testing program. The Swiss have been statically testing all new bridges since 1892. Bridges constructed between 1892 and 1913 and from 1970 to the present have also been tested dynamically. Some load testing has also been performed on existing bridges. The standardized procedures used in Switzerland for dynamic testing, measuring, and data processing were assembled by Rosli and Voellmy in the 1950's.

The Ministry of Transportation of Ontario also has a significant amount of experience using nondestructive load testing. The Ministry has tested over 250 bridges, statically and dynamically, in recent years and research has been performed in the area. After performing an overview of the results of these bridge load tests, the principle conclusion reached was that for each bridge there was an aspect that was overlooked during analysis. This is one of the primary reasons that testing should be performed on existing bridges.

Nondestructive load testing of bridges is beginning to become more widespread. More research and testing is being performed in this area, as it is becoming more critical that existing bridges be used to their full potential.

1.3 Objective and Scope

The objectives of this thesis are to:

(1) Summarize the work of previous studies in the area of dynamic load testing of bridges.

(2) Outline the procedures for using nondestructive load testing, such as validating the need for testing on a particular structure, executing the testing, and reducing the recorded data.

(3) Use a case study to exemplify procedures and results from static and dynamic load tests.

CHAPTER 2

NONDESTRUCTIVE LOAD TESTING

2.1 Definition of Nondestructive Load Testing

Nondestructive load testing is the measurement of the response of bridge members subjected to loading. Using this method, the existing properties of a structure may be found without altering the structural elements. Strain sensors, displacement transducers, and/or accelerometers are attached to the bridge members at critical locations to measure the structures response to applied loading conditions. The field measurements, obtained by the instrumentation, may be compared to the results from calculations for the same loading. The data may then be used to adjust a load rating or computer model.

2.1.1 Static Load Testing

Static load tests are performed using a vehicle, such as truck or train, or a mass, such as a concrete block, of known weight. The results that may be obtained are deflection, stress, and strain. The measured behavior of the structure resulting from this type of test can be directly and easily compared to analytic calculations with elementary structural analysis. Comparison of these results verify if the assumptions made for the original analysis were correct. Additionally, static test results may be used to calibrate mathematical models used for structural analysis, thus obtaining a more accurate rendering of the structure's responses.

2.1.2 Dynamic Load Testing

Dynamic load tests are performed using a typical in-service vehicle, such as truck or train, or another type of machine that simulates live loading. Deflection, stress, and strain may be the results determined, but the data must be used to calculate dynamic properties, such as mode shapes, frequency and impact factors. A mathematical model, such as a finite element model that may be calibrated from the static load test, may be used to calculate frequency and mode shapes of the bridge deck and then the theoretical and field results can be compared. The other results of this type of test, such as mode shapes, and damping, can not be compared with calculated values or corresponding data from codes. Thus, it is harder to justify the use of dynamic testing. For these reasons, standardization and experience is imperative in this type of testing. Switzerland has a database of 200 dynamic load test results. Such a resource may be very useful, since it provides a means for comparison.

The response of a bridge under a moving load is complex. It depends on many factors involving the interaction between the vehicle and the bridge. Some factors are: vehicle characteristics, bridge geometry, supports, stiffness, pavement roughness, and number of vehicles. Although much research has been done in this area, a clear correlation between all the parameters and the response has yet to be generated.

2.2 When and Why Nondestructive Load Testing is Used

Bridges often exhibit higher strengths than indicated by American Association of State Highway Transportation Officials (AASHTO) or American Railway Engineering Association (AREA) rating procedures, due to the conservative nature of the codes. One reason the codes may be conservative is because the additional cost associated with using conservative performance factors for new construction is minimal, while the unknowns are high. The opposite is true for existing bridges. The cost of adding capacity or posting limitations is high, and the unknowns are lower. Safety factors are needed to account for the unknowns, such as load effects and variability of materials and construction practices. For rating bridges, the factors of safety can be lower for existing bridges because the knowledge of loading and behavior is more precise and the condition of the elements can be inspected.

Nondestructive load testing may be used to reduce the uncertainties, such as load distribution and the effect on stiffness by parapets and curbing. Developments in technology make it feasible to investigate existing bridges and provide more accurate site-specific load and response data for evaluation process. Testing also presents the participating engineers with the opportunity to find the true capacity of the structural elements, as well as other properties, and to use their experience to determine what percentage of the tested existing capacity may be used for bridge rating procedures.

2.2.1 Evaluation to Determine if Nondestructive Load Testing is Essential

Nondestructive load testing may be necessary when the following situations arise: if higher than designed loads are expected, if calculations show that a structure can not meet present standards, when section loss falls below that required for design strength, or when there is reason to believe that bridge boundary conditions, load distribution, or section resistance are different from that assumed during analysis.

2.2.2 The Need for Dynamic Load Testing

Live load is an important load component when evaluating bridges. The effect of live load depends on many parameters such as vehicle weight, axle configuration, and span length. The static load test, though easier to justify, can not practically measure these significant effects. Some results measured from dynamic load tests may be incorporated into calibrating finite element models. This yields a more accurate representation of the structure than a calibration using static load results, since the actual loadings are usually dynamic rather that static.

Dynamic load testing may also play a key role in the seismic evaluation of existing bridges, since seismic design has been incorporated into some codes recently. Since most existing bridges were not designed for seismic loads, determining their dynamic properties is significant.

2.3 Methods of Dynamic Load Testing

There are two types of load testing: diagnostic and proof. Diagnostic tests may involve in-service or controlled loading conditions. Depending on the results that are desired, the more effective method of testing may be determined. Force distribution, dynamic response, and fatigue estimates may be determined using in-service diagnostic load testing. This technique ordinarily uses the type of vehicle(s) that would normally traverse the bridge. Controlled loading involves a vehicle(s) of known weight traversing the bridge at known speeds. Dynamic properties, such as frequency and mode shape, may be determined. To determine the effect of an overweight vehicle, the results from these diagnostic tests may be extrapolated. Although this may not be as accurate as a proof load test, the risk involved is much lower.

A proof test normally involves the use of atypical loading. Capacity can be checked by using this type of load test. The purpose is to verify the bridge's ability to withstand the lower in-service loads and possible overweight loads. This method can also be used to observe failure behavior. The primary drawback is the possibility of damaging the bridge during the testing.

2.3.1 Instrumentation

A full-scale dynamic test uses different instruments to record all the necessary data. Various responses are measured with accelerometers, strain sensors, and displacement transducers, which record deformation and displacement data. These instruments are customarily distributed on the main span at critical locations and connected to a microcomputer-controlled data acquisition system. Strain sensors are placed on elements where maximum strain is expected. Displacement transducers measure vertical displacement and are attached from the ground to a girder. Low-frequency accelerometers measure vertical acceleration response. A data acquisition and control unit is used to record the test data. The best types of data acquisition systems are those which are programmable.

2.3.2 Results from Testing

For an existing bridge, the outcome of nondestructive dynamic load testing is the acquisition of data that furnishes the engineers with a better understanding of the structure's behavior. There are many aspects of the structure that may be examined through load testing. Strength capacity may be proven, thus producing lower factors of safety to be used during the rating process. Force distribution assumptions may be corrected, if field measurements exhibit that the original assumptions were inaccurate. The structure's stiffness may be measured, thus establishing the true composite action of the structure and its connections and, also, confirming the material properties of the bridge. Linear behavior may be examined by monitoring the reversibility of deformation after the load is removed. Serviceability is another property of the bridge that may be recorded and used to predict the future reliability. All results obtained may be used to alter the computer analysis model to reflect the actual properties of the structure.

The load model may also be improved. During the evaluation, pavement cores may be taken to measure the thickness of the wearing surface and the fixtures attached to the bridge may be noted to adjust the assumed dead load. The actual traffic flow may be recorded to adjust the assumptions used for the live load. The impact value may be modified after the relationship of actual live load to actual dead load is examined.

2.4 Recent Developments

Switzerland was the first country to recognize the benefit of performing nondestructive load testing. Canada and the United States have recently begun to recognize this concept also, due to the continuing deterioration of infrastructure. New Jersey Institute of Technology (NJIT) has become a leader in the field, due to the utilization of a dynamic load testing system designed at NJIT.

2.4.1 Field Work

The New York State Thruway Authority has recently used diagnostic nondestructive dynamic and static load testing, to identify the existing capacity and determine the portion of that tested capacity that may be reliably used to establish the bridges' load ratings. The project stemmed from the fact that the state's interstate highways are subjected to a high volume of overweight vehicles. The immediate purpose was to monitor the performance and safety of the bridges during the passage of overweight vehicles.

One example of how strain sensor technology may be used effectively throughout construction is the Sunshine Skyway cable-stayed bridge in Florida. During construction, 500 strain sensors were installed to monitor the bridge during erection and throughout its useful life. Eight remote signal processors feed into a single microcomputer. The primary application, during construction, was to compare the design assumptions, such as those for shrinkage, to the actual conditions. During its life, the bridge's strain sensors can be used to confirm the integrity by measuring the concrete strain variations, changes in vertical deflections and rotations. The use of these strain sensors should reduce the amount of time needed for periodic inspections drastically.

An example of the economic feasibility of using load testing is the case of a multi-girder "jackarch" bridge in Stueben County, New York. Conventional analysis resulted in the determination to post load and speed limits. However, nondestructive load testing established that the capacity of the bridge was such that the bridge could remain open with no limits posted.

Standard procedures and databases are being created to facilitate the use of nondestructive load testing. Moses and Verma (1987) proposed a procedure to rate bridges depending on the amount of data available and the effort expended by the rating engineer. The load factor utilized is determined by truck volume, overweight trucks, deck smoothness, method of girder distribution analysis, and quality of inspection and maintenance. The Quebec Ministry of Transportation is currently setting up standard procedures and a database of dynamic load testing. Testing and research performed at the University of Sherbrook resulted in an outline of procedures to execute dynamic load testing within 1-2 days, thus providing rapid evaluation of dynamic properties.

Some studies have been performed to prove that the codes are conservative and what factors make them so. Ghosn, Moses, and Gobieski (1985) in conjunction with the Ministry of Transportation of Ontario determined maximum stress in highway bridges tested were significantly below values predicted by conventional rating procedures. Unintended composite action, additional stiffness contribution to section modulus from overlays, parapets, curbs, etc., impact values, and girder load distributions were some of the factors that were proven to be more conservative than predicted by AASHTO.

2.4.2 Theoretical Studies

Recent theoretical studies have focused on improving system reliability and live load models, and on the factors influencing the strength capacity and dynamic amplification factor. Cantieni (1983) in conjunction with the Swiss Federal Laboratories for Materials Testing and Research has performed research involving the correlation of the fundamental frequency and the maximum span, and the effect of vehicle speed and pavement roughness on the dynamic response. Burdette and Goodpasture (1988) performed a study which analyzed test data and the factors that effect the bridge capacity. The study involved the effect of variables which are not normally considered during evaluation, such as unintended composite action and unintended continuity on the strength capacity.

A different type of research is being performed by the Texas DOT and the Center for Transportation Research at the University of Texas at Austin. The development of a mobile load simulator, capable of simulating real traffic loading, may aid in the use of nondestructive bridge load testing. Although it is being developed to test pavement, this type of device may be useful tool in understanding the live load impacts on bridges without having to use actual vehicles.

CHAPTER 3

DYNAMIC LOAD TESTING USING STRAIN SENSORS

3.1 General

For a full-scale bridge test, a complete three-dimensional finite-element model should be developed for every bridge, prior to its testing. The results from these model studies are used to select critical instrument locations on the bridge and predict static displacements. Once testing is complete, the measured frequencies and mode shapes can be used to calibrate the model. The model can then be used as a basis for the study of the influence of certain parameters on the dynamic response of the structure: the influence of secondary structural elements (barrier walls, sidewalks, etc.) the cracking of deck slabs, and the effects of long-term concrete creep and shrinkage.

3.2 Typical Instrumentation

The use of strain sensors is often desirable because of their low cost, high sensitivity, simplicity of use and easy access in enclosed spaces. However, one major drawback is the susceptibility to electrical noise. Wheatstone bridge circuit modulation has been shown to effectively decouple the strain signal from the noise, even at very low strain levels. Also, over time, new sensors may need to be installed due to tampering or weather may affect the accuracy of the instruments.

3.2.1 Strain Sensor Selection

Many factors, such as test-time duration, strain range required, and operating temperature, must be considered in selecting the best strain sensor for a given test. Gage length is usually the first parameter to be defined. Strain sensors are capable of measuring maximum elongation in the range of 3%-5%, since most structural materials yield well below this limit. Other factors are sensor resistance, sensor factor, and transverse sensitivity.

Strain sensors with resistance of 120 and 350 ohms are commonly used in experimental stress analysis testing. For most applications, 120-ohm sensors are suitable; 350-ohm sensors would be used to reduce heat generation, or to improve signal-to-noise ratios. Gage factor is the measure of sensitivity produced by a strain sensor. All sensors are sensitive to strains transverse to the grid direction; this factor will be supplied with the sensors.

There are two different methods to attach strain sensors to the members, welding and adhesive bonding. Welding may be more durable and weather resistant, but adhesive bonding gives a more accurate representation of the structural member.

3.3 Preparation

Installation of strain sensors on relatively smooth surfaces, such as steel members is straight-forward. Strain sensors can be satisfactorily bonded to almost any solid material if the surface is properly prepared. For smooth surfaces on nonporous materials, the first step is to abrade with a course grinding wheel to remove rust and pitting. This is followed by a finer grinding wheel used to rub the surface to a flat mirror finish. The surface is washed with a mild acid followed by a solution to neutralize the acid. Finally, the surface is ready to receive the sensors.

The sensors are then prepared by placing each sensor face-down (the side that will be attached to the structural member is down) on a flat surface. Each sensor is framed with tape, which is used to hold sensor in place while being installed. The adhesive is deposited on each predetermined member and the sensors are pressed and held into place for approximately a minute. Once the glue is dried, the tape is removed. A dental pick may be used to assure that all edges of the sensors are secure. The wires are connected to the sensors and the data acquisition system. All wires should be numbered so the readings from the sensors will not be confused. Once the sensors are installed, the wires are checked for continuity and each individual sensor should be checked for response.

3.3.1 Strain Sensor Preparation for Concrete Structures

The installation of strain sensors for concrete structures presents several unique challenges to the installer. Special preparation is required to ensure that strains on the irregular surface are fully transmitted to the strain sensor. An extra step from the procedures outlined above is needed to fill the voids and seal the surface with a suitable precoating before the sensor is bonded. Usually a long gage length is used for concrete members to account for a gage being placed over a flaw.

3.3.2 Installation and Removal of Reusable Strain Sensors

Reusable strain sensors may be installed using C-clamps or tabs with adhesive. For either method, the surface of the structural members should be prepared as described in Section 3.3.1. Clamps may be used for steel structures, since the sensors can be directly clamped to the flanges or plates. Clamping makes removing the strain sensors easy. The alternative to clamping is using the tab attachment method. The manufacturer's procedures must be followed carefully for installation and removal, or the sensors may be damaged in the process or during the testing.

3.3.3 Common Installation Problems

The most common problems following installation are unbonding of the sensor and/or sensor tabs and sensor grid failure. Loss of bond before maximum sensor elongation is reached is usually due to contaminated or improperly prepared surface, or improper use of adhesive. Cured adhesive on the back of the strain sensor but not on the specimen generally indicates improper or incomplete surface preparation. Gage tab unbonding is often due to an excessive amount of solder, which reinforces the sensor tabs, and cause them to unbond as a result of inflexibility. Drafting tape is recommended for restricting the amount of solder. Assuming that the strain sensor readings are within the strain range capability of the sensor, and that the backing remains bonded, premature grid failures are often the result of high local strains within the area covered by the sensor. Since the strain sensor will indicate the average strain along its grid length, steep strain gradients can cause localized excessive strain damage while the sensor may have been indicating a strain within the elongation limits. Grid failure may also result from inclusion of particles in the adhesive layer or an uneven layer of adhesive, often caused by uneven or pitted specimen surfaces.

3.3.4 Planning Location of Sensors

The position of the sensors is determined by the critical areas. Depending on the results desired, this may be determined by a finite element computer model. A typical position for a sensor on a girder would be where the maximum deflection occurs.

3.3.5 Determining Timing of Samples

The most important factor in determining the timing of the samples is the speed of the loading. Other factors that effect the determination are: the data acquisition system, the type of results required, the type of test vehicles used, and the amount of data required. Depending on the amount of samples per second and the data acquisition system, the total time of each sample may be determined.

3.4 Execution

3.4.1 Trial Runs

In order to establish that the equipment is working properly, a number of tests should be executed and evaluated before the actual sampling is performed. This may involve taking a series of readings during actual traffic conditions to assure that all sensors are working properly, as is the data acquisition system. The results should be assessed by an experienced engineer to assure that the results are feasible. These first sets of data may be compared with theoretical results to insure the strains are of the correct order of magnitude.

3.4.2 Testing

Actual testing depends on the type of test, static or dynamic, and on the loading conditions, ambient or controlled. The procedures are uncomplicated.

3.4.2.1 Static Loading

Static loading is performed under controlled loading conditions. The typical testing program has fixed positions for a the test load to be located. The sample may begin as the load is being positioned or once it is already in position.. A total time of 10 seconds is normally adequate. However, since the testing rate, in samples per second, of a static load test is slower than that of a dynamic load test, the total time of each sample may be longer if desired. Only one reading per sensor, the maximum strain, is usually utilized, so the total time of the sample must be long enough for the test load to maximize its influence throughout the bridge

3.4.2.2 Dynamic Loading

Dynamic loading can be performed with ambient or controlled loading conditions. If the conditions are ambient, samples may be taken at any interval to record normal traffic. If the conditions are controlled, then an individual must be utilized to warn the computer system operator when to begin the sample, so the whole event (when the vehicle is on the structure) may be recorded. The timing is very important, because of the high sampling rate, on the order of 100 samples per second, of the data acquisition system. If the sample time becomes too long the data acquisition system may become overloaded and produce some random errors.

3.5 Determination of Results

3.5.1 Reduction of Data

Depending on the type of data acquisition system, the data may be in a number of different formats. A gage factor is supplied with all sets of gages. This gage factor is utilized in a formula furnished by the manufacturer to reduce the raw data into strain. Usually the raw data obtained is in a binary form to allow for fast collection of data without delay.

3.5.2 Graphics

As with most testing procedures, graphs may give the best representation of the structural response . For a static load test, maximum strain versus load position may be graphed. More than one sensor may be graphed at a time in this case. Figures C.1 and C.2 are examples of the static load test results. However, in a dynamic load test, a graph for each sensor displaying strain versus time is required to yield a footprint of the reaction for that member. Figures D.1 through D.17 are examples of the dynamic load test results.

CHAPTER 4

EXPERIMENTAL PROGRAM

4.1 General

This experimental program was performed on New Jersey Transit's Boonton Line UG 7.96 railroad bridge over Broadway in Newark, New Jersey. A plan and elevation of the bridge is given in Figure 4.1 and a cross section of the bridge and floor trough system is given in Figure 4.2. The load deformation behavior of the steel trough floor system was the focus of the testing. The bridge had rated below what was designate as safe, but was needed for regular light-passenger traffic and heavy haul cargo trains. The purpose of the test was to obtain data that could be used to modify the finite element model. As a part of the structural evaluation, tests were performed focusing on deformation under dynamic loading. The testing took two days; one day to prepare and install the strain sensors and one day to perform the testing.

