National Cooperative Highway Research Program

NCHRP Synthesis 235

Application of Full-Scale Accelerated Pavement Testing

A Synthesis of Highway Practice

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National Cooperative Highway Research Program

Synthesis of Highway Practice 235

Application of Full-Scale Accelerated Pavement Testing

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NATIONAL ACADEMY PRESS
Washington, D.C. 1996

Subject Area
Highway and Facility Design,
Pavement Design, Management,
and Performance

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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NCHRP SYNTHESIS 235

Project 20-5 FY 1993 (Topic 26-07)
ISSN 0547-5570
ISBN 0-309-6008-7
Library of Congress Catalog Card No. 96-061900

Price $23.00

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis, which describes the state of the practice for full-scale accelerated pavement testing (APT), will be of interest to state department of transportation (DOT) pavement design and materials engineers; DOT research staff, including field and laboratory materials testing personnel; and private industry APT equipment suppliers. State DOT administration and management personnel will have a particular interest in the application of APT results toward more efficient and effective pavement designs. Local transportation agencies may also have an interest in the topic. This synthesis reviews the capabilities and limitations of the major APT facilities available worldwide and describes the role and application of full-scale accelerated pavement testing in the development of pavement technology.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board (TRB) presents data obtained from a review of the literature and a survey of the state DOTs, Canadian transportation agencies, and international organizations. A brief historical overview of APT, a discussion of the application of APT to research, and the application of APT to practice are included. Profiles of APT facilities throughout the world are included in an appendix.

The interest and, therefore, literature on this topic continue to grow. In addition to the references cited in the published report, there are many more, especially international sources of information. As a result, the consultant for the project agreed to hold and occasionally update an extensive bibliography on the topic. This bibliography contains several hundred references at this time. Another useful source of information is NHI Training Course No. 13130 Workbook, Pavement Deflection Analysis—Participant Workbook, Publication No. FHWA-HI-94-021, Feb. 1994, FHWA, Washington, D.C. Data on the TRANSPORT CD-ROM by Silverplatter include additional references from TRB's Transportation Research Information Service as well as a few European research data bases. Also available is a CD-ROM from PIARC with more than 8,000 pages of resources and technical publications.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

John B. Metcalf, Freeport-McMoRan Professor, Department of Civil Engineering, Louisiana State University, was responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Ramon Bonaquist, Research Highway Engineer, Federal Highway Administration; Brian J. Coree, Materials Research Engineer, Indiana Department of Transportation; D.W. Dearasaugh, Jr., Engineer of Design, Transportation Research Board; Kenneth W. Fults, Director Pavements Section, Texas Department of Transportation; Amir N. Hanna, Senior Program Officer, Transportation Research Board; Roger M. Larson, Research Highway Engineer, Federal Highway Administration; William G. Miley, Special Projects Engineer, Florida Department of Transportation; William A. Nokes, Senior Transportation Engineer, California Department of Transportation; and Thomas D. White, Professor, School of Engineering, Purdue University.

The Principal Investigators responsible for the conduct of this synthesis were Sally D. Liff, Manager, Synthesis Studies, and Stephen F. Maher, Senior Program Officer. This synthesis was edited by Linda S. Mason.

Scott A. Sabol, Senior Program Officer, National Cooperative Highway Research Program, assisted the NCHRP 20-05 staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

APPLICATION OF FULL-SCALE ACCELERATED PAVEMENT TESTING

SUMMARY

A critical problem for the pavement engineer is the design of heavy-duty pavements where traffic load differs significantly in weight, number, or configurations from previous experience. The traditional method of establishing a satisfactory design—building an experimental section of pavement and observing the behavior and performance of the pavement under in-service traffic—may not provide sufficient or timely guidance. Even where such an experiment can be built on a major route, it is still possible that the rate of growth of traffic load on the in-service pavements will exceed the loading accumulated by the experimental pavement so that no reliable predictive basis can be established. This problem can occur when highway pavements experience unanticipated traffic growth, and when airport or industrial pavements experience different stresses due to developments in wheel assemblies and loads of aircraft or specialized vehicles.

The engineer needs also to evaluate the potential of new materials quickly enough to be taken into account in advancing practice. A particular problem with the experimental road approach is where insufficient time exists to collect and analyze performance evidence, and where the consequence of unsatisfactory performance of a new material, a different pavement configuration, or the impact of increased loading is a severe loss of road serviceability. The experimental pavement approach is also complicated by the variability of the many parameters affecting behavior and performance, such as frequency of loading, material properties, and climate.

Under these circumstances, a methodology is needed to allow exploration of new pavement configurations with controlled traffic load parameters that can accumulate damage faster than the anticipated growth of traffic or changes in vehicle technology. Ideally, the method also has to control nontraffic load factors, such as material variability and environmental variation, to reduce the number of variables in any experiment.

Many road organizations and academic researchers have sought to address these issues with ''accelerated pavement testing'' (APT), allied to the development of theoretical models of pavement behavior. There is a pattern of development of this approach in which the first studies, in the laboratory, used static loads on pavement materials confined in some type of tank to measure the strains and deformations in a partial simulation of a road pavement. Such attempts soon moved to using repeated loading on multilayer pavements, and on to the use of rolling wheel loading to better simulate the traffic but, still usually at less than full-scale. Further studies applied full-scale loads on plates or wheel assemblies applied to test sections of pavement, with static or repeated load systems. An early development here was the evaluation of concrete pavements and of the effects of aircraft loading configurations at full scale. The next stage was the construction of test roads, over which traffic load was provided by ordinary vehicles driven repeatedly over the pavement, and at about the same time, the first full-scale test tracks appeared. These facilities used fully loaded wheel assemblies running on a circular or linear pavement, built to full size either in a laboratory or in the field. In all the studies there was a large number of combinations of load, loading method, pavement size and type, and environment.

The current state of practice in full-scale accelerated pavement testing is the subject of this synthesis, for which the American Association of State Highway Officials (AASHO) Road Test was taken as a starting point. The scope and purpose of the study is outlined and set in its historical context. This includes the many major road experiments, both

with and without accelerated loading, in the United States and abroad, that have provided much of the current pavement technology. Definitions of the various testing procedures are given and the responses to a questionnaire survey are tabulated. The facilities active since the AASHO Road Test are described based on information from the questionnaire survey and the published literature. The loading, pavement, and instrumentation configurations are briefly described. An appendix summarizes the principal features of each facility. An interesting feature is that very limited effort is being directed to rigid pavements or to airfield pavements and aircraft loadings. Another feature is the general trend to use surface effects and nondestructive testing for the primary evaluations, although some of the newer test roads in the United States have been comprehensively instrumented.

Applications of APT to research and to practice are discussed. The early APT experiments, often at less than full scale, led to major benefits in validating and calibrating theoretical models of pavement behavior. The move to full scale has allowed further refinement of these models and supported the development of performance models.

Applications of APT to practice now concentrate on assessing the performance of full-scale pavement configurations and materials and the response and performance of full-scale pavements to full-scale loads on full-scale wheel assemblies and at speeds as close to traffic speeds as possible. An emphasis on pragmatic, goal-specific results is evident, as is the high degree of confidence in full-scale testing. It appears that longer-term basic studies are less prominent. It is recognized that accelerated testing can make only limited provision for the major influence of environmental factors on pavements. Changes in moisture conditions commonly experienced in pavements are difficult to simulate, but the effects of temperature can in part be controlled. Such effects can be taken into account, in pavement design, by models based on laboratory and accelerated testing of materials. It is clear that maximum benefit from APT results from a strategic approach to pavement research combining APT, laboratory, and long-term field evaluations.

Very few published reports of evaluations of the costs and benefits of APT were located. It is evident that the benefits are regarded as substantial and effective, as reflected in changes in procedures and practices in the various authorities concerned. However, published studies of the effectiveness of an APT program show substantial benefit-cost ratios.

It is evident from the many active programs of research with full-scale accelerated pavement testing facilities that the benefits are highly regarded and substantially exceed the costs of such programs. These benefits are seen in

- improved design procedures
- evaluation of pavement configurations
- validation of existing materials usage
- evaluation of new, nontraditional, and modified materials
- development and evaluation of rehabilitation techniques
- proof testing of pavements for special conditions
- evaluation of the effects of different loading configurations
- prediction of pavement life
- support of further research in the theory of road pavements.

In the development of APT, each participant has benefited from the others. Each program has had to select an appropriate approach to its particular circumstances, but within a broader strategy for pavement research. No machine is ideal for all tasks and some compromises must always be made. Thus, a number of different philosophies are embodied in the different facilities now active around the world. Recent advances in telecommunications will provide tools to facilitate better links between the APT programs worldwide. The new Transportation Research Board Committee on Full-Scale and Accelerated Pavement Testing will help to bring APT experts together to share ideas. In addition, in the United States, the proposed "National Accelerated Testing Program for Superpave Validation" may link several APT facilities in a long-term effort.

CHAPTER ONE

INTRODUCTION

Existing practices for pavement thickness design and material selection are firmly based on the findings of many full-scale load tests conducted worldwide, some with accelerated loading, but most on in-service road sections. However, from the 1950s, the volume and mass of truck traffic has continued to increase rapidly. This has led to a demand for heavy investment in highways in most industrial countries, for new routes to accommodate this traffic, for the rehabilitation of many existing routes, and for enhanced maintenance programs on many others. The design procedures of earlier years were typically derived from "in-service" experimental pavements, such as the Road Test conducted between 1958 and 1960 by the American Association of State Highway Officials (AASHO) [AASHO became AASHTO, the Association of State Highway and Transportation Officials in 1973]. The procedures did not anticipate the increased vehicle numbers and loads and the new axle and wheel configurations now encountered. The use of field trial experimental pavements is limited, the most heavily trafficked routes accumulate traffic loads faster than many experimental pavements yet they cannot be disrupted by experimental program constraints (Figure 1) (*1*). Extrapolation beyond current experience urgently needs support from research on pavements loaded to these new intensities (*1*). Freeme has presented South African data to show that the increase in traffic loading exceeded design expectations; in the period 1977 to 1981, the average equivalent single-axle load (ESAL) per vehicle increased from 0.3 to 0.5 (*2*).

The AASHO Road Test revolutionized the approach to pavement design. The concepts of structural number and pavement serviceability for the first time related pavement structural character to axle loading. Design concepts evolved from empirical relationships between wheel (or axle) load and pavement thickness, to using relationships including estimates of traffic load in the form of light, medium, or heavy traffic or of the numbers of (heavy) vehicles and an *ad hoc* measure of subgrade capacity (*3*), to designs requiring a specific measure of subgrade bearing capacity and an estimate of the traffic load in terms of wheel passes. The most widely used procedures of this type first suggested by Porter, (*4*) and since then modified and adapted to road and airfield design throughout the world, have also been used as the basis for developing mechanistic design procedures (*5*). The early pavement experiments also validated materials selection procedures, such as the Marshall mix design approach for asphalt (*6*), and included Hveem's development of deflection testing together with the concept of "resilience" testing of soils (*7*).

A new philosophy of cooperation among highway authorities, the trucking industry, and vehicle manufacturers has also created the need to evaluate the effects of new vehicle designs on road pavements. It is necessary to link the road and vehicle characteristics (e.g., suspension dynamics and design capabilities) with the taxation and regulation framework to optimize the road transportation system.

This has resulted in major research programs in several countries in which "in-service performance monitoring" is combined with accelerated full-scale pavement testing, laboratory materials characterization, and mechanistic models of pavement behavior to better understand road pavement performance.

This understanding of actual wheel loads can now be incorporated in the characteristics of accelerated loading facilities at least to some extent. The load patterns can also be approximated in laboratory characterization of pavement materials.

The research also led to the beginnings of understanding of the significance and characteristics of dynamic (truck) load spectra, though this may not yet readily be incorporated in design. The Organization for Economic Cooperation and Development (OECD) Dynamic Interaction Vehicle-Infrastructure Experiment (DIVINE) project will use the New Zealand Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to study the inter-relationship of pavement life and vehicle suspension (*8*). The Texas Mobile Load Simulator (TxMLS) also has the capability to examine suspension effect and multiple full tandem axles.

DEFINITION OF FULL-SCALE ACCELERATED PAVEMENT TESTING

Full-scale accelerated pavement testing (APT) is defined as the **controlled** application of a **prototype wheel loading, at or above the appropriate legal load limit** to a **prototype or actual, layered, structural pavement** system to determine pavement response and performance under a controlled, **accelerated**, accumulation of damage in a **compressed time period.**

The acceleration of damage is achieved by means of increased repetitions, modified loading conditions, imposed climatic conditions (e.g. temperature and/or moisture), the use of thinner pavements with a decreased structural capacity

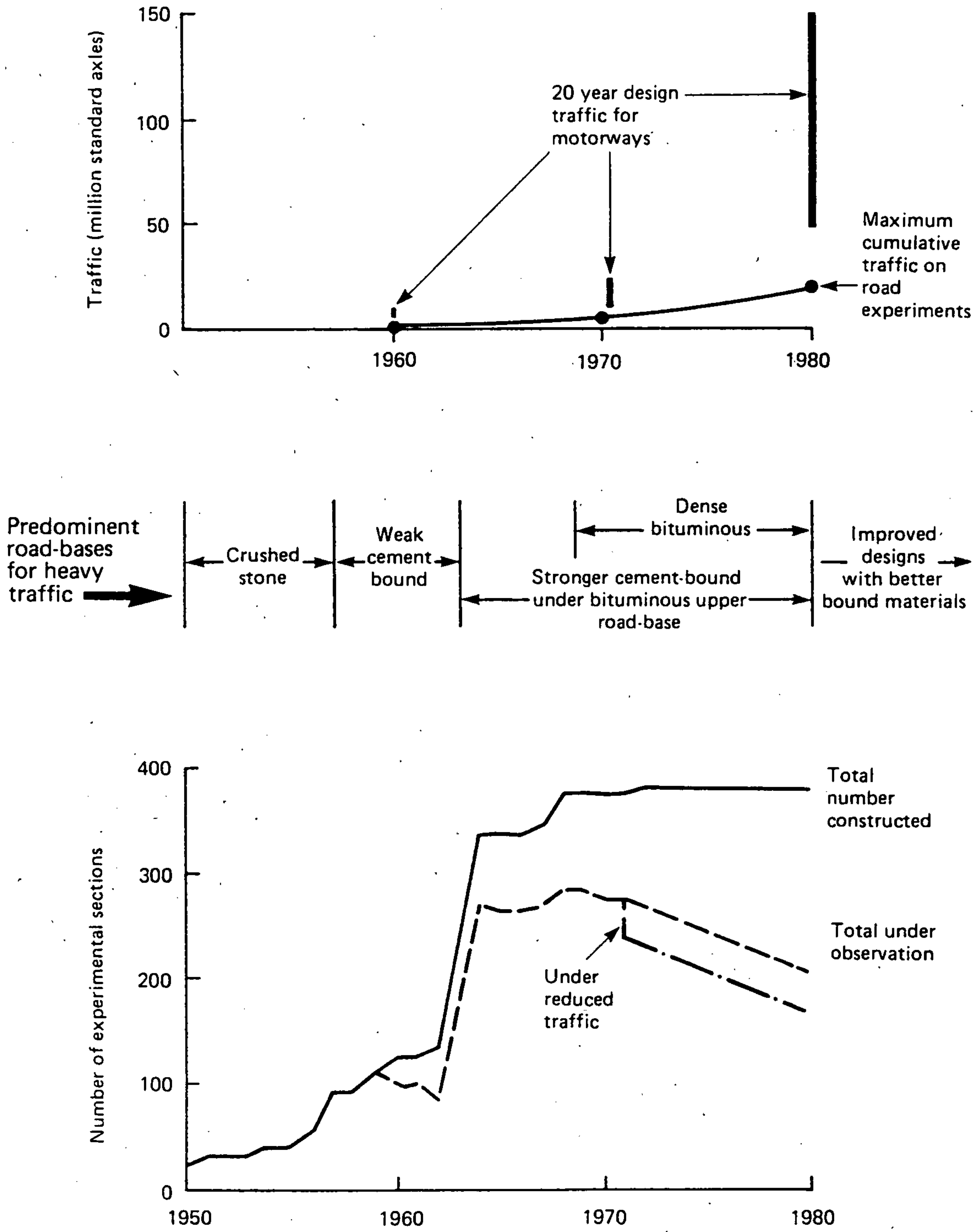


FIGURE 1 Change in full-scale experimental activity, design practice and traffic (*1*).

and thus shorter design lives or a combination of these factors. Full-scale construction by conventional plant and processes is necessary so that real world conditions are modeled.

For many years, pavement engineers have successfully used accelerated full-scale pavement testing for developing and verifying design procedures and evaluating material and pavement performance.

Early pavement testing was performed with simulated or actual traffic on test roads like the Bates experimental road, the Maryland Test Road, the Western Association of State Highway Officials (WASHO) Road Test, the AASHO Road Test, and similar projects in other countries. These pavement test programs, with and without accelerated loading, have been extensively reported and reviewed (*1,6,9–15*). Therefore, this synthesis does not discuss them further nor does it discuss in any detail in-service experimental roads (where a stretch of highway is built or selected for the purpose of observing behavior and performance under normal traffic), the Strategic Highway Research Program (SHRP) General Pavement (GPS) and Special Pavement Studies (SPS), or similar research in other countries. In these projects, thinner than standard pavements often have been designed to produce results in a shorter time frame (still usually a period of years rather than months) without control or acceleration of the traffic loading. Such experiments are not considered full-scale accelerated testing within the definition adopted for this synthesis. The sheer volume of material also precludes inclusion; the SHRP program alone has some 900 GPS test sites and 200 SPS projects with over 1,000 test sections (*16*).

Test roads such as the MnRoad (Minnesota) and WesTrack (Nevada) programs are the development of this approach in 1995.

There also have been a number of **test track** facilities where simulated loading was applied by means of loaded wheels or plates to a section of test pavement constructed in a pit or trough, usually circular or linear in form. Early examples of this approach are the work of the United States Army Corps of Engineers (USAE) (*6*), the Washington State University (Figure 2) (*17*) and the University of Illinois facilities (*18*).

In 1995, mechanical loading machines such as the Australian Accelerated Loading Facility (ALF), also used at the United States Federal Highway Administration Turner Fairbank Laboratory, the Chinese Research Institute for Highways, and the Louisiana Transportation Research Center Pavement Research Facility (Figure 3); the French Manège de Fatigue (Figure 4); the Indiana Accelerated Pavement Testing Facility (Figure 5), and the South African Heavy Vehicle Simulator (HVS) (Figure 6) were being used to simulate repeated traffic loading on test tracks under at least partially controlled conditions.

At a 1985 Pavement Testing Conference, held by the Federal Highway Administration (FHWA) in Washington,

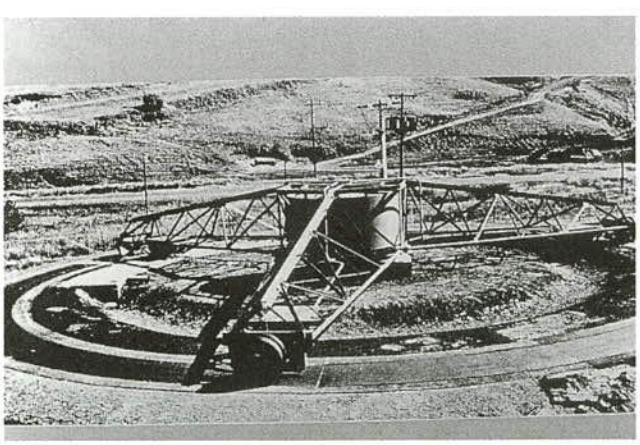


FIGURE 2 Washington State University Circular Test Track.

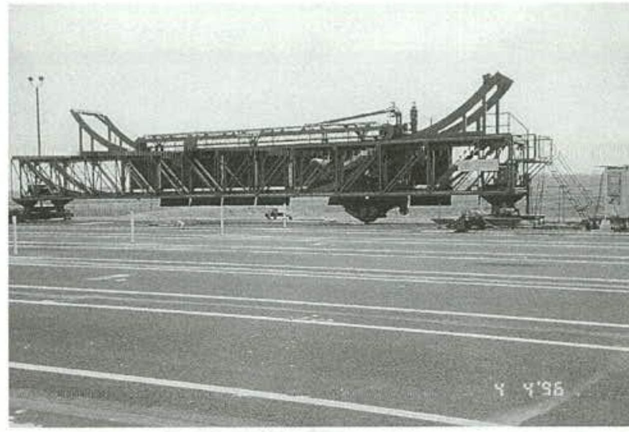


FIGURE 3 Louisiana PRF.

FIGURE 4 Manège de Fatigue - LCPC France.

D.C. and organized to develop a national pavement testing program it was concluded that the program must be structured to

- "better understand and predict pavement performance,
- establish a higher degree of credibility, and
- produce early (within 5 years) results."

Specific objectives should be

- "improving rehabilitation technologies,
- improving design and performance predictions, and
- evaluating new materials and construction techniques."

It was agreed that such a program would require test roads and major mechanical accelerated pavement testing facilities on at least a regional level.

Ideal criteria proposed by Larson for the full-scale test road and test track approach were

- "pavements must be subject to controlled loading,
- such loading must be accelerated but realistic,
- speeds should be representative, and

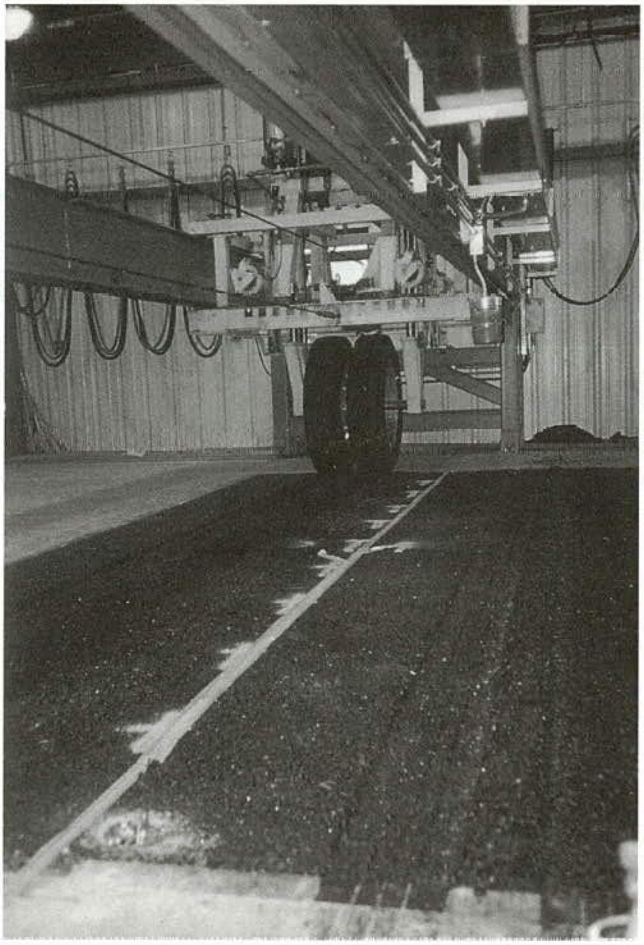


FIGURE 5 Indiana DOT/Purdue APT.

FIGURE 6 Heavy Vehicle Simulator - South Africa.

- environmental conditions must be recognized in analysis.''

Lister (*19*) further suggested that mechanical pavement test track facilities should use rolling wheels because of the particular characteristics of such loading, the rotating stress field, and truly tri-axial stresses (which cannot be adequately simulated in laboratory tests). As the properties of paving materials change with time, he also proposed that consideration be given to ''aging'' a pavement before and during testing. He pointed out that environmental moisture effects cannot be accelerated but can be closely monitored and included in any analysis.

Other speakers (Lytton (*20*) and Darter (*21*)) at the Conference dealt with Long Term Pavement Performance (LTPP) studies and the use of ''in-service'' performance data. Such studies are an integral part of any pavement research strategy that needs to combine laboratory testing, to characterize materials; theoretical modeling, to predict materials response and pavement performance; accelerated pavement testing, to allow calibration of the theoretical models; empirical comparison of different pavements and observations of response and performance under simulated traffic loads and 'in-service' LTPP studies, to confirm the findings of the research in practice.

A variety of accelerated pavement testing facilities has been developed and used, in past and current research projects worldwide. This synthesis reviews the capabilities and limitations of the major APT facilities available in 1995 and summarizes how transportation and research agencies have applied APT. Several agencies are currently conducting or are planning and implementing research projects that involve APT. New machines, such as the Texas Mobile Load Simulator (TxMLS), commisioned in 1995, are under development while new test roads, such as WesTrack are beginning service.

A survey (Appendix A) of the states, Canadian provinces and international organizations was conducted and supported by a literature review. Of the 66 North American organizations surveyed, the 47 replies showed five currently active facilities and two previously active; two states were planning future facilities (Table 1). Abroad, nine of the 41 organizations surveyed responded, and eight active facilities were identified; one country (Finland) is planning a future facility.

The literature review and personal enquiry revealed another seven facilities in North America and seven abroad. Three more organizations' planning facilities were identified in the United States. Thirty-five accelerated pavement testing facilities have been identified around the world, of which 19 currently have active research programs.

This synthesis will describe the role and application of full-scale accelerated pavement testing in the development of pavement technology.

