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16. Abstract

This report describes CTR Study 1246, which proved to be very dynamic, in that the initial objectives were not only met, but they were followed up by new objectives. This was due to decisions taken by the project steering committee during the execution of the project. Following initial exploratory studies in 1988, the Texas SDHPT initiated the present study through which a strategy for the acquisition of a mobile accelerated pavement testing device had to be developed.

Initially, the study focussed on e feasibility of accelerated testing and the need for it in Texas. As part of the initial study, the relationship of accelerated testing to overall pavement engineering was reviewed in detail. Once the feasibility had been illustrated, the objectives were redirected to the acquisition of a mobile accelerated pavement device.

The different available methods and machines were evaluated, and subsequently the Mobile Load Simulator (MLS) was selected for future application on pavements in the state of Texas. The decision was based on the higher degree of traffic simulation attainable through the proposed MLS in comparison to the South African Heavy Vehicle Simulator (HVS) and the Accelerated Loading Facility (ALF). The latter was developed by the FHWA in 1984 and is based on the Australian patented ALF.

The MLS is based on a provision patent by Dr. Frederick Hugo. To evaluate the workability and feasibility of the development, a ten to one scaled model was constructed. A theoretical study was done to assess the degree of real traffic simulation of the full-scale prototype. Factors that were evaluated in the study included speed, dynamic loading of the pavement, and deflection and stress analyses for proposed axle configurations. Based on these results, recommendations for the mechanical design of the MLS were made. A theoretical comparison was also made between stresses and deflections obtained with the model MLS loads on a model pavement and values obtained with the full-scale MLS loads. Excellent comparison was found.

The operational impact of the MLS test program in the Texas situation was evaluated and recommendations for immediate and future application were made. Estimates of development and operational costs were done without having the benefit of an operational prototype of known production rate. The problem was somewhat alleviated by the availability of information on existing accelerated pavement testing facilities.

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mobile accelerated pavement testing device, Mobile Load Simulator (MLS), pavements, loading, simulation, speed, deflection, stress, prototype, model

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by

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Research Report Number 1246-2F

Research Project 3-10-90-1246

Development of Strategy for Acquiring and Using Mobile Load Analysis Simulator

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the

U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
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THE UNIVERSITY OF TEXAS AT AUSTIN

November 1990

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the State Department of Highways and Public Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

This is the first report on accelerated pavement testing in the state of Texas.

The study was conducted by the Center for Transportation Research and was sponsored jointly by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration under an agreement with The University of Texas and the Texas State Department of Highways and Public Transportation.

The 10-to-1 scale model of the Mobile Load Simulator (MLS) was designed and constructed at the University of Stellenbosch under the guidance of Dr. Fred Hugo, holder of a provisional patent on the MLS. Appreciation is due to that team for their prompt engineering of the model.

With the completion of Project 1246, the first phase of the Texas MLS program will have been completed. The design and manufacture of a prototype MLS is the next phase of the program.

ABSTRACT

The report describes a study which proved to be very dynamic, inasmuch as the initial objectives were not only met, but were followed up by new objectives. This was due to decisions made by the project steering committee during the execution of the project. Following initial exploratory studies in 1988, the Texas SDHPT initiated the present study, through which a strategy for the acquisition of a mobile accelerated pavement testing device could be developed.

Initially, the study focused on the feasibility of accelerated testing and the need for it in Texas. As part of the initial study, the relationship of accelerated testing to overall pavement engineering was reviewed in detail. Once the feasibility had been illustrated, the objectives were redirected to the acquisition of a mobile accelerated pavement testing device.

Different available methods and machines were evaluated, and subsequently the Mobile Load Simulator (MLS) was selected for future application on pavements in the state of Texas. The decision was based on the higher degree of traffic simulation attainable through the proposed MLS in comparison with the South African Heavy Vehicle Simulator (HVS) and the Accelerated Loading Facility (ALF). The latter was developed by the FHWA in 1984 and is based on the Australian-patented ALF.

The MLS is based on a provisional patent by Dr. Frederick Hugo. To evaluate the workability and feasibility of the development, a 10-to-1 scale model was constructed. A theoretical study was done to assess the degree of real-traffic simulation of the full-scale prototype. Factors evaluated in the study included speed, dynamic loading of the pavement, and deflection and stress analyses for proposed axle configurations. Based on these results, recommendations were made for the mechanical design of the MLS. A theoretical comparison was also made between stresses and deflections obtained with the model MLS loads on a model pavement and values obtained with the full-scale MLS loads. Excellent comparison was found.

The operational impact of the MLS test program in Texas was evaluated, and recommendations for immediate and future application were made. Estimates of development and operational costs were done without the benefit of an operational prototype of known production rate. The problem was somewhat alleviated by the availability of information on existing accelerated pavement testing facilities.

SUMMARY

Accelerated pavement testing provides the pavement engineer with a valuable tool for the refinement of pavement engineering technology, which has been shown worldwide to yield substantial benefit/cost ratios. Accelerated pavement testing is therefore proving to be a logical step in pavement engineering, stemming from the need for fast and reliable pavement performance results.

Following initial exploratory studies in 1988, the Texas SDHPT initiated the present study, through which a strategy for the acquisition of a mobile accelerated pavement testing device was developed. The report describes this study, which proved to be very dynamic inasmuch as the initial objectives were not only met, but were followed up by new objectives. This was due to decisions made by the project steering committee during the execution of the project.

Initially, the study focused on the feasibility of accelerated testing and the need for it in Texas; subsequently, the objectives were redirected to the acquisition of a mobile accelerated pavement testing device.

All available methods and machines were evaluated, and subsequently the Mobile Load Simulator (MLS) was selected for use on pavements in the state of Texas. The decision was based on the illustrated improvement of the South African Heavy Vehicle Simulator (HVS) and the Accelerated Loading Facility (ALF). The latter was developed by the FHWA in 1984 and is based on the Australian-patented ALF.

The MLS is based on a provisional patent by Dr. Frederick Hugo. To evaluate the workability and feasibility of the development, a 10-to-1 scale model was constructed. A theoretical study was done to assess the degree of real-traffic simulation of the full-scale prototype. Factors studied included speed, dynamic loading of the pavement, and deflection and stress analyses for proposed axle configurations. Based on the findings, recommendations were made for the mechanical design of the MLS. A theoretical comparison was also made between stresses and deflections obtained with the model MLS loads on a model pavement and values obtained with the full-scale MLS loads. Excellent comparison was found.

The operational impact of the MLS test program in Texas was evaluated, and recommendations for immediate and future application were made. A project for the development of the full-scale MLS began in September 1990.

IMPLEMENTATION STATEMENT

The recommendations made in this report are serving as guidance for the implementation of the Texas accelerated pavement testing program using the Mobile Load Simulator (MLS).

The first step in this process has already been taken with the structuring of a project for the design and manufacture of a prototype full-scale MLS testing machine. It is expected that tests will be completed within 24 months.

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CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

Complexities in pavement engineering and the beneficial results obtained with accelerated pavement testing devices have led authorities to conclude that these devices are necessary tools in pavement engineering. All over the world, provision for accelerated testing is made in one form or another, from plate loading devices to full-scale test tracks. This new commitment is easily understood when one considers the investment in pavement structures and the need for testing them in a cost-effective way.

Following initial exploratory studies in 1988, the SDHPT initiated the present study, through which a strategy for the acquisition of a mobile accelerated pavement testing device could be developed by the Center for Transportation Research at The University of Texas at Austin. A steering committee was created to guide the development of the project. The composition of the steering committee is set out in Appendix A.

The study focused on the feasibility of accelerated testing and the need for it in Texas; however, once the feasibility had been illustrated, the objectives were redirected to the acquisition of a mobile accelerated pavement testing device.

1.2. OBJECTIVES OF THE STUDY

The prime objective of the study was the formulation of a strategy for acquiring, operating, maintaining, and managing a load simulator machine or machines to satisfy the needs of the SDHPT, with due consideration being given to the following:

(1) the role of accelerated pavement testing (APT) and mobile load simulators in pavement engineering, the pavement management system, and research, using the systems approach;
(2) the ability of the presently used simulator machines to satisfy the needs of the Department;
(3) the feasibility of developing a new generation of mobile load simulating machine(s) to overcome some of the shortcomings of the presently-used machines, such as limitations on the number of load applications per day and use of partial axle systems;
(4) the anticipated operational needs and running cost of an accelerated pavement testing system; and
(5) recommendations for follow-on phases after completion of the present study.

The project was very dynamic; its objectives and achievements were reviewed by the steering committee during and throughout the execution of the project.

1.3. METHODOLOGY

The steering committee was formed under the chairmanship of the Deputy Director of Design and Construction of the SDHPT, with representatives from D-8, D-9, D-10, and the FHWA. The steering committee guided the development of the investigation and made decisions concerning the priority of topics to be investigated, thereby ensuring that the necessary cooperation and integration took place between the SDHPT and CTR. The project was developed in consecutive phases.

Phase 1 established a strategic plan and addressed specific questions related to pavement engineering as well as to the feasibility of developing a new generation of mobile accelerated pavement testing devices, since it was apparent that existing machines have some inherent qualities which can be improved upon. Some of the most important factors concerning this issue are:

(1) the necessity for the present machines to use an overloaded wheel to accelerate the load application;
(2) the inability to actually model multi axles;
(3) the possibility of reducing the cost of construction of APT machines and the subsequent maintenance of such; and
(4) the possibility of narrowing the width so that the use of the machines on heavily-trafficked pavements will become more feasible.

In Phase 2, alternative options were considered. The first option was to develop a prototype of the proposed new Mobile Load Simulator (MLS) and to thoroughly test the machine to ensure that all the necessary information for developing or purchasing a full-scale machine was obtained. The second option was to purchase or manufacture one of the existing APT machines for utilization in Texas. Decisions about these options were made by the steering committee, based on recommendations by CTR after all aspects of the project had been studied.

1.4. DETAILS OF THE RESEARCH PROGRAM

The topics considered in the study were:

(1) a survey of existing APT devices;
(2) the immediate benefits to be gained by the use of existing APT devices;
(3) the number of APT devices required to satisfy the Department needs;
(4) the impact on the use of mobile APT devices on traffic operations;

(5) the feasibility of developing a new generation of APT devices;
(6) the benefits to be gained from such a development;
(7) the viability of simulating and accelerating environmental affects in conjunction with load acceleration;
(8) the availability of data acquisition systems and the most suitable subsystem for the Texas situation;
(9) the extent and need for concurrent related tests which have to be done in conjunction with accelerated pavement testing;
(10) the determination of circumstances which necessitate the use of a mobile APT;
(11) possible short and long-term strategies to be followed with the use of specially-constructed test sections and/or existing pavements;
(12) the anticipated cost of purchasing or manufacturing one of the presently-existing mobile APT devices for the SDHPT; and
(13) the anticipated cost to operate and transport a unit of the existing APT devices in the Texas environment.

1.5. ORGANIZATION OF REPORT

Apart from the introduction in Chapter 1, the remainder of the report is set out as follows.

Chapter 2 presents an overview of pavement testing and discusses the role of APT relative to other pavement evaluation methods. Factors to be borne in mind in the selection of a range of methods for acquiring pavement knowledge are discussed on a conceptual basis.

Chapter 3 reviews accelerated pavement testing devices ranging from impulse loading devices to full-scale test tracks. Worldwide examples of the beneficial application of some of the testing methods are discussed and listed.

In Chapter 4, conceptual future applications for accelerated pavement testing methods are discussed.

In Chapter 5, the decision by the Texas SDHPT to proceed with the acquisition of a mobile accelerated pavement testing machine is explained and further discussed. The three options for mobile accelerated pavement testing machines (ALF, HVS, MLS) are discussed and evaluated, and the design of the MLS – the selection of the SDHPT – is further evaluated. Data acquisition systems that are to be employed in conjunction with MLS pavement testing are discussed under items such as measurements, instrumentation, and data synthesis.

Chapter 6 discusses the characteristics of wheel loads and the detailed knowledge required by both the developer and the experimenter using the MLS to apprehend these characteristics. An overview of pavement stresses is presented. Regulations governing axle loads and truck dimensions are discussed. Suspension components that affect the dynamic loading of pavements are evaluated.

Chapter 7 evaluates the proposed design of the prototype MLS for accuracy of traffic simulation. The effects of machine speed and following distances of bogies are evaluated against real conditions. Recommendations for the design of the prototype are made.

Chapter 8 discusses the projected impact on the Texas situation stemming from the implementation of MLS testing. Issues affecting the operation and determination of the program size are considered. Two brainstorming sessions on accelerated pavement testing are discussed in this chapter. The first one was held in 1988 to determine the feasibility of accelerated pavement testing. The second was held in October 1990 to establish the specific needs for the accelerated pavement testing program in Texas and also to determine the need for accelerated environmental simulation in the program. These brainstorming sessions will serve as the basis for development of a global test program in which accelerated pavement testing and accelerated environmental simulation play important roles.

In a final overview, Chapter 9 assimilates and discusses the conclusions and recommendations of the study.

CHAPTER 2. PAVEMENT TESTING IN PERSPECTIVE

2.1. AN OVERVIEW OF PAVEMENT TESTING

To link pavement performance and the theoretical models predicting the performance of pavement materials, certain tests are performed. The challenge to engineers and researchers is to accurately model the behavior of pavement materials with the aid of such testing. Faced with the vast number of variables that affect the stress-strain relationships of materials, a repeated process of design, design implementation, performance evaluation, and re-design is used to improve longevity of pavement facilities. This is accomplished by observing pavement behavior over time when the material is subjected to a set of conditions. The results are then used to improve the mixture design and, therefore, the effective physical material properties necessary to resist certain modes of failure—i.e., rutting or subbase pumping. The same method is also used to obtain optimum structural combinations, or balanced pavement structures, by determining the layer thicknesses that would not allow overstressing in any particular layer.

Use of so-called Mechanistic Design Procedures provides engineers with a well-established method for effective pavement design. In the mechanistic-empirical methods, theoretical models are used to analyze stress, strain, and deformation (response or behavior) for given loadings in a pavement structure, whereas the development of roughness, rutting, and cracking (performance) is empirically related, or calibrated, to the response. The object is to model the pavement behavior through transform functions as a multi-layered elastic or visco-elastic structure. These models will be subject to a certain degree of uncertainty stemming from inexact descriptions of the input variables such as traffic, environment, subgrade properties, and material characteristics. Researchers recognize that pavement performance prediction will likely also be influenced by a number of factors which were not included in the models, or not accurately modeled by mechanistic methods; thus the necessity of calibration. Many comparisons have been made in the past between calculated and measured values, and most of these comparisons have been found acceptable. Poor relationships can often be the result of omitted or inaccurate measurements of pavement behavior which, in the latter case, can be blamed on instrumentation. Also, it may be that the modeling was incorrect, which necessitates large shift factors.

Mechanistic-empirical relationships should be capable of predicting the rate of both functional and structural deterioration at a specific time in the future. The most commonly used relationships are based on two factors:

(1) tensile stress or strain at the bottom of bound layers, to predict structural deterioration in terms of cracking; and
(2) compressive stress or strain at the top of unbound material to predict functional deterioration in terms of increased roughness or rutting.

Distress criteria include fatigue cracking, thermal cracking, frost effects, reflection cracking, faulting, punchouts, et cetera.

There are many test methods by which the calibration of models is accomplished, and the reliability, duration, and costs of these methods encompass a wide range. The methods can be categorized into the following groups:

(1) computer simulation,
(2) direct sampling methods and laboratory testing,
(3) non-destructive evaluation or field testing,
(4) test roads,
(5) accelerated pavement testing, and
(6) condition monitoring of in-service pavements.

Depending on the availability of funding for these methods, existing mechanistic models are used, material samples are tested, or the total pavement can be evaluated. In Fig 2.1, these methods are shown graphically in their respective ranges of contribution to the sum total of pavement engineering knowledge, and how this has changed since the 1930's. In Fig 2.2, the cost associated with the range of utilization is related to the degree of reliability of the knowledge to be gained through the use of that method.

From this diagram it will be apparent that:

(1) knowledge is gained only after a minimum investment has been made, and
(2) the initial investment in any test method yields an increase in knowledge only after it is augmented with further investment.

Figure 2.2 also shows how a specific investment impacts a specific portion of technology related to the test method and application. Collectively, the acquired information yields pavement engineering knowledge.

In a very comprehensive analysis of the state of the art during the Fifth International (Ann Arbor) Conference on the Structural Design of Asphalt Pavements 1982 (31), the following statements were made:

> "Modern theoretical models now appear to be capable of providing suitable predictions, this to a better extent for bituminous-bound materials than for soils and unbound granular materials."

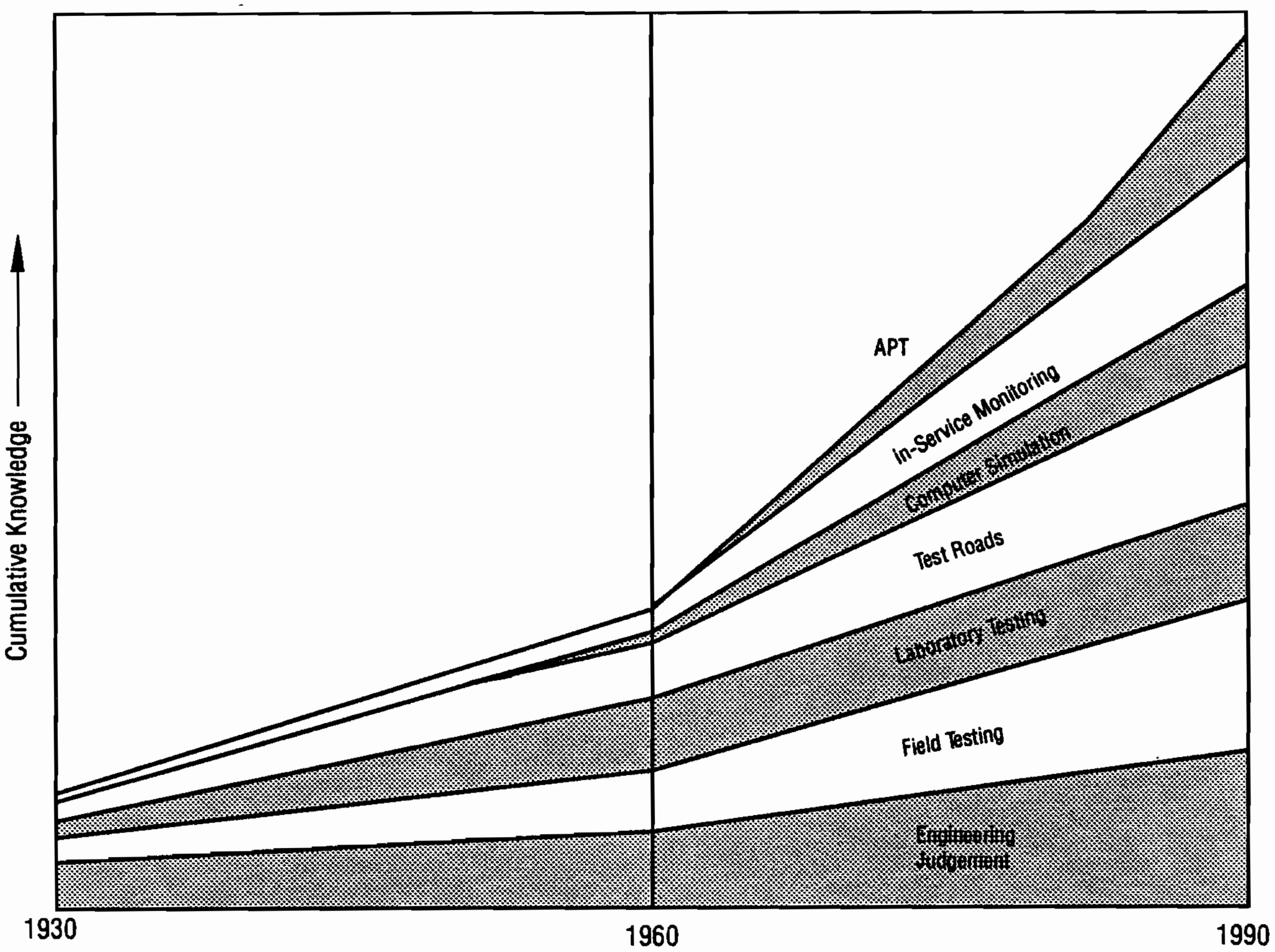


Fig 2.1. The utilization of various methods to gain knowledge in pavement engineering over the last sixty years.

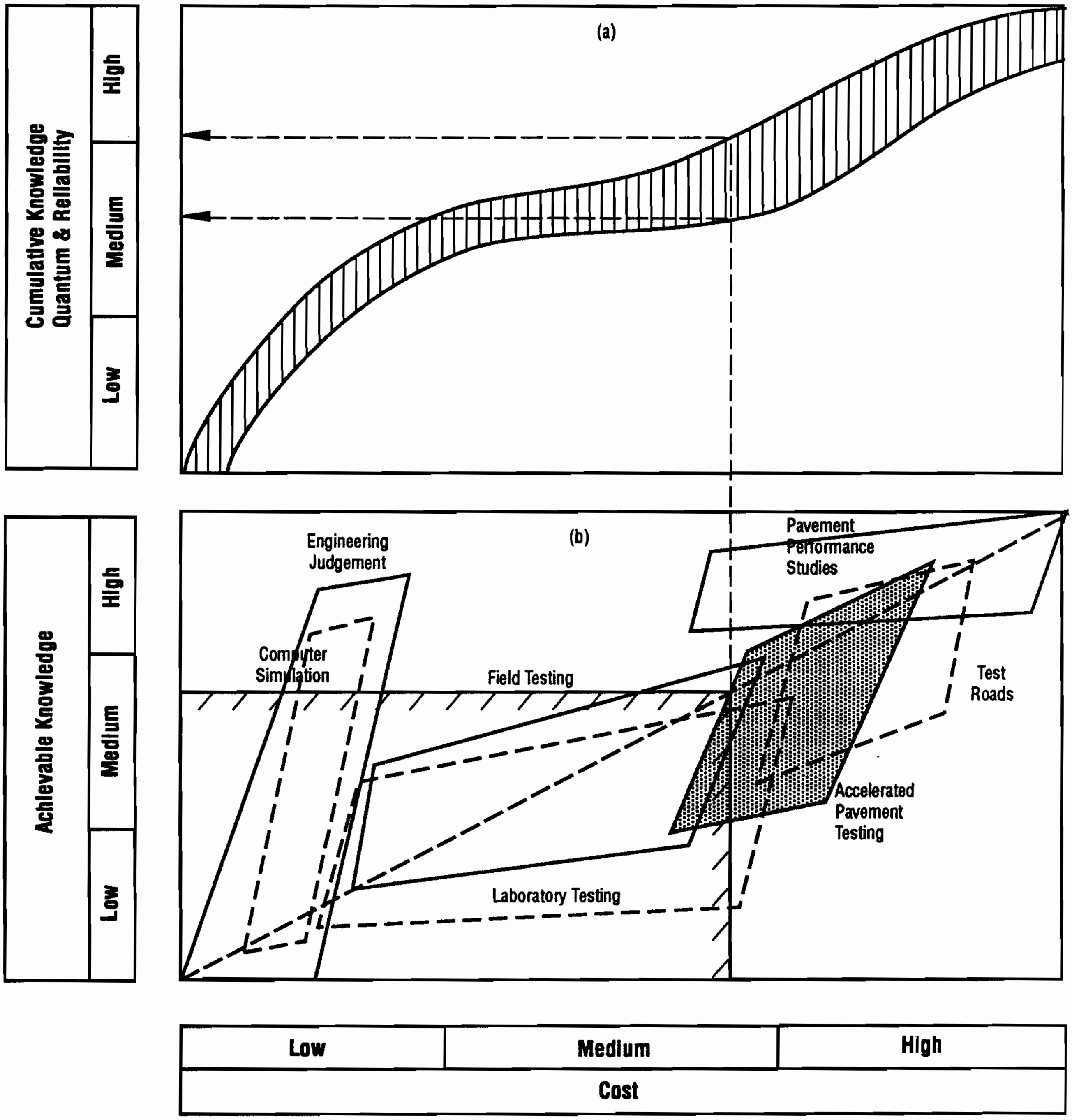


Fig 2.2. Financial investment capabilities and associated achievable knowledge.

> "These good predictions are part of what is defined as the 'calibration' work for the development of a pavement model. On the other hand there is still a greater need for true verifications on pavements completely different from those used for establishing the calibrations of the models."

The major objective of the Fifth Conference was the presentation of methods for structural design, with emphasis on concepts for rehabilitation and management of pavements.

In order to evaluate the changes in the state of the art, the purpose of the Sixth International Conference on the Structural Design of Asphalt Pavements, in 1987, was to promote presentations of the latest developments in the analytical or mechanistic methods for the design of new pavements, reconstruction of existing ones, and strengthening of overlays. Results from destructive or non-destructive pavement tests on full-scale pavements and their use for model verification and design developments were particularly encouraged. The scope of the Conference included recycling of materials, material characterization, and vehicle loading. Presentations on pavement management included design-related economic considerations with emphasis on specific applications as opposed to general concepts.

It was found (21) that even though pavement evaluation techniques had received increased attention since the previous conference, there remained various gaps which needed to be addressed. The areas related to this study included:

(1) development of evaluation techniques that are uniform and transportable across agency boundaries,
(2) determination of the effect of the time of year on measurements, and
(3) improvement of the speed and productivity of evaluation techniques.

Furthermore, it was stated that "the relationship between measured long-term pavement performance, performance prediction, and accelerated testing needs to be established," and that "long-term pavement performance information will provide a greater confidence in the results. Accelerated testing, either using machines such as the HVS or ALF, or through concentrating heavy traffic on specially constructed sections, will enable timely evaluations of predicted performance" (21).

2.2. TEST FACTORS THAT PROVIDE THE BUILDING BLOCKS OF PAVEMENT ENGINEERING

Many factors affect the behavior of pavement structures under load and environmental conditions. A list of the most important ones is contained in Table 2.1.

TABLE 2.1. TESTING FACTORS FORMING THE BASIS OF ENGINEERING KNOWLEDGE

Material and Constuction

1) Material Layer System
2) Micro Material Structure
3) Material Anisotropy
4) Subgrade Compaction
5) Subgrade Stiffness
6) Subgrade Plastic Behavior
7) Friction Between Layers
8) Application of Rejuvenators
9) New Materials/Mixtures
10) D-Cracking
11) Construction Variation
12) Flexible Bases
13) Lime Treated Bases
14) Cement Treated Bases
15) Recycled Asphalt

Structural Factors

1) Structural Systems
2) Voids Beneath Concrete
3) Effect of Shoulders
4) Balanced Structural Composition

Environmental Factors

1) Surficial Water (Artificial)
2) Sub-Surface Water
3) Artificial Environment and Accelerated Load
4) Wind
5) Temperature
6) Humidity

Peripheral Pavement Engineering

1) Traffic Monitoring Devices
2) Durability of Road Markings
3) Effects of Gradients
4) Tire Types

Pavement Management and Performance

1) Maintenance Strategies
2) Rehabilitation Strategies
3) Load Transfer in Joints
4) Percent Steel
5) Stripping of Asphalt
6) Rutting
7) Skid Resistance
8) Wear of Aggregate
9) Steel Concrete Bond
10) Concrete Joint Behavior
11) Fatigue Cracking
12) Structural Condition
13) Surface Condition
14) Residual Life
15) Delamination
16) Pavement Performance (PSI)

Load Factors

1) Vehicle Speed
2) Dynamic Wheel Loads
3) Multi-Axle Loads
4) Actual Traffic Loads
6) Selected Traffic Loads
7) Selected Tire Type
8) Selected Tire Pressure
9) Lateral Load Distribution
10) Axle Equivalancy
11) Suspension Type
12) Overloads

These factors are grouped in six categories as follows:

(1) material and construction,
(2) pavement management and performance,
(3) structure,
(4) load,
(5) environment, and
(6) peripheral components.

Most problems experienced in pavement engineering today can be related to the factors contained in Table 2.1. This table is featured again later in this report, to evaluate the applicability of various accelerated test methods for improving these aspects of pavement engineering.

Although these areas are well-known to pavement engineers in 1990, their extent has only gradually become known during the growth of pavement engineering over the past sixty years. During this period, the challenge of the design and construction of pavements has been met with the best available tools at any specific time. As with other fields of engineering, these methods have grown extensively over the past sixty years. This growth is graphically depicted in Fig 2.1.

In 1930, most of the problems were solved by three basic tools: engineering judgement, field trials and observations, and very limited laboratory experimentation (Casagrande). Essentially, the physical characteristics of the materials were used primarily to compare materials. In this way it was possible to relate successful field experience to new areas of application.

Industrial and transportation developments that resulted from the two World Wars led to new demands of pavements and especially airfields. By the 1960's, a number of techniques were used to predict pavement performance to make possible the construction of pavement structures that would meet the new demands. The introduction of the computer in this era made a dramatic impression on the collective engineering knowledge base. Computer analysis was still very expensive to use, but the analysis of pavement structures was soon to become feasible. Extensive material sampling and testing was done in laboratories, and a number of test roads were constructed. The costly results from test roads such as the AASHO Road Test were being analyzed and put into use, resulting in the development of valuable pavement engineering concepts such as PSI and equivalency. Structural aspects, such as the CTB to reduce the effect of pumping, were established.

The road tests introduced to pavement engineers the concept of accelerated testing . Accelerated pavement testing exists in many forms in which the rest periods of the pavement are reduced and/or overloads are used. The AASHO Road Test is an example of accelerated pavement testing employing real loads with trucks. The construction of test roads as a method for accelerated testing was soon proved to be cost-prohibitive; moreover, results obtained were limited in geographical application and extrapolation. However, pavement engineers accepted the concept of accelerated pavement testing as a method to establish fast and reliable predictions of pavement performance. By the early 1970's, developments in heavy machinery manufacturing led to the development of mobile accelerated test machines that utilize simulated traffic loading such as the HVS in South Africa, and, later, the ALF in Australia.

Another method to gain knowledge of pavements was first established in a widely encompassing and structured fashion in the mid-1980's. Traditionally known as performance observations, data have always been collected in data bases of various sizes, ranging from county data bases to statewide data bases. However, a combined data base for the U. S. was established in the 1980's as part of the Strategic Highway Research Program, and was named Long Term Pavement Performance Studies. It is generally considered to be the ultimate testing method in which the real loading condition (traffic and environment) of the pavement is evaluated in real time.

All the test methods shown in Fig 2.1 have been used to various extents by pavement agencies to obtain the necessary knowledge of pavement performance. In the study of the feasibility of simulated accelerated pavement testing in Texas, it was necessary to examine the factors shown in Table 2.1 to determine to what extent accelerated pavement testing would be able to evaluate these factors. Such an evaluation would play an important role in establishing the need for accelerated pavement testing as well as a long-term test program. Table 2.1 was used to develop a number of tables with dependent and independent test and experimental variables. These tables were used in a 'brainstorming' session in October 1990 to determine relative weights of factors to be evaluated through an accelerated pavement testing program. A full description, the findings, and an analysis of the survey are contained in Chapter 8.

2.3. CONSIDERATIONS IN THE SELECTION OF A RANGE OF DECISION TOOLS TO SATISFY THE NEEDS OF AN AGENCY

The range and types of decision tools selected to provide an agency with the knowledge to design, construct, and manage highways, depends largely on the agency's ability to finance a particular combination of systems. Decision tools available to engineers are mapped out in Fig 2.2 relative to cost and knowledge associated with each method. As indicated by Fig 2.2b, a selection of a certain range of methods should encompass all the methods to the left of the affordable cut-off, and below the horizontal line going out from the intersection with the turn line. The shape of the turn line in Fig 2.2b (shown to be straight) depends on a number of factors, such as labor costs and technological development, which vary from agency to agency. The shape of the turn line in Fig 2.2b also determines the position of the s-curve band shown in Fig 2.2a. The s-curve is obtained from a summation of the enclosed test method areas in Fig 2.2b. The band is shown to represent a range of knowledge that stems from a high or low utilization of the test methods.

Engineering judgement forms an important part of any selection and is supplemented by the other methods in various degrees. It is well-known by engineers that materials will fail at a certain time, when the accumulated stress exceeds the strength. In the low cost range, experience is often used to determine the specific weakness(es) or failure criteria that led to the progressive loss in serviceability. This information is then applied to the design of a new system that will withstand the expected conditions better than the previous condition. In other words, each material has a certain strength or resistance limit when subjected to cycles of certain combinations of stresses. Overall, the objective is to balance the strength characteristics in the pavement structure on the basis of load stress, temperature stress, and moisture stress limits of the material layers. This must be done as inexpensively as possible. Many agencies rely solely on this knowledge to provide a pavement infrastructure, which may be the only affordable method, but is also one which answers adequately the needs of the agency.

However, in order to increase the dependability of a pavement system, more reliable methods must be used to support engineering decisions. A range of methods can be utilized to provide the engineer with better information about the likelihood of distress occurrences. After the selection of a distress criterion, a plan must be developed and equipment acquired to obtain the necessary information, such as moduli that would relate the distress criteria to pavement performance. Computer simulation is shown to be an inexpensive evaluation method in Fig 2.2; however, obtaining accurate data and deriving or improving the models for higher reliability in computer modeling is relatively expensive.

Laboratory testing appears in a large range of costs with a small increase in reliable knowledge. The so-called one-way testing method is usually utilized, where all variables are kept constant except for the one to be evaluated, such as in stabilometer testing of asphalt concrete mixtures where only the asphalt content is varied. Field testing can range from simple penetration tests to obtaining undisturbed samples for testing in the conventional manner in a laboratory. Field testing attempts to evaluate changes in the pertinent properties that occurred because of environmental and traffic influences, which can be either in-situ destructive or non-destructive testing and evaluation. It may also include short-term evaluation of behavior, such as early-age cracking of PCC pavements and static load-deflection measurements. The objective is to evaluate more of the system so that the field-effective parameters can be utilized in the analysis of pavement behavior.

Accelerated Pavement Testing (APT) is utilized in many forms to provide the information necessary to develop and evaluate distress criteria. This method has increased in popularity in the last twenty years owing to the high benefit/cost ratios attainable and to the method's ability to test pavement responses not otherwise possible.

Accelerated simulated traffic cannot fully account for real traffic because of the low speeds of some methods. Furthermore, it can only partially evaluate environmental influences by testing at different environmental situations for the same structure. The aging/hardening effect that is retarded by the kneading action of traffic cannot be evaluated unless it is done artificially. Accelerated testing of materials can be done by a variety of methods to shorten the life of facilities or hasten their degradation during utilization. The aim is to obtain data quickly which, when properly modeled and analyzed, give desired information on the life or performance of the facility under normal use so that time and money are saved. This report describes the implementation of accelerated pavement testing in the state of Texas.

Test methods that utilize test tracks, such as the AASHO Road Test, also accelerate the testing process, but higher vehicle speeds are attainable, which make the test method more representative. However, these methods involve high cost and, therefore, there are limitations on the number of environments and subgrades that can be evaluated. On the far right of Fig 2.2, "pavement performance studies" present the researcher with the full spectrum of elements at the highest cost and highest degree of difficulty of implementation.

An FHWA-sponsored pavement testing conference (36) concluded that a national pavement testing program is needed together with a rehabilitation program which requires early answers. Simultaneously, a long-term nationwide in-service pavement monitoring system needs to be introduced using both existing and new pavements with untrafficked loops. Accelerated pavement testing using vehicle simulators and laboratory testing must be employed to provide fast answers which must be calibrated against long-term performance of pavements.

The purpose of materials testing, as mentioned before, is to gain knowledge of the field effective parameters of the materials in the pavement system. Accept for engineering judgement, that forms part of any selection, methods on the left hand side of Fig 2.2, estimate parameters without interaction of other variables. To the right, increased interaction of the variables are experienced. Methods to the right, therefore, utilizes better experimental design due to the increased variance of indicators. The disadvantage of these methods is their high cost, which limits the numbers of systems that can be evaluated. However, it is evident that none of the methods is the final solution and that all the methods should supplement one another.

2.4. FACTORS THAT AFFECT THE PRACTICALITY AND RELIABILITY OF TEST METHODS

A number of issues must be borne in mind when a selection of a range of test methods is made. Full utilization of a test method may not be practical, and this will affect the statistical reliability of data when they are correlated with actual pavements.

2.4.1. PERFORMANCE, DISTRESS, AND FAILURE

As previously stated, each test method requires the selection of a distress criterion, according to which data are collected. Test data can be divided into two types, namely, structural life or integrity and functional performance. Structural data can be complete; that is, all specimens will have failed, or can be censored. "Censored data" is a statistical term defining readings taken during a finite period in the life of a product or facility. "Censored before testing" implies only that failure time is known to occur before a certain time. This is shown by failure criterion (FC) 3 in Fig 2.3.

"Censored after testing" indicates that some specimens have not failed by the conclusion of the test period (FC 2 in Fig 2.3). Singly-censored can be either time-censored, where testing is stopped at a certain time due to restraints (time and money), or failure-censored (FC 1), when certain failure criteria are met. Combinations of the above also exist. One may be interested in knowing how the product *performance* decreases with age, for which purpose the same types of data can be used.

An accelerated testing rate can be accomplished either by increasing the loading rate or by increasing stresses through larger loads. The assumption with increased rate of application is that the number of cycles to failure at high and normal usage rates are interchangeable. With pavement materials, this is usually not possible to do. Factors such as pore pressures and degrees of stress relief are important parameters determining material performance.

Overstress testing uses higher-than-normal levels of load to shorten the life or to hasten performance reduction. For economic reasons a combination of the above is often employed. In most tests, it is easier to maintain constant stress levels, because test models for constant stress are better developed and empirically verified for some materials.

Step-stress loading, as indicated in Fig 2.4, is often employed; it yields quick failures, but these failures do not guarantee more accurate estimates. A constant stress test with a few failures usually yields greater accuracy than a shorter step-stress test where all specimens fail. Total testing time determines accuracy, not the number of failures.

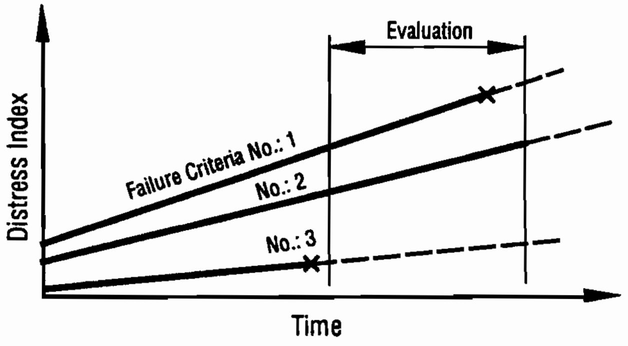


Fig 2.3. Constant stress versus step-stress performance.

