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16. Abstract

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The traffic data recording system and the summary processes were utilized in a field experiment conducted near Georgetown, Texas, over a 20-month period. The summary technique was used to estimate the magnitude and location of dynamic tire forces that were exerted on designated test sections of a pavement by vehicles crossing small bumps (3/4 inch high) on the surface of an otherwise smooth roadway. Dynaflect measurements and optical level surveys were used to monitor the condition of the pavement in the test sections. The dynamic wheel loading resulted in slightly larger pavement deflections after some 25,000 truck passes than comparable wheel loads on an adjacent smooth surface.

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DYNAMIC TRAFFIC LOADING OF PAVEMENTS

by

Randy Machemehl
Clyde E. Lee

Research Report Number 160-1F

Dynamic Traffic Loading of Highway Pavements
Research Project 3-8-71-160

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

December 1974

PREFACE

This is the first, and final, published report on Research Project 3-8-71-160, "Dynamic Traffic Loading of Highway Pavements." The authors acknowledge and extend thanks to the many individuals who have contributed to this research study. The administration of the Texas Highway Department, personnel of the District 14 office and D-10 Research Section all provided very valuable assistance. Harold H. Dalrymple perfected much of the electronic instrumentation employed in the field studies. Robert F. Inman and Charlie Copeland aided immeasurably in the reduction of data.

Randy Machemehl
Clyde E. Lee

December 1974

ABSTRACT

Application of a technique for mathematical simulation of the interaction of heavy highway vehicles with a defined road surface profile is described. The simulation technique is used to develop a practical methodology for summarizing the dynamic vehicular loading experience of a highway pavement under mixed traffic. The design of a traffic survey instrumentation system which automatically records all vehicular characteristics needed for the simulation and summarization processes is presented.

The traffic data recording system and the summary processes were utilized in a field experiment conducted near Georgetown, Texas, over a 20-month period. The summary technique was used to estimate the magnitude and location of dynamic tire forces that were exerted on designated test sections of a pavement by vehicles crossing small bumps (3/4 inch high) on the surface of an otherwise smooth roadway. Dynaflect measurements and optical level surveys were used to monitor the condition of the pavement in the test sections. The dynamic wheel loading resulted in slightly larger pavement deflections after some 25,000 truck passes than comparable wheel loads on an adjacent smooth surface.

KEY WORDS: pavements, dynamic loading, traffic survey, surface profile, instrumentation systems, Dynaflect.

SUMMARY

A practical methodology for estimating the cumulative dynamic vehicular loading experience of a highway pavement under mixed traffic is developed and tested with representative field data. The summary technique utilizes mathematical simulation of the interaction of vehicles with a defined road surface profile. An instrument system which automatically senses and records all information needed for characterizing the vehicles is described.

The relative effects of the dynamic wheel loads caused by several thousand heavily loaded trucks operating over small surfaces irregularities on an otherwise smooth pavement are assessed in a controlled field experiment. Dynaflect measurements show that the impacting wheel loads resulted in somewhat more pavement distress than the same wheels passing over an adjacent section of smooth pavement.

IMPLEMENTATION STATEMENT

Experience with roads in service and the results of controlled road tests have shown that rough pavements deteriorate more rapidly under traffic than smooth pavements, and even though this accelerated damage can probably be attributed largely to dynamic loading by traffic, there has been no practical method for determining the magnitude and placement of dynamic wheel loads on pavements. This study has developed such a method.

As a result of this study, engineers and researchers concerned with evaluating the performance of existing pavements and with developing improved pavement design procedures have a means for obtaining realistic traffic loading data for direct use in stress computations and in design analyses. Also, materials engineers have representative patterns of loading which can be used for conducting laboratory studies of the behavior of paving materials under repeated loads.

The instrument system for measuring traffic and roadway parameters needed in monitoring and forecasting dynamic wheel loads is a tool that can be used by planning engineers who provide the statistical data required for highway design. Maintenance engineers can begin to develop quantitative data regarding pavement performance under dynamic loading and subsequently establish procedures for optimizing pavement smooth-up operations to prevent excessive distress caused by rough surfaces.

Since dynamic loading of highway structures has long been a problem, the results of this study will be of interest and of potential usefulness to design engineers in most state highway departments and in the Federal Highway Administration.

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CHAPTER 1. INTRODUCTION

The design of highway pavement is a highly complex process. Pavement designers attempt to characterize all parameters that affect the performance of the structure including material properties and potential traffic loading in the most realistic manner possible. Although most designers have recognized for years that pavement loading by traffic is dynamic in nature, a static loading criterion is still utilized in virtually all currently accepted pavement design procedures. The complex and variable nature of dynamic vehicular highway loading has caused engineers to shun its consideration in their analyses. Several recent research efforts that are detailed in Refs 15, 10 and 4 have produced hardware and techniques which make it possible to characterize dynamic vehicular loading in specific engineering terms.

The information contained in this report uses these innovations to develop a method for summarizing the dynamic loading experience of a highway pavement and for predicting the loading that might result from specified roadway and traffic conditions. Materials testing related to dynamic vehicular loading is also discussed. The combination of more realistically defined traffic loading and an accurate assessment of the behavior of pavement materials in response to these loads provides a significant part of the fundamental information that is needed for improving pavement design and analysis procedures and for building and maintaining safer and more economical highway structures.

Objectives

The objectives of this study are as follows:

(1) Develop a method for predicting the magnitude and location of dynamic wheel loads on highway pavements.

(2) Develop a technique for summarizing and displaying the cumulative dynamic loads which will occur along any given roadway profile as the result of mixed traffic.

(3) Devise a practical field procedure for monitoring the traffic and roadway parameters needed for predicting dynamic wheel loads.

(4) Demonstrate the validity of the prediction method and the accelerated destructive effects of dynamic loads caused by rough surface profiles in a designed field experiment.

Scope

The overall approach to the research project as well as a general outline of study activities is shown in Fig 1.1. Success in scheduling certain study activities determined the final scope and magnitude of the accomplishments that were possible. Traffic rerouting, for example, proved to be difficult to initiate and enforce and thus influenced the amount of data that could be procured in the field studies within the time frame available. All objectives of the study were, however, included in the scope of either the experimental phase or the theoretical phase of the project.

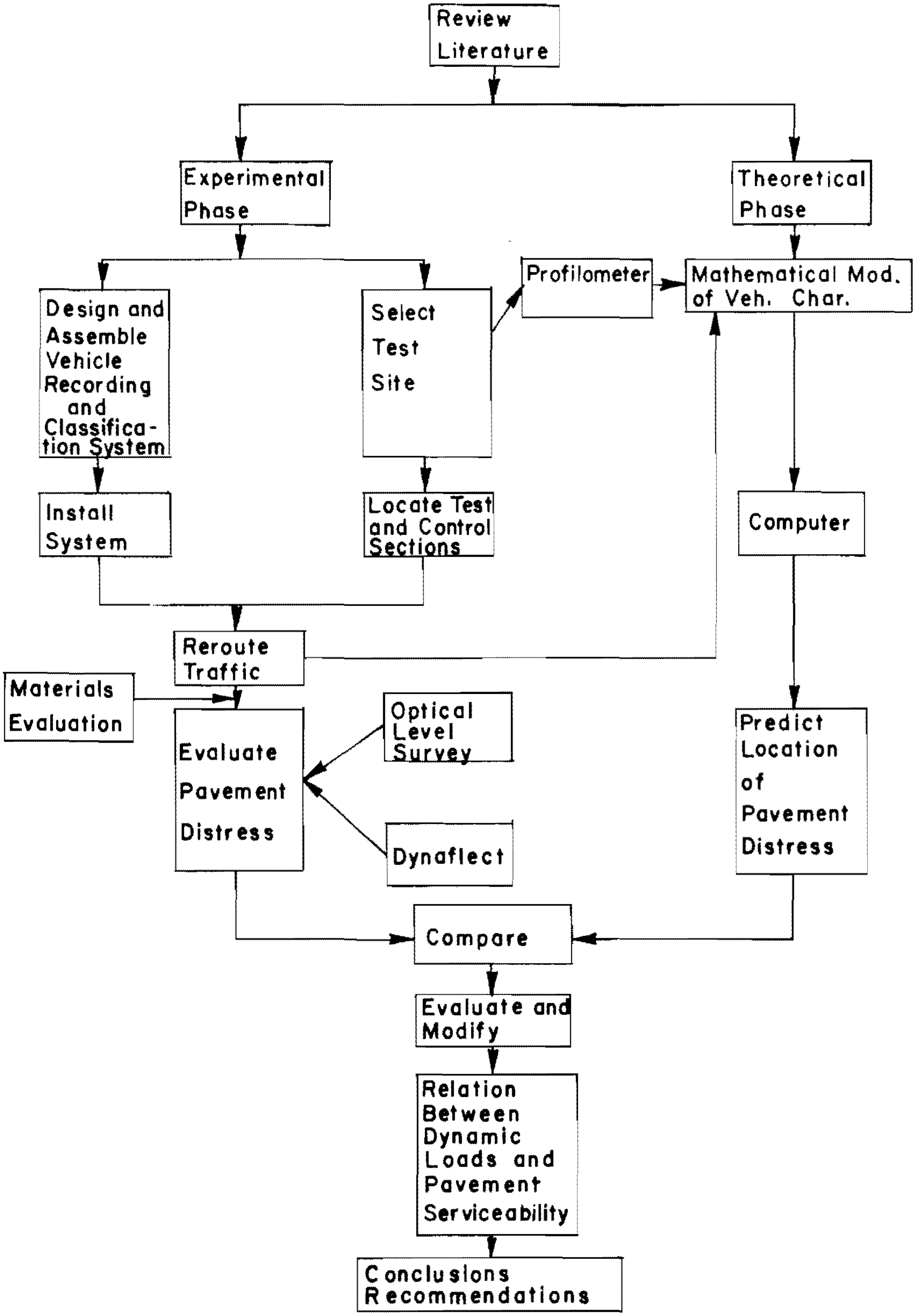


Fig 1.1. Outline of study activities.

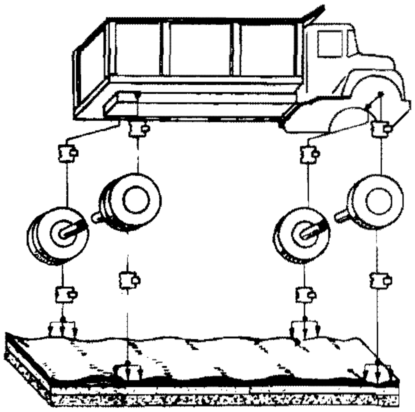
CHAPTER 2. MODELS FOR PREDICTING VEHICULAR WHEEL FORCES

Any vehicle moving on a roadway surface produces wheel forces which vary continuously with time. Mathematical models may be used to study the dynamic forces which result from the complex interaction between a vehicle and a defined road profile. It is desirable to use experimentally measured vehicle and roadway characteristics as input to the mathematical models, which are expected to predict the response of vehicles to a selected road surface profile, but estimated parameters may be used to produce satisfactory results. The following paragraphs briefly describe the mathematical modeling technique which was employed in this study.

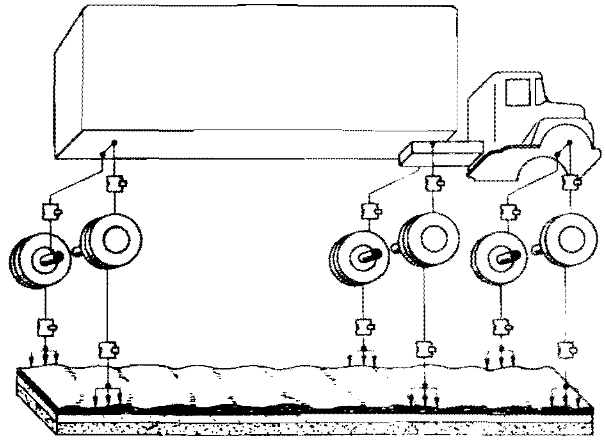
Mathematical Vehicular Modeling

In a previous research study (see Ref 4), a series of mathematical vehicular models was developed, documented, and calibrated. This series consists of five models, one to represent each of five predominant classes of trucks that normally use the highways. The schematic representation and class designations of the five models are shown in Figs 2.1a - 2.1e. As illustrated in the figures, the model elements consist of masses connected by springs and dashpots. One differential equation of motion has been written to describe the type of movement that is considered for each mass. Each type of movement that is allowed for each mass provides one degree of freedom. The seven degrees of freedom for the Class I model are listed in Table 2.1. Similar types of motion are considered for models of the other four classes of vehicles, and degrees of freedom range from 9 to 16 for the Class II through Class V models, respectively.

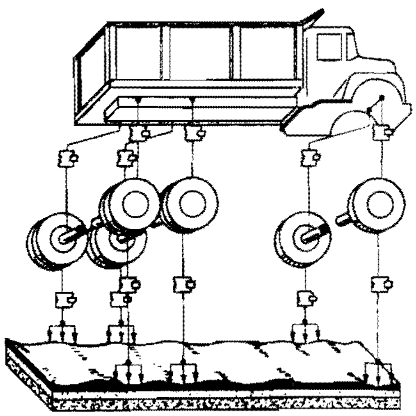
The differential equations of motion which describe each of the above mentioned classes have been programmed for solution by a digital computer using an iterative process. The derivation of these equations and their solutions are presented in Ref 4.



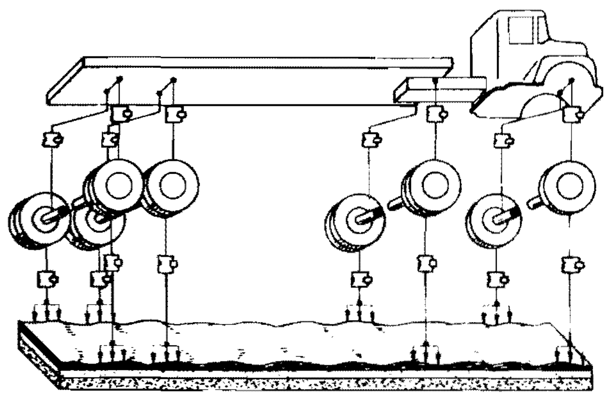
a. Class I vehicle model.



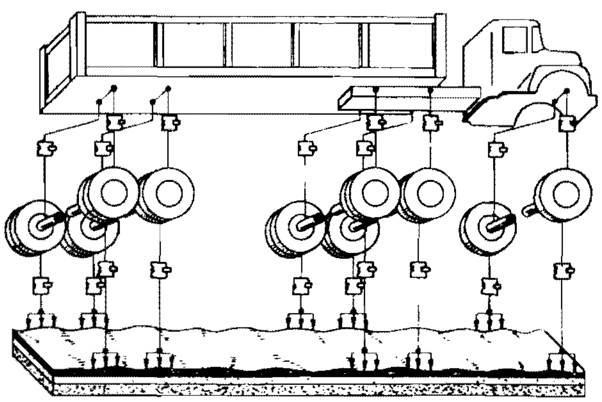
b. Class I vehicle model.



c. Refined Class III model.



d. Refined Class IV model.



e. Refined Class V model.

Fig 2.1. Vehicular models.

TABLE 2.1. DEGREES OF FREEDOM FOR CLASS I MODEL

Degree of Freedom	Type of Movement
1	Vertical translation of right front wheel
2	Vertical translation of left front wheel
3	Vertical translation of right rear wheel
4	Vertical translation of left rear wheel
5	Vertical translation of body
6	Rolling of body
7	Pitching of body

Input Data for Models

In order to use the models, three types of input data must be supplied. These data include the parameters needed to characterize the vehicle, the roadway profile upon which the vehicle operates, and the speed of the vehicle.

Vehicle parameters consist of spring stiffness values for all springs (both tire and suspension), viscous damping coefficients for all dashpots, axle spacings and widths, and weight or mass values for all masses in the models (see Figs 2.1a - 2.1e). The roadway parameters consist of digital information which describes the road profile in each wheel path. This information may be obtained either by measurement of actual field conditions or by mathematical simulation of theoretical conditions. Field profile measurements may be obtained by any of several methods ranging from rod and level surveys to use of sophisticated road profile measuring devices. Speed should be representative of the range of traffic speeds observed or expected at the site.

The modeling technique may be used to simulate any individually selected vehicle by devising a set of input parameters which characterize that vehicle. However, by selecting a set of input parameters which are representative of all vehicles in one class, it is possible to produce a generalized model for a vehicular class. Although some precision is sacrificed when a generalized model is used, a theoretical and experimental sensitivity analysis (Ref 4) indicated that the loss in precision is small. Therefore, for purposes of this study a typical vehicle of each class was formulated to represent all members of the class. The vehicle input parameters which are common for each class include all spring stiffness and viscous damping values. The process that was used to determine each set of common input values is detailed in Ref 4, although it is based on a simple comparison of predicted and measured dynamic forces in an iterative process.

Representative parameters for the Class I through Class V models are shown in Tables 2.2 through 2.6. In previous model studies, agreement between measured and predicted forces and displacements was good except for those cases involving tandem axles when vehicle speed was greater than 30 mph. Apparently the modeled tandem axle configuration that incorporated a direct interconnection of the two axles underwent severe pitching at high speeds causing erroneous tire force prediction. For this reason, the tandem axle

TABLE 2.2. VEHICLE SUSPENSION CHARACTERISTICS FOR CLASS I VEHICLE

Axle	Tire* Stiffness, lb/in.	Tire Damping, %	Spring Stiffness, lb/in.	Spring Damping, %
1	4,000	2	535	5
2	8,000	2	3,750	3

TABLE 2.3. VEHICLE SUSPENSION CHARACTERISTICS FOR CLASS II VEHICLE

Axle	Tire* Stiffness, lb/in.	Tire Damping, %	Spring Stiffness, lb/in.	Spring Damping, %
1	4,000	.25	1,750	3
2	8,000	.50	5,000	6
3	8,000	.75	6,000	8

TABLE 2.4. VEHICLE SUSPENSION CHARACTERISTICS FOR CLASS III VEHICLE

Axle	Tire* Stiffness, lb/in.	Tire Damping, %	Spring Stiffness, lb/in.	Spring Damping, %
1	4,000	0.5	1,750	5
2	8,000	1.0	5,000	6
3	8,000	1.0	5,000	6

* - Values represent the combined stiffness of the dual tires on one side of all axles except Axle 1, which is assumed to have a single tire.