HISTORICAL BACKGROUND

Test Roads

Full-scale accelerated pavement testing in the United States (*9,13*) began at the Arlington, Virginia, test road in 1919, where a circular track was loaded by a truck. Tests

TABLE 1 FACILITIES WITH PREVIOUS, ACTIVE OR PLANNED PROGRAMS AT JANUARY 1996

Active Facilities	Previously Active	Planned Facilities
North America		
California	Pennsylvania	Kansas
Louisiana	Montana (see FHWA)	Florida
Minnesota {2}		*Ohio*
Texas	Washington	*Alabama (Auburn)*
Federal Highway Administration (FHWA)	*Illinois*	*Federal Aviation Authority*
	USAE-CRREL	
	USAE-WES	
Indiana	*Florida UCF*	
Nevada	*Michigan*	
Saskatchewan		
Overseas		
Australia	*United Kingdom*	Finland
China	*Italy*	
France	*Japan*	
Japan	Netherlands	
Mexico		
Netherlands		
Spain		
Romania		
United Kingdom		
New Zealand		
Switzerland {2}		
Denmark		
South Africa		
Germany		
Slovakia		

[a] *italics—entry from literature or personal communication, not questionnaire survey*

continued until the mid 1930s and contributed greatly to concrete pavement design. This study was closely followed in 1920 by the Bates Road Test in Illinois. This was the first controlled traffic test that gave basic test data on various materials, including brick, asphalt, and concrete from a 4-km (2.5-mi) test road with 68 sections under controlled wheel loads of between one and six tonnes (2,000-13,000 lb). Another test of concrete pavements, on a 168 m (560 ft) loop, was conducted from 1920 to 1923 in Pittsburg, California. The Hybla Valley Non Rigid Pavement study between 1944 and 1954 was the first national effort. The oval track had 240-m (800-ft) tangents connected by circular curves. Loading was by plates and a significant finding was that pavements deflect considerably. Road Test One Maryland was conceived in 1949 with support from truck manufacturers and petroleum producers in association with government. The test was conducted on a 1.8-km (1.1-mi) plain concrete pavement and provided significant evidence of the effects of increased axle loading on pumping distress. Strains were measured in the slab surfaces and the subsoil and analysis showed that stresses at 64 km/h (40 mph) were 20 percent less than those at creep speed.

These early studies were primarily directed at the structural design of both flexible and rigid pavements in which the USAE played a major part. Ahlvin (*6*) has summarized this large body of research for the period 1940 to 1980. During this period the USAE had responsibility for military road and airfield pavements and, in the latter half of the period, worked with the Federal Aviation Administration (FAA) on civilian projects. Most studies were conducted at the Waterways Experiment Station (USAE-WES) from 1941 to 1956, with some rigid pavement studies at the Construction Engineering Research Laboratory (CERL) and freeze-thaw studies at the Cold Regions Research and Engineering Laboratory (CRREL). Ahlvin described the contributions of full-scale accelerated pavement testing to the development of the California Bearing Ratio (CBR) based pavement design procedures, including the application to aircraft multiwheel assemblies using the Newmark influence charts, and the introduction of wheel load repetitions into the designs. The first studies to characterize materials by CBR were conducted in the 1950s. Similarly, the Marshall stability test for asphalt was coming into use based on tests conducted at USAE-WES in 1944 (*14*), when the results of a 5-year project led to stability and other mix criteria for asphalt pavements. Studies of the effects of high tire pressures (1.7MPa (240 psi)) for aircraft started in the 1940s and by the mid 1950s channelized traffic and heavier aircraft with even higher tire pressures (2.1MPa (300 psi)) were being studied. Mellinger (*22*) conducted accelerated tests with controlled traffic on airfield pavements and showed that

- repetitive traffic by slow moving aircraft is the critical load condition
- impact on landing can be ignored
- 5,000 coverages represented 10 to 20 years' lifespan
- heavier aircraft channelize wheel coverage such that 30,000 coverages better represent a useful life.

These tests resulted in changes to thickness and mix design procedures. Rigid pavement design was approached using the Westergaard theories, starting in 1942, when static and dynamic load tests were conducted by dropping loaded aircraft tires onto 20 × 20-ft pavement slabs. Revised design procedures were then introduced before ever-increasing loads required yet another series of design revisions. The USAE-WES and many other loading tests, conducted between 1940 and 1960, provided thickness design procedures for both rigid and flexible pavements and the material evaluation methods on which much present day practice is still based.

In 1951, The WASHO test road was significant for demonstrating the value of statistical analysis for the first time in this application. Test findings included

- for the same total thickness, 100 mm asphalt surfaces performed far better than 50 mm surfaces;

- outer wheel paths suffered more damage than inner paths, but shoulder support enhanced performance;
- distress (rutting and cracking) was greater under heavier loads;
- subsidence (rutting) of the pavement layers was due to lateral displacement not compression;
- most distress was observed in the spring when the subsoil was wettest; and
- tandem axles can carry about 50 percent greater load than single axles and give the same distress for the same number of passes.

This was a major advance in the understanding of pavements and traffic.

Similar studies were underway in other parts of the world. Lister (*23*) has described the program in the United Kingdom, where some 400 test sections were in place on in-service major roads by the 1960s. An analytically based design method was sought when simple two-layer and three-layer elastic stress computations were completed (*24,25*). The program was complemented by an equal number of test sections examining wearing course parameters. There was some intentional under-design of the structural test sections (to give more rapid deterioration) but no control of traffic load. Nevertheless, the program had a major influence on the main types of road base used in the UK.

In this synthesis, the AASHO Road Test is used to mark the first modern road pavement testing using controlled, accelerated loading, as opposed to the typical field trial experimental pavement built into a highway network and subject to normal traffic. Such projects typically used one or more normal vehicles driven repeatedly (but not often continuously) across a test road built following standard specifications. Thus, traffic was partially controlled and slightly accelerated, in comparison to traffic on an experimental section of an operating highway.

From 1958 to 1960, the AASHO Road Test (*26*) established robust statistical relationships between pavement design parameters, axle load and configuration, and the number of load repetitions. While it was clear that these relationships were specific to the conditions of the site, they have proved widely applicable and form the basis for many design procedures and regulations worldwide. This major experiment, on a test road of specially constructed pavements trafficked by specially loaded trucks driven repeatedly over the test pavement sections, had five specific objectives:

1. to determine the significant relationships between the number of repetitions of specified axle loads of different magnitude and arrangement and the performance of different thicknesses of uniformly designed and constructed asphalt concrete, plain portland cement concrete, and reinforced portland cement concrete surfaces on different thicknesses of bases and subbases when on a basement soil of known characteristics,
2. to determine the significant effects of specified vehicle axle loads and gross vehicle loads when applied at known frequency on bridges of known design and characteristics,
3. to make special studies dealing with such subjects as paved shoulders, base types, pavement fatigue, tire size and pressures, and heavy military vehicles, and to correlate the findings of these special studies with the results of the basic research,
4. to provide a record of the type and extent of effort and materials required to keep each of the test sections or portions thereof in a satisfactory condition until discontinued for test purposes,
5. to develop instrumentation, test procedures, data, charts, graphs, and formulas, which will reflect the capabilities of the various test sections; and which will be helpful in future highway design, in the evaluation of the load carrying capabilities of existing highways and in determining the most promising areas for further highway research.

The AASHO test made great progress on all the areas targeted, and most significantly, introduced the concept of pavement serviceablity as a realistic and practicable measure of the performance of a pavement. The change from using a nominal wheel load and/or traffic classification to designing specifically for an estimated number of passes of a standard axle load came from the AASHO Road Test from which the ESAL concept originated. This in turn led to the development of technologies to weigh vehicles in motion (w-i-m), which obtained more accurate estimates of the magnitude and frequency of loads carried by roads, thus allowing designs to be based on more accurate estimates of load profiles.

However, the problems addressed by the AASHO objectives are not yet resolved and the changes in pavement design and configurations, in the materials available, and in the characteristics of traffic create continuing need for research and the application of full-scale APT. All the programs reported herein reflect some aspect of AASHO objectives.

The most recent examples of this approach are those at the Minnesota, Nevada, and Ohio facilities described in chapter 2.

Test Tracks

Perhaps the first test track facility for research into pavements was the installation at the Public Works Department in Detroit. This circular facility (called the "Paving Determinator") was constructed in 1909 (*15*), and was closely followed by a circular track with steel (and later rubber) wheels at the British National Physical Laboratory in 1912 (*10*). The Detroit track had steel shod shoes on one end of the rotating arm and an iron-rimmed wheel on the other to simulate horse and cart traffic. The tests showed concrete to have "the best resistance" compared to brick, granite, creosote, and cedar blocks. By the 1940s, a number of such facilities were built in various countries. Examples are the "Road Machine" built in 1933 and rebuilt in 1963, at the (then) British Road Research Laboratory and the 1967 Washington State University installation, the G.A. Riedesel Pavement Test Facility. Over the past 50 years, many government, industry, and university organizations have built and operated a wide variety of test tracks. This synthesis will focus on those that have been active since the time of the AASHO road test; these are described in detail in chapter 2.

There are three basic types of test track, those in which the load is applied through a wheel(s) rotating around a central pillar on a circular track (e.g., the French Manège de Fatigue), those in which the wheel assembly moves in a straight line along the linear test pavement (e.g., the various ALFs), and those in which a moving wheel assembly is constrained to move around a free-form but usually again circular or oval, test pavement (e.g., the Spanish facility). The last category includes the use of a remotely controlled vehicle to traffic the test pavement; the Public Works Research Institute (PWRI) in Japan and the WesTrack facility use this approach.

A special form of linear track that was tried in Australia in 1961 (Figure 7), was used at a model scale at Washington State University (*27*). A related, independently developed device was used to test model scale pavements in South Africa. This formed the basis for the development of the full-scale prototype TxMLS (Figure 8) (*28*). Four of the model devices are in use at the Institution for Transport Technology (ITT), Stellenbosch, South Africa; the Texas Department of Transportation (TxDOT); the Arizona State University; and the Indonesian Road Research Center (F. Hugo, personal communication 1995). The value of the model devices in conjunction with full-scale APT is discussed by Hugo et al. (*29*) and in other work (*30–35*).

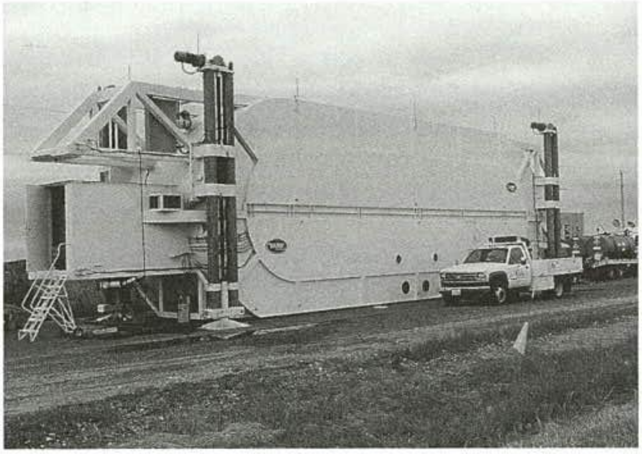


FIGURE 8 Texas Mobile Load Simulator.

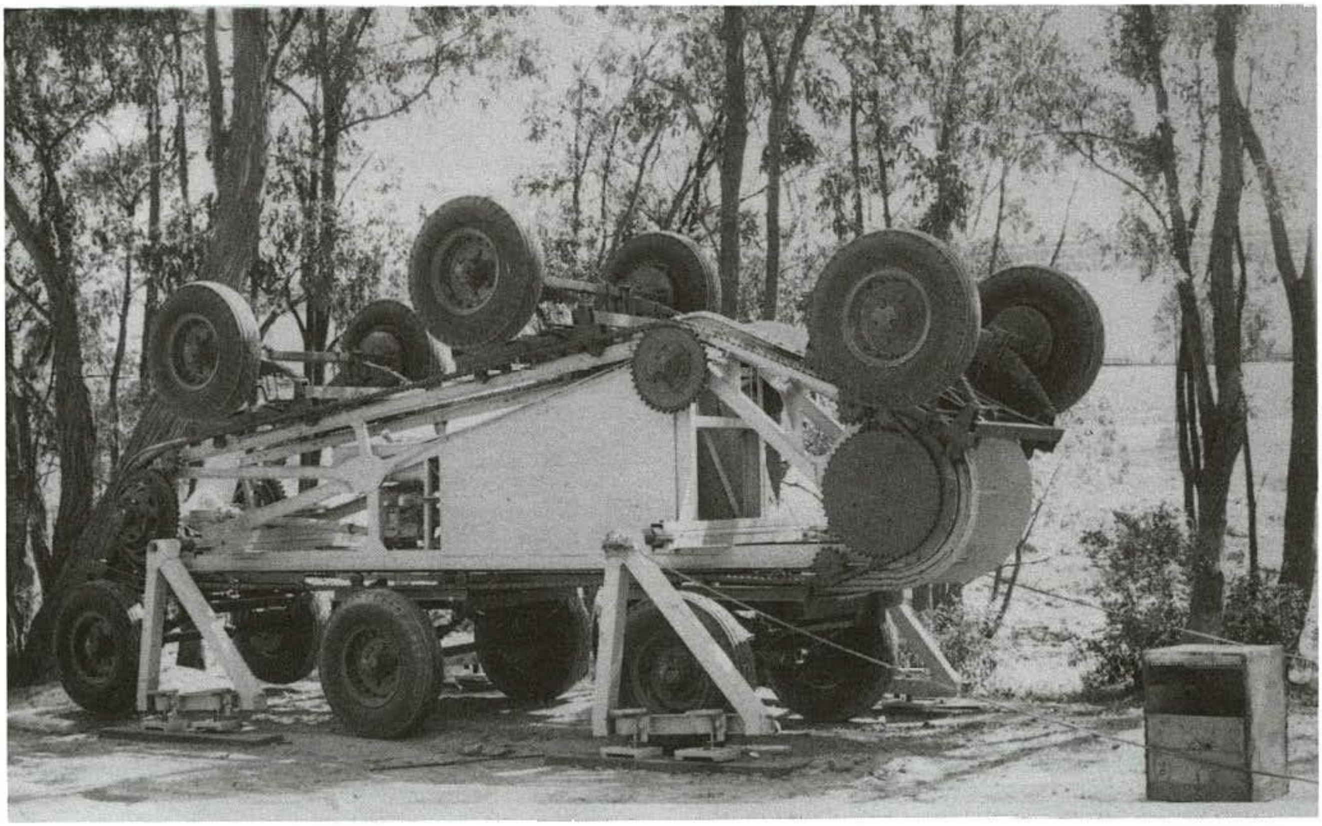


FIGURE 7 Australian Prototype Linear Loading Facility.

A fourth category of test track is static or pulsed loading being applied to a pavement section through a plate or a nonrolling wheel/tire assembly. Several very early accelerated pavement tests used this approach (e.g., the HYBLA Valley series) and some organizations have used this approach in association with one of the above facilities. Possibly the most active facility of this type at present is the installation at the German Road Research Laboratory, Bundesanstalt für Strassenwesen (BASt) (Figure 9).

Other Configurations

A number of less than full-scale facilities have been used for various pavement research studies, notably the rolling-wheel linear test track installation at Nottingham University and the Shell circular track installation in Amsterdam. Some full-scale load but small-scale pavement facilities, such as the BASt vertical drum machine, have been used for testing tire/road interaction, noise, and surface friction phenomena. These are not described in detail in this report, but the contributions of the Nottingham and Shell research are recognized.

PAVEMENT RESEARCH STRATEGY

The long and successful history of full-scale tests demonstrates that the application of full-scale accelerated testing is an essential part of pavement research strategy. Ideally, APT projects should not begin until a strategy exists and the roles for the various components of the strategy have been defined and prioritized. Components such as in-service LTPP studies, weigh-in-motion data collection and analysis, development of mathematical models of pavement response and performance, and laboratory characterization of materials must take an appropriate allocation of resources in the strategy.

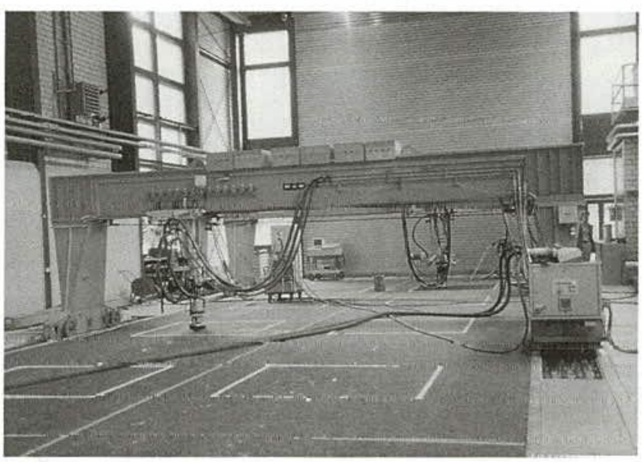


FIGURE 9 BASt Pulse Loading Facility - Germany.

Accelerated testing can, however, have a specific application to

- extrapolating existing designs for conventional materials to heavier traffic levels;
- introducing designs for new materials and pavement configurations;
- evaluating nontraditional, recycled, by-product, and waste materials;
- evaluating stabilization and geofabric treatments for subgrades;
- defining pavement deterioration phenomena;
- characterizing the effects of new axle, wheel, and tire loads, and configurations;
- investigating environmental effects, especially frost heave; and
- estimating remaining pavement life.

The testing must be accompanied by refinement of the analytical models for prediction of stresses and strains, including dynamic effects, prediction of deflection and deformation, and estimation of the onset and progress of distress.

Continued interest in this approach to improving pavement technology is evidenced by the existing active programs and the number of organizations actively planning to commission future facilities and to embark on research programs.

For background in implementation of APT programs, the recent studies in Florida (*36*), Indiana (*37*), Texas (*28*) and for the FAA (*38*) are valuable.

Reporting the state of the practice is always hindered by lack of timely access to information, constantly changing outputs, and the need to select and summarize the information. In 1979, Breyer (*39*) listed 23 European facilities and eight others. In 1985, the Organization for Economic Cooperation and Development (OECD) (*40*) identified 11 circular and six linear tracks, described 15 test roads and three other accelerated pavement test installations. However, the contribution of full-scale accelerated pavement testing to pavement technology is clearly evident from this continued interest, and the potential for future development is obvious.

The interest and, therefore, literature on this topic continue to grow. In addition to the references cited in the published report, there are many more, especially international, sources of information. As a result, the consultant for the project agreed to hold and to occasionally update an extensive bibliography on the topic. The bibliography contains several hundred references at this time. Another useful source of information is NHI Training Course No. 13130 Workbook, ''Pavement Deflection Analysis—Participant Workbook,'' publication No. FHWA-HI-94-021, February 1994, FHWA, Washington, D.C. Data on the TRANSPORT CD-ROM by Silverplatter include additional references from TRB's Tranpsortation Research Information Service (TRIS), as well as a few European research data bases. Also available is a CD-ROM from PIARC with more than 8,000 pages of resources and technical publications.

CHAPTER TWO

FULL-SCALE ACCELERATED PAVEMENT TESTING FACILITIES

This chapter describes the full-scale accelerated pavement testing facilities that have been active since the AASHO Road Test in the early 1960s. Table 2 lists the facilities and gives initial costs, both at the date of commissioning and for annual operation, in 1995 US dollars. The primary features, capabilities, and limitations of each facility are discussed in this chapter and are indexed to a fact sheet for each facility, provided in Appendix B. The chapter includes five tables that compare and contrast facility features, loading configurations, pavement configurations and materials, instrumentation, data collected and analysis procedures used. In presenting these features, a "soft" conversion to metric units has been used.

The Washington State University (WSU) circular test track (Figure 2), active from 1967 to 1983, was among the first full-scale accelerated pavement testing facilities worldwide. A contemporary contender was the original "Road Machine" in the United Kingdom, which was rebuilt in 1963. Facilities like these provided the technologies and justifications for the current generation of pavement test facilities.

In Australia, a repeated loading plate test facility (Table 2), was active in the 1960s (*41*), contemporaneous with an attempt to operate a full-scale linear tracking machine (Figure 7). The technology was lacking for successful operation so the next stage was to go to a multiple plate arrangement (*42*) to attempt to simulate a rolling load, and to move to a quarter-scale rolling wheel (*43*) on a laboratory track. Experience with these facilities led to proposals for a program based on the ALF design (*44,45*). The lack of good simulation of loads by the plate approach led to the wheel loading requirement, the observation of directional effects at the laboratory scale led to the uni-directional loading format, and considerations of cost and complexity led to the simple, energy-efficient configuration selected and now in use by Australian Transport Research Ltd (formerly the Australian Road Research Board), the Federal Highway Administration (USA) at the Turner-Fairbank Highway Research Center, the Research Institute for Highways, Beijing, China, and the Louisiana Transportation Research Center (Figure 3). Developments occurring in other countries resulted in the range of facilities, selected for their distinguishing characteristics, described below.

The facilities described are divided into three groups: test roads, with controlled, accelerated traffic; test tracks, of circular, linear, or free-form layout, and other configurations with static or pulsed loading assemblies.

TEST ROADS

The Minnesota test road (Index B1) is the centerpiece of MnRoad, the Minnesota Road Research project started in 1993. This outdoor project operates under the auspices of the Minnesota Department of Transportation and has a strong link with the University of Minnesota. The test road consists of two pavements, a 4.8-km (3-mi) 2-lane roadway for high-volume traffic research and a 4-km (2.5-mi) 2-lane closed loop for low-volume traffic. Forty 152.4 m (500 ft) test sections are included (Figure 10), with a comprehensive range of instrumentation incorporated.

Loading of the high traffic lanes is accomplished by diverting westbound traffic on Interstate route I-94 onto the test pavement. Approximately 14,000 vehicles, 15 percent of which are heavy trucks, use this route daily. Of the 23 sections, some have been designed to last 5 years and the remainder 10 years. There are 9 cement concrete sections and 14 asphalt concrete sections with a variety of base course configurations. A weigh-in-motion scale is installed in I-94 to collect vehicle classification, mass, axle spacing, and speed data. Although this is not strictly an accelerated load facility (because the loads are uncontrolled), the combination of this detailed knowledge of the in-service traffic loading, high traffic volume, and the use of thin structural pavements with short design lives merits inclusion in this report.

The 17 sections of the low-volume loop will be trafficked by calibrated test trucks and thus will be a controlled full-scale accelerated loading experiment. Concrete, asphalt, sealed, and gravel sections have a 3-year design life, trafficked by a 5-axle semi-trailer truck. The truck runs loaded to the legal axle load in one lane and overloaded in the other lane. (Figure 10)

A feature of this program is the extensive instrumentation—4572 sensors of 17 different types. Soil pressure cells and strain gauges are mounted horizontally and vertically at different levels in the pavement and subgrade. Moisture content is measured by time-domain reflectometry, moisture blocks, and a neutron probe. The frozen zone is determined by resistivity probes and temperature is monitored by thermocouples. An open standpipe measures the water table and static and dynamic pore pressures are detected by modified pore pressure cells.

The Nardo test road, near Brindisi, Italy, which is circular with a radius of 2 km (1.24 mi), is a center for high speed and endurance testing of motor vehicles (Index B2). It has six lanes (two for trucks and four for cars). In 1979, a new

TABLE 2 APT FACILITIES ACTIVE SINCE 1962

App. B Index	Acronym	Location	Year Commissioned	Nr. Tests Reported	In Use 1995	Initial Cost ($)	Annual Costs ($)
	TEST ROADS						
B1	MnROAD	Minnesota	1993	40	yes	2,500,000	500,000
B2	NARDO	Italy	1979		no		
B3	PTI	Pennsylvania	1971	17	no		
B4	PWRI	Japan	1979		yes	500,000	200,000
B5	WesTrack	Nevada	1995	new	yes		
	CIRCULAR TEST TRACKS						
B6	C - TIC	Saskatchewan	1978	3	no	400,000	
B7	CAPTIF (1)	New Zealand	1987	20	yes	300,000	
B8	ISETH	Switzerland	1979			750,000	
B9	IUT	Illinois	1963		no		
B10	JHPC	Japan	1979		yes		
B11	LCPC	France	1978	130	yes	5,000,000	800,000
B12	Road Machine (2)	United Kingdom	1963		no		
B13	RRT	Romania	1982	40	yes	420,000	100,000
B14	Shell	Netherlands	1967		no		
B15	S - KSD	Slovakia	1994		yes		
B16	UCF	Florida	1988		yes	250,000	
B17	UNAM	Mexico	1970	100	yes	480,000	190,000
B18	WSU	Washington	1965	12	no		
	LINEAR TEST TRACKS						
B19	ALF	Australia	1984	158	yes	1,000,000	600,000
B20	FHWA - PTF	Washington D.C.	1986	25	yes	1,100,000	275,000
B21	RIOH-ALF	China	1990	16	yes	1,000,000	
B22	PRF - LA	Louisiana	1995	new	yes	1,800,000	200,000
B23	DRTM	Denmark	1973		yes	200,000	100,000
B24	EPFL	Switzerland	1977				
B25	HVS	South Africa	1971	500	yes		
B26	CAL-APT	California	1994	new	yes	1,700,000	1,200,000
B27	LINTRACK	The Netherlands	1991	2	yes	1,000,000	164,000
B28	Minne-ALF	Minnesota	1990	new		200,000	
B29	PTF	United Kingdom	1984		yes	1,700,000	
B30	INDOT/PURDUE	Indiana	1992	32	yes	140,000	49,000
B31	TxMLS	Texas	1995	2	yes	2,500,000	
B32	CEDEX	Spain	1987	new	yes	2,100,000	
	OTHER						
B33	BASt	Germany	1963	15	yes		
B34	MSU	Michigan	1990		no	100,000	
B35	PHRI	Japan	1969				

Replaced earlier facility commissioned (1) - 1967 (2) - 1933

FIGURE 10 Minnesota Test Road (Courtesy: MnDOT).

test section was constructed as a chord across the original circle (*40,46*). The section was 1.8 km (1.11 mi) long with two 500 m (1,640 ft) transitions and a central 800 m (2,620 ft) straight; this straight had one rigid and three flexible pavement sections. Accelerated loading was achieved by diverting trucks circulating on the main track to the chord section and carefully channelizing the wheel paths across test pavement sections. The primary experiment was an evaluation of various pavement strain instrumentation devices and techniques (*47,48*).