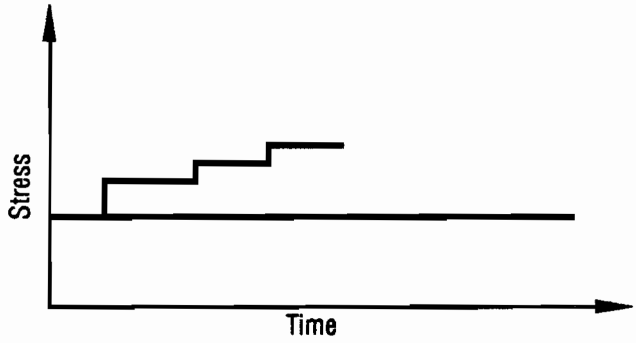


Fig 2.4. Typical theoretical performance curve versus actual curves.

Time to failure is the dependent variable in accelerated life testing, and thus failure must be precisely defined. Catastrophic failure is seldom encountered as far as pavements are concerned. Generally, user-defined failure is used in pavement performance. Engineer or management-defined failure is usually more conservative than user-defined failure. This is shown in Fig 2.5, where engineering failure would be represented by the typical performance curve.

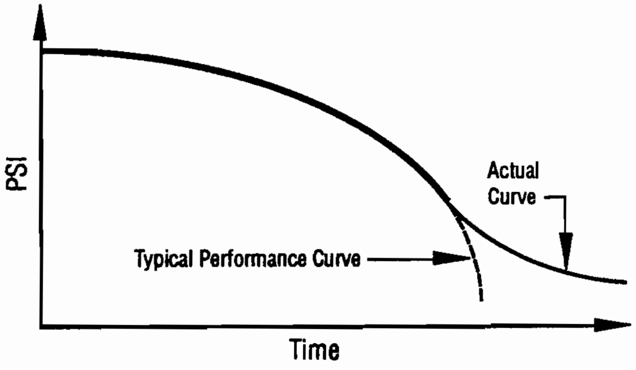


Fig 2.5. Engineer/management-defined failure curve versus user-defined failure curve.

2.4.2. *TEST SECTION OR TOTAL PAVEMENT LENGTH EVALUATION*

Test sections (specimens) differ from the total pavement, and these differences may not be obvious. The assumption is that the section life is comparable to or less than pavement life. Most of the time the pavement will provide more accurate answers because statisticians will acknowledge only that test sections yield estimates of section life. If a section is used, however, it must be a truly representative and/or random sample. Depending on what component needs to be evaluated, variables that affect the behavior can be kept constant, or specimens with extreme values of observed covariates may be chosen for a test. Advocated by Taguchi, among others (48), such a wide range of covariate values provides more accurate estimates of their effect.

2.4.3. *LABORATORY TESTING OF TEST SECTIONS OR EVALUATION OF PAVEMENTS UNDER ACTUAL USER CONDITIONS*

Test conditions should exactly simulate user conditions. Many tests differ from actual use but are still reliable. The level of reliability of these experiments is based mostly on experience and other correlations. It is assumed that a section which performs well on such a test will perform well in actual use. These so-called engineering tests or index tests are often just solving the better or worse state condition and give a rough but useful measure of performance in actual use. Thus, the question with accelerated testing is how well a test simulates actual use or whether it can be utilized only for comparative studies.

2.4.4. *VARIABLES*

Apart from stresses or strains as variables in the matrix, many other independent or explanatory variables, such as design, material, manufacturing, operation or test, and environment, will affect the behavior. A variable can be either (1) investigated at different levels to learn its effect; (2) held fixed; (3) varied uncontrolled to learn its effect (Taguchi); or (4) varied uncontrolled and unobserved. An uncontrolled, observed covariate is correlated with life or performance, which means that a cause-and-effect relationship between the covariate and performance is established. A significant covariate can be used to control behavior and a less significant covariate can be used to predict behavior. In most accelerated tests there are uncontrolled and unobserved variables which may be either negligible, unknown, or difficult to measure. Through randomization or standard specimens, the effects of consistency of test equipment, technique, and conditions are monitored.

2.4.5. *MEASUREMENTS*

Except when pavement life observations are made at discrete intervals and failure is known to have occurred only within that interval, pavement life is easily measured. Stresses cannot be measured directly, but can be derived from deformation measurements which can be written as strains in a stress-strain relationship. Measurements of variables need to be made with an accuracy that is sufficiently smaller than differences in variables between specimens.

2.4.6. *MODELS*

Models are based on experience and on physical theory, and they must be satisfactory over the ranges desired for the variables and must be selected before testing takes place. Frequently called the weak-link, extreme-value theory, the Weibull distribution is often used for product life, because it easily models either increasing or decreasing failure rates for products of various components.

2.5. CONCLUSION

To relate theory to performance, testing of pavements must take place. Mechanistic concepts relate behavior and performance through a transfer function. For example, stress is used in a fatigue model along with variability to predict area cracking. After this, calibration takes place to provide rational results. These mechanistic-empirical design procedures are used to predict total pavement structure performance. Many methods are used to calibrate these procedures, so that balanced pavement structures can be constructed.

In Chapter 2 it was stated that current models, to describe pavement behavior, are in an advanced state, but that current methods through which these models are to be calibrated are either lacking in their level of reliability or are too expensive to incorporate into the system of most agencies. Shown to be in the middle of these two extremes, full-scale accelerated pavement testing in its many forms has proved to present the optimum solution to the problem. However, a detailed knowledge of the factors involved in the selection of a range of pavement testing methods is required to fully benefit from the application of accelerated pavement testing in pavement evaluation. These factors are described in Chapter 2. This report mainly describes the process of implementation of accelerated pavement testing that utilizes vehicular simulation for the Texas SDHPT, and for this purpose a detailed study of existing facilities is made in Chapter 3.

CHAPTER 3. REVIEW OF EXISTING ACCELERATED PAVEMENT TESTING FACILITIES AND APPLICATIONS

3.1. INTRODUCTION

This chapter deals with the types of full-scale accelerated testing methods that are currently operational worldwide. Important applications and utilizations of accelerated pavement testing are also discussed. These applications have been documented in detail elsewhere.

The first section of the chapter is based on an OECD (Organization for Economic Cooperation and Development) report titled "Full-Scale Pavement Tests" (46), which was compiled from responses to a questionnaire by delegates to the OECD pavement group. An FHWA report that had been compiled from the Pavement Testing Conference held in March 1984 (36) was also reviewed.

The testing facilities presented here are those designed for studying problems associated with pavement design, i.e., those facilities having wheel loads in the typical range of trucks and operating on complete pavement structures. Subgrades can be either natural or imported. Lighter wheel load facilities, intended for studying the behavior of single layers, are not included.

3.2. EXISTING TESTING FACILITIES

Test facilities can be presented in four different categories, according to their design and method of load acceleration:

(1) full-scale test tracks,
(2) circular testing devices,
(3) linear testing devices, and
(4) impulse loading devices.

A common feature of the first three categories is the transmission of a load to the pavement through a rolling wheel, to give as close as possible a representation of real vehicle loads (full-scale test tracks incorporate actual vehicles). The fourth category uses a load applied through the use of one or more hydraulic jacks, with the load transmitted to the pavement surface through a steel plate. A common feature of the last three methods is the simulation of vehicle loads.

3.2.1. FULL-SCALE TEST TRACKS

This type of accelerated testing was used in the AASHO Road Test (1958-1961) and, before that, the Bates Experimental Road in Illinois (1920), the Maryland Test Road (1941), the WASHO Road Test in Idaho, and many other prototype pavements constructed by the FHWA and the US Army Corps of Engineers.

The OECD report on full-scale pavement testing (46) also lists test roads with controlled real vehicle loading, such as: the mile loop at Pennsylvania State University; the Public Works Research Institute in Japan, with automatically guided tracks; the Nardo Test Track in Italy, which utilizes a vehicle test track; the approximately 2-mile-long (3-km) Virtaa Test Field in Finland; and the eight instrumented test sections of the Alberta Research Council of Canada.

3.2.2. CIRCULAR TEST TRACKS

Due to the simplicity of operation and the high rate of load application achievable through the use of these facilities, circular test tracks are rapidly rising in popularity. Most of these test facilities make use of a loaded wheel assembly resembling a half-axle which tests a circular track with an expandable and foldable arm serving as the guide which rotates at the center of the circle, while the loaded wheel assembly is rotating around the circular track. Most of the smaller (less than 40-foot-diameter) facilities are housed in special buildings while the larger facilities are operated outdoors. The two methods of propulsion are providing rotation power either at the circle center or at the wheel in contact with the pavement. The speed range is up to 75 mph, and a production rate of more than 5,000 loadings per hour is achievable.

Although most test machines follow a half-axle concept for the loading and have single- or dual-tired wheels in single- or tandem-axle arrangement, some installations offer alternative options. The test track of the University of Karlsruhe simulates one-half of a two-axle truck, with one front wheel (representing the steering wheel) and a dual wheel behind it (the driving axle). Certain test facilities in eastern Europe also have arrangements with complete axles. These give rise to concern about the unnatural shear that develops between dual tires if both are driven. To compensate for this effect, only inside or outside wheels are powered. Innovative transmissions that provide the correct wheel speed at different radii can be provided by manufacturers, although most circular facilities operate without this option. Loads may reach 22.5 kips on dual tires or 34 kips on complete axles, where the loading is achieved using either a mass (ballast) or a hydraulic force on the smaller tracks. Some facilities use gradient or longitudinal shoving simulating methods. This is achieved by applying braking at the center point of rotation, thus requiring the driven wheel to work against the additional force. Most of the facilities provide a variable wheel slip angle, which is of value when cornering or tire wear effects are being studied.

All of these machines incorporate a system allowing transverse distribution of loading. This is achieved either through a central pivot on a planetary gear or through extendable arms.

Different test sections are built into the circular test track by dividing it into thirds and quarters, and these are loaded at the same rate, thus permitting a direct comparison of the behavior of these structures under the same environmental conditions. The type of equipment used for construction of the test pavements depends largely on the size of the facility. While manual construction is usual for smaller facilities, different construction machines of up to normal size may be used with increased radii of the track. Manufacturers of a circular type facility, the RTT Captif of New Zealand, have shown that the effect of the circular track becomes negligible at a radius above 46 feet.

Circular type facilities are excluded from application on as-built and in-service pavements to predict performance of a specific pavement section. Construction methods for these test tracks vary somewhat from real conditions, especially on smaller tracks. On the other hand, these facilities benefit from the fact that an accurately controlled environment, which also serves as noise pollution control, is provided by the enclosed housing on the smaller facilities. Questions arise as to the accuracy or ability to induce various environmental effects into the structure even under these controlled conditions. Instrumentation of the tracks is well developed and can be left in place due to the secure housing.

Depending on the size of the facility, a decision as to whether to ship roadbed material to the facility is often made. However, the effect of evaluating of materials in an environment different from that of the actual application must be taken into consideration. An extensive comparative table of circular test tracks is included in the OECD report titled "Full-Scale Pavement Tests" (46).

3.2.3. LINEAR TEST FACILITIES

Linear type test facilities come in a variety of shapes and sizes depending on their intended application. This will determine if the facility will be used at a fixed location, such as a laboratory, or if its intent is to evaluate in-service pavements, therefore requiring mobility of the facility. These types of machines achieves loading of pavements through rolling wheels which are loaded down and translated in a straight line across a section of pavement.

3.2.3.1. Fixed Location Test Facilities

Many testing centers, such as the Transport and Road Research Laboratory, have elected to build and construct linear testing facilities (43, 46) of practical dimensions. These facilities do not need as much room as circular test tracks and, therefore, benefit greatly from the ease of logistics and environmental simulation. Provided that the size and the accessibility of the housing are adequate, full-size construction equipment can be employed, which provides closer simulation of real conditions. Pavements are constructed either on specially selected fills or inside trapezoidal or rectangular channels.

N. W. Lister of TRRL (43) states that this method allows researchers to take moderate steps away from observed performance—that is, for extending designs in conventional materials for heavier traffic, in varying relative thicknesses of the pavement layers, and for introducing modest changes in materials. However, major innovations continue to require the observation of actual pavement behavior, both as a basis for applying design theory and to give confidence to designers in introducing innovation.

3.2.3.2. Mobile Test Facilities

Apart from the proposed Texas Mobile Load Simulator, which is in the development stage and is fully discussed in Chapter 5, only two types of linear mobile machines have been built to apply accelerated wheel loads to pavement sections at any location. One of the two mobile linear machines is the Heavy Vehicle Simulator (HVS), developed at the end of the 1960's in South Africa. Three improved HVS's are still operational. The other machine is the Accelerated Loading Facility (ALF), in use in Australia since 1984 and operational in the U. S. since October 1986.

The HVS has the dimensions of an oversized heavy vehicle. Over long distances it can be pulled as a trailer by hooking the goose neck to a three-axle truck tractor and transporting it on two axles of twelve wheels total. Steerable wheels and a drive train allow movement of the machine over short distances without a tractor. The test wheel applies bi- or uni-directional loading over a length of 32.8 feet, and is pulled back and forth by a hydraulic system. Successive passes are being distributed over a track width of up to 5 feet at a top speed of 9 mph. Although the wheel is normally variable up to 22.5 kips, loadings of 45 kips have been achieved for the testing of airport pavements. The mechanical workings and features of the HVS are described in the proceedings of the 1984 and 1985 Annual Transportation Convention of the South African Department of Transport.

The Australian Accelerated Loading Facility (ALF) is owned by the Australian Road Research Board and has been operational since February 1984. FHWA interest in the machine stemmed from the March 1984 International Pavement Conference in McLean, Virginia (36). In mid-1984, the plans and authority to build the U. S. ALF were acquired, and the machine was delivered in August 1986. The ALF is patented in twenty countries.

Using dual truck tires with loads ranging from 9,000 to 22,500 pounds, the ALF applies accelerated loading to the pavement at a rate of 9,200 applications per day at a speed of 12 miles per hour on a test section 33 feet long. The load is carried with the load wheel and is energy-efficient, due to the utilization of gravity in the start-up procedure, allowing gravity to provide the acceleration and deceleration of the load. Electric motors are used for replacing energy lost due to friction. Lateral load distribution is provided, with various loading patterns to select from. The manufacturing of the U.S. ALF is fully documented in a 1987 FHWA Technical Report (51).

3.2.4. IMPULSE LOADING DEVICES

Two impulse loading devices exist in the Federal Republic of Germany—one at the Federal Laboratory for Road Construction at Berisch-Gladgach, another at the laboratories of the University of Hanover. The first utilizes hydraulic pulsators acting on movable circular plates with a longitudinal displacement device to simulate moving traffic. The second employs four hydraulic jacks in a straight line, which are activated in sequence to simulate traffic moving at up to 60 miles per hour. A hydraulic pulse-loading device is also used in Switzerland, to study pavement material properties with loads of 100 to 300 pounds at 3 hertz. A similar type of arrangement is used in a test facility of the University of New South Wales in Sydney and at the University of Florida at Gainesville.

The basic advantage of this type of equipment lies in the reduced dimensions required. The degree of simulation of real conditions is not as high as that for facilities using the rolling wheel concept, and this may be the reason why this relatively inexpensive solution is not in more widespread use throughout the world.

A viability study undertaken at The University of Texas in 1986 concluded that, for the test location at the Balcones Research Center, a facility of this type for the evaluation of a specific concrete overlay could be provided at a cost of $60,000. Because the limestone bedrock is shallow, the roadbed material would be imported fill material which would produce dynaflect results similar to those of the real pavement section being evaluated. At the time it was concluded that the design of the facility was subject to the creation of a loading system and a supporting structure that could apply continuous cyclic loads at three to five cycles per second. Another limitation would be the accurate design of a roadbed system that would adequately simulate a continuous highway pavement roadbed. Both these problems required a detailed knowledge of the soil structure at the proposed site and a detailed analysis of the load paths of the action loads applied to the specimen.

All the methods discussed above have been applied to pavement engineering, leading to major increases in benefit/cost ratios in the countries of application. Apart from full-scale tests (such as the AASHO Road Test, results of which are used throughout the world), wider use of of the knowledge gained through accelerated testing is not applied on an international basis.

3.3. WORLDWIDE EXAMPLES AND APPLICATIONS OF ACCELERATED PAVEMENT TESTING

Many of the results obtained through accelerated pavement evaluation are aimed at answering problem-specific questions in the countries of origin. For this reason, it appears that such results were published, but were not presented at international conferences. Most of the detailed papers presented on the subject originate from countries such as Australia, South Africa, and the United Kingdom. An OECD study group published a report in 1985 entitled "Full-Scale Pavement Testing" (46). The members of the group were Austria, Belgium, Canada, Denmark, France, West Germany, Greece, Iceland, Ireland, Italy, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the U. K., the U. S. A., Japan, Finland, Australia, and New Zealand,

Accelerated pavement testing has been selected as the method for pavement evaluation in the state of Texas; some of the major documented contributions to pavement engineering are discussed here.

3.3.1. CALCULATION OF LOAD EQUIVALENCY AT THE NARDO TEST SITE

One of the most important areas for utilization of accelerated pavement testing is in the determination of load equivalency. This section covers the testing done by OECD (31) member countries in the international testing effort that was completed in 1984 in Nardo, Italy. The purpose was to evaluate the destructive effect of different trucks in terms of fatigue cracking in the bituminous layers of flexible pavements.

3.3.1.1. Flexible Pavements

The purpose of the test was to make a quantitative comparison of the destructive effects of different types of freight vehicles in terms of fatigue cracking in the bituminous courses of flexible pavements.

Different heavy vehicles were driven at a speed of 80 km/h over a pavement structure composed of a 10-centimeter bituminous course laid over a 20-centimeter granular course. Unit tensile strains induced by each of the components of the vehicle axles were measured with strain gages, as discussed in Section 3.5.1.1. The front axle of each vehicle was a single wheel axle bearing a 15.7-kip load. The unit tensile strain (ε_α) induced by the front axle was taken as the reference value in the expression of unit tensile strains (ε) caused by each of the constituents of the other vehicle axles (ratio $R = (\varepsilon/\varepsilon_\alpha)$. The values of the strain measurements were adjusted to correspond to those at a temperature of 25°C.

Since the fatigue produced in bituminous courses is considered to be a consequence of cyclic tensile strains, the ratio R is an expression of the damaging effect (the higher R, the greater this effect).

In regard to various axle types and loads, the fatigue law for bituminous mixtures and Miner's law were then used to determine the damage to bituminous courses caused by different types of trucks. Experimental results were used in investigating an equivalence law for different loads in terms of fatigue damage caused to bituminous courses. To this end, the unit strain measurements were introduced into the fatigue law equation used in Italy for bituminous materials, i.e.,

$$\varepsilon = 47.4\text{x}10^{-4} \text{ x } N^{-0.234} \tag{3.1}$$

where

ε = strain and
N = number of axles,

and pavement life (N) was thus determined for the cases in which each of the components of the different axles is assumed to act alone.

The findings resulted in an equivalence law of the same form as that derived from the AASHO test. The exponent, however, depends on the type of axle considered and varies between 1.85 and 2.95. The mean value was found to be 2 (31).

3.3.1.2. Rigid Pavements

As with the testing of flexible pavements, the purpose of the rigid pavement test at Nardo was to make a quantitative comparison of the destructive effects of different types of heavy vehicles in terms of fatigue cracking in cement concrete surfacings.

The procedure was to drive heavy vehicles at a speed of 30 km/h over four pavement sections with cement concrete surfacings composed as follows:

(1) non-dowelled, 18 cm thick,
(2) dowelled, 18 cm thick,
(3) non-dowelled, 24 cm thick, and
(4) dowelled, 24 cm thick.

All slabs were of 5 meters long and were placed on a 15-cm-thick course of lean concrete. The unit tensile strains induced by each of the axles of the vehicle were measured with strain gages at the base of the slabs.

The conclusions were that, since fatigue in concrete slabs is a consequence of repeated tensile strains, the unit strain (ε) gives an expression for the destructive effect. Using the relationships between strain and load, the fatigue life of a structure was determined on the basis of the cement concrete fatigue law proposed by the Portland Cement Association. The fatigue law is:

$$\varepsilon/\varepsilon_T = s/s_T = 0.9715 - 0.0824 \log N \tag{3.2}$$

where

ε = unit strain,
ε_T = unit strain at failure under a single load,
s = stress,
s_T = stress at failure under a single load, and
N = number of repetitions of ε or s needed to produce failure through fatigue.

The authors did not seek to obtain a load equivalence law, although a correlation corresponding to a standard load of 30 kips was established between the load carried and the equivalence factor (EF). This correlation is written as

$$EF = 1.26\text{x}10^{-5} \text{ x } L^{4.44} \tag{3.3}$$

where

EF = equivalence factor and
L = load.

In the familiar form of the load equivalence law equation, this can be rewritten as

$$N^i/N^j = (L^j/L^i)^{4.44} \tag{3.4}$$

3.3.2. PAVEMENT PERFORMANCE EVALUATION IN FRANCE, USING CIRCULAR TEST TRACKS

Other tests cited in the OECD report (31) include the Finnish test in Virtaa, which had the same purpose as the test in Nardo described above, although permanent deformation in the granular layers and subgrade was also evaluated.

In the case of the French test at Nantes, a circular test track was used to study the damaging effects of two axles bearing different loads. It was concluded from this test, as in all other cases, that the load equivalence factor depends on the type of distress. In the case of permanent deformation, the value for the exponent was 8 and 2 for fatigue cracking of a bituminous coarse.

3.3.3. CALCULATION OF THE LOAD EQUIVALENCY FACTOR IN SOUTH AFRICA USING THE HVS

It is well known that the load equivalency factor relates the number of a given axle load to the equivalent number of standard axles to introduce a specific level of a specific distress.

Through the use of a Heavy Vehicle Simulator (34), measurements are taken of the pavement under trafficking and are used in the calculation of the load equivalency factor. Moduli determined in methods set out in the previous section of this chapter were used as input values to calculate the mechanistic life of the pavement under various wheel loads. From these lives, the equivalency coefficient (n) would be calculated:

$$F = (L / ESAL)^n \quad (3.5)$$

where

F = load equivalency factor,
L = wheel load applied by HVS,
ESAL = Equivalent Single Axle Load (40 kN), and
n = equivalency coefficient.

It was shown that there is no common equivalent coefficient for the different pavement layers. Through analysis of the data, it was calculated that the coefficient for the thin surface layer is, surprisingly, a negative value at the start of the test. The implication is that lighter wheel loads cause more fatigue of the surface layers than heavier loads. However, these calculated values were much less than the observed lives; and shift factors of up to 5, to predict field behavior from laboratory measurements, were required. This implies that the negative value may not necessarily be correct. Equivalence factors for other layers varied according to the pavement category. Equivalency coefficients for crushed-stone bases decreased from 4.8 to 2.4 and down to 0.7 at higher loads. After the application of water, the equivalency dropped to zero. This implies that under saturated conditions, the load is no longer of importance. Measurements of the radius of curvature at various wheel loads confirmed the belief that radii of curvature were higher at heavy loads. Generally, the calculated lives of surface layers were much less than observed lives.

It was also proposed that the equivalency factor can also be calculated from the rate of change in permanent deformation measured under the different wheel loads.

3.3.4. DETERMINATION OF THE FIELD EFFECTIVE MODULI USING THE SOUTH AFRICAN HVS

A method for determining the field effective moduli and stress dependence of pavement materials is described in, among other publications, *Transportation Research Record* (13). The effective moduli were determined from resilient deflections measured with a multi-depth deflectometer at different depths within pavement structures. Measurements are reported on four structures, ranging from light, unbound pavements to stronger inverted structures. The South African HVS was used to produce deflections at different wheel loads at various stages of trafficking. Subsequently, a linear elastic-layered program, ELSYM5, was used in an iterative technique to produce the measured deflections. In this way, a very good record of the change in structural response of the pavement was obtained.

The stress stiffening behavior of granular materials and the stress softening behavior of subgrade materials were demonstrated. Stress-dependent models for granular and cohesive materials were applied to the effective moduli, especially to the moduli of the unbound crushed-stone bases. The regression constants were determined for different moisture conditions and at various stages of trafficking. This study also verified the sensitivity of the regression constants in the analysis of various moisture levels. The stress dependence of the subgrade moduli was generally less than that of the base, but the effect on the total deflection was probably just as pronounced. It was shown that not all subgrades exhibit stress softening behavior.

A shift factor of 0.3 to 0.5 had to be applied to moduli determined through the use of constant confining pressure triaxial tests, but trends similar to those observed suggest that the actual wheel load could influence the shift factor.

The whole South African mechanistic design method, derived from use of Heavy Vehicle Simulation, includes input for moduli for typical pavement materials corresponding to legal axle loads as equivalent axles (E80's). For different loading conditions, such as overloading, or for airport pavements, adjustments to moduli are necessary. This stress dependence of unbound materials confirms the importance of a non-linear approach to analysis of pavement structures.

3.3.5. SURFACE CRACKING OF ASPHALT MIXTURES

Over a number of years, field, laboratory, and analytical studies were carried out in South Africa on surface cracking of asphalt mixtures (52). Field studies included analysis of a full-scale load test, condition surveys, and determination of material characteristics, particularly viscosity. It was found that gap- and semi-gap-graded types of asphalt may require special protective measures to prevent cracking due to the age-aggressive environment in parts of South Africa. The problem is further complicated by residual stresses resulting from the elasto-plastic behavior of the material. Thermal effects were also found to have the potential to cause surface cracking. A report by Hugo and Kennedy (52) cites Ruth et al who state that fracturing of asphalt will occur when stresses or strains due to any combination of material, environmental, and loading characteristics exceed threshold limits. This can happen as a result of the following:

- — excessive hardening of the binder,
- — excessive stresses due to external loads or temperature changes,
- — excessive volume changes of the asphalt,
- — excessive loss of subgrade support,
- — excessive volume change of non-asphalt components of the pavement structure, and
- — excessive post-construction compaction.

Results on full-depth asphalt (Hugo citing Scullion in 1977) indicate that surface cracking evaluated with the use of the Heavy Vehicle Simulator is extremely dependent on the road surface temperature. On a cold day, cracking was clearly visible and tended to form hatched patterns on the road surface; whereas on a hot day, the cracks seemed to have completely healed, with very little evidence of cracking.

Other beneficial applications of the HVS have been

- the development of the concept of pavement strength balance, which is defined as the state in which none of the pavement layers is overstressed, which will ultimately lead to the simultaneous failure of all the layers;
- the realization of the full potential of crushed stone bases, a cost-effective heavy-duty pavement structure, and the determination of optimum thicknesses for these layers;
- significant improvements in the use of natural gravel bases, identifying the three stages of deterioration, namely, densification, steady state moulding, and fast deterioration, with increase in water content;
- significant advances in the understanding of the behavior of pavements with cementitious layers, developing accurate prediction models for structural capacity in terms of the expected average rate of deformation development;
- the establishment of an effective pavement evaluation method utilizing the dynamic cone penetrometer;
- the characterization of new and alternative materials;
- a demonstration of the importance of timely maintenance;
- the determination of the water sensitivity of different types of pavement structures;
- better understanding of the pumping mechanism;
- improvements in pavement design methods which have led to avoidance of premature failures; reduction in pavement costs due to better structural balance; improvement and verification of mechanistic design models, such as showing that the quasi-elastic approach for the determination of subgrade permanent deformation, using vertical compressive strain criteria, was accurate, and also that designs based on soaked laboratory CBR values are overly conservative in some conditions;
- identification and evaluation of cost-effective rehabilitation measures for the upgrading of existing roads;
- the effect of surface temperature on the deformability of asphalt layers utilizing artificial (infrared) accelerated heating of the surface;
- the quantification of crushing failures of cemented gravel bases; and
- a classification system for thin surfaced flexible pavements.

3.3.6. ACCELERATED PAVEMENT TESTING IN THE U. K.

The construction of full-scale road experiments was preferred in the U. K. (43), primarily because of the ability to control and measure in detail during construction and to obtain a more complete record of pavement performance. The consideration of traffic disruption also weighed heavy in the decision. The original aim was to vary the design parameters of material type, characteristics, and/or thickness as systematically as possible at any one site.

The U. K. has a mild maritime climate that varies relatively little across the lowland of the country. It can, therefore, be considered as one temperature region, and temperature variables, such as frost susceptibility, need not be considered in the design of experiments.

The development of the full-scale testing program revealed limitations that had to be taken into account. It was decided that reductions in thicknesses to produce early failures would give misleading information due to the seasonal deterioration seen in the deformation of bituminous pavements. It proved to be impossible to obtain a subgrade of sufficiently uniform strength to enable direct comparisons between sections to be made in a single experiment.

It was found that full-scale experiments based on testing of in-service roads, although highly attractive in principle because of the apparent simplicity, did in practice present problems in obtaining practical results in reasonable time.

Models based on fatigue cracking obtained in laboratory testing resulted in an under-estimate of the onset of cracking in the road by a factor of 1,000, which has been confirmed by limited testing in a circular pavement testing facility at TRRL. A partial explanation of the discrepancy lies in the use of laboratory testing, which is a simplification of stress conditions in the road. Similarly a subgrade strain criterion cannot be a totally satisfactory surrogate for the development of deformation in all layers of the road, owing to neglect of the internal deformability of the pavement layers.

Back analysis of the results of full-scale road experiments, in which the effects of mixed wheel loads and temperature variation cannot be directly disentangled, must remain a relatively crude approach to the derivation of these performance criteria but must be used in the absence of experimentation that quantifies the effects systematically.

Therefore authorities decided to develop a more efficient mechanical testing system that would provide detailed information of pavement behavior under controlled temperature and loading conditions. This would serve as a solution to the problem of waiting for evidence of long-term pavement performance. Detailed accelerated testing of in-service roads was not envisaged as being practical on densely trafficked roads in the U. K., and a static facility was preferred.

The Pavement Testing Facility (PTF)

The choice between a linear and a circular facility fell to the linear facility, due to the fact that both loading and temperature variations could be evaluated. This facility reaches a maximum speed of 12.5 mph over a 22-foot section. Both uni and bi-directional loading are possible, with the latter producing 900 load applications per hour. Loads of up to 22.5 kips are applied to single or dual wheels.

Pavements are laid with conventional machinery in a 3-m-deep pit which allows for 10 strips to be accommodated side by side. Pavement temperatures are simulated by oblique infrared heating of the pavement from banks of heaters on either side of the pavement. Supplemented testing includes dynamic stiffness, creep deformation, fatigue plate bearing, and Falling Weight Deflectometer measurements.

Increasing emphasis is placed on the evaluation of structural performance and the performance of various maintenance treatments. The Special Pavement Studies program covers a wide range of topics. Long-term experiments are still considered necessary for the assessment of surface characteristics and of materials and designs for which there is no acceptable analytical design method. These include improved, dense, and open-textured bituminous surfacing materials and reinforced surfacings over lean concrete. The program also includes sections of improved and new roadbase materials, which were laid primarily to establish that their properties, determined in laboratory and pilot-scale research, can be obtained under contractual conditions on the road.

3.3.7. ACCELERATED PAVEMENT TESTING IN THE U. S. A. USING THE ACCELERATED LOADING FACILITY

Test pavements were constructed in 1986 at the Turner-Fairbanks Highway Research Center in McLean, Virginia (14), and during the first phase of testing, a range of loads and tire pressures was used to evaluate a range of loads and tire pressures on each of the eight test sections. The objectives of the first phase of research were:

- to establish load equivalencies for 11,600, 14,100, and 19,000 pounds;
- to compare calculated versus measured pavement response (strains, deflections, cracking, rutting, and roughness); and
- to evaluate the accuracy of the AASHTO design procedure, which was used to design the test pavements.

The ALF was used in the evaluation of the rutting potential of the asphalt concrete layer of each test pavement. The initial conclusions were that rutting was not a problem and that the designed pavement structure performed satisfactorily. Rutting, cracking, longitudinal roughness, PSI, and structural response to non-destructive testing and the ALF wheel loadings were used to study the pavement performance. After this, a post-mortem evaluation of the two pavements was conducted.

3.3.8. ACCELERATED PAVEMENT TESTING IN AUSTRALIA USING THE ALF

In 1985-86, a test trial was carried out with the use of the ALF where the objectives were to investigate the performance of a test pavement composed of an unbound base and subbase and a spray and chip seal surface and subjected to simulated heavy traffic loading. Other objectives included the following:

- to investigate the distress mechanisms of the pavement;
- to examine the reaction of the pavement to different wheel loads;
- to investigate the sensitivity of the pavement to environmental factors and to changes in moisture content within the pavement; and
- to test the reliability of the ALF.

The pavement was subjected to 1.4 million cycles of 18-kip dual wheel loads. Pavement response and performance were monitored in terms of residual and resilient deformation, the latter both at the surface and within the pavement.

It was shown that the rate of deflections decreased over a time after the initial rapid increase. The rate of permanent deformation was not related to the magnitude of the applied dynamic loads. Although the pavement did not deteriorate structurally, the surface seal had to be fully rehabilitated twice, and minor repairs were carried out in order to maintain a waterproof surface.

Analysis of the results indicated load sensitivity of the pavement materials. Ignoring the non-linear characteristics of the pavement led to significant errors in the estimation of pavement life under different load magnitudes and traffic conditions. The pavement damage, assuming linear behavior, was 1.45 times larger than that calculated from the measured pavement response.

Falling Weight Deflectometer and multi-depth deflection readings were taken to examine deflection bowls and load-dependent pavement responses. Layer moduli were back-calculated from surface deflection data and produced values close to measured values. The back-calculated moduli were found to be load-specific. It was also found that the in situ CBR's of the pavement materials at the end of trafficking were much higher than those indicated by preliminary testing. The PI values recorded after the completion of trafficking were also much higher than the initial values.

3.4. CONCLUSION

In Chapter 3, all types of accelerated pavement testing facilities were listed, and major applications were mentioned that resulted in valuable information for both the local agency and the international pavement community. Most researchers realize that there exist vast areas in pavement engineering that can be successfully addressed with the aid of accelerated pavement testing. Knowledge generated will feature a high reliability/cost ratio in comparison with other available methods, as discussed in Chapter 2. In Chapter 4, the options for further utilization of accelerated pavement testing are conceptually explored.

CHAPTER 4. APPLICATION CONCEPTS FOR ACCELERATED PAVEMENT TESTING

4.1. INTRODUCTION

In Chapter 3, existing accelerated pavement testing methods were examined and a number of the major applications of these methods related to this study were discussed. Accelerated pavement testing which employs vehicular simulation is a relatively new concept. In the first years of application, machines were invariably used on pavements as diagnostic tools for the detection of faulty designs or inaccurate modelling. Most of the machines mentioned in Chapter 3 are currently still being used for these purposes; however, many proposals for future uses, other than simple testing, have been put forward in areas such as pavement management, where remaining life concepts have to be validated and the effect of climatic influences will form a major part of future accelerated pavement testing.

4.2. ACCELERATED PAVEMENT TESTING AND PAVEMENT MANAGEMENT

Pavement management systems operate at the network level and at the project level. The primary objective of the network management system when it includes an optimization feature is to provide systematic and consistent information to decision makers. This provides a forum for discussion between technician and decision makers to help them determine the most cost-effective policies for pavement renewal strategies. These strategies or policies should achieve and maintain the required performance standards for different roads in the network with a minimum cost to the highway agency and the community.

Utilization of the MLS would affect existing pavement management systems. Optimization and cost-effectiveness studies to derive priorities would all be performed at the network level. Since rates of deterioration can be determined, projections of costs can be made based on what needs to be done, where and when. At the project level, responsibilities would be shifted to the establishment of representative test sites, participation in testing, and feedback on the performance of the selected maintenance measures. Distress occurrences relative to traffic counts would have to be determined and relayed back to form part of the centralized data base, as before, but the data would now also be used to evaluate the accuracy of predictions obtained through accelerated testing. In other words, the data would be utilized to calibrate or adjust predictions of the accelerated testing.

The primary objective of the project management system is to determine the most cost-effective renewal action for a given project over a specified analysis period. Up to now, network level analysis has always suffered from the fact that life predictions at this level are of low reliability. With the use of accelerated pavement testing, it is proposed that if performance prediction of pavement sections at the project level can be quantified at a high reliability/cost ratio, projections can then be made to the network level where missing key aspects such as determination of structural capacities, remaining life of the network, and climatic influences can be improved.

4.3. DETERMINATION OF STRUCTURAL CAPACITIES OF PAVEMENTS THROUGH ACCELERATED PAVEMENT TESTING

The most noteworthy contribution of accelerated pavement testing to pavement management will be its extensive use in determining the remaining life of a pavement and in the calibration of non-destructive testing methods. The concept of remaining life was included in the AASHTO Design Guide (47) as the basis for the determination of the effective structural capacity of the pavement at the time of overlay. The role of the MLS would be to verify or refine structural capacity predictions by non-destructive testing in terms of the number of loads that can be applied before failure occurs.

Conceptually, the AASHTO Pavement Design method implies that, as the initial serviceability decreases, the initial structural number of a pavement, SN_0, is reduced, due to pavement damage caused by traffic. At any number of cumulative traffic repetitions (n), the pavement has a serviceability of (p_1) and an effective structural number of SC_{eff}. If (n) repetitions corresponds to the time at which an overlay is required, the approach taken is to determine what new structural capacity (SC_y) would be required to support the traffic (y) on the overlaid structure. The required overlay or additional structural number needed at the time of overlay would simply be

$$SN_{ol} = SN_y\,(\text{new}) - SN_{eff}\,(\text{existing}) \qquad (4.1)$$

Also important to the understanding of the effective thickness approach is the concept of the pavement condition factor (C). For any number of repetitions, at a given time, there exists a condition factor that relates the effective capacity to the initial structural capacity of the pavement. Thus,

$$C = SC_{eff}/SC_0 \tag{4.2}$$

where the limits of C are between one (new) and zero (terminal).

For a pavement with no previous overlay rehabilitation, Eq 4.2 is

$$C_x = SC_{xeff}/SC_0 \ , \tag{4.3}$$

and for an overlaid pavement the equation changes to

$$Cy = SC_{yeff}/SC_y \ . \tag{4.4}$$

Although SC_0 and SC_y are not equal, $Cx = Cy = 1$ at the time of testing, which may also be at the time of construction or overlay.