4.2 Why Testing was Performed

4.2.1 Observed Flaws

Most points of inspection were rated fair to poor. However, the most significant flaw was the visible deflection of the trough floor system that was observed during inspection. It was later found that concrete had been specified to be poured over the floor trough system, but had been omitted.

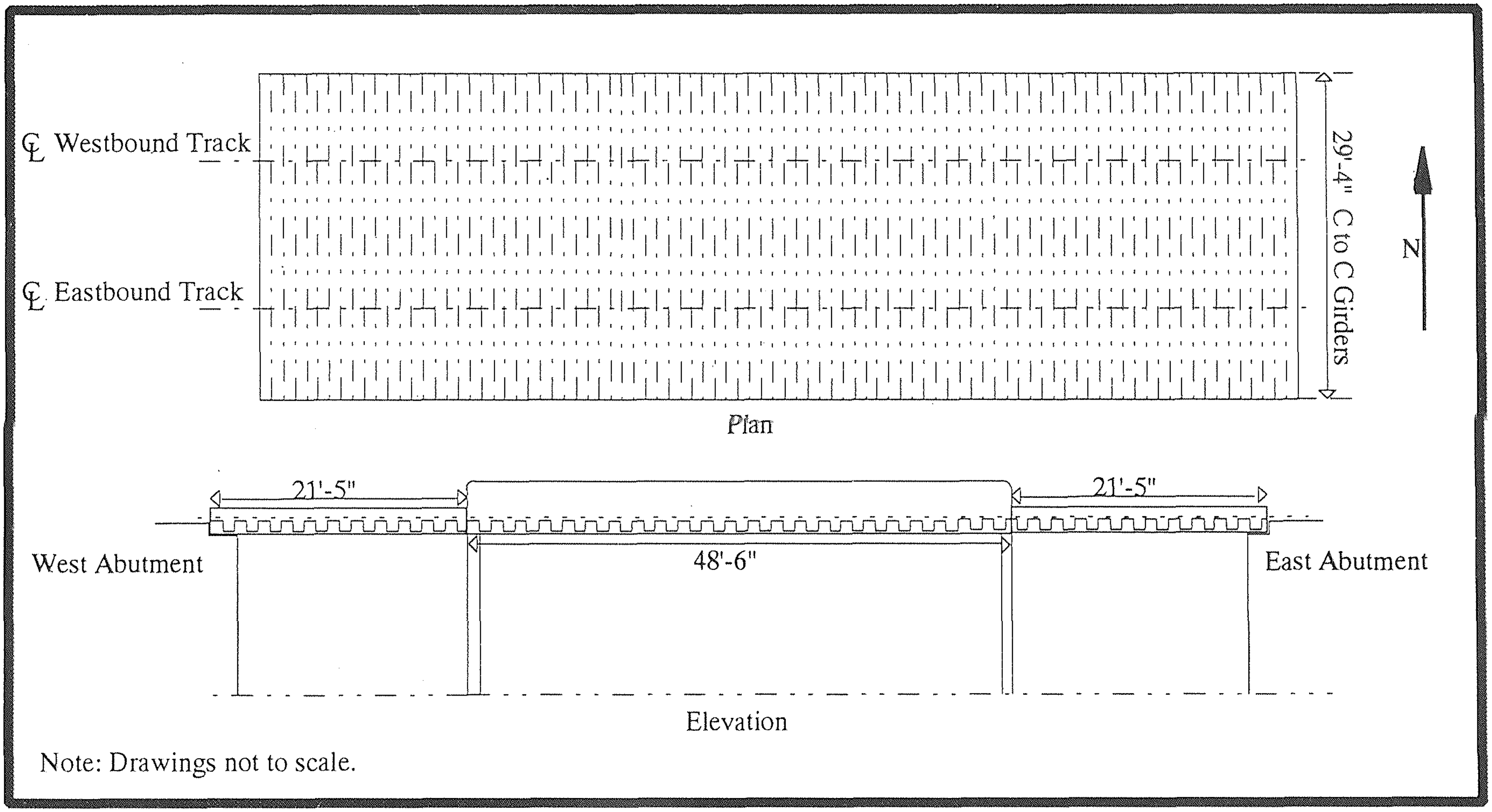
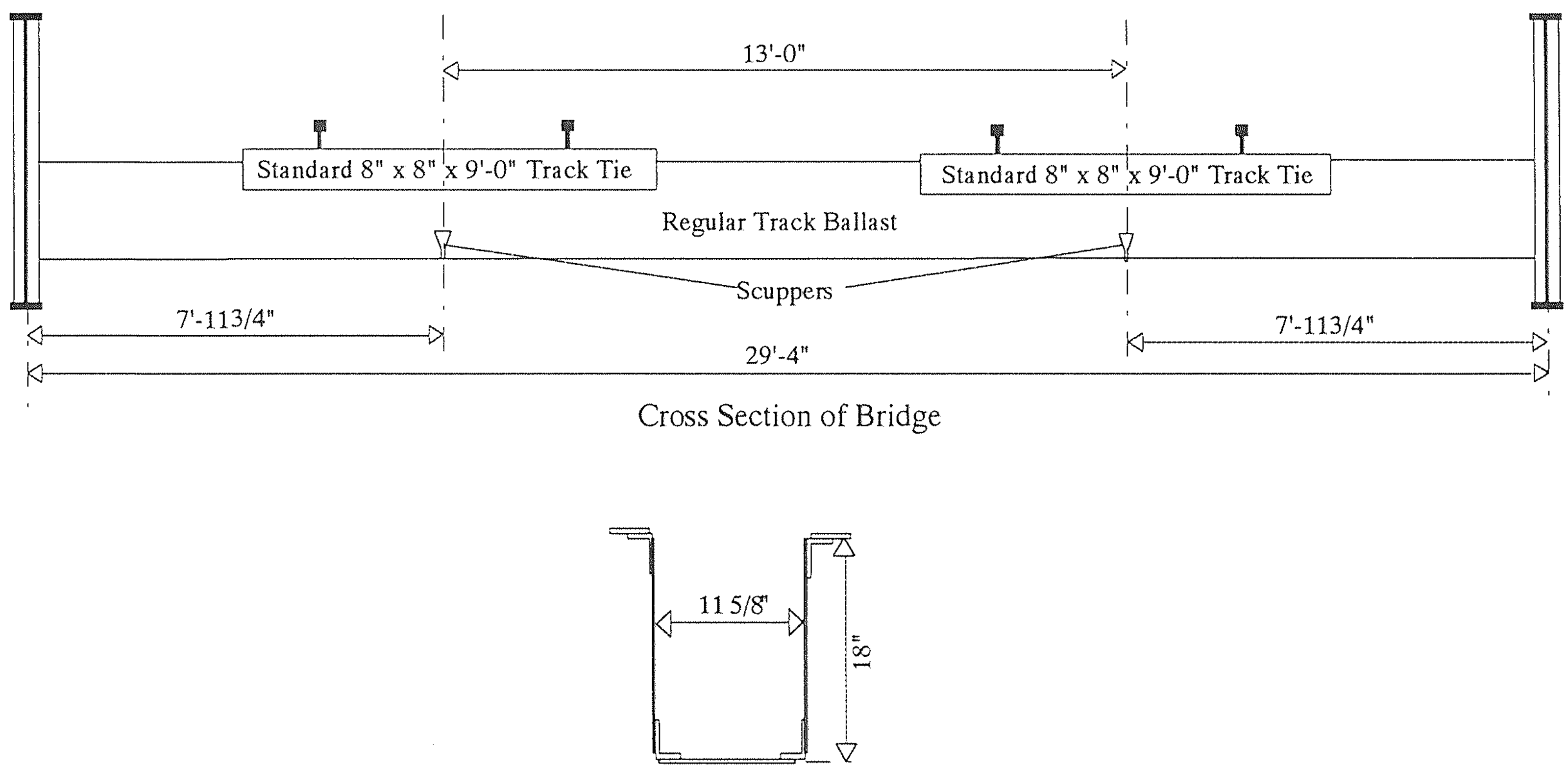


Figure 4.1
Bridge Plan and Elevation



Section of Floor Trough

Note: Drawings not to scale.

Figure 4.2
Cross Section of Bridge and Section of Floor Trough

4.2.2 Theoretical Problems

As mentioned earlier, the AREA code has been found to be a conservative means of rating a bridge. When this bridge was evaluated, the result was an as-built rating of E0. A rating of E0 means that the bridge is not able to withstand any load. Considering the omission of the concrete over the floor trough system, this is not surprising. However, the bridge continued to carry normal loads.

4.3 Instrumentation

4.3.1 Strain Sensor System

The test was conducted using 11 electrical resistance strain sensors placed on various locations of the floor trough system. The strain gages were numbered to facilitate identification. The schematic location of the strain sensors is shown in Figure 4.3. Of the 11 gages installed, ten were fastened on the bottom plates of the floor system at critical positions. The eleventh, which was installed on an unstressed element, was used to establish a datum. The datum was to establish the effects of temperature and electrical noise.

The gages were foil backed, single grid, 120 ohm resistance gages with a gage factor of 2.085 manufactured by Measurements Group, Inc. of Raleigh, North Carolina. As per the manufacture's instructions, the sensors were adhesively bonded to the structural members. The strain gages were bonded electrical resistance sensors suitable for general purpose static and dynamic stress measurements. The gages were bonded to

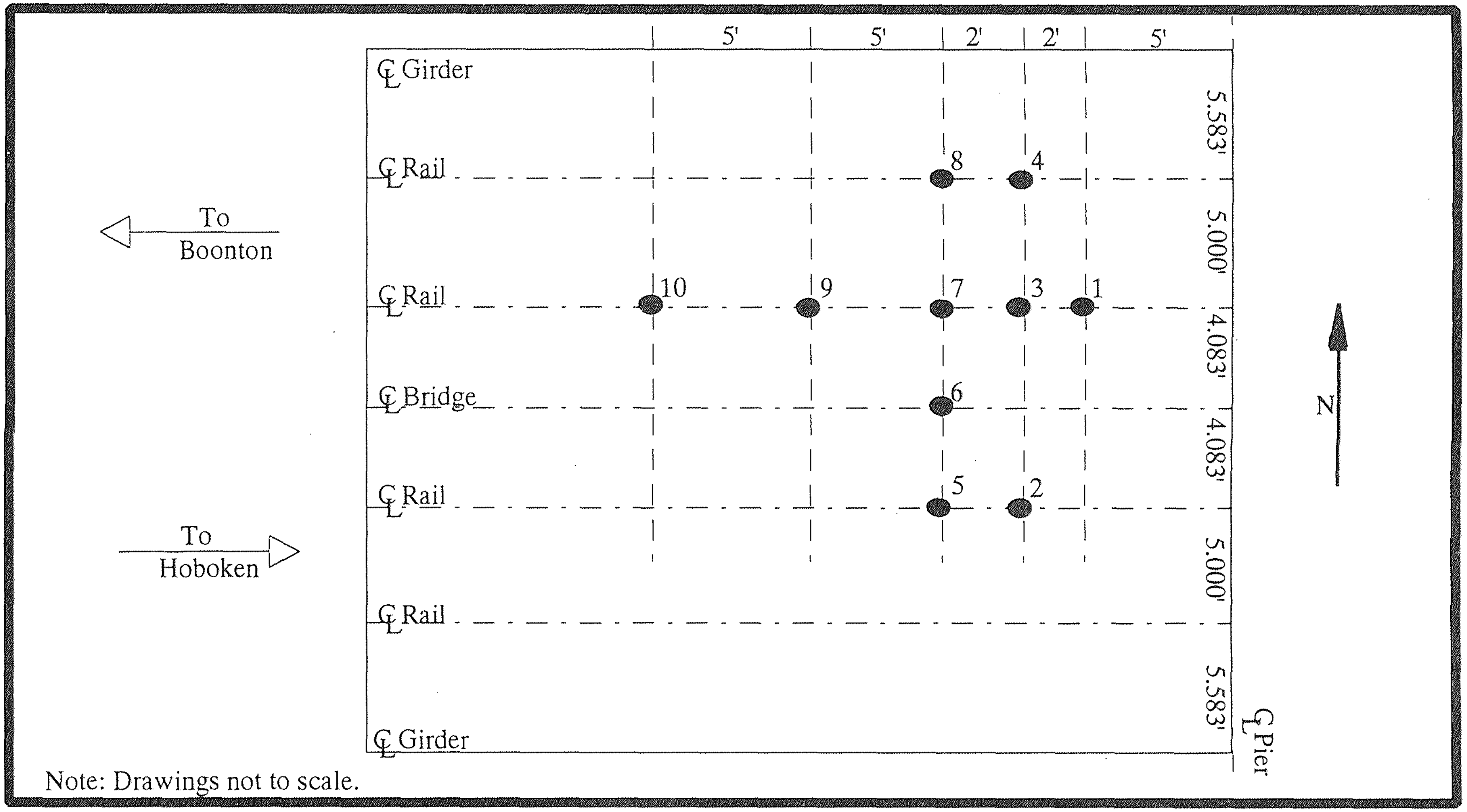


Figure 4.3
Strain Gage Locations

the bare steel with a special adhesive and protected from moisture by acrylic and polysulfide protective coatings. Lead wires were soldered to each sensor for monitoring by a data acquisition system.

The installation of strain gages and lead wires was performed by personnel from New Jersey Institute of Technology (NJIT) and Frederic R. Harris on November 10, 1994.

4.3.2 Computer System

The data obtained from the strain gages was monitored by an Elexor XL-1900 data logger controlled by a Toshiba notebook personal computer. Typical readings were recorded at a frequency of 100 Hz, thus permitting 33,000 points of data to be stored through the eleven recording channels. For the dynamic testing and in-service monitoring under normal traffic the sampling rate was 100 samples per second for the duration of the event. For the static load tests, the sampling rate was 1 sample per second over a total duration of 30 seconds. Periodically throughout the testing, data was downloaded to floppy disks for further reduction in the office. The data acquisition system was supplied and operated by NJIT Engineers.

4.4 Test Loads

The load for the static load test consisted of two E80 locomotives, coupled rear to front. The load configuration of the axles can be seen in Figure 4.4. The engines represent the load for which the bridge was designed.

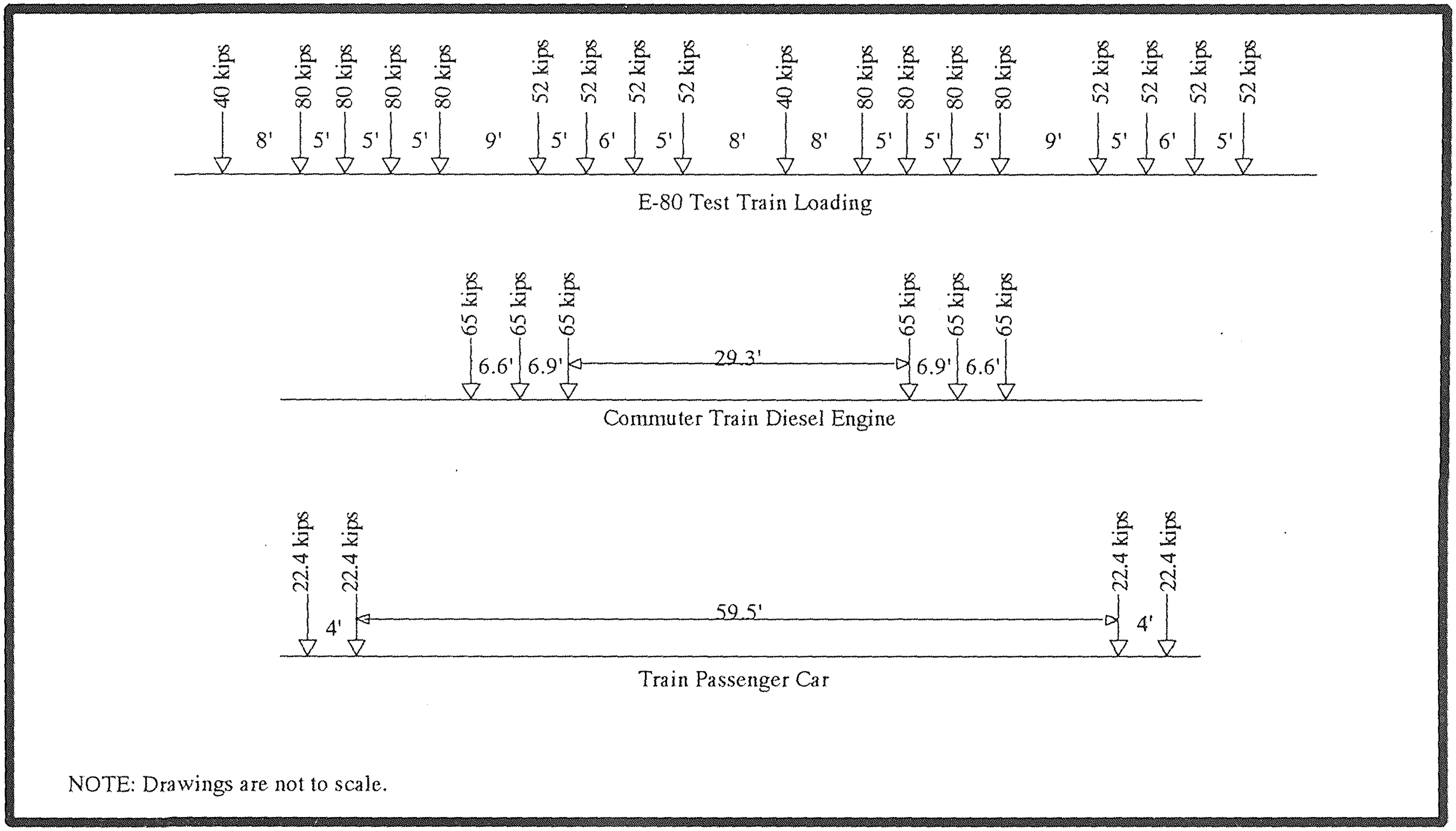


Figure 4.4
Loading Configurations

The test loads for dynamic load tests consisted of in-service light-rail passenger cars with a diesel engine. The load configuration can be seen in Figure 4.4. The two E80 locomotives were also used for dynamic testing at controlled speeds of 10, 20 and 30 mph.

4.5 Testing Procedure

The testing was performed for both controlled and ambient loading conditions. The ambient loading consisted of dynamically monitoring commuter trains at their normal speed in the morning and evening rush. The controlled loading consisted of statically and dynamically monitoring a test train consisting of two work locomotives. Table 4.1 lists each test along with its pertinent information.

4.5.1 Static Loading

Static tests were designed to provide results for a known train load at a given static position on the structure. The purpose of these tests was to measure strains at critical locations for evaluation of flexural strength and fatigue. A typical test involved positioning the train, initializing the data acquisition system and recording data from the strain gages for 30 seconds. During the first series of static load tests, the test load was moved along the westbound track, by sequentially advancing the test load to 20 load positions. The positions of the static load tests are presented in Figure 4.5. The sequence was then repeated on the eastbound track. Appendix C presents examples of the results from the static load tests.