The Pennsylvania Transportation Institute (PTI) research facilities, designed and built in the early 1970s, include a test road (Index B3) intended as a satellite to the AASHO Road Test. The test road is a 1.6-km (1.0 mi) loop on which four cycles of experiments were conducted, the last ending in 1983. The several rigid and flexible pavement sections were trafficked by different truck trailer combinations, including single- and tri-axles with wheel loads from 6.8 t (15,000 lb) on steer axles to a maximum of 29.2 t (64,000 lb) on a single axle (*49*).

The Public Works Research Institute (PWRI), Japan, has the most sophisticated facility of this type (Index B4). A looped track has two segments, one 870 m (2,850 ft) long and the smaller 628 m (2,060 ft) long providing for up to 67 experimental sections some 15 m (50 ft) long and 7 m (30 ft) wide; the small loop is used most with 19 test sections about 25 m (90 ft) long by 5 m (18 ft) wide. Trafficking is by three radio remote-controlled trucks for which the rear axle loads can be varied between 60 and 160 kN (13,200 to 36,000 lb) at speeds up to 40 km/h (25 mph).

WesTrack is a new test road located at the Nevada Automotive Test Center proving grounds (Index B5). A 2.8-km (1.7-mi) oval has 26 experimental hot-mix asphalt pavement sections. The layout is two straights connected by spiral curves, with the test sections located in the tangents. The pavement has two 3.6-m (12-ft) lanes with an outside shoulder of 1.2 m (4 ft) asphalt and 1.8 m (4 ft) gravel. The inside shoulder is a 0.6-m (2-ft) gravel strip. The outer lane is the test path; the inner lane provides extra shoulder width for trials of placement methods. Each experimental section is 70 m (230 ft) long. The primary purpose of the test road is the evaluation of asphalt pavements. The dry climate, with no frost penetration, is suited for direct evaluation of materials properties and construction effects. Loading is accomplished by four triple-vehicle combinations, a semi-trailer pulls two single-axle trailers, providing 10.3 ESALs per vehicle pass. The axle loads are 53.4 kN (12,000 lb) front axle, 178 kN (40,000 lb) tandem axle and five single axles at 89 kN

(20,000 lb). Vehicle speed is 64 km/h (40 mph). Trafficking commenced in late 1995.

Ohio has completed a 4.8-km (3-mi) test road with 31 fully instrumented sections. Loading will be by normal highway traffic but provision is made for specific investigations under controlled special vehicles.

Circular Test Tracks

A circular track has been active at the Central Laboratory of Saskatchewan Highways and Transportation (SHT), Canada, since 1978. In 1994 it was transferred to a joint venture renamed the Canadian Transportation Innovation Center C-TIC (Index B6). The track is 12 m (40 ft) in diameter running over a 3.6 m × 1.25 m (12 × 4 ft) deep pit. Single or dual-wheel loads up to 60 kN (13,500 lb) can be applied at speeds up to 29 km/h (18 mph) (*50*).

The Canterbury Accelerated Pavement Testing Indoor Facility, CAPTIF, (Index B7) was commissioned in 1987 in Christchurch, New Zealand (*51*). It is currently conducting trials related to the dynamic loading of pavements by different truck suspensions as a part of the OECD DIVINE project (*8*). The loading assembly has two arms and can accommodate different axle groups, single- and dual-wheel and single- to twin-axle bogies. The loading radius is 9.26 m (30.4 ft) over a 1.5-m (5-ft) deep annular pit. Loads from 21 to 60 kN (4,600 to 10,150 lb) can be run at speeds up to 50 km/h (31 mph).

This track replaced an earlier outdoor facility of 19.7 m (64.6 ft) mean diameter with two dual-wheels, each loaded to between 13.3 and 40 kN (2,930 and 8,810 lb), and operating at 19 km/h (11.8 mph) (*52*).

There are two tracks in Switzerland (*53*), a circular facility at Dubendorf, near Zurich, and a linear track at Lausanne. The Dubendorf campus of the Institute for Road, Railroads and Rock Engineering at the Federal Institute of Technology (ISETH) in Zurich (Index B8) has a three-arm rotating loading mechanism capable of loads from 50-80 kN (11,000-17,600 lb) at speeds up to 80 km/h (50 mph). The test rings are built in a 32 m (105 ft) (centerline) diameter pit. The facility was commissioned in 1978 and three experimental programs were completed by 1982.

The University of Illinois previously operated a circular track, built in 1963 (Index B9). It had a 2.5-m (8-ft) mean radius with a 0.8-m (2.6-ft) spread of loading by single tire single wheels, loaded from 84 to 145 kN (18,500 to 32,000 lb). A lime fly-ash pavement was tested at speeds up to 24 km/h (15 mph) and a study of permeable bases was conducted (*18,54*).

The Japan Highway Public Corporation (JHPC) has an Accelerated Loading and Environmental Simulator (ALES), a circular track (Index B10) 20 m (66 ft) in diameter with four load arms capable of wheel loads to 70 kN (32,000 lb) at speeds to 100 km/h (62 mph) with temperature control from −20° to 60° C (−4° to 140° F), and simulated rain. JHPC also has a linear track and a pulse loading machine capable of simulating speeds up to 4 km/h (2.5 mph) (*55*).

The largest circular test track operating in 1996 is the Manège de Fatigue of the Laboratoire Central des Ponts et Chausées (LCPC), at Nantes, France (Index B11). This facility has a four-arm rotating loading system, running two wheel assemblies on an inner track, 30 m (100 ft) diameter, and an outer track, 40 m (131 ft) diameter (Figure 4) (*56*). The loading system can be moved from one test track ring to either of two other rings at the same location to allow construction and post mortem testing to be conducted simultaneously with trafficking. Loads of 40 to 75 kN (8,800 to 16,520 lb) on a dual-wheel, simulating a single-axle load of 80 to 150 kN (17,600 to 33,000 lb), can be applied at speeds up to 105 km/h (65 mph). It is possible to simulate tandem axles of 280 kN (61,500 lb) at lower speeds and to simulate single-wheel loadings. The first test was conducted in 1978 and 130 pavement sections had been tested as of mid 1995.

In 1933, a 'road machine' (Index B12) was built at the UK Road Research Laboratory (now the Transport Research Laboratory [TRL]). Load up to 23 t (50,000 lb) was provided by an electrically driven truck chassis at the end of a 17-m (56-ft) arm, which could operate at 48-72 km/h (30-45 mph). The facility was updated in 1963 to run a single wheel loaded to 7 t (15,400 lb) at 40 km/h (25 mph) and applied mainly to investigate stress/strain distributions (*10*).

The Technical University in Iassy, Romania, commissioned a circular track [dia. 10 m (32 ft)] in 1957, which tested over 40 pavements before it was replaced in 1982 by a 15-m (51-ft) diameter facility (Index B13).

The Shell Laboratories in Amsterdam (Index B14) had a circular track in 1967, with a 3 m (10 ft) diameter, 0.9 m (3 ft) wide pavement built in a concrete pit. A two-wheel single-tire load up to 20 kN (44,000 lb) was run at speeds up to 20 km/h (12.4 mph) (*57,58*). Research at this facility, though it was not a full-scale pavement, led to the Shell pavement design manual (*59*).

In Slovakia, a 30-m (100-ft) diameter circular track with three arms, each controlling a bogie with a full truck single-axle dual-tire load, can operate at 30 km/h (19 mph) (Index B15).

The University of Central Florida facility (Index B16) was commissioned in 1988 and has three dual-wheel half axles that can be loaded from 45 to 136 kN (9,900 to 30,000 lb) wheel load at speeds to 48 km/h (30 mph) on the 15.6-m (51-ft) diameter track. The Florida Department of Transportation conducted a feasibility study for a proposed new track in 1994 that contains an excellent summary of the various features of many existing machines (*36*).

The Universidad Nacional Autonoma de Mexico (UNMA) in Mexico City commissioned a circular, three-arm loading assembly track in 1970 (Index B17). By 1973, 18 pavement sections in six rings had been tested, comprising a base course and surface treatment on a clayey loam subgrade compacted to different densities. Base thicknesses from 150-700 mm (6-28 in.) were constructed over 200-

1000 mm (8-40 in.) subgrades, to a total thickness of 1500 mm (60 in.). Loading is by a three-arm assembly with 100 kN (22,000 lb) dual truck wheels at speeds of 4-40 km/h, (2.5-25 mph) usually 10 km/h (6 mph) (*60*). Further research will include studies of the performance of 50-120 mm (2-5 in.) bituminous surfacing over various base, subbase, and subgrade designs. By the end of 1995, more than 100 sections had been tested under various environmental conditions.

The Washington State University track (Index B18) operated at speeds up to 24 km/h (15 mph) with a three-arm loading assembly (Figure 2) running single-wheel dual tires at loads up to 45 kN (9,900 lb) (*61,62*).

Linear Tracks

Nottingham University, UK, has a linear track facility (*63*) with loads up to 15 kN (3,300 lb) and a speed of 16 km/h (10 mph), operating over a test length of 4.8 m (16 ft) in a pit 2.4 m (8 ft) wide and 1.5 m (5 ft) deep. This and other less than full-scale facilities are not discussed further; they did, however, make a major contribution to the development of accelerated pavement testing methods, to analysis procedures, and to pavement design and material characterization.

The German Bundesanstalt für Strassenwesen (BASt) had a linear test track operating in 1967 (*64*) that applied a single-wheel single-tire load of 40 to 200 kN (8,800 to 44,000 lb) at speeds up to 50 km/h (31 mph).

The ALF (Accelerated Loading Facility) designed in Australia (Figure 3) is now operated at five locations by four organizations. This technology was first commissioned in 1983 at the Australian Transport Research Center (Index B19). The first FHWA machine was installed at the Pavement Testing Facility (FHWA-PTF), Turner-Fairbank Highway Research Center in McLean, Virginia (Index B20), in 1986 and the second in 1995. The Chinese ALF (Index B21) was installed at the Research Institute of Highways, Beijing (RIOH-ALF) in 1990 and the Louisiana Transportation Research Center Pavement Research Facility (PRF-LA) was opened in 1994 (Index B22). The Australian facility has been in continuous operation since 1983 and by 1995 had completed 13 major experiments, applying over 14 million load cycles in 31,000 hr.

ALF applies loads from 40 to 80 kN (8,800 to 17,600 lb) through a dual-tire single-wheel assembly to a 12 m (40 ft) test length, at a constant speed of 20 km/h (12.5 mph). A particular feature of ALF is that it loads in one direction only, a feature selected because traffic usually only operates one-way and laboratory scale tests on flexible pavements had shown deformation patterns clearly related to the direction of loading (*43*). The same patterns are observed at full-scale under ALF (*65*). Pumping and faulting in rigid pavements are also sensitive to the direction of loading. The Turner-Fairbank facility has been modified to operate a super-single tire assembly. Transverse movement of the loading path covers 1.4 m (4.5 ft) and one load cycle is applied approximately every 7 sec. ALF is a transportable machine designed for use on in-service highways or on specially constructed test pavements. Both modes of operation are currently being used for the five machines.

The Danish Road Testing Machine (Index B23) is a linear track facility capable of testing full-scale pavements under wheel loads up to 65 kN (14,300 lb) at speeds up to 30 km/h (18.6 mph). The pavement is constructed in a pit and can be temperature controlled between −10° and +30° C (14° to 86° F).

The linear track at the École Polytechnique Fédéral, Lausanne (EPFL) (Index B24) is an indoor test pit with two loading assemblies, a hydraulic pulse loading frame capable of plate loads 500 kN (110,000 lb) static and 300 kN (66,000 lb) dynamic, up to 3 Hz, and a rolling axle with dual-tire single wheels that can be loaded to 120 kN (75,000 lb) at 10 km/h (6.2 mph) over the central part of the 5 m (16.3 ft) loaded length, transverse movement is possible over 0.8 m (32 in.). The pit is 19 × 5 m (62 × 16.5 ft) at the surface with a depth of 2 m (6.5 ft), one end has a 5-m (16.3-ft) diameter circular insert, 8 m (26 ft) deep. The 2 m (6.5 ft) deep portion is temperature controlled between −20° and +20° C (−4° to 68° F). The surface can be heated to +40° C (104° F) by infrared heaters (*66*).

South Africa was the first to develop a mobile linear facility, the Heavy Vehicle Simulator (HVS) (Index B25) which can operate on in-service highways (Figure 6). Originally developed between 1968 and 1972, four HVSs have been in continuous use since 1982. More than 500 test sections have been trafficked with 1.4 billion ESALs. The HVS has a hydraulically operated loading assembly carrying a single- or dual-tire test wheel, and capable of loading from 20 to 100 kN (4,400 to 22,000 lb) at speeds up to 14 km/h (8.6 mph). The wheel load has been increased to 200 kN (44,000 lb) for airfield pavement tests. The wheel loads were originally evenly distributed over a track width of 0.9 m (3 ft) but more recent models can distribute load over a 1.5-m (5-ft) width to a nominated distribution. Typically loading is two-way over an 8-m (26.2-ft) test length (*67*), however, one-way loading can be applied when required, for example, when testing jointed concrete pavement (*68*). Observed performance on in-service pavements over nearly 20 years is cited as providing validation of HVS-based predictions derived from two-way loading with heavy, usually 100 kN (22,000 lb) test wheel loads.

The HVS technology is now being applied in California by the Department of Transportation (CALTRANS). In 1994, it began its CAL-APT program (Index B26) after successfully completing a pilot program using an HVS in South Africa during 1993 (*69*). CALTRANS purchased two refurbished HVSs and will deploy one at field sites on in-service highways as was done originally in South Africa and later in Australia. The second HVS is meant to run in a more controlled laboratory environment at the University of California at Berkeley (UCB). The CAL-APT program includes access to and support for retrieval and analysis of test results contained in South Africa's extensive (> 4 Megabyte) database from HVS tests on over 500 pavements.

The Road and Railroads Research Laboratory of Delft University of Technology, the Netherlands, (TUDelft), has a linear facility, LINTRACK (Index B27). The loading wheel assembly permits single-, dual- or super single-wheel mounting at loads from 15 to 100 kN (3,300 to 22,000 lb), and traverses the test section at 20 km/h (12.5 mph). The test section is 11.5 (38 ft) m long but acceleration and deceleration of the wheel assembly takes 4 m (13 ft) each, so instrumentation is concentrated in the central 3.5 m (11.5 ft). One- and two-way loading can be applied, with 1,000 wheel passes per hour in the two-way mode. Loading is distributed transversely 1m (3.2 ft) each side of the center line. The whole loading assembly is mounted on rails across a 55-m (180-ft) long test area in which transverse test sections can be constructed by conventional equipment. TUDelft also had a dynamic plate loading facility, which has been superseded by LINTRACK.

The University of Minnesota houses Minnie-ALF (Index B28), a single-tire load assembly working on a 4.5 m (15 ft) long by 3.6 m (12 ft) wide test pavement. The equipment is in a laboratory that allows partial control of temperature gradients. The testing length is 2.4 m (8 ft) with a maximum load of 11 tons (24,000 lb) and speeds up to 90 km/h (55 mph).

The Pavement Test Facility (PTF) at the UK Transport Research Laboratory (TRL) was commissioned in 1985 (Index B29). The PTF (Figure 11) is capable of one-way and two-way loading on single or dual tires at loads to 102 kN (22,500 lb). The operating speed is 20 km/h (12.5 mph) over a 6.7 m (22 ft) test section. One experiment, on a thick asphalt pavement, indicated that the difference in one-way or two-way loading was likely to be less than the difference between two tests with the same loading, thus two-way loading is now standard (R. Addis, personal communication 1995). However, this is likely to depend on the failure mode induced. Little use is now made of pavement strain gauges, but a simple and effective multidepth deflection/deformation gauge has been developed because rutting is the primary performance measure for the thick asphalt pavements typical of UK practice. Subgrade pressure cells showed such high variation that they were also discarded.

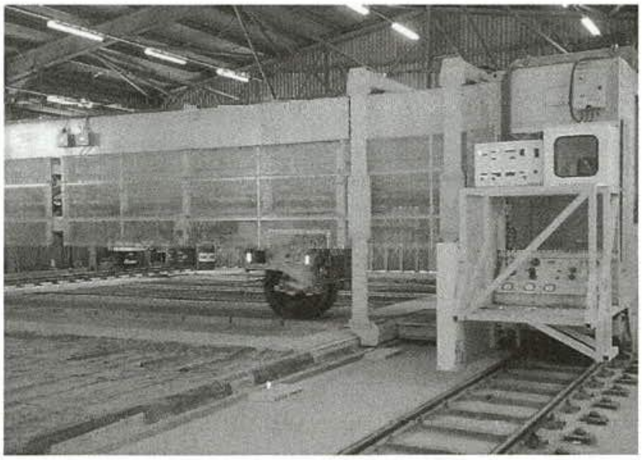


FIGURE 11 PTF - United Kingdom.

Indiana Department of Transportation, in association with Purdue University, has an Accelerated Pavement Testing facility (InDoT-Purdue APT) that operates in an environmentally controlled building (Index B30). The test pit, 6.1 × 6.1 × 1.8 m (20 × 20 × 6 ft) deep allows control of the water table and heating to 50° C (122° F), future provision for freezing has been considered. Loads can be applied by a dual-wheel or super-single half axle traveling at 8 km/h (5 mph) uni- or bi-directionally (Figure 5). A constant load up to 91 kN (20,000 lb) can be maintained, and provision exists to increase this to 182 kN (40,000 lb) as a static or programmed dynamic load (*37*).

Texas (*28,70*) has recently commissioned the Texas Mobile Load Simulator (TxMLS), which is a transportable linear device capable of applying six single- or dual-tire bogies with tandem axles loaded up to a nominal 190 kN (42,000 lb), at test speeds up to 20 km/h (12.5 mph) (Figure 8). The test pavement length is 11 m (36 ft) with optional transverse tracking over 0.6 m (24 in.) (Index B31). The facility has the following unique features:

- full axles instead of the more usual half-axle,
- regular truck suspensions to simulate short wavelength dynamics,
- load frequency up to 8800 per hour, and
- a fully enclosed chamber for environmental control as desired.

Two of the bogies are powered by 120 kW electric motors with a belt drive to one axle, the remaining four bogies are trailing axles. The device is capable of being dismantled and reassembled in one day and can be jacked up to allow in situ testing. The device can be used for test sections on in service highways.

Spain has a major facility at the Road Research Center (Centro de Estudios de Carreteras CEC) near Madrid (Index B32). This center is part of the Center for Public Works Studies and Experimentation (Centro de Estudios y Experimentación de Obras Publicas (CEDEX)) which falls under the Ministry of Public Works Transport and Environment. The facility has two parallel straights each of three 25-m (82-ft) sections joined by circular arcs (Figure 12). The test sections are built with normal construction equipment in a U-shaped concrete box, 8 m (26.2 ft) wide by 2.6 m (8.5 ft) deep, which allows control of moisture content. The straight sections are covered but rain can be simulated. Load is applied by two bogies, each guided by an internal perimeter wall, which are capable of mounting one-, two-, or three-wheel, single- or dual-tire half axles. The load is by gravity at speeds up to 60 km/h (37 mph) and axle loads between 110 and 150 kN (24,200-33,000 lb). Pavement instrumentation is monitored from a control center that also operates the vehicles.

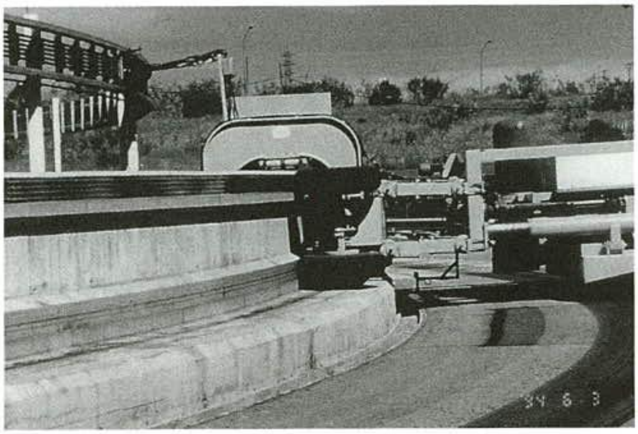


FIGURE 12 CEDEX - Spain.

OTHER CONFIGURATIONS

The BASt Pulse Loading Facility (Index B33) has three hydraulic plate loading rigs (Figure 9) currently testing a base course of various waste/recycled materials, mainly recycled pavement or building materials (*71*). The pulse load plates move along the test section to simulate traffic at approximately 20 km/h (12.5 mph) and applies loads to 200 kN (44,000 lb). The legal axle load is 100 kN (22,000 lb) but 115 kN (25,000 lb) axle loads are anticipated as a result of European Economic Community (EEC) regulation. Hydraulic pressure gauges, H-bar strain gauges, and surface deformation measurements, with a traveling straight edge on two reference points, are used. Temperature can be controlled to plus or minus 20° C (−4 to +68° F), and the water table is controlled. Pavements are built with full-scale equipment. The 1995 experiment is on an expanded polystyrene foam insulation layer under concrete, cement treated base (CTB), and fine crushed rock base (FCR); the latter deformed severely.

Michigan State University commissioned a pulse loading assembly in 1990 to simulate wheel loads across cracked pavement slabs. The facility was decommissioned in 1993 (Index B34).

In Japan, several facilities have been in use since 1969. The first was a testing tank at the Port and Harbor Research Institute (PHRI), which could apply plate loads to 2200 kN (484,000 lb) and repeated loads to 500 kN (110,000 lb) on a dual-tandem aircraft wheel assembly (B 747) at speeds to 30 km/h (18.6 mph). The water levels in the track could be controlled (Index B 35).

COMPARISON OF FEATURES

The features of the currently and recently active facilities are compared and summarized in Tables 3, 4, 5, 8, and 9. Incomplete questionnaire responses have been amplified with information from the literature review where possible. However, not all the features have been publicly documented and at many facilities, improvements and detail modifications have continued throughout the life of the programs. Comparisons are made to highlight the features common to groups of facilities where these seem to reflect a consensus in the approach to APT.

What is clear is the commitment of many organizations worldwide to this approach to improving our knowledge of road pavement response and performance.

The cost data reported (Table 2) cannot be closely compared as (a) insufficient information is available to adjust the figures to a consistent basis, and (b) the costs clearly reflect different price regimes in different countries. However, the data are indicative of the order of magnitude of the resources necessary for a coherent program. It is evident that some facilities are supported as part of concerted regional or national programs, planned to continue for a number of years, while others are more opportunistic in nature. There is an even division between linear and circular tracks that are used for a wide range of programs. In 1995, they were mainly directed to the evaluation of flexible pavements and bound bases. Pulse loading machines are used for the evaluation of thick, flexible pavements where rutting is the failure mode, and for the evaluation of joint or crack behavior in rigid pavements.

Loading Configuration

The most common means of accelerating damage to test sections of pavement is to increase the wheel load applied, and Table 3 gives loading configurations now in use that cover a range from single plate, to single-wheel single-tire assemblies, to full truck loading. Wheel loads vary from 15 kN (3,300 lb) to more than 150 kN (33,000 lb) at speeds up to 105 km/h (65 mph). The second way of accelerating damage is to increase the frequency of loading by increasing the speed of operation, as in many circular tracks or by using a multi-wheel load assembly or vehicle in linear tracks. Test roads or tracks operating multi-axle load systems can operate at higher total loads and apply more ESALs per pass of the load assembly or vehicle.