Accelerated Load Simulation can be used for the determination of time zero structural capacity, which is now defined as any time before failure when an assessment of capacity to failure is to be made. From the accurate assessment of future capacities, reliable priority predictions in network level pavement management can be derived. The rate at which traffic will accumulate will provide the timetable for improvements on pavements. However, the accuracy of the prediction is further enhanced by the fact that environmental or seasonal effects can be taken into account to be included in the predictions. This is achieved by applying accelerated loading on similar pavement sections during periods of different environmental conditions within a short time. The number of MLS loads in a period of thawing is expected to be less than the number obtained on an adjacent section tested in frozen periods. Over a period of time, sensitivity analysis of MLS predictions of this nature would become available through LTPP studies of that particular pavement, which will result in reliable prioritizing.

4.3.1. PAVEMENT DAMAGE AND REMAINING LIFE

Under the heading of structural capacities of pavement structures, an important concept to be evaluated with the aid of the accelerated pavement testing is the concept of effective structural capacity, also known as remaining life.

Increasing traffic (N_x repetitions) results in decreasing serviceability. In other words, for a given pavement structure with initial structural capacity (SC), there is a certain number of repetitions (N_{fx}) that define a failure serviceability level. The aim is to arrive at a relationship that describes changes in structural capacity and accumulated load applications relative to each other. Valuable assessments of structural capacities in terms of the number of loads can be made for various combinations of pavement layers through the use of the MLS. This will also include the evaluation of types and thicknesses of overlays at various stages of distress of the existing pavement. Always accompanied by material classifications and nondestructive testing methods, these findings will serve as the basis for design methods which will range from computerized models to catalogue designs.

Knowing the future load capacity and the rate at which the remaining life of the existing pavement will decrease with time, a sensitivity analysis of various rehabilitation alternatives at various stages can be made. The methodology is set out below.

If N_{fx} is the number of repetitions at failure, thus, at any interim time between the initial and final conditions, i.e., N_x repetitions, damage sustained by the pavement is:

$$d_x = N_x / N_{fx} \tag{4.5}$$

which results in $d_x = 1.0$ at failure.

Thus, the remaining life of the structure at time x (RL_x) may be derived as follows:

$$\begin{aligned} RL_x &= 1 - d_x \\ &= 1 - (N_x/N_{fx}) \\ &= (N_{fx} - N_x)/N_{fx} \end{aligned} \tag{4.6}$$

with the boundary conditions of $R_{Lx} = 1$ at time zero and $R_{Lx} = 0$ at failure.

Similarly, it can be shown how the structural capacity changes with traffic to arrive at an effective structural capacity after (N_x) repetitions, given by SC_{xeff}.

The placement of an overlay on the pavement at N_x repetitions that would last the intended duration over the remaining life would have to provide for the remaining repetitions. If the intended duration is equal to the original intended duration of the original pavement, no overlay is required. Thus, the structural capacity for the remaining life ($SC_{(Nfx - Nx)}$) is the same as the effective structural capacity (SC_{xeff}). From Eq 4.2 it follows then that

$$C_x = SC_{(Nfx - Nx)} / SC_0 \ . \tag{4.7}$$

Equation 4.7 would allow us to compute the N_{fx} repetitions to reach a failure serviceability of P_f. Likewise, after N_x repetitions, it would be possible to compute the required structural capacity of a pavement to last (N_{fx} - N_x repetitions) to that same failure serviceability. The structural capacity at that time is given by $SC_{(Nfx - Nx)}$.

The remaining life at time x (RL_x) as a function of final traffic repetitions and repetitions at time x is shown in Eq 4.6. C_x (Eq 4.7), on the other hand, is a function of the remaining structural capacity at time x. Equating remaining life, in terms of repetitions, to remaining structural capacity yields a relationship at time x of the form

$$C_j = f(RL_j) \tag{4.8}$$

Since structural capacity is the same as the effective structural number, Eq 4.1 is written as follows:

$$SN_{ol} = SN_y - SN_{xeff} \; . \qquad (4.9)$$

Equation 4.9 represents the overlay methodology which assumes that the structural capacity of the existing structure is changing at a slower rate during the overlay period. It assumes that the C_x factor remains at the value it had at the time of the overlay for any number of traffic applications into the overlay period. In other words, the damaged existing pavement is incorrectly presumed to have a deterioration rate that is equal to a new pavement at the start of the overlay. This is not fundamentally correct, and the concept of the reduction in remaining life of the existing pavement after overlay must be introduced. The result of reducing the remaining life will be an increase in overlay thicknesses. Thus Eq 4.9 becomes

$$SN_{ol} = SN_y - SN_{xeff}(F_{RL}) \qquad (4.10)$$

where F_{RL} is the remaining life factor in the AASHTO Guide, given as a function of RL_y and RL_x.

In conclusion, therefore, it can be said that a major application of accelerated pavement testing would be the verification of the function which describes F_{RL} in terms of RL_x and RL_y. Applying a multiplier to the design overlay traffic repetitions and using Eq 4.9 can also be evaluated.

4.4. EVALUATION OF CLIMATIC FACTORS USING ACCELERATED PAVEMENT TESTING

Miner's hypothesis is an example of damage accumulation theory which is often used to describe pavement fatigue behavior under different traffic and environmental conditions. The cumulative damage to which pavements are subjected under specific conditions for a specific number of load repetitions is given by the following equation:

$$D = \Sigma f(n_i, N_i) \qquad (4.11)$$

where

D = accumulated damage,
N_i = the number of cycles to produce failure, and
n_i = the number of cycles at any time.

The pavement will thus fail when the sums of the cumulative damage (D), corresponding to each of the climatic subdivisions of the year, equals one. The law is statistical in nature and applies to any pavement or distress mechanism. It does not take into account the sequence in which pavement loading is accumulated.

In the determination of structural capacities of pavements, to carry a certain number of load applications until failure occurs, designers make use of period-dependent strengths of the facility. Pavement strength and its ability to withstand traffic loading is a constantly varying phenomenon. Temperature affects asphaltic layers, resulting in different strengths at different times. Seasonal variations in moisture content together with temperature fluctuations, also have an effect on pavement strengths. Thus, depending on the degree of accuracy required, the designer determines periods in which the strengths would be fairly similar, for which he would then obtain an average strength parameter for the structure, such as modulus of elasticity. This quantity may vary between seasonal analysis to daily, or even half-daily, analysis periods. It is then determined what the number of loads will be that the structure will be required to carry in that period. However, for subsequent periods of similar strengths, there may be different numbers of loads utilizing the facility. All these loads (n_i in Eq 4.11) must be normalized.

For each period or strength condition, there exists a finite number of loads (N_i) that can be carried before fatigue failure of the facility occurs. Normalization of n_i is done through division with N_i. N_i is usually experimentally determined. If no other factors except for fatigue affect the capacity of the structure, the sum of all subsequent n_i's is normalized by dividing it with N_i. If N_i does not change from period to period, then N_i is a constant with respect to each n_i. Eq 4.11 can be written as follows:

$$D = f(n_{11}+n_{12}+\ldots,N_1) + f(n_{21}+n_{22}+\ldots,N_2) + f(n_{31}+n_{32}+\ldots,N_3) \qquad (4.12)$$

If the designer wants to take into account the aging or environmental effect of the pavement, a number of N_i's will be used, ranging from two to as many individual periods there are in the total analysis period.

It is proposed by the authors of this report that accelerated pavement testing be utilized in the determination of the N_i of pavement sections. In Fig 4.1b, it is shown how two similar pavement sections are tested to failure under the same environmental conditions but at different times during the life of the pavement. The difference in the number of accelerated load applications (N1 and N2) can be attributed to two factors, namely the additional traffic that utilized the second section as well as aging or environmental effects. Since the traffic between testing of the first and second sections, $N_{traffic}$, can be easily measured, the reduction or even increase in some cases, of N_2, the remaining life, must be attributable to environmental effects, as given in Eq 4.13b.

$$N_1 = N_2 + N_{traffic} + N_{environment}$$

$$N_{env} = N_1 - N_2 - N_{traffic} \qquad (4.13)$$

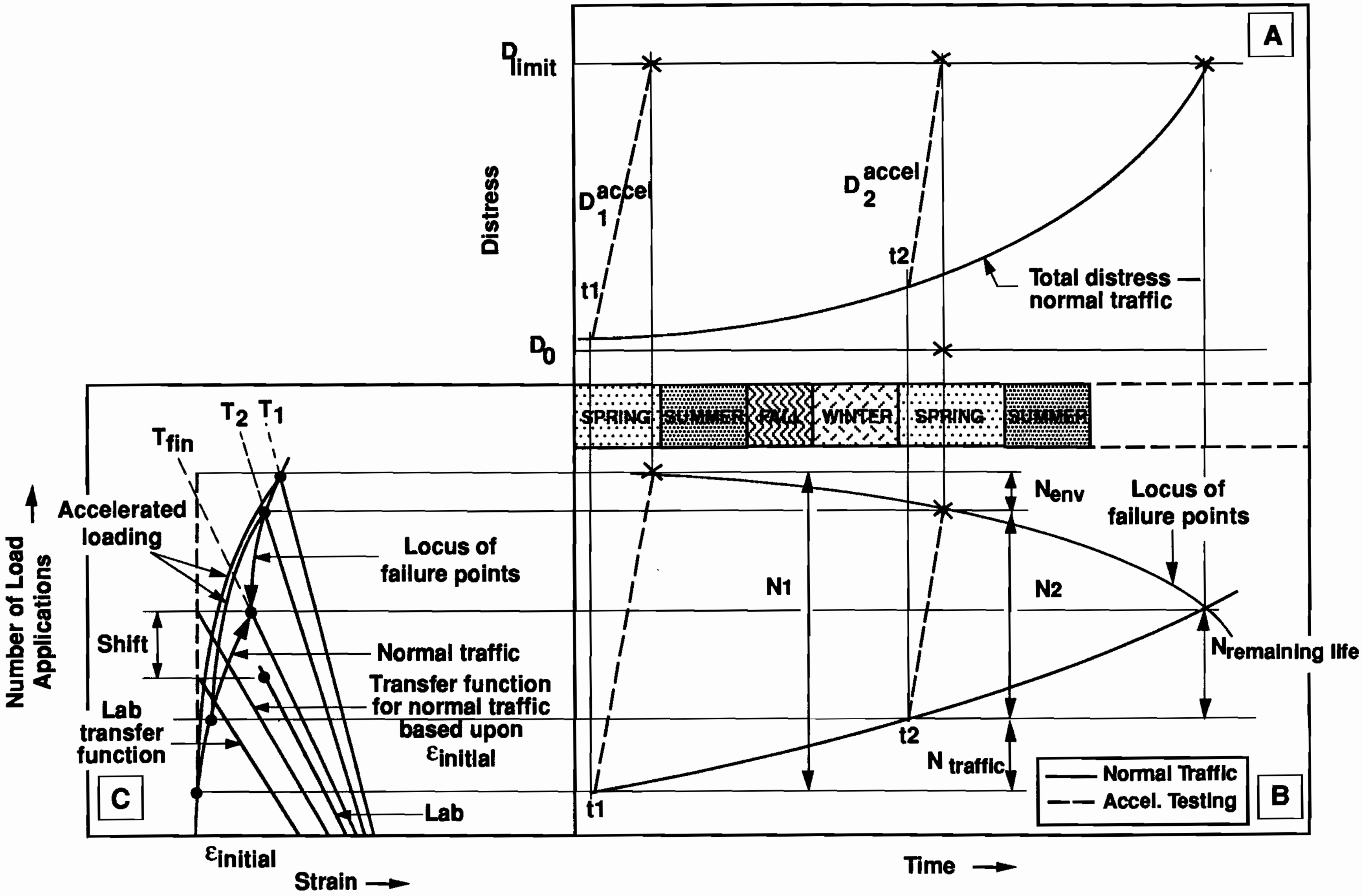


Fig 4.1. Conceptual application of accelerated pavement testing and Miner's Hypothesis in the evaluation of environmental effects on pavements for a specific load.

In Eq. 4.13 and the following discussion, it is assumed that environmental effects lead to a reduction in pavement life. This need not be true throughout the pavement life; however, the same principles apply for the case in which environment leads to an *in*crease in pavement life, as well as for a mixture of beneficial and detrimental effects.

In Fig 4.1a, the traditional curves between distress, relative to time, are shown. This figure illustrates that certain distress manifestation occurs in a pavement owing to the combined effects of load and environment. The rate of distress occurrence increases at an increasing rate, especially toward the latter end of the structure's life, because of dynamic loading, resulting from rougher pavements. At any given time, the relative contributions of the environment and loading, to produce the total distress manifestation, are not assessable. However, when accelerated loading is employed to hasten the distress to a limiting distress level, the rate at which distress occurs (slope of D1 and D2 in Fig 4.1a) is an indication of the relative position of t1 and t2 on the time scale. Conceptually it can be shown that an infinite distress accumulation rate would be reached at the distress limit, when the structure is tested without acceleration. Therefore, the rate of distress occurrence at a given time, using statistically-based data, can be utilized to estimate the remaining life of a structure.

Plotting the number of load application versus time as shown in Fig 4.1b, a locus of failure points is given, from an interpolation of accelerated failure points at different times (t1,t2), as well as the failure point of the unaccelerated structure. Accelerated loading occurs at a constant rate, resulting in parallel lines that lead to a certain failure mode at different numbers of load applications, as given in Eq 4.13.

Two families of curves are presented in Fig 4.1c. The straight lines represent the transfer functions which relate strain to the number of load applications, at failure, that can be expected at a given constant stress level. Currently, laboratory results are being used to determine these relationships. These laboratory results often underestimate fatigue life of the material under real traffic and environmental conditions, which necessitate the use of shift factors to prevent costly over-designing of pavement structures. Great uncertainty exists about the magnitude of these shift factors, given that the ultimate goal is to determine T_{fin} shown in Fig 4.1c.

The second family of curves are the curved relationships that depict the strain path versus number of load applications followed by a material under constant stress loading. In the case of constant strain, these paths are represented by straight, vertical lines. In Fig 4.1c, strain is shown as the dependent variable. Since strain is not easily derived on in-service pavements, surface deflections are usually used in lieu of strain.

Accelerated testing provides the researcher with the ability to locate the exact position of t_{fin}, by testing at different times during the life of a pavement structure. For a specific structure, defining the position of the transfer functions at T1 and T2, will define the coinciding origin for the relationships at one load application. All transfer functions, including t_{fin}, for that particular structure will originate from this point, thus establishing one point on the line. The transfer functions at T1 and T2 are established by doing accelerated testing at different levels of constant stress, leading to different times to failure. Connecting the failure points resulted in the two accelerated load transfer functions.

Establishing the other point on T_{fin} requires the strain paths for at least three accelerated test periods and the application of the same load magnitudes. These are the accelerated strain paths at t1, t2, and t3 (t3 is not shown on Fig 4.1c). Because of the mixture of traffic, the strain path for traffic is represented by a weighted average strain caused by the traffic, which in turn defines the strain to be used for the accelerated testing.

Plotting the strain paths for t1, t2, and t3 will result in failure points on each respective transfer function after a certain number of applications. The strain path for the normally trafficked pavement between t1 and t3 is also plotted and serves as the points of origin for accelerated testing strain paths. The traffic strain path is then extrapolated to the T3 transfer function (not shown). To establish the second point on T_{fin}, which lies on the traffic strain path, the locus of failure points is extrapolated until it coincides with the traffic strain path, thus establishing the second point on T_{fin}.

In this way, a family of transfer functions, relating strain to the number of load applications, can be established for different combinations of environment and load. This can be done in a period of time considerably shorter than would normally be required using long-term pavement performance studies.

4.5. CONCLUSION

Chapter 4 discusses conceptually the future applications of accelerated pavement testing in pavement engineering. Most current applications, such as rehabilitation evaluations, are in essence diagnostic because of the immediate returns on the effort. This aspect of accelerated testing was the main focus of the South African HVS program in the earlier years, after which it was applied to the formulation of a catalogue design method.

Performance model validation, calibration, and acceptable load equivalency factors have led many agencies to explore accelerated pavement testing. The dedication of resources to this aspect of pavement evaluation should be an important issue in the overall policy. Apart from accelerated pavement testing, other methodologies have also become available which will contribute to make accelerated pavement testing easier and more cost effective. The ability to measure PSI over short distances and the non-destructive ability to measure loss of stiffness of materials, such as spectral wave analysis, are but a few.

CHAPTER 5. ACCELERATED PAVEMENT TESTING IN TEXAS, USING VEHICLE SIMULATION

5.1. INTRODUCTION

Texas has more highway mileage than any other state in the U. S. A. with vast ranges in environmental conditions, traffic, and materials. It is, therefore, not surprising that the Texas SDHPT recognized the need for and benefit of accelerated pavement testing and has elected to proceed with the acquisition of a mobile vehicle simulator.

The Texas SDHPT eventually needs to decide the scale and magnitude of an accelerated pavement testing program, but full knowledge of the requirements for applying the program in the most cost-efficient manner is needed first. For this purpose a brainstorming session was held in September 1990, at which time certain problems requiring in-depth research were identified. The results of this brainstorming session are summarized in Appendix A.

Based on the current state of pavement engineering with respect to accelerated pavement testing, this chapter presents the scope of applications for accelerated pavement testing and the equipment available to fulfill the specific needs of the Texas SDHPT.

5.2. NEEDS AND APPLICATION OPTIONS FOR THE TEXAS SDHPT

After deliberations with the Highway Department, it was established that a full-scale pavement testing method would address most of the issues and that a specially-constructed test road, similar to the AASHO Road Test, would not be attempted. Since the AASHO Road Test, many agencies have opposed the establishment of full-scale test tracks, due to the high cost and relatively low benefit gained through this method. In contrast, the FHWA study group on testing methods (36) concluded that regional test-track programs on a smaller scale would yield significant benefits by supporting the in-service pavement monitoring and mechanical testing programs. The major benefits were concluded to be

- the uniformity in material testing, performance measurement, and data analysis;
- applicability to regional materials and environmental conditions; and
- credibility of the tests and acceptance of the results for engineering and legal purposes.

It was concluded that no new test tracks should be constructed until the existing ones were thoroughly studied.

It is the opinion of the authors of the report (36) that the existing test tracks can be extremely helpful in the calibration and acceptance of accelerated vehicle simulators and that participation of the Texas SDHPT in such programs is highly warranted.

The implementation of mobile accelerated pavement testing in Texas will provide the SDHPT with the ability to acquire knowledge on pavement behavior earlier and at a lower cost than was previously possible. The versatility of the method allows information to be obtained from various sources depending on specific needs and variable control requirements. Environmentally-controlled effects can be evaluated under laboratory conditions by executing either full-scale accelerated load simulation or modelled accelerated load simulation pavement studies. However, the same full-scale mobile equipment will also allow studies of in-service pavements. This is possible due to the mobility of the proposed test equipment, called the Mobile Load Simulator (MLS), whose mechanical concepts will be discussed later in this chapter.

5.2.1. IN-SERVICE TESTING

Two types of in-service testing were identified by the FHWA study group on testing methods (36). These are long-term monitoring of existing pavements and controlled new pavement monitoring on specially designed highway sections or loops, constructed in-line with or parallel to existing operating highways. In addition to these methods, accelerated pavement testing of both types of pavements will also be possible in the Texas situation once the system is functional.

Factors involved include the cost and difficulty of establishing a data base for long-term pavement studies as well as a lengthy analysis period. However, in the Texas situation, the data will be useful from the outset in verification studies of accelerated pavement testing machines. As an example, a test section can have applied a certain amount of accelerated loading; it can then be compared with similar unaccelerated sections to evaluate the accuracy of the simulation.

In heavy traffic situations on new pavements, parallel test sections or loops can be constructed and accelerated loading can be applied to provide data for maintenance and rehabilitation programming.

5.2.2. LABORATORY ACCELERATED PAVEMENT TESTING

Accelerated pavement testing can also be utilized in a laboratory situation. This type of pavement testing implies that pavement structures are specially constructed under regulated conditions. The construction process tries as far as possible to make use of conventional road building equipment and techniques. During the accelerated testing of the pavement, the method of loading may vary from full-scale loaded truck axles to single wheels of a variety of sizes.

As part of the feasibility study concerned with the implementation of accelerated pavement testing in the state of Texas, a 1-to-10 scale model of the proposed MLS was constructed and presented to the steering committee. The initial purpose of the manufacture of the model was for use as a demonstration exhibit, to solicit the participation of interested parties in the process of developing the equipment. A theoretical evaluation of modelled pavement studies, using the model MLS, showed not only that this type of testing was feasible but that valuable results could be obtained through it. Similar testing of modelled pavement structures was reported by Van Wijk (22) of the Shell Laboratory, Amsterdam.

It must, however, be noted that laboratory-constructed pavement structures, modelled or full-scale, which are subjected to accelerated testing often exhibit higher rates of distress occurrence than would be expected in the field. This is due mainly to accelerated testing on pavements where the time-dependent strengths of materials are of importance. Accelerated testing on early-age structures may not be representative of real-life conditions.

5.2.2.1. Full-Scale Accelerated Pavement Testing

The machine that would most closely resemble actual traffic loading, the prosed MLS, is ideally suited for laboratory testing. Studies for the implementation of the machine in this respect are now an ongoing process. Laboratory testing with the full-scale Mobile Load Simulator is recommended during the run-in phase of the machine. This type of testing would be especially beneficial at that time because of ease of accessibility of both services and personnel.

5.2.2.2. Modelled Accelerated Pavement Testing

In the evaluation of modelled asphalt surface layers, the model MLS can be utilized. The model is currently operational and undergoing mechanical evaluation at different speeds and loads, and certain enhancements can be made that would allow material testing at high load repetitions. Future experimentation will include evaluation of mechanical and electrical components while testing at different levels of the following:

- loads,
- speeds,
- wheel pressures,
- roughness of contact surface, and
- suspension stiffness.

Simultaneously with evaluation of machine durability, the experiment can include an evaluation of a pavement characteristic of thin asphalt layers which are placed on base mats of varying resilience. These experiments may, for instance, evaluate the rutting potential of asphalt mixtures by evaluating one of the following:

- effects of various aging rates,
- levels of void contents,
- levels of viscosity of the binder,
- binders with or without admixtures,
- high and low temperatures of the layer,
- moisture susceptibility,
- types of gradations,
- aggregate shapes, and
- aggregate types.

Because the modelled test section is relatively long (5 feet), the replication of experiments can be minimized. Between four and six divisions of the total testing length will provide the researcher with the necessary replication for statistical analysis. It is believed that the rate of load application will be on the order of 100,000 per day, resulting in a testing duration of three months for one of the above rutting variables tested at two levels.

The model MLS may also be utilized as a demonstration exhibit to generate interest and funds for the full-scale prototype. The model currently consists of specially-cast wheels which have a resilience comparable to the down-scaled resilience of full-scale truck tires. The suspension springs provided for the model are similarly down-scaled. Other features of this model include the option of any combination of axle configuration, limited lateral wheel distribution, and electric motors on any single or dual set of axles. Power is supplied by 22-24 volts DC at 25 ampere.

The model may prove to be an important component in the overall strategy of prototype development, even though the aspect of mobility of the prototype has not been evaluated through the model.

5.3. AVAILABLE FULL-SCALE HARDWARE OPTIONS

The study concerning the feasibility of acquiring of a mobile accelerated vehicle simulator for the state of Texas was initiated in 1989 by the Texas SDHPT. At the time, the SDHPT had the option of proceeding with the acquisition of one of three machines: the South African Heavy Vehicle Simulator (HVS); the Australian Accelerated Loading Facility (ALF), currently also operational in the U. S.; and the proposed MLS.

The HVS was made available to the Texas SDHPT by the South African road authorities on a permanent loan basis including operating and training personnel and customized data acquisition systems at a cost of around $300,000 for the first year. The purpose was to present the SDHPT with the necessary interim equipment and personnel to train SDHPT personnel and establish the Texas program while a new machine was being developed.

The second option presented to the steering committee during its meeting on October 2, 1989, entailed the purchasing of an ALF which is licensed to Engineering Incorporated of Hampton, Virginia. It is patented in twenty countries, and Engineering Incorporated is the exclusive licensee for manufacture by the Department of Main Roads, New South Wales, Australia. The ALF was available for the purchase price of $1,500,000 and could be delivered to the SDHPT one year after the date of order.

The steering committee elected not to proceed with either of the existing options. That decision was based on the conviction that the proposed MLS would greatly improve on the features of the other two facilities. It was decided to proceed with the acquisition of a prototype MLS, of which the operational one-tenth scale model was presented to the steering committee on March 6, 1990.

5.4. ACCELERATED LOAD SIMULATION USING THE TEXAS MLS

Based on a proposal by the Center for Transportation Research (CTR), in 1988, a research program was initiated through which CTR was to develop a strategy for the acquisition of an accelerated pavement testing device for the Texas SDHPT. Subsequently the Department opted to develop a testing machine, the Mobile Load Simulator (MLS). Technical information on the proposed MLS was collected and published by CTR on behalf of the Department under Project 1246 in a brochure for the benefit of interested parties and to solicit the services of a designer/constructor for the ultimate prototype. The brochure is included in Appendix A. Some relevant details are discussed briefly here.

5.4.1. THE PROPOSED PROTOTYPE MLS

The proposed MLS would be a mobile testing device capable of accelerated simulation of real traffic loading on any selected pavement section. Accelerated testing would be achievable either by overloading or by increasing the number of axles and/or the rate of application. The pavement sections could be existing roads or specially constructed test sections.

The MLS concept is a unique system featuring the energy-saving belt or closed-loop concept shown in Figure 5.1.

Rotation of the chain around the stationary frame, consisting of wheel bogies linked together, is achieved through electric motors on ordinary truck axles drawing current from a buss bar and transforming rotation of the wheels in contact with the pavement to translation of the chain around the frame.

5.4.2. MLS OPERATION

Twelve axles are included in the basic configuration. This configuration was selected based on factors such as pavement relaxation times under real traffic, deflection basins, and the operating speed of the machine. A detailed evaluation for accuracy of vehicle simulation is presented in Chapter 7. Other axle configurations could be selected provided symmetry is maintained as far as possible. Provisionally, a maximum of 16 axles is foreseen.

The Mobile Load Simulator features the ability to closely represent real traffic. Even though the attainable speeds would not be representative of real traffic, the MLS would exceed operating speeds for other existing linear load simulators. Additional MLS features, such as the utilization of real truck suspensions and axles, would provide the best available accelerated pavement evaluation tool using simulation of real traffic loading conditions.

The load applied to the pavement is governed by a combination of the suspension characteristics employed and the distance between the load beam and pavement. Variable loads can be simulated by using suspension systems with different spring characteristics.

The MLS would not only provide driving at the axles, but would also simulate longitudinal shoving caused by real traffic when ascending or descending inclines and overcoming wind resistance. In the MLS, this would be simulated by the motor driven axles working against the frictional resistance of the system. Additional adjustable-level friction could be imposed between the steel wheel and the steel beam (braking), as this would increase the simulation of longitudinal shoving (actual vehicle acceleration or braking). The shoving action could also be increased by having fewer driving axles to overcome the total friction at the same speed.

Environmental simulation could be achieved by utilizing the box-like structure of the MLS, which is closed on the sides, ends, and top. An environmental chamber would thus be provided where a certain degree of heating or cooling could be induced to the pavement.

5.4.3. TRANSPORTATION OPTIONS

Site establishment can be involved and time-consuming, and the challenge is to minimize this aspect of MLS operation through innovative design. These designs should facilitate transportation of the machine as complete and ready for testing as possible.

Utilizing the allowable legal lengths for a double trailer of 48 feet plus 48 feet or 56 feet for single semi-trailer, the machine is transported in sections over long distances. Figure 5.2 shows the possibilities for transportation in states that allow longer vehicles. Provided that sufficient clearances exist for the negotiation of most vertical curves and bridging structures, a viable strategy is to

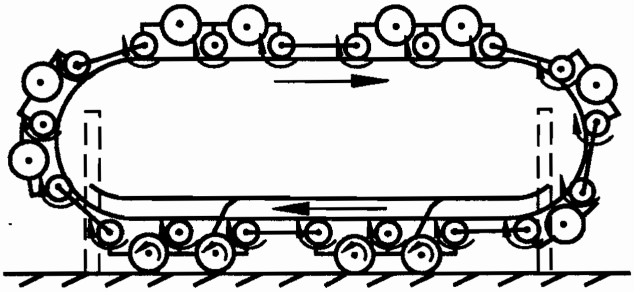
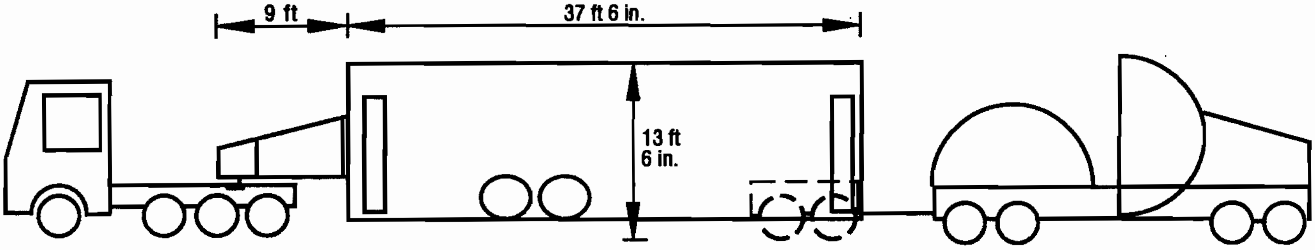
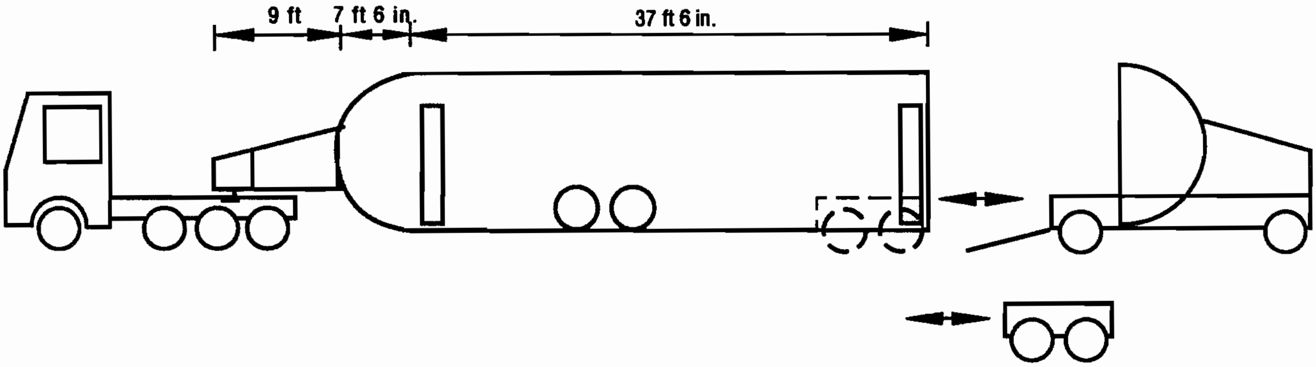


Fig 5.1. Conceptual layout of the MLS.



Legal Dimensions (Vertically Collapsed) for Long Haul on National Basis



Legal Long Haul Option in Texas (Vertically Collapsed)

Fig 5.2. Mobility options.

transport the machine intact. Permits for the transportation of oversized construction vehicles are issued in many states.

5.4.4. ANCILLARY EVALUATION OF TEST SECTIONS

This aspect of the operation could be addressed in various ways which would allow for the clearing of the pavement for measurements. Methods range from simply retracting the supports and hauling the machine longitudinally off the section, to jacking the test frame vertically. Specific site conditions could eliminate some of the options.

Lateral movement might not be possible on sites where shoulders are insufficient. Lengthwise removal can be a problem on sites where the length of the total test section plus the required length for on and off maneuvering is detrimental to road user safety or traffic flow. Lifting the machine vertically could result in stability problems owing to excessive bearing pressures which might result in differential settlement of the footings.

5.5. MLS JUSTIFICATION

An accelerated pavement testing machine can be an essential item in the permanent inventory of progressive pavement agencies. Some mobile accelerated pavement testing devices are in existence and are compared in Table 5.1. In Table 5.2, the applicability of the respective machines for testing various pavement aspects is indicated.

The most significant MLS benefit is the high rate of real load application in contrast to other systems which require overloading to accelerate the loading process. Using the expertise available from the other two programs, the implementation of the Texas MLS program should prove to be a quantum step in pavement engineering knowledge.

5.5.1. COMPARISON BETWEEN LINEAR MOBILE ACCELERATED PAVEMENT TESTERS

A comparative evaluation can be done on the three mobile accelerated pavement testing machines, as set out in Table 5.1. The most noticeable difference lies in the magnitude of wheel loads that are applied to the pavement to facilitate the necessary acceleration of the testing process. In the case of the ALF, the ballasts that are carried with the rolling wheel have a certain power requirement. In other words, for a certain motor capacity, a specific optimum exists as far as load and rate of load application are concerned. This stipulation poses a severe limitation on some aspects of pavement experimentation. It implies that the effect of

TABLE 5.1. COMPARISON OF CHARACTERISTICS OF VEHICLE SIMULATORS

	ALF	HVS	MLS
Test Loads/Axle (kip)			
Single/Dual Wheel	9.4 - 37.9	4.5 - 45	6 - 25
Test Wheel Size			
Single/Dual	11 x 22.5	14 x 20	11 x 22.5
Wheel Speed (mph)	12	8	20
Rep/Hour	380	1,200	10,920
Trafficked Length	40	32.8	35
Lateral Displacement			
of Test Wheels (ft)	26.5	4.9	3
Other Lengths (ft)			
Testing	92.6	74.15	60
Transportation	98.4	74.15	48 + 48
Overall Width (ft)	13.8	12.2	11
Overall Height (ft)			
Testing	22	13.8	17
Transportation	14.4	n/a	13.5
Total Mass (kips)	123	125	130

TABLE 5.2. APPLICABILITY OF TESTING DEVICES IN RELATION TO THE STUDY OF ENVIRONMENTAL AND LOAD FACTORS

Test Factors (Variables)	ALF	HVS	MLS Model	MLS Prototype
Environmental Factors				
1) Surficial Water (Artificial)	Q/P	Q/P		
2) Sub-Surface Water	Q/P	Q/P	N	
3) Artificial Environment and Accelerated Load	N			Q/P
4) Wind				
5) Temperature				
6) Humidity				
Load Factors				
1) Speed of Wheel Loads	N	N		
2) Dynamic Wheel Loads	Q/P	N	Q/P	
3) Selected Wheel Loads				
4) Multi-Axle Loads	N	N		
5) Actual Traffic Loads	N	N	N	
6) Selected Traffic Loads	Q/P	Q/P	N	
7) Selected Tire Type			N	
8) Selected Tire Pressure			N	
9) Lateral Load Distribution				
10) Axle Equivalancy	Q/P	Q/P	Q/P	
11) Suspension Type		N	N	
12) Overloads			N	

Key:
Q/P = Questionable or Partial Appl., N = Non-applicability, Open = Applicable

speed and load cannot be varied and studied independently.

A limitation with the HVS is the variation in speed of the wheel travelling across the test section. The wheel is pulled back and forth along the section, accelerating to a maximum of 8 miles per hour, decelerating, stopping, and changing direction. No experimentation was done with the HVS to evaluate the effect of wheel speed on pavements, which has been shown to have an effect on pavement distress (26). Furthermore, even though the HVS has the capability of simulating unidirectional traffic by applying lighter loads in one direction, this is not normally attempted because of the low rate of load application achievable through this method of testing.

In the development of the MLS prototype, both the above limitations must be addressed. This can be done by designing conservatively for power requirements and incorporating features that will allow easy adaptation to different axle configurations and loads.

5.5.2. A COMPARISON BETWEEN METHOD OF LOAD APPLICATIONS OF HVS, ALF, AND MLS

It can be seen in Fig 5.3 that differences exist in the methods of load application and that the best features of both the HVS and the ALF are contained in the MLS. A further improvement is the higher number of axles used with the MLS, which greatly increases the rate at which loads can be applied to a pavement.

Table 5.1 presents a dimensional comparison between the different machines. These numbers show current or estimated operational dimensions in the case of the MLS. The high rate of repetitions per hour is notable in the case of the MLS, and is based on a testing speed of 20 mph.

Because of the differences in their methods of loading, differences exist in the experimental applicability of the individual machines. These factors and their respective implications are shown in Tables 5.2, 5.3, and 5.4.

Evaluation of environmental factors in Table 5.2 may be partially realizable, and can vary from a small segment of the test section being subjected to environmental influences to total enclosure of the machine. The HVS lends itself well to the utilization of environmental chambers that can be built around the structure. In the cases of the MLS and the ALF, an environmental chamber will have to contain the whole machine and may prove to be cost-prohibitive. A discussion of this aspect of accelerated pavement testing, with the MLS in mind, is contained in section 8.4.1. Surface and subsurface water under overload conditions, as with ALF and HVS, does not provide reliable answers and is noted as questionable for evaluation as a variable.

Load factors in Table 5.2, and the study thereof, depend on the degree of overloading as compared to real traffic conditions. Reliable results can still be achieved in comparative studies, but projections of actual traffic conditions are not attempted in the cases of the ALF and the HVS. The proposed MLS does not make use of overloads to achieve acceleration and therefore finds more application in the evaluation of load factors.

For the same reasons as indicated above, material and construction factors shown in Table 5.3 can be evaluated to some degree by all the machines. Where overloading is the mode for achievement of accelerated pavement testing, only comparative studies are performed. Construction factors must always be taken into consideration as an interactive variable in the experimental design. Evaluation of construction variation can be observed in the uneven deformation of pavements that cannot be attributed to the testing method or to other material factors. The length of the test section is important, because a longer test section will yield more degrees of freedom in the statistical evaluation of this factor.

All structural factors in Table 5.3 can be evaluated comparatively by all the machines. These factors may all require a certain degree of overloading to obtain faster results. In the case of fatigue studies, the degree of overloading is critical, as are following distances, load duration, rest periods, and residual stresses.