TABLE 4.1

MASTER LIST OF TESTS

Test Type	Time	Track	Train Compostition	Location if applicable
Static	11:53 AM	Westbound	2 E80 engines	Appendix C
Static	12:58 PM	Eastbound	2 E80 engines	Appendix C
Dynamic - 10 mph	12:30 PM	Westbound	2 E80 engines	
Dynamic - 20 mph	12:40 PM	Westbound	2 E80 engines	Appendix D
Dynamic - 30 mph	12:45 PM	Westbound	2 E80 engines	
Dynamic - 10 mph	1:30 PM	Eastbound	2 E80 engines	Appendix D
Dynamic - 20 mph	1:32 PM	Eastbound	2 E80 engines	
Dynamic - 30 mph	1:35 PM	Eastbound	2 E80 engines	Appendix D
In-Service	8:45 AM	Eastbound	3 cars then engine	
In-Service	9:03 AM	Eastbound	3 cars then engine	
In-Service	2:05 PM	Westbound	Engine then 4 cars	Appendix D
In-Service	3:45 PM	Westbound	Engine the 5 cars	
In-Service	7:36 AM	Eastbound	5 cars then engine	
In-Service	8:03 AM	Eastbound and Westbound	4 cars then engine Engine then 3 cars	
In-Service	8:17 AM	Eastbound	4 cars then engine	
In-Service	4:53 PM	Westbound	Engine then 4 cars	
In-Service	5:03 PM	Eastbound	5 cars then engine	

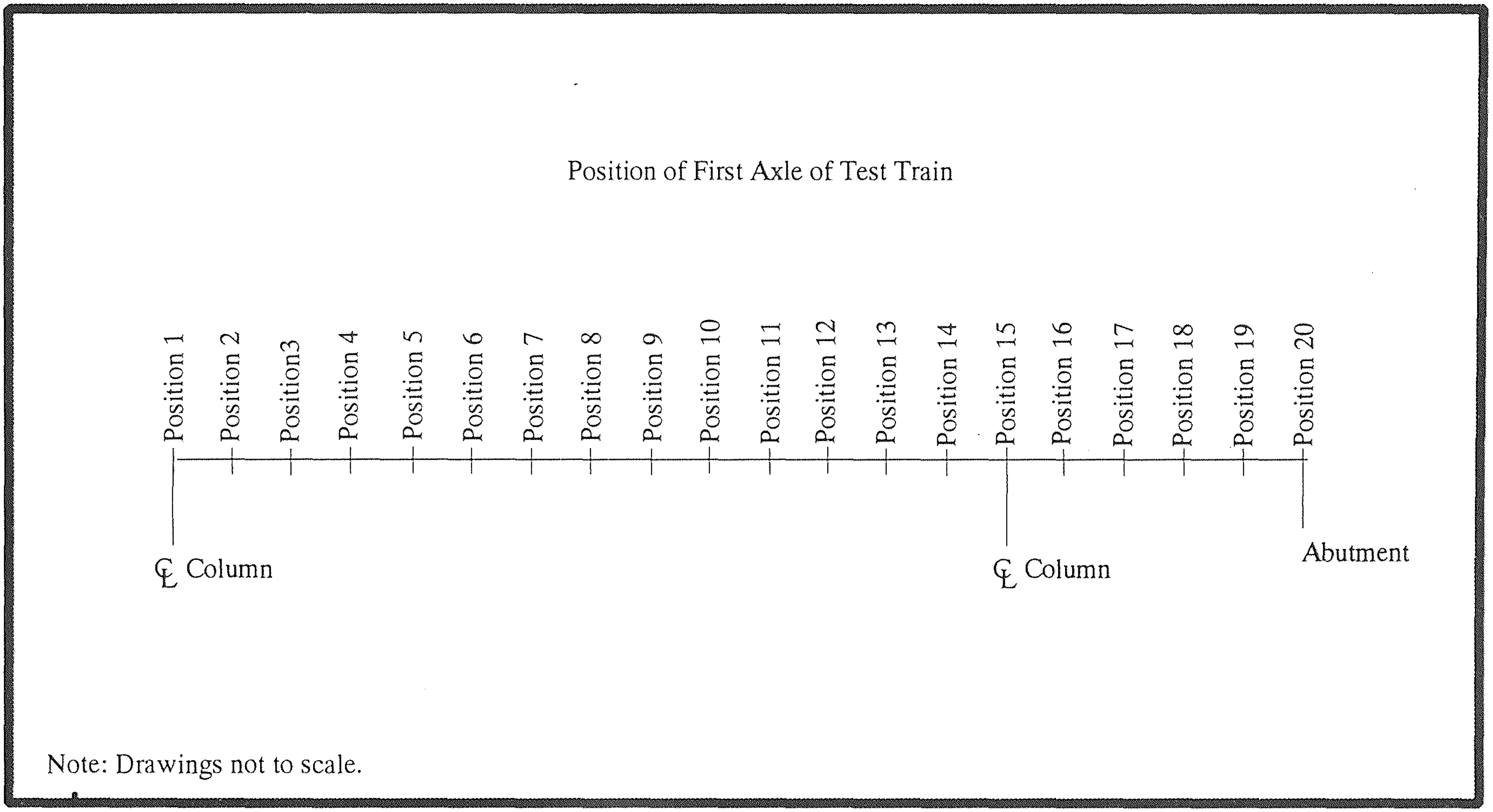


Figure 4.5
Static Test Load Positions

4.5.2 Dynamic Loading

The purpose of the dynamic tests was to evaluate the impact value and compare it to the AREA impact value. For the ambient portion of the testing, six passenger trains were observed during the morning test period and four during the afternoon testing period. 60% were eastbound and 40% were westbound. There was one side-by-side occurrence recorded. The data observed was: the time of each passing train, the direction of the train (eastbound or westbound), and the configuration of each train (number of cars and locomotive location).

For the controlled portion, the E80 test load was recorded traversing the bridge at 10 mph, 20 mph and 30 mph on each track, first the westbound and then the eastbound. Appendix D presents examples of the results from the dynamic load tests.

4.6 Factors Affecting Results

4.6.1 Noise

Noise is any signal that interferes with the signal of interest. There are three types of noise: interfering noise, drift noise, and device noise. Interfering and drift noise limit the sensitivity of the testing. The possible causes of noise in the testing are due to power lines, the length of the wires from the sensors to the PC, and the high rate of sampling per second. External noise can be reduced by shielding, using coaxial or triaxial cable, and using a filter. The noise in this test was monitored by sensor 11, and was determine to be tolerable. Some noise is related to the natural frequency of the bridge.

4.6.2 Location of Gages

The strain sensors were transversely located under the rails, which is a reasonable position. Longitudinally, however, the sensors are located within seven feet of the supports. It seems reasonable that measurements closer to midspan would have resulted in higher strains that may have been more comparable to theoretical results and provided a better understanding of the structure.

4.7 Theoretical Verification of Results

In order to confirm that the results of the experimental program were of the correct order of magnitude, the use of elementary structural analysis was employed. Appendices A and B present the calculations to determine theoretical strain and measured impact factors. Calculations were performed to determine the strains at three locations corresponding to positions of gage 1, gage 5, and gage 6. These positions were determined to give a good overview of the results.

The impact factors were also calculated according to AREA. Since AREA only takes into account the length of the span, all dynamic tests had the same impact factor of 32%.

4.8 Test Results

A master listing of all load test performed is presented in Table 4.1, which shows the test type, time, train direction, train composition and other pertinent data. Appendix C presents the results from the static load tests for sensors 1 through 6. The results are plotted as microstrain versus load position.

For the dynamic tests, strain sensors numbers 1, 5, and 6 were chosen to exemplify the results. Gages 1 and 5 represent data taken from beneath a rail from each track and sensor 6 represents data from the centerline of the structure. As may be seen in Appendix D, for each of the example sensors, the results are plotted for each direction at each speed for the controlled conditions, and in each direction for the in-service loading conditions. The results of gage 11, the datum gage, is included in order to exhibit that the non-stress related fluctuations recorded during the tests are consistent with external noise. The results are plotted as microstrain versus time. Table 4.2 presents a comparison of theoretical and recorded strains. In all cases, the measured strains were less than the theoretical values. The average percent difference was determined to be 48%.

The measured impact factor calculations are presented in Appendix B. Table 4.3 presents a comparison of theoretical and recorded impact values. Since the results varied as to whether the measured impact values were more or less conservative than the theoretical values, further analysis must be performed before a conclusion is drawn.

TABLE 4.2

COMPARISON OF THEORETICAL STRAIN TO RECORDED STRAIN

Test	Gage	Maximum Theoretical Strain (microstrain)	Maximum Recorded Strain (microstrain)	Percent Difference
Static, Westbound	1	-350	-170	51
Static, Westbound	5	-197	-93	53
Static, Westbound	6	-274	-129	53
Static, Eastbound	1	-197	-136	31
Static, Eastbound	5	-350	-215	39
Static, Eastbound	6	-274	-159	42
10 mph Eastbound	1	-261	-190	27
10 mph Eastbound	5	-462	-250	46
10 mph Eastbound	6	-361	-203	44
20 mph Westbound	1	-462	-230	50
20 mph Westbound	5	-261	-140	46
20 mph Westbound	6	-361	-173	52
30 mph Eastbound	1	-261	-175	33
30 mph Eastbound	5	-462	-250	46
30 mph Eastbound	6	-361	-204	43
In-service Westbound	1	-348	-197	43
In-service Westbound	5	-196	-122	38
In-service Westbound	6	-272	-187	31
In-service Eastbound	1	-196	-50	74
In-service Eastbound	5	-348	-145	58
In-service Eastbound	6	-272	-130	52

Average Percent Difference =	48

TABLE 4.3

COMPARISON OF THEORETICAL IMPACT FACTORS TO MEASURED IMPACT FACTORS

Test	Gage	Theoretical Impact Factor (%)	Measured Impact Factor (%)	Percent Difference
10 mph Eastbound	1	32	40	25
10 mph Eastbound	5	32	16	-50
10 mph Eastbound	6	32	28	-13
20 mph Westbound	1	32	35	9
20 mph Westbound	5	32	50	56
20 mph Westbound	6	32	34	6
30 mph Eastbound	1	32	28	-13
30 mph Eastbound	5	32	16	-50
30 mph Eastbound	6	32	28	-13

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 General Conclusions

1. Dynamic load testing is a valuable tool, but needs some refinements, such as more automation of direct data collection from strain sensor system to personal computer during operation.
2. Procedures that have been outlined for nondestructive bridge testing using strain sensors need to be implemented and integrated into the codes, so that testing may become more acceptably used in practice.

5.2 Experimental Program Conclusions

1. The theoretical strains were demonstrated to be conservative in comparison to the measured strains of the field study, as was expected. This was due to factors such as unintended composite action.
2. The theoretical impact factors were not conservative in comparison to the measured impact factors. One explanations the lack of stiffness of the bridge floor trough system, due to omission of the concrete over the floor plates.
3. The field study illustrates how a nondestructive dynamic load test can be performed in a short period of time with useful results.
4. The field study demonstrates the simplicity of carrying out the preparation, testing, and data reduction, which results in low cost.

5. The limited scope of the case study demonstrates the importance of making the right assumptions. Unless the correct assumptions are used, a more complicated analysis does not necessarily produce a more accurate answer.

5.3 Recommendations for Future Study Nondestructive Testing of Bridges

Due to the deterioration of infrastructure and the increasing cost of replacing existing bridges, rehabilitation is becoming a popular solution. Nondestructive bridge testing can give an accurate appraisal of a bridge's existing condition, and can identify areas that need the most improvement. Once guidelines have been incorporated into the codes, nondestructive testing will become a more practical solution. The most useful area for future study would be to determine how nondestructive testing may become an established method, so that it will be acceptable and integrated into code.

APPENDIX A

CALCULATION OF MOMENT OF INERTIA OF TYPICAL FLOOR SECTION

This appendix presents the calculation of area, neutral axis location, and moment of inertia for the typical floor section. These values will be used in determining the theoretical strain for the experimental test program. The following is included in this appendix:

Figure A.1 Floor Section Cross Section

Calculation of "y" - Neutral Axis Location

Area of Floor Section shown in Figure A.1

$2(5.25)(0.4375)+4(2.11)+2(17.25)(0.375)+17.25(0.4375) = 33.518\ \text{in}^2$

Neutral Axis Location "y"

$$\{2(5.25)(0.4375)(18.65625)+2(2.11)(17.5475+1.3275)+2(17.25)(0.375)(9.4375)$$
$$+17.25(0.4375)(0.21875)\}/33.518 = \mathbf{8.625\ in = y}$$

Calculation of Moment of Inertia

$$2(5.25)(0.4375^3)/12+2(5.25)(0.4375)(9.62025^2)+4(1.76)+2(2.11)(10.03125^2+7.2975^2)$$
$$+2(0.375)(17.25^2)/12+2(0.375)(17.25)(0.8125^2)+17.25(0.4375^3)/12$$
$$+17.25(0.4375)(8.40625^2) = \mathbf{1643\ in^3 = I}$$

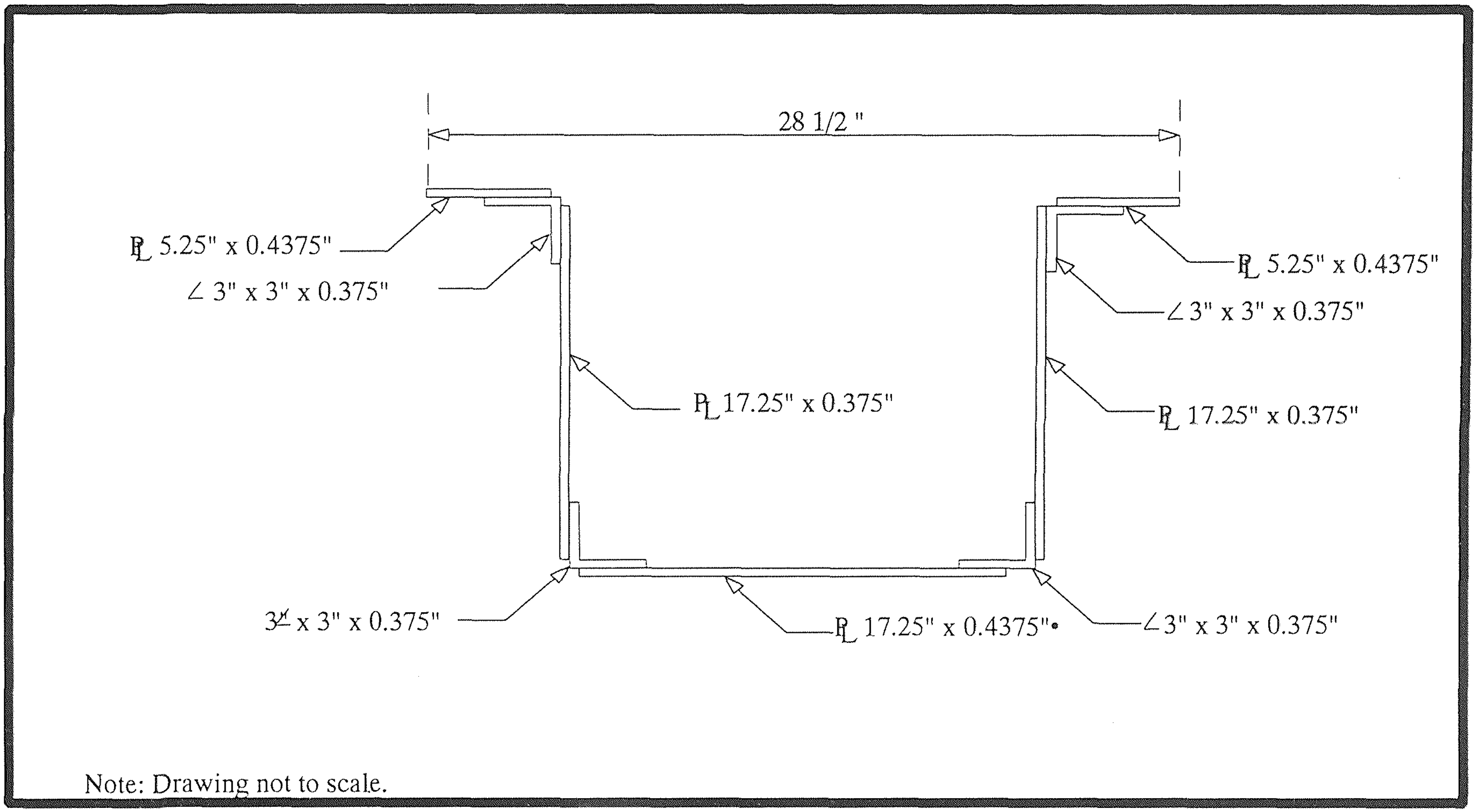


Figure A-1
Floor Section Cross Section

APPENDIX B

SAMPLE CALCULATIONS OF THEORETICAL STRAIN AND IMPACT FACTORS

The following is included in this appendix:

Figure B.1 Longitudinal Gage Locations
Figure B.2 Static Load Test Shear and Moment Diagrams
Figure B.3 Dynamic Load Test using In-Service Commuter Trains Diesel Engine Shear and Moment Diagrams
Figure B.4 Dynamic Load Test using In-Service Commuter Trains Passenger Car Shear and Moment Diagrams

Calculation of Strain

$\varepsilon = My/IE$

where: ε is strain

M is to be determined according to the load applied

y is determined from the floor section

I is determined from the floor section

E is the modulus of elasticity for steel 29000 ksi

All strains calculated are for loading on the Westbound Track.