Typically, loads are close to the local legal maximum for the wheel assembly, usually in the range 8-13 t (17,600-28,600 lb) applied at speeds in the 20-80 km/h (12.5-50 mph) range. Load frequencies vary from static load to 2 Hz. Most types of suspension have been used as well as a range of tire pressures, usually about 0.7 MPa (100 psi). Few tracks have the capability to monitor dynamic loads, relying on the design of the load system to provide constant or at least repeatable loads, and only some of the test roads continuously monitor wheel loads by w-i-m devices. (Table 3)

Pavement Configurations

The pavement configurations and materials tested are indicated in Table 4. They cover a wide range, with an

TABLE 3 APT FACILITIES—LOADING CONFIGURATION

App. B	Test Length/ Diameter (m)	Wander Width (m)	Temperature Control	Loading Type	Speed Range (Km/h)	Cycle Tyme (sec)	Wheel Load Range (kN)	Wheel Suspension	Tyre Pressure (MPa)	Power (kW)
B1			N	a,b	60–100		365–465 XX	1, 2, 3, 4	0.7–0.88	
B2			N					1		
B3	1600		N	a,b	36	2.66		1, 2, 3, 4		
B4	628		N	b	40	60	140 XX	1, 2, 3, 4		
B5	2800		N	f	65		676 XX			
B6	38/	1.3	H, C	a,b	36	3.8	55			
B7	58/		N	a,b	0–50	>2.25	21–60	1, 2, 3	0.56–0.84	55
B8	100/30	1.3	H, C	b	80	4.5	50–80			
B9	15	1		b	3–15	0.6	0–30			
B10	20/8	0.4	H, C, F		10–60		0–30			
B11	100/30	1	N	a,b,c,d	30–105	1–3.5	40–75	1, 4, 5	0.65–1	750
B12	105/34		H	a,b	32	12	67			
B13	48/15		N	a,b,c	5–40	2–17	100–160	2, 3	0.7–1	70
B14										
B15	50/16	0.95	N	a,b,e	10–70	1.6–12	83–130			110
B16	49/			a,b	24–58	7.2	45–133	2		220
B17	27		H	b	0–30	>1.25	40–65	2.3	0.5–0.57	90
B18	81	1.2		b			50			
B19	12	1.4	N, X	a,b,c	1–20	10	40–100	1, 3		50
B20	12	1.4	N, X	a,b,c	1–20	10	40–100	1, 3	0.54–0.99	50
B21	12	1.4	N, X	a,b,c	1–20	10	40–100	1, 3	0.90–0.95	50
B22	12	1.4	N, X	a,b,c	1–20	10	40–100	1, 3	0.72	50
B23	9	1	H, C, F	a,b	20–30	3.6	<65			
B24	5	0.8	H, C, F	b,c	10	>2	120			
B25	8	1.5	H, C	a,b	14	2.5	20–200	5	0.5–0.69	
B26	8	1.5	H, C	a,b,c	0–10	>0.45	20–200	5		
B27	16	2	H	a,b	10–20	3.65–7.2	15–100	1, 4	0.5–1.1	80
B28										
B29	7	1	H		1–20	3.6	< 100	3		
B30	6	0.3	H, C, F	a,b	8	15	13–182	5	0.63–0.95	
B31	12	0.6	N, X	abcdef	12–25	7	22.5–47.5	1, 2, 3, 4	0.64 (var)	240
B32	2*67	0.8	N	b	8–58	24	44–100	2		
B33	1.5		H, F			0.02	20–100	5, XXX		
B34	3.0		1	a	88	0.24	< 450	—	—	28
B35										

H - heat F - freeze a - single wheel b - dual wheel e - full axle 1 - airbag 2 - steel spring 3 - driven axle X - temperature control can be used C - cool N - none c - single axle d - dual tandem f - multiple axle 4 - towed axle 5 - hydraulic load control XX - the total weight of the vehicle XXX - circular plate

TABLE 4 APT FACILITIES: PAVEMENT CONFIGURATIONS

App. B.	Pavement Type	Thickness Range (mm)	Pit Cross Section (m) Width* Depth	Subgrade Material	Subbase Material	Subbase Thickness Range (mm)	Base Material	Base Thickness Range (mm)	Surface Material	Surface Thickness Range (mm)	Construction Procedure
B1	1, 3			n,b	g		a,b,c		a,e		N
B2											N
B3	1, 2	240–730	Y	n	g	100–520	a,c	100–200	a	38–64	N
B4	1	600–800		n	g	250–550	b,c	150–200	a	50–100	N
B5	1								a		
B6	1, 2	600–1200	1.25*3.6	n	g,d	100–450	c,d	100–150	a,f	50–100	
B7	1, 2	1500–1600	4*1.5	b	g,d	0–250	b	100–300	a,f	25–130	N
B8			2*4.5								
B9		–1300	1.3*3.1								
B10											
B11	1, 2	400–800		b	g,d	100–400	a,b,c,d	80–500	a,e	25–250	N
B12											
B13	1, 2, 3	200–500		n	g	0–200	a,c,d	100–200	a,e	40–100	N, S
B14											
B15											
B16											
B17	1	1450–1550	1.5*3	b	g	0–300	b	150–610	a,e	10–150	N
B18											
B19	1, 2	100–500		n,b	a,c,d,g	100–200	a,b,c,d	50–200	a,e	0–60	N, S
B20	1	250–650	Y	n	—	—	g	120–520	a	75–200	N
B21	1, 2, 4			n	d,g	60–270	a,c,d,g	120–390	a	60–150	N, S
B22	1, 2	410	Y	n	d,g	0–230	d,g	100–230	a	90	N
B23	1, 2, 3		2.5*2								
B24			5*1.5								
B25											N
B26	1	610–640		n	g	230	a,g	180–280	a	140	N
B27	1	80–150		b			a	80–150	a		N
B28											
B29	1, 2, 4		2.5*								
B30	3	480–600		b	g	100–230	e	300	a	75	N
B31	1, 2, 3, 4	500–650	Y	n	d	150	d,g	300	a	50–200	N
B32	1, 2	370–700	2.5*8	n	g,d	150–250	a,d	200–250	a	120–200	
B33											
B34	3								e		S
B35											

1 - flexible 3 - rigid Y - conventional cross-section a - asphaltic concrete d - stabilized with cement/lime f - surface treatment N - normal
2 - stabilised 4 - composite n - natural b - borrow c - stabilized with butumen e - cement concrete g - granular S - special

equally wide range of nominal design lives. Naturally, the facilities test the pavement configurations and materials typical of the country or region. Most APT pavements are built in pits or troughs that provide containment and fixed support to the test sections. In some cases this makes construction with normal equipment difficult. Most recent tracks have at least partial temperature control and a few have provision to control moisture content or water table level.

Instrumentation

Almost without exception, APT facilities have instrumented test pavements to measure the following known critical parameters (see Table 4):

- horizontal and vertical strain at various interfaces in the surfacing base and subbase;
- vertical pressures at base, subbase and subgrade interfaces;
- displacement, deformation and deflection, of the surface and at multiple depths in the various pavement layers;
- temperature, at the surface and at depth; and
- moisture movement.

Practice among the various facilities is summarized in Table 5 and Appendix C describes some features in more detail. The most widely used technique for horizontal strain measurement is the "H-bar" gauge (Figure 13). The life of an H-bar gauge is closely related to the bond between the gauge and the surrounding material; a good bond will result in strains close to theoretical estimates. However, high pavement temperatures can affect the bond and thus the results. Moisture entry and cable problems are encountered. Bison gauges have also been used to measure long-term static and dynamic vertical strains, but a high failure rate was reported at high temperatures. Various forms of pressure cells have been used, usually at subgrade level, but have a low rate of survival of the construction process; even lower survival was experienced under asphalt layers. Displacement transducers are widely used to measure deflection and deformation at the surface and, less often, at various depths within pavements. Temperature, ambient and in pavement, was measured at all but two sites. Moisture movement is less frequently measured or reported.

Strain Gauges

A strain measurement device in early use in full-scale pavement tests is the inductive coil strain gauge, first developed at the Illinois Institute of Technology Research (IITR). The technique was further developed by Bison Instrument Inc., Minneapolis, Minnesota (Table 5). These gauges have been applied to research on asphalt concrete pavements by many agencies, for example at the Washington State University Test Track (*17,72*) at the University of Canterbury, New Zealand (*51*), Delft University of Technology (*73*), and TRL (*74*).

Small-sized strain gauges of the rosette type have been used. Horizontal strain gauges (600-Ohm type, 30 mm (1.2 in.) active length) were cemented to the surface of successive 50 mm (2 in.) layer in both transverse and longitudinal directions. Vertical strain gauges (10 mm (0.4 in.) active length) were connected between pairs of small prefabricated blocks of sand asphalt, which were then incorporated into the layers (*57*). Gauges for measuring horizontal strains at the asphalt/base or subgrade interface had been mounted on carriers made of sand sheet or bituminous felt, embedded in the sand subgrade, or on carriers of asphalt concrete, which were placed in the asphalt layer. Test results showed that the strain signal at various levels was only roughly in agreement with that predicted by elastic theory.

The strain transducer now most widely used in full-scale pavement testing is the embedment strain gauge (*73*). The gauges are normally encapsulated in a plastic strip to which two brass anchors are attached, forming the H-bar, ensuring a proper fixation in the asphalt layer for measuring the horizontal tensile or compressive strain at the bottom of the lower asphalt layer. In another type of H-bar, the gauge is cemented to an aluminum plate and protected by a resin coating (*40*). Gauges that remain tightly bonded measure values of strain that agree well with theoretical calculations. However, loose H-bar gauges consistently yield strains significantly less than theoretical strains.

A considerably improved H-bar strain gauge was used in Denmark. The gauge had been tested for more than 2 years in moist conditions in an asphalt specimen, and had been subjected to more than one million large strain repetitions and to several freeze/thaw cycles without any damage. Figure 14 gives the results of comparison between measured strain and theoretical results (*75*).

Another strain gauge type that was successfully used was the Finnish made VTT gauge (*76*), also used in the FHWA ALF test track and the OECD FORCE full-scale pavement test for strain measurement in bituminous layers (*77,47*).

Strain gauges adhered to or embedded in carrier blocks were used to measure the transverse and longitudinal strains in pavements at the Nardo Test Site, the MnRoad project, and under the FHWA program.

There are several instruments used for measuring the vertical strains in pavement. Two of them use vertical strain gauges or use multi-depth or partial-depth deflection gauges. The basic principle for both methods is to measure relative displacement between different depths in the pavement.

The vertical strain gauge used at the Danish RTM, TRL, and the OECD FORCE full-scale pavement test are based on an LVDT (Linear Variable Differential Transformer). An LVDT measures the relative displacement between a plate bonded in the surface of the asphalt layer and a reference plate placed at the desired depth during pavement construction.

TABLE 5 APT FACILITIES: INSTRUMENTATION

App. B	Strain Gauges Placement	Strain Gauges Type	Pressure Cells	Permanent Deformation	Temperature Measurement	Moisture Measurement Water Table	Moisture Measurement Moisture Content
B1	1	H, Biaxial	1, 2, 3		yes	TDR, Standpipe	TDR, watermark blocks
B2							
B3					no		
B4							
B5				profile			
B6	1, 2, 3	Bison	1, 2, 3		yes		
B7	1, 2, 3		3		yes	Standpipes	TDR
B8							
B9							
B10							
B11	1, 2, 3		2, 3		yes	Piezometer	nuclear method
B12							
B13			1, 2, 3	profile	yes	Standpipes	densimeter
B14							
B15							
B16							
B17	1		1, 2, 3		no		ASTM-Specs
B18		Bison					
B19	1, 2		3	MDDT	yes		
B20	1	H, retrofit, LVDT		profile	yes	no	reflectometry, nuclear
B21	1, 2	H, MDDT	1, 3		yes		
B22	1, 2, 3	H, MM, MDDT	1, 3	profile	yes	yes	nuclear
B23	1, 2, 3	H, LVDT	123		yes		tensiometer
B24							
B25				MDDT, profile	yes		nuclear
B26	in future tests		in future tests	MDDT, profile	yes		elect. resist. nuclear
B27	1, 2		3		yes	DIP gauge	
B28							
B29							
B30				LVDT	yes		
B31	1, 2, 3	H, MM, MDDT	1, 2, 3	MDDT, profile	yes	TDR	GPR, TDR
B32							
B33							
B34	1						
B35							

1 - surface/base interface 3 - subbase/subgrade interface LVDT - Linear Variable Differential Transformer TDR - Time Domain Refrectometer
2 - base/subbase interface MDDT - multidepth deflection MM - Micromeasurement strain gauge GPR - Ground Penetration Radar

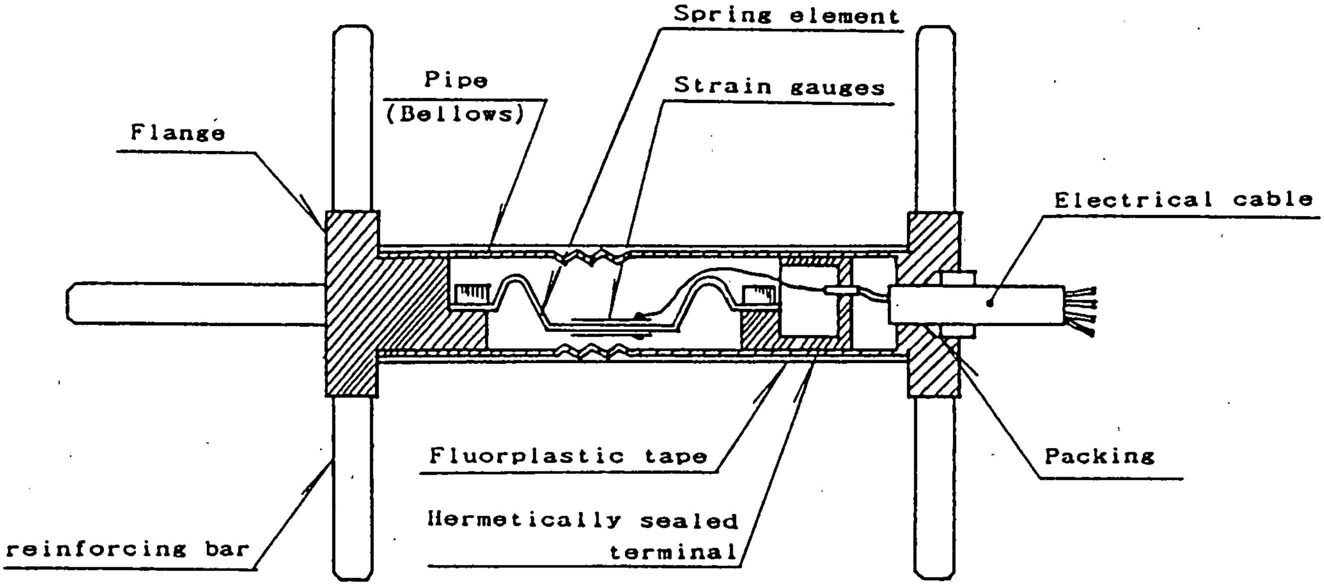


FIGURE 13 Cross-section of the embedment strain gauge KM-100-HB (*65*).

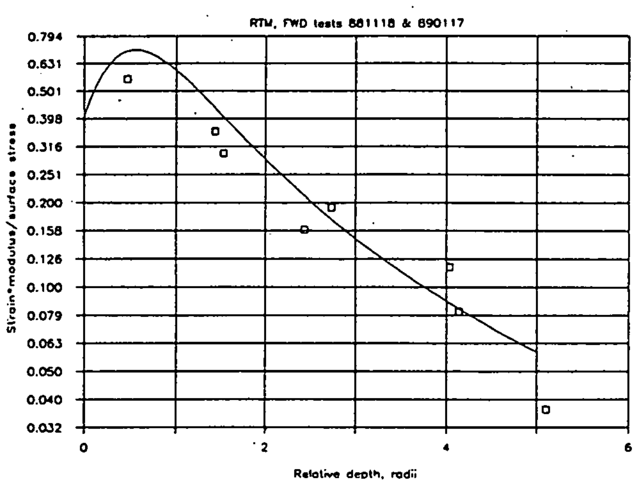


FIGURE 14 Measured strain compared to Boussinesq's equation (*67*).

Another strain gauge, based on an LVDT, was also used at TRL and a variation of the gauge was used in the FHWA program (*78*).

At the LCPC test track, strain gauges and displacement transducers are used to measure strains and deformations in concrete pavements (*79*). Two longitudinal strain gauges are glued to the top and bottom surface of a dowel, providing information about bending strains; two diagonal gauges, glued to the dowels at mid-height, provide information about shearing strains. Displacement sensors are installed to measure horizontal movement of joints.

Other types of strain gauge used in the OECD Test at Nardo are shown in Table 6 (*46*). Group 1.1, 1.2 and 2.3 gauges worked well but a high proportion of the group 1.2 type gauges were lost in construction.

Pressure Cell

There are many types of pressure cells for measuring the compressive stress in pavements. The diaphragm type pressure cell is the most widely used. The principle of this gauge is that the pressure on the thin diaphragm of the cell causes a deflection, which is transformed into an electrical signal by a strain gauge or a small LVDT, or a vibrating wire transducer glued on the inside diaphragm (*75,80*). Pressure cells are usually installed in the subgrade at different depths, in aggregate material layers, and at the interface of the base course and the asphalt concrete layer. Test data from and survival rates of pressure cells are very limited. This kind of gauge is sensitive to environmental factors such as moisture and temperature.

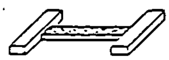
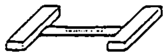
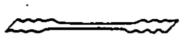
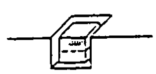
A piezo-electric gauge (Figure 15) was used to measure subgrade stress at TRL. This gauge was used in many full-scale test pavements and proved to be durable (*81*).

Displacement Gauges

A gauge to measure transient and long-term displacement in test road pavement was developed for the University of Illinois Pavement Test Track (*18*). An LVDT core was attached to a stainless steel anchor rod that was anchored to a base plate in the bottom of the test track pit or at a certain pit under the pavement layer. The housing of the LVDT was bonded to the base or surface layer material. As the wheel load caused the pavement to deflect, the LVDT housing moved relative to the core and the displacement between the housing point and base plate was recorded.

A similar displacement gauge based on LVDT and anchor plates was used by TRL (*82,83*) and at the Washington State

TABLE 6 GAUGES USED AT NARDO (*46*)

Group	Schematic Construction	Gauge Model	Active Length of Wire/Anchor	Resistance Ω	Cost (US$)	Team	Assembly
1.1		Kyowa KM-120-H2-11L 100-3	70 mm/104 mm	120 ± 1%	40	3	Fixation of anchor bars in the lab
		Kyowa KM-120-H2-11L 100-3	70 mm/106 mm	120 ± 1%	35	5	
		Kyowa KM-120-H2-11L 100-3	70 mm/100 mm	120 ± 1%	75	7	
1.2		Kyowa KC-70-A1-11	67 mm/130 mm	120	35	2	Gauge glued to support & fixation of anchor bars in the lab
		PL30 ou Kyowa KFC-30-C1-11	30 mm/100 mm	120	23	6	
1.3		HBM DA 3	88 mm/140 mm	350	180	1	
2.1		HBM LP 60-120	60 mm/60 mm	128	12	1	Glued on Marshall specimen, cut to 1/3 height
		BLH FAE-300-35 PL	76 mm/76 mm	350	35	8	
2.2		HBM 20/600 XA21	20 mm/20 mm	600 ± 0.25	10	9	Glued in the center of a lab specimen
2.3		Metal Foil Gauge	13 mm/25 mm	120	15	4	Glued on a block of sheet asphalt
3.1		HBM LP 21 60-120	60 mm/60 mm	120	12	1	Glued on core taken from the pavement
		HBM 60/600 LP 21		600 ± 0.25	15	3	

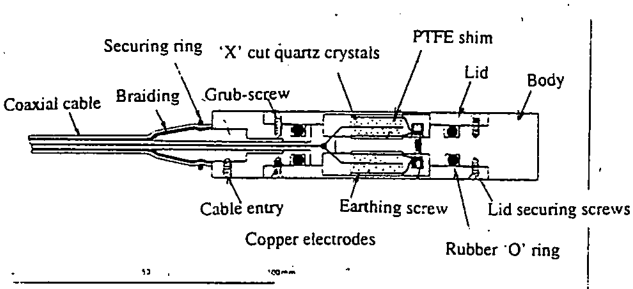


FIGURE 15 A piezo-electric stress gauge used at TRL (*73*).

University Test Track (*17,72*). The results were used to examine the effect on pavement response of different types of gravel aggregate in bituminous bases and base courses.

Two types of displacement gauges most widely used are the TRL 'spring' gauge (Figure 16) and the multi-depth (MDDG) (Figure 17) and partial-depth (PDDG) displacement gauges. MDDG gauges were used in South Africa in the 1970s, where much of the current technology was developed. Studies of deflections at different depths, used to estimate working stress and strain levels under vehicle loading, led to the systematic development of a series of multi-depth gauges capable of measuring displacement at up to eight depths simultaneously, to supplement surface

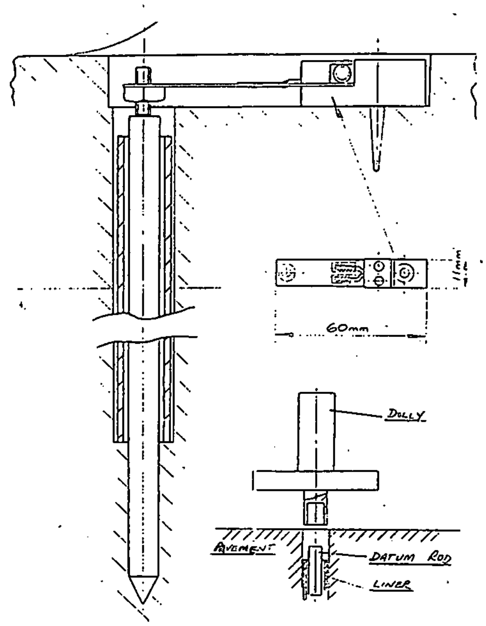


FIGURE 16 TRL 'spring' deflection gauge used in OECD FORCE full scale pavement test (*73*).

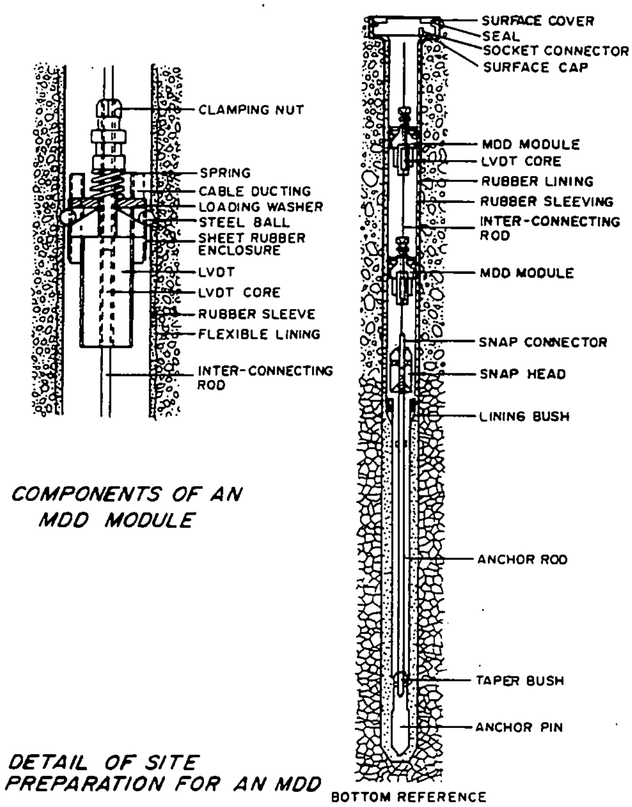


FIGURE 17 Multiple depth deflection gauge (MDDG) (*132*).

deflection measurements (*84,85*). The application of MDDG data to in situ materials characterization and load-equivalency estimation was also initiated (*86*). The Australian, FHWA, and Chinese ALF programs (*87,88*); the Texas Transportation Institute (*89*); TRL (*76*); and other organizations all use MDDG techniques to measure the vertical strain in unbound materials.

A heavy-duty deflectometer was also developed for concrete pavements (*90*). Surface deflections measured by the falling weight deflectometer (FWD) or similar devices are replacing the Benkelman beam favored in the 1970s to 1980s (*91*).

The Crack-Activity Meter (CAM) was developed in South Africa to measure the relative movements of cracks or joints in a pavement caused by moving wheel loads (*91*). The CAM has two LVDTs, one positioned vertically and one horizontally (Figure 18) to measure vertical and horizontal movements of cracks or joints simultaneously, and to measure relative movements directly.

A horizontal clip gauge was used at the MnRoad project to measure the static horizontal movement at concrete joints. The clip gauge consists of an inverted U-shaped steel strip with electrical resistance strain gauges bound to the top of the strip (*92*). The gauge measures horizontal joint movement by attaching one end of the strip to the concrete on each side of a joint.

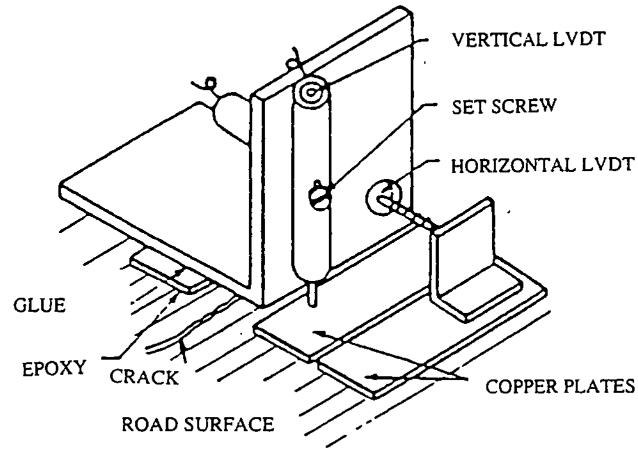


FIGURE 18 The crack-activity meter (CAM) (*83*).

Temperature Gauges

The most commonly used temperature gauges are thermocouples of various types (copper-constantan, type T, type K) (*40,73,77,81,92–94*). Thermocouples were normally installed at various depths in different pavement structures (especially in asphalt layers) at the time of construction to monitor pavement temperatures. Thermistor temperature gauges have been used but are considered less robust than thermocouples.