TABLE 2.5. VEHICLE SUSPENSION CHARACTERISTICS FOR CLASS IV VEHICLE

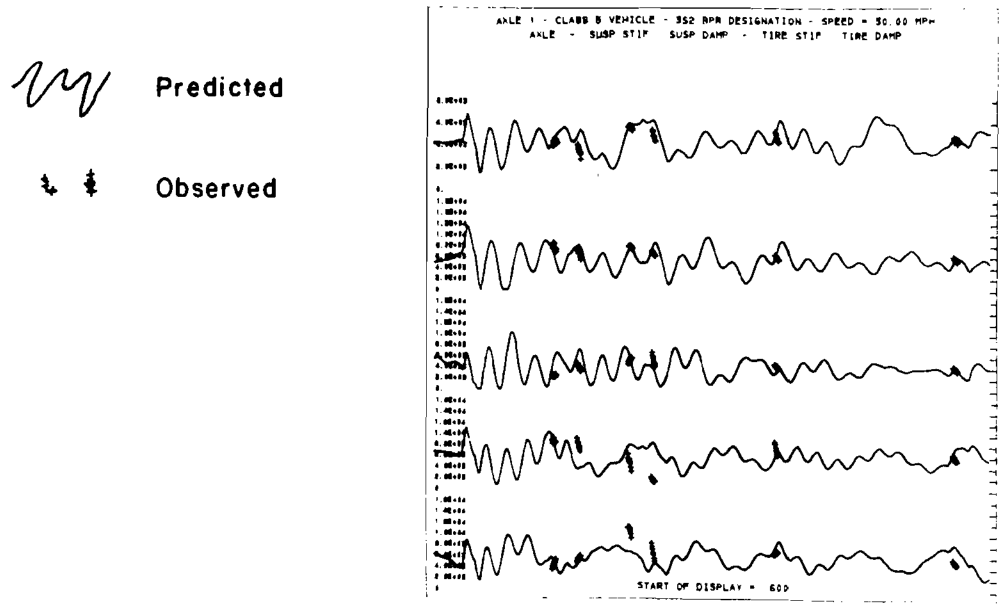
Axle	Tire* Stiffness, lb/in.	Tire Damping, %	Spring Stiffness, lb/in.	Spring Damping, %
1	4,500	.01	2,000	4
2	8,000	.50	6,000	3
3	7,500	.25	5,500	1.5
4	7,500	.25	5,500	1.5

TABLE 2.6. VEHICLE SUSPENSION CHARACTERISTICS FOR CLASS V VEHICLE

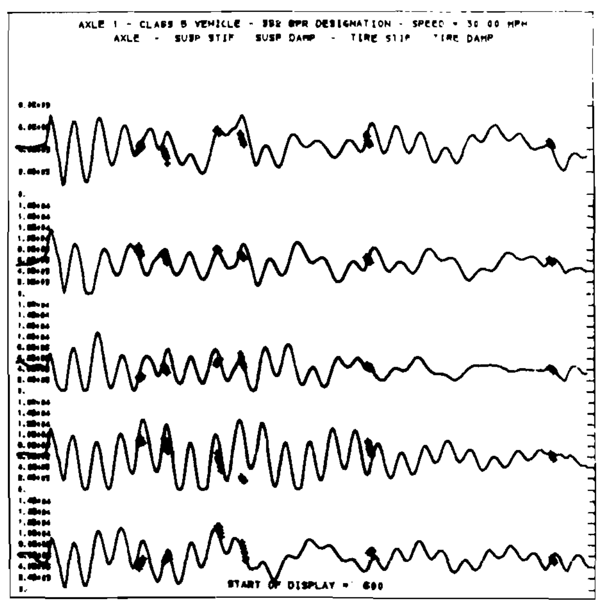
Axle	Tire* Stiffness, lb/in.	Tire Damping, %	Spring Stiffness, lb/in.	Spring Damping, %
1	4,500	.01	2,000	4.5
2	8,000	.50	6,000	3.0
3	8,000	.50	4,500	3.0
4	7,500	.25	6,000	1.5
5	7,500	.25	6,000	1.5

configuration that was originally utilized in the models (see Ref 4) was changed to that shown in Figs 2.1c, d and e. The improved agreement obtained through this "independent axle" modification is illustrated in Fig 2.2, which shows predicted and observed data for the Class V vehicle traveling at 60 mph, for both the original and modified tandem axles.

By using a properly configured mathematical model of the vehicles, a descriptive representation of the road surface profiles in each wheel path, and selected vehicular speeds, it is possible to estimate the movements of the vehicles as well as the magnitude and placement of the dynamic wheel forces that will be imposed on the pavement surface. A great variety of conditions and combinations of conditions can be evaluated in a short time by successive runs of the mathematical models. This simulation technique provides the practical basis for characterizing dynamic traffic loads.



(a) Original tandem axle configuration.



(b) Modified tandem axle configuration.

Fig 2.2. Predicted versus observed data for the Class V vehicle for original and modified tandem axle.

CHAPTER 3. CUMULATIVE DYNAMIC LOADING CAUSED BY MIXED TRAFFIC

The research which resulted in the development of the mathematical vehicle modeling technique referenced in the preceding chapter indicates that trucks moving at normal speed over roads with surface irregularities as small as 1/2 to 3/4-inch high can produce dynamic tire forces that range in magnitude up to twice the static wheel load. Impact forces of this magnitude are of concern in the design of highway structures, particularly if the maximum forces are concentrated at or near the same location on a pavement or bridge.

While vehicle modeling techniques have been used successfully for predicting the tire loading patterns imposed on the road surface by selected vehicles (Refs 4 and 10) the problem of forecasting the cumulative dynamic tire forces that will be produced by mixed traffic at selected locations along the roadway has not previously been solved. A procedure for estimating these cumulative dynamic forces and for identifying zones of maximum load concentration is described in this chapter. Mathematical modeling techniques are used to simulate the complex interaction between moving vehicles and defined roadway profiles, and summarizing techniques are structured for practical application of the modeling methodology in evaluating the wheel loading patterns produced by mixed traffic.

Adequate vehicular traffic data (observed or predicted) including number of vehicles, number and spacing of axles, axle weights, and speeds for a defined period of time are needed. A traffic data recording system that automatically records such field data is described in the next chapter.

The summary technique requires that the following eight steps be accomplished:

(1) Group the traffic data according to the five vehicular classes described in Chapter 2.

(2) Group the data into gross vehicle weight classes.

(3) Determine the overall distribution of gross weight among axles.

(4) Determine the number of models required to represent the traffic.

(5) Obtain road profile information.

(6) Select the speed or speeds to be used for modeling.

(7) Compute the dynamic loading profile.

(8) Determine the critical loading zone.

The following paragraphs discuss each of these steps and give an example of how to determine the zone of maximum concentration of dynamic wheel forces that are generated by mixed traffic operating over a pavement with two abrupt bumps on the surface.

Step 1. Division Into Vehicular Classes

The first step in the summary technique involves placing every vehicle that is included in the traffic data set into one of the five vehicular classes that are discussed in Chapter 2. Although these five classes obviously do not represent exactly all vehicles that compose a mixed traffic stream, an adequate approximation can be made in nearly all cases. A previous study documented in Ref 4 indicates that they include the majority of commercial vehicles; therefore, truck traffic may be grouped into these five basic classes according to number and arrangement of axles.

Step 2. Grouping by Gross Weights

The next step consists of subdividing each of the five vehicular classes into gross vehicle weight groups. Five or six gross weight groups in each vehicle class are usually sufficient. The example which follows illustrates that 10-kip gross weight classes give satisfactory results.

Step 3. Gross Weight Distribution Among Axles

The discussion of mathematical modeling in Chapter 2 indicates that the static weight must be specified for each wheel of any vehicle to be modeled. The third step in the summary process provides this information. The average distribution of the gross vehicle weight among axles for each class of vehicle is calculated from the traffic weight data and presented as a set of distribution factors. These distribution factors are then multiplied by each respective gross vehicle weight included in the data set to yield representative static axle weights for the vehicles in each gross weight group. In turn, static wheel weights are assumed to be half the axle weight. Of course, it is possible to work with wheel weight distributions on each side of the vehicle if data are available, but such refinement is probably not warranted.

Step 4. Determine the Required Number of Models for Each Class

Referring to the data of Step 2, several gross weight groups from each class of vehicle may be selected for modeling. The number of groups selected for each class will depend on the desired accuracy of results. As a practical matter, no more than four or five groups should be selected for any class since the necessary computer time for modeling increases significantly if more models are used. The models selected for inclusion in the following example account for over 90 percent of the members of each class by using four or fewer gross weight classes in any one vehicle class.

Step 5. Obtain Road Profile Information

The next step requires a description of the road profile in each wheel path for which the dynamic traffic loading estimates are desired. As noted in Chapter 2, the profile may be created mathematically without any field data, or it may be measured by one of several techniques. Profile information utilized in the example presented later in this chapter was obtained by a combination of rod and level survey and use of a high-speed (GMR) profilometer.

Step 6. Select the Speed or Speeds for Modeling

The average speed for each gross weight group of each class of vehicle is determined next. The mean speed for each case is used with each respective model selected in Step 4. If the speeds for all groups are very nearly equal, it will be necessary to use only one speed for all models.

When this step has been completed, all information necessary for mathematical modeling is available. The vehicle models may now be "driven" over the defined roadway profile.

Step 7. Compute Dynamic Loading Profile

The output from each vehicle model, speed, and profile combination consists of the predicted magnitude and location of the dynamic tire forces acting on the roadway surface. The number of vehicles represented by each model may be multiplied by the tire force predicted by the respective model for all locations along the roadway. If this is done for all models and the results superimposed, a complete cumulative dynamic loading profile can be created. Figure 3.1 illustrates such a profile in graphical form. A comparison can be made of the cumulative static wheel loads that would result from the imposed traffic and the cumulative dynamic loads along the surface.

Step 8. Determine Critical Loading Zone

A graphical presentation such as Fig 3.1 provides a ready means of locating the critical loading zone, or the zone in which dynamic loading is most severe. This zone is indicated by light shading. Tabular data can be examined for this purpose, also.

Example of Summary Technique

The following example illustrates the use of the summary technique to determine the cumulative dynamic vehicular loading for a selected section of pavement. The data may be considered to be a general set of information obtained at any site although this particular set was obtained at a field test site near Georgetown, Texas between July 1971 and January 1973. The test site consisted of two pavement test sections each of which had a pair of small bumps approximately 3/4-inch high and 18 inches long on an otherwise smooth pavement surface. The data recording system and the test section designs are discussed in detail in the following chapters.

Step 1. Division Into Vehicular Classes. The first step in the summarization process consists of grouping all recorded traffic into the five classes of vehicles that are described in Chapter 2. Approximately 25,000 trucks were included in the recorded data set. Figure 3.2 illustrates the proportion of trucks in each class as recorded at the field test site during a one and one-half year period ending January 1973. Note that Classes II through V constitute over 70 percent of all recorded truck traffic at this site.

Step 2. Grouping by Gross Weights. Once the traffic has been grouped by class of vehicle, each class is then examined and separated into gross vehicle weight groups. For purposes of this example, 10-kip gross weight groups were used for all classes.

The 10-kip groups were chosen primarily for simplicity although the resolution of the recording system used in the field experiment justifies a

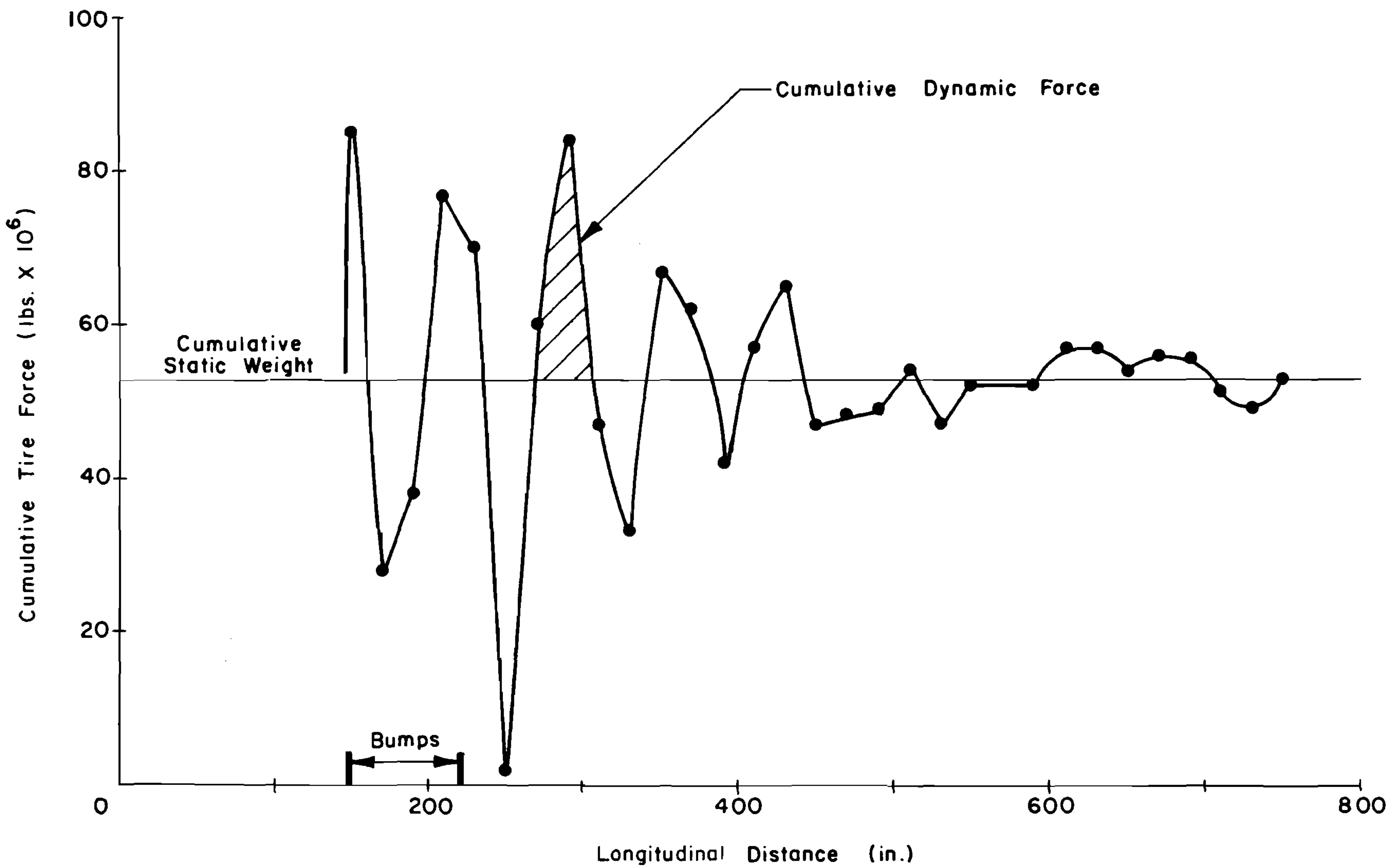


Fig 3.1. Cumulative dynamic vehicular loading profile in one wheel path.

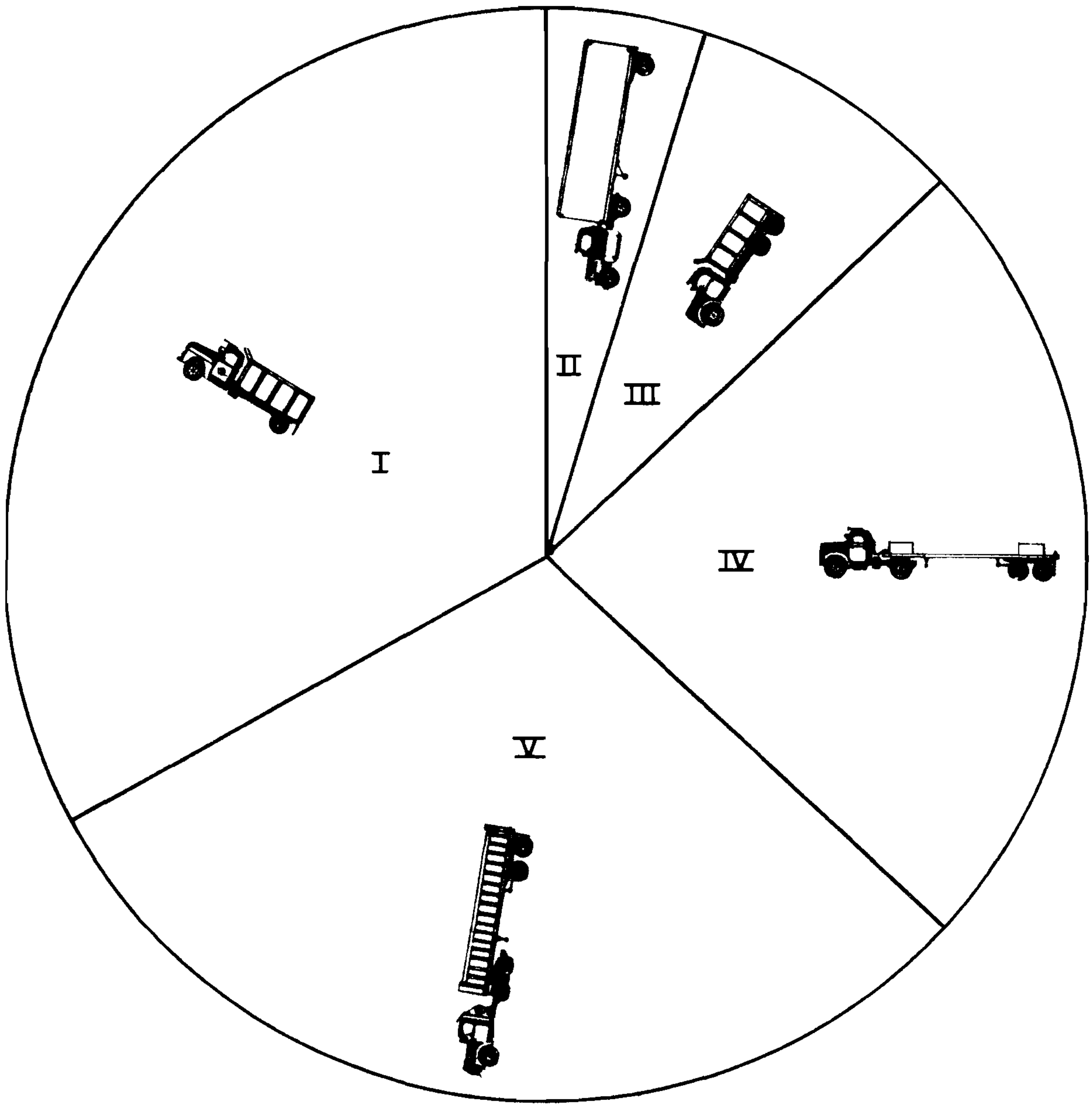


Fig 3.2. **Classification of test traffic into five principal classes.**

somewhat smaller grouping. That is, the system resolution was ±2 kips per wheel which means that the weight of a Class I vehicle (two axles) could be resolved within ±4 kips while the weight of a five-axle vehicle could be resolved within ±7 kips. The 10-kip groups were deemed adequate and are desirable because the larger groups reduce the amount of model simulation which is necessary. (For some purposes a smaller grouping might be desirable). The results of separating vehicles of each class into 10-kip weight groups are shown graphically in Figs 3.3 and 3.4.