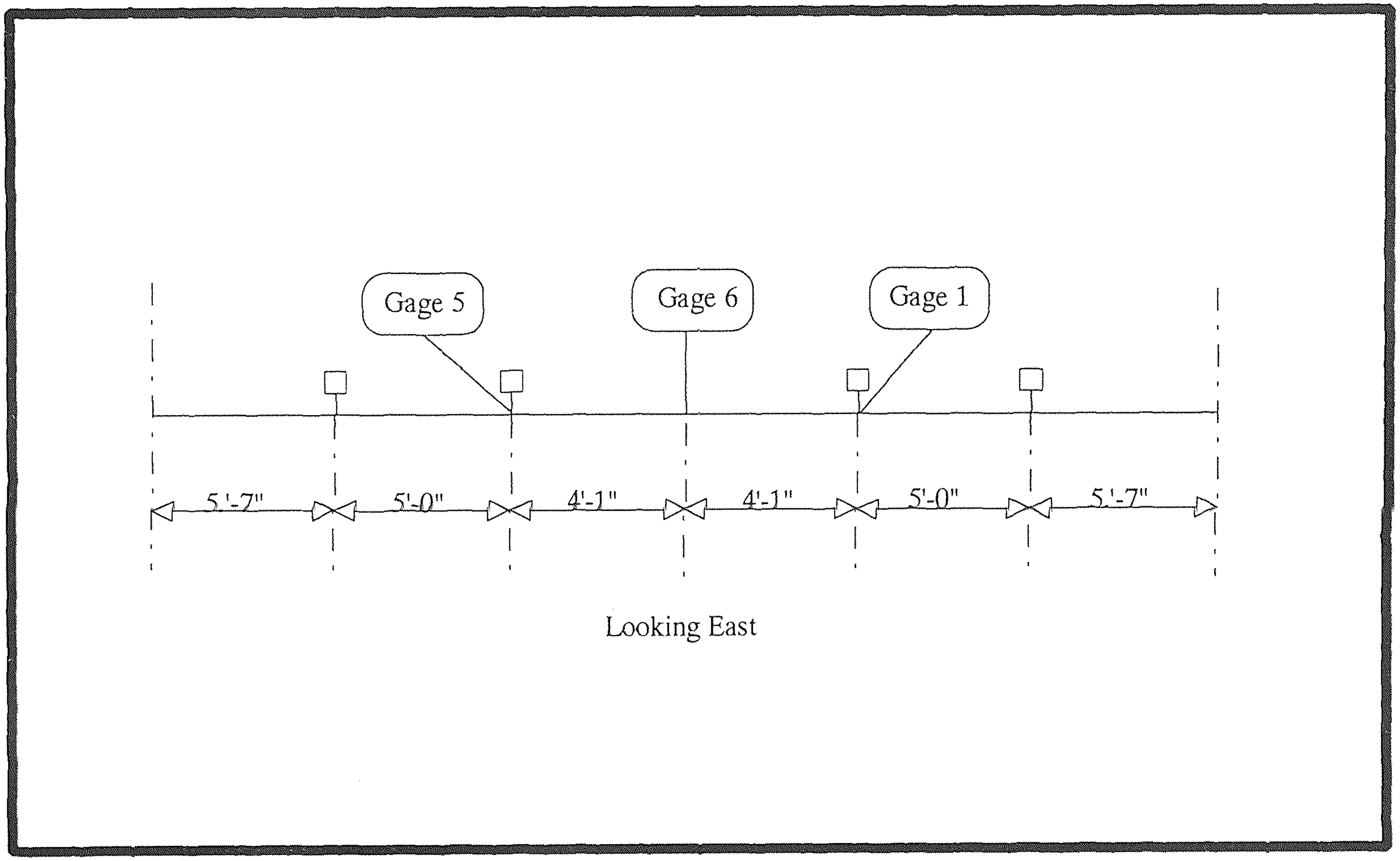


Figure B-1
Longitudinal Gage Locations

Static Load Test Using E80 Test Train

From "Standard Handbook of Civil Engineers", 3rd ed., McGraw Hill 1983, p 17-11

The equivalent uniform load for a 63' span is 13.12 kips for an E80 loading.

For each floor section the load is:

$$13.12\cdot\frac{28.5}{12} = 31.16 \quad \text{kips}$$

: where 28.5 is the distance center to center of floor trough section as shown in Figure A.1.

The moments in the following calculations are from Figure B-2 and the resulting strains are as follows:

Gage 1 $$\frac{160.979\cdot 12\cdot 8.625}{1643\cdot 29000} = 3.497\cdot 10^{-4}$$

Gage 6 $$\frac{125.992\cdot 12\cdot 8.625}{1643\cdot 29000} = 2.737\cdot 10^{-4}$$

Gage 5 $$\frac{90.866\cdot 12\cdot 8.625}{1643\cdot 29000} = 1.974\cdot 10^{-4}$$

Dyanamic Load Test Using E80 Test Train

Impact Factor = $$40 - \frac{3L^2}{1600}$$

$$40 - 3\cdot\frac{63^2}{1600} = 32.558 \quad \%$$

Gage 1 $$3.497\cdot 10^{-4}\cdot 1.32 = 4.616\cdot 10^{-4}$$

Gage 6 $$2.737\cdot 10^{-4}\cdot 1.32 = 3.613\cdot 10^{-4}$$

Gage 5 $$1.974\cdot 10^{-4}\cdot 1.32 = 2.606\cdot 10^{-4}$$

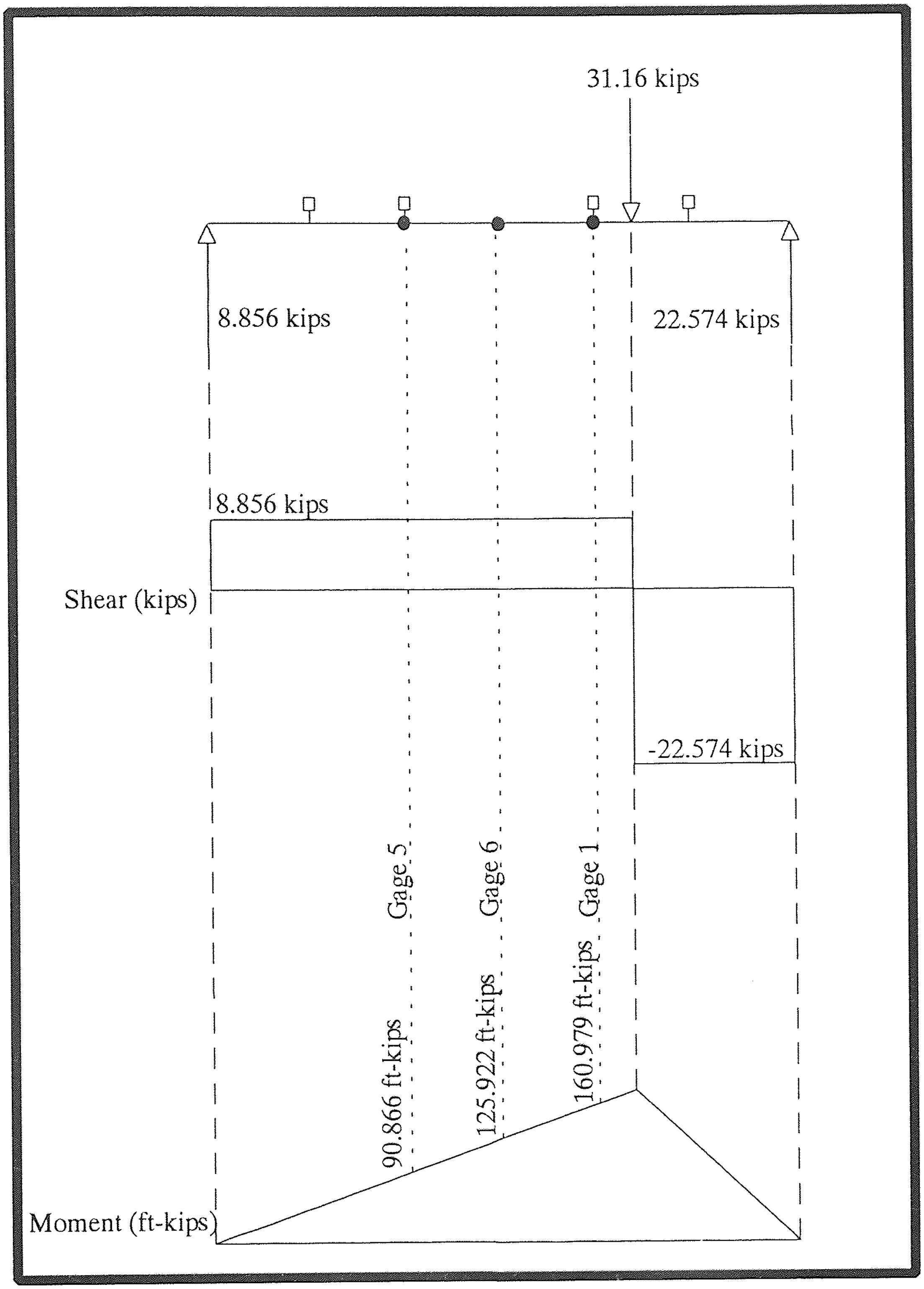


Figure B-2
Static Load Test
Shear and Moment Diagrams

Dynamic Load Test Using In-service Commuter Trains

Refer to Figure 4.4 for axle loads and spacing

The diesel engine axle load will be distributed over a minimum of 6.6'

$$\frac{6.6\cdot 12}{28.5} = 2.779$$ Number of floor sections to which each axle load is distributed

$$\frac{65}{2.779} = 23.39$$ kips Load on each floor section

The passenger car axle loads will be distributed over a minimum of 4'

$$\frac{4\cdot 12}{28.5} = 1.684$$ Number of floor sections to which each axle load is distributed

$$\frac{22.4}{1.684} = 13.302$$ kips Load on each floor section

Strains from Diesel Engine

The moments in the following calculations are from Figure B-3 and the resulting strains are as follows:

Gage 1 $$\frac{121.394\cdot 12\cdot 8.625}{1643\cdot 29000}\cdot 1.32 = 3.481\cdot 10^{-4}$$

Gage 6 $$\frac{94.960\cdot 12\cdot 8.625}{1643\cdot 29000}\cdot 1.32 = 2.723\cdot 10^{-4}$$

Gage 5 $$\frac{68.527\cdot 12\cdot 8.625}{1643\cdot 29000}\cdot 1.32 = 1.965\cdot 10^{-4}$$

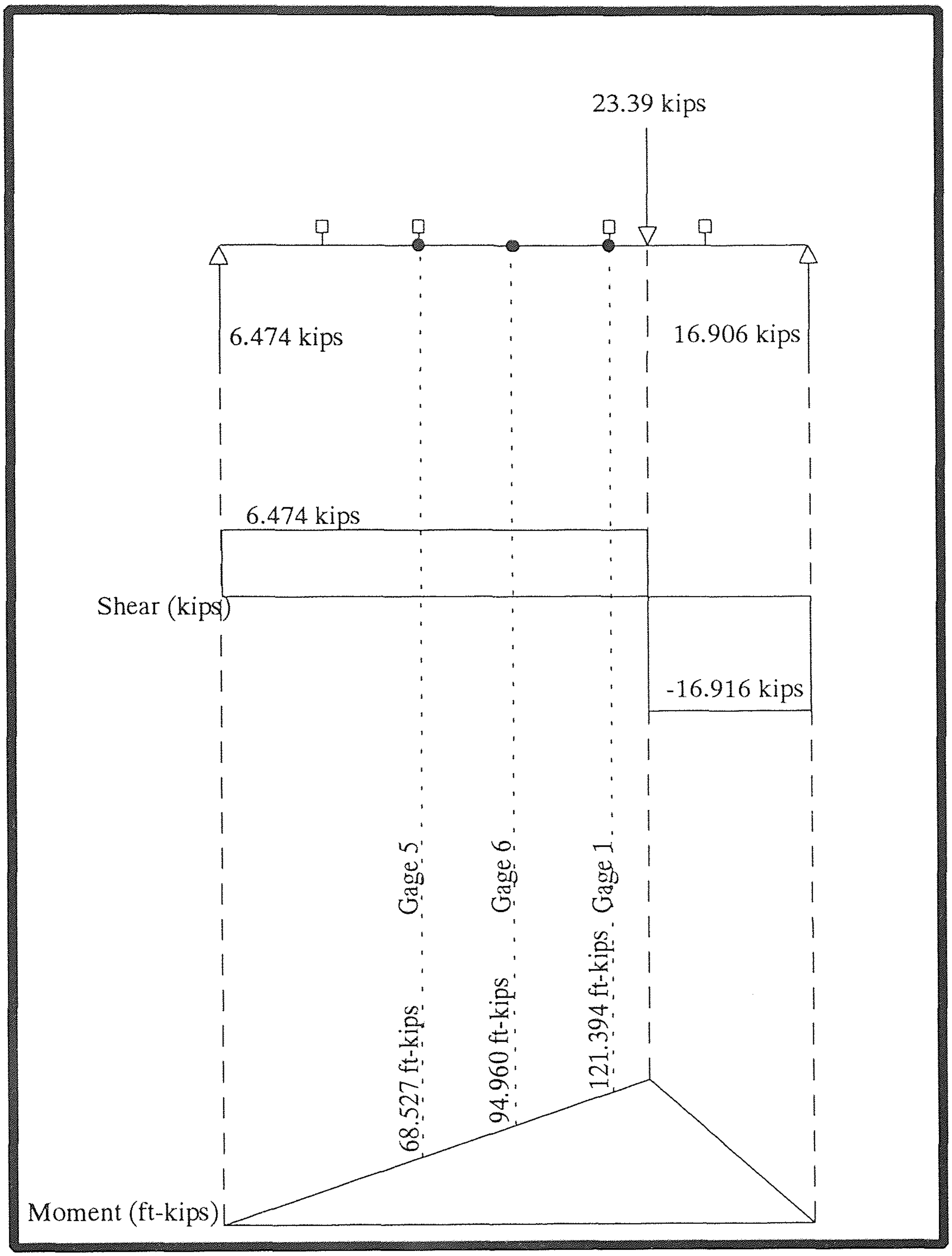


Figure B-3
Dynamic Load Test Using In-Service Commuter Trains
Diesel Engine
Shear and Moment Diagrams

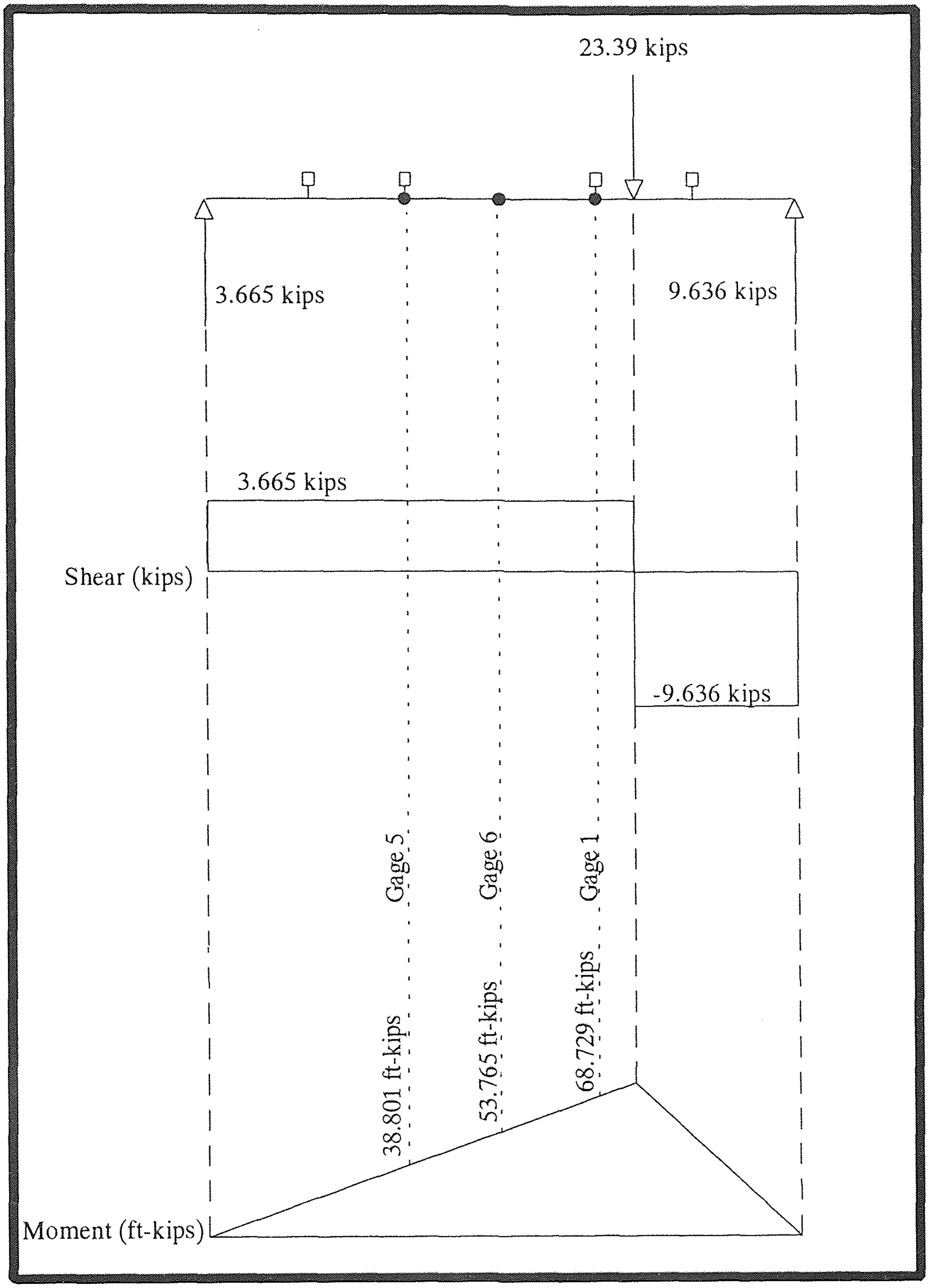


Figure B-4
Dynamic Load Test Using In-Service Commuter Trains
Passenger Car
Shear and Moment Diagrams

Strains from Passenger Car

The moments in the following calculations are from Figure B-4 and the resulting strains are as follows:

Gage 1 $\dfrac{68.729 \cdot 12 \cdot 8.625}{1643 \cdot 29000} \cdot 1.32 = 1.971 \cdot 10^{-4}$

Gage 6 $\dfrac{53.765 \cdot 12 \cdot 8.625}{1643 \cdot 29000} \cdot 1.32 = 1.542 \cdot 10^{-4}$

Gage 5 $\dfrac{38.801 \cdot 12 \cdot 8.625}{1643 \cdot 29000} \cdot 1.32 = 1.113 \cdot 10^{-4}$

Calculation of Actual Impact Values

Using E80 Test Train Recorded Values

Actual Impact Value = (Dynamic ε - Static ε)/Static ε

For 10 mph on the Eastbound Track

Gage 1 $\quad I= \dfrac{190-136}{136} = 0.397$

Gage 5 $\quad I= \dfrac{250-215}{215} = 0.163$

Gage 6 $\quad I= \dfrac{203-159}{159} = 0.277$

For 20 mph on the Westbound Track

Gage 1 $\quad I= \dfrac{230-170}{170} = 0.353$

Gage 5 $\quad I= \dfrac{140-93}{93} = 0.505$

Gage 6 $\quad I= \dfrac{173-129}{129} = 0.341$

For 30 mph on the Eastbound Track

Gage 1 $\quad I= \dfrac{175-136}{136} = 0.287$

Gage 5 $\quad I= \dfrac{250-215}{215} = 0.163$

Gage 6 $\quad I= \dfrac{204-159}{159} = 0.283$

APPENDIX C

STATIC LOAD TEST RESULTS

The following appendix presents data collected using the strain sensor data acquisition system during the experimental static load test program. Results are presented for two tests recorded for each of seven gages, Gage 1 through Gage 6 and Gage 11, the datum gage. The following is included in this appendix:

Table C.1 Static Load Test Results, Westbound Track
Figure C.1 Static Load Test, Westbound Track
Table C.2 Static Load Test Results, Eastbound Track
Figure C.2 Static Load Test, Eastbound Track

Table C-1
Static Load Test Results
Westbound Track

	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6	Gage 11
Position 0	0	0	0	0	0	0	0
Position 1	7	14	19	14	19	10	16
Position 2	13	13	15	11	13	8	15
Position 3	12	13	22	13	18	5	13
Position 4	11	16	24	20	12	10	11
Position 5	9	24	27	25	9	10	11
Position 6	3	31	40	36	0	-1	9
Position 7	-10	53	69	61	-24	-40	12
Position 8	-52	81	110	84	-54	-84	11
Position 9	-96	113	136	74	-70	-103	10
Position 10	-146	126	144	114	-79	-109	10
Position 11	-155	129	152	110	-88	-121	10
Position 12	-162	138	174	106	-93	-129	12
Position 13	-170	137	169	113	-91	-123	12
Position 14	-166	132	161	120	-82	-114	12
Position 15	-156	130	175	123	-77	-107	11
Position 16	-153	119	152	116	-56	-77	15
Position 17	-113	81	99	83	-19	-29	11
Position 18	-69	50	72	54	5	2	14
Position 19	-11	30	41	36	15	18	17
Position 20	4	26	36	30	18	20	15

Note: Gage 11 installed on unstressed member for temperature and noise reference.