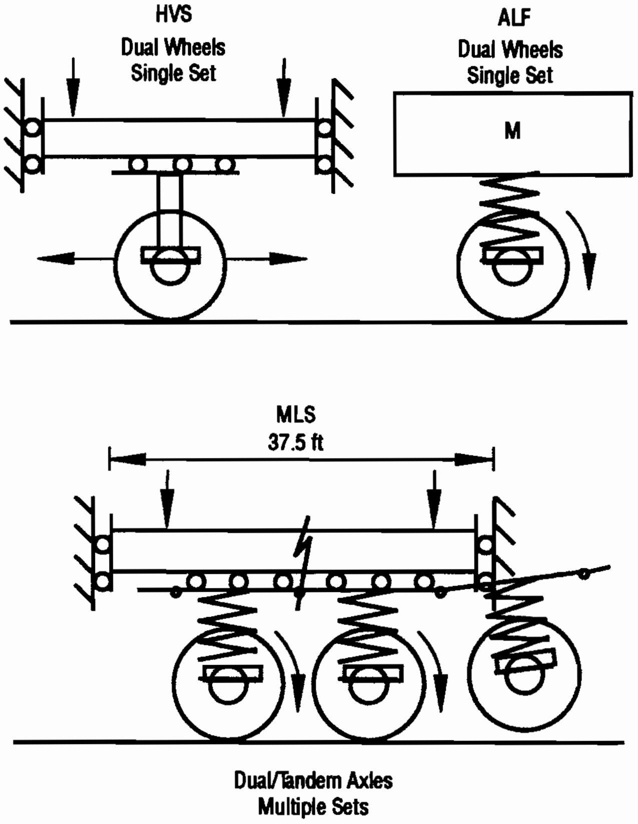


Fig 5.3. A comparison between methods of load applications of HVS, ALF, and MLS.

Pavement performance and evaluation of rehabilitation strategies and design, shown in Table 5.4, comprise one of the major areas of application for mobile accelerated pavement testers. In this respect, mostly comparative studies are made. Remaining life of the pavements will, therefore, be an important utilization of the MLS. Because of its higher degree of real load simulation, experimenters will be more confident in evaluating remaining life and performing correlations with other non-destructive pavement testing devices in conjunction with MLS testing.

Peripheral pavement testing can take place simultaneously with other testing to augment the utilization of a machine. This approach would be mainly applicable to the MLS owing to stress sensitivities of materials. This type of testing should be attempted in a joint effort with industries, such as road markings manufacturers and the heavy vehicle construction industries, for the evaluation of suspension components.

5.6. DATA COLLECTION PLANNING AND SYNTHESIS

In a broad review of data needs both now and in the future, the FHWA Long-Term Pavement Performance Subcommittee on Instrumentation (35) recognized that there is a need for the development of a pavement instrumentation plan. Such a plan will be equally applicable to accelerated testing, and factors to be considered in such a plan include

(1) theory (linear, non-linear, visco-elastic);
(2) loads, climate, and other contributory factors;
(3) background data (in-situ material properties and potential changes in those properties);
(4) pavement performance data (roughness, distress);
(5) instrumentation (sensors, replication, service life, security);
(6) data handling (collection, reduction, storage); and
(7) training (installation, operation).

From the extent of the above list, a conclusion could be drawn that pavement instrumentation, whether LTPP studies or accelerated testing, should be undertaken when a clear purpose exists for the application of the data. The means must also exist not only to record but also to reduce and store the data for recall and analysis. Data collected require extensive handling and manipulation and will in many cases be filed without being utilized. Therefore, the purpose, scope, and utilization of equipment should be very well defined *before* application in accelerated pavement testing. Applicable theory, the models to describe the physical behavior of materials in a structure, and pavement loading are important issues which must be considered in light of the capabilities of measuring instruments. Measurements of traffic and pavement interaction are made to generate input values for the models and must be executed bearing in mind the type of loading and the theoretical model that best describes the material reaction.

5.6.1. INSTRUMENTATION

Pavement instrumentation can be classified according to data collected through its use. These data fall into one of the following categories:

(1) responsive attributes, i.e., behavior (loads, stresses, strains, deflections, deformations, pore-pressures);
(2) background data (CBR, FWD, plate bearing, moisture/density); and
(3) condition (roughness, cracking, rutting, patching).

Measurements of behavior utilize strain gages, linear variable differential transducers (LVDTs), inductance coils, velocity gages, accelerometers, pressure cells, pore pressure cells, fixed reference points, or some combination thereof.

TABLE 5.3. APPLICABILITY OF TESTING DEVICES IN RELATION TO THE STUDY OF MATERIAL, CONSTRUCTION, AND STRUCTURAL FACTORS

Test Factors (Variables)	ALF	HVS	MLS Model	MLS Prototype
Material and Constuction				
1) Material Layer System	Q/P	Q/P	N	
2) Micro Material Structure	Q/P	Q/P		
3) Material Anisotropy				
4) Subgrade Compaction	Q/P	Q/P	N	
5) Subgrade Stiffness	Q/P	Q/P	N	
6) Subgrade Plastic Behavior	Q/P	N	N	
7) Friction Between Layers	Q/P	N	N	
8) Application of Rejuvenators				
9) New Materials/Mixtures				
10) D-Cracking			N	
11) Construction Variation			N	
12) Flexible Bases	Q/P	Q/P	N	
13) Lime-Treated Bases	Q/P	Q/P	N	
14) Cement-Treated Bases	Q/P	Q/P	N	
15) Recycled Asphalt				
Structural Factors				
1) Structural Systems			N	
2) Voids Beneath Concrete			Q/P	
3) Effect of Shoulders			N	
4) Balanced Structural Composition			N	

Key:
Q/P = Questionable or Partial Appl., N = Non-applicability, Open = Applicable

Current pavement instrumentation technology is relatively labor intensive. Operation of instrumentation involves sensor maintenance and calibration as well as on-site operation of data recording and storage equipment and, potentially, data analysis. It is felt that the infrequent use of pavement instrumentation has resulted in a lack of innovation in instrumentation and data collection. Pavement research associated with SHRP and accelerated pavement testing may provide the motivation to develop electronic and telemetry packages that would allow options such as self-calibration of sensors and on-site storage with periodic data transmission by telephone lines. These techniques are constantly being improved, and research using accelerated testing can benefit greatly from the use of these innovations, which will lead to the development of appropriate new packages.

5.6.1.1. Strain Gages

Electrical strain gages are the most widely used devices for measuring strain in pavements. However, they must be attached to or embedded in the cemented layer of the pavement in which the strain is to be measured. Strain gages must be oriented properly in order to measure strain. The primary orientations of interest for flexible pavements are parallel and transverse to the direction of traffic. Strain gage orientation for rigid pavements is primarily parallel or transverse to a key feature of the pavement, i.e., a joint or an edge.

Strain gages are generally selected on the basis of their length, and, for pavement application, this length varies from 1 to 6 inches. The length selected for a specific pavement should be based on the maximum aggregate size of the layer to be evaluated. As a rule of thumb, the gage should be two to four times the maximum aggregate size. This length of gage will ensure that the strain will reflect a strain in the combined matrix of the mixture including aggregate and mortar. A length of 4 inches for asphalt and 6 inches for concrete is considered adequate.

Experience has shown that the survivability of surface or internally-mounted strain gages is poor. Surface mounted gages are placed in 1/4-inch-deep grooves, which improves durability. To minimize gage loss during construction, it was decided at the Nardo Test in Italy that

(1) the temperature of the as-placed mix should not exceed 266°F,

(2) rubber-tired rollers would be used, and

(3) vibratory compaction would not be used.

In the Nardo experiment, the survival rate of the gages was generally better than the expected loss rate of 50 percent. Other than being a result of taking the above precautions, this finding could also be due to the high air void ratio and the extra care taken during placing. The Australian team (ARR142) reported high losses, especially on the bottom layer. After additional protection was added, the survival rate improved greatly.

5.6.1.2. Deflection Gages

Deflection gages record deflection and deformation in a pavement structure and generally are fixed at the surface (total deflection) or at different depths (multi-depth deflection) in the pavement layers; they record the movement at the point of fixture relative to a rod that is embedded at a reference depth (6 to 20 feet) which is not expected to deflect noticeably. Sensitivity of the gage depends on the maximum displacement that can be measured; for example, a gage that can accommodate a large displacements has low sensitivity and cannot detect small deflections. The opposite is also true, and overstrain of sensitive gages can easily occur. For instance, the analysis of deflection bowls requires sensitive gages around the outside of the bowl and less sensitive ones towards

TABLE 5.4. APPLICABILITY OF TESTING DEVICES IN RELATION TO THE STUDY OF PAVEMENT PERFORMANCE AND PERIPHERAL ASPECTS

Test Factors (Variables)	ALF	HVS	MLS Model	MLS Prototype
Pavement Management and Performance				
1) Maintenance Strategies			N	
2) Rehabilitation Strategies			N	
3) Load Transfer in Joints	Q/P	Q/P	N	
4) Percent Steel	Q/P	Q/P	N	
5) Stripping of Asphalt	Q/P	Q/P		
6) Rutting	Q/P	Q/P		
7) Skid Resistance	Q/P	N	Q/P	
8) Wear of Aggregate	Q/P	N	Q/P	Q/P
9) Steel Concrete Bond	Q/P	Q/P	N	Q/P
10) Concrete Joint Behavior	Q/P	Q/P	N	
11) Fatigue Cracking	Q/P	Q/P	Q/P	
12) Structural Condition	Q/P	Q/P	N	
13) Surface Condition	Q/P	Q/P	N	
14) Residual Life	Q/P	Q/P	N	
15) Delamination			N	
16) Pavement Performance (PSI)	Q/P	Q/P	N	
Peripheral Pavement Engineering				
1) Traffic Monitoring Devices	N	N	N	
2) Durability of Road Markings	N	N	N	
3) Effects of Gradients	N	N	N	
4) Tire Types	Q/P	Q/P	N	

Key:
Q/P = Questionable or Partial Appl., N = Non-applicability, Open = Applicable

the center. When speeds are evaluated, on smooth pavements, large deflections are expected under stationary or low-speed loads. Deflections under higher speeds are expected to decrease.

5.6.1.3. Horizontal Movements

Measurement of horizontal movements of rigid pavement provides data on the effect of openings at cracks and joints on load transfer. These types of measurements help to determine joint sealer reservoir requirements, and cumulative movement of cracks and joints sets criteria for contraction or expansion joints. Usually, horizontal movement is measured by installing survey points at various places on the surface or across cracks or joints.

5.6.1.4. Pressure Cells

The use of pressure cells in pavements has not generally been successful, with the exception of pressure cells designed by the U. S. Army Corps of Engineers Waterways Experiment Station. These are the WES Soil Pressure Cells, which are designed to measure the average stress on the gage face-plate, and the SE Soil Pressure Cell, which is designed to measure dynamic stresses.

5.6.1.5. Pore Pressure Cells

Analysis of the state of stress in a pavement foundation requires consideration of the state of saturation of the structure. If changing pore water pressure conditions exist, pore pressures would be expected to modify the state of stress in the foundation and make the difference between a total or an effective stress analysis.

5.6.1.6. Temperature

Field testing involving measurement of pavement temperatures has utilized thermistors, thermocouples, or a solid-state resistance sensor. Temperatures can be logged periodically or continuously. Pavement temperatures can change rapidly in the shade of clouds or testing equipment. It may often be necessary to apply additional heating to a pavement in a shaded area to simulate direct sun or even to accelerate the effect of radiation. Temperatures must also be measured at strain gage positions. Also, specific attention should be given to the placement for subsequent analysis of sensors in asphalt overlays of concrete. Because of the black surface, the temperature range of the underlying concrete pavement may be substantially higher than normal.

5.6.1.7. Moisture and Density

The areas of interest with respect to moisture and accelerated pavement testing are the moisture content in the various structural layers and the moisture content in the foundation of the pavement structure. Moisture content and density in large part establish the strength of the materials. For moisture content measurements, destructive, direct sampling and nuclear methods appear to be most satisfactory. Measurements of the moisture content in the subgrade material are essential in the design, since these values will affect the level of frost heave and consolidation or compaction that will be experienced.

5.6.2. TESTING ON TEST TRACKS VERSUS IN-SERVICE PAVEMENTS

The number and complexity of measurements in test tracks and in-service pavements differ due to the type of instrumentation that can be installed. When test tracks are laid, instrumentation, such as strain gages, can be placed during the construction phase to provide results of the changes that occur during the evaluation of the section. In-service pavement measurements are limited to the types of instruments that can be placed without altering the existing condition of the pavement too severely. One such device is the multi-depth deflection gage, developed in South Africa.

5.6.2.1. Measurements on Test Tracks (34)

In the evaluation of specially-constructed test tracks, the stages have been identified during which the respective measurements and observations are frequently made. Environmental readings are taken throughout the test. Furthermore, it is also feasible to monitor the stiffness of the pavement layers throughout the test using seismic technology. The stages, measurements, and observations are as follows:

(1) Before construction of the pavement: subgrade characterization tests and depth of frost penetration.
(2) During construction of the pavement: elastic modulus testing on base materials, bound layers, and surfacing.
(3) After construction of the pavement: surface profile, degree of compaction, moisture contents, and bearing capacity.
(4) During loading of the pavement: pavement temperature, rutting, deflection, pavement stresses and strains, visual evaluation, and number of loads.
(5) After loading of the pavement taking non-destructive test measurements: surface profile, rutting, compaction, failure condition, and general condition surveying.
(6) During removal or replacement of the test pavement changes: in aggregate gradations, elastic moduli, binder and penetration, and bonding between layers are evaluated.

Environmental readings are taken throughout the test duration. Furthermore, it is also feasible to monitor the stiffness of the pavement layers throughout the duration of the test using seismic technology.

The purpose of the test and the failure criteria used will dictate what measurements are made with respect to pavement performance. The fatigue criterion can be adopted—i.e., choose to measure strain in the pavement; or, on the other hand, choose to evaluate cracking and/or the surface profile of the pavement to determine performance. Because of uncertainty as to which failure mode will be decisive, a range of measurements is usually made.

5.6.2.2. Measurements on In-Service Pavements

When in-service pavements are to be evaluated, it is first necessary to identify the specific research problem, after which a pavement or sections of a specific pavement must be located that will be suitable for both accelerated testing and for evaluation of the specific problem and that will also conform to certain safety and aesthetic requirements. This means that pavements must be selected which combine the relevant independent variables in a suitable way. Typically, the variables which need be considered are

(1) pavement type,
(2) materials used,
(3) different layer thicknesses,
(4) age and performance data of the pavement,
(5) topographical and drainage conditions,
(6) climatic conditions,
(7) safety, such as site distances to the elected site, and
(8) location or availability of services.

Naturally, such selection processes must include close collaboration with local and state authorities and are dependent both on construction completion records and on the experience of the local authorities' engineers.

Once a road that suitably combines all the relevant variables has been selected, it becomes necessary to choose a precise location for the tests. Here the problem is to ensure that such a site is truly representative, either of the pavement as a whole or of the problem. For this reason emphasis is placed on the use of statistically-based selection procedures.

Based upon the problem to be investigated, a number of sites, each 10 to 20 yards in length, are selected, using a visual survey, on a specific length of roadway. Through subjective evaluation of each section with respect to safety variables, such as sight distance and pavement width, the number of candidate sections will be considerably reduced. This leads to the second phase, in which the remaining sites are intensively surveyed. These surveys include the faster, non-destructive testing methods, such as Dynaflect measurements; permanent deformation measurements, such as rut depths; and roughness measurements. By rating the suitability of each section in terms of the pavement condition or of the problem to be evaluated, a further reduction can be accomplished by weight allocation of the pertinent variables and by a statistical selection. In the third step, the object is to reduce the number of test sections further so that the available number of sections ranges from three to six. This would allow adequate correlation studies to be undertaken between the sites to ensure a high degree of reliability. Such studies involves trial borings and the opening of test pits to sample material and measure thicknesses. Non-destructive tests and in-situ density tests may also be conducted at this stage.

After completion of the test program, the pavement is normally subjected to a final set of measurements using the elected performance indicators. During the accelerated testing, many changes may have been induced into the pavement structure to enhance the effect of the acceleration. For instance, water may have been allowed to saturate the pavement layers at a certain rate; extreme temperature conditions may have been induced; or aggregate properties may have changed. Test pits are excavated so that visual inspections can take place, and this also provides an opportunity to examine the end-of-life condition of the structure by performing in-situ testing and taking samples for analysis at various depths. These findings will be compared with values obtained through the evaluation of the control sections.

The final step is to reconstruct the pavement section through acceptable construction techniques and open it to traffic.

5.6.3. DATA HANDLING

Several approaches may be followed in data handling. A minimum on-site data handling system could consist of a power source, signal conditioners for the sensors, and a recorder. The data are processed at a central location. If the data are collected in analog form, then they have to be digitized for computer processing. The process of sampling the data provides some filtering, but the best way to filter the data is with an analog filter prior to digitizing. A multiple Bessel filter is satisfactory. Digital filters can truncate data if the window of sampling is not properly selected. An alternate method of filtering the data includes an electronic filter in the data collection system. Digital acquisition systems should be selected based on the number of channels of data and the desired sampling frequency.

An expanded data handling system may combine data collection with on-site data reduction, analysis, and storage. Two examples of an expanded system are those used in LTPP studies by the Construction Technology Laboratories, Portland Cement Association (PCA) and the Alberta Research Council (35). Both organizations have complete systems installed in motor homes, which include a variety of software that supports data reduction, analysis, and presentation.

Standards need to be set for data collection (i.e., what is measured, how, when, where, and with what). Sample selection procedures, frequency, and quality controls need to be set. Where possible, peripheral testing equipment must be standardized and a process for equipment calibration must be established.

Development of new or improved data collection methods, such as the use of infrared, radar, sonar, lasers, photography, video, radio, fiber optics, and other technologies to permit faster and better sensing, recording, and transmission of data, must be encouraged. As stated at the 1984 FHWA Pavement Testing Conference: "The development of computer-based expert systems in which computer programs emulate the problem-solving behavior of human experts by interrogation, interpretation, inference, diagnosis, prescription, and recommendation holds much promise."

5.6.3.1. Redundancy and Replication

Redundancy suggests multiple gages which would compensate for failure of one or perhaps more sensors or gage installations and would insure data at a given location or feature. Replication, on the other hand, refers to different sites that are similarly instrumented at the same level of redundancy. Replication is considered only where various sites are to be compared, either through testing or for calibration purposes. Accounting for the variability in this fashion will enhance the statistical significance of the data.

The measured response of flexible pavements depends on where the load is located with respect to the gages, and multiple gages would improve the chances of accurately measuring peak responses over a randomly-distributed tracking path. In such cases redundancy can compensate for gage failure, enhance the collection data, and provide variability of the data. On the other hand, instrumentation is installed in rigid pavements to measure the response of key features, such as mid-slab, edge joint, or crack. In this case, redundancy will compensate for gage failure and will also measure distribution and variability of responses.

When placed in test pavements, sensors or gages that are not accessible (such as strain gages, pressure cells, and pore pressure gages) have proved satisfactory with a redundancy of three sensors. This redundancy has also proved satisfactory for obtaining peak response values of flexible pavements with deflection gages. Accessible gages, such as deflection gages and temperature sensors, can be repaired or reinstalled without difficulty. For example, one deflection gage may be installed at each key feature of a rigid pavement slab.

Instrumentation for both rigid and flexible pavements should be selected based on uniformity of the pavement section both in depth and in extent. Replication through flexible pavement instrumentation is frequently not achievable. This lack of replication has masked the variability in data collected from supposedly homogeneous pavement sections. On the other hand, instrumentation of at least three slabs has been a common practice for rigid pavements and has provided limited replication within a site.

5.6.3.2. Environmental Data

Collection of pavement instrumentation data can be specific, e.g., to evaluate load equivalency, or more general, e.g., to study seasonal changes in pavement response. In the latter case, data might be collected at three or four specific times of the year or even on an hourly basis. The former can be spring, late summer/fall, and winter, or it can be winter, transitional, summer, and transitional. Hourly measurements are often made immediately after placement of PCC pavements. In climates where spring thaw is a factor, temperature measurements may help to identify the critical period of thaw.

Accelerated testing lends itself perfectly to the evaluation of the strength of pavement structures during the various seasonal changes, according to Miner's Law. This evaluation is performed by accelerated loading only under specific seasonal conditions. If a pavement is expected to carry a certain number of loads during spring thaw, that number of accelerated loads can be applied in one or two sessions of spring thaw condition.

Climatic data can be recorded using a complete package or using a system built with components. The following parameters are generally used:

(1) air temperature,
(2) humidity,
(3) wind speed,
(4) wind direction,
(5) solar radiation,
(6) precipitation,
(7) soil temperatures,
(8) soil moisture, and
(9) cloud cover.

These collection units have internal processors which collect the data and transmit the data to a central processor. In the second case, a customized unit can be assembled by obtaining components from various suppliers.

5.6.4. MEASURING SYSTEMS AND METHODOLOGIES

Researchers are very familiar with the problems of making measurements on pavements, and many attempts have been made to gather all the information on the need for various measurements, the techniques used, and the interpretation of results.

The aim of a full-scale pavement test determines the type of measurements to be made. There will always be a number of similar measurements and a number of special measurements for different tests. For example, the characterization of soils and assessments of paving materials are generally made using well-established and reliable techniques; and if vehicle suspensions, road markings, or structural capacities of bridging structures are to be evaluated, a set of special measurements will be needed.

Current trends in pavement data acquisition are mainly to speed up the sampling rates, increase reliability, and increase rates of data synthesis, storage, and handling. Pavement data include measurements of deflection, riding comfort or roughness, distress, surface friction, and traffic volumes and weights. According to a study by Hudson (27), advances in pavement evaluation technologies include

(1) seismic and dynamic test methods,
(2) radar,
(3) sonic and ultrasonic testing,
(4) laser,
(5) thermal infrared photography,
(6) continuous 35mm photography, and
(7) video.

Many of these systems could be used and correlated with one another in the proposed MLS program. New methods could also be evaluated for accuracy and ease of application. Until now, many of the traditional methods for measuring roughness and surface profiling have proved to be inadequate with mobile accelerated pavement testing because of the short testing lengths. However, new measuring techniques make it feasible to determine reliably the surface profile and the consequential PSI over much shorter lengths.

It was stated in a 1988 publication on the Pavement Testing Facility (14) that the evaluation of the PSI calculated using the AASHTO equation showed that the slope variance term is the predominant factor in the reduction of the PSI. The calculated slope variances were sensitive to the accuracy of the longitudinal profile measurements, which were based upon rod and level readings estimated to the nearest 0.001 foot. Furthermore, it was stated that the addition of an automatic profiling system in the next cycle should significantly improve the precision of the profiles and should make it possible to obtain more reliable PSI values for the test sections, or even for partial test sections.

Most pavement authorities use full-scale pavement testing facilities to provide information of a basic research nature on the effects of changes in material mixtures—for example, on the damaging influence of wheel loads or the rutting potential of an improved mixture. The information is used to compare the performances of new or improved pavement materials or construction methods or to assist in the development of pavement design methods. In Canada, for instance, a full-scale testing facility has been used in the evaluation of concrete bridge deck panels.

The purpose of the test will usually also determine the method elected for the evaluation of the performance, but this will be influenced as well by modes of failure of roads in service in a particular area. Some institutions adopt only one criterion of failure throughout (31). Most adopt one of three or four criteria, depending on the purpose of the test being undertaken, to serve as the leading indicator, with the rest serving as secondary indicators of performance. In Italy, fatigue of the bound layer is the only criterion of failure, whereas in Germany only permanent deformation (rutting) is used. Several countries use failure criteria in combination. Canada, for instance, monitors surface abrasion and loss of aggregate in surface dressings with deformation and roughness. The longitudinal profile of the tested pavement is used in Switzerland as a measure of pavement performance, while roughness, rutting, and fatigue are used as failure criteria in Denmark. Studies of the mode of failure were undertaken in France to improve the choice of failure criteria for pavement tests in that country.

In order to bring about failure of the test pavement in a reasonable time, most facilities introduce some means of accelerating the test. This may take the form of overloading, a higher rate of load applications than would normally be experienced by the pavement in service, or the use of a test pavement deliberately constructed with lower structural numbers to fail after a relatively short time. The aim is to get faster results that can be extrapolated for application in other pavements. Most OECD countries adopt the latter technique and associate this with tests on pavements of normal thickness in order to calibrate the accelerated results (46). These techniques usually require large shift factors to relate to standard pavements, reducing the credibility and reliability of the findings. The stress-dependent behavior of materials in the pavement structure is very sensitive to the changes mentioned above, and adequate knowledge to describe this phenomenon is not yet available

5.7. RECOMMENDATIONS AND CONCLUSIONS

The MLS steering committee recognized that development of the MLS would be undertaken in close collaboration with personnel who are part of other accelerated pavement testing programs, in order to benefit from their experience on mechanics, data acquisition and synthesis, and organization in general.

The publication and distribution of a technical brochure (Appendix B) on the MLS, to pavement agencies, generated a great deal of interest on a nationwide and international basis. The SDHPT can undertake the development of the equipment in conjunction with another pavement agency or agencies, although this may lead to complications regarding allotment of equipment and payment of royalties to developers and non-developers. Future costs for MLS testing by non-developing agencies have not been established at this juncture.

Application of the model MLS for purposes other than demonstration of mechanical feasibility and generation of interest in the program, such as on modelled pavements, was met with mixed reaction by the steering committee. However, it is the opinion of the authors that materials testing with the model would be especially beneficial in comparative studies of asphaltic surfacing. Although modelled material evaluation falls outside the scope of this report, an analytical comparison was made between real and down-scaled loads; this is presented in Chapter 7.

In Chapter 5, the reason for the decision to proceed with the acquisition of an MLS was explained. The decision was based on the proof of mechanical feasibility demonstrated by the model MLS and the knowledge that the full-scale MLS would more closely simulate real traffic than the HVS or the ALF. However, it is necessary to study real loads to enable researchers to evaluate the degree of real load simulation of the MLS. For this purpose, Chapter 6 discusses pertinent facts concerning real truck loads.

CHAPTER 6. FACTORS INFLUENCING THE SIMULATION OF AXLE LOADS

6.1. INTRODUCTION

Loads are an important factor contributing to pavement distress, and the main purpose of accelerated pavement testing is to intensify the rate of axle loading for a specific section of pavement. In order to achieve acceptability of and recognition for findings stemming from accelerated pavement testing, real loads must be simulated as closely as possible. For this reason, it is necessary to define the characteristics of real loading conditions, which include magnitude, amount and character of traffic, tire pressures, and location of loading.

After presenting an overview of pavement distress, this chapter proceeds to discuss some of the regulations that limit axle loading. It then proceeds to evaluate lateral load distribution of truck axles, mechanical aspects that concern load simulation, and some aspects of dynamic wheel loads.

6.2. PAVEMENT DISTRESS

When assessing pavement damage due to heavy vehicles, a distinction must be made between surface and structural distress. Structural characteristics of pavements are random variables of which the probability density functions vary in space and change with time and accumulated use of the facility. The aging and damage that affect pavement behavior can range from simple surface defects to complete loss of structural capacity. Both aging and damage are distinct phenomena influenced by different factors, although their simultaneous occurrence and the resulting interactions make pavement behavior very complex to model. Accelerated testing of pavements involving environmental factors, other than temperature (and, partially, surface moisture), does not seem to be feasible. Therefore, the central role and application of accelerated pavement testing lies in the study of the various mechanisms of pavement deterioration under traffic loading and the generation of data for the development of analytical methods. The development of such analytical methods based on accelerated testing must consider two sources of uncertainties, namely,

- uncertainties in the structure under environmental and traffic loading conditions and
- uncertainties that are part of the accelerated testing method.

Structural distress is caused by loads affecting the pavement courses, including the subgrade soil. It results from inadequate structural strength (design), adverse weather conditions, and the use of materials that are unsuitable for the prevailing traffic. The most typical modes of structural distress are fatigue cracking in bound courses and permanent deformation of bituminous courses, unbound base layers, and subgrades.

With respect to structural distress, the notion of equivalence between loads in terms of the damage they cause was developed as part of the AASHO Road Test and is now in general use throughout the world. The equivalence is expressed in the form of a law:

$$(N_i/N_j) = (P_j/P_i)^{\gamma} \qquad (6.1)$$

where

N_i = number of loads of magnitude P_i to cause failure,
N_j = number of standard loads of magnitude P_j, and
γ = load equivalency factor (LEF).

As applied to a specific type of pavement structure (flexible or rigid), this load equivalence law is practically unaffected by climatic conditions, due to the fact that the test was conducted over a period of two years. The load equivalence equation was developed from different pavement structures subjected to traffic loads, and an equivalence between loads, expressed by their magnitude and the number of applications, was established.

The relationship greatly simplified the approaches toward rational pavement design, i.e., the calculation of pavement thickness as a function of subgrade strengths, traffic, and climate. It opened up the possibility of replacing actual traffic data, e.g., loads and number of applications, by theoretical traffic loads having equivalent damage potential. In making this conversion, use is made of a specified standard load recurring a number of times. For the purpose of practical application worldwide, however, there were a number of problems because of certain characteristics of the AASHO test, such as the types of materials used, the loads applied, and the prevailing climates. There was, therefore, a need to assess the general validity of the AASHO results.

Recent interpretations of the AASHO test have complicated the situation even further, since it was shown that there is a different load equivalence factor for each distress mechanism, for each type of pavement, and for each climactic zone. Detailed studies undertaken by OECD countries have shown that, notwithstanding the recent complications of this law, it still remains valid and practical for most purposes, provided that a distinction is made between different types of pavements. It is accepted that this relationship is not a physical law but a statistical relationship. This conclusion is not surprising in view of road building materials and the statistical nature of the distress mechanisms. In three studies (31)—in Nardo, Italy; Virtaa, Finland; and Nantes, France—conducted to investigate the destructive effect of heavy vehicles, it was found that load equivalence is associated not only with loads but also with pavement structures, the properties of their constituent materials, and the distress mechanisms to which they are subject.

The wide dispersion of load equivalence methods, using the fourth-power approach as shown by Yoder and Witczak, is an indication of the inadequacy of using only the fourth-power rule for all structures and traffic loading conditions. These finding were also confirmed at the 69th Annual Meeting of the Transportation Research Board (TRB) in 1990. Using an extension of load equivalence for different pavement conditions, Uzdan and Sidess (53) showed that the dependence of LEF on pavement condition is similar and milder for multiple wheel loads than for single and tandem axles. It was also reflected by Kenis and Cobb (54) that a number of factors such as axle spacings, vehicle spacings, transverse position of the vehicle on the pavement, speed, and tire pressures were not evaluated during the AASHO test, from which the fourth-power law was derived. These factors all can now be simulated and assessed through accelerated pavement testing, as proved by HVS testing (6).

Detailed knowledge of actual traffic loads is required before the proposed MLS program can provide accurate estimations of traffic impacts on pavements. Even though the proposed system is estimated to be a major advance in pavement engineering, its limitations and its actual degree of real traffic simulation must be recognized and its components and working evaluated against the real traffic components that it is meant to duplicate and accelerate.

6.3. REGULATIONS ON AXLE LOADS OF TRUCKS

Legal controls of trucks are separated into two groups: one governs dimensions and the other governs axle weights. These are important considerations in the proposed MLS program, because (1) the testing should represent real traffic as closely as possible and (2) the mobility of the machine renders it subject to the national pavement regulations. For the latter reason, all mechanical aspects are based on the assumption that the MLS will be legally transportable.

The first Federal control was established in 1956 (12). This act provided for a maximum of 18,000 pounds on single axles, 32,000 on tandem axles, 73,280 pounds overall gross weight, and a 96-inch width. The Federal-Aid Highway Amendments of 1974 provided for, respectively, 20,000 maximum, 34,000, and 80,000 pounds. In both acts, grandfather clauses were inserted to protect states having weight requirements different from the national standard. In 1981, 15 states had higher single axle limits, 17 states had higher tandem limits, and 12 states had higher gross limits. In 1983, Federal laws switched from permissive to mandatory. Widths were increased to 102 inches and length limits were established for the first time. On the designated system of Interstate and primary highways, the overall length of the single and double trailer configurations cannot be set by the states; on these roadways the maximum lengths are 48 feet for single trailers and 28 feet for twin trailers. These dimensions will be the transportation dimensions of the proposed MLS. Tremendous differences exist regarding the use of special permits for divisional loads, with some states allowing annual permits at low fees for extremely high axle weights on construction vehicles, the category into which the MLS falls.

6.4. WHEEL LOADING ON HIGHWAYS

Wheel loading as it appears on pavements today is an important aspect of study in accelerated pavement testing. The objective is to provide a pavement testing facility that will simulate real wheel loads as closely as possible. Various factors must be taken into consideration in the design of the MLS prototype, such as the frequency of certain magnitudes of wheel loads and wheel load distribution. Figure 6.1 shows a typical frequency distribution of tractor/semi-trailer wheel distribution.

Traffic count projections and categories are an important variable in accelerated pavement testing. This information must be utilized in the MLS to provide a similar type of loading. It is achievable by making provision in the prototype design for any configuration of lateral load distribution. A mixture of load magnitudes is easily provided by varying the spring constants on axle bogies. Modern-day air springs have the most ready capability of changing spring constants and are also easily measurable.

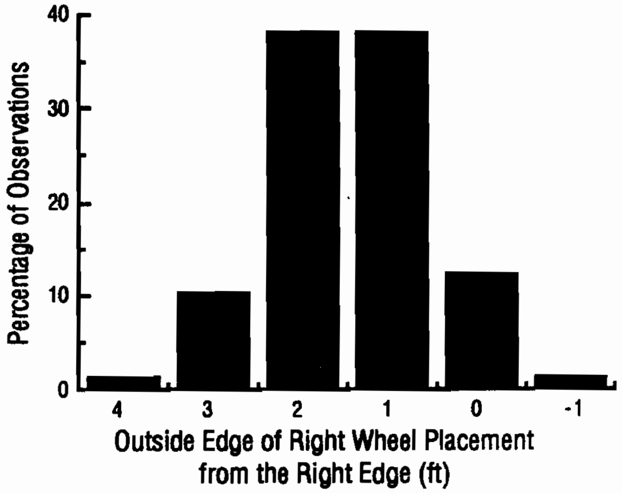


Fig 6.1. Frequency distribution of lateral placement of tractor/semi-trailer trucks on straight section (Ref 32).

6.5. MECHANICAL ASPECTS OF LOADS TO BE CONSIDERED IN SIMULATION OF REAL TRAFFIC

The following discussion is meant to provide background knowledge of the pertinent mechanical properties of heavy vehicles with respect to the MLS. These properties will be incorporated into the MLS in that real truck components will be used and will therefore increase the degree of real load simulation. Since there are many variations in the designs of each of these components, the MLS must be as adaptable as possible so that the effects of different components and combinations of components can be evaluated. This adaptability may interest manufacturers of these components in testing new developments in their respective fields with the proposed MLS, which will further enhance the utilization of the MLS in transportation technology.

The components that will be used as they are and purchased from truck manufacturers are:

- axles,
- tires, and
- suspensions.

The MLS prototype will be designed to facilitate specific combinations of single, double, or tridem axles. However, the proposed design of the prototype will feature six sets of dual axles as discussed in Chapter 6. The basic principle of a tandem axle is that the load is evenly distributed to both axles. There are certain cases with uneven load distribution, but they always keep the same ratio of load distribution. A special case is a tandem axle in which the driving axle has a full single axle load and the other axle has only a single tire load. For instance, if the tandem axle limit is 36,000 pounds, 25,000 pounds are on the driving axle and 16,000 pounds are on the carrying axle. Most frequently this arrangement is not in the original design by the vehicle manufacturer but is added later by firms which specialize in that kind of work. There is no special name for this kind of tandem axle, but "mixed tandem axles," "poor man's tandem," and "auxiliary axles" have been used. In principle, the ratio, even or uneven, should be the same in static and in moving situations. However, it is well known that this equalization does not always work well on uneven roads. The phenomenon of dynamic loads was discussed in section 4.5.

There are many innovative designs in vehicle suspension systems, and much research goes into the development of systems that will enable increased "ease of ride" and more economical transportation of goods. All these factors are important considerations in the MLS prototype design, for not only must the MLS be able to simulate traffic as accurately as possible, but it must also be able, as far as possible, to assess impacts to pavements as a result of new mechanical designs.

6.5.1. AXLES

Even though the basic type of axle is a single axle, the objective of the MLS design is to be so versatile as to incorporate any combination of axles that are in existence. It will be mounted on a rigid bogie called the load frame, as discussed in Appendix A. Axles should include driven or non-driven axles and should be easily adaptable so as to incorporate different suspension systems, transmission systems, motors, and breaking devices.

6.5.2. TIRES

According to the Fact Book of the Mechanical Properties of the Components for Single-unit and Articulated Heavy Trucks (45), tires produce the primary forces which cause the vehicle to turn, stop, or increase speed. Two basic types of tires are encountered:

(1) bias tires and
(2) radial tires.

In the past, bias tires were used everywhere, but at present they are employed only in the United States and Canada. Radial tires were developed in the 1960's. The tread is formed by a belt with steel wire reinforcing and the sides are correspondingly more flexible. The contact pressure distribution at the road/tire interface varies considerably from one make to another. Side wall flexibility is increased with radial tires, which improves the handling of the vehicle. This results in the decrease of wheel distribution or, statistically, results in a decrease of the standard deviation of the wheel path distribution.

Air in tires acts as a suspension material, and the damping effect of tires is therefore very small. The tire spring rate is smaller (softer) than that of most suspensions and can be varied by altering the tire air pressure. However, the possibility of modifying the tire spring constant is very restricted owing to the fact that the air pressure is determined by the load the tire is supposed to carry. In practice, the same maximum tire pressure is often used in all tires. The recommendation for the selection of tire pressures is based solely on the criterion of ensuring high tire endurance.

Tire pressures are constantly increasing, and 110 psi was cited by an OECD report in 1985 as very common (31).

The mean contact pressure between the road and the tire is related to the tire pressure, but the change in air pressure does not cause as great a change in contact pressure. The contact pressure is not uniform and is different for driving and load-carrying axles because of different tractive forces. Average contact and tire pressures are considered equal only as a first approximation, and they neglect side wall effects.

In order to increase the load-carrying capacity of axles, two tires are mounted next to each other, an arrangement known as dual tires. The load will not, however, be evenly distributed to both tires. Furthermore, the tire pressures are not equal, because of temperature differences between the tires, road surface irregularities, bending of the axle, road profile, etc. Moreover, a very common situation is that one tire is new and the other is used, and thus their diameters are slightly different.

Wide-based or super-single tires are often used instead of dual tires. The wide-based tires are wider than ordinary tires, and one tire can carry the same load as dual tires can. The use of wide-based tires is new, but their use in trailers and semi-trailers has increased very rapidly.