Step 3. Gross Weight Distribution Among Axles. The gross weight data must be further analyzed to provide representative static wheel weights for the vehicles of each class which are to be simulated. Evaluation of the data presented in Ref 4 indicates that on the average, members of any given vehicle class have similar weight distribution among axles when the vehicles are loaded. Therefore, an average distribution of the gross vehicle weight among axles for the loaded vehicles of each class was derived. These distributions are shown as a percentage of gross weight per axle in Table 3.1. The distribution factors of Table 3.1 for any vehicle class can be multiplied by the average value of each gross weight group in that class to yield representative static axle weights for use in the mathematical model. If an equal distribution of axle weight between wheels is assumed, all necessary weight information for vehicle simulation is available.

Step 4. Determine the Required Number of Models for Each Class. In order to obtain a practical summary of the cumulative dynamic loading conditions produced by the observed traffic, enough 10-kip gross weight groups were provided in each class to account for 90 percent or more of all vehicles. The heaviest and lightest vehicles that occurred in small numbers were not included in the analysis in order to conserve computer time without significantly affecting the results. The groups used in each class are shaded in Figs 3.3 and 3.4. This analysis produced 17 separate model vehicles to be simulated.

Step 5. Obtain Road Profile Information. The simulation requires profile information for the test section to be modeled. This information was provided by the combination of the GMR road profilometer (see Chapter 2) and a rod and level survey. Since no visible surface deterioration was produced

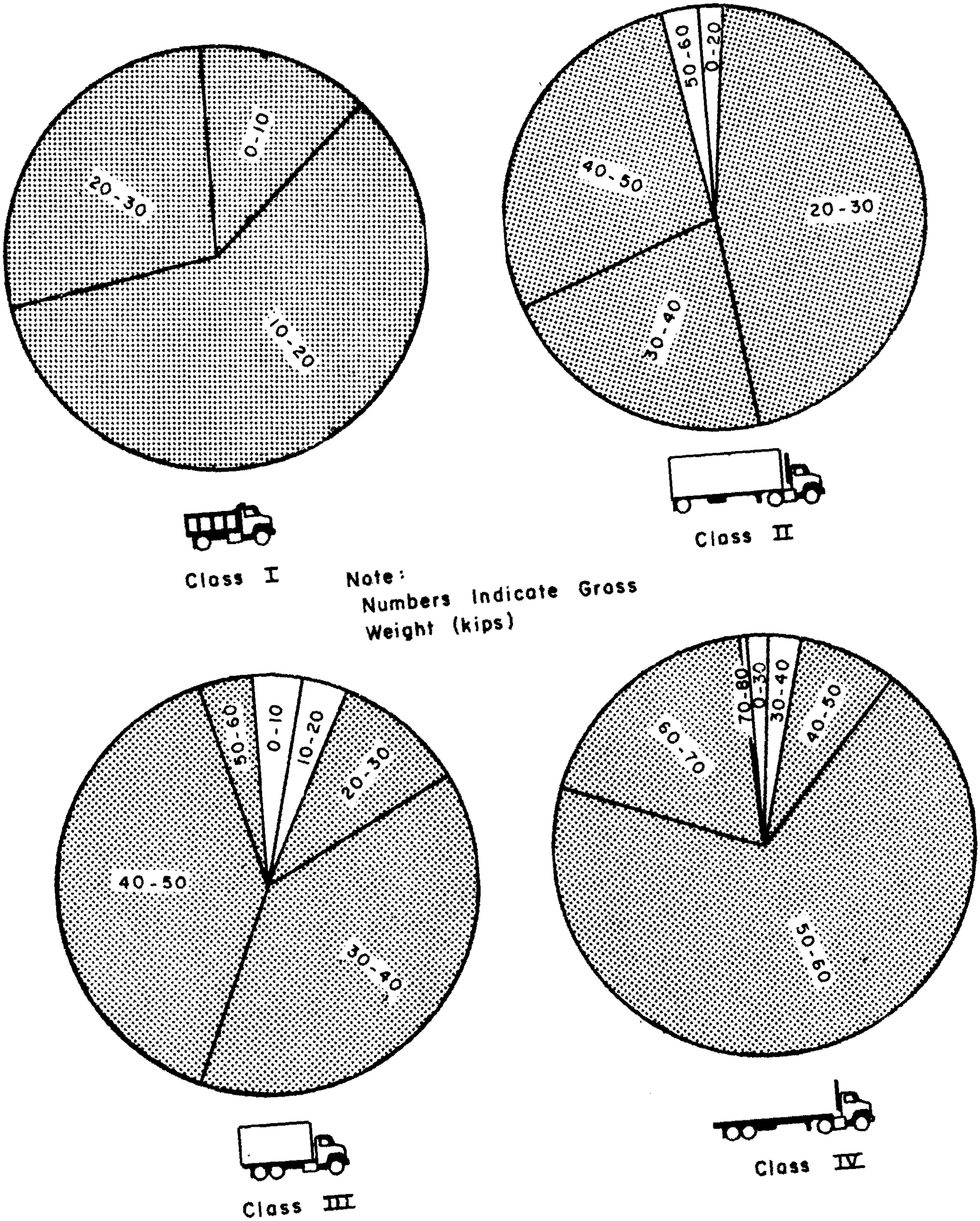


Fig 3.3. Gross vehicle weight groups for Class I through IV vehicles.

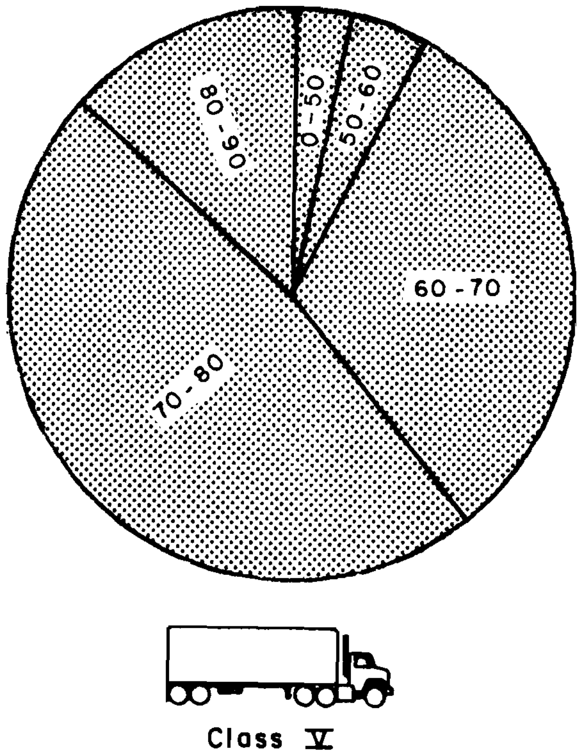


Fig 3.4. Gross vehicle weight groups for Class V vehicles.

TABLE 3.1. GROSS WEIGHT DISTRIBUTION AMONG AXLES FOR LOADED VEHICLES

Class/Axle	Percent of Gross Weight
I/1	45.5
I/2	54.5
II/1	32.2
II/2	33.9
II/3	33.9
III/1	28.5
III/2	36.2
III/3	35.3
IV/1	15.7
IV/2	33.4
IV/3	27.3
IV/4	24.6
V/1	12.7
V/2	22.2
V/3	20.2
V/4	23.5
V/5	21.4

during the observation period, no consideration of a changing profile was made in the analysis.

Step 6. Select the Speed for Modeling. The vehicle speed used in the simulation was 30 mph. A study of vehicle speeds in the test section indicated that the average speed of all vehicles was 29 mph with a standard deviation of 8 mph. Therefore, the 30-mph speed was used for all model runs.

Step 7. Compute Dynamic Loading Profile. The static weight information and the roadway profile provided all necessary input information for the generalized models discussed previously. Therefore, each of the 17 model vehicles was "driven" over the measured roadway profile producing a predicted tire force plot of the type shown by the continuous lines in Fig 3.5.

The continuous tire force predictions from each model can be multiplied by the number of vehicles of that type and the predictions for all vehicle models can be superimposed. Figure 3.1 is such a superimposed plot of dynamic loading for all members of each of the 17 generalized model vehicles for the test section pavement. This figure represents the loading history of the pavement for the time period August 1970 through August 1972.

Step 8. Determine Critical Loading Zone. In addition to plotting complete loading histories, the predicted tire force diagrams can be used to yield predicted peak dynamic forces and their locations. The predicted peak wheel forces for each of the 17 model vehicles are shown in Fig 3.6.

The critical loading zone or the area of the highest cumulative dynamic loading may also be determined for all recorded traffic. This area is shown lightly shaded in Fig 3.1.

Summary

The mathematical modeling procedure provides a practical means for characterizing the dynamic loading of a pavement surface by mixed traffic operating at various speeds. The example used to illustrate the step-by-step computational procedure shows that the cumulative dynamic force applied by truck traffic at a point approximately 12 feet downstream from two 3/4-inch high surface irregularities was about 60 percent greater than the cumulative force that was applied to a smooth pavement (see Fig 3.1). Peak wheel forces were as much as 100 percent greater than the static weight of the wheels that

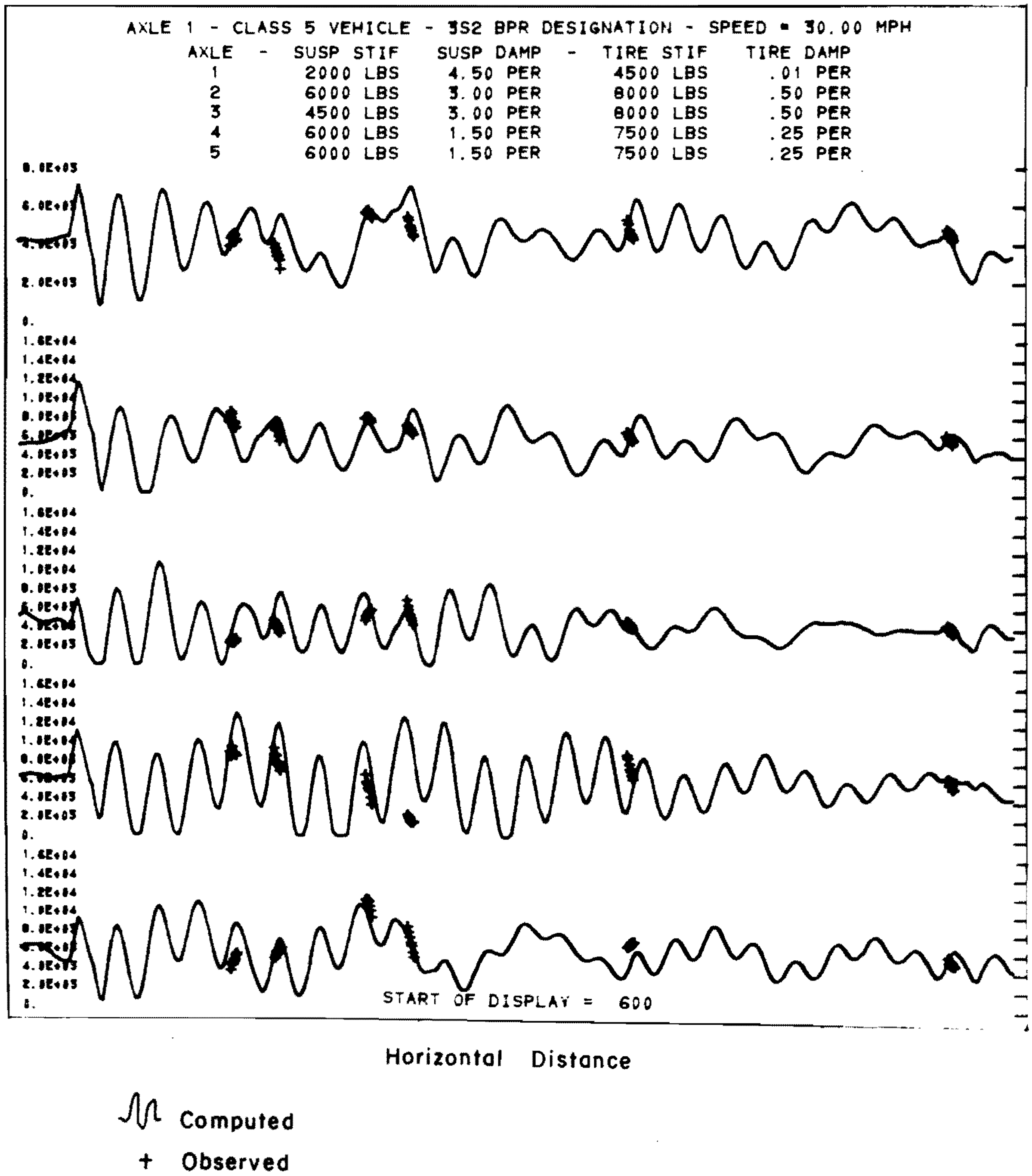


Fig 3.5. Predicted tire force plot for Class V vehicle.

were excited by these relatively small bumps. The effects of such loads on stress and strain in the pavement structure can be analyzed by techniques presented in Chapter 6.

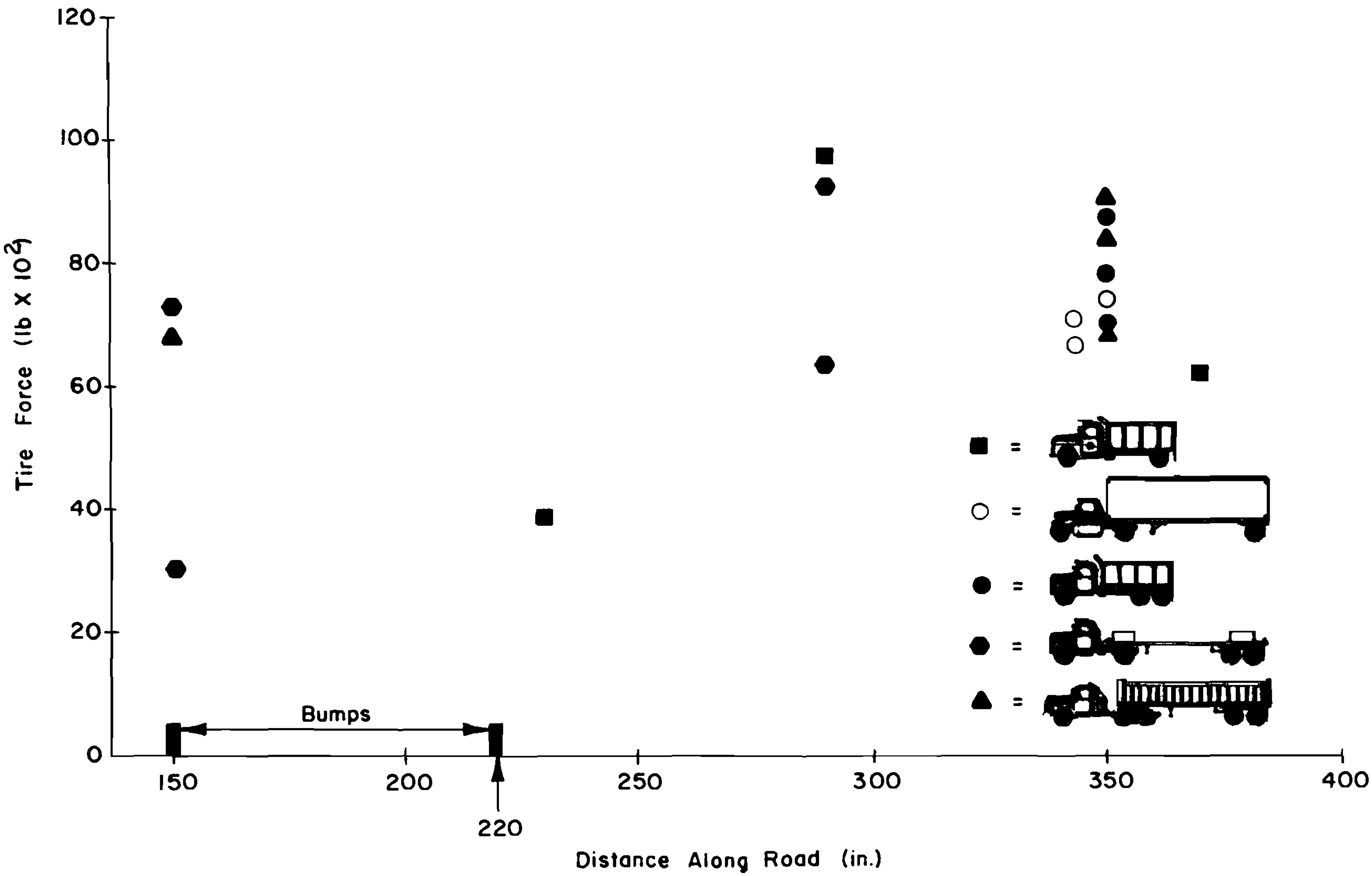


Fig 3.6. Peak dynamic plus static force generated and its location.

CHAPTER 4. DEVELOPMENT OF FIELD TRAFFIC DATA RECORDING PROCEDURES

This chapter describes the development of equipment and procedures for monitoring the traffic parameters needed for predicting dynamic wheel loads. As noted in Chapter 2, mathematical modeling requires information about both vehicle and road surface characteristics. Road profile measurements can be made readily by using rod and level surveys or by using measuring equipment such as the GMR profilometer, but the required traffic parameters which include speed, axle spacing, number of axles per vehicle, and wheel weights can best be determined by a special instrument system. Such a system was devised and used for this research study.

Data Classification and Recording System

The data classification and recording system, or DCR system, was designed to operate unattended while recording continuously all information necessary for characterizing each truck passing in an instrumented lane. The DCR system senses and records the weight of each right vehicle wheel, the axle spacing, the speed of the vehicle, and the time of day at which the record was made.

The layout of the detection system components is shown in Fig 4.1, and a block diagram of the information flow is provided in Fig 4.2. The system consists of three loop detectors which sense vehicle presence, an electronic transducer, a data classification system, and a paper tape punch for recording all data. The first loop detector, located 100 feet in advance of the system, starts the paper tape punch and allows enough time for the punch to come to running speed before an approaching vehicle reaches the force transducer. The other two loop detectors, located 12 feet apart, are a matched pair having similar operating characteristics and are used to measure vehicle speed. The vehicle speed counter is initiated by Loop 2 and stopped by Loop 3 thus providing a measure of vehicle travel time between loops. The counter has a capacity of eight coded binary bits and is driven by a 500 H_z signal. The right side wheel force is detected by the electronic wheel force transducer.