Note: Load positions are shown in Figure 4.5, in addition Position 0 is a "no load" position.

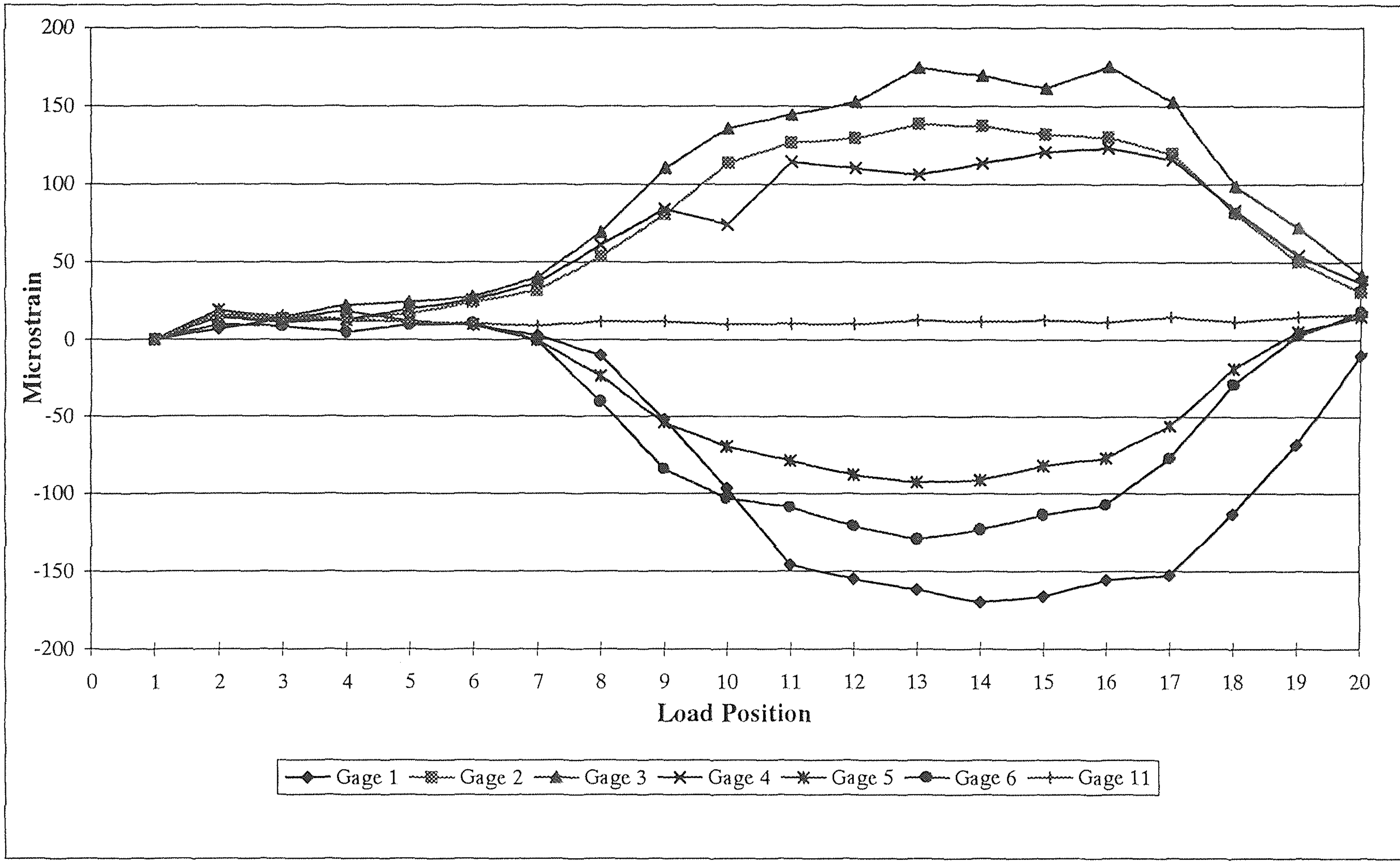


Figure C-1
Static Load Test
Westbound Track

Table C-2
Static Load Test Results
Eastbound Track

	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6	Gage 11
Position 0	0	0	0	0	0	0	0
Position 1	0	1	2	1	2	3	-18
Position 2	0	4	4	2	-2	-1	-18
Position 3	-3	4	9	1	6	-7	-18
Position 4	-5	6	4	2	-11	-9	-18
Position 5	-9	7	7	2	-22	-20	-18
Position 6	-21	21	16	8	-49	-40	-18
Position 7	-41	62	40	20	-104	-85	-18
Position 8	-74	134	76	37	-179	-130	-18
Position 9	-108	173	104	52	-200	-150	-18
Position 10	-126	167	97	48	-197	-150	-18
Position 11	-127	155	95	46	-202	-153	-18
Position 12	-129	165	103	49	-216	-159	-18
Position 13	-135	177	101	48	-201	-152	-18
Position 14	-136	152	86	40	-190	-145	-18
Position 15	-126	146	82	35	-185	-140	-18
Position 16	-126	131	73	29	-157	-120	-18
Position 17	-103	70	34	9	-82	-71	-18
Position 18	-67	20	7	1	-47	-39	-18
Position 19	-48	-8	-12	-9	-37	-32	-18
Position 20	-34	-17	-21	-16	-29	-30	-18

Note: Gage 11 installed on unstressed member for temperature and noise reference.

Note: Load positions are shown in Figure 4.5, in addition Position 0 is a "no load" position.

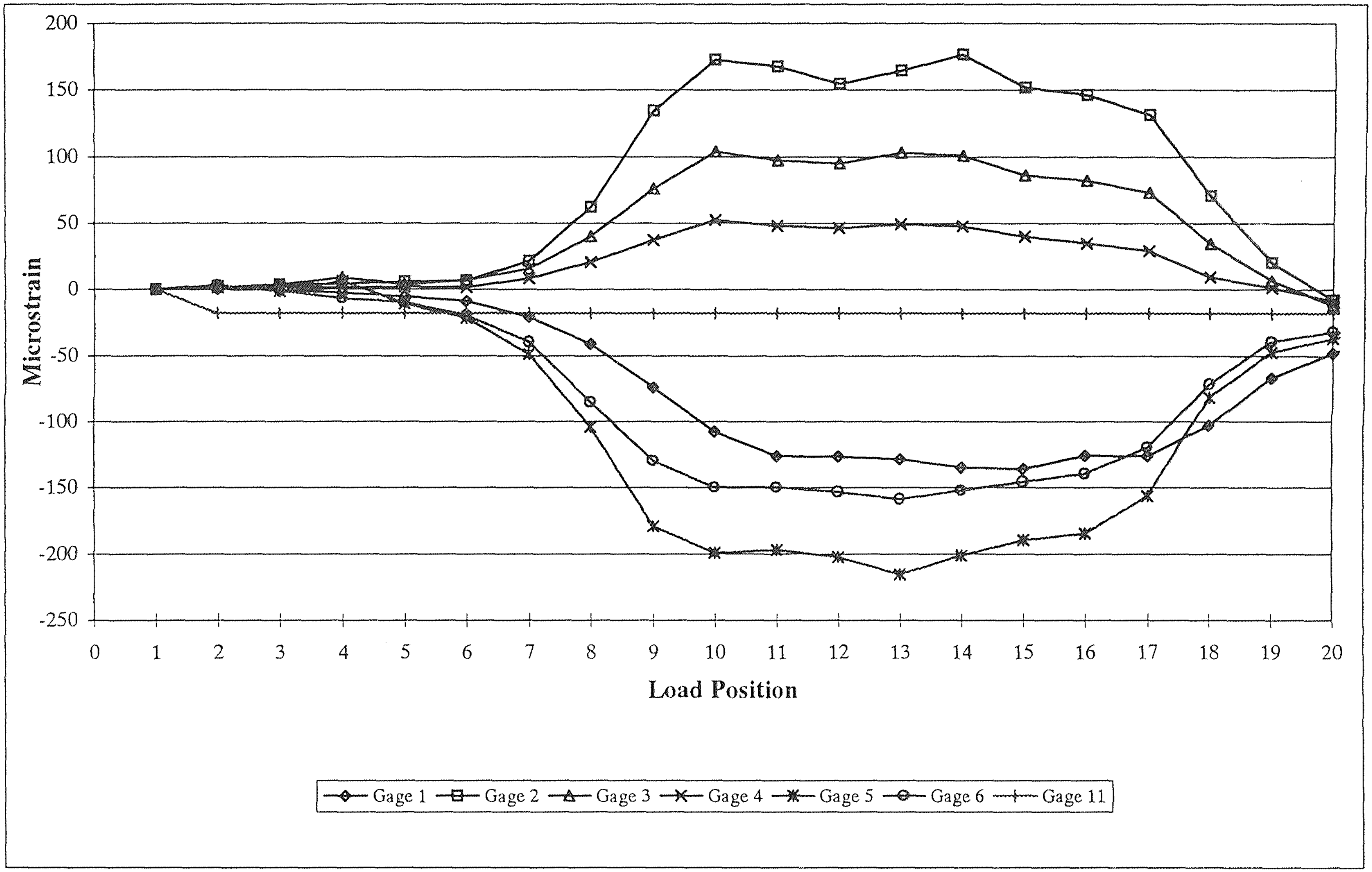


Figure C-2
Static Load Test
Eastbound Track

APPENDIX D

DYNAMIC LOAD TEST RESULTS

The following appendix presents data collected using the strain sensor data acquisition system during the experimental dynamic load test program. Results are presented for five tests recorded for each of three gages, Gage 1, Gage 5 and Gage 6. The results from Gage 11, the datum gage, are also included for two tests. The following figures are included in this appendix:

D.1 Dynamic Load Test, 10 MPH, Eastbound Track, Traveling East - Gage 1
D.2 Dynamic Load Test, 10 MPH, Eastbound Track, Traveling East - Gage 5
D.3 Dynamic Load Test, 10 MPH, Eastbound Track, Traveling East - Gage 6
D.4 Dynamic Load Test, 20 MPH, Westbound Track, Traveling East - Gage 1
D.5 Dynamic Load Test, 20 MPH, Westbound Track, Traveling East - Gage 5
D.6 Dynamic Load Test, 20 MPH, Westbound Track, Traveling East - Gage 6
D.7 Dynamic Load Test, 30 MPH, Eastbound Track, Traveling East - Gage 1
D.8 Dynamic Load Test, 30 MPH, Eastbound Track, Traveling East - Gage 5
D.9 Dynamic Load Test, 30 MPH, Eastbound Track, Traveling East - Gage 6
D.10 Dynamic Load Test, 30 MPH, Eastbound Track, Traveling East - Gage 11
D.11 Dynamic Load Test, Westbound Commuter - Gage 1
D.12 Dynamic Load Test, Westbound Commuter - Gage 5
D.13 Dynamic Load Test, Westbound Commuter - Gage 6
D.14 Dynamic Load Test, Eastbound Commuter - Gage 1
D.15 Dynamic Load Test, Eastbound Commuter - Gage 5
D.16 Dynamic Load Test, Eastbound Commuter - Gage 6
D.17 Dynamic Load Test, Eastbound Commuter - Gage 11