6.5.3. SUSPENSIONS

Requirements for suspensions range from the ability to carry the load and enhance ride quality to considerations of cost, weight, maintainability, and service life. Suspensions play important roles in determining the dynamic load conditions of the tires, orientation of the tires, and the motions of the vehicle body. Of importance to MLS studies are

- composite vertical stiffness and damping, and
- load equalization.

Vertical stiffness is defined as the vertical force required per unit of deflection and is composed of the sum of the stiffnesses of all the springs of the suspension, which includes the tires.

The basic types of suspensions used in heavy vehicles are

- conventional steel leaf spring,
- taper leaf spring,
- air spring, and
- torsion bars.

The most common, the conventional steel spring, consists of several steel leaves, which are clamped together with cramp irons. The spring action is produced by the elasticity of the leaves in bending. A characteristic of the leaf spring is friction forces, which are generated by the sliding of the leaves over one another, creating a damping effect. Additional damping is not usually provided on vehicles with this type of suspension, while buses are often furnished with viscous dampers (shock absorbers).

The taper leaf spring is characterized by the fact that the leaves are not in contact with each other, except for the mountings of the spring in the vehicle body and the axle. This means that there is very little inherent damping in the spring and that damping is normally brought about by viscous damping.

The air spring is based on the elastic properties of air or gas, which is under compression in a rubber bellow. The air spring totally lacks inherent damping except for the very small hysteresis losses in the thin walls of the rubber bellow and as long as auxiliary air volume is not provided. This type of suspension is therefore always furnished with an external viscous damper.

A certain amount of damping is required to lessen vehicle vibration. Friction damping is not as effective as viscous damping but is much better than no damping at all. However, from the truck manufacturer's point of view, the total damping has to be carefully attuned to the vehicle, suspension, and road surface to minimize the dynamic effect that can have damaging effects on cargoes. Low damping may result in suspension oscillations, known as tandem axle tramp, chatter, or hop, which can provide very high dynamic loads.

Because of the low speeds, evaluation of dynamic loads with the MLS is believed to be possible through variation in damping or by excluding it altogether. Studies of dynamic behavior of wheel loads may be offset by factors such as the effect of the undamped wheels on the machine stability as a whole.

To carry very high loads, vehicles are often equipped with multi-axle suspensions. To avoid excessive dynamic loading, axles are often equipped with inter-connected mechanisms intended to maintain equal loading between the axles. The most common (31) tandem suspensions are the "four spring" and the "walking beam." In a two-spring suspension, leaf springs, fastened to the axles at each end and pivoted at the center, much like a walking beam, provide both the spring and load balance functions. So-called "parallel plumbing" of the air springs on adjacent air-suspended axles is another way in which load equalization is achieved for tandems.

6.6. DYNAMIC LOADS AND THEIR ESTIMATION

According to an OECD report (31), dynamic loads can range up to a maximum of 130 to 150 percent of the comparable static loads on particularly rough roads, but the typical range is up to 110 percent. Studies done by Whittemore et al (35) showed dynamic loads of up to double the static load. Substantial and continuing advances in instrumentation technology have markedly accelerated developments in the field. Basically, two areas are involved here. The first concerns vehicle dynamics and how the vehicle-suspension/tire system applies the load to the pavement. The second area involves estimating dynamic loads and relates to the way in which dynamic loads can be measured in the pavement and the applications of data measured. Dynamic loading is primarily a low-frequency phenomenon which is largely dependent on suspension and other vehicle parameters. With tandem suspensions, for example, it occurs in the two to four-Hertz range with the additional components at the higher ten-Hertz axle hop frequency. The purpose of this section on dynamic loads is mainly to inform the reader of the importance of this phenomenon.

Accelerated pavement testing, utilizing vehicle simulation, provides the researcher with an easier and more credible methodology to assess pavement damage resulting from dynamic loading. Although the linear-type testing devices do not approach traffic speeds, valuable knowledge can be gained from evaluation at lower speeds.

6.6.1. SENSITIVITIES OF DYNAMIC LOADS

Results presented in a TRRL Report by Mace et al in 1989 (42) showed that the dynamic load coefficient (dlc), i.e., the standard deviation of the dynamic load divided by static load, was found to range between 0.05 and 0.15 for a loaded trailer and up to 0.20 for an unloaded trailer.

Even though there is a marked difference in the road profiles in each wheel path, it was shown that the dlc's were approximately equal. There also appears to be a positive linear relationship between road profile roughness and the dlc. Unloaded trailers appear to give rise to larger values of dlc, particularly where the road profile roughness is greater than 0.07 inches.

Cross-ply tires gave higher values of dlc than radial-ply tires. Since this occurrence was more noticeable with the unloaded trailer, it would appear that tire stiffness is significant where stiffer tires produce higher dlc's.

Dual wheels were found to produce higher dlc's than single wheels. This was assumed to be due to the the fact that twin wheels doubled the effective tire stiffness and at the same time increased the unsprung mass. No differences were found between the front and rear axles in tandem configuration. This would imply that vertical bounce is more important than pitch.

When the trailer was loaded, there did not appear to be much difference in the dynamic load coefficients at the two speeds, except in cases when the road profile roughness was greater than 0.07 inches, at which time higher dlc's were produced at 40 mph than at 20 mph. This was also the case for the unloaded trailer.

Damping did not appear to have any effect on the dynamic load coefficient. This lack of effect was attributed to stiction at the ends of the leaf springs, which reduce the movement of the axles relative to the trailer and, therefore, the movement and effectiveness of the dampers.

6.6.2. TECHNIQUES FOR DYNAMIC LOAD ESTIMATION (31)

There are several in-situ weigh-in-motion techniques for measuring dynamic loads, such as plate-in-ground systems, strain gage transducer systems, and a new method developed in France which incorporates the use of piezo electric cables.

The first involves an instrumented plate embedded in the road, flush with the pavement surface. Two types of plates are available; one consists of a thin section to which strain gages are fixed, while the other is a larger structure seated on load cells. The second technique utilizes strain gage transducers, which form part of the larger transducer. Both techniques incorporate transducers which produce signal outputs in response to the passage of vehicles over the transducers. These outputs represent the instantaneous dynamic loads exerted by the vehicle or the static load after suitable processing. An instantaneous load may be measured with these systems within 1 percent.

Other systems include the low-speed plate-in-ground, which is used mainly for enforcement purposes. Of these types, the well-known PAT system is commonly used in Europe for either screening or enforcement weighing, while the load-cell-based system of TRRL design is used extensively throughout the U. K. for both enforcement and surveys.

A bridge-based design has been used in Belgium. It incorporates strain gages into bridge expansion joints and has proved to give promising results. A 1985 OECD report stated that, although still in an early stage, it gives clean, predictable signals, which finding encourages further development. Ongoing work has attempted to sort out problems with joint movements and some long-term reliability difficulties.

Another method of measuring weights makes use of on-board transducers. At least three types of these systems are available; they monitor either suspension deflection, axle housing strain, or the deflection between vehicle body and chassis. However, a six-month in-service evaluation program undertaken by TRRL (Newton) revealed that none of the systems could meet the target accuracy of 4 percent on individual axle loads. The target percentage was established so that the equipment could be used in truck load enforcement. It was found that the accuracy of the suspension deflection systems was 20 percent while that of the axle strain system was 8 percent. The latter figure was comparable to the 5 percent quoted by Nojiri from a Japanese manufacturer's study. Figures were not available for the body/chassis load system, which could monitor only individual axles on a two-axle truck. These on-board measuring methods can be used for surveying purposes, although it must be recognized that there will be logistic difficulties with introducing such a system into the vehicle fleet, as well as problems with data collection.

The most advanced stage of development cited is that which is currently in use in France. Here, piezo cables, marketed under the name 'Vibracoax,' are being used in systems for simultaneous traffic detection, traffic classification, and dynamic load measurements. A great number of these systems have been installed and are proving to be both robust and reliable, with the failure rate of cables over a five-year period less than 2 percent. Weighing accuracies achieved by the French were not specified in a form which would allow direct comparison with the accuracies of other weighing systems, such as the empirically-determined numbers quoted by Samuels, obtained from high-speed systems in Australia.

Similar developments have occurred in Denmark although on a smaller scale. The Danish approach, however, is rather unique. They have adopted a procedure in which the cable is set in an epoxy material which is constrained in a U-section metal channel. This channel is set with epoxy into a saw cut in the road surface. According to Banke, this procedure improves the quality of the signals produced by the cable and further minimizes the number of phantom axle detections. Minor variations, owing to pavement temperatures, have been observed. The system comes complete with a data logging system for international application.

6.6.3. DYNAMIC LOADING AND LOAD EQUIVALENCE

If a pavement has an uneven longitudinal profile the load equivalence takes the form

$$Ni/Ns = \alpha\,(Ps/Pi)^{\gamma} \qquad (6.2)$$

where α is a coefficient that takes the dynamic effect of loads into account ($\alpha = 1$ on a plane surface).

Every vehicle is a dynamic system with a number of components mentioned before, such as masses, springs and damping devices, which create a complex and variable dynamic response determined by parameters such as vehicle speed and road profile. In quantifying the dynamic effects of loads, the coefficient of impact (lc or dlc), which is the ratio of dynamic load to static load, is an important concept.

6.7. SUMMARY

The demand for accurate traffic-simulating testing equipment has come to light under the current SHRP Program in which the state of Texas plays an important role. Full-scale pavement testing in the form of the MLS is believed to provide the most comprehensive combination of real, heavy vehicle features yet provided in a facility of this kind. Speeds of 20-plus miles per hour yielding some degree of dynamic loading, real suspensions, driving and non-driving axles, simulated shoving or braking, lateral load distribution, and overloading, are among the mechanical features that can be simulated through the utilization of the proposed MLS.

This chapter provides the reader with the real-life situation of pavement loading and how this affects MLS design, operation, and use in accelerated pavement testing. The MLS will be used to evaluate heavy vehicle regulations, but must also conform to these regulations as far as its own transportation is concerned. Together with this compliance, and by providing an easily-adaptable device for evaluating many different combinations of loading characteristics, the machine will provide a valuable tool in pavement engineering technology.

CHAPTER 7. EVALUATION OF PROPOSED MLS DESIGN

7.1. INTRODUCTION

Previous chapters have dealt with issues such as accelerated testing, accelerated testing of pavements, accelerated pavement testing devices and methods, and the use of the MLS as the accelerated pavement testing device selected by the Texas SDHPT for future use. This chapter estimates the degree of real traffic simulation that would be achievable with the use of the MLS. However, it must be borne in mind that these estimates are theoretical in nature and have been made without the benefit of a detailed design or a working prototype.

Aspects to be addressed are:

(1) The design methodology followed to arrive at optimum operational dimensions for the MLS.
(2) The degree of real traffic simulation of the moving loads of the MLS for specific speed and loading conditions.
(3) The degree of real traffic simulation using different pavement types and static loading conditions.
(4) A practical evaluation of the equipment considering items (1) through (3) to optimize the vehicle configuration between simulation accuracy and rate of accelerated load production.
(5) An analytical comparison between the proposed full-scale MLS and the 10-to-1 scale model, using ELSYM5.

The discussions in this chapter are based on a proposed design of the MLS which, in turn, is based on practical limitations and maximization of loading rates. The computer program ELSYM5 was used to develop the data for the deflection analysis of pavement structures. This analysis is, therefore, subject to the limitations and assumptions inherent in the program.

Since the design of the MLS incorporates full axles, as found on actual trucks, only longitudinal influences are evaluated. The effects of lateral load distribution are assumed to be the same for the MLS as for real traffic.

7.2. THE PROPOSED MLS DESIGN

The proposed MLS design was presented to the Texas SDHPT in the form of a 10-to-1 scale model. As previously mentioned, this model not only served as an indication of the feasibility of the MLS concept but could also be utilized in modeled pavement studies. The model design was established only after due consideration was given to those design aspects to be incorporated in the full-scale prototype. The design aspects considered are discussed in this section, and they illustrate the decision process used to arrive at a machine configuration that optimizes between load simulation accuracy and rate of production. A theoretical comparison is drawn between the scaled version and the full-scale prototype in section 7.3.7, which shows the proportionality of scaled ratios.

Utilization of the model will be valuable in an evaluation of the stress condition that exists in the link chain during operation. Centripetal forces generated by bogie masses negotiating the half-circles at each end, will be carried in the link chain as tensile stress. Providing that masses are balanced, i.e., spaced half a cycle apart, no lateral movement of the structure is expected to take place because of unbalanced changes in momentum. The balanced stress condition, however, will be offset by the influence of gravity working on masses negotiating the curves. This influence will lead to higher tension stresses in the top section of the link, with a subsequent reduction of tension stresses at the bottom. Furthermore, rolling resistance will vary around the structure as normal forces between pavement and vehicle wheels, and rail and link chain wheels, vary.

7.2.1. LINK LENGTHS AND AXLE SPACINGS

As mentioned previously, when a chain type arrangement is to be translated (as opposed to rotated) around a shape consisting of both straight and curved surfaces, the rigid chain links must be of equal length. This condition permits constant chain stress owing to the link chain's being compatible with the body shape around which it translates. The following paragraphs explain the design procedure followed to arrive at the selected axle configuration of the MLS.

Axle spacings on trucks are on the order of 4 feet for most truck bogies. Designing the bogies for the MLS so that they form part of the chain determines the minimum lengths for chain links that also incorporate a suspension. Fixing the chain link length at around 50 inches results in discrete possible dimensions of the total load frame. However, the load frame dimensions are governed by practical considerations, such as the maximum permissible heights and lengths for transportation purposes on highways, as well as the minimum straight loading section to allow statistical authenticity, or redundancy. The maximum allowable height for vehicles on highways is 13.5 feet, and the allowable length is 56 feet. Provided that some degree of mechanical height reduction can be accomplished for transportation purposes, the height between center points of the load transfer wheels must be no less than 11 to 12 feet.

Calculations were performed to optimize the overall MLS load frame dimensions, and these are given in two examples. Nomenclature is indicated in Fig 7.1.

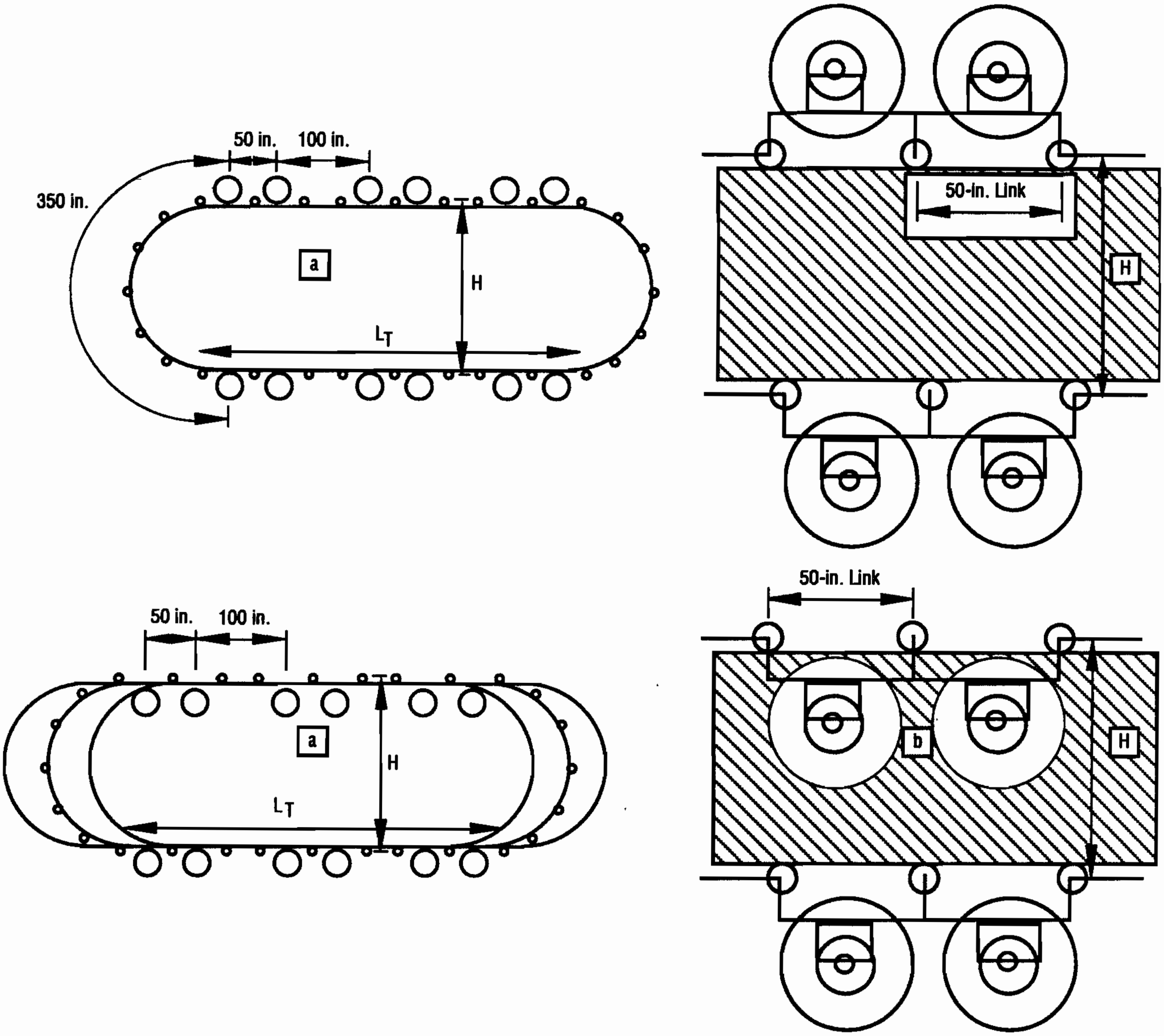


Fig 7.1. MLS dimensions and possible axle configurations.

Example 7.1

If it is decided that the overall length of the MLS should be 48 feet, including a goose neck of 9 feet, the effective equipment length is therefore 39 feet. Using the effective length and the chain length as fixed parameters, equations for the height of the machine between center points of link chain wheels as well as the straight or tangent section length may be derived.

First, if the two half-circles at each end are considered as a unit and the chain link length is fixed at 50 inches in this example (circle cords), the height (diameter) may now be computed by finding an even number of circle cords of 50 inches that surrounds the circle.

$$50 = H \sin(\Pi/n_c)$$

or

$$H = 50 / \sin(\Pi/n_c) \qquad (7.1)$$

where

n_c = selected, even number of 50-inch chain links fitting around a circle of diameter H, and

H = diameter of circle (also height of machine between center points of steel wheels—see Fig 7.1.

The length of the tangent sections (L_T—also test length) may be derived by subtracting the diameter of the circle from the effective length (39 ft):

$$L_T = 468 - H . \tag{7.2}$$

Since a discrete number of links must be used, L_T from Eq 7.2 should be rounded down to the closest multiple of 50 inches (L_T'). The number of links in the tangent section is then (top and bottom):

$$n_s = 2 * L_T'/50 . \tag{7.3}$$

The total number of links is then:

$$n_T = n_c + n_s . \tag{7.4}$$

If various even numbers of links are assumed for the circle, the values in Table 7.1 may be derived.

The force in the chain, connecting the masses, is inversely proportional to the radius of the circular path of the rail on which the masses are travelling. In order to keep the chain forces within reasonable limits, a maximum practical H must be selected. If an H of 13.5 feet is selected, it must be borne in mind that actual structure height is one load wheel diameter smaller, due to the fact that the distance between load wheel center points is defined as H.

Example 7.2

In many cases, overall length dimensions are not the only aspects to be taken into consideration. Elsewhere it was shown that the object is to put as many axles as possible in the chain system subject to limitations, such as deflection basin influences and following distances, to provide adequate recovering time or rest periods for flexible pavements, as indicated in Fig 7.1. If the proposed configuration calls for 12 axles in two groups to provide two open sections totalling $n_T = 28$ links needed, it then follows from Eq 7.4:

$$28 = n_c + n_s . \tag{7.4}$$

Applying Eq 7.1 for a range of even n_c values, n_s can be determined together with H and L_T as shown in Table 7.2.

The proposed design for the MLS features the dimensions indicated by $n_c = 10$ for 28 links total. The overall lengthwise dimension prohibits the intact transportation of the machine; however, the increased test length and the ability to simulate following distances between travelling vehicles offset the duration of assembly on site.

To arrive at a selection for structure height, the following steps had to be taken:

(1) Determine link lengths (shown to be 50 inches in Examples 7.1 and 7.2).
(2) Determine H based on physical and practical restrictions.
(3) Select chain wheel diameter.
(4) Determine chain wheel diameter to meet load specifications.
(5) Subtract chain wheel diameter from H.
(6) Re-evaluate structure height.
(7) Change link lengths, return to (1), and continue to evaluate until optimum structure height is determined; allow for enough play in system.

TABLE 7.1. MLS DIMENSIONS FOR A FIXED MACHINE LENGTH OF 39 FEET

1 n circle	2 H (in) (eq.1)	3 H (ft)	4 L T (in.) (eq.2)	5 L T' (in.)	6 n straight (eq.3)	7 n total (1+6)	8 Effective Test Length (ft)
6	100	8.33	368.00	350	14	20	29.17
8	131	10.89	337.34	300	12	20	25.00
10	162	13.48	306.20	300	12	22	25.00
12	193	16.10	274.81	250	10	22	20.83

TABLE 7.2. MLS DIMENSIONS FOR A FIXED NUMBER OF 50-INCH LENGTHS

1 n circle	2 H (in.) (eq.1)	3 H (ft)	4 28 - 1	5 Effective Test Length (ft)	6 Effective Test Length (ft)
6	100	8.33	22	550.00	45.83
8	131	10.89	20	500.00	41.67
10	162	13.48	18	450.00	37.50
12	193	16.10	16	400.00	33.33

7.2.2. DESIGN SPEED

Theoretically, high translation speeds are possible with the MLS. However, loads on the chain and connectors are a function of the angular velocity squared. At high speeds unbalanced components will cause vibrations and oscillations that may become more pronounced with resonance. Therefore, practical dimensions and mobility will determine operating speeds of the machine and not the other way around. It was found that, in circular testing devices, operating speeds have to be varied, because of operation close to the natural frequency of the system.

With these factors in mind, an upper limit was set for the design of the prototype MLS. Twenty miles per hour was selected, not only to provide better stability, but also to improve on other existing linear accelerated pavement machines as far as speed is concerned. Power requirements will, therefore, be based on a top speed of 20 mph attainable within two minutes.

In this section, an ordinary design methodology was followed with the MLS. A selection of specific design criteria (i.e., axle spacing and speed) was made based on practical considerations. In section 7.3, the selected design or configuration is evaluated against the expected values for real traffic.

7.3. MLS DESIGN AND ACCURACY OF LOAD SIMULATION

Mechanical features that will be the same in both the MLS and trucks are not evaluated. These include features such as springs, wheels, and resistance transmitted as a force to the surface of the pavement.

Criteria to be evaluated include the following:

- — speed,
- — sprung weight,
- — unsprung weight,
- — loading intervals and load duration,
- — lateral load distribution of tandems,
- — effect of strength variability in the pavement on pavement deterioration under MLS loading, and
- — deflection and stress influences between axles and bogies for static loads.

7.3.1. SPEED

In the literature (40), the dynamic effect of traffic loading is based on estimations of the dynamic loading coefficient, which is the standard deviation of the ratio of dynamic load to the static load, and is a function of the sprung mass acceleration. Since mechanical aspects such as unsprung mass, spring stiffness, tire stiffness, and suspension types are the same in the MLS as in real trucks, these need not be evaluated. However, speed and sprung mass will differ considerably.

The results of a TRRL theoretical study to evaluate the dynamic behavior of a wheel for a single axle vehicle suspension system are shown in Fig 7.2. The impact factor (IF), which is the common name for the ratio of dynamic force to the static wheel force applied to the road, was used. For the purpose of this study, the 20 mph operating speed of the MLS and a truck operating speed of 60 mph have been superimposed as arrows on the horizontal axis of the figure.

Figure 7.2 was derived by evaluating axle hop at speeds varying from 10 to 60 km/h over a 40-mm-by-250-mm bump. It shows that the first, second, and third impact factors, or hops, increase with speed, but that the second and third maximum IF are expected at 33 km/h. For the first peak, an IF maximum of 3.0 is calculated at a speed of 100 km/h. Figure 7.2 shows that a 17 percent reduction for the first peak can be expected for the MLS operating at 20 mph, in comparison with a truck travelling at 60 mph. An overestimation of 17 and 9 percent, respectively, is expected for the second and third peaks.

7.3.2. SPRUNG WEIGHT

Sprung weight of vehicles is defined (40) as the weight of vehicle mass that rides on top of a suspension system. Since the impact factor, or dynamic load of a pavement, is dependent on this weight parameter, the amount of sprung mass for the MLS needs to be evaluated.

The sprung weight per axle on the MLS will be more than (between 20 and 100 percent more than) the typical sprung weights of trucks. Overloading is being incorporated to prevent lifting of the structure, thereby maintaining constant force applied to the pavement by the wheels. The TRRL study shows that, for the first and second peaks, a reduction of 0.5 can occur in the impact factor, and a reduction of 0.1 for the third peak, for twice the sprung weight (2,400 kg) of a standard wheel. The percentage reduction in the impact factor (IF) from standard

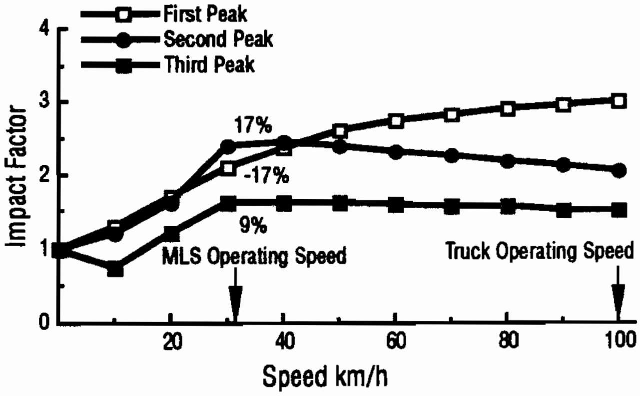


Fig 7.2. Speed and impact factor (IF) (Ref 40).

vehicle to MLS is indicated in Fig 7.3 for the first, second, and third peaks at 100 percent overloading.

7.3.3. UNSPRUNG WEIGHT

Depending on the design of the load transfer bogies translating around the frame, the unsprung weight can either be similar to, or in excess of, actual truck unsprung weights; of these two possibilities, the first is preferable. Accurate numbers can be derived only through detailed design of the positioning with regard to the electrical motor and the transmission. A typical electric motor of around 40 to 50 horsepower with the transmission could add from 600 to 1,000 pounds to the unsprung weight if placed below the suspension. Furthermore, redundant parts should be removed. An effort should be made to place additional parts as close as possible to the rail, thereby locating the center of gravity on the shortest radial path around the half-circles at each end of the structure.

7.3.4. LOAD INTERVALS

Loaded and unloaded times and intervals are important aspects to be considered, especially for structures that follow visco-elastic stress/strain relationships. The six-bogie design for the MLS can be evaluated for its degree of load simulation accuracy by comparing the load intervals given by the MLS to those produced by trucks travelling at different speeds. This comparison is shown in Fig 7.4. Also indicated in Fig 7.4 is a typical experimental modulus of rupture testing rate.

For the calculation of real load intervals, the following assumptions were made:

(1) Vehicle speed: 40/60 mph = 58.6/88 ft/sec;
(2) Two-second vehicle following distances;
(3) Point loads;
(4) Axle spacing on bogie: 4 feet; and
(5) Axle spacing between bogies: 38 feet.

For the calculation of MLS loads, the following assumptions were made:

(1) Machine speed: 20 mph = 30 ft/sec;
(2) Point load; and
(3) Axle spacing as shown under MLS design above.

An evaluation of the load intervals shows that there is a similarity in the loading patterns of the pavement material. For modulus of rupture testing, stresses are always applied at the same level and frequencies, which may not be the case for real pavement loading because of variations in traffic loading conditions. For all four situations, the longer resting periods are similar; however, the intervals between axles on the same bogie for the MLS and axles on the same bogie for a truck differ by the ratio of truck speed to machine speed, which is two and three times smaller for the truck. This is due to the selected design of the machine, which features actual truck bogies for reasons of economy and better load simulation.

Increasing the speed of the machine would greatly improve the accuracy of the simulation of resting periods for tandem axles, but would also lead to a decrease in resting periods for the longer sections. An alternative would be the removal of the middle bogie in each set of three bogies. This will reduce the total number of axles to eight, which will considerably increase test duration for the same number of loads. Problems may also arise with irregular rotation speeds, owing to fewer axles on the pavement providing rotation and translation.

7.3.5. LATERAL LOAD DISTRIBUTION

The previous provision for intervals of loading will be offset in practice by the effect of lateral load distribution of actual traffic. Axles on the same tractor bogie and trailer bogie will produce two coverages per cycle. To obtain as much variance as possible yet striving for accuracy of simulation, an engineering decision determines that axles on the same bogie of the machine will follow the same wheel paths, with the different bogies spaced randomly within a total distribution of 36 inches, as shown in Fig.7.5.

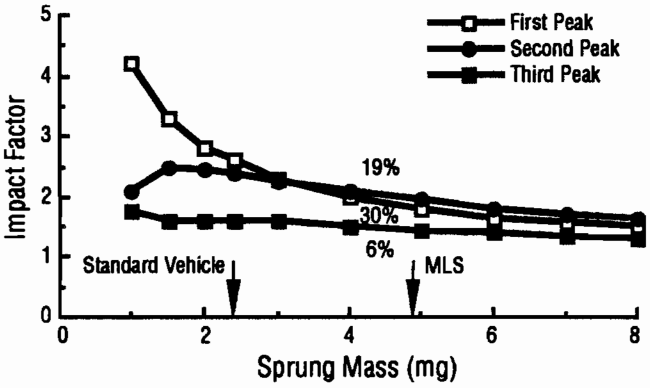


Fig 7.3. Sprung mass and impact factor (IF) (Ref 40).

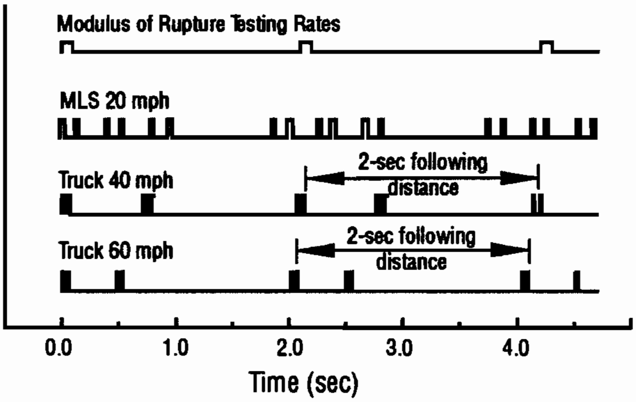


Fig 7.4. Typical load intervals for a point on a pavement.

Wheel loading as it appears on pavements today is an important aspect to be studied in accelerated pavement testing. The objective is to provide a pavement testing facility that will simulate real wheel loads as closely as possible. Various factors must be taken into consideration in the design of the MLS prototype, such as the frequency of certain magnitudes of wheel loads and wheel load distribution. However, it is also an advantage to be able to control the wheel loads, from which validation of mechanistic pavement design can be done.

Figure 7.6 shows a typical frequency distribution of tractor/semi-trailer wheel distribution. It can be seen that almost 75 percent of loads fall within a band width of 12 inches.

Traffic count projections and categories are an important variable in accelerated pavement testing. This information must be utilized in the MLS to provide a similar type of loading. It is achievable by making provision in the prototype design for any configuration of lateral load distribution. A mixture of load magnitudes is easily provided by varying the spring constants on axle bogies. Modern-day air springs have the best capability of changing spring constants and are also easily measurable.

The final decision with respect to having discrete or continuous lateral wheel distributions will depend on practicalities to be determined by the manufacturer. Future changes in the distributions must, however, be allowed for in planning the equipment. An example of discrete distribution for dual wheel paths is shown in Fig 7.7.

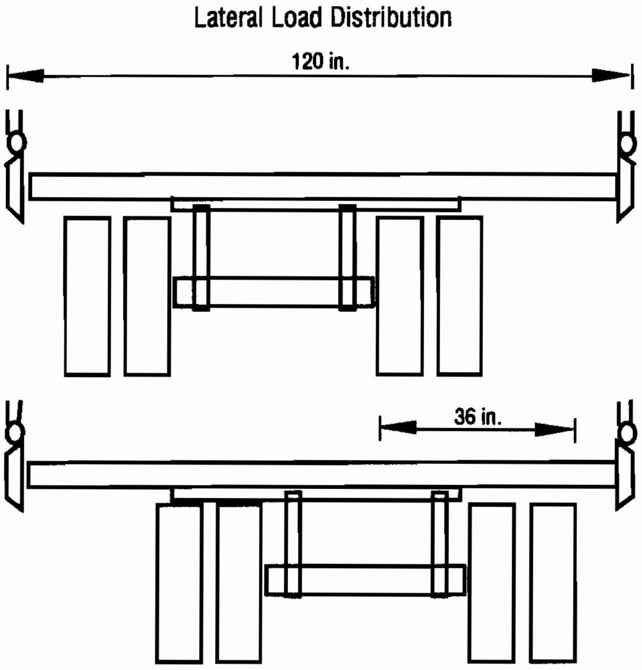


Fig 7.5. Lateral load distribution for full axle.

7.3.6. DEFLECTION BOWL INFLUENCES BETWEEN BOGIES

An evaluation of pavement deflections needs to be addressed at two levels. The first aspect has to do with the progressive differential deformation of the pavement surface during testing, leading to changing loads and deflections. This effect may correspond to real loading conditions, but it does not represent traditional constant strain or constant stress conditions which simplify behavior modeling. The primary cause of variations in deflections would stem from the inherent pavement variability. The second is an evaluation of the influence of overlapping deflection bowls caused by wheel sets too closely spaced on the MLS. An analysis of this nature would allow the designer of the MLS to arrive at an optimum axle

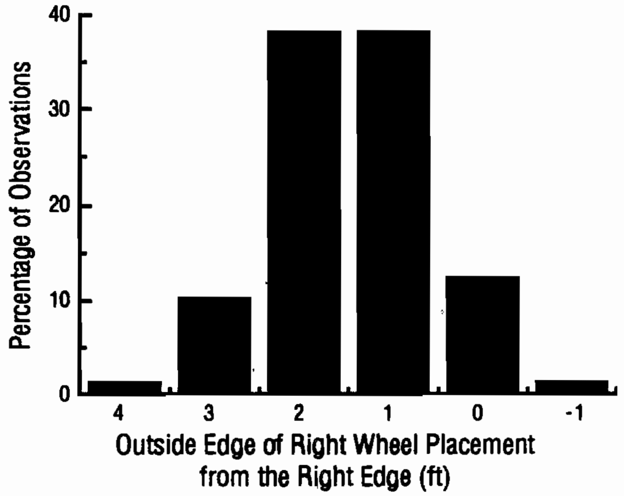
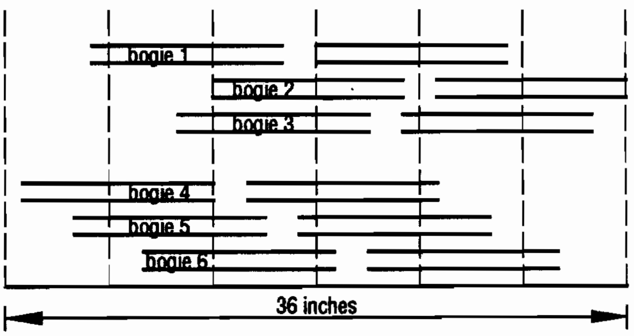


Fig 7.6. Frequency distribution of lateral placement of tractor/semi-trailer trucks on straight section (Ref 32).



- Discrete intervals of 1 in.
- Max possible displacement from left Boundary is 12 in.
- Mean displacement of bogies is 6.6 in.
- Standard deviation of displacement is 4.1 in.

Fig 7.7. Lateral wheel distributions for six bogies on the MLS.

spacing with subsequent power requirements and yields reliable test results.

7.3.6.1. Effect of Strength Variability of the Pavement on Testing

The design of the MLS features the concept of a rigid load beam against which the rolling loads react to provide the desired load at contact. Given a specific spring stiffness for the suspensions, this reaction against the load beam and action on the pavement will remain constant provided the distance between the load beam and the pavement remains constant. Under this condition, a constant stress testing pattern will be provided.

Owing to progressive permanent deformation of the pavement under accumulated loading, the constant stress situation exists only if the load beam is progressively lowered to maintain the same average distance between beam and pavement in order to apply the same wheel forces.

This aspect of the testing process is further complicated by differential deformation of the pavement section stemming from the variability in strengths of the pavement materials. It will require that the load beam follow the undulations while keeping the distance between pavement and the load beam constant, as shown in Fig 7.8. The need for adjustment to the load rail will have to be determined by comparing the dynamic load variation of the MLS to those actually experienced by a typical travelling truck. Proposed designs for the load beam feature actuation of the beam with adjustable supports spaced at intervals from the main structure. The distance between hinges in the beam, where the supports will be fixed, determines the shortest wavelength of pavement undulations that can be followed by the actuated load beam. A rigid beam may also be selected, whereby deformations similar to long wavelengths may be achieved. The wavelengths simulated in this fashion are dependent on the beam stiffness, overall structure stiffness, and power requirements to facilitate deformation.

An alternative to this design is based on the monitoring of changes in the stress level the average stress level along the test section is kept constant. The proposed methods are shown in Figs 7.9, 7.10, and 7.11. This is accomplished by keeping constant the average elevation between the straight load beam and deforming pavement, i.e., by reducing the load beam height as settlement, failure, or failure occurs.

Monitoring can be accomplished through the placement of static or moving load cells on the machine or by monitoring contact pressures on the surface of the pavement through piezo-electric pressure pads as shown in Fig 7.9.

Pressure pads are very accurate, and, although limited performance data are available, it is suspected that durability will be limited under continuous usage. Measurements at regular intervals should be adequate in most instances. The biggest advantage gained through the use of pressure pads is that accurate measurements of actual contact pressures can be obtained.

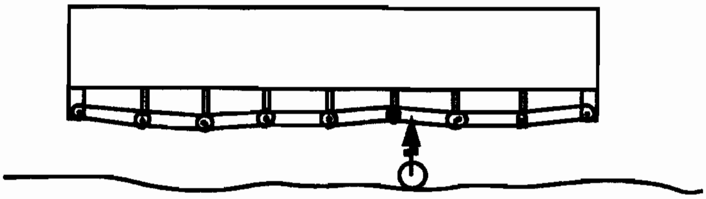


Fig 7.8. Actuated load beam: constant stress.