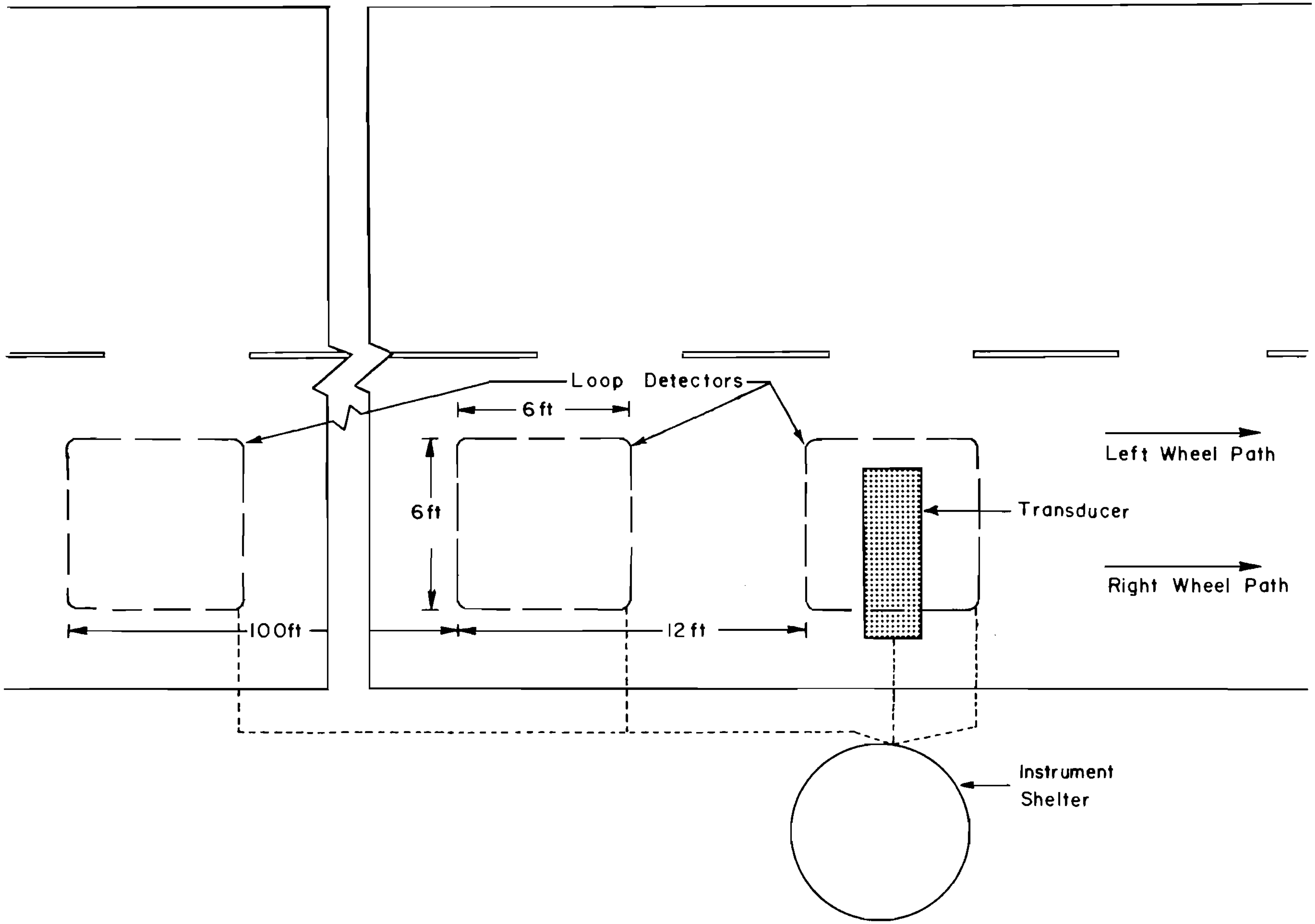


Fig 4.1. Layout of vehicular data classification and recording system.

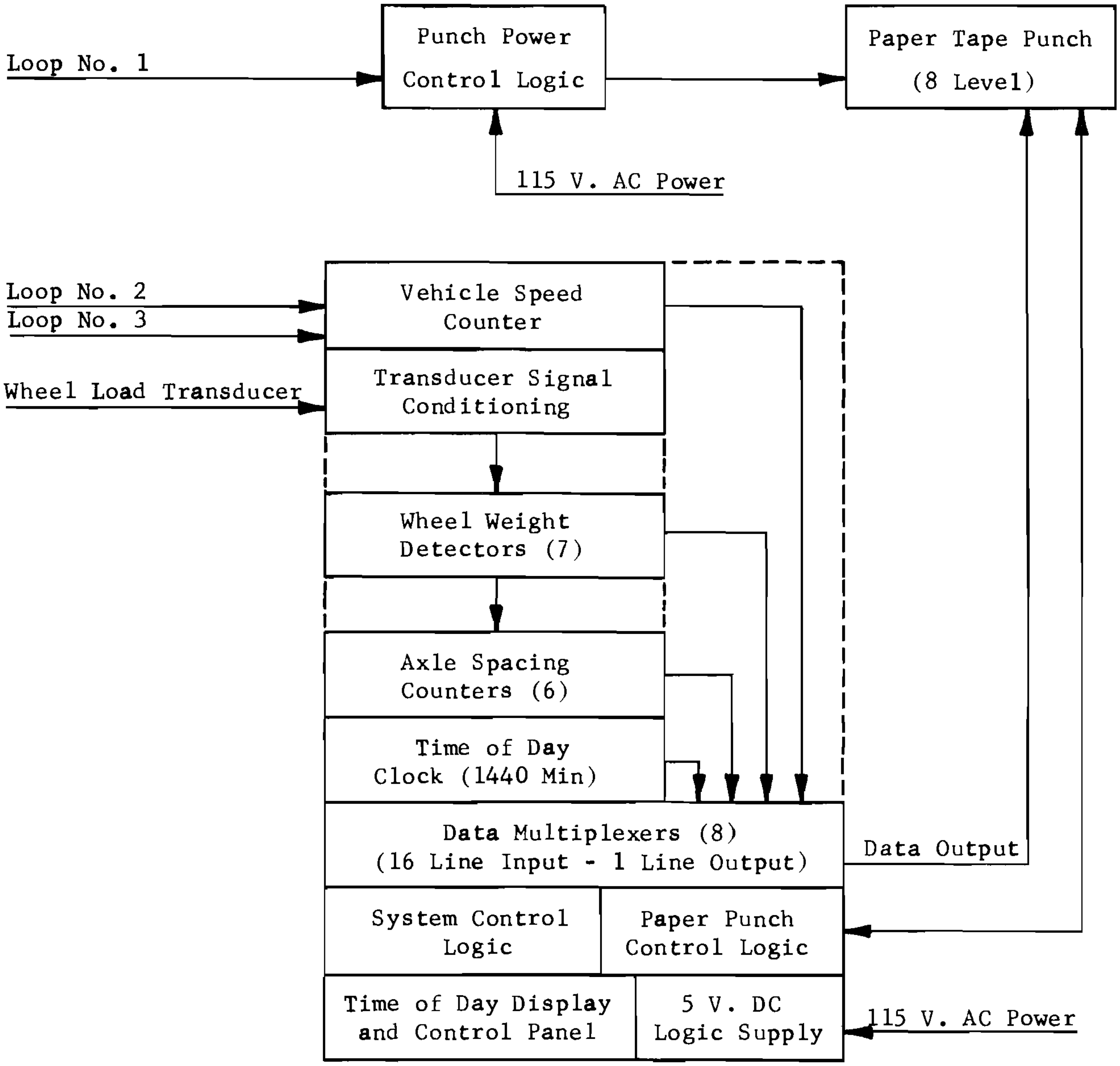


Fig 4.2. Block diagram of data recording system.

The strain gage circuit in the transducer produces a voltage which is directly proportional to normal applied force. The transducer output signal is amplified to provide compatibility with five voltage level detector circuits. Each detector circuit consists of a separately adjusted voltage comparator, which is set to a desired voltage level. Output from a given comparator thus indicates a wheel force in excess of the amount set on that comparator. By this process, all wheel weights are placed in one of the six classes shown in Table 4.1.

Axle spacings are measured by six separate time counters which measure elapsed time between each succeeding pair of weight pulses. The first counter begins accumulating time when the first wheel weight pulse exceeds the lowest weight detector level and continues until the second weight pulse exceeds the same weight level. The second counter begins as the first counter stops and continues until weight pulse three stops it, or until the third loop is no longer occupied by the vehicle.

The third loop returning to normal initiates the transfer of data to the paper tape punch along with time of day information. As transfer is completed, the entire system is reset for the next vehicle and power is removed from the tape punch motor. The paper tape output format for each 13-frame record is shown in Fig 4.3. The fixed punches provide a consistently recognizable pattern for each record thus facilitating data reduction. A typical record with the proper interpretation is shown in Fig 4.4.

Data Reduction

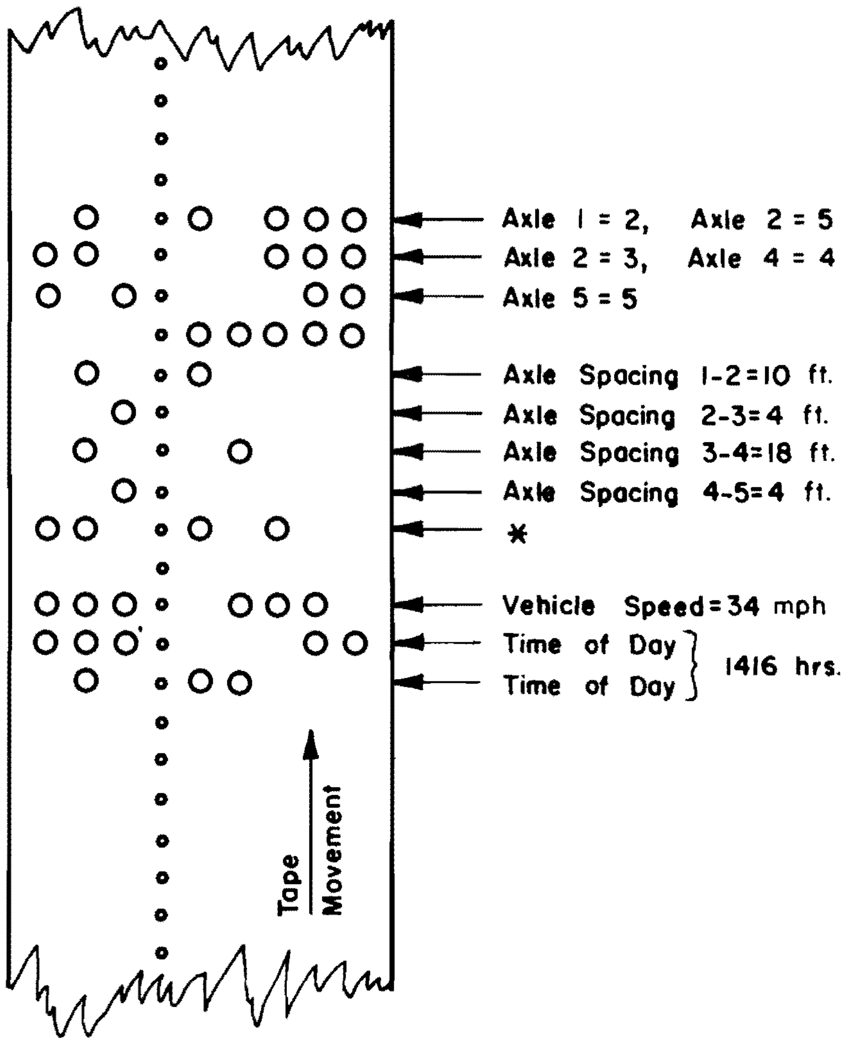
The raw data on punched paper tape must then be reduced to a readily usable form. A computer program for the CDC 6600/6400 computer system at The University of Texas at Austin was written for this purpose. The paper tape is read by a remote teletype terminal, processed and output in several forms. One output form (shown in Fig 4.5) consists of a record-by-record listing of the raw and reduced data. The weight data is also summarized by gross weights for each of the five vehicle classes discussed in Chapter 2. A typical weight summary is shown in Fig 4.6. In addition, the data is stored on punched cards and magnetic tape for future reference. Once the data is reduced to this form, all vehicular information necessary for mathematical modeling of any recorded vehicle is available.

TABLE 4.1. RECORDED WHEEL WEIGHTS AND CLASS DESIGNATIONS

Recorded Wheel Weight, kips	Weight Class Designation
Less than 2	0 (Shown on punched paper tape as blank)
2 to 4	1
4 to 6	2
6 to 8	3
8 to 10	4
Greater than 10	5

Frame	1	2	4	Level	8	16	32	64	128
	1	2	3		4	5	6	7	8
1	← Axle 1 → (Weight Class)			o	← Axle 2 → (Weight Class)			O	O
2	← Axle 3 →			o	← Axle 4 →			O	O
3	← Axle 5 →			o	← Axle 6 →			O	O
4	← Axle 7 →			o	O	O	O	O	O
5	← Time Between Axles: Axles 1-2 →			o					
6	← Axles 2-3 →			o					
7	← Axles 3-4 →			o					
8	← Axles 4-5 →			o					
9	← Axles 5-6 →			o					
10	← Axles 6-7 →			o					
11	← Vehicle Speed →			o					
12	O	O	O	o	← Time of Day → 1 / 1	2 / 2	7 / 4	15 / 8	31 / 16
13	← Time of Day → 63 / 32	127 / 64	255 / 128	o	511 / 256	1023 / 512	2047 / 1024		

Fig 4.3. Paper tape output format.



* Ignore Last Set of Punches Related to Time Between Axles.

Fig 4.4. Typical data record.

FILF ID = 97 10 5 10 19

	Weightclass Wheel 1	Weightclass Wheel 2	Axle Spacing 1–2							Vehicle Speed		Time of day				
Raw Data	0	2	0	0	0	0	0	6	35	0	0	0	0	106	1153	0
Reduced Data	1	2	6.8	0.0	0.0	0.0	0.0	0.0		38.6		19 12				
	2	2	2	0	0	0	0	8	4	39	0	0	0	168	1154	1
	3	3	5.7	2.9	0.0	0.0	0.0	0.0		24.4		19 13				
One Record	2	2	0	0	0	0	0	7	37	0	0	0	0	158	1157	2
One Record	1	2	5.3	0.0	0.0	0.0	0.0	0.0		25.9		19 16				
	2	2	0	0	0	0	0	9	39	0	0	0	0	106	930	3
	1	2	10.2	0.0	0.0	0.0	0.0	0.0		38.6		15 29				
	2	2	2	2	2	0	0	1	10	12	4	47	0	104	934	4
	7	5	1.2	11.5	13.8	4.6	0.0	0.0		39.3		15 33				
	0	2	2	2	2	0	2	1	10	2	13	1	3	112	934	5
	9	7	1.1	10.7	2.1	13.9	1.1	3.2		36.5		15 33				
	2	2	0	0	0	0	0	10	39	0	0	0	0	126	934	6
	1	2	9.5	0.0	0.0	0.0	0.0	0.0		32.5		15 33				
	3	3	10.4	1.5	0.0	0.0	0.0	0.0		50.5		15 41				
	2	0	2	0	0	0	0	1	7	39	0	0	0	103	944	9
	2	3	1.2	8.2	0.0	0.0	0.0	0.0		39.7		15 43				
	2	2	2	2	2	2	2	9	4	15	1	3	1	108	945	10
	9	7	10.0	4.4	16.7	1.1	3.3	1.1		37.9		15 44				
	2	2	0	0	0	0	0	9	37	0	0	0	0	122	947	11
	1	2	8.9	0.0	0.0	0.0	0.0	0.0		33.5		15 46				
	2	2	2	2	2	2	0	1	12	4	14	4	46	103	948	12
	8	6	1.2	14.0	4.7	16.3	4.7	0.0		39.7		15 47				
	2	2	0	0	0	0	0	7	34	0	0	0	0	94	948	13
	1	2	8.9	0.0	0.0	0.0	0.0	0.0		43.5		15 47				
	2	2	0	0	0	0	0	8	34	0	0	0	0	89	949	14
	1	2	10.8	0.0	0.0	0.0	0.0	0.0		46.0		15 48				
	2	2	0	0	0	0	0	6	33	0	0	0	0	72	950	15
	1	2	10.0	0.0	0.0	0.0	0.0	0.0		56.8		15 49				
	2	0	2	2	0	0	0	1	8	1	41	0	0	152	952	16
	4	4	.8	6.3	.8	0.0	0.0	0.0		26.9		15 51				
	2	2	0	0	0	0	0	7	34	0	0	0	0	211	952	17
	1	2	4.0	0.0	0.0	0.0	0.0	0.0		19.4		15 51				

Fig 4.5. Record-by-record listing of raw data.

CUMULATIVE SUMMARY

FILE IDENTIFICATION: 101 11 10 11 21

WHEEL WEIGHTS (KIPS)

CLASS/AXLE	0	2	4	6	8	10+	TOTAL
1/1	823	7247	13050	2181	27	23	23351
1/2	598	5708	13257	1933	1117	738	23351
2/1	101	301	933	122	4	2	1463
2/2	42	167	1016	115	88	35	1463
2/3	124	214	917	95	52	61	1463
3/1	57	199	1277	681	12	20	2246
3/2	56	207	972	157	473	381	2246
3/3	23	299	1003	528	274	120	2247
4/1	253	2123	8582	1366	3	4	12331
4/2	84	160	3055	219	350	8463	12331
4/3	217	209	2995	471	3461	4980	12333
4/4	55	362	3233	3100	5351	231	12332
5/1	178	927	8245	714	1	2	10067
5/2	40	204	2421	718	4144	2540	10067
5/3	97	272	2530	2668	4052	448	10067
5/4	37	206	2182	317	2309	5016	10067
5/5	18	316	2268	2112	4722	631	10067
TOTAL	2803191216793617497264402369 5						

GROSS WEIGHTS (KIPS)

CLASS	0	10	20	30	40	50	60	70	80	90+	TOTAL
1	6969	15875	489	20	0	1	0	0	5	0	23359
2	183	221	892	127	39	1	0	0	2	0	1465
3	152	200	1002	505	376	14	0	2	1	0	2252
4	7	243	365	2973	353	4716	3630	49	2	0	12338
5	2	9	210	253	2108	329	2071	3113	1972	4	10071
TOTAL	7313	16548	2958	3878	2876	5061	5701	3164	1982	4	49485

TOTAL NUMBER OF VEHICLES PROCESSED=51347

Fig 4.6. Typical weight summary.

CHAPTER 5. FIELD TEST SITE

The contents of this chapter describe a field testing program which was designed to demonstrate the effects of dynamic wheel loads caused by rough pavement surface profiles in a controlled field experiment. An additional objective of the field test was to provide realistic data for illustrating the use of the summary technique developed in Chapters 2 and 3. These traffic data are contained in the previously presented example problem.