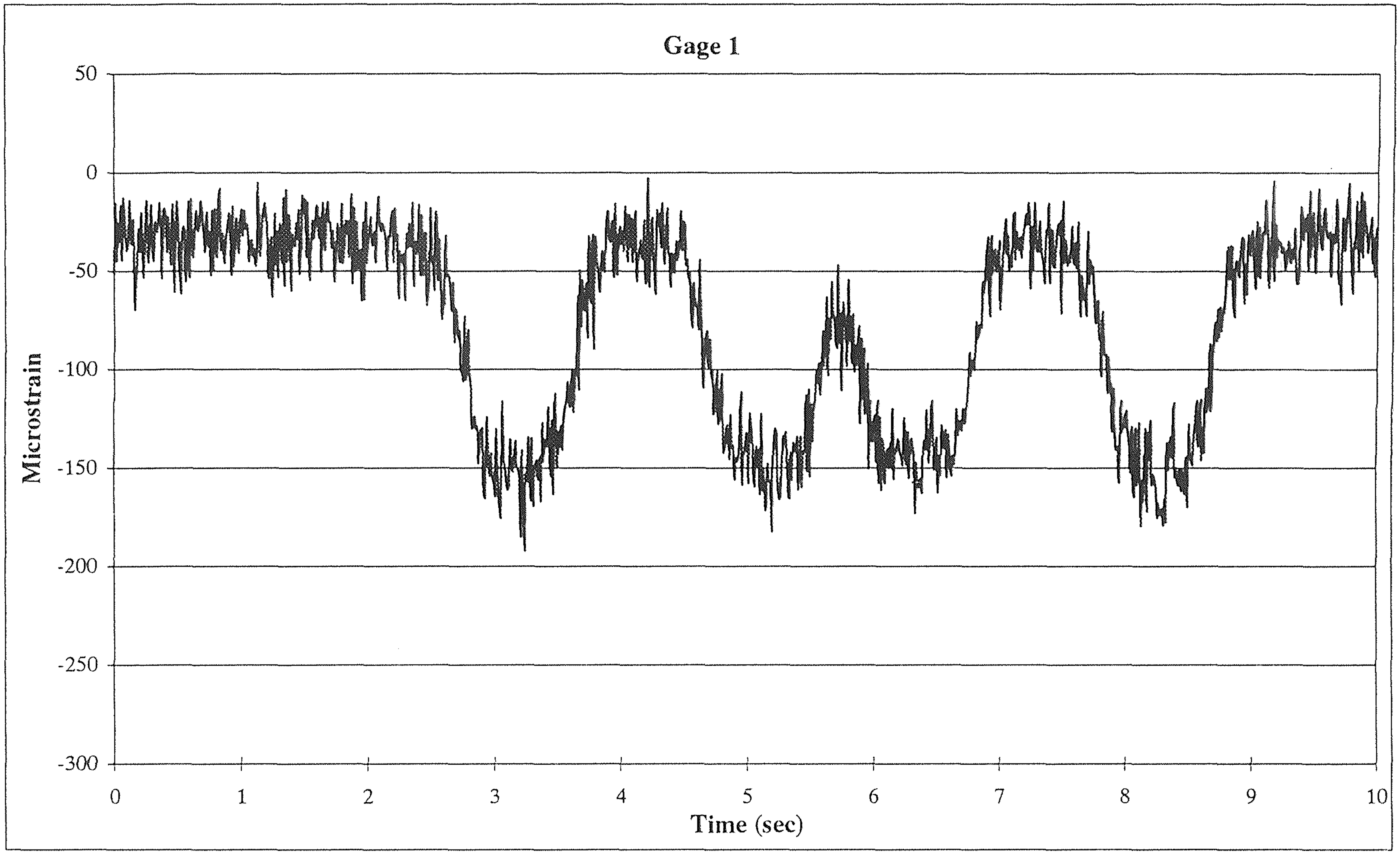


Figure D-1
Dynamic Load Test
10 MPH, Eastbound Track, Traveling East

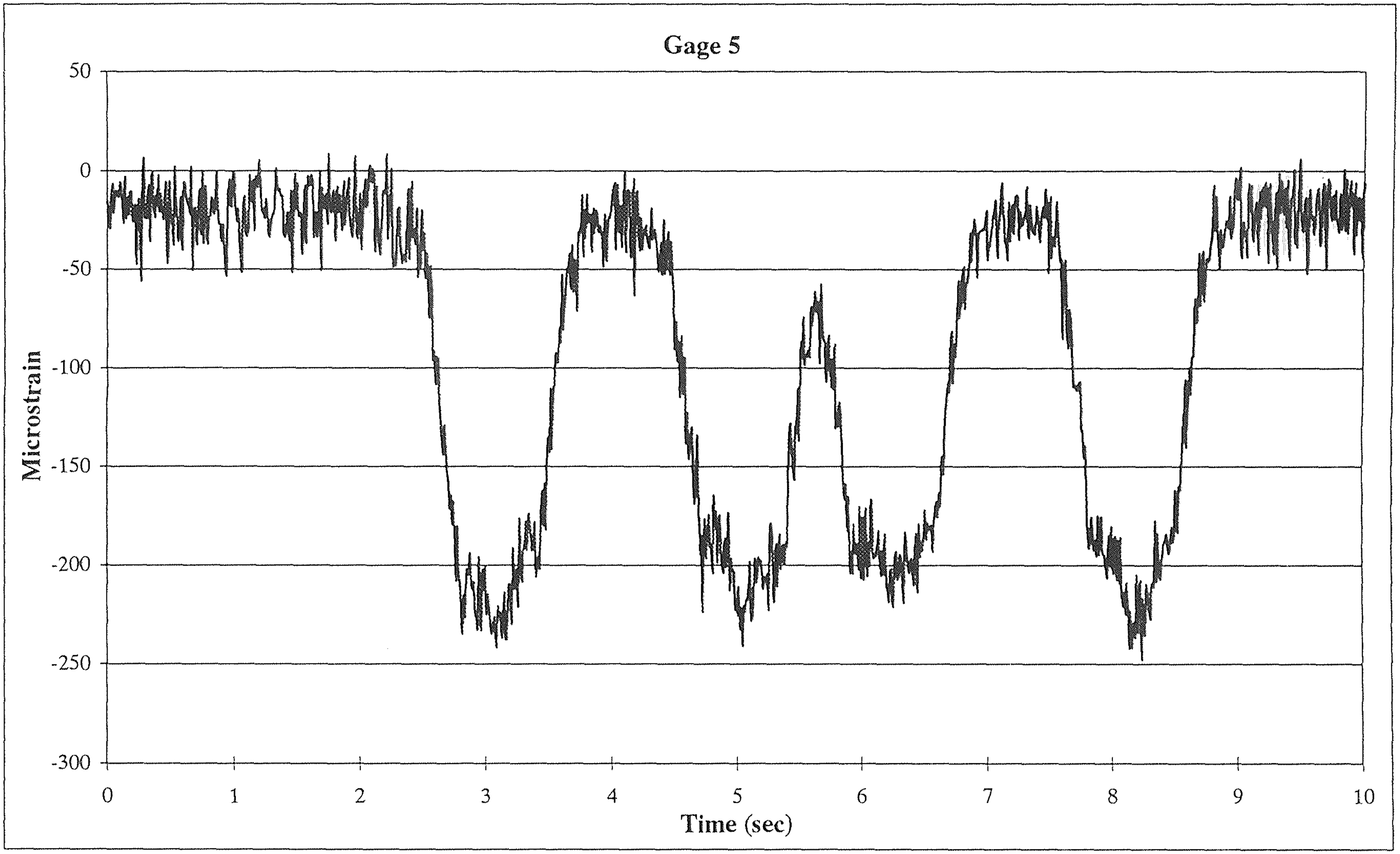


Figure D-2
Dynamic Load Test
10 MPH, Eastbound Track, Traveling East

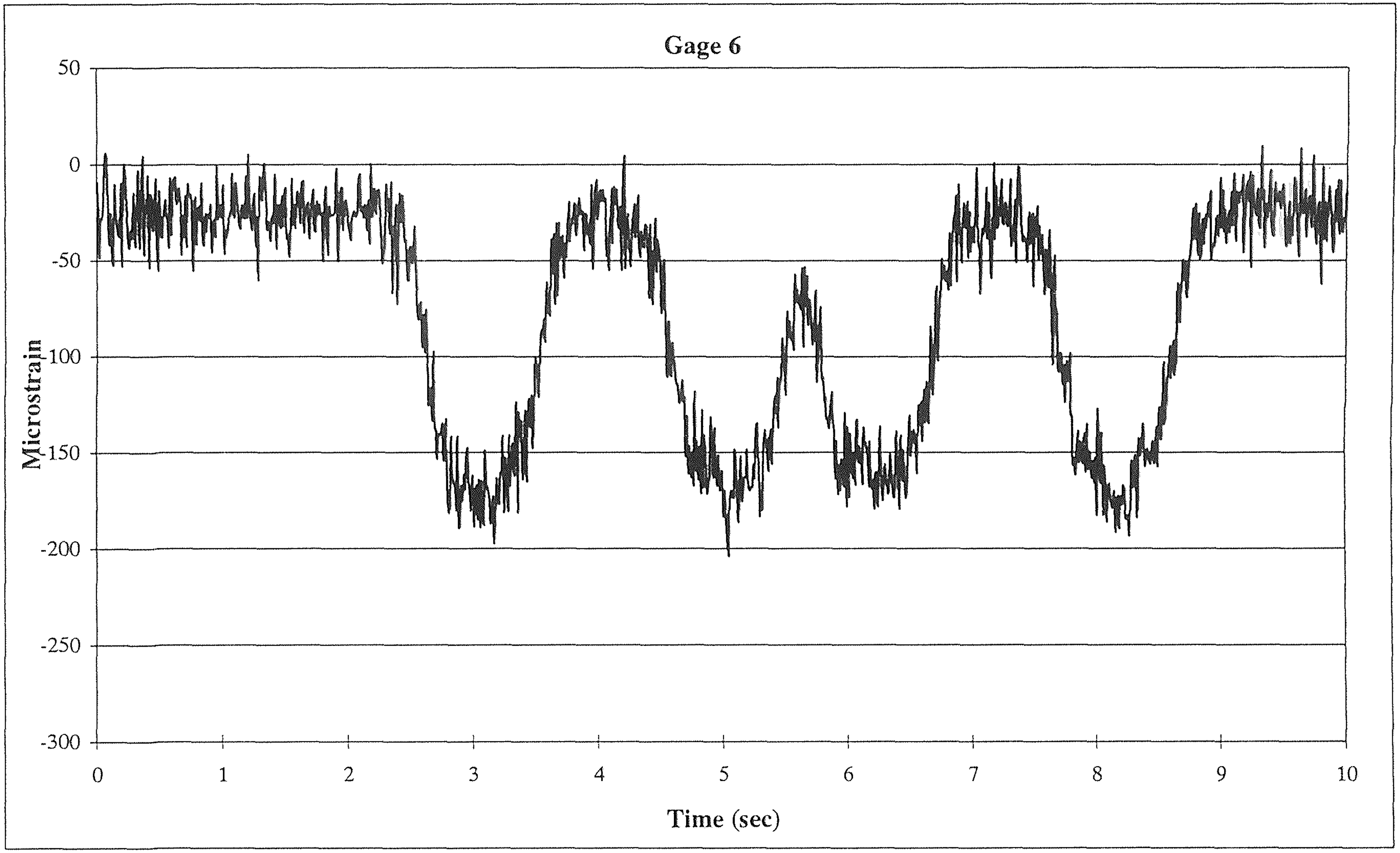


Figure D-3
Dynamic Load Test
10 MPH, Eastbound Track, Traveling East

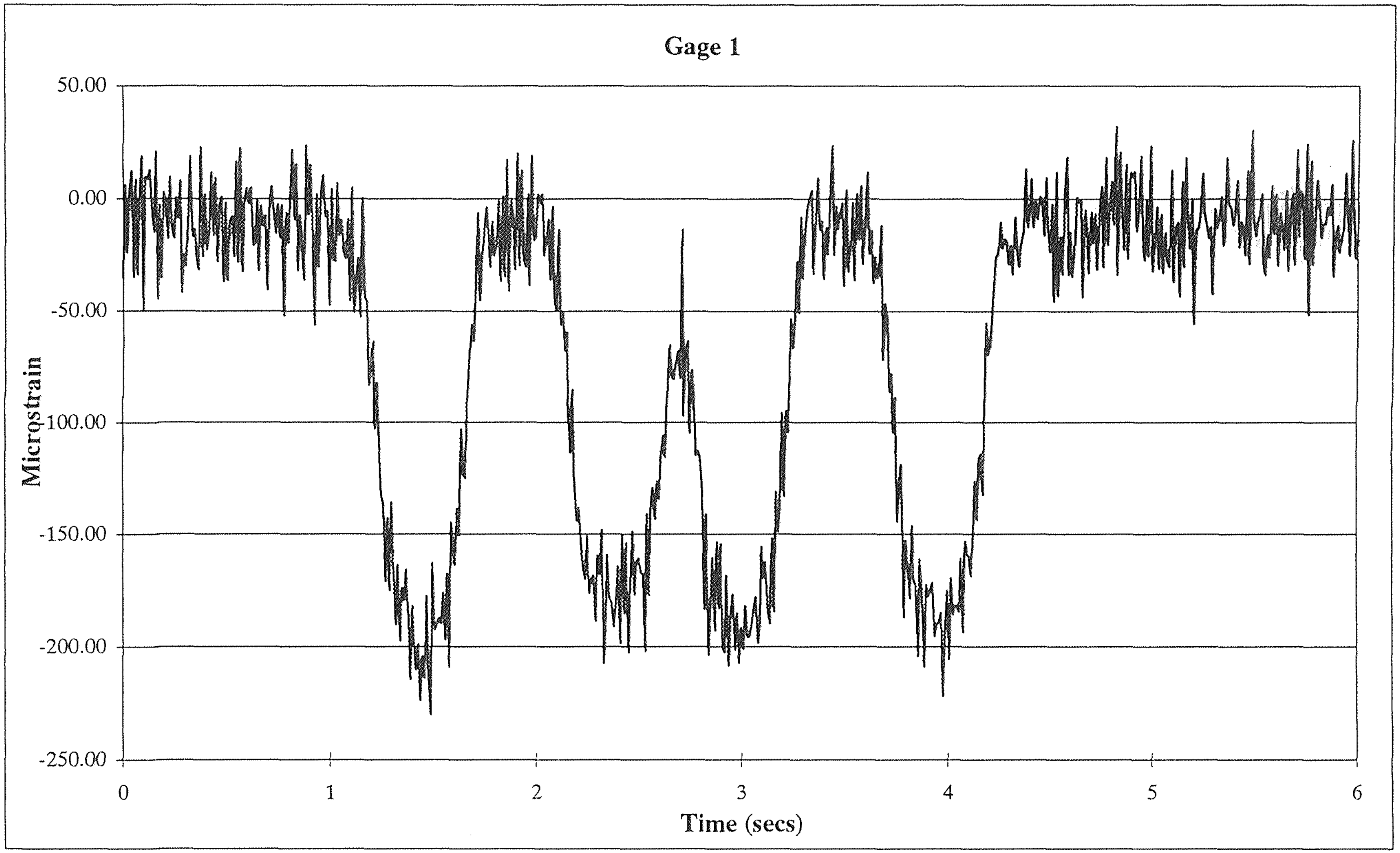


Figure D-4
Dynamic Load Test
20 MPH, Westbound Track Traveling East

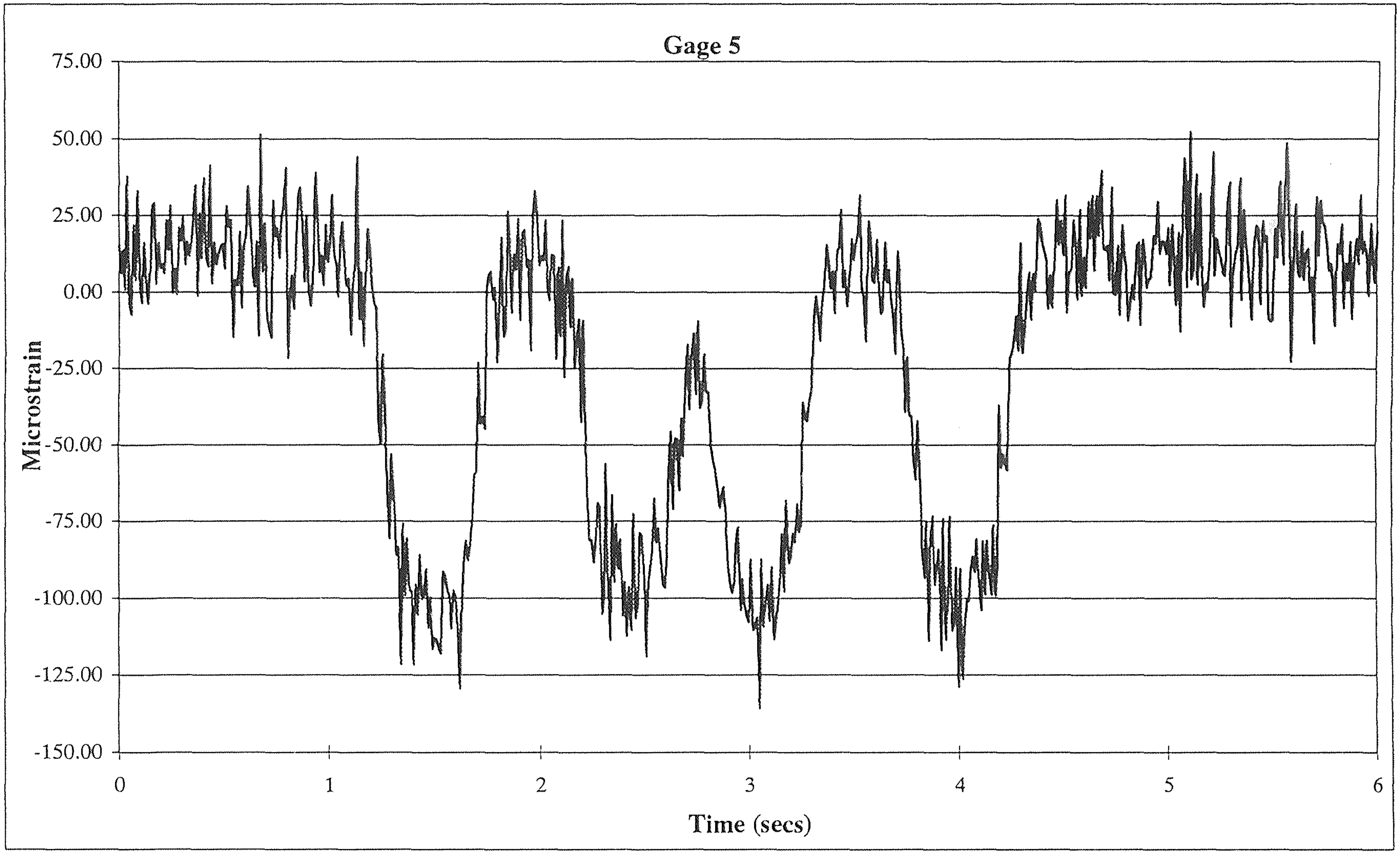


Figure D-5
Dynamic Load Test
20 MPH, Westbound Track, Traveling East

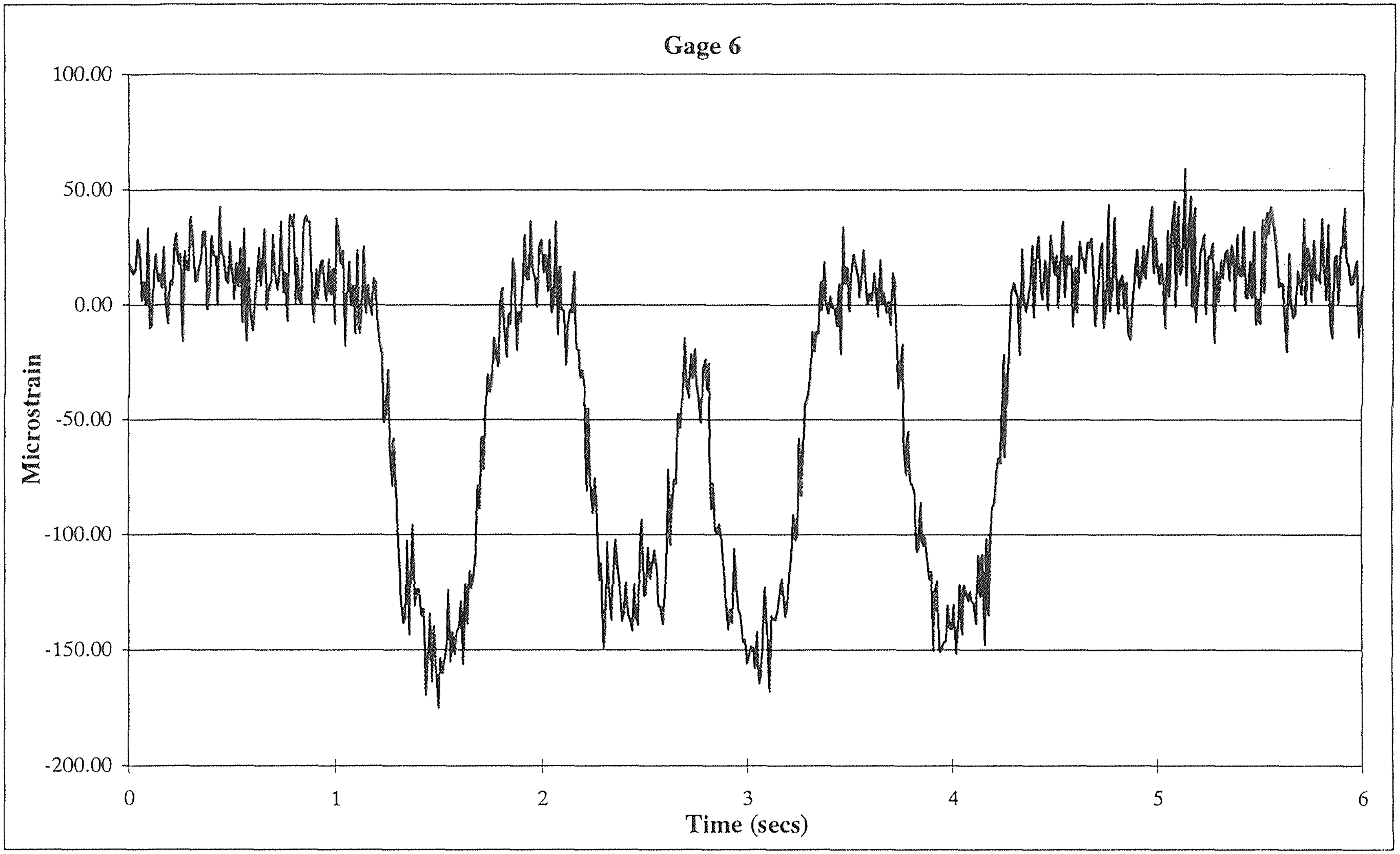