Subgrade Moisture Cells

Resistance type moisture cells were used at the FHWA PTF. Time domain reflectometry (TDR) is a new technology being used in the Minnesota Road Research Project (*92*) to measure soil moisture content.

Other types of gauges used at MnRoad (Table 7) are open standpipes to measure water table, dynamic and static pore water pressure cells to measure positive pore water pressure, resistivity probes to measure frozen soil location, and the tipping bucket to measure subsurface drainage runoff.

The MnRoad project is one of the most comprehensively instrumented full-scale accelerated pavement research facilities of the last 20 years. Over that time, 4,572 electronic gauges, including 1,151 pavement load response gauges and 3,421 environmental gauges, were installed in 40 pavement test sections.

Data

The data collected at various facilities are summarized in Table 8. Most collected surface deformation and deflection, and all recorded ambient and pavement temperatures. All record or can closely estimate the number of load cycles applied but few could record the actual dynamic wheel load on the pavement. The TxMLS and ALF facilities monitor

TABLE 7 GAUGES INSTALLED AT MNROAD (*92*)

Sens.	Description	Make/Model	# Installed
SURFACE SENSORS			
BL	Biaxial Longitudinal Strain Gauge	Alberta Research Council Design	20
BT	Biaxial Transverse Strain Gauge	Alberta Research Council Design	20
CD	Concrete Embedment Strain Gauge	Dynatest PAST-2PCC	128
CE	Concrete Embedment Strain Gauge	Tokyo Sokki PML-60	436
DT	Linear Variable Differential Transformer	Schaevitz HCD-500	119
HC	Horizontal Clip Gauge	Tokyo Sokki TML-P15	80
LE	Longitudinal Embedment Strain Gauge	Dynatest PAST-2AC	27
PA	Piezo-Accelerometer	Kistler 8628 B50	42
PG	Dynamic Soil Pressure Cell	Geokon 3500 w/Ashcroft Trans	106
PK	Dynamic Soil Pressure Cell	Kulite 0234	66
SS	Steel Strain Gauge	Micromeas. LWK-06-W250B-350	45
TE	Transverse Embedment Strain Gauge	Dynatest PAST-2AC	102
TL	Tiltmeter Longitudinal	Applied Geomechanics 756-1129	15
TT	Tiltmeter Transverse	Applied Geomechanics 756-1129	15
VW	Vibrating Wire Strain Gauge	Geokon VCE 4200	162
XV	Thermistor in Vibrating Wire Strain Gauge		162
SUBSURFACE SENSORS			
DW	Dynamic Pore Water Pressure Cell	Geokon 3410S	52
XD	Thermistor in Dynamic Pore Water Pressure Cell		52
NP	Neutron Probe Access Tube		73
OS	Open Stand Pipe		40
PL	Static Lateral Pressure Cell	Geokon 4800E	13
XL	Thermistor in Lateral Pressure Cell		13
PT	Static Soil Pressure Cell	Geokon 4800E	53
XT	Thermistor in Soil Pressure Cell		53
RP	Resistivity Probe		103
SW	Static Pore Water Pressure Cell	Geokon 4500SL	49
XS	Thermistor in Static Pore Water Pressure Cell		49
TB	Tipping Bucket		14
TC	Thermocouple	T-Type	1047
TD	Time Domain Reflectometer		708
WM	Moisture Block	Watermark 200-x	708

wheel loads continuously and the Indiana facility relies on a constant force mechanism. Strain or pressure measurements are commonly made at specific intervals and often with the equipment running at reduced speed to facilitate data collection, though data collected at highway speeds could be of great value. Low-speed data are not strictly valid at higher speeds. Few facilities measured roughness directly; however, transverse measurements of pavement permanent deformation allow rut depth and longitudinal profile to be calculated and roughness parameters may be derived. An important missing parameter is cracking; there is as yet no adequate standard procedure for categorizing and quantifying the development of cracks.

All facilities had laboratory and field testing programs to determine in situ and laboratory parameters to characterize the materials used. Soil, aggregate, asphalt, and cement concrete tests are performed and in situ densities are recorded. "As constructed" or post mortem materials investigations are less clearly reported. The sophistication of the materials testing programs also varied considerably (Table 9). The major effort in data collection and recording is directed at surface phenomena, primarily rutting, and the related development of roughness and cracking.

Capabilites and Limitations

The capabilities and limitations of the various approaches to full-scale accelerated pavement testing are summarized in Table 10. All are limited insofar as the effect of environmental factors can be controlled or varied in some facilities, and measured; but the combined effects of environment and

TABLE 8 APT FACILITIES: DATA COLLECTED

App. B	Load	Deflection			Profile		Permanent	Roughness	Strain		Temperature
		BB	FWD	Other	Longitudinal	Transversal	Deformation		Tensile	Compression	
B1	B	yes	yes	HWD	yes	yes	1, 2	PaveTech			a,b,c
B2											
B3											
B4		no	yes		yes	yes	2	no			—
B5		no	yes		yes	yes					
B6							2			yes	a,b,c
B7		yes	yes	CAPTIF	yes	yes	1, 2	no			a,b,c
B8											
B9											
B10	A										
B11	C	yes	yes	Inclinometer	yes	yes	1, 2				a,b,c
B12											
B13		yes	yes	Curvature meter	yes	yes	1, 2	no			a,b,c
B14											
B15											
B16								no			
B17		yes	no		yes	yes	1, 2, 3				c
B18				RoadRater					yes	yes	
B19	A, D	yes	yes		yes	yes	1, 2, 3				a,b,c
B20	A	no	yes		yes	yes	1, 2, 3				
B21	A	yes	yes		yes	yes	1, 2, 3				
B22	A	no	yes	Dynaflect	no	yes	1				
B23			yes				3				a,b,c
B24											
B25	A	yes	yes	RSD, MDD	yes	yes	2, 3	no	no	no	a,b,c
B26		no	yes	RSD, MDD	yes	yes	1, 2	no	future	future	a,b,c
B27		no	yes		no	yes	1, 2	no			a,b,c
B28											
B29											
B30	C	no	no								
B31	B, E		yes	RDD, SSAW	yes	yes	1, 2, 3	yes	yes	yes	a, b, c
B32											
B33							2				
B34				LVDT					yes		a
B35											

A - on wheel transducers B - WIM BB - Benkelmann Beam FWD - Falling Weight Deflectometer 1 - Surface Profile 2 - Rut Depth 3 - Multidepth Rut
C - constant load suspension D - dead load SSAW - surface spectral analysis of waves RDD - Rolling Dynamic Deflectometer a - Air b - Surface c - Pavement

TABLE 9 APT FACILITIES: MATERIAL PARAMETERS

App. B	Modulus		Compressive Strength		Tensile Strength		Asphalt Stability	
	Construction	Post-Mortem	Construction	Post-Mortem	Construction	Post-Mortem	Construction	Post-Mortem
B1	yes	yes	yes	no	yes	no	yes	no
B2								
B3								
B4	no	no	no	no	no	no	no	no
B5								
B6								
B7	yes	yes	yes	yes	yes	yes	no	no
B8								
B9								
B10								
B11	yes	yes	yes	yes	yes	yes	yes	yes
B12								
B13	yes	no	yes	yes	yes	no	yes	no
B14								
B15								
B16								
B17	yes	yes	yes	yes	yes	yes	yes	yes
B18								
B19	yes	yes	yes	yes	no	no	no	no
B20	yes	yes	yes	no	no	yes	yes	yes
B21	yes	yes	yes	no	yes	no	no	no
B22	yes	yes	yes	yes	yes	yes	yes	yes
B23	yes	yes						
B24								
B25	yes	yes						
B26	yes	yes	no	no	yes	yes	yes	yes
B27	yes	yes	yes	yes	yes	yes	yes	yes
B28								
B29								
B30	no	yes	no	no	no	no	no	yes
B31	no	yes	no	yes	no	yes	no	yes
B32								
B33								
B34								
B35								

TABLE 10 CAPABILITIES AND LIMITATIONS OF FULL-SCALE ACCELERATED PAVEMENT TESTING FACILITIES

Capabilities	Limitations
Test Roads	
in-service traffic	limited scope for acceleration of loading
normal construction	no climate control
high credibility	limited control of traffic speed and loading
multiple sections tested	fixed location
Circular Tracks	
high-speed operation	shear forces at small radii
fully controlled loading	failure of one section affects others
high level of acceleration	pavement construction can be difficult
mechanically simple	fixed location
multiple sections tested	
partial environmental control	
Linear Tracks	
one or two-way loading, fully controlled	limited speed
transportable	mechanically less simple
can be used on in-service roads	
normal construction	
partial environmental control	
section failure does not affect others	
Free form tracks	
normal construction	moderate speed
partial environmental control	section failure may affect others
fully controlled loading	mechanically more complex
	fixed location
Other configurations	
mechanically simple system	limited simulation
can be climate controlled	pavement construction can be difficult
section failure does not affect others	fixed location
fully controlled loading	

time cannot be simulated. Traffic load can be more closely controlled, varied, and measured; again, the full spectrum of in-service load is not applied.

Test Roads provide very convincing evidence of pavement performance but lack environmental control and are expensive to operate if an appreciable acceleration of damage is to be attained through controlled loading. The use of thinner pavements to reduce structural capacity can assist but such sections are less representative of high-volume roads.

Circular Tracks have advantages in operating at high speed and can test several pavement sections at the same time. However, should one section fail, the performance of all other sections will be affected, and unless the track is of sufficient diameter, lateral shear forces (and consequent high tire wear) can be a problem. There may also be some difficulty in constructing the annular pavement with normal equipment and to normal standards.

Linear Track facilities have traffic speed limitations and, with few exceptions, use two-way loading that may affect pavement response and performance. Three of the existing facilities are readily transportable and can operate on in-service pavements. These versions also operate on test areas constructed without constraint on normal practice. Section failure does not influence the remaining tests.

The use of **pulse or static loading** is declining with the notable exception of the BASt facility. This type of facility has advantages of simplicity. However, the capability to observe and measure the effects of realistic loads at realistic speeds at a controlled, higher rate than is possible on in-service roads, provides sufficient benefit for some 35 organizations to pursue this approach to the development of new pavement technologies in 1995.

CHAPTER THREE

APPLICATION OF APT TO RESEARCH

This chapter briefly describes the application of APT to research, where there has been a direct use of APT results to improve and validate theoretical models and analyses, and where APT has been used to develop instrumentation and data acquisition technologies.

In many countries, mechanistic pavement design procedures are being developed and implemented but they still have not entirely replaced existing empirical or semi-empirical methods, or design "catalogues." The development and validation of the necessary response models and performance prediction procedures is thus an important feature of APT programs.

Various analysis techniques have been used for the interpretation of results from full-scale accelerated pavement testing. Response to the questionnaire circulated to all known facilities and the state transportation agencies of North America indicates the general approaches used (Table 11) but elicited little specific information. Less than half the facilities reported the application of results to developing rut depth predictions, to estimating material layer moduli, or for the validation of models of material behavior. Only nine facilities linked the experimental programs to long-term performance monitoring of the APT pavement sections.

Therefore, the discussion below is based primarily on an evaluation of published reports.

In all the programs reported, there was evident pressure to arrive at short-term, practical assessments of the behavior and performance of the tested pavements. The simplest and most effective have often been comparative evaluations of pavement or load configurations, with few or later attempts to model behavior, to analyze structural behavior, or to predict performance mathematically.

Much of the appeal of full-scale accelerated tests has been the visual observation of the test section pavements in comparison to other pavements and to in-service pavements under traffic loading.

The primary measures used in more formal pavement performance comparisons have been deformation—transverse (rut depth) and longitudinal (profile and roughness), deflection, surface cracking, and serviceability. These four parameters have been measured at most of the facilities with varying degrees of success. In addition, many facilities have measured strains and pressures generated in pavements under static and dynamic loading (Table 8).

All the analyses and evaluations are qualified by the differences from in-service pavements due to such factors as loading rate, frequency, and environmental changes. With respect to the latter, the focus primarily has been on controlled temperature testing (*95*). A procedure for evaluating the effect of aging was formulated by Hugo et al. (*29*) and has been incorporated into the TxMLS test plan. HVS testing with artificial aging has been reported (*96*).

The analyses conducted can be grouped into the framework below:

Pavement Performance	empirical comparison
	serviceability
Pavement Response	stress/strain modeling
	deflection modeling
	deformation modeling
	fatigue modeling
Material response	back calculation of modulus
Material and Layer equivalencies	
Load equivalencies	wheel and axle configurations

An example of each of the above is given based on the literature; more examples and detail may be found in the references quoted and in the bibliography (available on request from the consultant). The text concentrates attention on the application of APT to the various analyses in practice and research.

PAVEMENT PERFORMANCE

Empirical Comparison

All accelerated pavement tests provide an empirical comparison of the performance of the different pavement sections and load regimes tested. In circular tracks or test roads, this comparison of pavement sections is direct and immediate, as all the sections are tested at the same time and under the same load. Indeed, a disadvantage of this type of test is that the distress of any section can affect the loading on other sections and thus potentially distort the comparison. This difficulty does not arise with linear tracks, which are very infrequently segmented. However, in facilities without environmental control, there is some risk of change in environment during the course of an experiment if the test sections are tested in sequence, which may affect the results. The direct comparison of pavement condition, supported by measurement of rutting and cracking, is still an intuitively satisfying and powerful indicator of relative performance.

The comparisons are formalized by measurement of the extent and severity of rutting and cracking, and are frequently

TABLE 11 APT FACILITIES: APPLICATIONS TO ANALYSIS

Code	Rut Depth and Cracking	Moduli Calculation	Material Behavior	Laboratory Studies	Long-term Performance
B1	yes	yes	yes	yes	yes
B2	—	yes	yes	—	no
B3	yes	—	yes	—	yes
B4	yes	no	no	no	no
B5	new	new	new	new	new
B6	yes	yes	yes	—	—
B7	yes	yes	yes	yes	yes
B8	yes	yes	yes	—	yes
B9	yes	—	yes	—	—
B10	—	—	—	—	—
B11	yes	yes	yes	yes	yes
B12	yes	yes	yes		
B13	yes	yes	yes	yes	
B14	yes	yes	yes	yes	
B15	new	new	new	new	new
B16	—	—	—	—	—
B17	yes	yes	yes	yes	yes
B18	yes	—	yes	yes	
B19	yes	yes	yes	yes	yes
B20	yes	yes	yes	yes	no
B21	yes	yes	yes	yes	yes
B22	yes	yes	yes	yes	yes
B23	yes	yes	yes	yes	—
B24	yes	—	—	—	—
B25	yes	yes	yes	yes	yes
B26	yes	yes	yes	yes	yes
B27	yes	yes	yes	yes	yes
B28	new	new	new	new	new
B29	yes	yes	yes	—	—
B30	yes	yes	yes	no	yes
B31	yes	yes	yes	yes	yes
B32	new	new	new	new	new
B33	yes	yes	yes	—	—
B34	—	—	—	—	—
B35	yes	—	—	—	—

— not known

supported by measurement of deflection under the applied loads, or by a nondestructive testing procedure, such as the falling weight deflectometer (FWD) or Benkelman beam. The comparisons can thus be documented and quantified, and statistical techniques can be applied where appropriate.

An early example is the use of the Present Serviceability Index (PSI), calculated from the AASHO equations, to compare flexible and stabilized bases on the Illinois track (*18*). The change in slope and rut depth of the two pavement types was measured and used to calculate the number of load repetitions before the PSI dropped to nominal values (Table 12). More recently, the Texas Department of Transportation has reported measurement of stiffness changes with the progression of traffic loading (*97*).

A second example of the empirical approach is that used at the Swiss ISETH facility where Scazziga (*98*) reported a small loss of serviceability (PSI) in asphalt-surfaced cement-stabilized base pavements, and concluded that existing design procedures were conservative and that a 50 mm (2 in.) reduction in typical surfacing could be achieved.

Similar comparisons, based on one or more of the easily measured/observed parameters, have been used at many facilities and form the bases for the applications listed in chapter 4.

Serviceability

The only facilities at which serviceability has been estimated by observation or from profile measurements are the test roads, but some attempt has been made to use the PSI estimated from longitudinal profile data on test sections of linear and circular tracks. A problem is that contributions from profile wavelengths greater than the length of the test section cannot be evaluated.

PAVEMENT BEHAVIOR

Stress/strain modeling

Most experiments with the various APT facilities include studies of the stress/strain behavior of pavement layers. The measured strains were compared with estimated strains based on laboratory determinations of moduli and from back calculation of moduli from static or pulsed, field plate or tire load deflection bowls, or from the use of FWD and Benkelman deflection data.

It is common to find claims of reasonable agreement between theoretical and measured values, but usually after some adjustment of estimates for local conditions. The models used developed from two- and three-layer linear elastic models, assuming homogenous, isotropic, semi-infinite layers, to multi-layer linear and non-linear elastic models, to visco-elastic and to finite element models capable of calculating strains under non-linear, visco-elastic, anisotropic, finite, and inhomogeneous conditions.

Brown and Pappin (*63*) reported studies of stress/strain models using data from the Nottingham test track. They concluded that resilient strains could be adequately modeled but that stress estimates were less satisfactory. Permanent strain and deformations could be adequately modeled. Studies at the Shell facility (*57*) led to the BISAR and CHEVRON models.

Scazziga (*99*) applied APT to the evaluation of pavement stress/strain measurement technologies for bituminous pavements at the NARDO test road. This showed the strain measurements to be susceptible to large variations due to the inhomogeneity of the materials and layers, to temperature variations, and to the exact position of the loads imposed.

TABLE 12 LOAD REPETITIONS TO NOMINAL PSI VALUES (*12*)

Pavement	Base Thickness	Surface Thickness	Repetitions to PSI 4 To PSI 4.0	Repetitions to PSI 3 To PSI 3.0	Repetitions to PSI 2 To PSI 2.5
A1	200mm	Nominal	1 000	3 000	6 000
A2	150	Nominal	1 000	2 000	3 000
A4	200	Nominal	1 000	2 000	4 000
B3	135	Nominal	a	a	a
B4	147	Nominal	a	a	a
B6	135	Nominal	a	a	a
C1	150	Asphalt 25 mm	500	1 000	1 000
C5	150	Asphalt 75 mm	5 000	10 000	a
C6	150	Asphalt 50 mm	500	2 000	5 000
C1A	150	Asphalt 100 mm	1 000	3 000	23 000

Notes: A—crushed stone with slurry seal;
B—lime-fly ash stabilized gravel with mortar seal;
C—crushed stone with asphaltic concrete surface.
'a' means serviceability did not drop to this level.

Temperature had to be measured at the strain gauge position for adequate correction of strain estimates. The position of the load in relation to a gauge was also critical to the comparison of predicted and measured strains. In an evaluation of strain measurements conducted in 1991, it was reported that using both horizontal and vertical strains could produce moduli closer to back-calculated values and demonstrated that the effect of increased speed of loading, from 32 to 80 km/h (20-50 mph) was a 50 percent increase in the modulus of an asphalt layer (*100*).

The difficulties in correlating measured and predicted strains and deformations have been attributed in part to residual stresses from the construction process (*101*) and from the "plastic" behavior of the materials (*102*).

A typical model (*5*) for pavement life relating subgrade vertical strain to life is

$$N = (8511/e_{cv})^{7.14}$$

where N is the number of load repetitions and e_{cv} is the subgrade vertical compressive strain.

This relationship is derived from measurements of strain and pavement performance to a failure defined by a 25-mm (1-in.) rut. The strain is measured directly or estimated from the CIRCLY multi-layer analysis package using laboratory or field (FWD) derived moduli.

In 1994, results were reported from LINTRACK (*103,104*) indicating that with "virgin" asphalt, linear-elastic theory seemed adequate for the prediction of longitudinal and transverse strain, but after simulated traffic loading, non-linear effects were clearly observed. Under intensive traffic, a significant buildup of residual strains occurred. FWD testing after a sustained (continuous from Monday afternoon through Friday morning) loading sequence differed substantially from results after the 2-day rest. It was also reported that closely spaced FWD tests on trafficked and untrafficked sections could reveal the effects of loading.

Deflection Modeling

The modeling of deflection takes comparative evaluations a step further by including directly in the evaluation the effects of thickness, pavement material properties and load characteristics.

Deflection may be measured under rolling wheel loads by the Benkelman beam, at creep speed, or by "in-pavement" transducers at up to the operating speeds of the various facilities, or independently by the FWD or similar techniques. Deflection may also be measured by in-pavement transducers.

Deflections are speed dependent; for example, the deflection at 3 km/h (1.75 mph) is predicted to be significantly higher than at 16 km/h (10 mph), with less difference between 16 km/h (10 mph) and 48 km/h (30 mph). Similarly rut depth is expected to be speed dependent (*105*).

Experiments on the Washington State University track (*72*) used Benkelman beam and "in-pavement" LVDTs to measure deflections, and used the data to yield "equivalent" thicknesses of various bases in comparison to a typical untreated crushed stone base (Table 13). They noted the severe impact of spring thaw conditions and that the conclusions could only be applied to the conditions encountered in the experiment.

The Pennsylvania experiments were among the first to introduce the concept of the Surface Curvature Index (SCI) as an indicator of remaining life using test road data. The pavements were considered to have failed when cracking had reached the stage at which the PSI was about 2.0 (*106*).

TABLE 13 WASHINGTON MATERIAL EQUIVALENCIES (*72*)

Material	Equivalency Spring	Fall
untreated base	1.00	1.00
emulsion treated crushed stone	0.75	0.32
asphalt treated base	0.42	0.21
asphalt concrete base	0.42	0.21
sand asphalt base	0.67	0.21

Deflections measured by a "Road Rater" were related to SCI and loading of the test pavements to give a method for predicting remaining life, based on non-destructive testing.

A more detailed approach to deflection modeling requires either the use of a multi-layer stress/strain model, to estimate and sum vertical strains to a deflection, or deformation, or the direct application of deflection to establish the number of repetitions to some deflection failure criterion.

Deformation Modeling

The application of deformation modeling requires the estimation of material behavior to evaluate the permanent strain response under repeated loading. Studies at the Shell facility (*107,57*) led to the Shell design method for asphalt pavements. The evaluation of linear elastic theory showed that the models did not agree well with pavement response and the importance of temperature effects on asphalt pavements was demonstrated. Moving load effects are not accounted for by static load elastic-models (*105*).

Brown and Bell (*74*) used laboratory materials testing to estimate stress/permanent strain relationships to estimate permanent deformation for comparison with their test track data. They concluded that materials testing must be conducted at the appropriate stress levels, that "off-axis" strains were important and that non-linear stress-strain behavior was important at higher temperatures.

Eisenmann and Hilmer (*108*) showed the importance of wheel load, inflation pressure, contact pressures, and tire arrangement on rutting, where the deformation was confined to the asphalt layers and occurred at constant volume. Under these conditions, a good fit to elastic theory was claimed.

Deformation results obtained under the repeated plate loading facility at BASt were used to derive an empirical relation (*109*) between loading and rut depth of the form:

$$\text{rut depth} = \text{constant} \times (\text{No. of passes})^{0.5}$$

This relation applies to thick asphalt pavements where the major part of the deformation is confined to the asphalt layers, which is often the case for dynamic loading.

Mexico (*60*) reported a pavement life model of the form:

$$\log \text{ESALs} = A \log \text{CBR (California Bearing Ratio)}$$

for failure at a rut depth of 25 mm (1 in.). In this case, the rutting was mainly attributed to the subgrade.

Fatigue Modeling

Many attempts have been made to develop robust fatigue models and several are now coming into use. In early studies (*110*), attempts to predict fatigue behavior from horizontal tensile strain were unable to produce satisfactory results. Hofstra and Valkering (*107*) foresaw the need for a non-linear elastic or visco-elastic model to adequately predict strains.

Studies of fatigue life for full-depth asphalt pavements (Ullidtz (*111*) at the Danish facility), concluded that with respect to cracking, there was "a considerable difference between the predicted and the observed number of loads. . . (at failure)," indicating difficulty in comparing asphalt fatigue behavior in the laboratory and under accelerated full-scale loading. The FWD tests gave better moduli values than those estimated from measured strains.

A study of fatigue under accelerated loading (*112*) used data from 14 experiments on three cement treated crushed rock (CTCR) bases under more than 2 million ESALs. The pavement configurations were

- 140 mm (5.5 in.) CTCR, 30 mm (1.2 in.) asphalt wearing course,
- 180 mm (7 in.) CTCR (placed in two layers bonded by a cement slurry with a retarder in the bottom layer), 30 mm asphalt (1.2 in.) and,
- 180 mm (7 in.) CTCR (no bonding), 30 mm (1.2 in.) asphalt.