Test Site

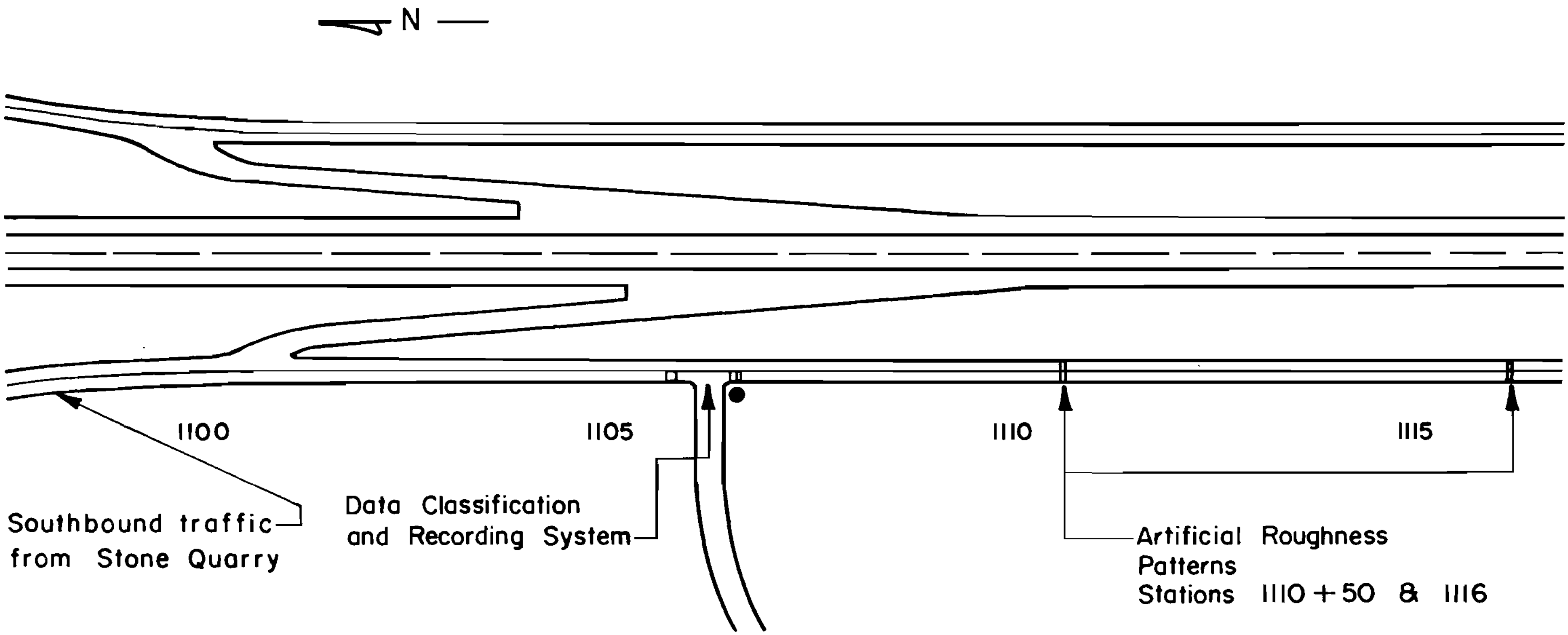
After a careful reconnaissance of potential study sites, a section of the southbound lane of the west frontage road along IH 35 near Georgetown, Texas, was chosen. The site was particularly desirable because it was adjacent to a stone quarry which produced a large volume of heavy truck traffic and involved minimal inconvenience to normal traffic. A plan view of the test site and the surrounding area is shown in Fig 5.1. As shown in the figure, the test site accommodated the data classification and recording system and two pavement test sections.

The DCR system was installed in advance of the test sections in a partially buried culvert section. The shelter and DCR system are shown in Fig 5.2.

Pavement Test Sections

As illustrated in Fig 5.1, the two pavement test sections were located approximately 400 and 900 feet downstream from the DCR system. Each test section was divided into a 100-foot control zone, followed by a 50-foot dynamic loading zone, and a 50-foot buffer zone (see Fig 5.3).

Immediately adjacent to and in advance of each dynamic loading zone, a specially designed road surface irregularity (or bump pattern) was introduced to excite the suspension system of all southbound vehicles. Two bumps, formed with asphalt premix, were installed in July of 1971 in each test section.



I. H. 35 & Frontage Roads

Williamson County

Fig 5.1. Plan view of test site and surrounding area.

Fig 4.4. Interior and exterior view of instrument shelter.

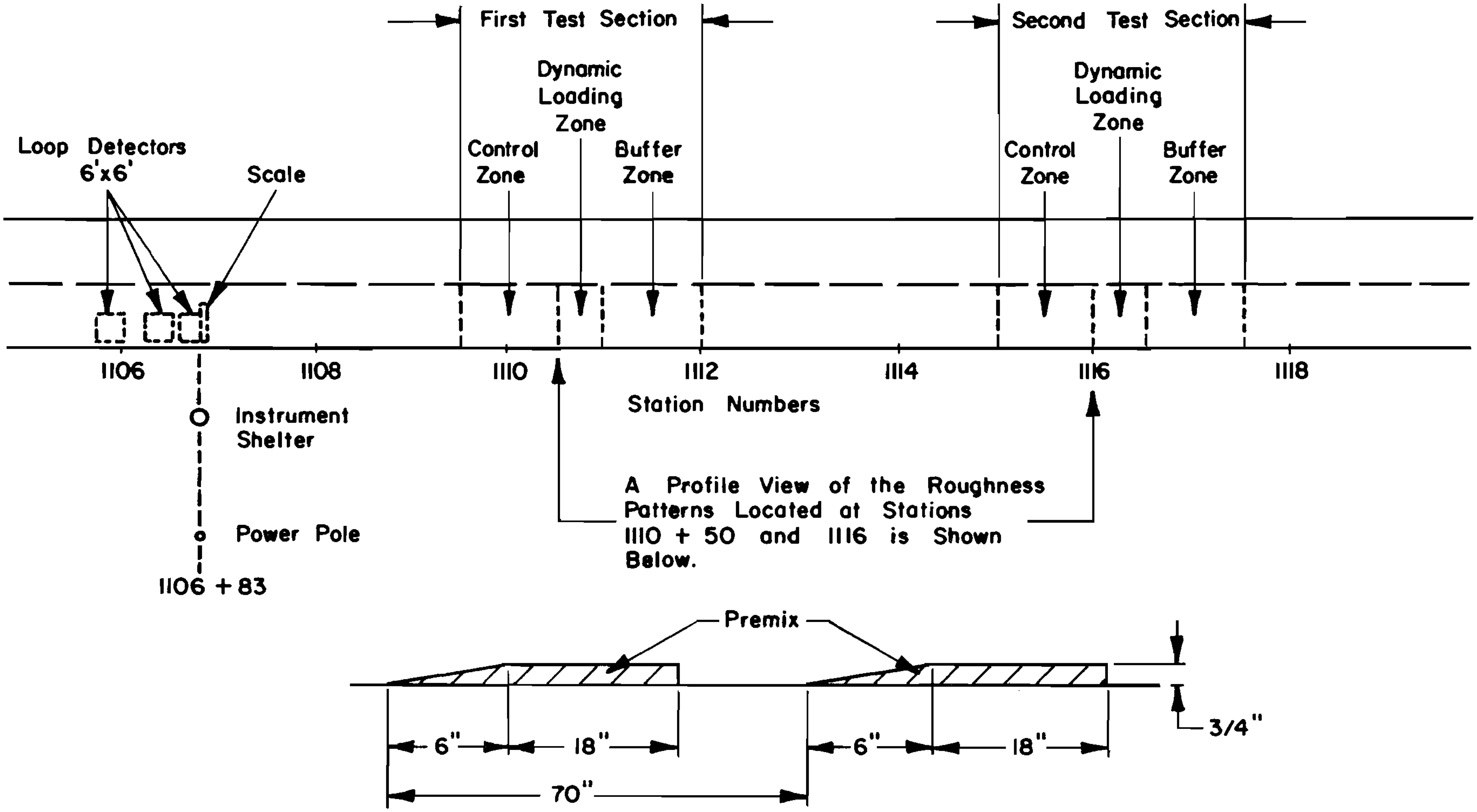


Fig 5.3. Layout of test sections and data recording system in field test site.

Each bump was approximately 3/4-inch high and 18 inches long with a 6-inch ramp on the leading edge (see Fig 5.3). Originally, the bumps were installed only in the southbound lane, but when the truck drivers began circumventing these, it was necessary to extend the bumps across the northbound lane.

On the basis of a field speed study and model analysis conducted prior to installation of the bumps, a spacing of 70 inches from leading edge to leading edge was chosen. The speed study consisted of recording the speed of southbound traffic for part of a normal weekday. The mean speed for the 139 trucks observed was 42.8 mph with a standard deviation of 2.8 mph. A mathematical model analysis for vehicles operating at a speed of 42 mph showed that the frequency of oscillation of the suspension systems of the vehicles ranged from 9 to 11 H_z at 40 to 45 mph, or approximately 1 cycle every 0.1 second. In order to obtain maximum effect from the bumps, they were placed approximately 0.1 second or about 70 inches apart.

Observation of traffic later showed this spacing to be almost overly successful since drivers of most trucks began decreasing speed and otherwise attempting to avoid the effect of the bumps. As a result of these driver reactions, the first of each pair of bumps was removed in August of 1972. This reduced the dynamic traffic loads considerably, but the single bumps still resulted in dynamic wheel forces that were about 60 to 100 percent greater than static wheel weights for vehicles operating at 30 to 40 miles per hour.

Test Traffic

The field installation was completed in late July 1971 and opened immediately to test traffic. Figure 5.4 shows the timewise accumulation of traffic through the test sections. Since most of the heavy vehicular traffic, consisting primarily of Classes IV and V vehicles, was originating at the Texas Crushed Stone Quarry, a number of attempts were made to persuade the truck drivers to use the frontage road through the test sections voluntarily and enter IH 35 at the next downstream ramp a mile south rather than entering the freeway directly and bypassing the test sections. This, of course, involved a slight time loss and some inconvenience as well as additional wear on the vehicles as compared to the direct freeway route.

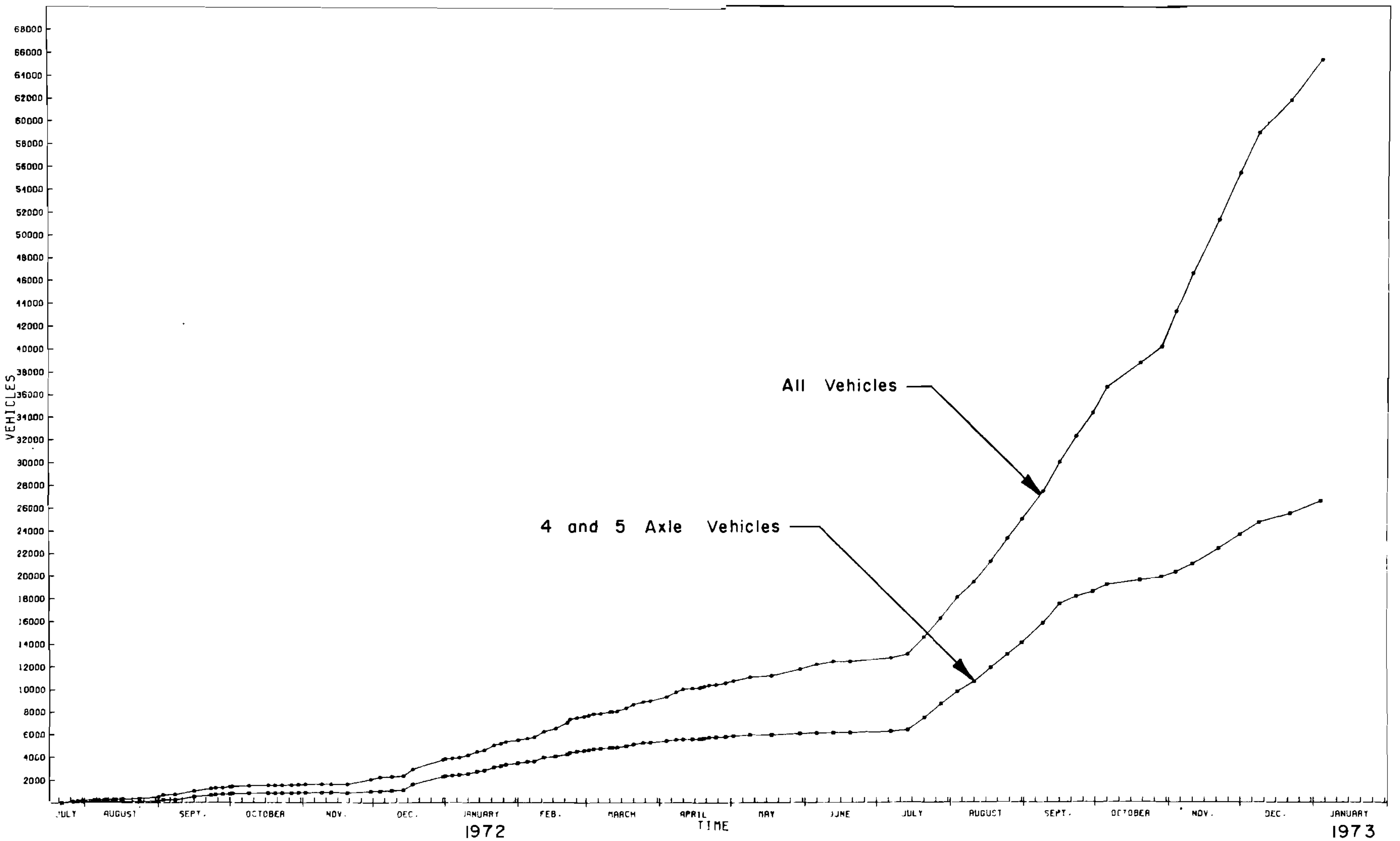


Fig 5.4. Timewise accumulation of traffic through test sections.

Initially, pamphlets handed to each driver and a large sign in advance of the first entrance ramp were used to encourage drivers to use the frontage road. However, after some cooperation until about mid-September (see Fig 5.4), few drivers used the frontage road. For the next ten months several other attempts to get voluntary use were tried, but these were at best only moderately successful. Finally in late July 1972, upon approval by administrators of the Texas Highway Department, the entrance ramp north of the test area was temporarily closed and all southbound frontage road traffic was rerouted over the test sections. As may be seen in Fig 5.4, barricading this ramp resulted in a steady volume of heavy four and five-axle vehicles.

By mid-January 1973 when the barricades were removed, more than 65,000 vehicles (25,000 Class IV and V) had passed over the test sections. The cumulative loading dynamic diagram for this traffic is presented in Chapter 3.

CHAPTER 6. PAVEMENT STRESS ANALYSIS

In order to study the effects of dynamic loading that resulted from the traffic over the pavement test sections, an analysis of the state of stress and strain in the pavement structure was conducted. This investigation is described in the following paragraphs.

Prediction of Stresses for an Elastic Layered System

The predicted peak dynamic forces of Fig 3.6 were used in the Chevron elastic layered computer program to estimate the stresses caused by dynamic vehicular loading. This program computes stresses, strains and displacements in an elastic layered system consisting of up to five layers. The load is assumed to be uniformly distributed on a circular area, and each layer is assumed to be homogeneous, linearly elastic, of uniform thickness, and of infinite dimensions horizontally. The bottom layer is assumed to be an elastic half-space. In addition, it is assumed that adjacent layers are bonded and no slip occurs at the interfaces.

In general, the program has the following additional limitations:

(1) It does not allow any body forces or couples to be present, and inertia forces are neglected.

(2) The stresses and strains produced must be small enough to be described by infinitesimal elastic theory.

(3) The system is axisymmetric, which means that each layer is uniform, homogeneous, and isotropic.

More sophisticated techniques for predicting stresses and strains in pavements are currently available; but this particular program was selected because it is highly user-oriented, and it is adequate for qualitatively comparing the effects of dynamic and static loading.

While this analysis may not be theoretically exact, it at least serves as a qualitative analysis tool. That is, the results of this analysis may be regarded as a qualitative comparison of stress conditions resulting from dynamic as compared to static loading rather than as a quantitative comparison of the possible stress conditions.

Before stress conditions could be predicted the pavement structure in the test sections had to be characterized. Therefore a limited soils investigation was conducted early in the research study.

Soil Sampling

To obtain samples with minimum disturbance to the pavement structure, 12 bore holes were drilled in the pavement at the locations indicated in Figs 6.1 and 6.2. Later, in July 1973 after all traffic testing was completed, the pavement was trenched at station 1110+00 and 1110+55. Nuclear and conventional methods were used to determine base and subbase densities and moisture contents. The dry density for the base was found to be about 122 pcf while the subbase (clay fill) was about 115 pcf with moisture contents of approximately 7 and 12 percent respectively.

The depths of the base and subbase materials are shown graphically in Figs 6.1 and 6.2. Note that the first test section is located on a relatively deep clay fill while the fill in the second section is much shallower. The 12-inch base thickness as shown on construction plans seems to be quite uniform, varying from about 12 to 14 inches in all areas sampled.

Samples of the base and subbase material were obtained from each of the 12 bore holes. Atterberg limit determinations were made on the -200 fraction of each of these samples (Figs 6.1 and 6.2 show the results of this analysis). In addition, undisturbed samples of the clay fill in the first test section were obtained at the top, middle, and bottom of each hole. The caliche portion of the fill in the second test section prevented obtaining undisturbed samples in that area.

Testing Procedures

In addition to Atterberg limits and moisture content determinations which were performed on all samples, the resilient modulus or M_R test was performed on the undisturbed samples of the clay material and on several recompacted specimens from the fill in the second test section.