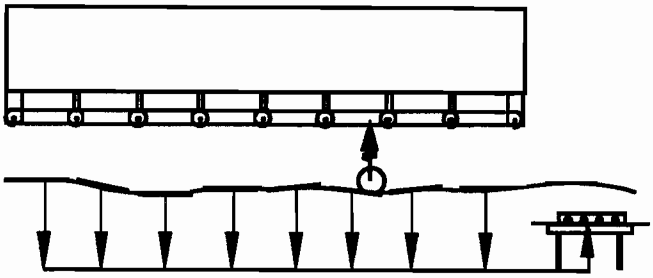


Fig 7.9. Rigid load beam: wheel stress monitoring.

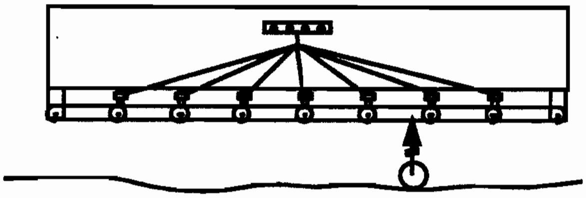


Fig 7.10. Rigid or straight load beam: stress average monitoring.

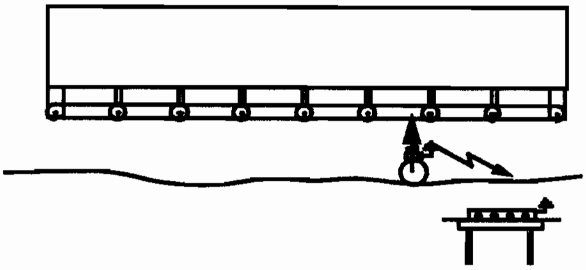


Fig 7.11. Rigid or straight load beam: constant remote stress monitoring.

Static load cells can be used as part of the supports of the actuated or rigid beam and continuously measure forces exerted by the moving loads, as shown in Fig 7.10.

Data retrieval is not complicated, and the accuracy is determined by the load cell intervals.

Moving load cells can be incorporated into the structure of the moving load frames such as monitoring of air pressures of air suspensions, as shown in Fig 7.11. Remote data retrieval is then used, which is a costly process. This method benefits from having a continuous and accurate rate of data sampling.

It is concluded that the MLS may lack the ability to produce a constant stress situation. However, even though this limitation poses problems in modelling, it does represent real traffic. Stress and strain are treated as variables of which levels can be easily determined. This is usually done by measuring the applied force and the corresponding deflections at various depths in the pavement. The provision of instantaneous height adjustment in the suspension system may initially be too costly and may prove to be unnecessary. Of the options presented for stress monitoring, the final solution will probably be a combination of the proposals in Figs 7.9, 7.10, and 7.11, to ensure accuracy and backup facilities.

A feature of having a reaction-type loading against a straight beam is that load can be varied over one test section using a wedge of distances between pavement and load beam. Having the end at which the chain system is entering slightly higher off the ground than the end at which the chain is exiting, will further enhance the smooth transition from fully loaded to fully unloaded. In doing this, the damage factor for a pavement can be determined in a single experiment. Knowing the variation in load over the test length, a given distress occurrence will gradually proceed from the overloaded end to the underloaded end of the test section. The rate at which such a distress proceeds is an indication of the load sensitivity of the pavement structure, which directly relates to the damage factor.

7.3.6.2. Deflection and Stress Influences Between Axles and Bogies for Full-Scale Static Loads

Using the program ELSYM5, two pavement types were evaluated to examine the influences of the respective deflection bowls created by the tandem axles of a stationary truck and those created by the MLS. For the three-layer system, modulus values were taken which were comparable to material properties expected in portland cement concrete pavements. For the four-layer system, material properties were used that are comparable to those of asphalt concrete pavements. (Refer to Fig 4.12.)

The analysis is subject to the usual assumptions for layered theory incorporated in the program, such as linear elasticity, infinite dimensions in a horizontal plane, and circular contact areas.

The analytical factorial is set out as follows:

Pavement Systems	3 Layer, 2 Layer
Dual Wheels @ 75psi (represented by one circular contact area)	12 kips, 9 kips, 5 kips
X Distances (13) (Fig 7.13)	12, 16, 20, 24, 28, 32, 36, 40, 48, 56, 64, 72, 80
Deflections	Between Axles, Between Bogies
Horizontal Stresses	sxx, syy (bottom of first layer)

Circular loads were assumed in the analysis, representing a set of dual wheels, and carrying a load of 9,000 pounds at 75 psi wheel pressure. This simplification was made since ELSYM5 evaluates a maximum of ten uniform loads.

As indicated by the plan view in Fig 7.13, deflection profiles were drawn for loading situations where the distance between bogies were varied. According to the Fact Book of Mechanical Properties of the Components for Heavy Trucks, typical offsets between the kingpin and center of rear axle or tandem axles of trucks are between 29 and 41 feet. The kingpin is located above the tractor drive axle or in the middle of the tractor tandems; thus, in adding 4 feet to the axle offsets for trucks (33 – 45 feet), to correspond with the x-distance selected for the analysis, a basis for comparison is established. The effect of steering axles was not taken into account. The design of the proposed MLS will have two discrete x-distances or spaces between bogies of 36 feet and four x-distances of 16 feet, as shown in Fig 7.1.

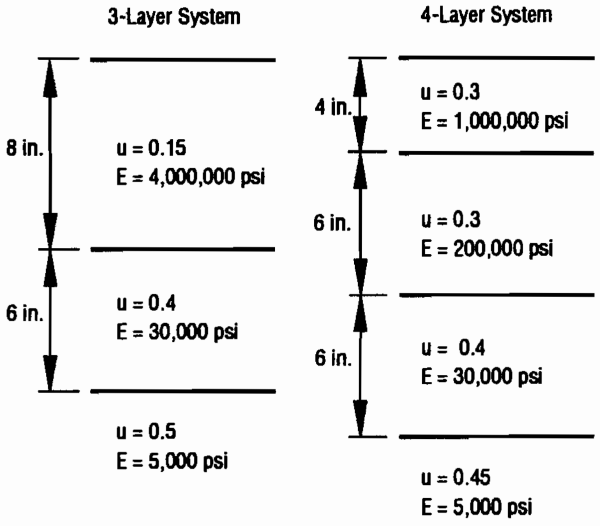


Fig 7.12. Pavement systems evaluated with ELSYM5.

To establish an upper limit for x-distances to be evaluated in the analysis, following distances of trucks travelling at 45 mph with a 2-second following distance were taken. Analyses at longer x-distances were not attempted owing to the obvious graphical trends observed in the plots.

The following conclusions can be made from an evaluation of the deflection and stress graphs of this analysis, which is contained in Appendix C.

1. At the 36-foot x-distance, surface deflections experienced with MLS loading are comparable and fall within the range of deflections for trucks measured between its axles and bogies.
2. Deflection measurements for x-distances over 25 feet show little sensitivity for higher spacings.
3. Stress variations in the x-direction for x-distances above 40 feet show little sensitivity for higher spacings.
4. Stress variations in the y-direction for x-distances above 30 feet show little sensitivity.

7.3.6.3. Theoretical Comparison of Stresses and Deflections between Full-Scale and Modelled Loads

As a follow-on of work done by Van Dijk (22), which was used to characterize fatigue of asphalt, it was proposed that an upgraded version of the model be utilized for modelled pavement research. To establish the validity of modelled comparisons, an analysis of stresses and strains was done, comparing the prototype and the model.

The critical parameters (deflections, stresses, and strains) were analytically determined using the ELSYM5 computer program. These parameters were calculated for a full-scale load configuration as well as for a 10-to-1 scale of the same configuration. Maximum stresses and strains were computed directly under the load as well as midway between the dual set of tires for certain pavement systems, as shown in Fig 7.14, parts (a) and (b).

From the results of the analysis, it can be concluded that similar stresses and strains are achieved with a one-tenth reduction in the total vertical deflection with the criteria set out in Table 7.3. Results of the computer analysis are shown in Table 7.4.

7.4. CONCLUSION AND RECOMMENDATION

Following the design evaluation procedure and the testing of various aspects of the MLS design against real traffic considerations, the accuracy of traffic simulation was considered.

In most cases the degree of simulation is sufficient to produce reliable accelerated pavement testing results. The most important recommendation is that of designing the MLS to incorporate a reduction in the total number of axles to eight (four bogies). In other words, the MLS must feature the ability to have as few as four single axles and as many as sixteen or twenty. This will have a significant impact on the mechanical design and power requirements for driving motors, which must allow as little speed fluctuations as possible. The MLS must maintain the ability to add any number and type of axles, ranging from steering, driving, tandem, tridem, and super-singles. A single axle with a lower load can easily be incorporated in place of the removed tandem axles to simulate the effect of the steering axles on trucks. Having lower spring constants for the suspension of this axle will provide the lower loads associated with steering axles on trucks.

The variation in loads must be monitored as testing and differential deformations of the pavement take place. The selected frequency and accuracy of load sampling is a matter of economics, since all the systems mentioned are available.

At this time, the amount of additional weight to provide stability in testing cannot be estimated. Overloading is needed to minimize the dynamic effects of an imbalance in rotating masses as well as to provide enough friction between supports and pavement to prevent movement of the total structure. The pressure on the support footings will also affect the deflection basins of the wheels on flexible pavements, and care will have to be taken to see that large enough contact areas are used. Imbedded anchors will be an option to prevent movement of the structure and to reduce loads on the footings.

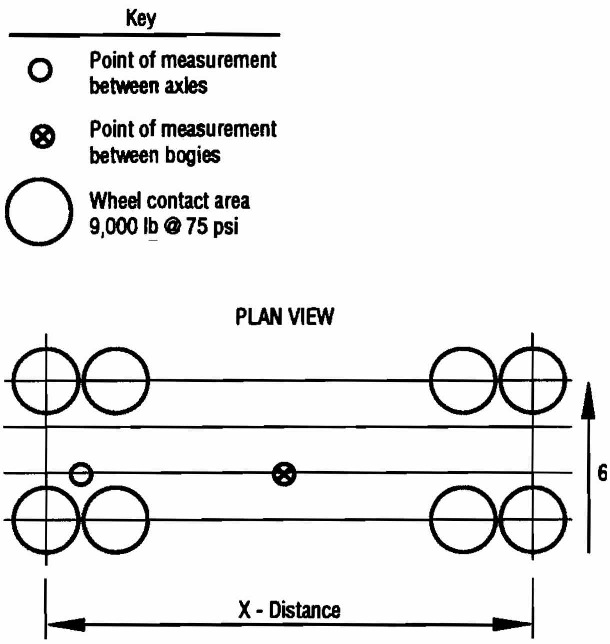


Fig 7.13. Diagram for computer analysis.

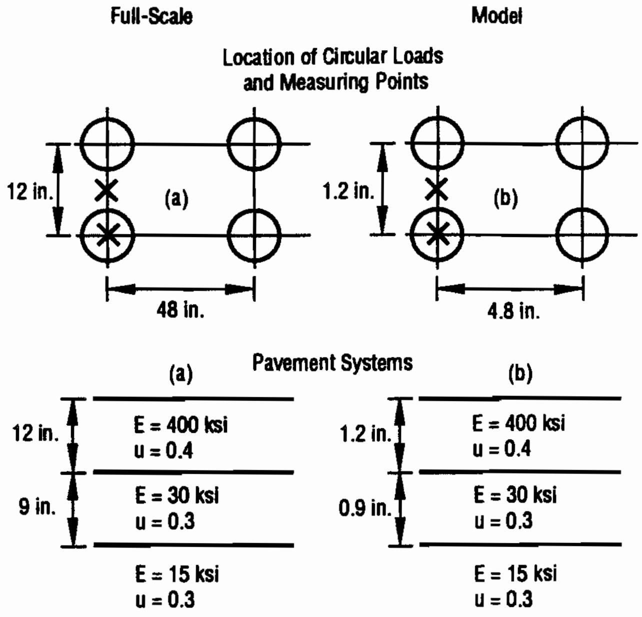


Fig 7.14. Diagram for computer analysis.

TABLE 7.3. INPUT DATA FOR STRESS AND DEFLECTION ANALYSIS

	Load (kips)	Contact Pressure (psi)	Radius of Load (in.)
Full-Scale	5	75	4.61
Model	0.05	75	0.46

TABLE 7.4. RESULTS OF COMPUTER ANALYSIS

	Depth Beneath Loads	Normal Vertical Stresses (psi)	Vertical Displacements (in.)	Normal Horizontal Strains
Full-Scale	0	-75.38	0.014	-0.0000774
Model	0	-75.38	0.0014	-0.0000775
Full-Scale	12 in.	-5.67	0.0128	0.0000738
Model	1.2 in.	-5.67	0.0013	0.0000738
Between Loads				
Full-Scale	0	1.99	0.013	-0.0000815
Model	0	1.99	0.00135	-0.0000815
Full-Scale	12 in.	-5.98	0.013	0.0000799
Model	1.2 in.	-5.99	0.00133	0.0000798

CHAPTER 8. OPERATIONAL IMPACT ON THE TEXAS SDHPT

8.1. BACKGROUND

It was shown in the previous chapters that an accelerated pavement testing program can be an essential component of most larger and progressive pavement agencies. The different methods of accelerated testing and support equipment were discussed and particular attention was given to the method selected by the Texas SDHPT. The so-called Mobile Load Simulator was presented conceptually to the SDHPT in a technical brochure and as a working model, and then accepted by the SDHPT as their future method of accelerated pavement testing. The pertinent mechanical and operational aspects were discussed, after which, based on the conceptual design, an evaluation was made of the accuracy of real load simulation. The evaluation clearly illustrated that a high degree of real traffic simulation is realizable, but, because of simplifications, assumptions, and limitations in the analysis, the prototype should be designed to incorporate a variety of axle combinations with adjustable axle spacings with subsequent conservative power requirements for the drive system.

It is shown below that the cost of testing per test section using the MLS relates closely to the costs of testing at the AASHO Road Test. The principal differences are that the MLS can accelerate loading of the pavement at a higher rate and is not limited to one geographical area.

AASHO Road Test

Number of Load Applications	1,114,000
Duration	2 years
Number of Test Sections	836
Lengths of Test Sections	160 - 260 feet
Total Cost of Test (1962)	$27,114,220
Present Value of Cost (4%)	$81,307,501
PV of Cost / Test Section	$97,257

The comparative cost of MLS testing is given in Table 8.2, later in this chapter, and calculates to roughly to $106,000 per test for 15,000,000 ESALS. Given the above, this chapter lists and discusses the issues relevant to the implementation of this program and the projected operational impact on the Texas SDHPT.

8.2. OPERATIONAL NEEDS AND ISSUES

The proposed MLS project is estimated to place high demands on the research and overall Texas SDHPT program. Similar programs in other countries have proved that there is no physical limit to the benefits which can be gained through well-planned use of accelerated pavement testing programs. Many developments, currently unforeseen, will arise as soon as the program is established, demanding attention and resource allocations. Some of these important issues are discussed in this chapter.

8.2.1. RESOURCES

A number of agency resources which will be drawn from in various degrees can be identified. The demand for resources depends largely on the size of the proposed MLS program, i.e., the number of machines. However, the degree of utilization which will be determined by the testing program will also have an effect on the resource demands. The goal should be to establish and maintain an optimum program that will result in maximum benefit/cost ratios.

8.2.1.1. Financial

A breakdown of the manufacturing costs of the MLS, spread over two years, is presented in Table 8.1. Table 8.2 shows an itemized budget for the proposed annual operation per MLS machine.

8.2.1.2. Staffing

Each operational machine will require full-time onsite staff provided by the SDHPT, consisting of an engineer and two assistants. Support personnel for aspects such as site establishment, traffic control, and clean-up, as well as other service personnel, will need to be provided by the district at times when the machine is utilized on in-service pavements. In the case of MLS testing at a research facility, provision will have to be made for resident staff. An itemized cost projection for annual utilization of the MLS, including personnel, is presented in Table 8.2 in Section 8.2.4. These costs are based on the operational costs projected by the ALF Task Group (23) and should be similar for MLS operation.

8.2.1.3. Management

A permanent executive committee, consisting of high-ranking state and federal officials as well as academics, must be called into existence to guide, plan, and evaluate results flowing from MLS testing. Meetings must be convened on a regular basis to plan future testing, discuss current testing, and review reports of previous test results. This must be done for every operational machine.

8.2.1.4. Plant

The MLS will be a self-contained unit to be operated with as little additional equipment as possible. The MLS will feature a permanent hoist and a power generator. Environmental test facilities are envisioned to form part of the MLS test program, although details of the combined testing of highway structures with the two facilities falls outside the scope of this study. Nevertheless, the MLS design will be such that it can be used in combination with the proposed environmental test facilities.

8.2.1.5. Equipment

The MLS will contain all the necessary equipment for the retrieval and logging of data. Limited data analysis will be performed to ensure correctness of testing equipment and data retrieval methods. Equipment for routine daily maintenance, such as lubrication, will be available to and familiar to the permanent operational personnel. Specialized maintenance, such as welding, should be undertaken by professional craftsmen. Due consideration should be given during the construction phase to spare parts in materials acquisition, such as additional electrical motors, additional steel wheels and axles, and bearings. The reason for this precaution would be not only to ensure availability on long-lead items, but also to take advantage of reduced item cost on bulk orders.

8.2.1.6. Laboratory (Verification or Ancillary Testing)

Depending on the type of testing, a number of traditional and new tests will in all cases be performed, either to complement MLS testing or to serve as verification of certain parameters. These types of tests are referred to in Section 5.6.2.

In the case of MLS application on the project level, where testing is performed for the benefit of an area-specific problem investigation, testing and analysis of data are to be performed by the district requesting the MLS evaluation. Depending on the capabilities of the district, the same stipulation would also apply in the case of network evaluations. The analysis and reporting in both cases will be executed under the close supervision and guidance of the management team of the MLS program.

Where MLS testing takes place under laboratory conditions, on specially-constructed test tracks, verification or traditional materials testing will form part of the total research effort.

8.2.1.7. Training

The training of SDHPT personnel to operate and maintain the fleet of MLS's will be undertaken by CTR, which will contract with various agencies to provide knowledgeable personnel in the areas of maintenance, pavement instrumentation, and data analysis and synthesis.

8.2.1.8. Infrastructure

Infrastructure will be of importance when an MLS is utilized in a laboratory environment. Facilities will have to be provided, such as access roads for construction equipment. Permanent facilities for long-term pavement testing at a laboratory would include permanent housing for the MLS as well as offices for supervising personnel. The test pavements may consist of either the channel or the fill-type subgrades, depending on the existing foundation conditions at the test site. Since environmental testing of highway structures can be evaluated with the MLS facility, the accommodation of the two facilities needs to be planned bearing in mind the ease of operation in limited laboratory space.

Utilities for in-service pavement testing will include electrical power, telephone services, and portable sanitary facilities.

8.2.1.9. Security

Protection against vandalism is not needed in the case of laboratory experimentation because the testing site will be within the laboratory grounds. However, testing on in-service pavements outside laboratory facility will need additional measures to protect equipment and personnel. An 8-foot-high fence should be erected around the total test area, with security personnel manning the site on a 24-hour basis.

8.2.1.10. Traffic Control

This aspect of safety to both MLS personnel and the travelling public will be the concern of the district where testing is to take place. Lane closures should be made in accordance with the Manual on Uniform Traffic Control Devices and should also carry the approval of the FHWA's Regional Traffic Safety Engineer. It was the conclusion of the ALF Montana study that no speed reductions should be imposed for vehicles travelling past the testing site, owing to problems with traffic slowdowns or stopping. Constructing loops to accommodate either traffic or MLS testing for new pavements is preferable in the future, although this implies that testing sites are selected in advance, where problems may not exist, or are not representative of the larger pavement section.

The importance of this aspect of in-service accelerated testing cannot be overemphasized. One accident took place during the Wyoming testing, and undocumented reports from South Africa state that six collisions involving the HVS have taken place in 15 years of operation, including one accident with four fatalities stemming from a high-speed police pursuit, as well as numerous damaged delineators, necessitating additional adequate traffic signs kept on site.

8.2.2. LEGAL AND PUBLIC RELATIONS ISSUES CONCERNING MLS TESTING

Various aspects of MLS testing may result in legal complications stemming from the amount of noise generated by the machine, from traffic flow interruptions and accidents, and, perhaps, for other aesthetic reasons. Once a test site has been selected, it appears that two steps must be taken to ensure uninterrupted testing at the specific site. The first step would be to obtain legal documentation allowing testing at the site, and the second would be to advertise well in advance through the local media that such testing is to take place for a specific duration at a given location. Although none of these measures have been undertaken or considered necessary in other countries, it is believed that public cooperation is achievable through informative media coverage. This will prevent problems which may lead to interference with MLS operation and should also reduce the chances for litigation. Media can also provide the SDHPT with a means of presenting to the public the positive aspects of the latest research being conducted.

8.2.3. ENVIRONMENTAL IMPACT

In the case of laboratory or any other pavement studies within city limits, the major environmental impact will be the amount of noise generated by the MLS. For this reason it may be necessary to perform testing in an enclosed housing. Although this measure will have a severe effect on the establishment cost of the program for laboratory testing, it would enable experimenters to utilize artificial environments for evaluation with pavement testing. Noise reduction may be achieved through innovative mechanical designs which limit noise generating vibration transmissions through the MLS structure. A study of resilient wheels, employed in some train transit systems, may be inappropriate for utilization in the MLS design (49, 50). Resilient wheels are used to reduce rail/wheel forces, reduce wheel wear, reduce some noise frequencies, and reduce wheel slip that generates high-frequency noise during braking and negotiating of curves. The load transfer wheels on the MLS will be travelling in straight lines with no braking applied on them, and would therefore not benefit from having resilient wheels.

8.2.4. PROJECTED ANNUAL OPERATIONAL COSTS

The projected annual costs will be affected by the developmental costs of the equipment and the number of years over which the costs are to be discounted. Table 8.1 shows the projected annual costs over two years for development of the prototype MLS.

Apart from the proposed executive committee to guide the project on a long-term basis, the following personnel will be needed on a permanent basis for each operational machine: one project engineer, two operators, and two graduate students.

For more than one machine, the annual costs per machine will be offset by costs of items such as the permanent steering committee, which will remain constant for five or fewer machines. Also, the initial cost to develop each machine may occur over one or two years, instead of over five as indicated by "equipment lease" in Table 8.2. This will depend on the development strategy followed by the Texas SDHPT.

TABLE 8.1. PROJECTED COSTS FOR MLS DEVELOPMENT OVER TWO YEARS

					Year One		Year Two	
Item	**Quantity**	**Manpower**	**Material**	**Total**	**Manpower**	**Material**	**Manpower**	**Material**
Structure	1	20,000	40,000	60,000	20,000	40,000	0	0
Axle Bogies	8	20,000	40,000	60,000	3,000	10,000	17,000	30,000
Electrical Motors	8	4,000	16,000	20,000	2,000	8,000	2,000	8,000
Power/ Electr System	1	4,000	6,000	10,000	2,000	6,000	2,000	0
Chain Axles and Links	28	28,000	140,000	168,000	10,000	55,000	18,000	85,000
Hydraulic Struts	4	6,000	20,000	26,000	4,000	10,000	2,000	10,000
Mobility Attachments	2	6,000	20,000	26,000	0	0	6,000	20,000
Total		88,000	282,000	370,000	41,000	129,000	47,000	153,000
					Year 1 Total = 170,000		**Year 2 Total = 200,000**	
	Direct Costs				**Direct Costs**			
	Salaries				**Salaries**			
	Prof.	37,500			Prof.	25,000		
	Sub Prof.	7,000			Sub Prof.	5,000		
	Clerical	3,500			Clerical	1,500		
	Total		48,000		Total		31,500	
	Fringe Ben		12,000		Fringe Ben		7,875	
	Operating Ex		4,000		Operating Ex		4,000	
	Construct MLS		170,000		Construct MLS		200,000	
	Total Direct Cost			234,000	Total Direct Cost			243,375
	Indir (7% Dir)			16,380	Indir (7% Dir)			17,036.3
	Year 1 Cost			250,380	Year 2 Cost			260,411
					Total Design and Construction Cost = 510,791			

TABLE 8.2. PROJECTED ANNUAL OPERATIONAL COSTS PER MACHINE

Cost Item	Unit	Unit Price	Quantity	Total
Personnel				
Steering Committee	hr	100	$80	$8,000
Project Engineer	yr	1	$90,000	$90,000
Graduate Students	yr	2	$11,000	$22,000
Operators	yr	2	$50,000	$100,000
Ancillary Testing and Support				
Test Section Preparation	test	5	$20,000	$100,000
Materials, NDT Testing	test	5	$10,000	$50,000
Travel				
Personnel	test	5	$5,000	$25,000
Machine Transportation	test	5	$2,000	$10,000
Equipment				
MLS Lease	yr	1	$100,000	$100,000
Maint & Supplies	yr	1	$25,000	$25,000
Total				**$530,000**

Any projection of the future needs of the Texas SDHPT concerning the number of machines required over the next ten to twenty years, should be based on the known performance of a single unit, the developmental and operational costs of each unit, and the number of pavement issues that need be addressed in that period in order to maintain a high-quality pavement network.

8.3. EVALUATION OF EXISTING ACCELERATED PAVEMENT TESTING PROGRAMS TO DETERMINE THE SIZE OF THE TEXAS MLS PROGRAM

Careful consideration has to be given to the various issues involved before any parallel is drawn to other programs. Although many projects of this nature throughout the world are in operation which can be evaluated and can serve as the basis for determining the extent and size of the Texas program, the Texas program remains unique. The program which most closely resembles that being planned by the SDHPT is the South African Heavy Vehicle Simulator program. It was started in the late 1960's with the construction of the first prototype of a Heavy Vehicle Simulator (1). Three more HVS's of improved design were commissioned soon afterwards and were operational by the late 1970's. In the ten-plus years of operation, a wealth of knowledge has been gained, most of it of a diagnostic nature. Many pavement sections were loaded to failure to evaluate materials at different locations in order to arrive at optimum balanced pavement structures. The HVS was also used in the creation of a catalogue pavement design method and is still being used in the evaluation of new and unproved materials for inclusion in the catalogues, which are the basis for South African pavement design.

It has been hypothesized that most of the information needed to justify the profitable application of the facilities in their diagnostic capacity was obtained by the mid-1980's. In the ten years of application, a benefit/cost ratio of 10-to-1 was achieved with machines operating mainly on the national and secondary networks of pavements. The machines are still in sound mechanical condition, but the whole program—around two million Rands annually—was recently scaled down due to other, more pressing needs and economic constraints.

The South African HVS program serves as the best example from which to project the size of the Texas MLS program, even though the Texas program will be started twenty years later. The ultimate performance rates of the proposed MLS will also differ radically from those of the HVS. Evaluation of an extrapolated comparison can be made and valuable lessons can be learned from the HVS program itself. Differences, such as traffic counts and composition, materials, total lengths of different pavement classes, different needs and intents, economical growth rates, and resources, will have to be taken into account when comparative studies are done. Table 8.3 compares the pavement mileages in 1985.

8.3.1. VARIABLES TO BE RECOGNIZED BY THE SDHPT IN DETERMINING THE EXTENT OF THE MLS PROGRAM

A commitment to full-scale accelerated testing involves a whole new approach to pavement management at all levels. Economic justification necessitates the continuous use of the machine to achieve optimum benefits. At the same time, the high volume of data generated by maximum usage sets a demanding schedule for the analysis of the data. Data collection should, therefore, be prudently done on a carefully-selected basis. This production of information will in return demand a major reallocation of resources.

Considerations in the establishment of the MLS program are discussed under the following categories:

— present and future needs in pavement engineering technology,

— determination of analysis period for economic evaluation of the program,

— management composition and project goals, and

— project restraints.

TABLE 8.3. A COMPARISON OF PAVEMENT CATEGORIES AND MILEAGES BETWEEN TEXAS AND SOUTH AFRICA

Location	Pavement Classification	Miles
Texas	State Control	65,500
	Local Control	146,300
	Federal Control	1,000
	Urban Mileage	69,500
	Total Mileage	282,300
S. Africa	Freeways	2,250
	Two-Lane (Paved)	28,820
	Unpaved	84,500
	Urban Mileage	26,700
	Total Mileage	142,270

8.3.1.1. Present and Future Needs in Pavement Engineering Technology

The two main categories of applications of the Mobile Load Simulator are in pavement management, where remaining life and the effect of various maintenance strategies are to be evaluated on in-service pavements, and in pavement theory, where applications on new pavements will allow evaluation of the accuracy of pavement behavioral prediction models and other aspects, such as the effect of tire pressures and the durability of markings, can be evaluated simultaneously with these two categories.

Because of large-scale, increasing international cooperation, the costs involved in research, and the promotion of technology transfer, many breakthroughs have occurred in the last twenty years of pavement technology history. These events have resulted in the elimination of redundancies. The middle, fast-climbing section of the learning curve experienced a slowdown over the latter part of the 1980's. Old methods are being phased out and are being replaced by better and more advanced methodologies to yield greater reliability in estimates of pavement performance.

It must, therefore, be decided at which rate problems will have to be solved to keep abreast of demands by the public on the pavement infrastructure and demands by district engineers to solve problem-specific issues. The ultimate goal is the enhancement of current pavement behavior models with minimized cost inputs.

8.3.1.2. Determination of Analysis Period for Economic Evaluation of the Program

In the process of establishing an accelerated pavement testing program, the period for which the program will be economically justified must be determined. A high rate of return must be maintained, even though it is to be expected that such a rate of return will decrease as the contributions of the program and other technological advances are incorporated. This tendency is believed to have occurred in the South African program, where authorities estimated the rate of return at ten times the overall investment in 1985. The recent down-scaling of the project indicates that lower rates of return were experienced at the end of the 1980's, although this indication has to be viewed in conjunction with socio-economic developments in the region. The latter have led to major constraints on the available funds for highway development and other related expenditures.

The stage at which the rate of return will fall below a certain minimum for the MLS program will have to be determined. It is believed that the program will still be useful in providing answers after this time, but it may not operate as profitably as it did during the initial analysis period. Factors to take into account would be the mechanical life of equipment, improvements in later models, and developments in other fields of pavement engineering. This process will determine the number of, and timetable for the development of, additional testing facilities.

The load applications required for resolving problems in all the respective categories must also be determined. Every problem will require a number of applications to permit adequate study of that specific pavement response. This information has to be equated to the production rate and number of facilities as well as the duration of the total program (Eq 8.1). The production rate will be determined through a performance evaluation of the prototype. Also to be taken into account is the mechanical life (Eq 8.2) of each facility.

The equations describing this relationships are:

$$M = (n \times a)/(r \times d) \tag{8.1}$$

and

$$M = (n \times a)/L \tag{8.2}$$

where

M = number of MLS's required,
n = number of tests,
a = number of load applications needed for study (loads/test),
r = rate of load application (loads/month),
d = duration of MLS program (months), and
L = life of MLS (loads).

The number of MLS's required will be highest value of M in Eqs 8.1 and 8.2.

8.3.1.3. Management Composition and Goals

The MLS project can be classified and utilized in a number of ways that will determine its managerial composition and will have an effect on its goals. These classifications can be:

- — pavement design orientated (validation of models),
- — pavement research orientated (behavior of materials),
- — pavement construction orientated (quality control), or
- — a combination of the above.

Many of the applications of the testing facilities will consist in the development of specifications for pavement materials and the evaluation of construction techniques. In this capacity, MLS's will be utilized as testing apparati for evaluation on specific projects. This could have a significant effect on specific project costs.

By viewing the MLS project as research, the program would call for the utilization of University staff in consultation with the SDHPT. Active involvement of research personnel in the early stages is very important in order to establish which mechanical functions and data acquisition systems can be automated or improved. This function implies the assignment of a permanent technical crew and an inter-agency agreement with active federal involvement. It is believed that the Mobile Load Simulator program will make a valuable contribution to graduate programs of universities in Texas.

Various options exist for methods of fund allocation. The best solution, in the opinion of the authors, is to underwrite each separate application of the facility as an individual project with a unique cost and duration. Cost could then be determined on a project basis and related to design verification or to a problem-specific machine application. Testing would then be executed in conjunction with and in parallel to research. The benefit of this combination is that research funds will not be reallocated.

The most important responsibility of personnel in charge of the program is to ensure continuous advance planning. Planning involves the selection and preparation of sites, site evaluation using equipment such as Falling Weight Deflectometers, condition surveys, and other destructive classification methods. All pre-trafficking measurements are important; they should be thorough and complete so that any changes that may occur during trafficking can be evaluated. This function, together with follow-up studies, justifies the creation of a permanent steering committee to do advance planning, prioritizing, financing, report evaluations, and liaisons with district or other personnel. This group should consist of members from academic institutions as well as members from state and federal transportation bodies. Additional part-time members should include mechanical, electrical, computer software, and trucking industry experts. The group must be in existence well in advance of any testing, with alternative personnel and communication lines established. Commitment of personnel over the duration of the Mobile Load Simulator project is important not only for continuity but also for successful and profitable results.

8.3.1.4. Project Restraints

It is accepted that the Texas SDHPT will maintain its liberal view regarding research and the funding thereof. In this respect, funding of the MLS project will not be met with overly restrictive policies. A two-year development period for the prototype is indicative of this approach, which is essential to the success of the project. The program is expected to generate interest, resulting in less expensive pavement testing devices' being used and evaluated concurrently with MLS testing. Overly ambitious acceleration of the MLS project would spread too thin the availability of funding for resources and co-development of NDT devices.

8.4. ESTABLISHMENT OF A LONG-TERM TEST PROGRAM FEATURING MLS MACHINES AND ENVIRONMENTAL SIMULATION FACILITIES

The Texas MLS program, of which this report and its recommendations will form the basis, was first introduced to the SDHPT in a brainstorming session in 1988. The results of this meeting are contained in Appendix A. The purpose of this initial session was to determine the feasibility of accelerated pavement testing in the state of Texas. It was concluded that there was a definite role for accelerated pavement testing, justifying as a first step a pilot study in which the state of the art and its future in Texas would be evaluated. This report documents the evaluation and the decisions made during the ensuing one-year study.

As a logical conclusion to the pilot study, a second brainstorming session was held. This session had the following aims:

1. (1) To determine the relative importance of aspects to be evaluated in future pavement testing, both by discussion and through subjective ratings of dependent and independent pavement variables.
2. (2) To determine the role of MLS testing in evaluating the respective independent pavement variables.
3. (3) To establish the need for and extent of an environmental simulation facility for testing pavement structures.
4. (4) To determine the role and required adaptation of the MLS to evaluate simulated environmental effects for test tracks and/or in-service pavements.

The information obtained will be used to define a global pavement engineering test strategy for Texas.

Details of such a strategy fall outside the scope of this report; however, mainline conclusions and comments flowing from the second brainstorming session are given below.

8.4.1. OVERVIEW OF THE BRAINSTORMING SESSION ON MLS TESTING AND EVALUATION

Having a global plan through which, in general, research is to be executed, is especially important with respect to MLS testing. This view was confirmed by delegates to the second brainstorming session, who insisted that a long-term program with dedicated funding be in existence before any testing was to take place.

Delegates were divided into three groups, and each group had an opportunity to rate the relative importance of dependent and independent variables pertaining to the three pavement categories selected. The independent variable categories were:

- environmental factors,
- load factors,
- material and construction factors, and
- structural factors.

These independent variables were taken from the factors in Table 2.1 (Chapter 2), and a condensed version (see Appendix A) was presented to delegates at the second brainstorming session for prioritization. All the factors are self-explanatory, although the environmental factors and their simulation call for some further explanation. Load simulation was discussed in detail in Chapters 6 and 7.

8.4.2. ENVIRONMENTAL FACTORS AND ACCELERATED PAVEMENT TESTING

Environmental simulation requires the ability to combine, within financial constraints, a number of environmental effects in such a way that a large portion of the real environmental spectrum can be evaluated under controlled conditions. Simulated environmental effects are separated by their respective methods of mechanical generation, which are the following:

- wind,
- water,
- humidity,
- heat, and
- cold.

In order to identify which environmental effects can be simulated and used in conjunction with accelerated pavement testing, Table 8.4 was developed. Water and humidity were omitted from Table 8.4 to simplify the selection of practical and financial executable combinations.

Effects of water are generally evaluated in two areas: surface water and foundation moisture content. Both of these can easily be studied at two levels, at a dry or drenched surface or at an existing or saturated foundation moisture content. At these extremes, the results of the variables also are easily studied and measured. In an accelerated test environment, changes in foundation moisture content are difficult to induce apart from saturated conditions. Therefore, except for measuring existing moisture contents, little can be done to evaluate the effect of moisture content at levels below saturation.

The evaluation of changes in the humidity of the environment is considered feasible. However, in combination with wind effects, a closed-loop wind tunnel is required if other than ambient conditions are to be evaluated. Therefore, humidity is easily studied in a windless environment, and then requires only humidifiers and measuring equipment additionally.

The comments relating to the matrix in Table 8.4 are based on the following assumptions:

(1) Static heat and cold conditions can be successfully applied to pavements, either concurrently with accelerated loading or non-concurrently with accelerated loading. (Rows 1, 2)

(2) Environmental effects are most severe after placement of materials, until full strength is reached. In this period no traffic loading is experienced. Therefore, simulating the environment and evaluating the effects thereof through accelerated loading are non-concurrent events, leading to less costly designs for the equipment. (Rows 3, 4, 5, 6)

(3) In the Texas environment, the generation of cold under warm ambient conditions is more expensive than the generation of heat under cold ambient conditions. (Rows 11, 13, 15, 17 vs 12, 14, 16, 18)

(4) Using other than ambient air conditions in the wind tunnel, requiring the recycling of air, is very expensive and therefore cost-prohibitive. (Rows 11-18)

(5) Controlling of relative humidity is expensive with wind and/or accelerated loading.

(6) Regulation of wind speed is within plausible limits.

Thus, for evaluating the possible combinations for environmental and load simulation, a relatively simple environmental facility is foreseen. The dimensions should be compatible with the MLS design. An arrangement for accelerated pavement testing in a laboratory is conceptually shown in Fig 8.1. It is also envisaged that mobile units, such as cooling and heating boxes, will form part of MLS testing on in-service pavements.