Figure D-6
Dynamic Load Test
20 MPH, Westbound Track, Traveling East

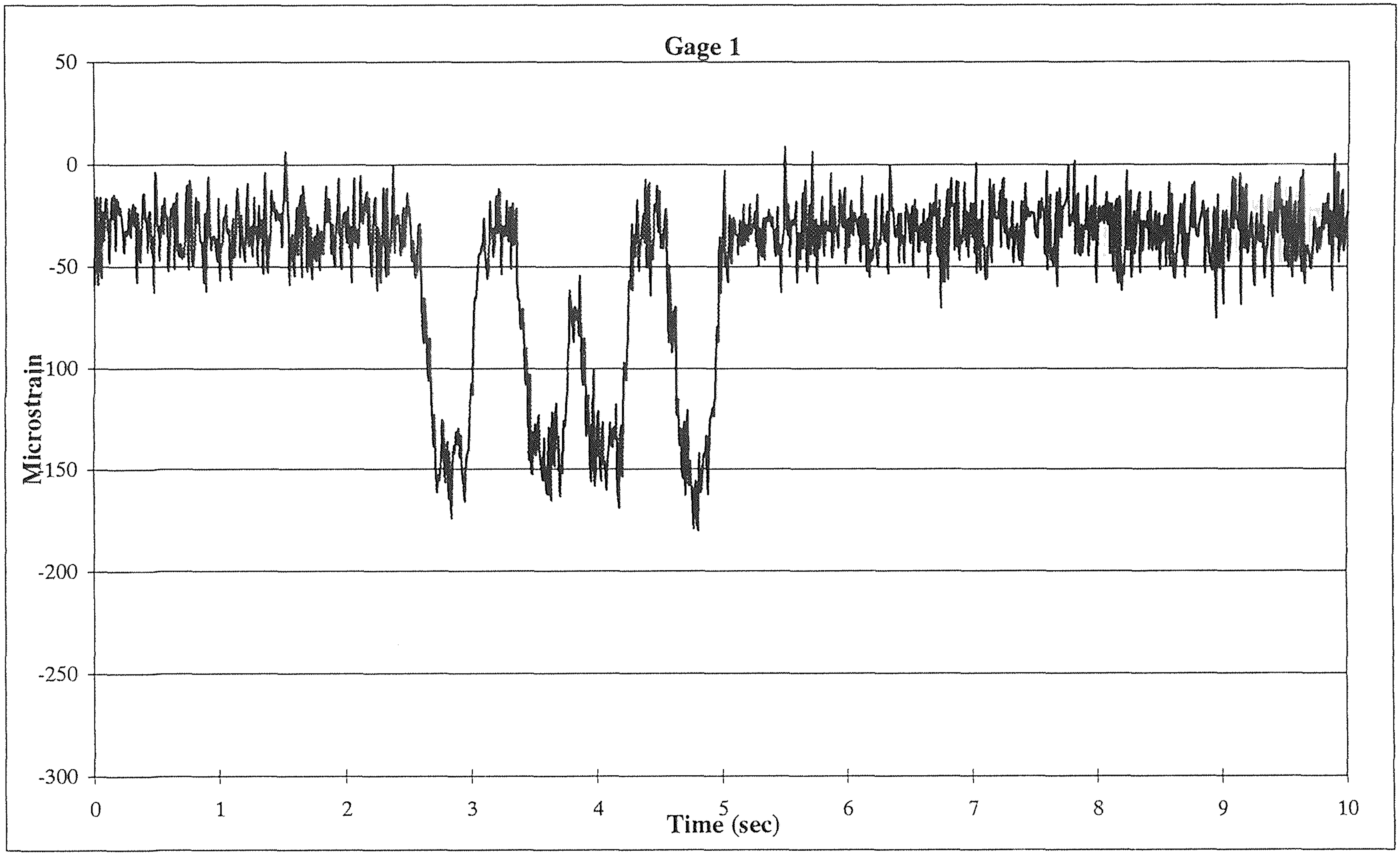


Figure D-7
Dynamic Load Test
30 MPH, Eastbound Track, Traveling East

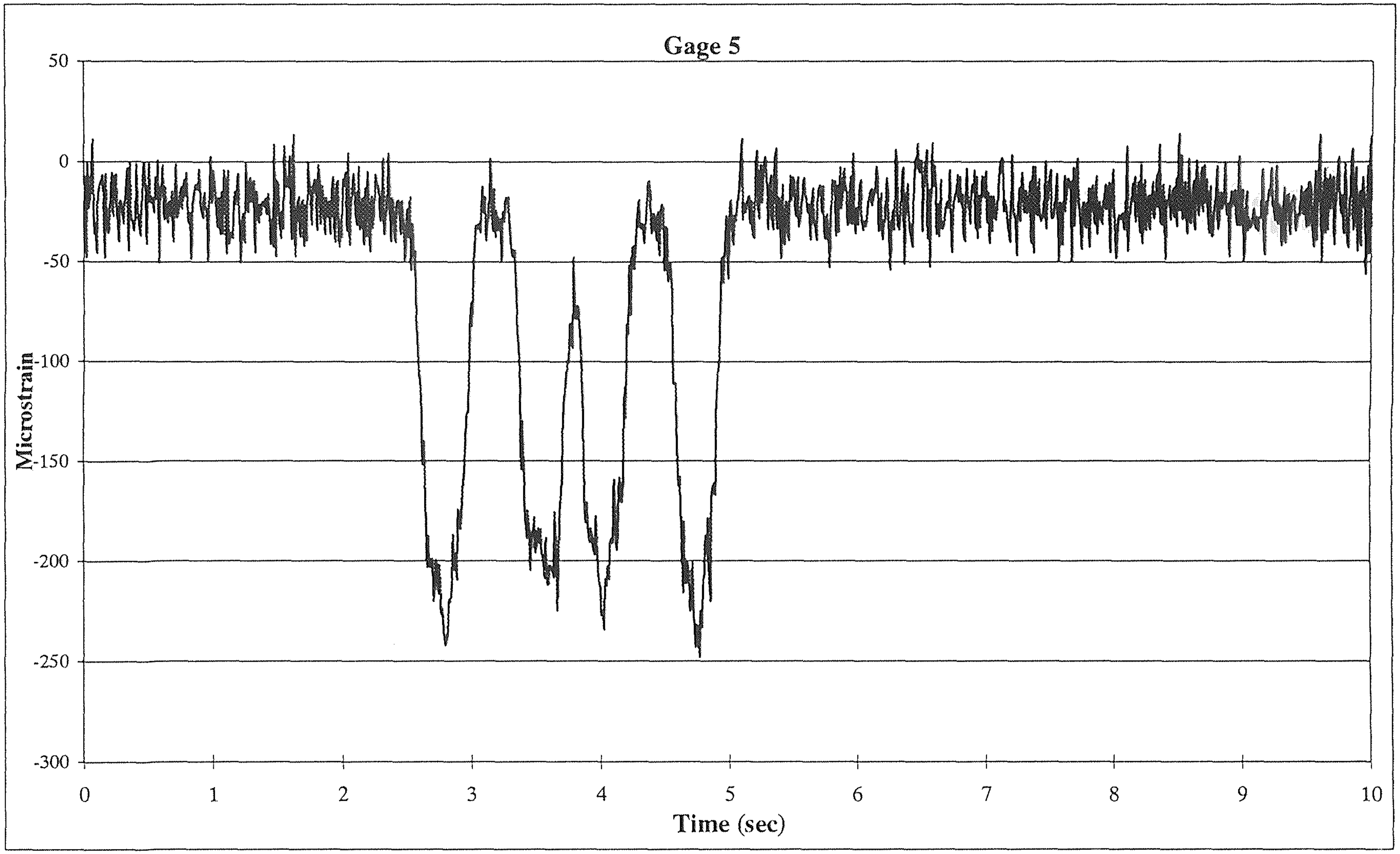


Figure D-8
Dynamic Load Test
30 MPH, Eastbound Track, Traveling East

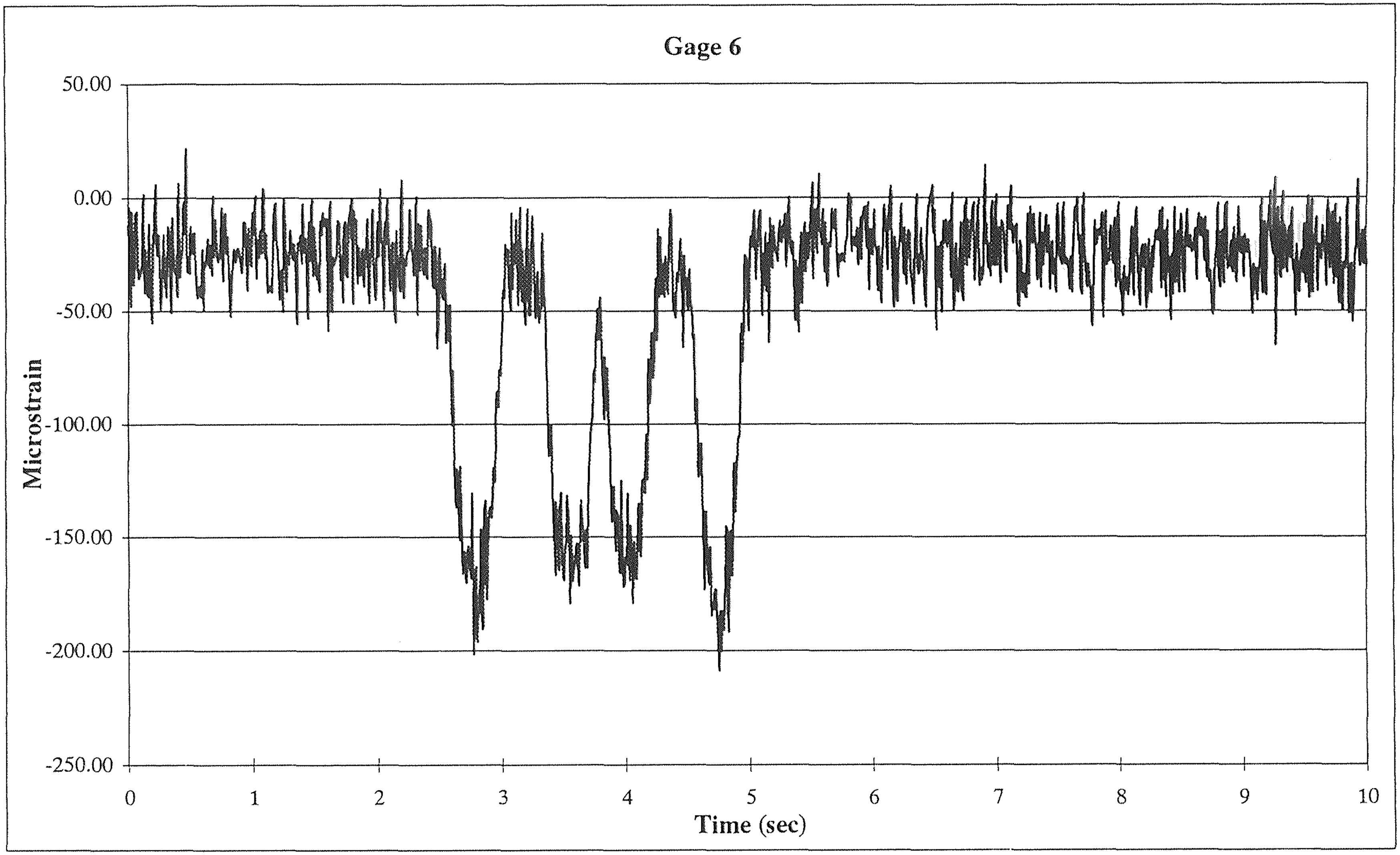


Figure D-9
Dynamic Load Test
30 MPH, Eastbound Track, Traveling East

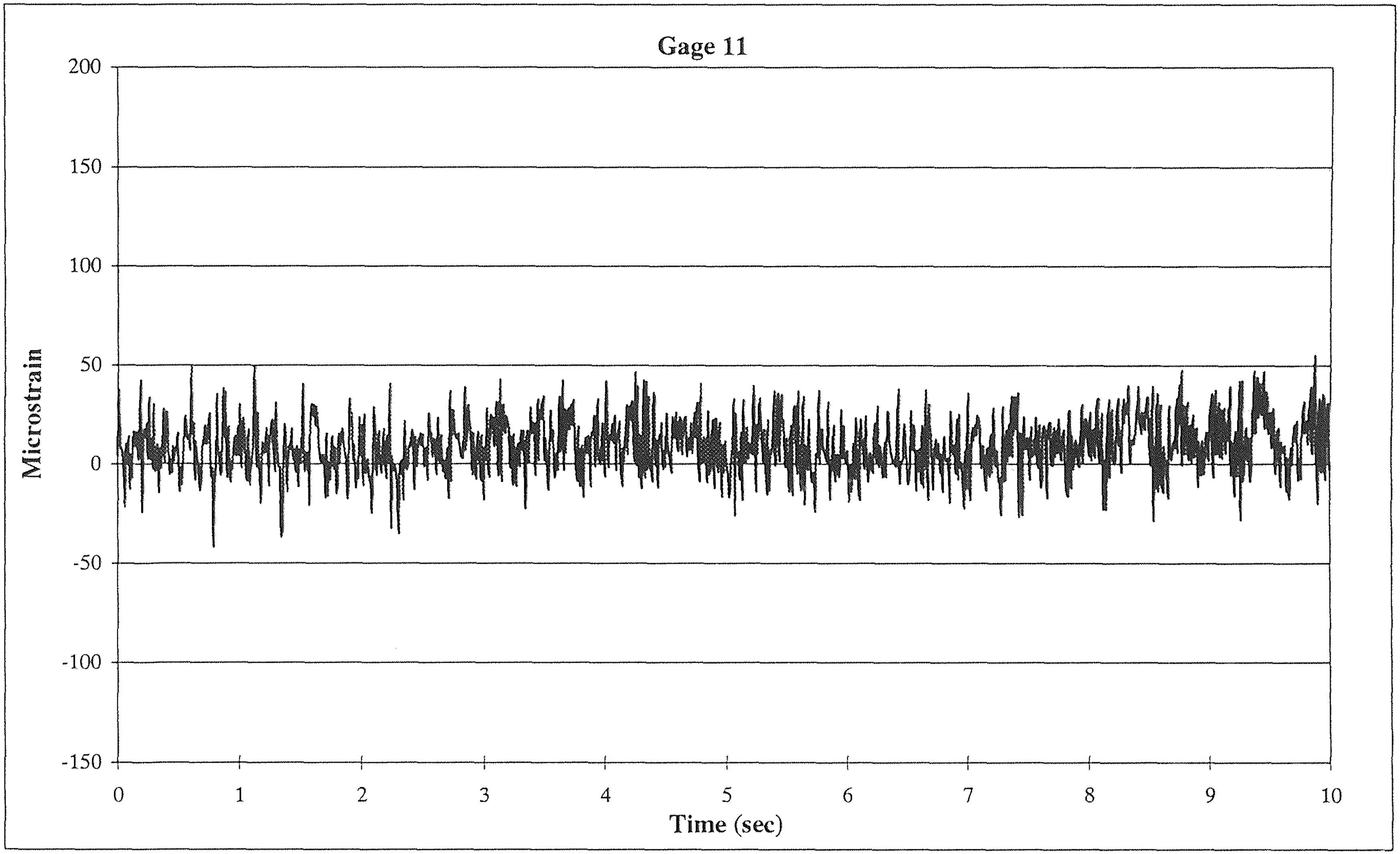


Figure D-10
Dynamic Load Test
30 MPH, Eastbound Track, Traveling East

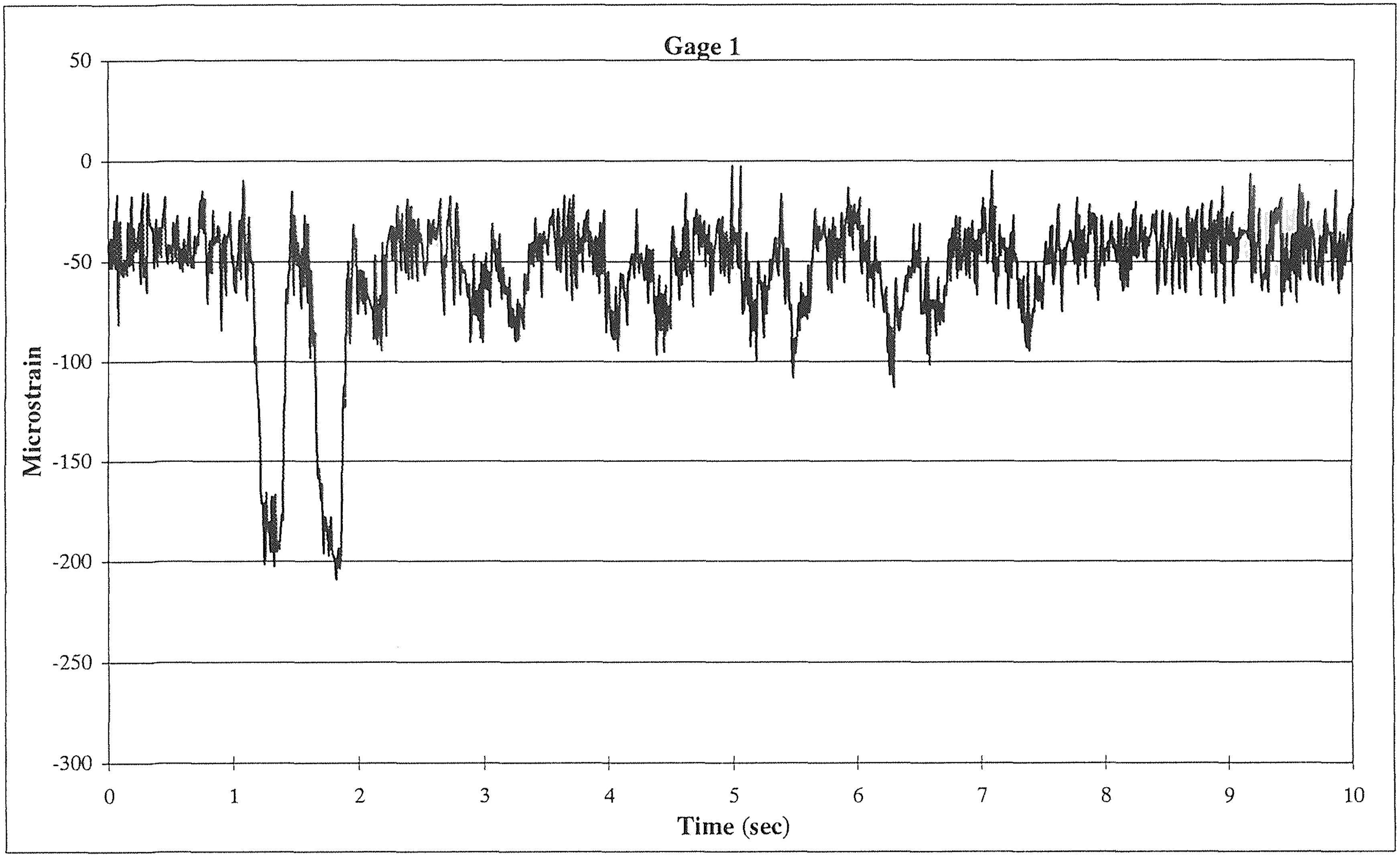


Figure D-11
Dynamic Load Test
Westbound Commuter