No conclusion was reported on the bonding but in earlier trials there had been a failure mechanism in which debonding of the cemented layers allowed water ingress, followed by erosion of the bottom of the upper layer, and eventual breakup of the top layer (Figure 19). This failure mode also occurred on the nearby in-service highway of the same construction (*113*). The moduli were determined by back calcu-

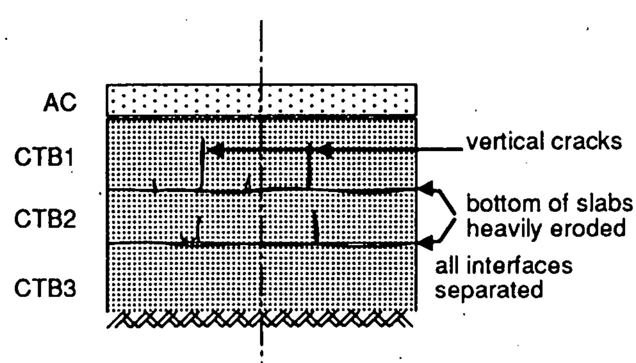


FIGURE 19 Typical failure mode of CTB pavement at Beerburrum, Australia (*103*).

lation from FWD measurements and the fatigue life was estimated from the severity of cracking with the length of cracks used as the failure criterion. Fatigue relationships were developed for two definitions of pavement life: for pavements with less than 100 mm cover over the CTCR, life was defined in terms of the extent and severity of cracking; for more than 100 mm cover, life was the number of repetitions to the stage at which the CTCR modulus had dropped to half the initial value.

The relationships were

$$N = (28400/e_t M_r^{0.41})^{7.1}$$

where N is the number of load repetitions, e_t the tensile strain, and M_r the resilient modulus, for less than 100 mm (4 in.) cover and 10 per cent cracked area,

$$N = (35000/e_t M_r^{0.45})^{8}$$

for more than 100 mm (4 in.) cover and half initial modulus.

These results differ considerably from the existing Australian pavement design guide equation for cement treated base,

$$N = (280/e_t)^{18}$$

The results indicate that Australian design practice is conservative. Revisions to the national design manual were recommended. There is some doubt about the dependence of fatigue life on modulus and laboratory studies of the fatigue life of cemented materials are needed.

At a pilot experiment with the HVS conducted for Caltrans, it was reported that predictions of fatigue life, for dense-graded and rubber-asphalt mixes, developed from fatigue life-strain relationships and maximum tensile strain, calculated from elastic layer theory, correlated strongly with the measured performance and validated the Caltrans overlay design procedure (*69*).

MATERIAL RESPONSE

Back Calculation of Modulus

Several software packages have been developed for the back calculation of layer moduli from surface and layer deflection data. The availability of APT results has assisted in the refinement of such packages. For example, an analysis of a granular pavement (*114,115*) used the EFROMD2 back-calculation model to estimate moduli from FWD and Benkelman beam deflection data. The subgrade modulus from Benkelman results was unrealistic but FWD data used in the Australian rut depth model gave satisfactory predictions.

The back-calculated modulus of cement treated crushed rock (CTCR) was shown to decrease with loading cycles, before surface cracking was detected. The moduli decreased by half at one-tenth the load repetitions to the first hairline cracks. CTCR fatigue relationships predicted lower lives than the current procedures (*102*). This is similar to the measured loss in stiffness of asphalt reported by TxDOT (*97*).

MATERIAL AND LAYER EQUIVALENCIES

Many of the early experiments empirically compared materials and pavement layers to assist in local assessments of innovative pavement configurations. The first ALF trial, for example, concluded that the large stone bitumen macadam base adopted for a freeway pavement would be more than adequate for the design life adopted. A later trial (*116*) examined the comparative performance of several bitumen modifiers in pavement overlays (Figure 20) at Callington, South Australia, concluding that such modified binders displayed significant advantages over conventional bitumen binders of different viscosity grades, and clearly demonstrated extended pavement life in terms of both rut depth and extent of cracking (Figure 21).

Studies of the relative ranking of mixes of the same grading and composition showed that the minimum creep slope, as determined from the laboratory creep test, correctly predicted to variations due to binder type, but there were doubts about its ability to correctly predict the relative performance of mixes with different grading. The creep slope was highly dependent on the air voids content, especially for the mixes having conventional binders (*117*).

The Washington State University facility also focused attention on the relative performance of various base materials, particularly the potential for using treated bases of "inferior" materials, and of sulfur extended asphalt. The "equiva-

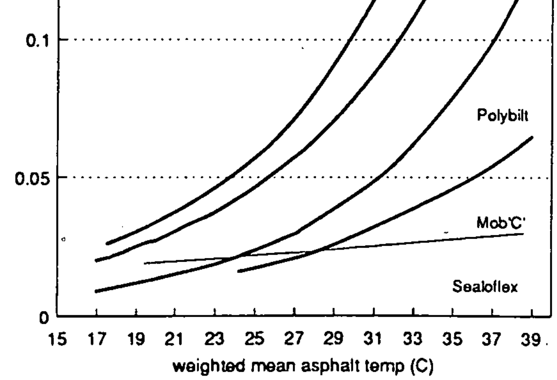


FIGURE 20 Deformation of modified binder pavements (*106*).

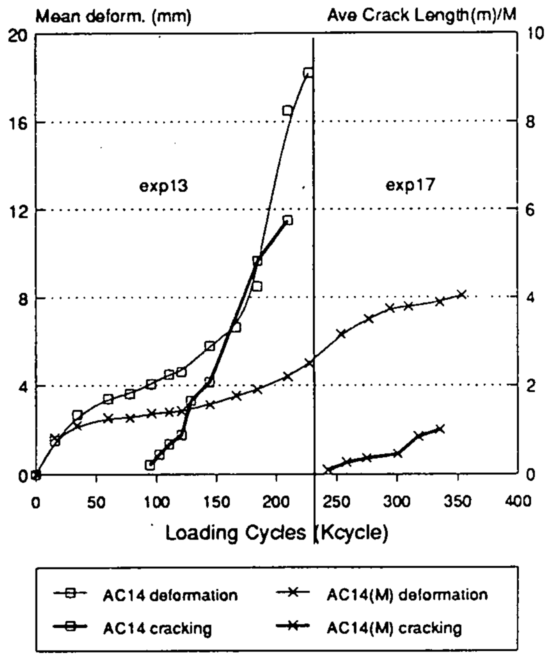


FIGURE 21 Cracks and deformation in modified binder pavement overlays (*106*).

lencies,'' which relate the ''equivalent'' thickness of various base courses to a unit thickness of untreated base under spring climate conditions were adopted (Table 13) (*72*). At the same time, the results clearly demonstrated the effects of spring thaw conditions and the need for a well-drained subgrade. A study of sulfur extended asphalt showed little difference in fatigue behavior compared to a conventional mix (*27*).

Current studies of the rut resistance of asphalt mixes have shown that although laboratory determination of the creep slope will rank asphalt mixes of the same gradation in terms of binder type, it is not evident that this relative ranking will extend to performance measured under accelerated loading in the field where different gradations are used (*118*).

LOAD EQUIVALENCIES

Equivalency of wheel loads and axle groups has been a concern since the WASHO test showed tandem axles could carry greater loads than single axles for the same distress (*119*). A study at the Pennsylvania test road looked at the equivalency of tri-axles (*120*), and early results from the first Australian ALF experiment (*121*) showed that the number of repetitions to reach a 4-mm (0.16-in.) rut depth with an 80-kN (17,600-lb) wheel load was related to the repetitions required of a 120-kN (26,400 lb) load approximately by the ''4th power law.''

A typical example of the use of rut depth as a damage criterion can be seen from the CAPTIF study of the relative damaging effect of super-single and dual tires (*51*). The vertical permanent deformations (ruts) caused by a single low-profile radial tire (14.00/80 R 20) and dual standard tires (10.00 R 20), both with a 40-kN (8,800-lb) load were compared (Figure 22). The pavement was 40 mm (1.5 in.) open-graded asphalt over a 150-mm (6-in.) high-quality crushed aggregate base and a 150-mm (6-in.) coarse aggregate subbase (max. particle size 65 mm −2.5 in.) on a clayey loess subgrade with an average CBR of 30. After 16,000 loading cycles, the average rut depth under the single tire was 92 percent greater than that under the dual tires. Other studies on the facility had typically shown rut depths increasing rapidly at first and only very slowly thereafter, as has also been shown in ALF studies and, most recently, at the TxMLS (*97*).

The FORCE experiments compared 10-t axle loads with the proposed European 11.5-t (25,300-lb) standard axle. It was found that the ''powers'' varied from 2 to 9 for the flexible pavements (Figure 23) (*47,48*). A crack ''pattern'' criterion was adopted, which differed from the cracked area approach used at the ASSHO test, but showed a clear log-linear relationship between cracking and number of load repetitions; the values of the ''power'' increased linearly with both the degree of cracking and the length of crack.

South African studies (*52*) developed a load equivalency of 3.8-4.5, based on terminal serviceability, whereas rut depth data suggested power ratios of 6.0-8.7 and crack initia-

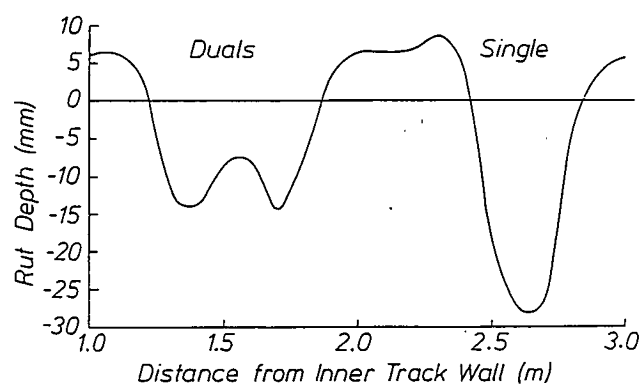


FIGURE 22 Dual vs single tire average rut depth (*129*).

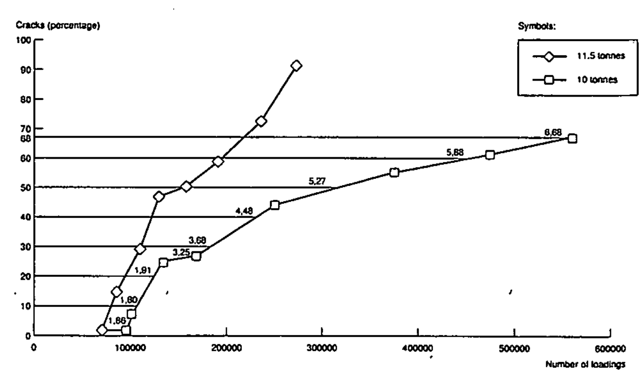


FIGURE 23 The ''power'' based on cracking percentage (*41*).

tion criteria for cement treated bases gave 3-12. These studies were consolidated (*67*) into the range shown in Table 14, and it was proposed that the usual equation,

$$F = (w_1/w_{80})^n$$

be replaced by a function

$$F = f(\text{load, moisture, temperature, structure, materials}).$$

An average value of $n = 4$ is still generally used.

Results of a similar nature were obtained from many other programs, typically a wheel/axle-load configuration equivalency was established for the particular pavement configuration and failure mode. The ubiquity of the "fourth power law" often has been called into question, "powers" from 2 to 10 are commonly quoted depending on the failure mode selected and the pavement configuration (*93,122,123*). While the concept of a load equivalency is attractive, it is far from simple in practice when the many factors relating pavement damage to wheel load and vehicle configuration are taken into account. Theoretical estimates of damage are possible (*105*) but the use of APT is still relevant to support the theory with experimental data.

TABLE 14 LOAD EQUIVALENCY EXPONENTS—SOUTH AFRICA (*67*)

Pavement Base	Exponent
Natural Gravel	2–3
Crushed stone	3–4
Asphalt	4
Cement treated	6

SUMMARY

There have been a great many attempts to define pavement behavior and performance using theoretical models of material stress/strain response, with varying degrees of success. All the models, however, rely on many simplifying assumptions, and are applicable only in constrained situations. The effects of dynamic loading, of the load distributions of in service traffic, of the environment, of the variability of pavement layers thickness, material properties, and subgrade support may now be analyzed in terms of pavement and material response but are not yet readily applied in routine practice. There is some application of APT to improving mechanistic pavement design, but such design procedures are used principally for highly specialized situations where the cost of the establishment of appropriate materials parameters can be justified by the importance of the pavement structure, for example, where very high truck traffic volumes or extreme wheel load conditions are encountered. Laboratory characterization of materials is still the subject of much research.

The personal computer makes calculation of static load, linear elastic pavement responses quick and easy. However, the many assumptions associated with these models limit the validity of the results. The more advanced three- dimensional, dynamic finite element models still require workstation grade computers.

A load or material equivalency is simple in concept but complex in application. The equivalency is dependent on the load level and speed, on the material type, and on the criteria by which the equivalency is established. Thus the failure mode, rutting, cracking, serviceability, or stress/strain level must be defined and the application of an equivalency constrained to that specific context.

CHAPTER FOUR

APPLICATION OF APT TO PRACTICE

This chapter describes the purposes for which the various facilities were built, and summarizes the experiments conducted at those facilities. Only rarely were trials focused on a single objective and application. Table 15 gives a summary of the types of applications at various facilities and the scope of studies conducted since 1962. Results have been applied in

- modification of design procedures
  - —measurement of pavement response and performance
  - —prediction of pavement performance and failure mechanism
  - —estimation of pavement life
- pavement configuration comparisons
- improvement of construction practice
- evaluation of maintenance and rehabilitation practices.

The objectives of the various trials and their applications, taken from the survey responses and the literature, are assembled below, grouped by country. Limited space and the availability of information dictate that the report be selective rather than comprehensive. It is intended to convey an overview assessment of the various programs, not to list in detail the entire sequence of experiments. Every effort has been made to present a balanced view, but given the time frame from the 1960s to 1996, the major programs in South Africa and Australia are predominant. A bibliography, available on request, provides material for further investigation.

AUSTRALIA

The Australian ALF program, which started in 1984, is summarized in Table 14. The first trial (Somersby, New South Wales) on an "in-service" freeway proved the mechanical reliability of the machine and confirmed that the large stone macadam base pavement could carry the design traffic (*124*). It showed clearly that ALF could function on a highway carrying traffic, provided adequate provision was made to maintain traffic flow. Australian states have modified design procedures and worked toward adopting new specifications incorporating the higher compaction levels shown to be needed for unbound bases for heavy-duty pavements (*125,126*). Trials conducted on specially constructed test facilities (Beerburrum, Queensland) and one in an area set aside for the program (Prospect, New South Wales) resulted in major changes to construction practice where multi-layer cement stabilized bases are constructed (*127,128*).

Prospect (*129*) pavement failures were traced to local conditions not related to performance of the base layers and the adequacy of an industrial by-product, blast furnace slag, was demonstrated. The introduction of polymer-modified binders in asphalt was supported by rut depth and cracking observations (Figures 20 and 21) at Callington, South Australia (*116,130*). A trial of cement-treated crushed rock in Mulgrave, Victoria, showed that back-calculated moduli decreased with loading cycles before cracking was detected. The moduli decreased by one-half at one-tenth the load repetitions to the first hairline cracks. CTCR fatigue relationships predicted lower lives than the current procedure (*131*).

A low-traffic rural road at a remote location (Brewarrina, New South Wales) was tested where a special concern was the maintenance of trafficability after a "wet" season with intermittent inundation of long lengths of pavement (*65*). This was the first trial in a remote area and was notable for significant input from local government authorities.

The eleventh trial (*132*) was at a site (Cooma, New South Wales) where freezing temperatures are encountered. Deep lift stabilization was studied for which pavements were constructed in single lifts to depths greater than 300 mm (12 in.). Conservative design is justified in view of the variability of existing materials, thickness, binder quality, compaction, and curing, to reduce the risk of premature failure and enable cost savings from deep-lift recycling. Narrow shrinkage cracks, at greater than 2.5 m (8.1 ft) spacing, where the surface seal remained intact, did not appear to affect performance.

A feature of the program is the retention of all the "in-service" sites as part of the Australian LTPP project.

CANADA

C-TIC has conducted 10 major experiments from 1977 to 1995. The first evaluated the effects of subgrade compaction on a pavement with a 20-mm (0.75-in.) cold-mix asphalt surfacing. The second compared full-depth asphalt with a crushed stone base and the third looked at a newly developed 600-mm (24-in.) polythene culvert. The next three experiments evaluated lime modification of clay, geotextile reinforcement of a base course and a select sand base over glacial till. The seventh experiment compared surface deflection measurements by Benkelman beam and inductive coupling

TABLE 15 APT FACILITIES: OVERVIEW OF APPLICATIONS

Objective	Layer Equivalencies	Material Equivalencies	Innovative Materials	Load Equivalencies	Pavement/Overlay Design
Application CODE	Pavement design catalogues	Material specification and utilization	Waste, by-product and non-natural materials, freeze-thaw insulation and free-draining layers	Equivalencies for load regulation and pavement design, effects of tire, wheel and axle configuration	Validated and modified design procedures, developed special procedures
B1		yes	yes	yes	yes
B2					yes
B4	yes	yes	yes	yes	yes
B3		yes	yes		
B5		yes	yes		
B6			yes		
B7	yes	yes		yes	yes
B8	yes			yes	yes
B9	yes	yes			
B10					
B11	yes	yes	yes	yes	yes
B12	yes	yes			yes
B13		yes	yes		
B14	yes	yes			yes
B15					
B16					
B17				yes	yes
B18		yes	yes		
B19	yes	yes	yes	yes	yes
B20		yes		yes	yes
B21	yes	yes		yes	
B22		yes	yes		
B23			yes		yes
B24			yes		
B25	yes	yes	yes	yes	yes
B26		yes			
B27					yes
B28					
B29	yes	yes	yes	yes	yes
B30		yes		yes	yes
B31	yes	yes		yes	yes
B32					
B33	yes	yes	yes		yes
B34					
B35					

strain gauges. A C-SHRP trial and an assessment of an asphalt paving "imprinting" process were conducted and in 1995, an experiment to investigate the impact of varying tire pressures on the performance of low-volume, thin membrane surface roads was in progress.

CHINA

China has in use an outdoor linear Australian ALF at RIOH-B in Beijing. A circular indoor track at the Research Institute of Highways, Chongqing (RIOH-C) was used from 1985 to 1990. (See Table 17.)

The Chongqing track was first used to study the fatigue characteristics of full-depth asphalt and lime stabilized crushed rock pavements. The field data were analyzed together with laboratory repeated loading test data to establish fatigue relationships. The equations were based on initial values of tensile stress, deflection, or curvature and the results were used to modify the national pavement design procedure and to evaluate in-service pavements (Li Yongqi, personal communication 1995). No English-language publications have been located.

Sixteen sections have been tested by the RIOH-ALF at three different locations. The sections included flexible, asphalt pavements, bases of cement treated crushed rock, soil-cement, lime-fly ash stabilized soils and aggregate. The first trial also incorporated rubber/polymer-modified asphalt layers and an existing stabilized base pavement that had carried traffic for 5 years. A later trial was conducted at a specially constructed site with 10 different asphalt surfacings on semi-rigid bases and, for desert areas, three specialized pavements with geotextiles.

DENMARK

Three series of tests had been conducted by 1982, in each of which stress and strain instrumentation was installed. A substantial effort was expended on modeling studies to extrapolate test track results to in situ traffic conditions. The first series showed response of the asphalt pavement was reasonably well predicted when the silty sand subgrade was assumed to be homogenous, isotropic, and linear elastic. This did not hold true for the second series where a clay subgrade was used. The stresses and strains were in poorest agreement for the particulate base course materials. The effect of freeze-thaw cycles on moduli was pronounced, with a large reduction on the first cycle that was not repeated for the second. The stabilized layer cracked at the first freeze-thaw cycle and there was a large variation in moduli along the test length. Some difficulty in constructing the short test section may be responsible, it was difficult to achieve an "as constructed" PSI greater than 2.0 (*111*).

FRANCE

The program of the Manège de Fatigue is summarized in Table 16. In some 22 experiments, more than 50 million truck loadings have been simulated on a range of pavement types, with load configurations including single and dual tires on single and tandem axles. The facility was also improved and a third test ring with the capability of controlling the water table was constructed. The various experiments have been applied to

- calibrating and validating theoretical models
- refinement of the catalogue of pavement designs
- revising the classification of granular materials
- establishing models for prediction of pavement damage
- demonstrating differing load equivalencies to cracking and rutting criteria
- showing that the timing of rehabilitation has less effect on final performance than anticipated, the primary factors influencing performance being the condition of the original pavement at the time of rehabilitation
- showing that because of the above, the use of a single 80-mm (3.2-in.) overlay was equally effective as two 40-mm (1.5-in.) layers
- showing that "upside down" pavements with a 120-mm (4.8-in.) layer of water bound macadam did not suffer reflective cracking
- evaluating several proprietary surfacing types
- demonstrating satisfactory performance of thin rolled asphalt overlays
- evaluating the performance of concrete slabs with and without dowels
- assessing the benefits of modified binders in reducing rutting
- evaluating thermal and kinetic effects on asphalt pavement fatigue
- comparing hot and cold asphalt mixes
- studying new materials, and
- comparing the effects of different load configurations.

GERMANY

The BASt Pulse Loading Facility has conducted some 15 experiments over 20 years. After the early projects, to prove the equipment, a major series of experiments on deformation of thick asphalt pavements gave a new model for rutting (*109*). No field experiments to validate findings have been possible because of very heavy traffic and a concern with the effects of the uncontrolled environment. However, when load equivalencies are taken into account, correlation has been reached with data from in-service pavement deformations. Results are sent to the German Federal Ministry of Transport, which persuades the states to apply them.

TABLE 16 APPLICATIONS OF ALF, AUSTRALIA

Objectives	Applications
Proof trial ALF. Evaluate macadam base	Structural adequacy of Somersby pavement confirmed. ALF confirmed as reliable and effective.
Evaluate high quality dense crushed rock base pavement for heavy traffic Compare performance of this pavement (double chip seal surface) with similar pavement tested at Somersby (asphaltic concrete surface).	Structural adequacy of Benalla pavement confirmed. Heavy compaction and prompt seal maintenance shown to be essential
Compare "thin" (200 mm) and "standard" (300 mm) cement-treated base (CTB). Compare pavements with and without a bitumen heavy cure coat interlayer and constructed in one lift instead of two or three lifts.	Failure mode was debonding of CTB layers, ingress of water at interfaces and subsequent erosion of bottom of upper layer, leading to break-up of top CTB layer. Failure mechanism of adjacent National highway found to be the same. Major changes to construction practice implemented.
Assess the use of unbound and stabilized slag as base materials.	Specification for road base materials adjusted to permit wider use of slag materials.
Determine the relative fatigue characteristics of various types of asphalt rehabilitations including geotextiles, modified asphalt and high asphalt content mixes in the 'tensile' zone applied to a distressed pavement.	Overlay trials demonstrated improved performance, for a modified binder compared to conventional binder; a significant impact on treatment for urban rehabilitation. SAMI successfully delayed crack propagation.
Establish relationships between back-calculated asphalt stiffness and CTCR modulus, determined from FWD deflection bowl data, pavement temperature and the severity and extent of surface cracking.	Asphalt fatigue relationships derived. Potential benefits much higher as use of heavy duty asphalt pavements in urban applications increases.
Compare the performance of two thicknesses of gravel pavements and the geotextile reinforced seal pavements.	Guidelines for the design, construction, maintenance and management of geotextile reinforced seal pavements prepared. Major long-term benefit is more effective use of local materials and scant resources in a location where it is imperative to maintain road links during the "wet" season.
Compare performance of different thicknesses of two qualities of recycled marginal unbound bases.	When subgrade in existing pavement is adequate for the design traffic, existing sandstone base can be reconstructed to support the seal and provide additional load capacity. Reconstructed sandstone base thicker than 125 mm (5 in.) may not enhance pavement performance, particularly for traffic with low axle loads (<40 kN -8,800 lb). Recycling existing sandstone bases by stabilizing with 2 percent bitumen and 2 percent cement could improve performance and resistance to water penetration.
Determine the effects of bitumen and bitumen/cement stabilization on the performance of a reconstructed high-quality crushed rock pavement	Recycling existing crushed rock bases by stabilizing with 2 percent bitumen and 2 percent cement could improve performance and resistance to water penetration. Performance was very sensitive to additive content and compaction level.
To determine the axle load equivalency for a typical crushed rock pavement, 300 mm (12 in.) thick, subject to accelerated loading under ALF single-axle dual-wheel loads of 40, 60 and 80 kN (8,800; 13,200; 17,600 lb)	Load equivalency factors of 10 and 8 respectively were estimated for a maximum surface deformation of 10 mm. (0.4 inch).
Compare the performance of crushed rock pavements, constructed at different moisture/compaction conditions at sealing and after drying-back and wetting-up after sealing.	At Beerburrum the low-plasticity, highly permeable crushed rock bases, when placed on a CTSB having a 3 percent cross fall, quickly dried back in the dry environment operating at that time.
Validate USAE-WES tentative classification for lateritic gravel for road and airfield pavements.	Performance of both materials constructed to both compaction standards was excellent when tested soon after construction. When the pavements were re-tested after a "wet season," the performance of the "good" material was still satisfactory but the "poor" material failed very quickly under traffic.
Quantify relative rut-resistance, of new and conventional mixes	The performance of the "AUSTROADS" mix was contrary to expectations because laboratory creep testing had indicated that this mix was more rut-resistant than the "control" mix.
Establish the performance of deep-lift recycled pavements using a slag/lime binder over subgrades of relatively low and relatively high strengths.	At Cooma, deep lift recycled pavements tested on a low-strength subgrade (CBR = 4) had fatigue lives at least twice that estimated for the adjacent National highway. The findings suggest that this type of pavement recycling is suitable for moderate rural arterial traffic.
To quantify rut-resistance of experimental mixes developed by industry compared with a conventional mix of known performance, both in the field and under accelerated loading.	The results associated with the "control" mix are yet to be analyzed.