TABLE 8.4. PARTIAL ENVIRONMENTAL SIMULATION AND ACCELERATED LOADING MATRIX

Row	Ambient Conditions		Artificial Conditions		Ambient Wind		Accelerated Load		
Number	Heat	Cold	Heat	Cold	Concurrent	Non-Concurrent	Concurrent	Non-Concurrent	Comments
1	X						X	X	Practical = HVS/Alf
2		X					X	X	Practical = HVS/Alf
3	X		X			X		X	Practical, < realistic
4		X		X		X		X	Practical, < realistic
5	X		X		X			X	Practical, > realistic
6		X		X	X			X	Practical, > realistic
7	X		X			X	X		Practical, < realistic
8		X		X		X	X		Practical, < realistic, > expensive
9	X		X		X		X	X	>> Realistic, > expensive
10		X		X	X		X	X	>> Realistic, > expensive
11	X			X		X		X	< Realistic, > expensive
12		X	X			X		X	< Realistic, > expensive
13	X			X	X			X	Impractical, >> expensive
14		X	X		X	X	X	X	Impractical, >> expensive
15	X			X		X	X	X	Impractical, >> expensive, < realistic
16		X	X			X	X	X	Impractical, >> expensive, < realistic
17	X			X	X		X	X	Impractical, >> expensive
18		X	X		X		X	X	Impractical, >> expensive

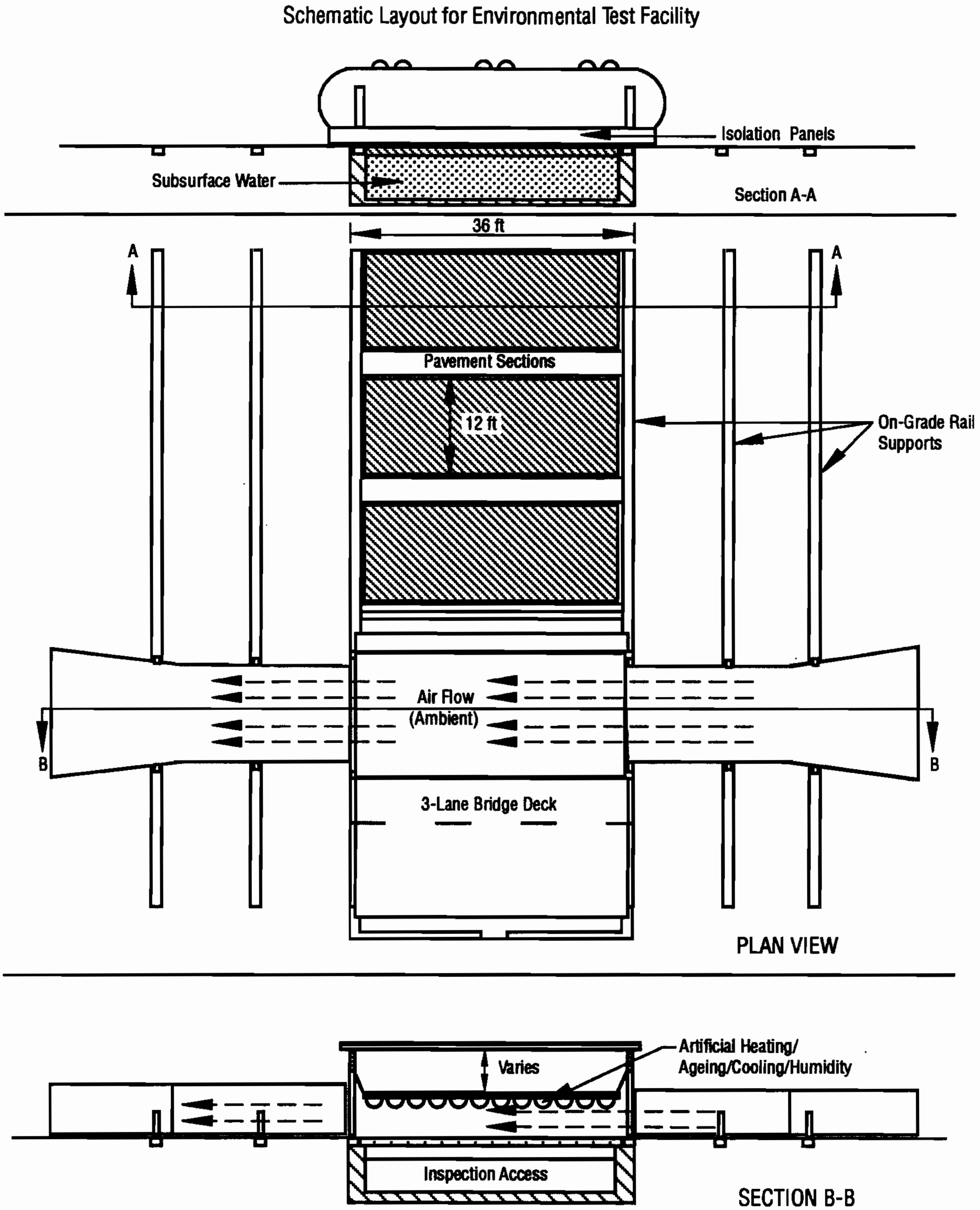


Fig 8.1. Schematic layout of environmental/MLS test facility.

8.4.3. COMMENTS FLOWING FROM THE SECOND BRAINSTORMING SESSION, SERVING AS BASIS FOR THE DEVELOPMENT OF A LONG-TERM TEST PROGRAM

The importance of having a long-term test program in existence, well before the completion of the accelerated testing facilities, cannot be overemphasized. Good experimental design must accompany such a program in order to maximize benefits. It is acknowledged that such a program will be interrupted from time to time to perform diagnostic evaluations, resulting in insufficient lead times for good experimental design. Although these types of testing are necessary, it must be recognized that low benefit/cost ratios could result from such tests and that they should therefore be minimized.

The second brainstorming session was divided into three sessions:

— bridging structures,
— light-duty pavements, and
— heavy-duty pavements.

These categories were selected because of differences in service, structure, and functionality. Scores given to the respective dependent and independent factors are contained in Appendix A.

8.4.3.1. Bridging Structures

Because of the possibility of MLS testing to some extent of bridging structures, an evaluation of the feasibility of this type of accelerated testing was included in the second brainstorming session.

It is a well-known fact that PCC structures are most susceptible to environmental influences in the first 24 to 48 hours after placement. During this period, and up to two weeks later, no loading is expected to be carried by the structure. Therefore, accelerated environmental effects and accelerated loading are mutually exclusive in the worst case. It is also agreed that the interaction of the two factors needs investigation; i.e., what are the relative influences of temperature versus load at various stages in the life cycle of the structure.

Remaining life of structures is still not a well-defined entity, and although the MLS will not be able to evaluate the in-situ structural capacity of long-span bridges, valuable information can be gained on bridge decks and overlays. The length of the MLS limits the span of structure that can be tested to approximately 36 feet. This is because the supports of the MLS carry additional weight not transmitted through the rolling wheels, which have to be placed on the abutments of the tested span. This testing can be carried to total failure in a laboratory with no endangerment to the MLS. The same statement applies to the evaluation of culverts.

Accelerated testing of structures should take second place to the testing of pavements, owing to the fact that 50 percent of the the total budget is spent on pavements, compared with only 20 percent on bridges.

Questions raised during the discussions were:

(1) Can corrosion be accelerated and structurally evaluated with the MLS as this is an important factor leading to structural distress?
(2) How does aggregate type influence structure behavior?
(3) Could temperature effects of placement of hot-mix bond breaker be evaluated?
(4) Could epoxy coating and cathodic protection of reinforcement be evaluated?
(5) Could bridge deck approaches, headers, retaining walls, and reinforced earth be evaluated?
(6) To what degree can long versus short span bridges be evaluated?

It was generally agreed that MLS testing with a partially-controlled environment was important and that it should be further pursued.

8.4.3.2. Light-Duty Pavements

Environmental effects are essential on this type of pavement. Temperature and moisture are the most important environmental factors. Temperature variations lead to cracking, and then water becomes important. Wind and humidity were not considered important. However, the relative influences of these factors need to be determined; this process could lead to the re-definition of specifications for construction. There is concern about being able to accelerate the aging process, in particular oxidation of asphalt. Asphalt pavements are affected by evaporation of the volatiles in the mixture, an effect that is worsened by hot, dry, windy conditions, and evaporation to a large degree to the aging process. Evaluating these relative influences is considered feasible with modelled pavement studies.

It is believed that modelled pavement studies of environmental influences will prove to be invaluable to future full-scale environmental studies. The applicability of Miner's Hypothesis can be determined, where short cycles of temperature variations are compared with long cycles. This comparison will also give an indication as to whether accelerated environmental simulation actually simulates the environment

Most foundation and structural materials can be successfully evaluated with the aid of MLS testing. Expansive clays would be difficult to evaluate because of the difficulty in controlling moisture contents in clays; however, different stabilizing agents can be evaluated. Innovative measuring equipment such as the multi-depth deflectometer enables the researcher to find single-layer deflections. Saturated conditions can be introduced into these layers at various depths to evaluate worse-case strength conditions. This will enable correlation to be made with traditional in-situ soil strength parameters. Generally, in-service pavements are tested at equilibrium moisture conditions and test tracks at the compacted moisture content. It is considered that freeze/thaw cycles are not as important as wet/dry cycles for evaluation in the Texas environment.

Load factors are important with respect to light-duty pavements. PSI calculations in Texas are based only on roughness, and dynamic loading becomes more important as PSI decreases.

Materials and construction factors are interdependent and very important for this class of pavement. New base materials are not as important, but new surface materials such as bitumen rubber and polymer-modified asphalts are well worth testing. The evaluation of mix compositions has much potential, and specifications, porous stone designs, and large aggregates are just some of the issues to be successfully addressed through accelerated testing. The evaluation of construction or material variability over a 36-foot pavement section is questionable. Generally, lengthwise variations in roughness are an indication of variability in structural quality, given all other factors are similar. Roughness measurements over short sections are currently being investigated for use with ALF testing.

In this and all other pavement classes, structural factors consist of two equally important factors: layer thickness and layer stiffness. The notion of balanced pavement structures combines these two parameters to resist certain loading conditions in the most economical way. Accelerated pavement testing lends itself perfectly to the evaluation of these structures, through which optimum pavement structures can be constructed.

8.4.3.3. Heavy-Duty Pavements

During the session on heavy-duty pavements, similar comments were heard as were heard in the other two sessions. It would seem that in this category of pavements, the same types of distress can have one or more causative factors. This emphasizes the importance of evaluating the interaction of variables during accelerated pavement testing. For instance, fatigue cracking is considered a secondary distress, and can be caused by loss of support in PCC pavements, leading to punchouts. Partly resolved through the use of stabilized base materials, this condition is still a problem in wet areas. Fatigue cracking can also be caused by loss of load transfer. Another example would be loss of skid resistance, which can be related to aggregate type, mix design, and tining method.

In this category of pavements it is important to distinguish between surface and sub-surface water, as well as between temperature effects when combined with wind in the early age of a pavement.

8.5. SUMMARY

In Chapter 8, the operational impact of the MLS program on the Texas SDHPT is discussed. The operational needs and issues are identified, and the uniqueness of the system is illustrated.

The MLS program will place a considerable demand on SDHPT resources with resulting benefit/cost variation as depicted in Fig 8.2. The increased scope of the program provided by the accelerated environmental simulation facility increases the initial cost of the program. It also results in higher benefit/cost ratios.

The only way that the higher benefit/cost ratios can be achieved is through careful planning and throughthe establishment of a long-term program for simulated pavement testing in Texas. The purpose of the first brainstorming session in 1988 was to determine applicable areas for accelerated pavement testing utilizing the MLS. The second brainstorming session was held to determine the value of having a simulated environmental testing facility to complement and enhance MLS testing.

In the second brainstorming session on accelerated testing in October 1990 , it was established that a consensus exists between delegates in that controlled environmental studies are essential to future pavement engineering knowledge. With the MLS, a credible method for evaluating these effects is also now available, thus setting the stage to obtain fast and reliable results.

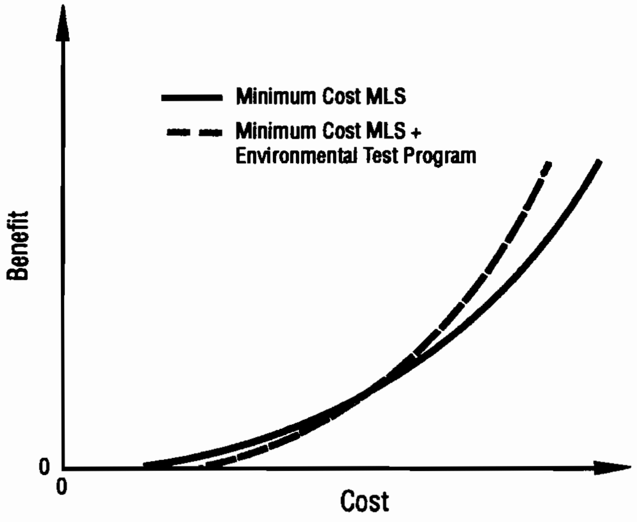


Fig 8.2. Probable benefit/cost variation for the MLS and environmental test program.

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

In the previous chapter, an overview was given of the relevant issues to be considered in an MLS program. This was done without the benefit of an operational prototype MLS on which to base the projections of the size of the program. Also discussed was the extended scope provided by the simulated environmental facilities. Detailed projections of the future SDHPT commitment can and should be made only after the first prototype facilities have produced significant results. The option also remains that the Texas SDHPT need not attempt the development of the program alone but could solicit the participation of other pavement agencies in the various developmental stages of the program.

Treating the matter of developing the Texas MLS program as a typical engineering problem implies that it must be viewed as an experiment and evaluated in the stages of its development for workability and the ability to provide reliable engineering solutions. Once this has been achieved, a formal production program will be easier to formulate and operate. The Center for Transportation Research has presented, as a first step, a concept for an accelerated pavement testing machine. This was followed by a presentation of the workability of the machine as set out in a technical brochure as well as by an operational model of the MLS. In the next phase, the detailed design and construction of a single prototype will be completed.

The development and subsequent utilization in pavement testing of the machine must be done over a period of time that is in accordance with the overall budget constraints of the Department. Manufacturing of subsequent machines should be undertaken only after a complete performance evaluation of the prototype has been completed and good experimental results have been obtained.

Ultimately the MLS can be viewed in one of two ways. It can be used as the main indicator of the behavior of pavement structures, which implies an extensive fleet of MLS's with a large dedicated work force over the next ten to twenty years. Alternatively, the MLS program can be viewed as a means by which the development of less expensive, faster, but still reliable evaluation methods can be developed for use long after the majority of the MLS testing has been phased out. This decision will have to be made at some future date.

Stemming from the recommendations of this report, the development of a prototype MLS has been set to take place over two years according to a budget as presented in Table 8.1. Concurrently with this development, the knowledge base on accelerated pavement testing should be broadened with the use of this model MLS.

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APPENDIX A. BRAINSTORMING SESSIONS

FIRST BRAINSTORMING SESSION: VIEW POINT SURVEY ON MLS TESTING

Name: ______________________________

Note: The following questions have been set to enhance the debate on the use of the MLS. Please read and answer carefully. % relates to present degree of readiness of MLS testing.

Pavement Management Issues

		No	Yes	%
1.	Can the MLS be used as a Pavement Management tool for:			
	1.1. structural condition,	___	___	___
	1.2. surface condition.	___	___	___
2.	Can the MLS be used to conduct Value Engineering studies	___	___	___
3.	Can the MLS fill gaps in knowledge on pavement behavior	___	___	___
4.	Can the MLS assist in the evaluation of residual life	___	___	___
5.	Can the MLS help to communicate with the public and their representatives.	___	___	___
6.	Is the MLS suited for:			
	6.1. concrete pavements	___	___	___
	6.2. asphalt pavements	___	___	___
7.	Does the MLS fill a gap in ability to asses new materials or strategies	___	___	___
8.	Can the MLS be used to predict performance	___	___	___

9. Will the MLS help to improve our knowledge on the equivalency of axle loads ? ___ ___ ___

10. Is the MLS a tool to monitor and collect PMS data ? ___ ___ ___

11. Is the MLS suited as a testing tool for any of the following:
    - 11.1. New design ___ ___ ___
    - 11.2. Maintenance ___ ___ ___
    - 11.3. Rehabilitation ___ ___ ___
    - 11.4. Research ___ ___ ___

Basic Engineering Issues

1. Does the deterministic nature of the MLS testing cause problems ___ ___ ___

2. Can the MLS simulate the action of water on the pavement structure and materials ? ___ ___ ___

3. Will the use of artificial environments with the testing of in situ pavements, eg. temperature, enhance test results ? ___ ___ ___

4. Can we accelerate the effect of the environment concurrently with accelerated loading ___ ___ ___

5. Will the MLS improve knowledge on concrete joint behavior ? ___ ___ ___

6. Will the MLS improve our knowledge on the allowable elastic and plastic subgrade strain ? ___ ___ ___

7. Will the MLS improve knowledge on the fatigue of materials ? ___ ___ ___

8. Will the MLS improve our knowledge on the effects of voids beneath concrete pavements ? ___ ___ ___

9. Is the speed of the MLS test wheels acceptable or not ? ___ ___ ___

10. Is the direction of load application important ? ___ ___ ___

11. Should the load be:
    11.1. uni-directional, ___ ___ ___
    11.2. bi-directional. ___ ___ ___

12. Can the MLS simulate dynamic effect of wheel loads ? ___ ___ ___

13. Does the MLS have advantages in comparison to laboratory testing or supplementary laboratory testing ? ___ ___ ___

14. Can we simulate muti-axles ? ___ ___ ___

Management and Organizational Issues

1. Should we:
    1.1. Construct special test sections ? ___ ___
    1.2. Use existing pavement lanes ? ___ ___ ___

2. Should a special organization be set up to operate MLS's ___ ___

3. Should the trucking industry be approached for support or joint support with the acquiring of MLS's ? ___ ___ ___

General

Give examples of any of the following:

a. Where MLS testing would have prevented premature failure,

b. Where MLS testing would have benefitted the design and/or construction decisions,

c. Where MLS testing would have resulted in dollar savings

Responses to questions in the first brainstorming session were as follows:

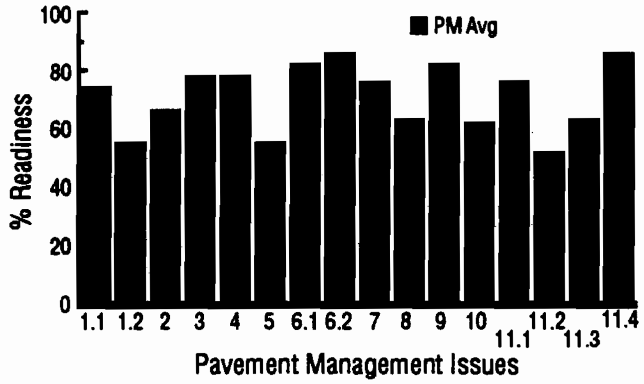


Fig A.1. Percent readiness of MLS in pavement management issues.

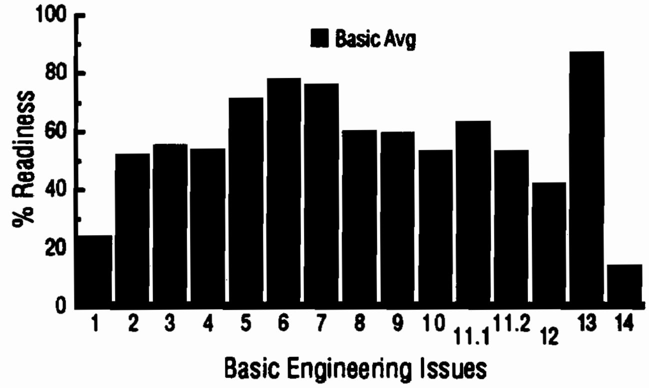


Fig A.2. Percent readiness of MLS in basic engineering issues.

SECOND BRAINSTORMING SESSION: MOBILE LOAD SIMULATION AND ENVIRONMENTAL TESTING

Table A.1 is derived from responses by delegates to the brainstorming session by allocating a score out of 5 on the most occurrence and also on the most costly to repair (5 = most costly and most common). These two factors are multiplied to give the factors in Table A.1.

Figure A.3 is derived through scoring of the degree to which the environment, loads, or a combination of load and environment contribute to the reduction in performance of the various pavement types. A scale of 1 to 3 is used (3 = great influence), based on experience, expertise, and judgement.

Table A.2. gives the average responses of delegates on the subjective importance (5 = most important) on the given independent variables. Four categories of highway structures were evaluated. Where large variations in responses occurred during the brainstorming session, discussions of viewpoints and interpretations of the variables ensued. Changes were made to individual scores based on clarifications and definition of the variable.

TABLE A.1. DEPENDENT PAVEMENT VARIABLE SCORES (COST X OCCURRENCE = 25 MAX)

		Pavement Structures		
Dependent Variables	**Bridging Structures**	**Unbound Flexible**	**Bound Flexible**	**Rigid**
Bridging Structures				
Shrinkage Cracking	9.50			
Loading/Stress Cracking	13.70			
Thermal Cracking	7.80			
Excessive Deflections	8.50			
Strength/Failure Modes	9.50			
Corrosion	16.00			
Permeability	9.60			
Freeze-Thaw	8.20			
Scaling	5.50			
Spalling/Delamination	13.20			
Skid Resistance	5.50			
Roughness	9.20			
Pavements Structures				
Surface Rutting		12.00	14.00	
Surface Cracking		8.00	11.50	7.70
PSI Degradation		10.00	9.75	7.50
Fatigue Cracking		14.70	13.75	14.40
Deep Consolidation		7.70	9.20	
Shoving		8.30	7.40	
Bleeding		6.70	15.50	
Stripping		6.00	9.00	
Surface Texture Degradation		3.30	5.50	8.00
Ravelling		4.00		
Deep Rutting		8.00		
Swelling Clay		7.00		
Pumping				12.90
Loss of Load Transfer				16.00

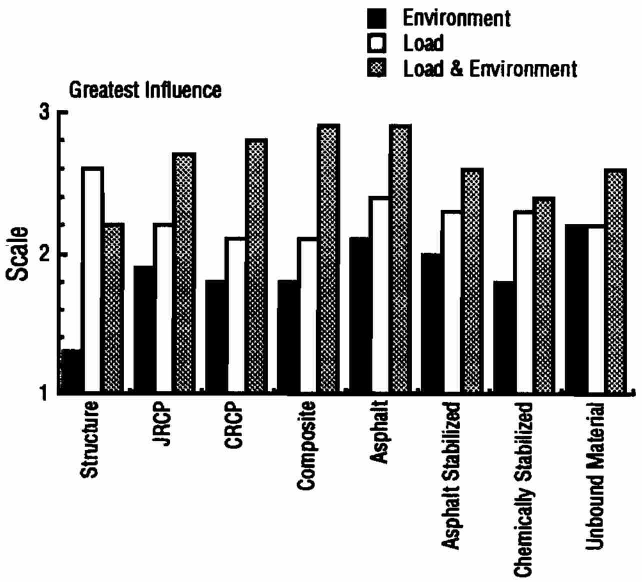


Fig A.3. Influence of load and environment on the reduction of performance for various highway structures.

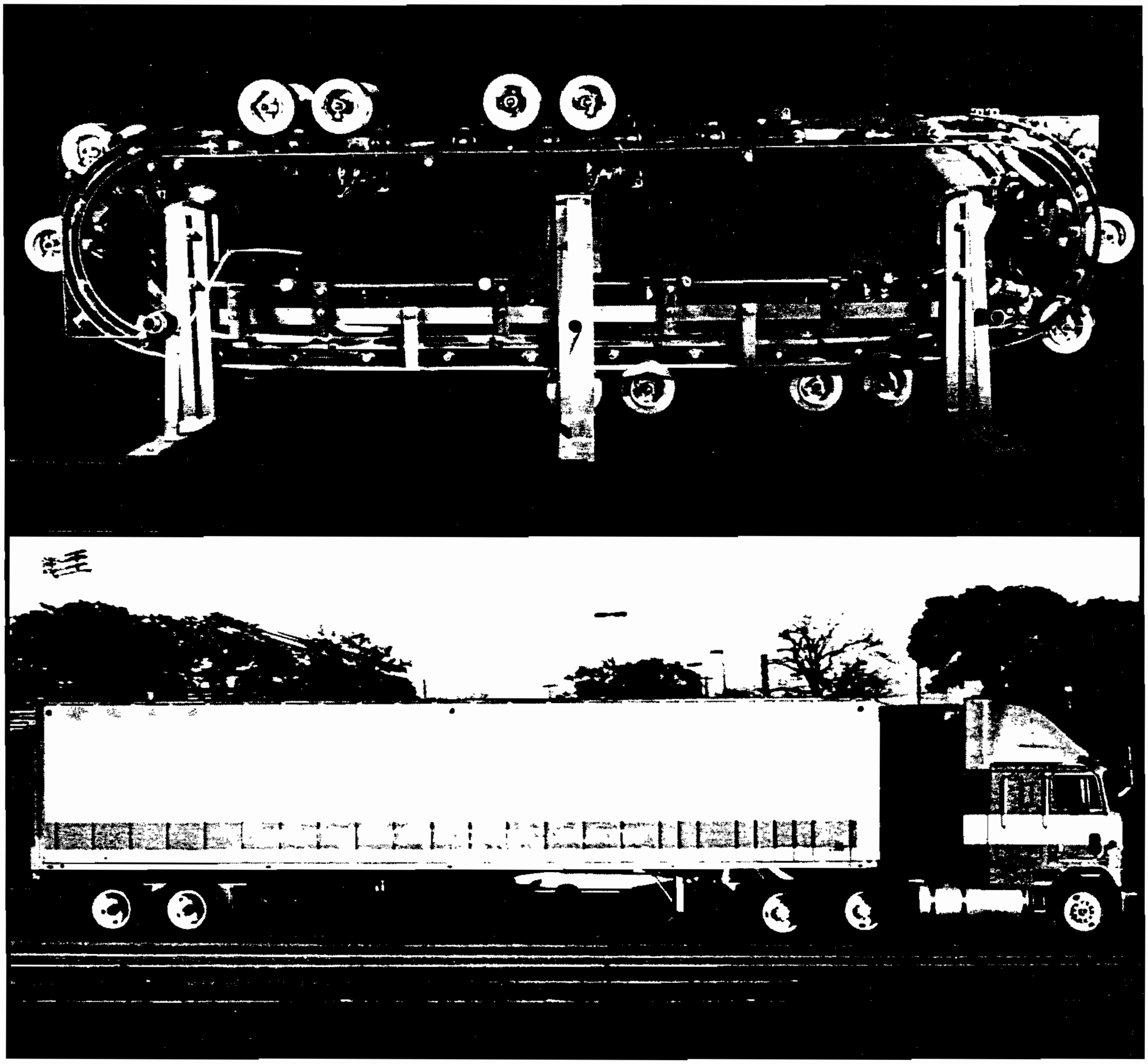
TABLE A.2. INDEPENDENT PAVEMENT VARIABLE SCORES (MOST IMPORTANT = 5)

		Pavement Structures		
Independent Variables	**Bridging Structures**	**Unbound Flexible**	**Bound Flexible**	**Rigid**
Environmental Factors				
Water	4.90	5.00	4.70	4.50
Wind	3.80	1.30	1.70	1.20
Temperature	3.80	4.70	4.20	4.00
Humidity	3.80	1.30	2.10	2.00
Load Factors				
Contact Pressures	3.10	4.30	4.00	3.10
Axle Combinations/Load Sequence	4.4	3.30	3.60	4.50
Speed		1.50	1.80	1.50
Load Magnitude	4.60	5.00	4.75	5.00
Roughness/Load Dynamics	4.50		3.50	4.00
Material and Construction Factors				
Layer Stiffnesses		4.30	4.00	3.20
Material Compaction		4.60	4.30	4.00
Material Mix Composition	4.30	4.30	4.00	3.50
New Materials	3.50	2.70	3.10	3.50
Material Properties	4.30			
Add Mixtures		1.50	3.20	3.20
Construction Variation		4.70	3.40	4.40
Material Placement Technique	4.10			
Layer Bonding/Debonding		1.30	4.10	3.00
Foundation Material Characteristics		4.30	3.80	3.80
Forming Methods	2.80			
Structural Factors				
Structural System	4.50			
Geometry/Dimensions	3.50			
Layer Thicknesses		4.70	4.40	4.50
Layer Stiffness Ratios		4.30	4.00	4.20

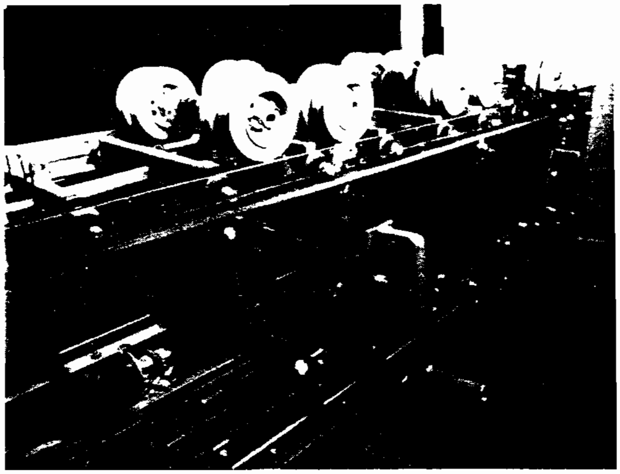
APPENDIX B

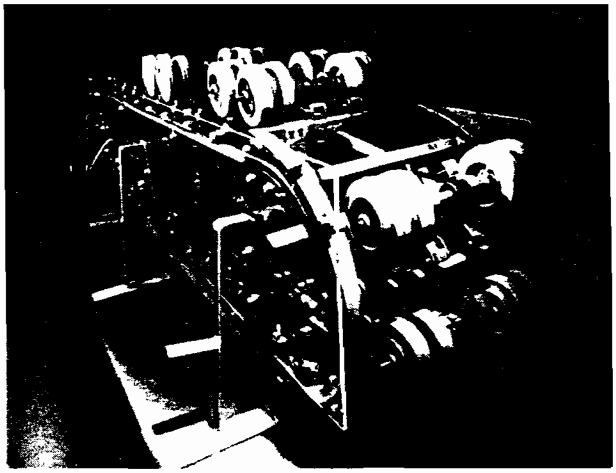
TECHNICAL BROCHURE ON THE TEXAS MLS

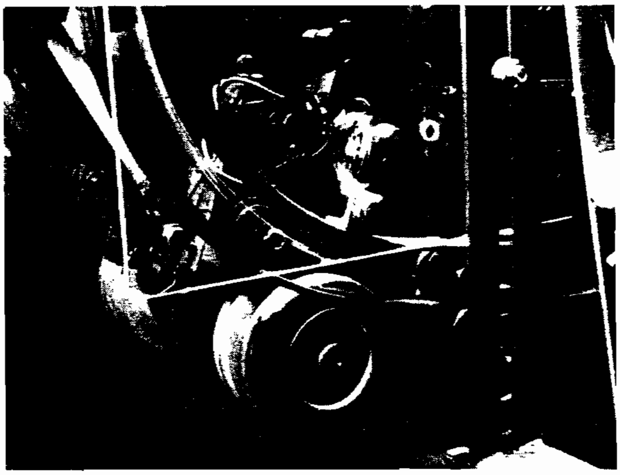
The Texas Mobile Load Simulator

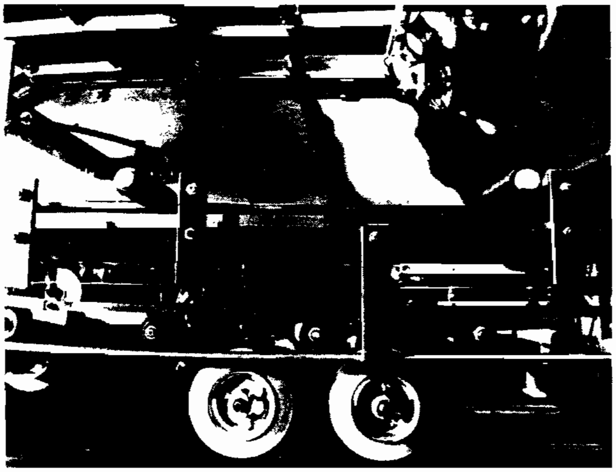


Accelerated Simulation of Real Traffic









■ FOREWORD

The State Department of Highways and Public Transportation is in the process of developing an accelerated vehicle simulator for testing pavements throughout the state. This is in line with the worldwide trend to enhance the capability of pavement engineers to predict pavement behavior and optimize new and rehabilitation designs.

The development is being done on the basis of the Mobile Load Simulator (MLS) which has been provisionally patented. An operational model has been acquired, and development of the full-scale prototype is scheduled to take place over the next eighteen months. This brochure gives some of the technical details of the testing device and its capabilities.

With this project the department aims to contribute substantially to pavement engineering, since the MLS simulates traffic closer than any known device of its kind. Any organizations interested in more information about the project are welcome to contact the Department.

R.G. Welsch, P.E.
Deputy Director for Design and Construction
State Department of Highways and Public Transportation
March 1990

ACCELERATED PAVEMENT TESTING (APT) USING THE TEXAS MLS

Based on a proposal by the Center for Transportation Research (CTR) at The University of Texas at Austin, in 1988, a research program was initialized by the Texas State Department of Highways and Public Transportation through which CTR was to develop a strategy for the acquisition of a device for carrying out full-scale tests on pavements using APT. After the first phase of the study, the Department decided to develop a new testing machine known as the Mobile Load Simulator (MLS), which is based on a provisional patent of Dr. Frederick Hugo. The purpose of this brochure is to relay technical information on the MLS to interested parties and designers of the ultimate prototype.

The MLS is a mobile testing device capable of accelerated simulation of real traffic loading on any selected pavement section. Accelerated testing is achievable either by overloading or by increasing the number of axles and/or the rate of application. The pavement sections may be existing roads or specially constructed test sections.

The MLS is a unique system featuring the energy saving belt or closed loop concept shown in **Figure 1**. Rotation of the chain arround the stationary frame, consisting of wheel bogies linked together in a chain, is achieved through electric motors on axles drawing current from a buss bar and transforming rotation of the wheels in contact with the pavement to translation of the chain around the frame.

MODEL MOBILE LOAD SIMULATOR

As a first step CTR acquired a one-to-ten scale model of the proposed MLS on behalf of the Department. The prime reason for this step was to evaluate the electrical system and the mechanical working for use in the design of the prototype. However, the model may also be utilized:

- as a demonstration exhibit to generate interest and funds for the prototype development, and
- to evaluate modeled pavements and materials.

The model, shown in the photographs, consists of specially cast wheels which have a resilience comparable to the downscaled resilience of full-scale truck tires. The suspension springs provided for the model are similarly downscaled. Other features of this model include the option of any combination of axle configuration, limited lateral wheel distribution, and electric motors on any single or dual set of axles. Power is supplied by way of 22-24 volt DC at a maximum of 25 ampere.

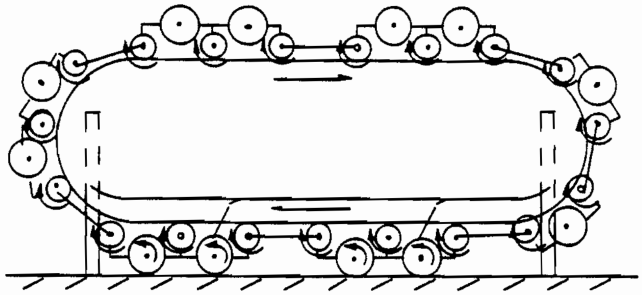


Figure 1: Conceptual Layout of the MLS

The model proved to be an important component to the overall strategy of prototype development, even though some of the aspects of mobility of the prototype can not be evaluated through the model.

MLS PROTOTYPE

Detailed design of prototype components fell outside the scope of the current SDHPT study; however, conceptual designs and calculations were made to evaluate the feasibility of the machine and its operational components. The basic structural components are

- rotating load transfer frames for standard suspensions and axles,
- a precision chain connecting load transfer frames,
- super structure/load beam, and
- supports.

Moving Load Frames

Figure 2 shows the conceptual design of the moving load frame of the prototype. The design featured here is comparable with the construction of the moving load frame of the model. The purpose of the load frame is to provide the movable load transfer from the main structure to the load beam, through the steel wheels, into the movable load frame, to the wheel suspensions, and last to the axles and wheels.

Of the two basic types of suspensions available for dual axles on trucks, namely two-spring and four-spring, the two-spring option should preferably not be incorporated into the design.

The two-spring bogie is slightly more complex and dynamically less stable than the four-axle system. The

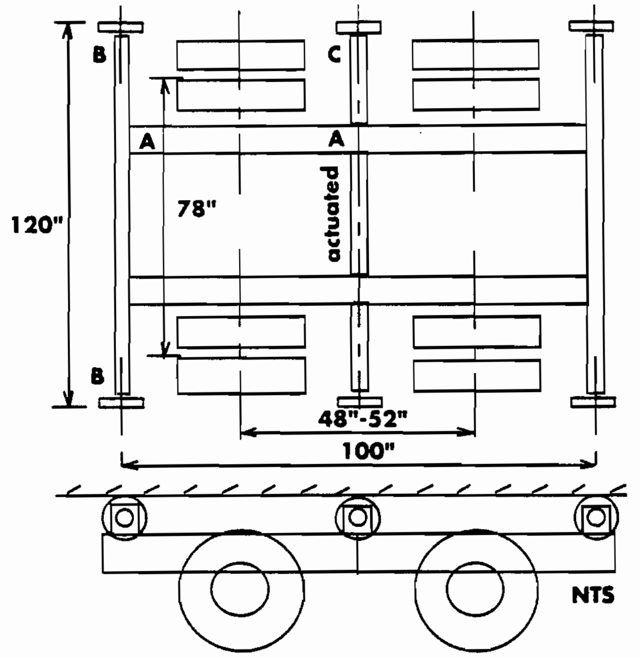


Figure 2: Conceptual Layout of Moving Load Frame

four-spring bogie allows a great number of spring systems to be incorporated, including air springs, as shown in **Figure 3**.

Overall Dimensions of the MLS

Width, 120 inches: The allowable width for a heavy vehicle travelling without a permit is 102 inches, which is inadequate for the MLS. In order to permit the necessary lateral wheel distribution, additional width will have to be built into the permanent width of the machine. However, increasing the width to 120 inches is expected to provide increased stability for the machine, both in transportation and in testing.

Based on comparisons of load distributions of 31.5 inches for the ALF and 60 inches for the HVS, it is intended to distribute the load over a width of 36 inches (**Figure 4**). Failure to provide adequately for load distribution may result in erroneous pavement responses. The recommendation, thus, is to set the overall width at between 110 inches and 120 inches depending on other structural components.