The resilient modulus testing procedure that was employed consisted of repetitive loading of a cylindrical specimen at three different axial stress

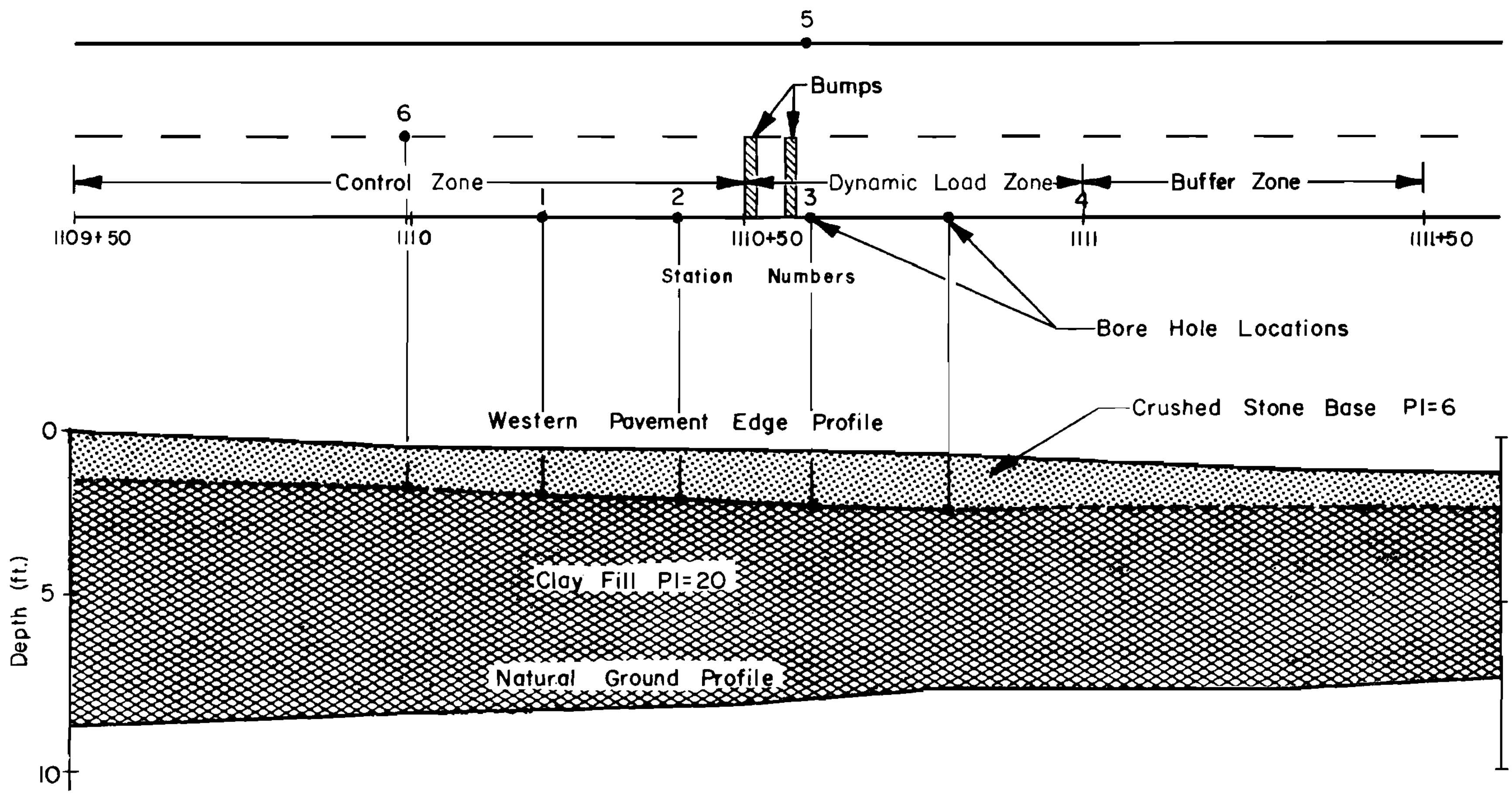


Fig 6.1. Layer thickness and bore hole locations in first test section.

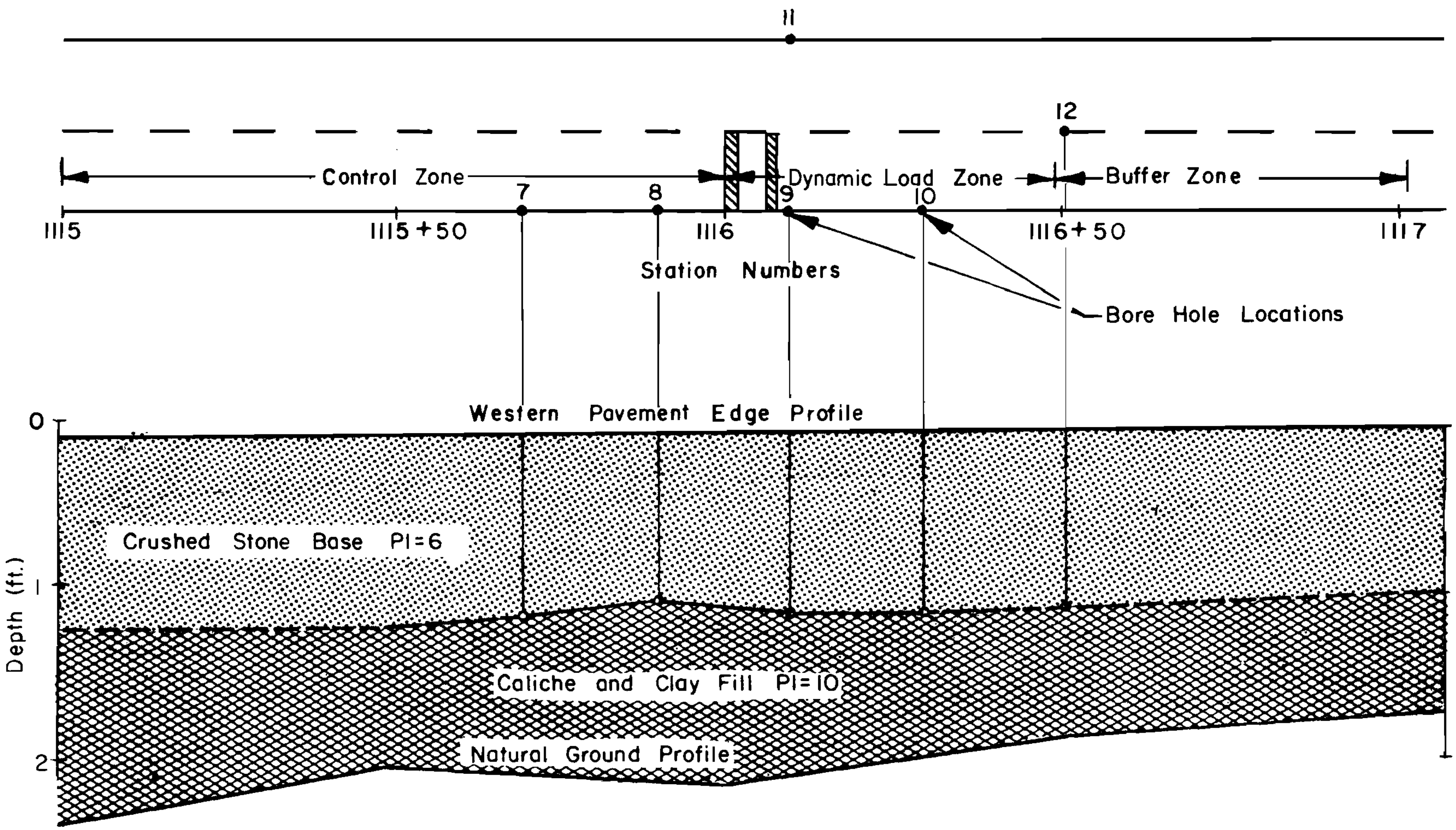


Fig 6.2. Layer thickness and bore hole locations in second test section.

levels and one lateral stress level. The specimens were approximately 3 inches in diameter and 6 inches high. A lateral stress of one psi was used throughout the program, while axial stress levels of 2, 6, and 12 psi were applied.

The deflection response with respect to time of each specimen under repetitive loading was recorded by an x-y plotter. Figure 6.3 is an example of such a plot. The recorded data consist of the axial deformation of the specimen under the first 12 load applications and the deflection immediately following 300, 600, and 900 load applications. As shown in the figure, the first 12 load applications provide an estimate of the permanent deformation of the samples for the particular stress level. A resilient modulus value can be determined for each vertical stress level and for each number of repetitions by dividing the vertical stress by the resilient strain. Figure 6.4 is an illustration of the kind of data provided by this test. The M_R test indicated that the clay material was stress sensitive, although it seemed to be only slightly affected by repetitive loading under the conditions used here. Figure 6.4 is representative of the data obtained from the M_R tests of both undisturbed and recompacted specimens of clay fill. That is, the elastic modulus values generally range from 12,000 to approximately 7,000 psi. Since the study of stress and strain discussed in the following paragraphs required a modulus value for all layers and the base was as yet unquantified, several recompacted specimens of the base material were also tested. It was recognized that recompaction and testing of this material using the M_R procedure was less than ideal, but the intention was merely to provide a crude estimate for use as a check on an iterative estimation procedure to be discussed later. The tests on the base material yielded modulus values of approximately 16,000 to 23,000 psi for the stress levels used here (see Fig 6.5).

Predictions of the State of Stress and Strain

The Chevron elastic layered computer program which was utilized to estimate the state of stress and strain in the test section pavement requires as inputs the thickness, elastic modulus, and Poisson's ratio for all layers. The thicknesses were readily available and since Poisson's ratio was not considered to be an extremely sensitive variable, it was assumed to be 0.5 for

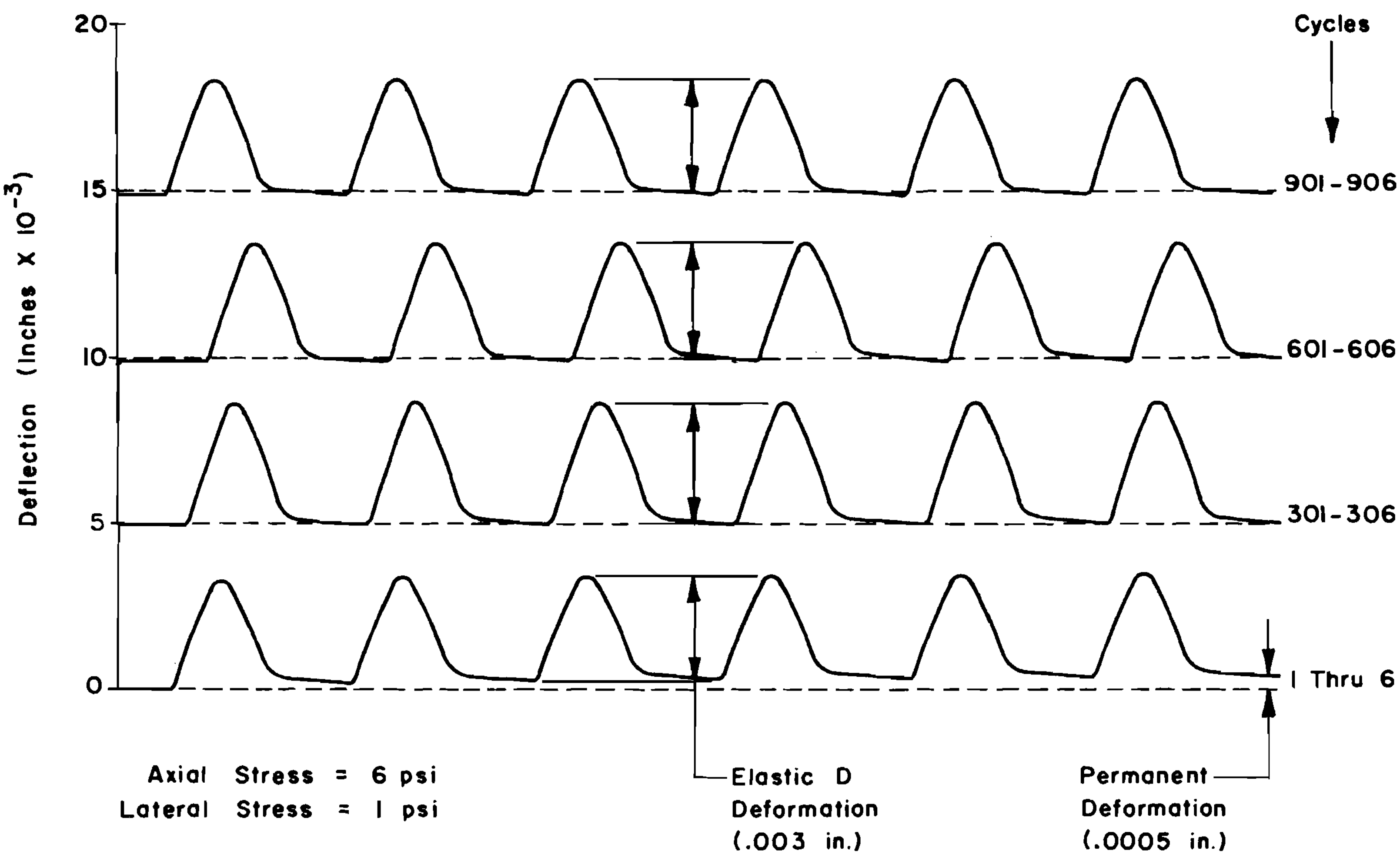


Fig 6.3. Typical deflection response of a specimen undergoing M_R testing.

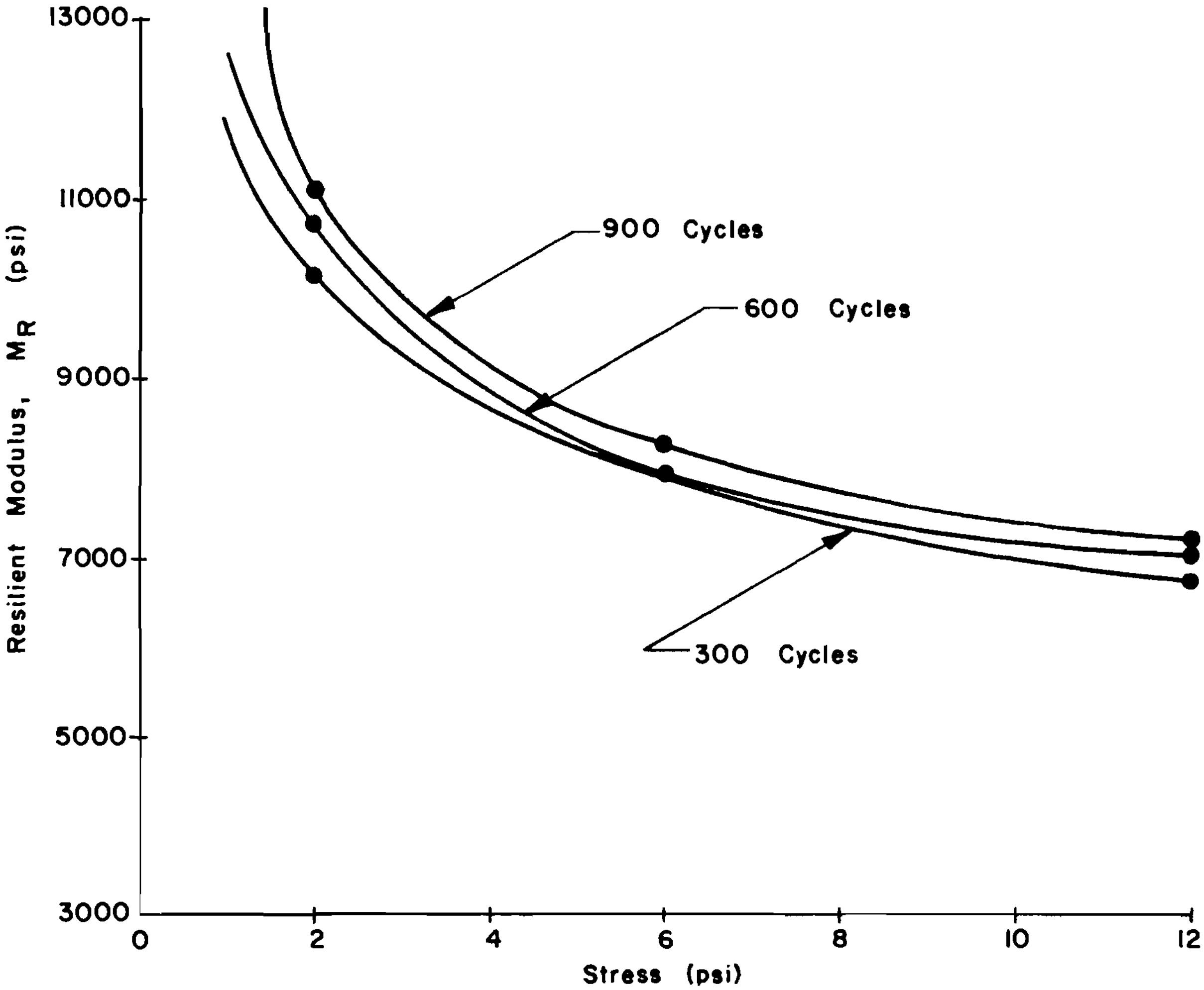


Fig 6.4. Resilient modulus versus axial stress for a typical specimen of clay fill.

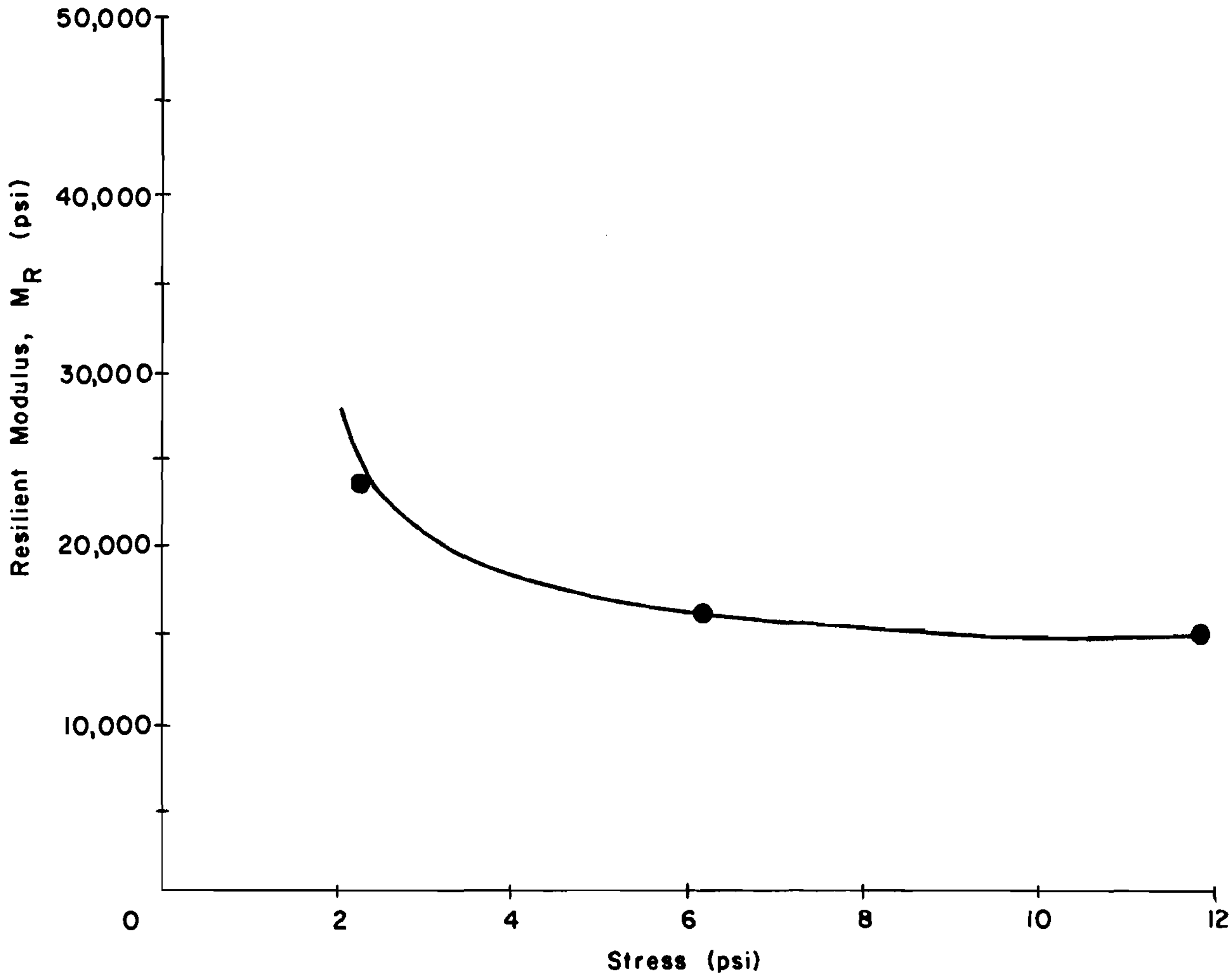


Fig 6.5. Resilient modulus versus axial stress for recompacted crushed stone base.

all layers. The pavement surfacing consisted of a two-course surface treatment and was therefore assumed to have no load carrying ability.