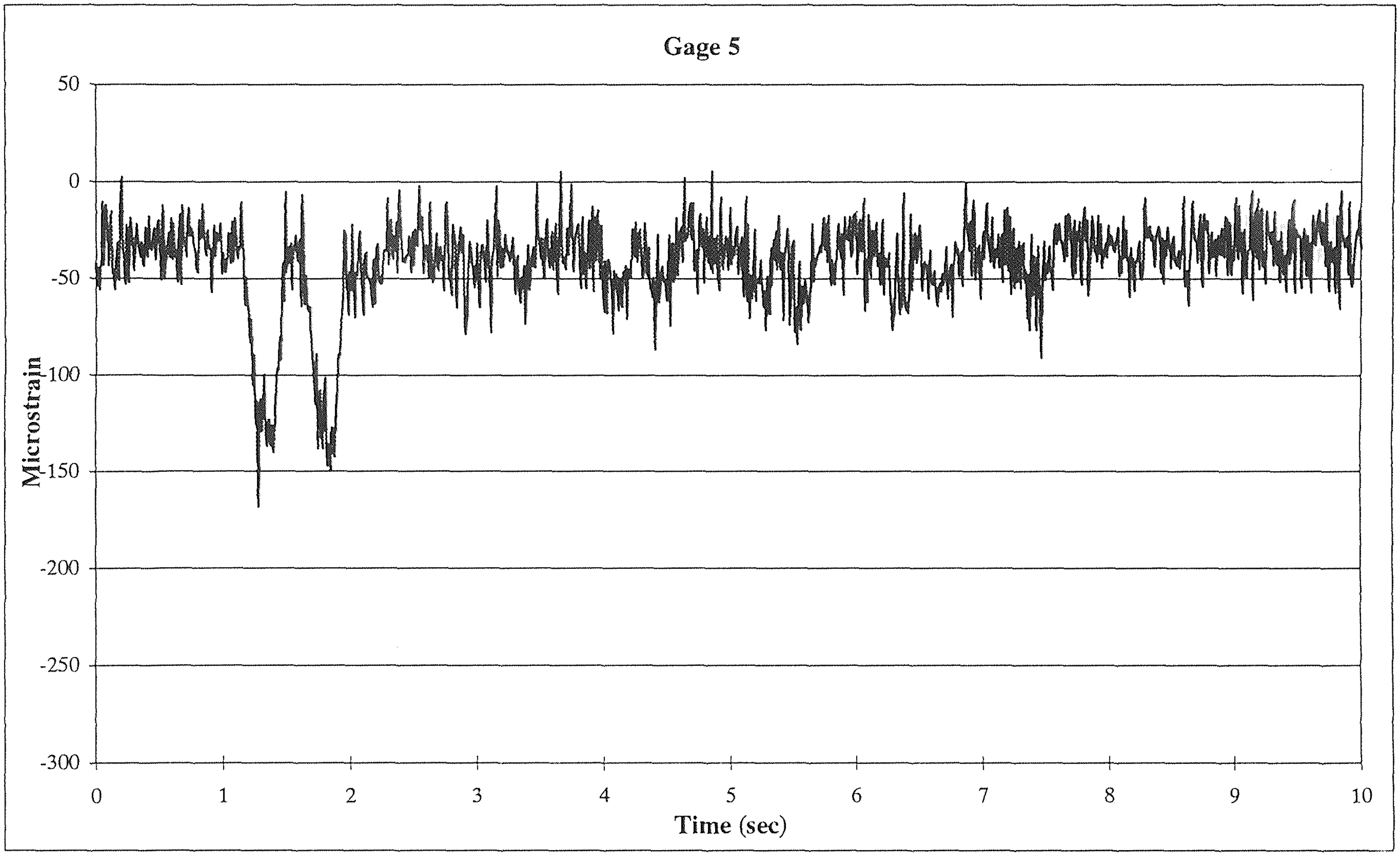


Figure D-12
Dynamic Load Test
Westbound Commuter

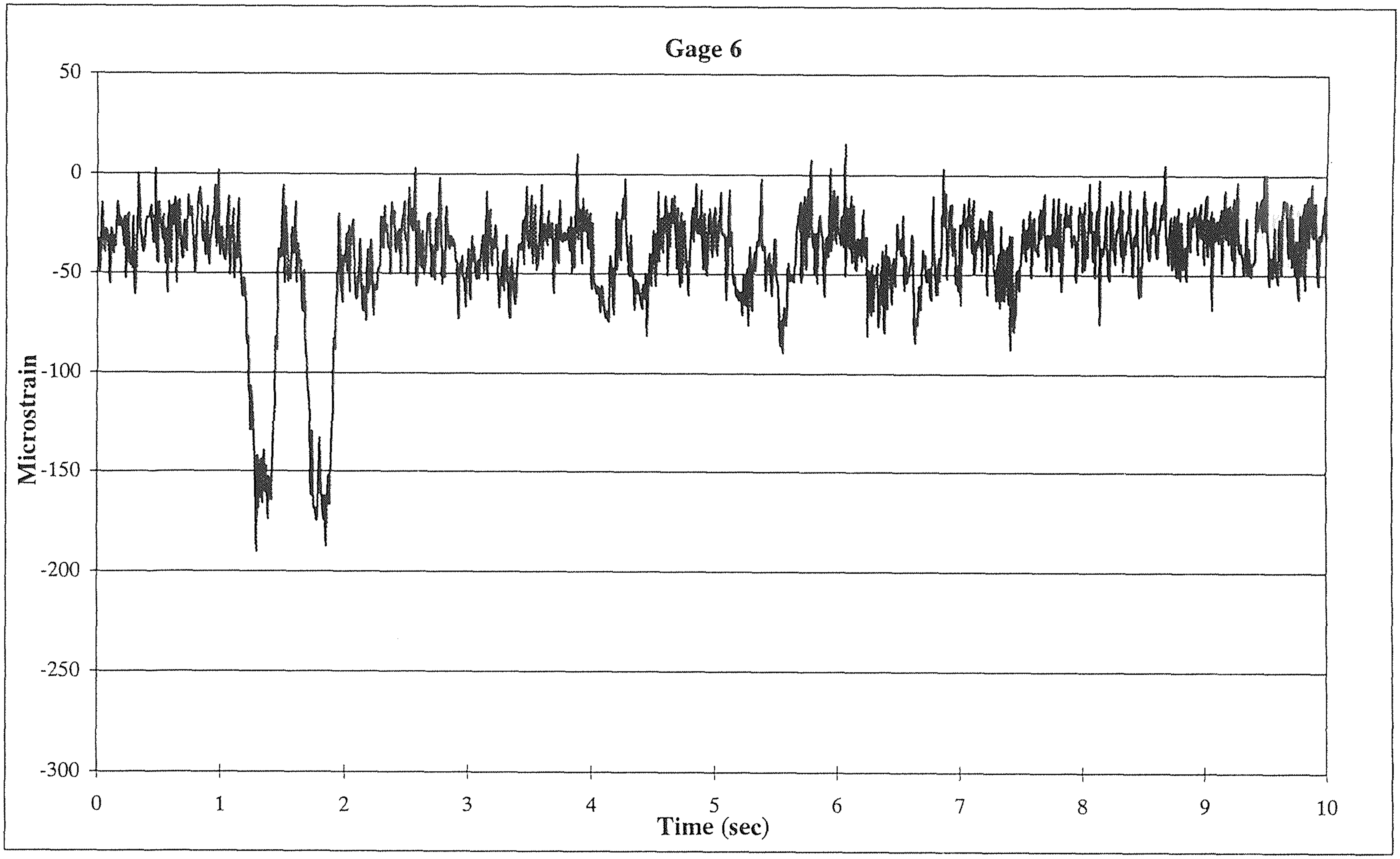


Figure D-13
Dynamic Load Test
Westbound Commuter

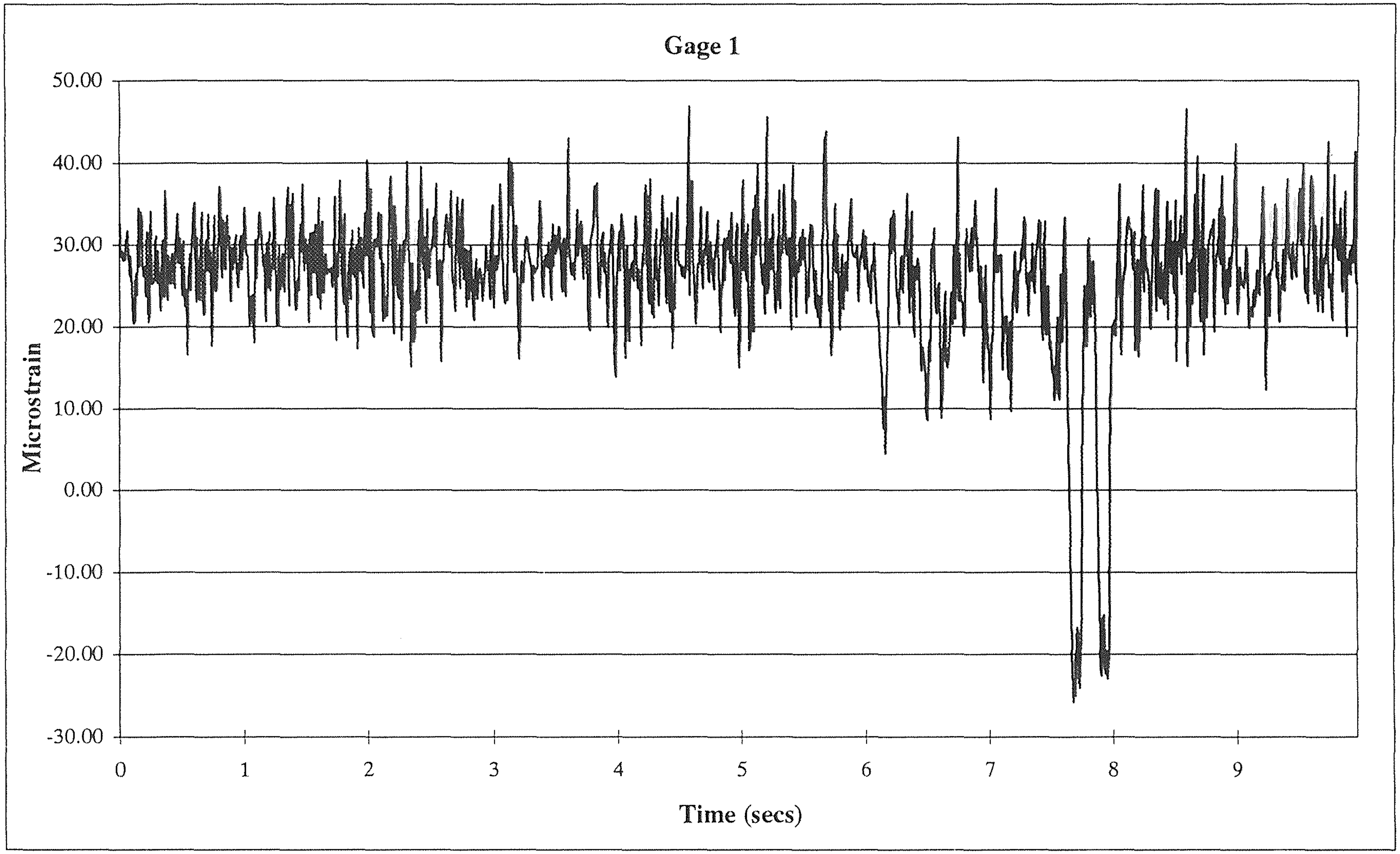


Figure D-14
Dynamic Load Test
Eastbound Commuter

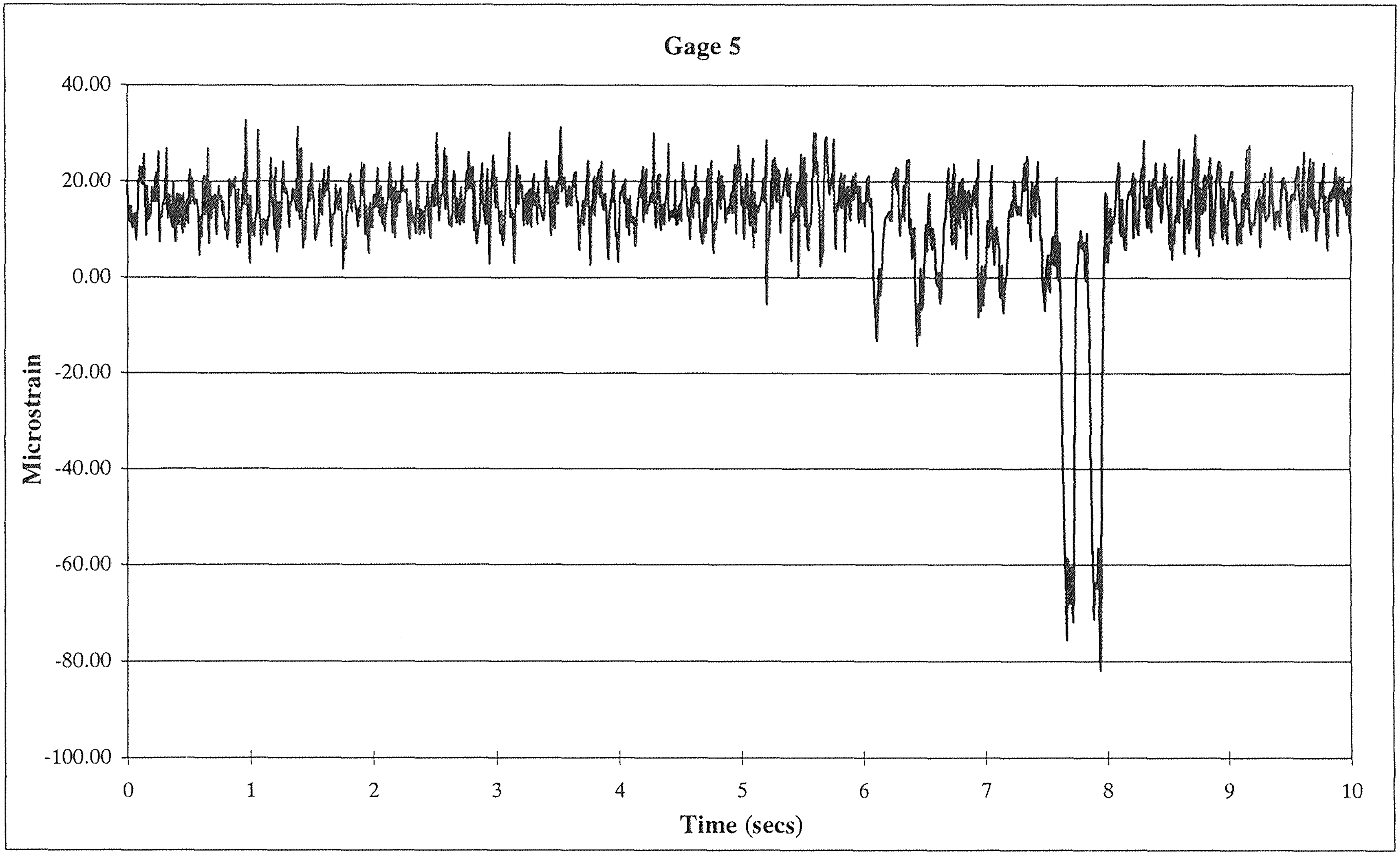


Figure D-15
Dynamic Load Test
Eastbound Commuter

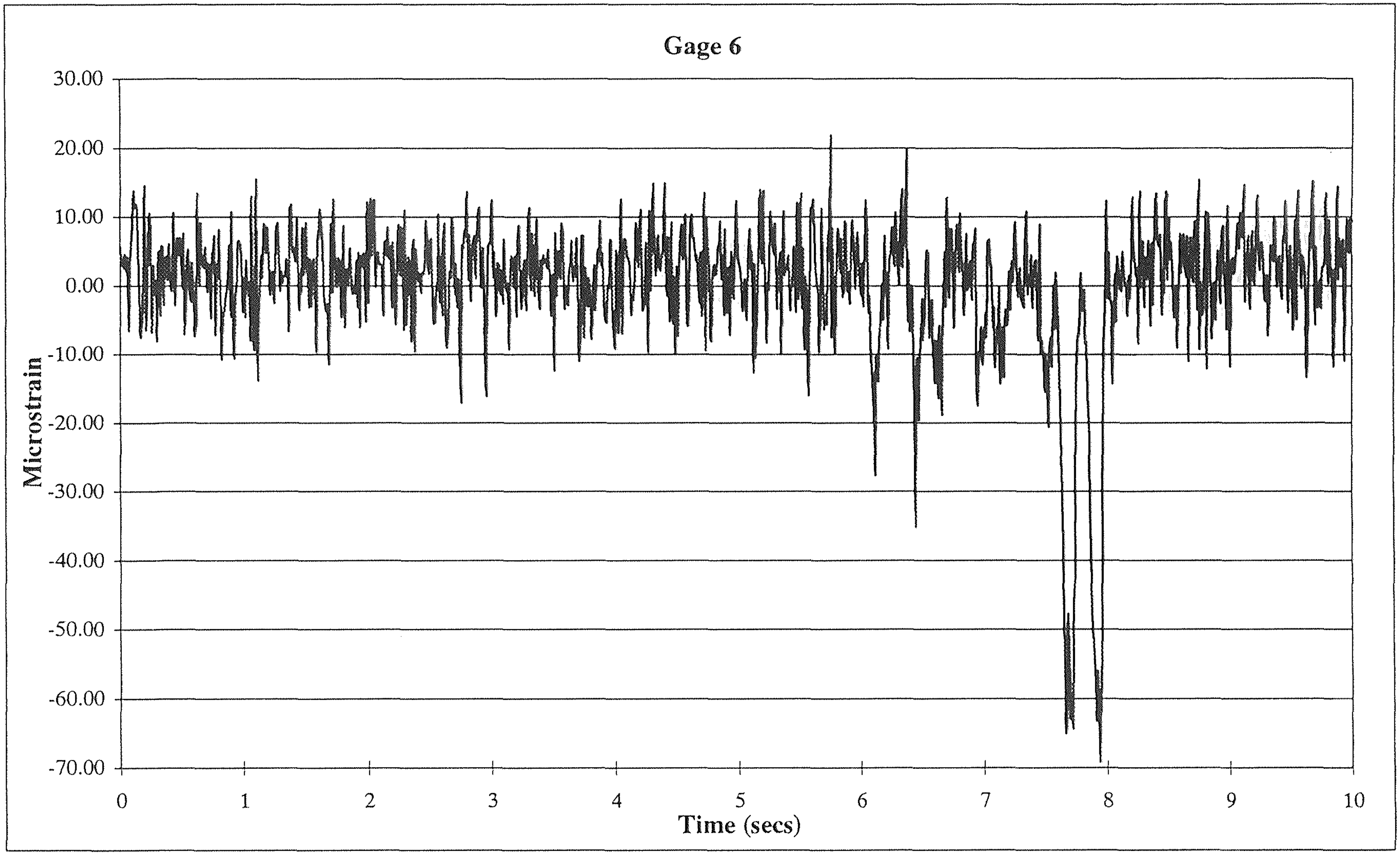


Figure D-16
Dynamic Load Test
Eastbound Commuter

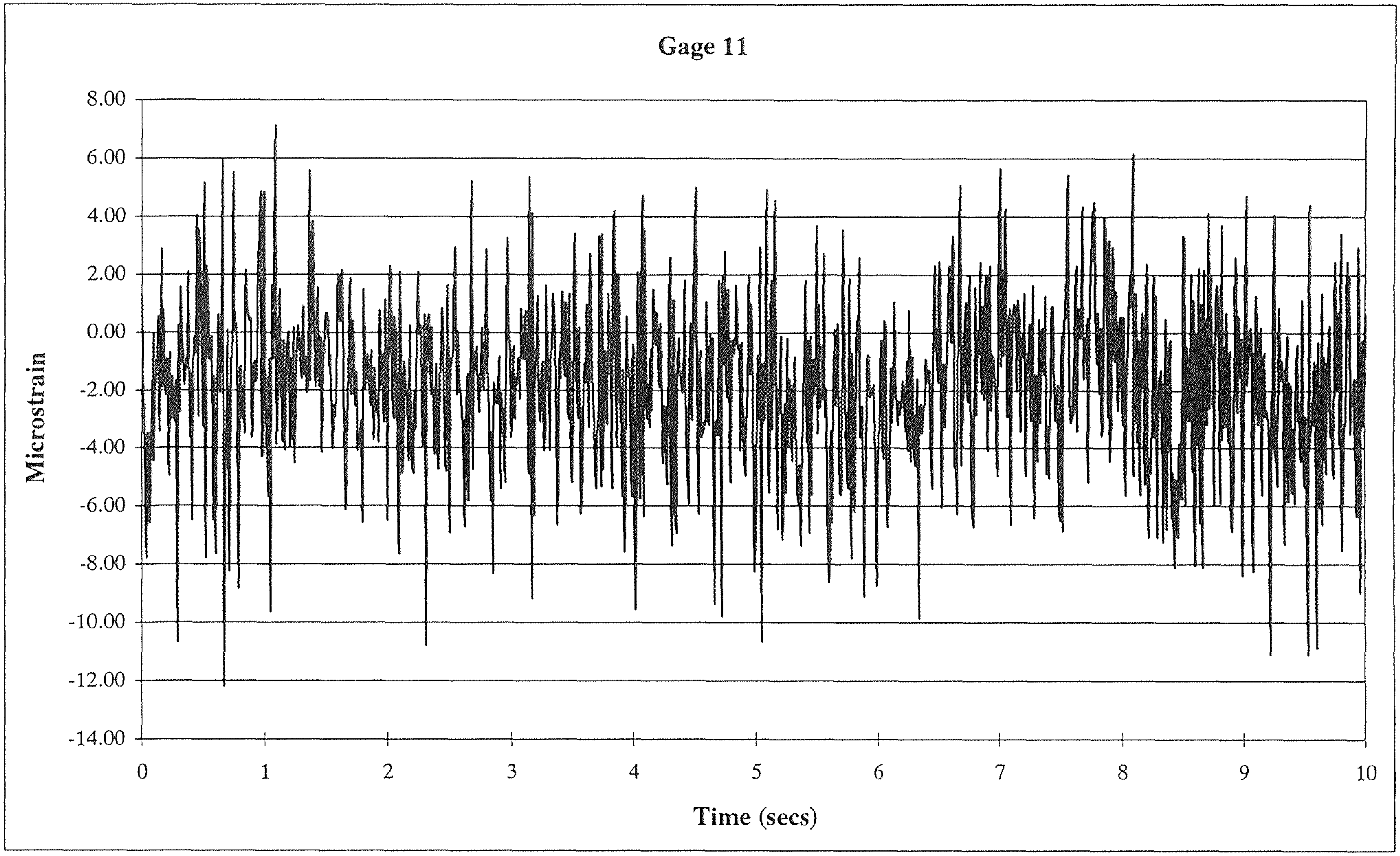


Figure D-17
Dynamic Load Test
Eastbound Commuter

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