In 1995 a pavement heating system, based on plans and advice provided by the US FHWA, was successfully commissioned with variations in pavement temperature, with depth, longitudinal, and transverse location, only about ±2°C for a nominal pavement temperature of 50°C (122°F).

TABLE 17 APPLICATIONS OF ALF, CHINA

Objective	Applications
Reduce pavement costs by using stabilized bases and thin asphalt surfacing	A 90-150 mm (3.5-6 in.) asphalt layer over a stabilized base was equivalent to 200 mm (8 in.) full depth asphalt
Reduce reflective and thermal cracking of asphalt pavements by using a rubber asphalt interlayer	Life to the onset of cracking was much improved
Investigate the performance of low cost heavy duty pavements with lime stabilized soil bases	Asphalt surfaced lime stabilized soil base pavement had a life in excess of 6 million ESALs
Determine the failure mechanism of axle load equivalencies for this type of pavement	Surface seal maintenance was important to prevent water entering cracks and precipitating failure
Determine the relative damaging effects of different axle loads in terms of structural failure and surface rutting	The current equivalent 'exponent' was increased
Compare the performance of 10 different asphalt pavement configurations	New asphalt pavement structures were recommended for the national specifications
Determine the fatigue performance of stabilized base materials using tensile strains	pavement life models using laboratory tensile (beam) tests did not correlate closely to behavior under ALF
Compare field measurements of stresses and strains and evaluate the theoretical model	A theoretical linear elastic model and back analysis procedure were amended to allow for conditions from full to no layer bonding
Evaluate the performance of the prototype desert pavements	A design for a desert highway was recommended and has been used

In 1995, bases of various recycled pavement or building materials are being tested (H. Werner, personal communication 1995). A current experiment is examining the potential of expanded polystyrene as a subbase/frost protection layer under a concrete pavement and flexible pavements with cement treated and fine crushed rock bases; the latter deformed severely. Empirical layer equivalencies have been proposed.

ITALY

The purpose of the Nardo experiment, conducted by OECD Scientific Expert Group I2 (*46*), was to measure and compare the strains in a bituminous pavement measured by a variety of methods under the same conditions. The pavement selected had a 130-mm (5-in.) bituminous layer over a 170-mm (6.7-in.) crushed rock base; traffic load was applied by three 2-axle vehicles with the same tires and axle loads traveling at 30 km/h (18.6mph). Layer moduli were estimated from FWD data and the BASt heavy vibrator test in the field, and from laboratory tests conducted by several of the participant laboratories.

The results showed that

- The pavement parameters, thickness, material quality, deflections, and temperatures were more variable than had been anticipated.
- The transverse distribution of load paths in relation to gauge position was critical in comparing strain results.
- Strain measurements in the bituminous layer showed good agreement with theory when the above factors were taken into account and the FWD derived moduli were used.

It was concluded that, because of the variabilities encountered, no direct application of the results to flexible pavement design was possible. Tests on rigid pavements (180 mm (7 in.) and 240 mm (9.5 in.) slabs, 4 m (13 ft) and 5 m (16.5 ft) over a 150-mm (6-in.) cement treated gravel base) showed that doweled joints gave 4.5 times the life of plain joints. A minimum thickness of 250 mm (10 in.) was recommended where heavy (50 percent) overloads can be anticipated (*133*).

JAPAN

Several facilities have been in use since 1969 to test road and airfield pavements (*55*).

The objective of the testing tank at the PHRI facility was to test pavements for large aircraft. Pavement structures for aircraft weighing up to 5000 kN (1,100 kips) and layer equivalencies for airport pavements in asphalt, continuously reinforced and prestressed concrete were developed. Joint performance was also studied under loads up to 100 t (220,000 lb) and speeds up to 48km/h (30 mph).

The ALES circular track at the Japan Highway Public Corporation is being used for research related to expressways

TABLE 18 APPLICATIONS OF THE MANÈGE DE FATIGUE—FRANCE

Objective	Application
Trafficking of three thick (up to 200 mm) structures of bitumen-treated materials	adjustment of the circular test track
Evaluation of four structures: CTM/CTM, CTM/CTM, BTM/CTM, CTM/UTM	Heavily traveled pavements with road bases treated with hydraulic binders
Comparison of the effects of 13 t and 10 t axles and of an 80 mm against two successive 40 mm overlays	to design of WRM and CTM road bases and overlay practice
Comparison of bitumen-treated materials on WRM and cement-treated sand subbases	Demonstration of separating layer of WRM to reduce reflective cracking
Tests of four free draining coated materials	ranking of performance in relation to rutting, cracking, drainage and frictional characteristics.
Two very thin rolled asphalt overlays assessed.	for maintenance motor way pavements
to compare: design methods and performance models; tandem axles versus standardized European axle	Working group 14 of the OECD tested 2 flexible and 1 semi-rigid pavement
evaluation of four structures of untreated materials having very different characteristics	funded by aggregate producers.
Evaluation of special materials	to acceptance of commercial mixes
Performance of doweled concrete pavements and different cements	revision of design procedure
study of high performance mixes and fatigue behavior	comparison with normal mixes and laboratory tests
observation of rutting behavior of bituminous concrete	evaluation of high performance mixes, influence of speed-temperature and wheel load effects
comparison of hot and cold bituminous mixes	development of maintenance techniques
comparison of very high modulus bituminous and cement treated materials	rehabilitation techniques
CTM: cement-treated (granular) materials. UTM: untreated materials	BTM: bitumen-treated materials. WRM: wet reconstituted materials.

such as developing more durable mixes against rutting, abrasion, and cracking.

However, perhaps the most innovative facility is the Public Works Research Institute (PWRI) Pavement Test Field. Pavements tested between 1973 and 1995 have included comparisons of base stabilization methods, the durability and performance of free draining asphalt pavements, and the durability of roller compacted concrete.

Benkelman beam deflections greater than 2-3 mm were found to indicate a pavement unsatisfactory for 100, 000 × 30 kN (6,600 lb) wheel loads. Overlays of asphalt, cut back or emulsion-stabilized materials, cement-stabilized materials, and granular pavement were evaluated for a maintenance manual (Table 19). The research program will continue with tests on surfacing for steel bridge decks, stabilized base course, improved pavement design procedures, and investigation of new materials.

TABLE 19 APPLICATIONS OF THE PAVEMENT TEST FIELD, PUBLIC WORKS RESEARCH INSTITUTE, JAPAN

Objective	Application
to compare low-volume road base courses	Base course materials were ranked in order of performance; a manual for low volume roads was prepared
to rank the durability of overlay treatments	findings were used in a maintenance manual

MEXICO

The facility at UNMA, still active, began testing in 1970. The primary objective was to develop a structural design procedure for flexible pavements. In 1974, from a series of 18 pavement sections, a relation between subgrade strength (log CBR)and Traffic (ESALs) was developed, using a tolerable deformation criterion of 20 percent of the pavement rutted to a depth of 25 mm (1 in.) (*134*). Other studies were directed at the fundamental properties of pavement materials, mathematical models for performance prediction, and the comparison of specific pavement configurations. Presently, an interactive computer design method for high standard routes has been developed to incorporate rutting and fatigue cracking (S. Corro, personal communication 1995).

NETHERLANDS

The LINTRACK facility was commissioned in 1991. The first experiment (*103*) measured longitudinal and transverse strains at the bottom of the asphalt layer and temperatures at the bottom, mid, and top layers in a full-depth asphalt pavement under super single and dual-wheel loading. FWD results for the pavements tested were found to correlate well with laboratory parameters measured at temperatures and loading frequencies corresponding to the field conditions. Laboratory values were determined by a cyclic 4-point bending test. The earlier studies, with a plate loading facility, were considered adequate for response studies but not for performance.

An earlier test track, at Shell Laboratories in Amsterdam, supported a number of studies of the behavior of asphalt mixes that had a major input to the development of structural models and an understanding of the characteristics of mixes. This track is still in use for research on improved rut resistance of new asphalt mixes.

NEW ZEALAND

CAPTIF projects, Table 20, have included tire and suspension load studies on base and surface course materials and configurations. (B. Pidwerbesky, personal communication 1995).

Studies of the fundamental behavior of unbound granular pavements (*135,136*) have shown that the Shell and New Zealand subgrade vertical compressive strain (e_{cv}) criterion,

$$e_{cv} = 0.028\ N^{-0.25},$$

for limiting rutting is very conservative, and the NZ highway authority has adopted the Australian subgrade strain criteria. This provides a better prediction of pavement life based on the measured subgrade strains and pavement performance. The facility is now (1996) engaged in testing pavement response to different suspension types for the DIVINE project (*137,138,139*).

ROMANIA

The two circular tracks at Iassy have been used for more than 70 experiments between 1957 and 1995. Both rigid and flexible pavements have been evaluated with various stabilized base course materials. Bitumen-cement, fly ash, pozzolanic rock, and raw and treated phospho-gypsum mixes were evaluated. The use of local materials and unconventional aggregates was investigated and the resistance to freezing assessed.

SLOVAKIA

The track at VUIS-Cesty, Bratislava, has been used for studies of wearing course mixes and more recently, for an evaluation of the impact of the European standard 11.5-t (25,000-lb) axle (J. Litzka, personal communication 1995).

SOUTH AFRICA

Many of the applications of the HVS technology stem directly from the capability to test in-service pavements in the highway network. A wide range of structures, comprising over 500 test sections, (Table 21,22) have been tested on most of the heavily trafficked routes in South Africa, and as a result, some pavement configurations are no longer used. Brief details of the extensive program are given in Table 21 (*67,68,140,141,142*).

The HVS has been a major focus and catalyst for developing and enhancing pavement technology with specific impact in

- Improved material design; the design manuals for asphalt mix design and for materials selection were modified; large stone mixes, the use of modified binders, and cement, lime and bituminous treated bases were studied.
- Innovative materials examined include roller compacted concrete, block pavements coarse ash, slag, rubberized bitumens, recycled materials, and treated natural aggregates.
- Structural design issues addressed include revision of the design catalogue and rehabilitation design, inverted pavements mechanistic design procedures incorporating rutting and fatigue prediction, and load equivalency studies.
- Environmental effects such as aging, temperature, and moisture effects have been simulated. Materials test methods have been developed for erosion of cemented

TABLE 20 APPLICATION OF CAPTIF, NEW ZEALAND

Objectives	Applications
Inaugural: 4 thicknesses unbound granular pavements under chip seals	Proving trials and assessment of traditional pavements
Comparative Rutting: dual and wide-base single tires	* tire studies, which compared single low profile, wide based, radial ply to standard dual tires, and showed 92 percent greater rutting for the singles
Effect of Particle Shape and Gradation on Base course Performance: 9 pavements	* New Zealand specifications currently limit the rounded aggregate content in base course to a maximum of 30 percent. The research showed that, while the best performance was obtained with this mix content, up to 50 percent could be tolerated (*110*) and that mixes with greater than 70 percent rounded aggregate could not be compacted
Lime-stabilized subbases: 3 thicknesses	* an experiment with lime stabilized subbase course showed that an increase in thickness from 150 to 250 mm (6 to 10 in.), would increase life by 15 times (*112*).
Strain response of subgrades and unbound granular pavements: wheel load, tire pressure and tire type	development of subgrade strain criteria for design
Asphalt Mixes with 4 modified and 2 conventional binders	* six asphaltic concrete layers compared high and conventional stiffness mixes. The sections showed little deterioration and the tests were truncated at a surface deformation of 4 mm (1/16 in.); at this stage the stiffer asphalt mixes were performing better than a thicker layer with conventional binder.
Life-cycle performance of a thin-surfaced unbound granular pavement	assessment of traditional pavement configuration
Dynamic wheel loads and pavement wear: single unit and multi-leaf spring suspensions	vehicle pavement interaction studies
DIVINE project; air bag and multi-leaf suspensions	vehicle pavement interaction studies

TABLE 21 SUMMARY OF PAVEMENT TYPES TESTED IN SOUTH AFRICA

Pavement type	Number of pavements	Number of tests	Total number of ESALs ($\times 10^6$)
Crushed stone bases	9	20	331
Gravel bases	3	11	55
Slag bases	1	2	61
Cemented bases	9	33	282
Asphalt premix bases	11	34	393
Concrete pavements	2	18	185
Water bound Macadam	2	5	137
Recycled materials	5	5	70
TOTAL	41	118	1514

materials, fatigue of modified binders, and dynamic field creep testing.

In one of the few recent accelerated loading tests on a rigid pavement, it was shown by an HVS experiment that thin (150 mm) jointed concrete pavements can carry heavy traffic if placed over a minimum of 150 mm non-erodable subbase. This finding was felt to be valid even though concrete pavement joint problems develop under uni-directional loading. It was also shown that a 160 mm jointed concrete pavement laid directly on a subgrade with a minimum CBR of 5 could carry low traffic volumes (*143*).

Tests on block pavements revealed the need for cemented subbases where subgrade support was suspect (*144,145*).

Marais (*146*) and Freeme (*147*) reported the application of HVS trials in two provinces. In Transvaal, revised pavement designs were developed that were expected to save US$1 million annually. The proven ability of crushed stone bases to carry the heaviest traffic loads was expected to save US$100,000 per km of 4-lane road compared to concrete and asphalt base construction. The Natal studies resulted in reduced costs for bituminous bases and asphalt surfacing under heavy traffic, delineation of limits for sandstone and red sand in stabilized subbase and better understanding of

TABLE 22 APPLICATIONS OF THE HVS 1973, SOUTH AFRICA

Objective	Application
Reduction of pavement cost by improved designs	new designs incorporated in the catalogue resulting in construction cost savings
Use of non standard materials	use of sands and sandstones in stabilized subbase specifications for emulsion treated bases use of blast furnace slag use of water bound macadam
Development of low risk maintenance strategies	better use of cemented materials for heavy traffic roads use of crushed stone bases for heavy traffic-15-20 ESALs reduced cost of bituminous bases for heavy traffic extended use of natural gravel importance of proper maintenance
Improved understanding of response and performance	improved mechanistic models improved load equivalency factors
Evaluation of rehabilitation	recycling of asphalt pavement advantages of early rehabilitation of crushed stone bases prediction of remaining life and recommended rehabilitation procedure for concrete pavement affected by alkali aggregate reaction rehabilitation of a deformed bitumen premix

water-bound macadam and emulsion treated crushes run stone bases. The application of HVS findings in support of Pavement Management Systems was also reported.

As a precursor to the purchase of two HVSs by the California Department of Transportation (CALTRANS), a small trial was conducted. The trial, summarized in Table 23, compared HVS results with laboratory tests and analysis at the University of California at Berkeley (UCB). After completion of 1.125 million test wheel repetitions (about 1.34 million ESALs) during 66 days of operation, CALTRANS concluded that the HVS can be used effectively for pavement response and performance studies (*69,148*).

SWITZERLAND

The substantive applications of the Swiss facility in Zurich (Table 24) were reported to have great benefit in allowing failures to be observed without risk from or hindrance to traffic. Results are also being applied to the development of new analytical methods for design (*99,135*).

The Lausanne facility (Table 25) has concentrated on low-temperature studies (*66*). The value of the very low temperature testing was emphasized; in contrast to experimental road studies where the last severe winter was experienced in 1962-1963, the facility allows freeze-thaw cycles to be imposed as needed.

TABLE 23 APPLICATION OF THE HVS, CALTRANS USA

Objectives	Applications
to compare rutting of a dense graded asphalt under channelized and normal traffic	channelized traffic doubled the rutting surface rut rates compared well with previous HVS trials at about 100,000 repetitions
to compare the fatigue performance of a rubber-bitumen mix to a conventional mix	life to cracking failure compared well with that calculated by the Caltrans overlay design procedure, a reduction of 50 percent in layer thickness is justified for the rubber-bitumen mix

TABLE 24 APPLICATION OF THE ISETH, SWITZERLAND

Objectives	Applications
comparison of pavement configurations	effective ranking procedure developed
evaluation of design procedure	existing practice shown to be conservative
evaluation of failures	construction quality shown to be a common factor

TABLE 25 APPLICATION OF THE EPFL, SWITZERLAND

Objectives	Applications
evaluation of frost protection design	existing practice shown to be conservative
evaluation of drainage layer	shown to be very effective in freeze/thaw environments
effects of temperature and loading pattern	dependence of rutting on temperature and transverse distribution of wheel path shown

UNITED KINGDOM

Early tests at the original road machine in Britain demonstrated the significance of temperature in assessing the response of pavement layers (Figure 25) (*82*).

The current TRL program started in 1985, with the PTF intended as a research tool. However, privatization has resulted in a shift to shorter term, more immediately applicable research to support Ministry of Transport specifications. Many studies are linked to joint support from industry, especially in the use of "new" materials. Eight recent examples of such studies are summarized in Table 26.

Legislation requires the National Joint Utilities Group to guarantee trench backfill for 2 years; PTF studies showed present methods to be more than adequate, but there is some risk that construction standards were higher in the experimental pavements than those achieved in practice. This raises the potential to reduce standards and costs, which may be undesirable. The new legislation proved effective because the standards were shown to be realistic.

The study of Ecopave, a commercial approach to concrete road pavements, was successful and the resulting design approach has been patented.

A contract for New Brunswick, Canada, where specialized vehicles are used on forest roads, called for a new design procedure and a study of effects of tire size and pressure. The results of this fundamental study formed the basis for recommendations for the life of pavements under the specialized vehicles.

The impact of public liability claims on county authorities led to a requirement for a design guide for sidewalks, to be followed by a maintenance guide. Damage to sidewalks, including block paving, by heavy vehicle access is expected to be exacerbated by the increase in legal maximum axle load from 100 to 115 kN (22,000 to 25,000 lb).

The use of slag, lime and cement binders, fly ash, and cement kiln dusts has been investigated. It has been demonstrated that such materials are structurally sound and free

TABLE 26 APPLICATION OF THE PTF-TRL, UK

Objectives	Applications
Trench reinstatement techniques	present methods shown to be conservative and thus legal requirements realistic
Ecopave evaluation	new concrete paving technology proven and patented
Forest road design	pavement design methods for specialized log traffic developed
Sidewalk damage by heavy vehicles	damage to sidewalks evaluated because of legal liability issues
Industrial by-products	specifications developed to permit use of several materials shown to be structurally adequate and environmentally safe
Nu-pave evaluation	thin fibre reinforced concrete overlay technique designed to crack without "failing"
Sub-base layer thickness	reduced thickness of stabilized layers or increased life criteria
Single vs Dual tire damage evaluation	Single tires cause twice the damage on the thick pavements typical of the UK and Europe

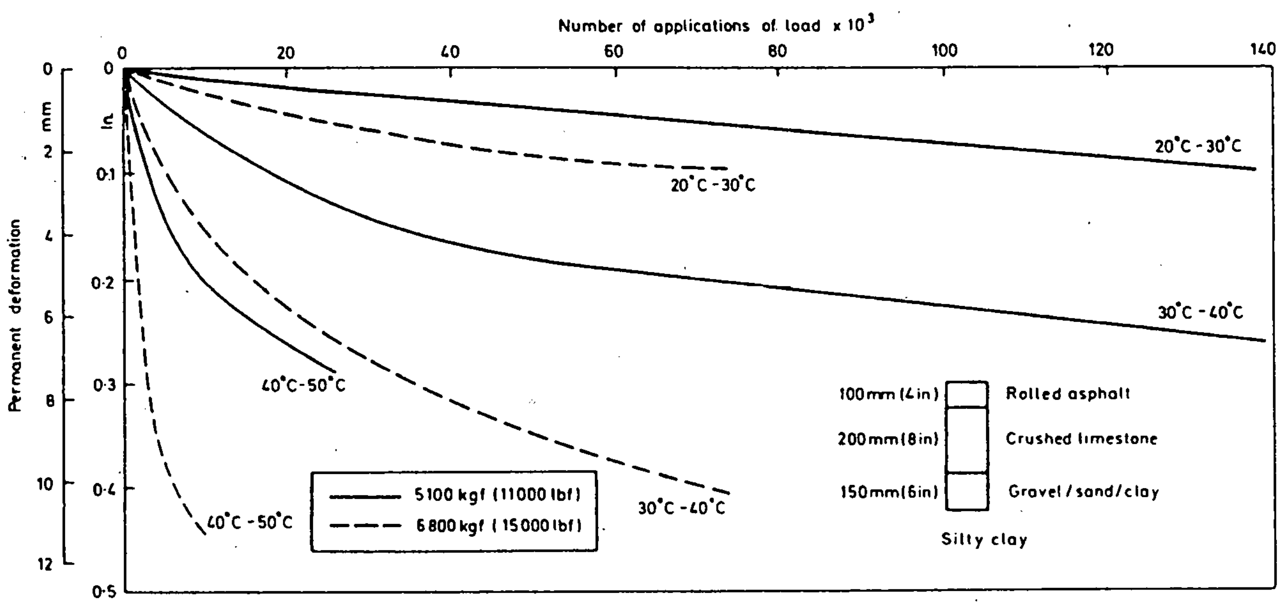


FIGURE 24 Relation between the permanent deformation of the road surface and repetitions of wheel load under different combinations of wheel load, size and surface temperature (*74*).

from environmentally detrimental leaching problems. Specifications are now being developed to incorporate a range of mix proportions. Long-term autogenous healing of cement treated materials is under study but requires a field trial for confirmation.

A thin concrete layer, with admixtures and fibers, is being investigated to overlay failed asphalt pavements; it is designed to crack without "failing."

The environmental pressures to restrict development of new or extended primary aggregate sources have led to increased attention to the use of stabilization. Reduced layer thicknesses of the stabilized or of superior layers and/or increased life are sought as economy measures, since UK practice typically fixes layer thicknesses with little regard to material type. However, a particular need is to ensure that government is open to solutions developed from industry-supported studies. This is accomplished by project panels, with government and industry involvement, to design, conduct, and analyze the experiments.

Super single tires, coming into favor in the trucking industry, cause twice the damage (rutting) of dual tires on the thick pavements used in UK. This finding differs from the work at FHWA because American pavements are typically thinner. The work will be applied by taxation/legislation action but may be confounded by EEC regulation.

TRL is no longer active in studies of failure prediction or mechanistic modeling because of pressure to work under commercial contract. Reports on commercial studies go to sponsors first, and in confidence, and often are left unpublished for commercial advantage.

There is also less effort on estimation of pavement life, with a few ad hoc life trials but some work on establishing empirical design procedures. Improvements in design and construction were the primary focus with effort concentrated on studies of material properties and modification.

TABLE 27 APPLICATION OF THE PTI FACILITY, USA

Objective	Application
develop structural equivalency factors	layer coefficients recommended
determine structural damage of tri-axles	approximate load equivalency factor of 2.6 established, varying with load and pavement configuration
determine in-situ moduli from surface deflection	moduli higher than laboratory estimates and affected by many variables
develop estimates of remaining service life	remaining service life can be predicted from Surface Curvature Index; effect of layer thickness considered in terms of structural number
rigid pavement repair	techniques validated
evaluation of recycled asphalt	technique validated
evaluation of free draining base course	shown to be compaction sensitive and best used deep in a pavement
structural coefficient of surface mixes	new materials and mixes performed in a similar manner to existing materials
overlay design	simplified mechanistic procedure based on Road Rater deflections
skid resistance	calibration service provided
roughness measurement	calibration technique developed using sinusoidal blocks

UNITED STATES OF AMERICA

The Pennsylvania Transportation Institute (PTI) facility was active from 1971 to 1983 during which time four series of experiments examined 17 pavements, to which eight sections were added and others rehabilitated in later trial series. Table 27 summarizes the outcomes of these trials.

In the first series (*149*), 17 pavements with base courses of cement stabilized aggregate (AC), asphalt concrete (BC), lime pozzulan stabilized aggregate (ALP) and asphalt stabilized aggregate (AB) were loaded with a 5-axle truck semi-trailer with full trailer rig, loaded from 72-109 kN (16-24 000 lb) per axle and traveling at 36 km/h (22.3 mph). The AASHO Road Test approach was used to estimate structural number from the performance history, determined as the change in PSI with load repetition. Assuming surface and subbase structural layer coefficients and knowing layer thicknesses, the structural layer coefficient for the various base courses was estimated (Table 28). There were notable discrepancies; the performance histories were linear not exponential as assumed in AASHO, and the layer coefficients varied with layer thickness. The proposed coefficients were lower than those estimated in the experiments to provide a conservative design.

TABLE 28 PENNSYLVANIA TRANSPORTATION INSTITUTE—STRUCTURAL LAYER COEFFICIENTS

Procedure	Structural Layer		Coefficients	
	AC	BC	ALP	AB
1974 designs	0.30	0.40	0.30	0.30
Performance	0.55	0.51	0.51	0.49
Surface deflection	1.58	0.44	1.00	0.41
Tensile failure	0.41	0.44	0.29	0.42
Proposed	0.44	0.44	0.40	0.30

The study also compared three linear elastic layer models, CHEVRON - 1963, CRANLAY - 1971, and BISAR - 1974, and evaluated the visco-elastic model VESYS II - 1974. It was reported that the models predicted surface deflection within about 10 percent of that measured under plate loading.