The pavement system used for analysis consisted of the two-layer system shown in Figs 6.1 and 6.2, with the addition of an assumed third layer extending infinitely below the second and having properties identical to the second.

The first step in this analysis consisted of using known pavement loading and the resulting deflections to determine a reasonable modulus value for the crushed stone base. Measured deflections and loading were provided by dynaflect readings taken on the test section pavements, and the process of determining the modulus which produces predicted deflections equal to observed deflections was greatly shortened by a computer program written for this purpose and documented in Ref 21. This program simply iterates through an elastic layered program changing an assumed modulus value until the predicted deflections become equal (within some tolerance) to the measured deflections.

This program predicted a modulus of approximately 41,000 psi when loaded by dynaflect. Although this value is high when compared to the M_R data cited earlier, it can possibly be explained by noting that the material is stress sensitive in nature and the dynaflect loading creates very small stresses, thus large moduli (see Fig 6.4). Reference 21 suggests that as a rule of thumb the modulus value derived from dynaflect data should be halved to provide a value commensurate with the usual range of highway loadings and resultant stresses. This rule of thumb appears to apply quite well in this case since it puts the derived modulus value in the range of values mentioned previously. Figure 6.6 represents a compilation of data concerning the modulus of the crushed stone base. This figure is the basis for elastic modulus values of the base used in the following paragraphs.

Results of Analysis by Elastic Layered Theory

The elastic layered study of stresses and strains in the pavement structure consisted of first predicting the stresses and strains resulting from static loading by the heaviest wheel of the 17 representative vehicles noted in the previous chapter. The process was then repeated using the peak dynamic wheel load in place of the static wheel load. The resulting stresses were then compared. It is recognized that using a dynamic load as if it were a static load is not entirely justified since the modulus values of the material

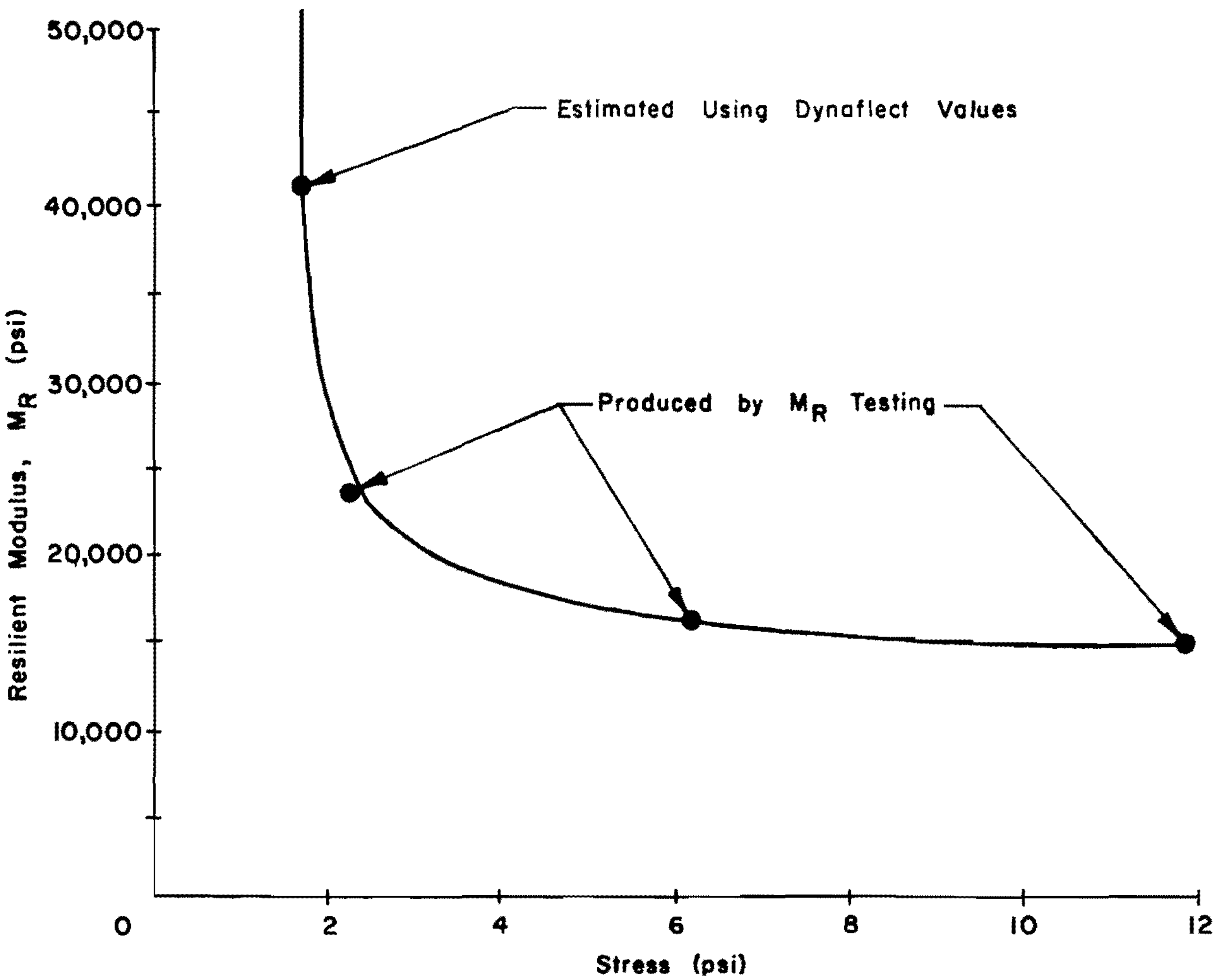


Fig 6.6. Resilient modulus and dynaflect determination of an elastic modulus for the crushed stone base.

probably change with time of loading and that inertial effects are present. Nevertheless, this analysis was conducted to demonstrate the results of a "worst case" situation.

Figure 6.7 is a graphical comparison of the stresses created by the static and dynamic loading at the bottom of the base layer at the location of the peak dynamic load for each of 5 representative vehicles in the first test section. Figure 6.8 represents the same type of comparison for the second test section. Although stresses and strains at other depths and radial distances were computed, the data illustrated here are representative.

Conclusions

The findings of this analysis may be summarized as follows:

(1) Since the materials in the pavement were stress sensitive, larger applied loads resulted in slightly lower modulus values (see Figs 6.4 and 6.5). This decrease in modulus due to higher stress tends to be offset by the increase in modulus that may be caused by short-duration dynamic loading; thus the effective modulus value is similar for both static and dynamic loading.

(2) If a similar modulus does exist during both kinds of loading and if dynamic loads are represented, for analysis purposes, by static loads of the same magnitude, then much higher stresses are created in the pavement than would occur under simple static vehicle weight.

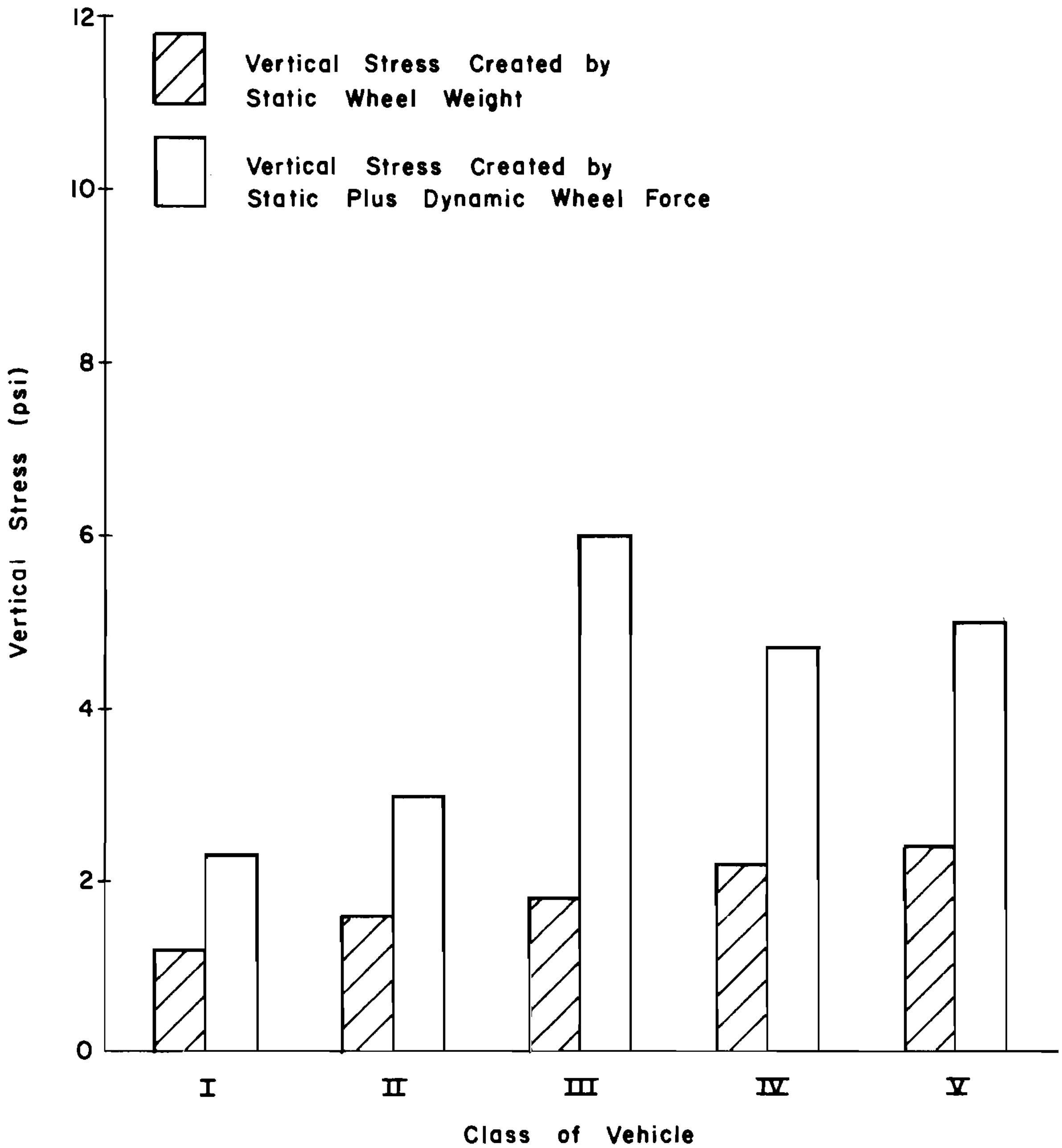


Fig 6.7. Comparison of stresses created by static and dynamic plus static loading for first test section.

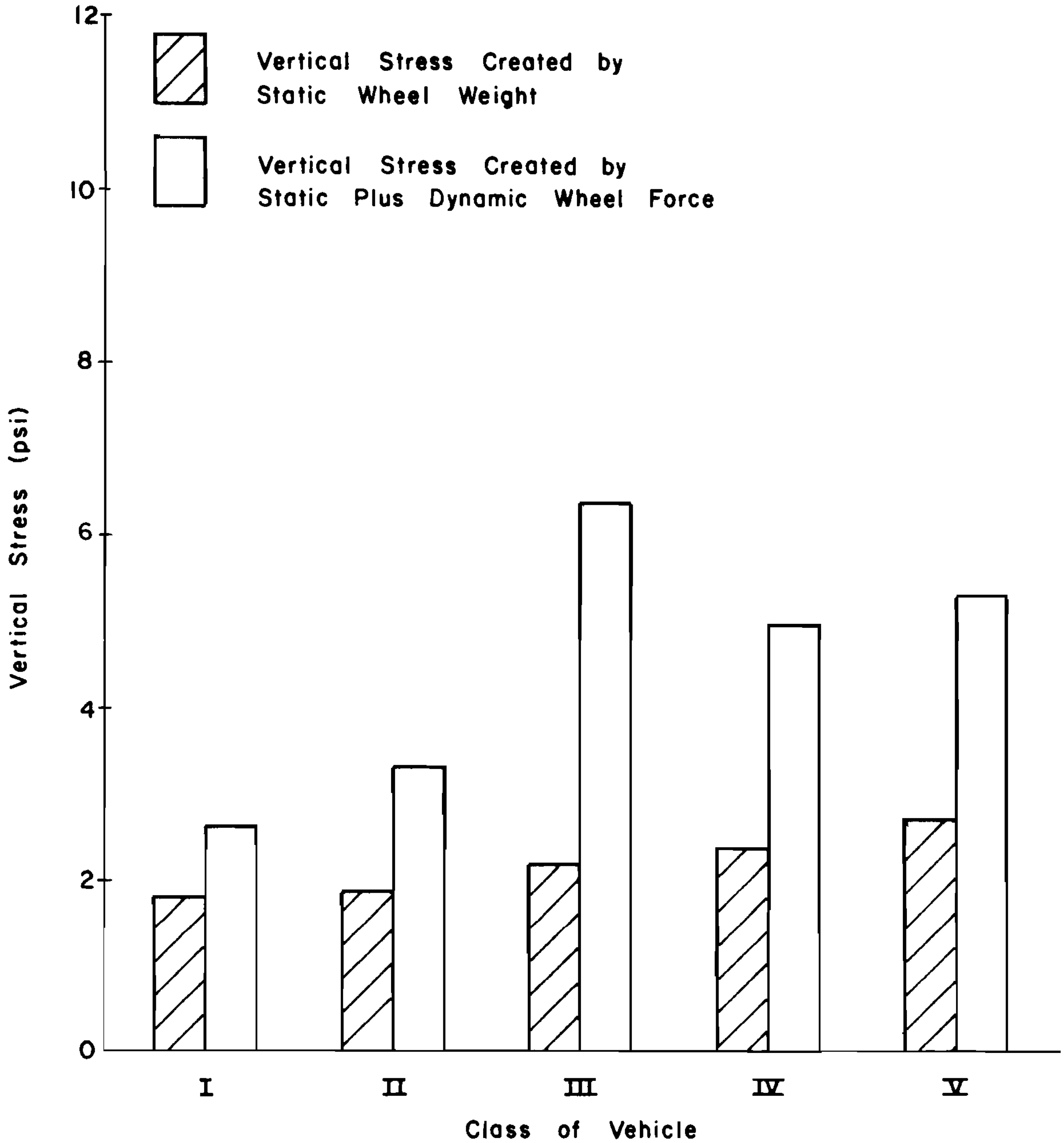


Fig 6.8. Comparison of stresses created by static and dynamic plus static loading for second test section.

CHAPTER 7. EFFECTS OF TRAFFIC LOADING

As noted in Chapter 5, a field testing program was conducted to compare the effects of dynamic wheel loads caused by mixed traffic operating on a rough pavement surface with the effects of the same traffic traveling over an adjacent smooth pavement surface. Qualitative evaluation suggested that the dynamic wheel loads of significantly greater magnitude than the static wheel weights would probably cause pavement distress more rapidly than the wheel loads imposed on a smooth pavement, but quantitative data were needed for a comparison. Two measuring techniques were used to assess the relative effects in quantitative terms: (1) a dynaflect survey, and (2) an optical level survey. The former technique gives measurements of vertical pavement surface deformation at selected locations in response to a sinusoidaldy varying magnitude of force applied at the pavement surface. The latter provides a means of detecting changes in pavement surface elevations at chosen points with respect to time. These measurements are discussed in subsequent sections of this chapter.

The test pavement that was selected for the field study was a typical medium-duty design chosen purposely so that perceptible damage to the structure was likely to occur under heavy truck traffic. The double surface treatment that was applied directly over a salvaged crushed stone base contained asphalt that had been in place for about seven years at the beginning of the traffic tests. While such a light surface contributes little to the structural stiffness of the pavement, it serves to bind and waterproof the base materials. An unexpected opportunity to observe the results of waterproofing on retarding freeze-thaw damage came in January and February of 1973. Dynamic loading by traffic had a definite influence on the behavior of the asphalt surface treatment under these conditions.

Dynamic Loading and Age Hardening of Asphalt

Following a period of three days in which about an inch of rain fell, the pavement test sections experienced below-freezing temperatures for approximately thirty-six hours during which time truck traffic was light. When the pavement thawed on the morning following this light freeze, the first few trucks began rutting the upper inch of the pavement so badly that the barricaded entrance ramp was opened and the traffic was routed away from the test area.

Extensive damage to the surface treatment was evident in both wheel paths of the traffic lane for a quarter mile adjacent to the test sections, but no rutting occurred in the dynamically loaded zones for about 50 feet downstream from the bumps. A chicken wire cracking pattern in the surface treatment had apparently allowed water to penetrate the pavement and freeze in all areas except where the heavy dynamic wheel loads had kept the cracks kneaded closed. Fine cracks of this type were also present in the northbound traffic lane adjacent to the test sections.

In order to determine the basic properties of the asphalt cement and whether or not the asphalt in the surfacing had been affected by the concentrated dynamic wheel loads, samples of the surface treatment were obtained (1) from the first dynamic loading zone, (2) from the adjacent buffer zone where damage was severe, and (3) from the northbound lane next to the test zone where damage was also evident. Standard extraction procedures were used by the Materials and Tests Division D-9 of the Texas Highway Department to recover a few grams of asphalt cement from each of these samples.