Length, 100 inches: The movable load frame forms part of the chain that connects the different load frames with one another, and thus it is also a link in the chain. When a chain type device is to be rotated around a body consisting of both circular and flat surfaces, it can be made up of any number of links, provided that they are of equal length. The overall height and length of the body are then governed by the length of the links and, subsequently, the number of links that would fit perfectly around two half circles and two parallel connecting straight sections.

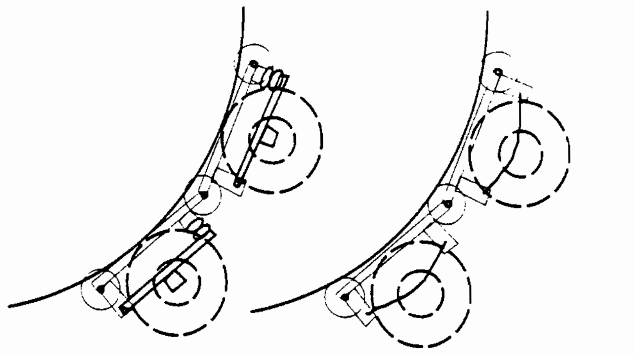


Figure 3: Air and Leaf Springs for the MLS Bogie

On a dual assembly, the axle distances range from 48 to 52 inches. This dimension, as shown in **Figure 2**, is then doubled to give the distance between the rolling supports. The length of 100 inches may be taken as the link length, although evaluation of the model MLS has shown that it may be necessary to provide for actuation of the load frame. These dimensions fix the length of links at 50 inches (Beam AA in **Figure 2**).

Overall Heights (H) of Machine and Lengths (L) of Straight Sections: The objective of Accelerated Vehicle Simulation is to apply as many ESALs as possible in a given time. However, this is subject to certain limitations, such as deflection basin influences, following distances for adequate recovery time, and degree of overloading. The basic configuration for the MLS calls for 12 axles in two groups (**Figure 5**), to provide two "open" sections requiring 28 links of 50 inches each. It then follows that H will be 13.26 feet between the center points of the bottom and top steel wheels. The length of the straight section works out to be 37.5 feet.

Weight of Moving Load Frame

The implication of a perfectly symmetrical or balanced system is that power requirements are reduced only to overcome frictional resistance once the intended rotation speed has been reached. Motor sizes are governed by the inertia of the total chain system, the amount of friction that will be generated, and the time duration until the required velocity is achieved (acceleration). Friction will consist of chain friction, steel wheel on steel beam friction, and rubber wheel rolling resistance on pavement surface.

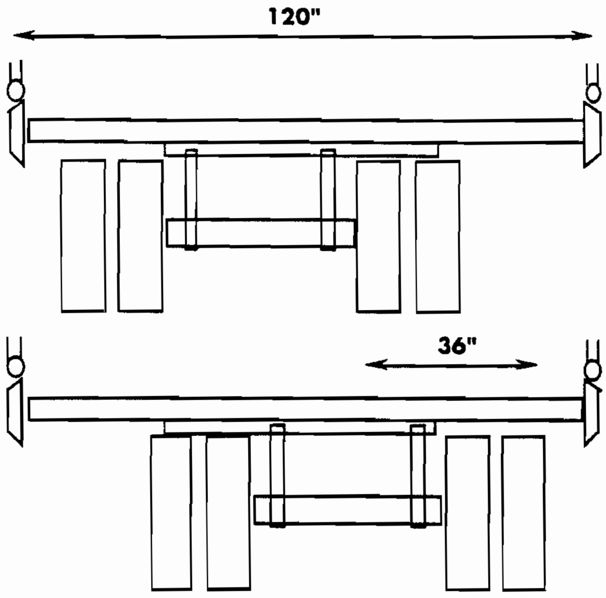


Figure 4: Lateral Load Distribution

Beam AA: The structural components of the movable load frame consist of four structural members, of which two resemble part of a truck frame. This beam is indicated by AA in **Figure 2**. The location of the load that this beam will experience depends largely on the type of suspension system that is used. If suspension mountings are placed in line with the rolling supports, no moment will be experienced in AA.

Beam BB: Half the load from Beam AA is carried to a point on Beam BB and similarly on the opposite side, resulting in two loads of 5000 pounds placed 44 inches apart, symmetrically around the middle. This will result in 5000 pounds transmitted to each the four outer rolling supports and 10000 pounds to each of the two middle rolling supports. As mentioned before, the overall width will exceed the 102-inch limit and, for the purpose of this exercise, the length of Beam BB between the rolling supports is taken as 120 inches.

Total Mass of Moving Load Frame

The total mass of the moving frame is important in the calculation of the forces that will be exerted on the chain due to the rotation or direction change (change in momentum) of the unit. Dynamic effects can be minimized by placing the frames in a symmetrical configuration. Nevertheless, shear forces on the main frame will have to be considered. The total mass of the moving load frame is made up of the following:

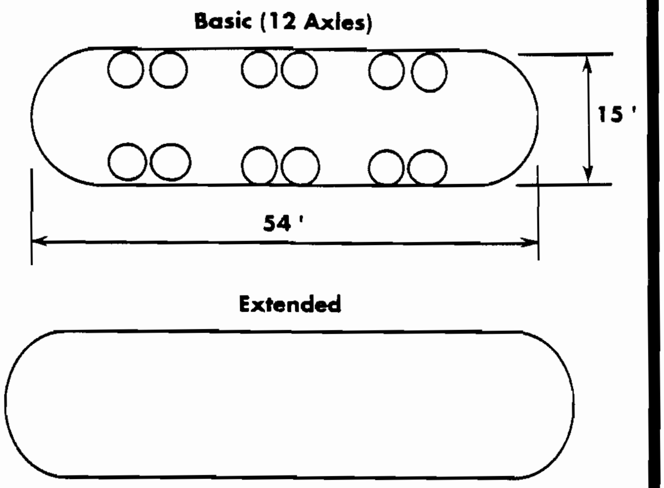


Figure 5: Compositional Options

	Pounds
Tractor Axle	2300 *
Trailer Axle	1760 *
Electrical Motor, 50 hp	1000
Structure	500
Total	5560

*Typical unsprung weights include axle, tires, and brakes

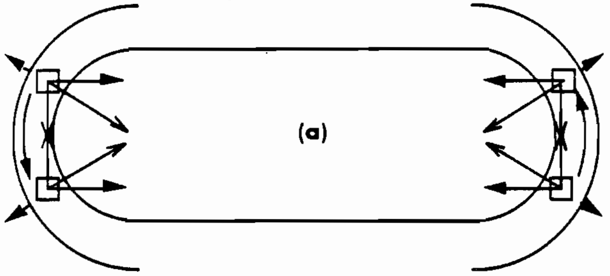
Structural Composition for Real Traffic and Environmental Simulation

The Mobile Load Simulator features the ability to closely represent real traffic. Even though the attainable speeds will not be representative of real traffic, the MLS would exceed speeds attainable for other existing linear load simulators. Additional MLS features, such as the utilization of real truck suspensions and axles, will provide the best available pavement evaluation tool.

Not only does the MLS provide driving at the axles, but it also simulates longitudinal shoving caused by forces when vehicles ascend or descend inclines, acceleration forces, and when overcoming wind resistance. In the MLS, these forces can be simulated by the motor driven axles working against the frictional resistance of the system. Changing degrees of friction may be imposed between the steel wheel and the steel beam by applying degrees of breaking, as this will increase the simulation of longitudinal shoving. The shoving action can also be increased by having fewer drive axles which will increase the amount of friction to be overcomed per drive axle at the same speed.

Environmental simulation can be achieved by utilizing

Forces on Chain Due to Angular Velocity of Rotating Masses



Forces on Chain Due to Weight Components of Rotating Masses

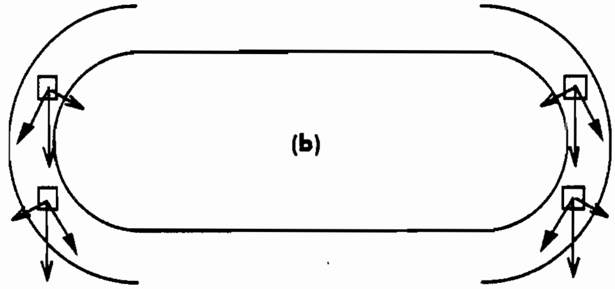


Figure 6: Forces on Chain

the box-like stucture of the MLS which is closed on the sides, ends, and top. An environmental chamber is thus provided, where a certain degree of heating or cooling can be induced to the pavement.

Precision Chain

Having a rotating system imposes a certain limit on the allowable speed due to the fact that large centripetal forces are being generated by the rotating masses. These forces are carried in the chain although a certain amount may be transfered to the outside guiding rail in the form of centrifugal forces as indicated in **Figure 6(a)**. A single unit as shown in **Figure 2** will weigh around 6000 pounds and travelling at the intended 20 miles per hour will exert forces on the chain, also shown graphically in **Figure 6(a)**. Chain forces due to gravity are shown in **Figure 6(b)**.

The factors that govern the stresses to be exerted on the chain are the total weight of the bodies that undergo a change in momentum at a given velocity and the forces on the chain due to gravity. The implication of the symmetry is that the chain forces are balanced on the other side. This will result in zero forces on the rest of the structure, which will maximize stability and minimize the possibility of resonance during testing.

Static Load Beam and Super Structure

The static load beam shown in **Figure 7** is a rigid element spanning the length between the two supports, and conceptually it indicates the loading mechanism that exists in the Mobile Load Simulator. The deflection requirements for the beam are such that upward forces due to the moving loads on the pavement should not result in a variation of deflections greater than a predetermined tolerance as the number and positions of wheels between load beam and pavement vary. The actual load rail is suspended from the rigid beam by means of adjustable supports. These adjustable supports, instrumented with load cells, enable compensation to be made for the differential pavement deformations as loading of the test section progresses. Spacing of supports for the load rail from the rigid beam must be governed by deflection criteria. A limit of 5 percent of the change in deflection of an axle system when subjected to loads varying between 75 and 125 percent of normal axle loads is envisioned.

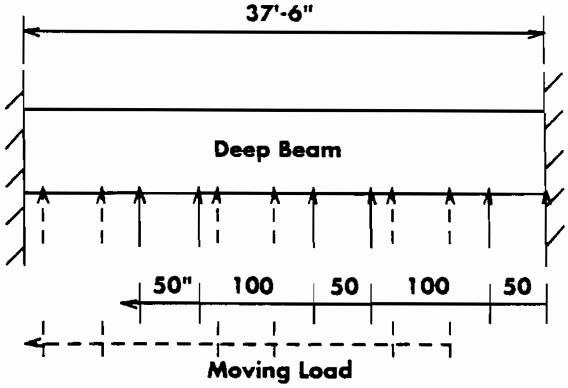


Figure 7: Static Load Beam and Moving Loads

A number of design alternatives exist for the static load beam. A deep beam with a solid flange as featured in the model will provide great rigidity and increase the permanent weight of the machine and can form part of an environmental chamber. A truss frame has a higher strength/weight ratio. It is believed that the final solution will be a combination of the two, bearing in mind that the top part has to be collapsible for transportation purposes.

Supports

Reducing the dynamic effect of inaccurate balancing will require a certain degree of overloading of the machine. Overloading implies that more than the selected load will be needed as the amount per axle required for testing purposes. This additional weight will have to be carried in the supports with adjustable heights. Adjusting the height will increase or decrease the applied pavement load.

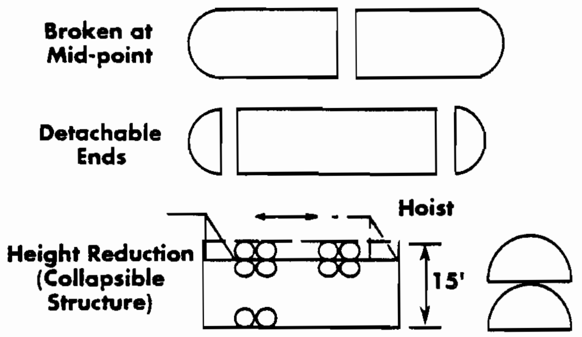


Figure 8: Transportation Configurations

M L S OPERATION

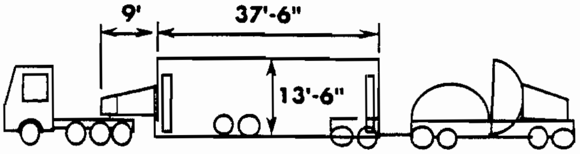
The basic configuration of the MLS is given in **Figure 5**. Twelve axles are included in this configuration, which is based on factors such as pavement relaxation times under real traffic, deflection bowls, and the operating speed of the machine. Other axle configurations may be selected provided symmetry is maintained as far as possible. Provisionally, a maximum of 16 axles are foreseen.

TRANSPORTATION OPTIONS

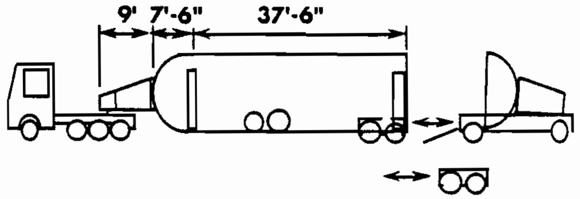
Site establishment can be involved and time-consuming, and the challenge is to minimize this aspect of MLS operation through innovative design. Due to the fact that legal lengths are exceeded and transportation of a machine of this length imposes great difficulty, several transportation configurations are shown in **Figure 8**. In order to minimize interference with the electrical system, the first option was discarded. In **Figure 9** the option of transporting the middle section intact is further explored. In this fashion the legal length is not exceeded.

Utilizing the allowable lengths of 48 feet plus 48 feet for a trailer, the machine can be transported in sections, over long distances. **Figure 9** also shows the possibilities for transportation in states that allow longer vehicles. Provided that sufficient clearances exist for the negotiation of most vertical curves and bridging structures, it may be decided that the machine is to be transported intact. Permits for the transportation of oversized construction vehicles are issued in many states.

ANCILLARY EVALUATION OF TEST SECTION



Legal Dimensions (Vertically Collapsed) for Long Haul on Interstate Basis



Legal Long Haul Option in Texas (Vertically Collapsed)

Figure 9: Mobility Options

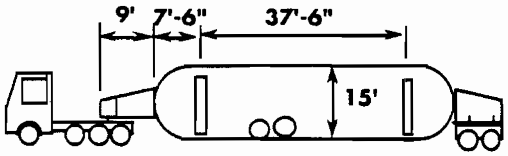
This aspect of the operation can be addressed in various ways which will allow for the clearing of the pavement for measurements. Methods range from simple retraction of the supports and hauling the machine longitudinally off the section, to jacking the test frame vertically. These options are presented in **Figure 10**. Specific site conditions may eliminate some of the options.

Lateral movement may not be possible on sites where sufficient shoulders are not in existence. Lengthwise removal can be problematic on sites where the length of the total test section plus the required length for on and off maneuvering is detrimental to road user safety or traffic flow. Lifting the machine vertically can result in stability and safety problems due to excessive bearing pressures which may result in differential settlement of the footings.

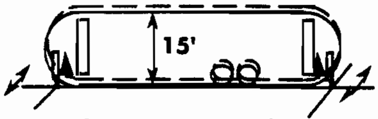
MLS JUSTIFICATION

Mobile Load Simulation has been proved to be an essential item in the permanent inventory of progressive pavement agencies. Other mobile accelerated loading devices are in existence, and a comparison of these devices is shown in **Table 1**. In **Table 2** the applicability of the respective machines for various pavements aspects is indicated.

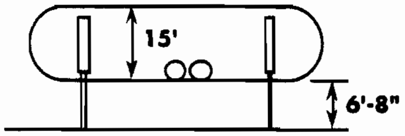
The most significant benefit to be gained through application of the MLS is the high rate of real load application in contrast to other systems requiring overloading to accelerate the loading process. Combined with the vast amount of expertise available from the other two programs, the implementation of the Texas MLS program should prove to be a quantum step in pavement engineering knowledge.



Longitudinal Movement to Clear Section or Short Haul where Permissible



Lateral Movement to Clear Section for Evaluation



Vertical Movement to Clear Section for Evaluation

Figure 10: Moving on Site

COMPARISON OF SPECIFICATIONS BETWEEN EXISTING SYSTEMS

	ALF	HVS	MLS
1. Test loads/Axle (kip)			
Single Wheel	9,4 - 37,9	4,5 - 45	6 - 25
Dual Wheel	9,4 - 37,9	4,5 - 45	6 - 25
2. Test Wheel Size			
Single/Dual	11 x 22.5	14 x 20	11 x 22.5
3. Wheel Speed	12 mph	8 mph	20 mph
4. Coverages/Hour	380	1200	10 920
5. Trafficked Length	40 ft	32.8 ft	35 ft
6. Lateral Displacement of Test Wheels	2.65 ft	4.9 ft	3 ft
7. Other Lengths			
Testing	92.6 ft	74.15 ft	60 ft
Transportation	98.4 ft	74.15 ft	48 + 48
8. Overall Width	13.8 ft	12.2 ft	11 ft
9. Overall Height			
Testing	22.0 ft	13.8 ft	17 ft
Transportation	14.4 ft	Unknown	13.5ft
10. Total Mass	123 kip	125 kip	130 kip*

* Estimated

Table 1: Comparison of Characteristics of Vehicle Simulators

Test Variables	ALF	HVS	MLS Model	MLS Prototype
Environmental Factors				
1. Surficial Water (Artificial)	Q/P	Q/P		
2. Sub Surface Water	Q/P	Q/P	N	
3. Artif. Env. and Accl Load	N			Q/P
Load Factors				
1. Varying Speed Wheel Loads	N	N		
2. Dynamic Wheel Loads	Q/P	N	Q/P	
3. Selected Wheel Configurations				Q/P
4. Multi-Axle Loads	N	N		
5. Actual Traffic loads	N	N	N	
6. Specific Traffic Loads	Q/P	Q/P	N	Q/P
7. Selected Tire Type			N	Q/P
8. Selected Tire Pressure			N	
9. Lateral Load Distribution				
10. Axle Equivalancy	Q/P	Q/P	Q/P	
11. Suspension Type		N	N	
12. Overloads			N	
Material & Const Factors				
1. Material Layer System	Q/P	Q/P	N	
2. Micro Material Structure	Q/P	Q/P		
3. Material Anisotropy				
4. Subgrade Compaction	Q/P	Q/P	N	
5. Various Subgrade Stiffness	Q/P	Q/P	N	
6. Various Subgrade Plastic Behav	Q/P	N	N	
7. Friction Between Layers	Q/P	N	N	
8. Application of Rejuvenators				
9. New Materials/Mixtures				
10. D-Cracking			N	
11. Construction Variation			N	
12. Flexible Bases	Q/P	Q/P	N	
13. Lime Treated Bases	Q/P	Q/P	N	
14. Cement Treated Bases	Q/P	Q/P	N	
15. Recycled Asphalt				
Structural Factors				
1. Various Structural Systems			N	
2. Voids Beneath Concrete			Q/P	
3. Effect of Shoulders			N	
4. Balanced Structural Composition			N	
Pavement Management and Performance (Real Pavements)				
1. Diff Maint Strategies			N	
2. Diff Rehab Strategies			N	
3. Load Transfer in Joints	Q/P	Q/P	N	
4. Percent Steel	Q/P	Q/P	N	
5. Stripping of Asphalt	Q/P	Q/P		
6. Rutting	Q/P	Q/P		
7. Skid Resistance	Q/P	N	Q/P	
8. Wear of Aggregate	Q/P	N	Q/P	Q/P
9. Steel Concrete Bond	Q/P	Q/P	N	Q/P
10. Concrete Joint Behavior	Q/P	Q/P	N	
11. Fatigue Cracking	Q/P	Q/P	Q/P	
12. Struct Cond of Pavement	Q/P	Q/P	N	
13. Surface Cond of Pavement	Q/P	Q/P	N	
14. Residual Life	Q/P	Q/P	N	
15. Delamination			N	
16. Pavement Performance (PSI)	Q/P	Q/P	N	
Periferal Pavement Eng				
1. Durability of Traffic Monitoring Dev	N	N	N	
2. Durability of Road Markings	N	N	N	
3. Effects of Gradients	N	N	N	Q/P
4. Tire Types	Q/P	Q/P	N	

Key
Q/P = Questionable or Partial Applicability
N = Non-applicability
Open = Applicable

Table 2: Test Applications

APPENDIX C. EFFECT OF AXLE SPACING ON PAVEMENT RESPONSE

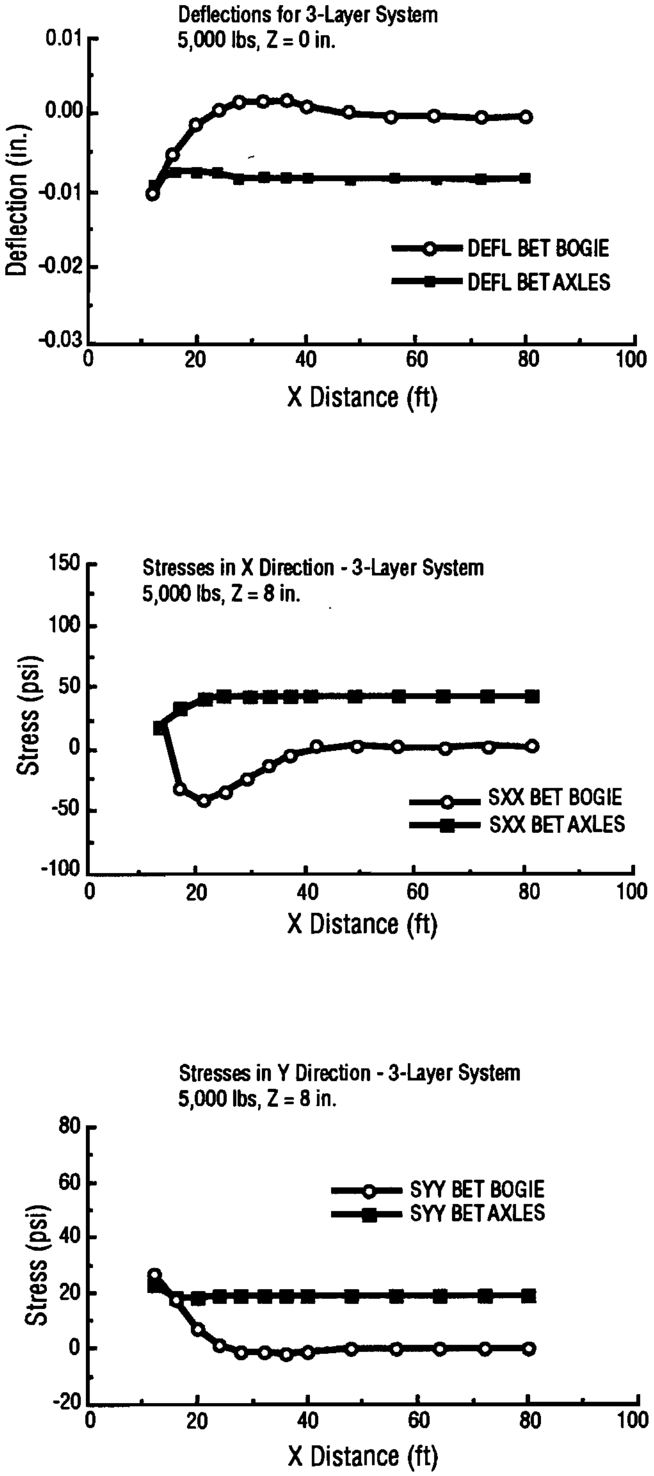


Fig C.1.a, b, c. Deflections and stresses for 5-kip loads on 3-layer system.

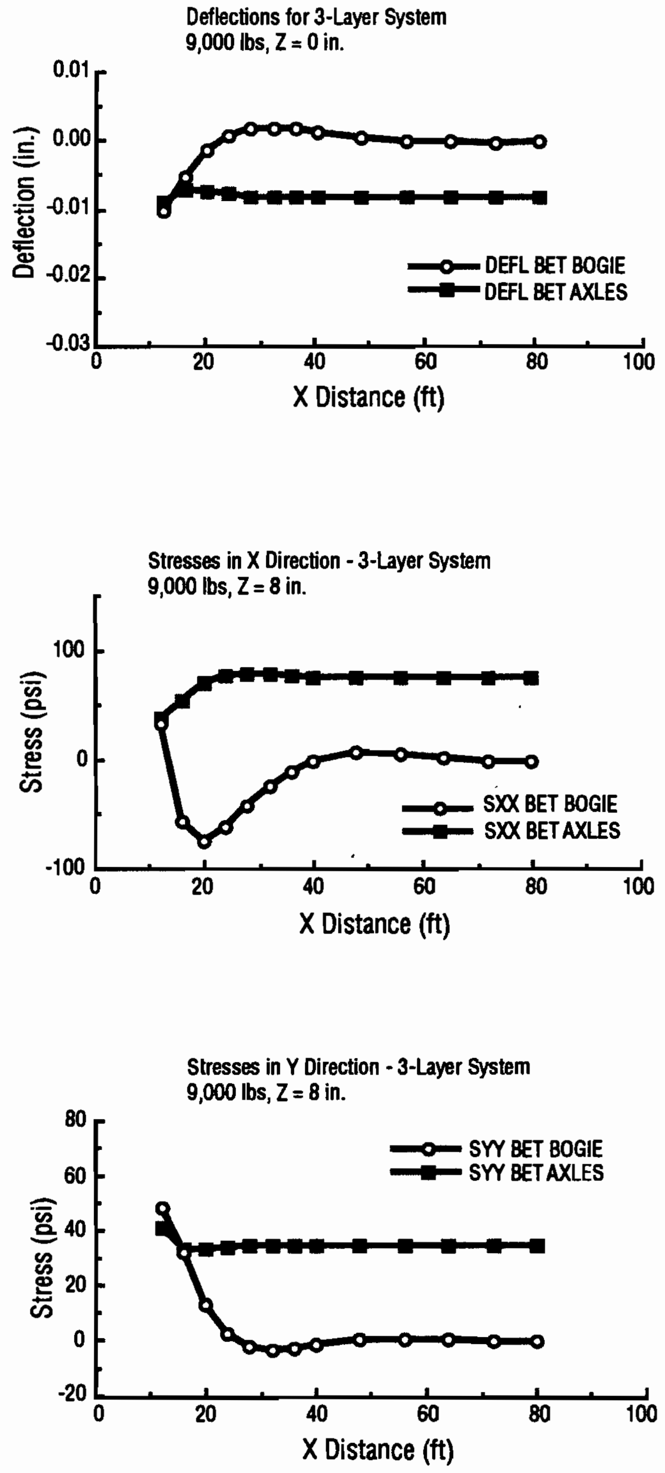


Fig C.2.a, b, c. Deflections and stresses for 9-kip loads on 3-layer system.

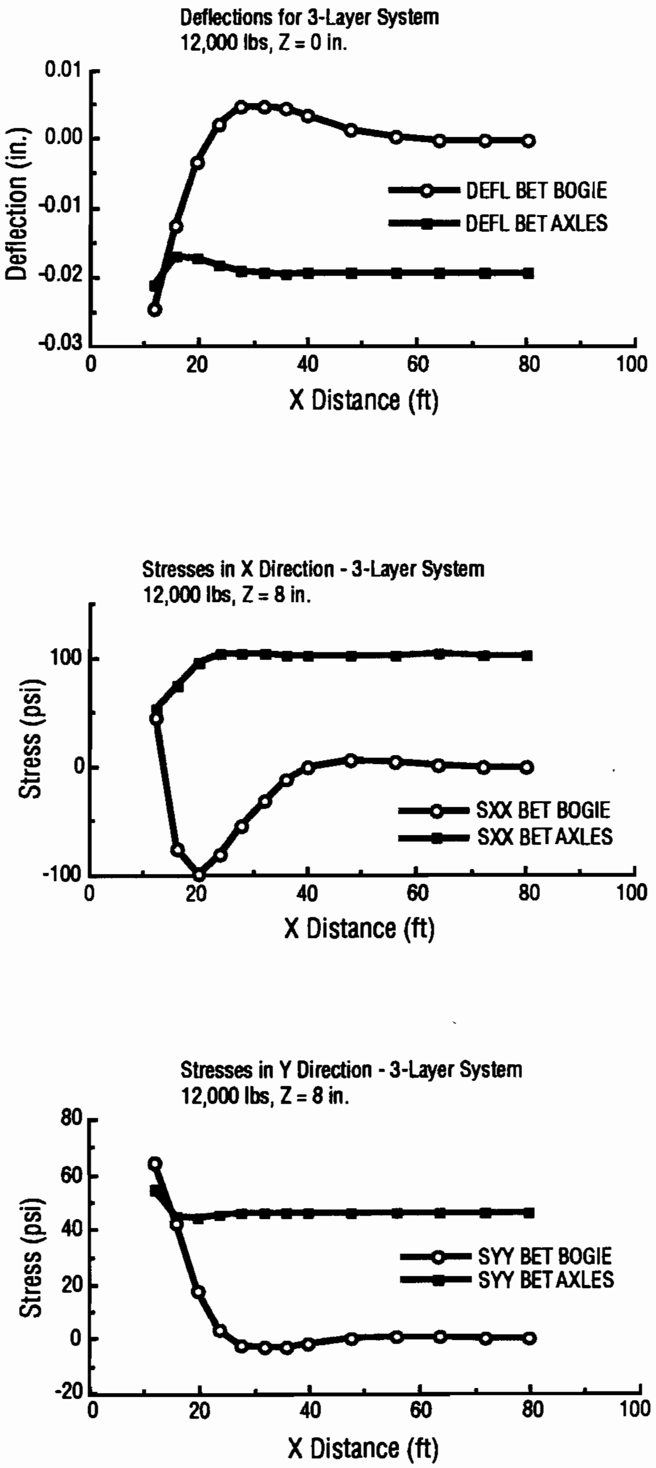
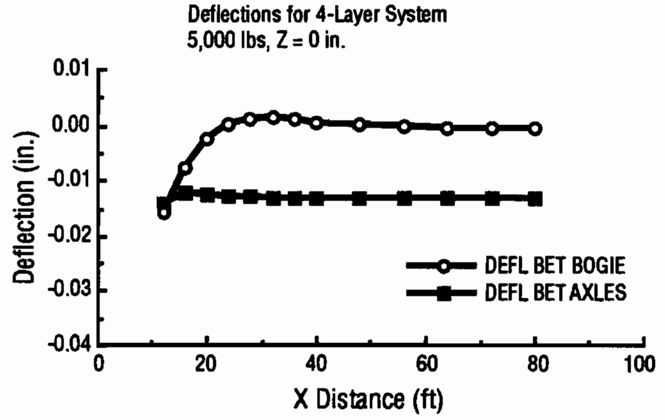
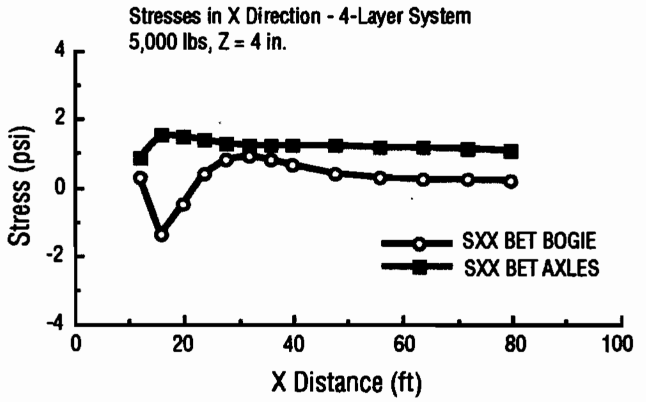


Fig C.3.a, b, c. Deflections and stresses for 12-kip loads on 3-layer system.





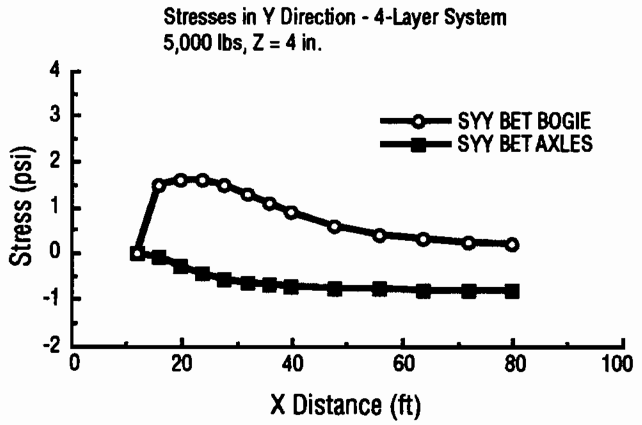
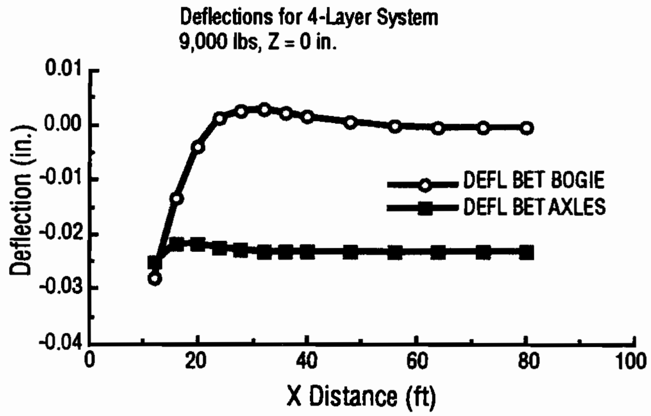
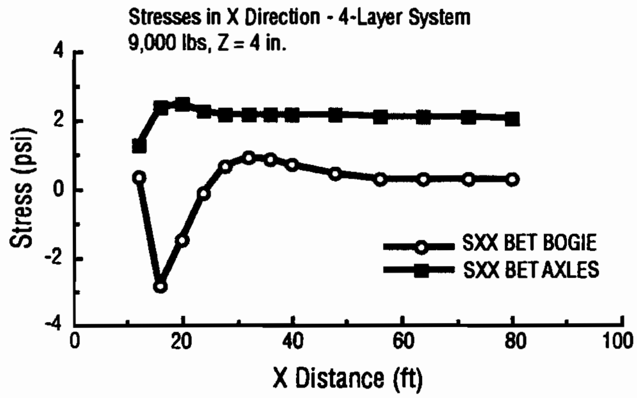


Fig C.4.a, b, c. Deflections and stresses for 5-kip loads on 4-layer system.





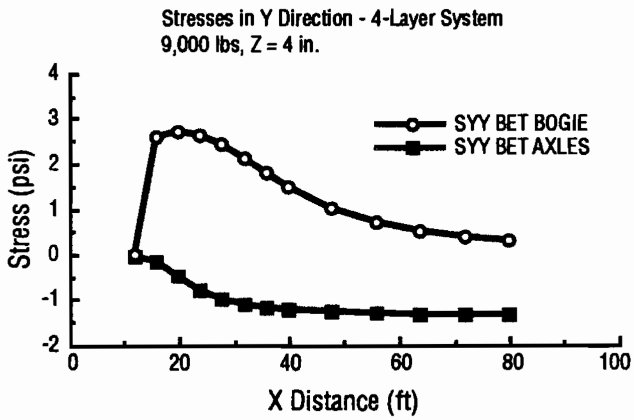


Fig C.5.a, b, c. Deflections and stresses for 9-kip loads on 4-layer system.

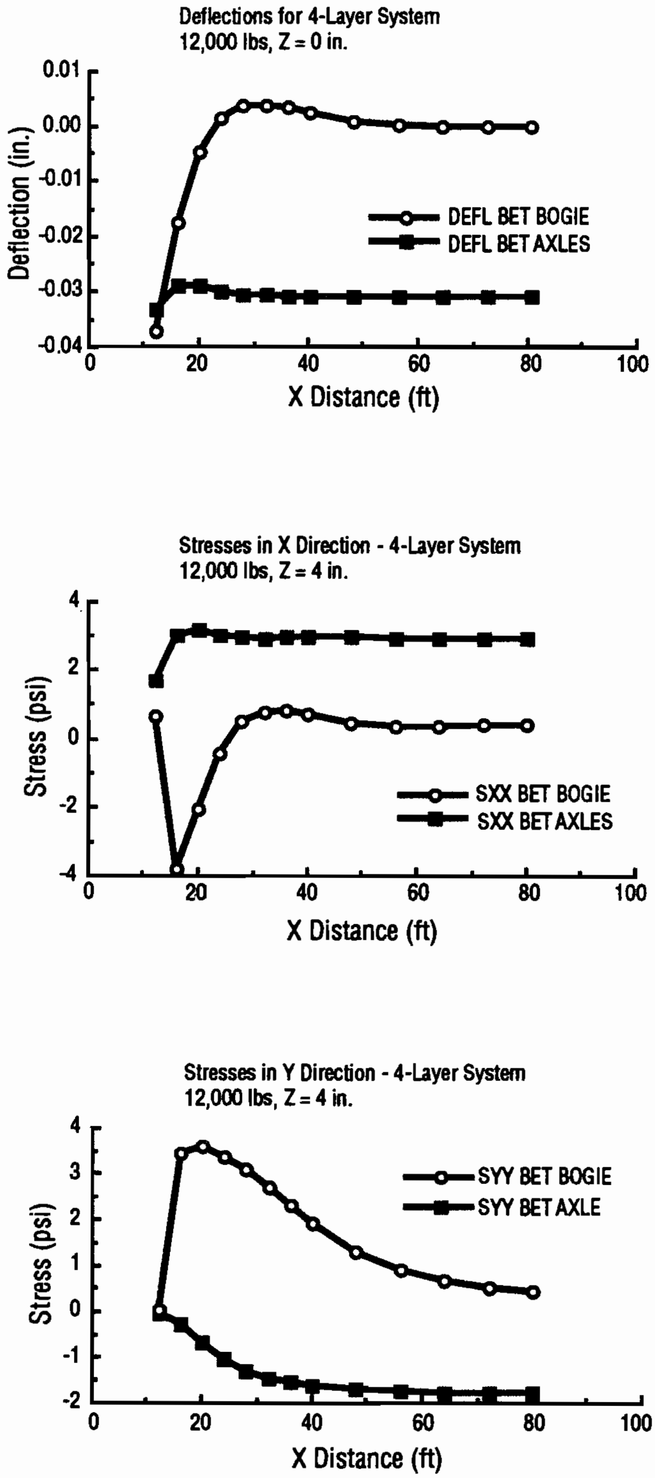


Fig C.1.a, b, c. Deflections and stresses for 12-kip loads on 4-layer system.