The sliding plate microviscometer (see Ref 32) was used to measure the viscosity of the recovered asphalt in a series of laboratory tests. Two sliding plate specimens were prepared from each sample, and the viscosity of all specimens was measured eight times over a 72-hour period. Since previous experience had shown that the viscosity of some asphalts increases rapidly with time immediately after heating or shearing, more frequent measurements of viscosity were made during the first few hours after specimen preparation. Figure 7.1 shows graphically that the asphalt from the dynamically loaded test section had a lower initial viscosity than that from the adjacent northbound lane that had not been as heavily loaded by traffic and that the viscosity of the asphalt recovered from both areas increased about 30 percent during the first few hours after specimen preparation.

These results substantiate the hypothesis presented in Ref 32 that repeated loading retards age hardening in asphalt and that shearing asphalt in thin films retards or prevents thixotropic viscosity increases. It may be concluded that the higher dynamic wheel loads induced by the surface roughness

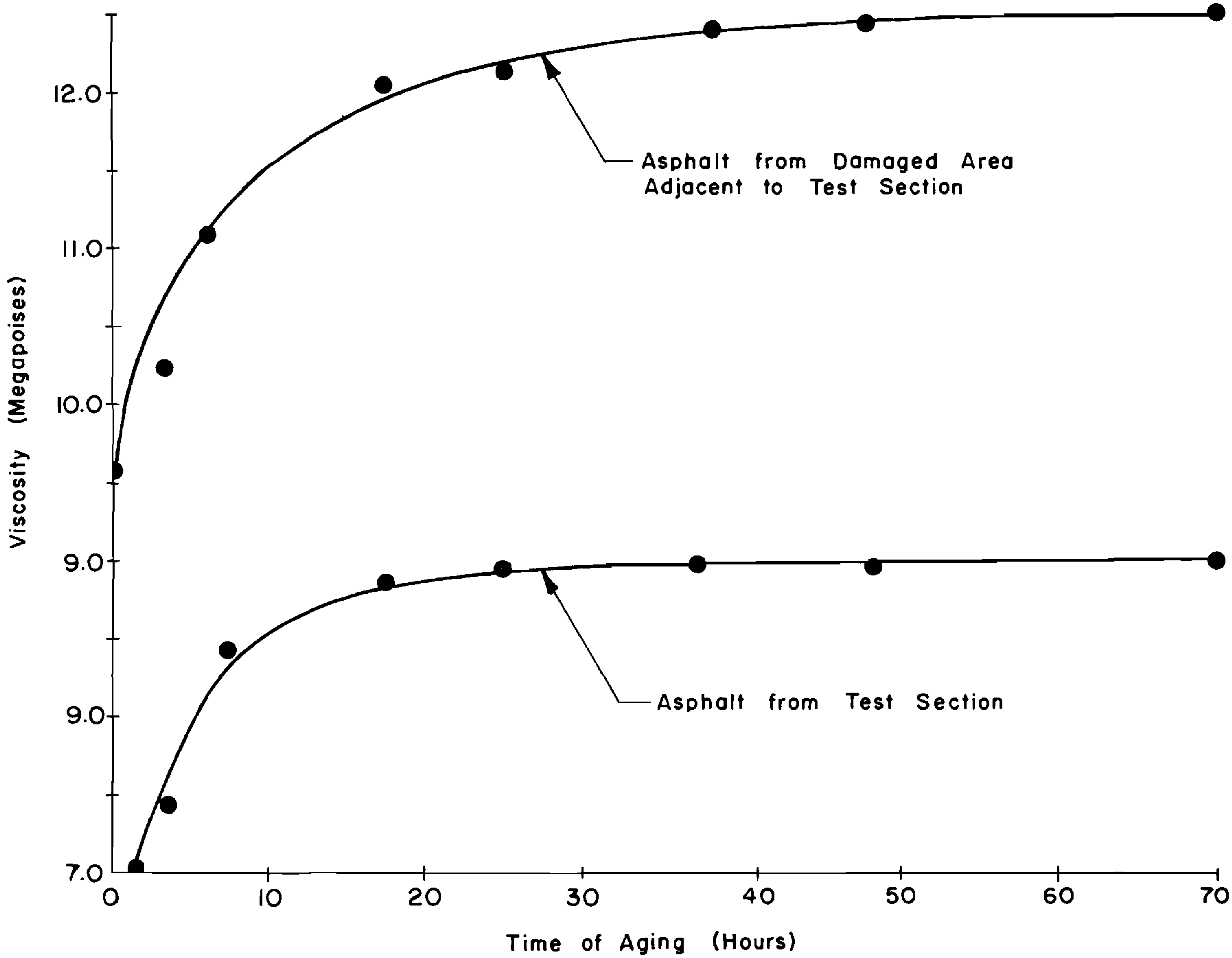


Fig 7.1. Preliminary results of asphalt viscosity measurements.

sheared the asphalt to a greater extent than traffic on the smooth sections and thereby kept it "alive." Water intrusion was thus prevented, and freeze-thaw damage was much less severe in this particular case. Contrary to general expectations, the concentrated dynamic wheel loads had a beneficial effect on pavement performance under these unusual circumstances.

Dynaflect Surveys

A dynaflect survey was performed approximately once every three months during dynamic traffic loading of the test section. These surveys consisted of measuring deflections in each wheel path of the southbound lane in the control, dynamic loading, and buffer zones. Measurements were obtained at 10-foot intervals in the control zone, while 2-foot measurement intervals were used for the first 30 feet of the dynamic loading zone and 5-foot intervals for the last 20 feet.

In order to test statistically the effects of traffic loading on the two control and the two dynamic loading zones, an analysis of variance was performed on the dynaflect data after it had been classified into a two-way system. The two classifications consisted of longitudinal position on the roadway and time of dynaflect measurement. As shown in Table 7.1, the two time categories were August 1971 and April 1973. The August 1971 measurements were performed before the traffic testing program began, while the April 1973 measurements were obtained near the end of the program. This classification was analyzed separately for each of the two control zones and each of the two dynamic loading zones. The analysis of variance tables for each of the four zones are shown in Table 7.2.

This analysis indicated that the changes in the dynaflect deflections that were measured before variation and after dynamic traffic loading were larger than could be attributed to chance alone in 70 out of 100 cases for all four sections. The before and after dynaflect measurements in both dynamic loading zones showed differences which were greater than could be attributed to chance in 95 out of 100 cases. In order to substantiate the results of this type of statistical testing, which is based on several assumptions about the data, a nonparametric one-way analysis test was also performed. The Kruskal-Wallis one-way analysis of variance by ranks was used to test the significance of the effects of dynamic loading on all four sections (Ref 31).

TABLE 7.1. LAYOUT OF TWO-WAY CLASSIFICATION FOR DYNAFLECT DATA

		Longitudinal Roadway Position (Station Number)									
		1	2	3	4	5	6	7	8	9	10
Time of Dynaflect Measurement	August 1971										
	April 1973										

ANALYSIS OF VARIANCE FOR TWO-WAY 2 X 11 TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARES	F RATIO
BETWEEN ROWS	1	.000040909091	.000040909091	1.000
BETWEEN COLS	10	.025409091	.0025409091	62.111
RESIDUALS	10	.00040909091	.000040909091	
TOTAL	21	.025859091		

(a) **Analysis of variance table for first control zone.**

ANALYSIS OF VARIANCE FOR TWO-WAY 2 X 11 TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARES	F RATIO
BETWEEN ROWS	1	.0010227273	.0010227273	1.642
BETWEEN COLS	10	.10388182	.010388182	16.682
RESIDUALS	10	.0062272727	.00062272727	
TOTAL	21	.11113182		

(b) **Analysis of variance table for second control zone.**

TABLE 7.2. ANALYSIS OF VARIANCE TABLES

ANALYSIS OF VARIANCE FOR TWO-WAY 2 X 10 TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARES	F RATIO
BETWEEN ROWS	1	.0068450000	.0068450000	7.696
BETWEEN COLS	9	.031805000	.0035338889	3.973
RESIDUALS	9	.0080050000	.00088944444	
TOTAL	19	.046655000		

(c) Analysis of variance table for first loading zone.

ANALYSIS OF VARIANCE FOR TWO-WAY 2 X 10 TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARES	F RATIO
BETWEEN ROWS	1	.026645000	.026645000	64.725
BETWEEN COLS	9	.013905000	.0015450000	3.753
RESIDUALS	9	.0037050000	.00041166667	
TOTAL	19	.044255000		

(d) Analysis of variance table for second loading zone.

TABLE 7.2. (Continued)

This test indicated the same trends shown by the parametric testing and thus supported the results.

Optical Level Surveys

Optical level surveys were conducted on a regular biweekly schedule throughout the field test period. These surveys consisted of reading the elevations of approximately 150 points on a grid in the control and dynamic loading zones. The points forming the grid were identified on the pavement surface by thumbtacks held in position with epoxy glue. The grid points in the control zone were spaced 10 feet longitudinally and 2 feet transversely while the intervals in the loading zone were 5 feet longitudinally and 1 foot transversely. These data were plotted in three-dimensional figures to show surface distortion. Figures 7.2 and 7.3 are three-dimensional plots for the first loading zone before and after loading by the test traffic.

Conclusions

The following statements are warranted by the findings of the dynaflect and optial level surveys. These statements are based on the assumptions which are applicable for the statistical tests employed (see Refs 27 and 31).

(1) After traffic loading, the dynamic loading zones demonstrated increases in dynaflect deflections which were on the average significant at the 95 percent confidence level.

(2) For the same traffic loading, the control zones demonstrated a corresponding increase in deflection measurements which was on the average significant at the 70 percent level.

(3) Only small variations in the pavement surface elevations were detected by the optical level surveys. Structural distress was not indicated by these observations.

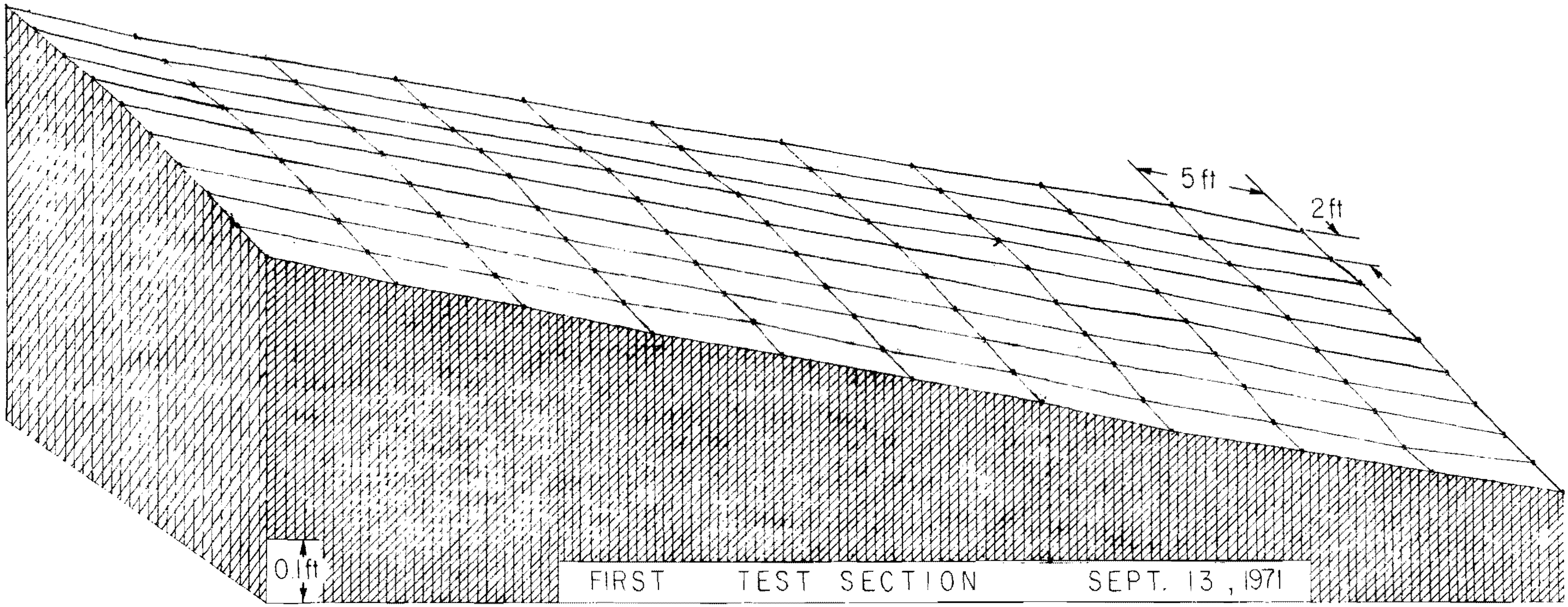


Fig 7.2. Three-dimensional plot of first dynamic loading zone surface profile at start of testing program.

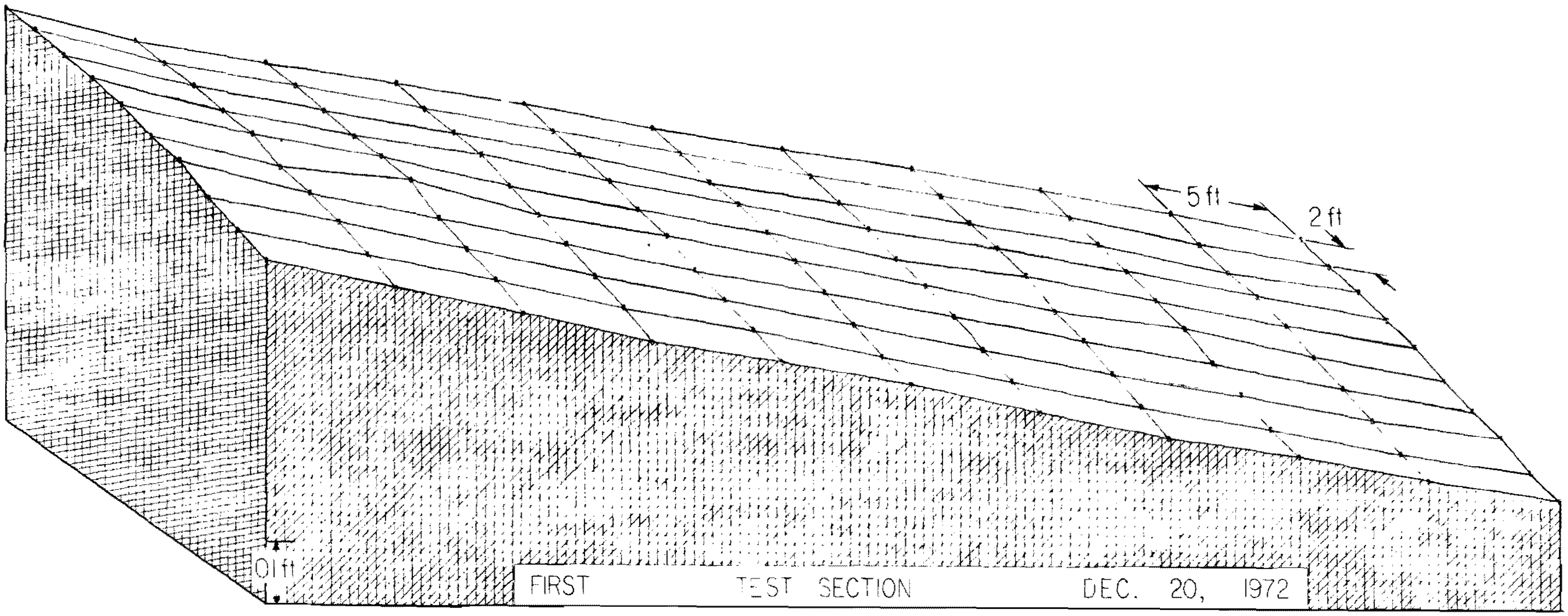


Fig 7.3. Three-dimensional plot of first dynamic loading zone surface profile at conclusion of testing program.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

The objectives of this research study included the development of a technique for summarizing the cumulative dynamic traffic loading experience of a highway pavement and the development of a field procedure for monitoring all traffic parameters necessary for such a summarization process. In conjunction with these objectives, an investigation into the state of pavement stress created by dynamic vehicular loading was to be conducted and the relative destructive effects of dynamic vehicular loading were to be demonstrated in a field experiment.

Conclusions

A practical technique for summarizing and displaying the cumulative dynamic wheel loads which occur along a defined roadway profile as the result of mixed traffic has been developed, an an example of the technique utilizing representative field data has been presented. The steps involved are as follows:

(1) Classify all traffic (observed or forecast) according to the five vehicle classes that are defined in Chapter 2.

(2) Group all vehicles into gross vehicle weight classes.

(3) Determine the distribution of gross weight among axles.

(4) Determine the number of mathematical models required to represent the traffic.

(5) Obtain road profile information

(6) Select the speed or speeds to be used for modeling.

(7) Compute the dynamic loading profile.

(8) Determine the critical loading zone.

This traffic analysis procedure makes it feasible to compare the magnitude and location of the cumulative dynamic wheel forces with the accumulated static wheel loads that have been, or will be, applied to any selected section of a highway pavement or bridge. The technique is versatile and practical.

A hardware system and the supporting software needed for obtaining field traffic data to characterize vehicles in a mathematical vehicle model was developed and used in the study for over 20 months with virtually no downtime. Information recorded on punched paper tape includes vehicle speed, wheel weights, axle spacings, and time of day. Samples of traffic data can be obtained at reasonable cost for any desired period of time with this data collection and recording system.

The traffic loading patterns that result from consideration of dynamic wheel forces make it possible to compare the stresses and strains that a pavement structure experiences when the surface is smooth and when it is rough. Evaluation of one surface profile subjected to mixed traffic indicated that even small surface irregularities caused substantially higher dynamic loads and therefore larger stresses than would result from the same traffic operating on a smooth road.

The accelerated destructive effects of dynamic traffic loading were demonstrated to a limited extent in a controlled field experiment. Two ramped surface bumps only 3/4-inch high, 18 inches long, and 70 inches apart on an otherwise smooth road caused truck drivers to reduce speed and complain considerably. Dynaflect measurements made on smooth control sections and on the impacted sections beyond the bumps after some 25,000 loaded trucks had passed showed significantly larger pavement surface deflections in all sections after traffic than before. Deflection changes in the dynamically loaded sections were somewhat larger than those in the control sections.

Recommendations

Experience with the traffic summarization technique for a variety of conditions is needed. Evaluation of different types of traffic and roadway surface conditions that are known to create premature structural distress should be made so that realistic traffic loading parameters can be correlated with this experience and then used in analyzing future designs.

Traffic loading conditions are only part of the input to the structural design process. Practical techniques for evaluating the stress-strain behavior of materials under representative dynamic loading are needed, and stress distribution theory which incorporates loading rate, stress level, and inertial consideration needs to be formulated and reduced to practice. The traffic analysis procedure outlined herein serves as one potentially useful tool for working on this complex problem.

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