In the second and third series (*150,151*), eight new pavements were added to the track, replacing first series sections 10-13. First series section 8 was overlaid for half the length and half was covered with a reinforcement fabric before overlay. Load equivalency factors were evaluated using mechanistic [BISAR], AASHO empirical, and semi-empirical approaches. This yielded a tri-axle group equivalency factor of 2.6 for the range of structural numbers tested to a terminal serviceability index of 2.0.

It was concluded that "*the load equivalency factors generated by the mechanistic approach are not compatible with those developed at the AASHO Road Test.*" It was also stated that "*equivalency factors vary significantly with the type of base course material*" and "*vary with load most for AC pavements and least for ALP pavements.*" And also that "*load equivalency factors developed from the rutting criteria were different for different levels of rutting . . . increase with an increase in structural number; . . . the opposite of that observed for fatigue*" (*120*).

The moduli, determined from surface deflection bowls, decreased with an increase in the cumulative traffic loading. The estimated moduli were higher than laboratory values reported by others.

A further objective of the series was to develop a method to determine the remaining service life of a flexible pavement using the PSI and fatigue cracking criteria and Road Rater deflection basins. The results showed that "*remaining service life could be predicted from Surface Curvature Index (SCI) values with the effect of layer thickness considered in terms of structural number (SN). The effect of SN was not as significant for full depth bituminous concrete pavements as for bituminous pavements with subbbase courses.*"

The fourth series, from 1982 to 1983, tested 21 asphalt and portland cement concrete sections, again with a 7-axle truck, 2-trailer combination. Loading patterns were varied from 7 t to 26.1 t (15,400-57,500 lb) and 1.1 million ESALs were applied; there was some reconstruction of deteriorated open-graded subbase pavement sections during the series (*49,152*). On the basis of condition surveys and pavement performance data, structural coefficients were determined for open-graded base course, cold recycled base and two wearing course mixtures. The Pennsylvania Department of Transportation overlay design procedure was revised and a personal computer version developed. An evaluation procedure for doweled joints in concrete pavements was developed based on a finite element analysis (*153*).

The University of Central Florida facility has been used mainly for ad hoc comparisons of bridge joints and joint sealants (*36*).

At the University of Illinois track, the major studies were of relative performance of different pavement thicknesses and materials (Table 12), from which the use of lime-fly ash stabilized gravel pozzolanic pavement materials came into practice. It was reported that the pozzolanic bases distributed load by slab action and should be regarded as rigid or semi-rigid.

The Washington State University facility also focused attention on the relative performance of various base materials, particularly the potential for using treated bases of "inferior" materials, and of sulfur extended asphalt. The "equivalencies," which relate the "equivalent" thickness of various base courses to a unit thickness of untreated base under spring climate conditions were adopted, Table 13 (*72*).

The first ALF in the United States, FHWA-PTF, commenced operations with eight test sections to be tested under a range of tire pressures and loads (*154*). Results of the initial tests on two sections showed a premature cracking failure on one section initiated by test coring but the second section performed as predicted (Table 29).

The PRF in Louisiana began testing in January 1996. The first group of experiments will compare traditional crushed stone and cement stabilized soil bases with innovative treatments using fibre reinforced soil cement and geotextile inserts.

The INDOT-PURDUE facility in Indiana completed an investigation of the effect of crushed rock content in asphalt pavements in 1995, and commenced a national pooled funds study to validate Superpave in 1996.

The MnRoad facility began testing in 1994 and by mid 1995 had applied 30,000 ESALs to the low-volume road sections. Data on pavement condition, roughness (Figure 26), rutting, and strains at various positions are being recorded.

The proving trials with the TxMLS were reported at the 1995 TRB Annual Meeting (*97*). The most significant finding was the reduction in stiffness, as measured by the SASW technique, in the asphalt mix due to trafficking. The first-year project for the TxMLS will focus on an instrumented

TABLE 29 APPLICATION OF THE FHWA-PTF, USA

Objectives	Applications
to establish load equivalencies	not yet complete
to compare estimated and measured pavement responses	there was general agreement between peak deflection, back-calculated moduli and strain data cracking was not a good indicator of failure unless the cracks propagate to the surface
to evaluate accuracy of AASHO designs used	good agreement was reached on one section the second section failed prematurely by cracking
to assess the impact of tire pressure on pavement response and performance	tire pressure effects shown to be less significant than load and temperature on flexible pavement response and performance

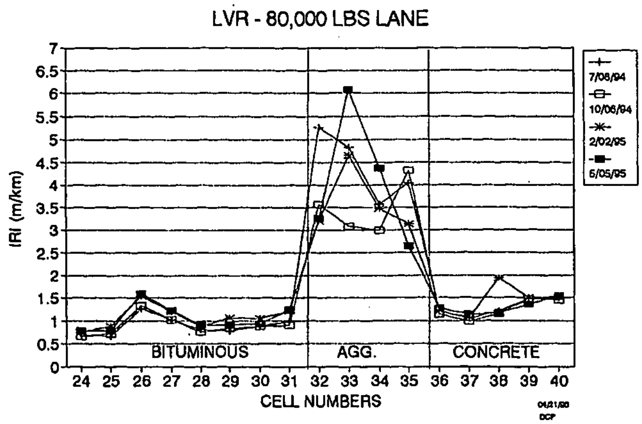


FIGURE 25 Data on pavement condition, International Roughness Index on MnRoad.

asphalt pavement to determine the response and compare the performance of alternative pavement structures and rehabilitation strategies under the multiple axle traffic simulation. Long-term objectives (*155*) are to

- Investigate load equivalency,
- Determine remaining life and its impact on rehabilitation guidelines,
- Investigate new pavement materials, including a Superpave evaluation, and
- Study truck component—pavement interaction.

In the CAL-APT program, the first HVS [CALHVS1] began testing a drained pavement section at UCB in early 1995 and, after completion, started testing an undrained pavement later in the year. The second facility [CALHVS2] started testing a second drained pavement section in late 1995, also at UCB, to facilitate staff training in operations and analysis. Final results will compare response and performance of standard CALTRANS pavements designed with and without a drainage layer.

Published results (*156,157,158*) from CAL-APT testing address high-priority issues for CALTRANS in pavement design and construction, e.g., limiting air-void content and raising mix placement temperatures. Rehabilitation will be studied, starting in fall 1996, when CALHVS2 tests asphalt rubber and conventional dense-graded hot-mix overlays on an in-service highway, while CALHVS1 tests similar overlays at UCB. Future tests are expected to study effects on pavements from changes in types of tires, construction quality, and maintenance strategies.

SUMMARY

Layer equivalencies were a common approach to the need to categorize different materials of different structural capacity and frequently were applied in an implicit, if not explicit form in many design catalogues where material type and layer thickness were combined to give pavement configurations for selected traffic conditions. Where a structural coefficient was not assigned, simple material equivalencies were often adopted with varying degrees of success. For example, in early attempts to quantify the difference between cement stabilized bases and unbound bases, a material equivalence of around 0.7 was suggested.

Stabilized and other innovative materials, e.g., blast furnace slag or laterite gravel, have been and can be successfully used for pavement base, and where long-term pavement performance has proven adequate these materials have been adopted into specifications. However, when the materials change or the traffic load or climatic environment differ from that which produced the direct experience, APT is an effective way of demonstrating the adequacy of such materials in a short time.

Load equivalencies are frequently the subject of vigorous debate as allowable axle loads directly affect vehicle load-carrying capacity and thus ton-mile costs. As different tire, wheel, axle, and suspension types have been marketed, the trucking industry has naturally sought favorable load regulations for them, while the road engineer has had concern for the long-term impact of new assemblies on pavement proven adequate only under older types of load assembly. The use of APT to establish the pavement damaging effects of new assemblies is a very appropriate use, as the influence of environmental change can effectively be discounted during the short duration of a testing cycle, and there is no need for a vehicle to be licenced for use on the road before the load characteristics have been evaluated.

Rehabilitation of pavements, because of distress occasioned by traffic load, climatic effects, or a combination of both, is of increasing concern to road engineers as the infrastructure ages. The concern is more acute where growth of commercial traffic is causing many pavements to reach the design life in terms of load repetitions in a much shorter elapsed time than originally envisaged, and yet these heavily trafficked pavements can only rarely be used for experiments into rehabilitation and overlay techniques. The APT facility has a direct and practical role in proving overlay designs and developing design procedures.

Finally, the APT facility allows testing of pavement configuration, material, load, and environmental combinations under controlled accelerated load with no consequence to in-service pavements under traffic.

CHAPTER FIVE

EVALUATIONS

Few formal evaluations of the effectiveness, implementation, and cost/benefit ratio of accelerated full-scale testing have been published. Notable exceptions are those of the Australian ALF program (*94*) and the South African HVS (*140*). However, a number of other facilities have reported the costs of the research and qualitative statements of the benefits with some estimates of the dollar value of the findings.

Krukar and Cook (*72*) reported early practical benefits from testing at the WSU facility in evaluating the performance of unbound and bitumen-stabilized bases and the importance of subgrade drainage under their conditions. They claimed that the test track could give quick and useful knowledge of the behavior of non-standard materials, but cautioned that environmental conditions during construction (and APT) may play as important a role in pavement life as the type or thickness of base.

Saskatchewan Highways and Transportation, Canada reported an initial capital cost of C$475,000 in 1977, and costs for each of the first three experiments between C$35,000 and C$50,000. The benefits are stated as coming from the gradual incorporation of results into practice in pavement thickness design, material and configuration selection, and the reassessment of compaction specifications. Economic returns were expected to be *"large . . . in terms of monetary savings and better pavement management"* (*50*).

Walker (*140*) reported that the South African HVS program cost about R1.8 million/year and that "very substantial benefits" had been achieved for the 240,000 km (149,000 mi) road network for which the annual budget was (1985) US$600 million. He reported that the HVS program had resulted in

- changes in the pavement design catalogue yielding reduced costs
- use of non-standard materials
- increased confidence in pavement performance under increased traffic and/or different climatic conditions. Major advances here include better use of cemented bases, use of crushed stone bases under heavy traffic, reduced cost and improved performance of asphalt bases and the wider use of natural gravel
- improvements in knowledge of load carrying capacity, mechanistic models and load equivalency
- evaluation of rehabilitation measures.

A conservative estimate of dollar benefits was given as US$10.2 million/year, compared to costs of about US$0.9 million/year.

Freeme et al. (*147*) had earlier stated that the HVS tests were directly reflected in the South African catalog of pavement designs with the full support of all South African road authorities and had achieved significant cost savings through better balanced designs, reductions in pavement thickness, and more cost-effective design and rehabilitation.

Horak (*141*) described the impact of the HVS program on South African road practice and compared the rate of return favorably with the AASHO Road Test. They report a 1985 base cost of the HVS program as US$15 million and derive present worth (1991) costs of US$60,000 per test section compared to their estimate for AASHO of US$97,000. They suggest a benefit-cost ratio of 12.8 for a total investment of about US$30 million by 1991.

The HVS contributed significantly to technological development in improved materials utilization, improved structural design, evaluation of environmental effects on pavements, improved materials test methods and to the general improvement of pavement technologies, thus avoiding failures by the use of unproven designs or abnormally heavy traffic and reducing pavement costs by better design, materials selection, and rehabilitation methods.

Scazziga (*98*) reported that empirical comparisons of pavements under conditions in Switzerland showed the design procedures to be conservative and that the asphalt layers of typical pavements tested could be reduced 50 mm (2 in.) and achieve the same life.

Kilareski and Anani (*106*) also noted the value of APT research in proving the use of non-destructive testing in predicting the remaining life of pavements.

Montana, evaluating the impact of the WASHO trial using the FHWA ALF on two Interstate pavements, reported the principal benefit as verification of a new asphalt mix design, with improved rutting resistance, already developed within the department. The positive results of the ALF trial supported the change rather than directly bringing about that change. The unpublished report (R.A. Garber, personal communication 1995) also concluded that "ALF proved to be a reliable all-weather pavement testing machine" and "the performance of both pavement test sections was easily quantified."

The evaluation of the effectiveness of ALF in Australia was carried out by an independent consultant (*159*) and considered reduced road authority and road user costs. Significant but unquantifiable benefits were identified. This evaluation not only demonstrated the cost-effectiveness of the ALF program but established a probability-based assessment procedure that could be applied to other APT programs. At the same time, an evaluation of the efficiency of the program was conducted (*94*).

The total cost per week of a trial has been decreasing, reflecting the increased mechanical efficiency of the machine and the increasing proficiency of the operating staff. In 1984, the weekly cost was approximately US$45,000 (adjusted by CPI) falling to less than US$30,000 in 1992. Part of the reduction is from 24-hour, 7-day operation, without labor penalty rates, and part from reduced levels of instrumentation in the later trials. The benefits were assembled from direct savings to the road authorities, because in the short time for the study, it was not possible to estimate the benefits from road user cost savings. The overall cost-benefit ranged from 4.0, at a discount rate of 8 percent, to 5.0 at a 4 percent rate. The ratios for individual trials ranged from 1.2 to 11.6. This result implies an internal rate of return of 20 percent on the investment. The unquantifiable but non-the-less real benefits include

- catalyzing of interest and expertise in pavement innovation
- generation of high quality data
- strengthening of links between laboratory and field studies
- increasing adoption of rational design methods
- reduction of expenditure on less effective field trials (one state authority estimated savings from this alone as of the order of US$300,000 per year
- reducing the costs of a new toll road
- improving cooperation between practitioners and researchers
- enhancing Australia's technical reputation.

The sale of four ALFs overseas was also of direct cash benefit.

At the research interface, the benefits of APT programs have been in validating theoretical models of pavement and material behavior and performance. Brown and Bell (*74*) reported their experiments as extremely useful in checking theoretical methods.

The impact of studies at the Shell Amsterdam facility, which was used for the basic studies resulting in the Shell design procedure for asphalt pavements, has not been quantified but must have been very considerable by the introduction and implementation of a widely used procedure.

An important feature of all the facilities is the need for clear, comprehensive, and accessible records of the data collected and reports prepared. South Africa and Australia are outstanding examples here, having available complete bibliographies offering data on disk for the many trials. (*94,160*)

Evaluation of APT effectiveness, implementation, and cost-benefit is historically limited and only rarely have been rigorously quantified. However, shrinking research budgets and privatization of facilities may result in more frequent, formal, and quantitative assessments in the future.

CHAPTER SIX

CONCLUSIONS

Increasing pressures to manage the road systems of all countries effectively and economically, in a context of increasing vehicle numbers, and heavier vehicle, axle, and wheel loads, requires continuing efforts to understand and improve the design, construction, maintenance, and rehabilitation technologies for road pavements, and to provide robust evidence for the regulation of traffic loadings.

The preceding chapters of this synthesis have described the development of pavement testing and surveyed the current state of practice in full-scale accelerated pavement testing. This chapter discusses the advantages and disadvantages of the various approaches, assembles the successful and unsuccessful applications of studies reported, and suggests some future directions for research.

Historically, many attempts to physically model pavement response under load have formed the basis for current design procedures and our understanding of the behavior of layered systems. This need to understand pavements so that their performance under increased traffic load can be predicted has been reinforced in a time of constrained funding for infrastructure by the demand for cost-effective rehabilitation of pavements built in the 1950s and 1960s that have reached or exceeded the original design life.

The Minnesota Department of Transportation, in developing the MnRoad program, cites the need for accelerated full-scale testing on the bases of

- awareness at policy and administrative levels of the need for such research,
- availability of improved technology, both for pavements and for research,
- increased traffic loadings,
- changed and new materials and resource constraints,
- coordination with the SHRP LTPP program,
- decreasing new construction, and
- increased maintenance and rehabilitation.

These pressures demand research into the behavior and performance of road pavements under conditions closely simulating real world conditions yet at a rate sufficiently accelerated to give results faster than experience with pavements under actual traffic load yields.

Many successful experiments with different, simple pavement layer and traffic load simulations, provided empirical evaluations of pavement configurations and assessments of the basis for theoretical models of multi-layer structures. The current approach to pavement testing has a strong focus on full-scale accelerated rolling wheel loading of full-scale pavements under controlled environmental conditions. There are four basic methods, each with advantages and disadvantages (Table 10). **Test Roads** provide very convincing evidence of pavement performance but lack environmental control and are expensive to operate if an appreciable acceleration of damage is to be attained through controlled loading. The use of thinner pavements to reduce structural capacity can assist but such sections are less realistic. **Circular tracks** have advantages in operating at high speed and can test several pavement sections at the same time. However, should one section fail, the performance of all other sections will be affected, and unless the track is of sufficient diameter, lateral shear forces (and consequent high tire wear) can be a problem. There may also be some difficulty in constructing the annular pavement with normal equipment and to normal standards. **Linear tracks** are limited as to traffic speed, and with few exceptions use 2-way loading that may affect pavement response and performance. Three of the existing tracks are readily transportable and can operate on in-service pavements. These versions also operate on test areas constructed without constraint on normal practice. Section failure does not influence the remaining tests.

The use of **pulse or static loading** is declining with the notable exception of the BASt facility. This type of facility has advantages of simplicity.

There has, as yet, been no comparative study of the various APT facilities and this is probably both impractical and inappropriate. Each facility has its own characteristics, advantages, and disadvantages. It is therefore unlikely that there will be any close correlation between results from different facilities. However, when close similarity occurs in the various programs, the degree of correlation should be evaluated.

All are limited insofar as the effect of environmental factors can be controlled, varied to small degree in some instances, and measured; but the combined effects of environment and time have not yet been simulated. Traffic load can be more closely controlled, varied, and measured, but again, the full spectra of load are not applied.

The primary application of APT has been to the empirical comparison of different pavement configurations, different materials, and different loading configurations. The secondary application has been to the validation of theoretical models of pavement response and material behavior.

Early APT results, using plate loading of material in pits or tanks, or on full-scale pavements, and using actual vehicle loading of pavement sections, underlie the first pavement design procedures for both roads and airfields. Since these early experiments, the test configurations and related theoretical model developments have increased in complexity and effectiveness, but still need to be calibrated for specific layer configurations, material combinations, and environmental conditions. Temperature effects in bituminous materials and pavement layers can now be adequately modeled, subject to appropriate calibration.

The application of APT to determining load equivalencies of different tires, wheel assemblies, and axle groups has yielded load factors for use in design and demonstrated that such factors are dependent also upon pavement configuration. Current studies under the OECD DIVINE program will begin the investigation of dynamic suspension parameters. Specific findings are assembled in chapter 4 of this synthesis and are detailed in the references.

All the facilities went through a trial or proving period, in which the mechanical capabilities of the equipment were established and some initial credibility of the pavement response and performance was achieved. In a similar manner, the various instrumentation and data processing regimes were tested and proven to give satisfactory outputs. A critical study of instrumentation was that reported from the NARDO experiment with controlled traffic on a test road. Strain, deflection and deformation measurements are now possible, and with careful attention to technique, yield results in accord with theoretical predictions. Temperature can also be measured and the effects incorporated in analyses. Moisture changes are less well determined.

Application of APT results to pavement design procedures has been reported by half the facilities, in the form of modifications of design catalogues and in development and validation of mechanistic pavement and overlay design. Existing and innovative material evaluation has also been the subject of studies at approximately one third of the facilities, with studies of new, recycled, and by-product materials, insulation layers, and freeze thaw susceptibilities. Load-related phenomena have also been the subject of investigation at many facilities; in the early years several studies of aircraft load effects were prominent but in more recent times the effects of super single tires, multi-wheel axle groups, and suspension dynamics have become active. The development of theoretical models, by contrast, has been limited to relatively few of the facilities, notably the Shell and Nottingham tracks, and more recently, the U.S. and Australian ALFs, the Indiana facility, and the South African HVS. The Indiana facility is most active in this direction. Many other facilities are concentrating on shorter-term, empirically based, comparative evaluations of materials and pavement layer configurations.

The evaluation of APT facilities has generally been reported favorably, but rarely in quantified terms. The fact that the APT approach has been long established and continuously developed to current levels of efficiency and effectiveness itself demonstrates that the qualitative evaluations are positive. An APT program can be costly but the following alternatives provide ample justification for APT programs:

1) waiting for results to accumulate at a low rate under actual traffic,
2) the potential embarrassment and cost of failures under such traffic,
3) the lack of control of major experimental, traffic, and environmental variables, and
4) the difficulties in extrapolating results to other than local applications.

This is especially so when the cost of such programs is set against the costs of the construction, maintenance, and rehabilitation of road networks.

Where attempts have been made to quantify the benefits in dollar terms, benefit/cost ratios from 1.2 to as high as 11.6 have been reported with conservative assumptions. Without attempting to value the spinoffs in improved expertise in and attention to pavement engineering; savings in slower and more limited field trials; protection against embarrassment from material or design failures; and enhanced cooperation between researchers and practitioners, and between vehicle designers, road engineers, and transport regulators, there is little doubt that APT is an efficient and effective approach to the many problems of pavement engineering. However, the privatization of facilities and reduced research budgets will require more formal assessment of proposed trial programs in quantifiable terms.

It is appropriate to begin the dialogue as to how the application of APT can be improved and whether and how it should be extended in the context of the existence of a number of APT facilities around the world, each with different features, and of the demonstrated relevance, effectiveness, efficiency, and economy of the full-scale accelerated pavement testing programs.

The primary requirement of any future APT program(s) is that it should be part of a coherent pavement research strategy; the APT facility experimental projects should be a component of an integrated program of laboratory materials characterization, APT, and LTPP studies. The laboratory program should be applied to characterize materials for use in mechanistic design procedures, the results of which can be confidently applied in the field to refine existing designs and generate new ones. APT studies should be applied to generate credible pavement response and performance data that can be used to validate the laboratory materials characterization and theoretical models of pavements in advance of ever-increasing traffic demands and changing vehicle designs. LTPP studies are then applied to validate, in real time, the results of the laboratory research, theoretical models, and APT experiments.

There are still a number of problems related to the effects of environmental change, moisture and temperature variation, and curing or aging of materials that can be addressed only to a limited extent by existing APT facilities.

Thus, such a future strategy should incorporate a strategic approach to pavement research wherever possible and should attempt to better coordinate the various APT programs so that each can build on the experiences of the other. Such coordination could be built on improved models of pavement response with compatible materials behavior and pavement performance criteria so that the results can be applied across a number of programs.

There are specific needs for further study:

- the time dependency of pavement response and performance,
- the time dependency of material properties and variability,
- the effects of construction and maintenance factors,
- the extent and effects of environmental changes, and
- dynamic traffic load parameters.

There is also a need to investigate the variability of the full-scale accelerated pavement testing process by testing pavements of identical configuration under identical test procedures.

In the development of APT, each participant has benefited from the others. Each program has had to select an appropriate approach to its particular circumstances, but within a broader strategy for pavement research. Metcalf (*148*), in developing the Australian program, noted that "no machine was ideal for all tasks and some compromise would need to be sought." Thus, a number of philosophies are embodied in the different facilities around the world. Recent advances in telecommunications, such as the video conference and the ability to transmit data, graphics, and video will provide tools to facilitate better links between the APT programs worldwide. Organizationally, groups like the new Transportation Research Board Committee on Full-Scale and Accelerated Pavement Testing will help to bring APT experts together to share ideas. In addition, in the United States, the proposed "National Accelerated Testing Program for Superpave Validation" may link several APT facilities in a long-term effort.

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APPENDIX A

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Project 20-5, Topic 26-07

APPLICATION OF FULL-SCALE ACCELERATED PAVEMENT TESTING

QUESTIONNAIRE

This questionnaire seeks information on full-scale accelerated testing conducted by your organization. If you do not own, operate or use such a facility, please dispose of this questionnaire and advise us that you cannot respond. However, if you can suggest any organization/s in your country/state to which the questionnaire should be sent, please advise us of that organization(s).

A. GENERAL DESCRIPTION

A.1. GENERAL DESCRIPTION OF THE FULL-SCALE ACCELERATED TESTING FACILITY

1.1. Name of Facility ______________________

1.2. Name of Institution ______________________

1.3. Address ______________________

State ________ Country ________ Zip Code ________

1.4. Contact Person ______________________

Phone ________ Fax ________ E-MAIL ________

NCHRP Project 20-5, Topic 26-07
Agency: ______________

A.2. MANAGEMENT OF PROJECT

2.1 **Sketch organization chart**, including any advisory structure and links to complementary studies and facilities (e.g. university laboratory, highway department laboratory)

2.2. **History** Number of pavements tested ________

Year of the first test ______ Year of the last test ______

Currently in use? YES ☐ NO ☐

2

A.3. TYPE OF FACILITY

3.1 **Loading Path** Circular ☐ Linear ☐

Oval ☐ Pulse loading machine ☐ Test road ☐

Normal vehicle loading ☐ Specialized loading vehicle ☐

Other ____________________

3.2 **Dimensions**

Linear Overall length__________ width__________

Loading path length__________ width__________

Circular outside radius__________ loading radius__________

Oval length of straight__________

width__________ outside radius__________ loading radius__________

Test Road length__________ width__________

shoulder__________ number of sections__________

SKETCH LAYOUT (PLAN, CROSS-SECTION)

3.3 **Utilization** passes /hour __________

Mechanical availability ______% utilization______%

loading hours/day __________ loading days/year__________

Power required __________KW source__________

3.4. **Location/Mobility** field ☐ laboratory ☐

mobile ☐ portable ☐ fixed ☐

3.5. **Address if different from A1.3.**

Address ____________________

State__________Country__________Zip Code__________

A.4.1 COST

4.1. **Initial Capital Cost** $__________ year__________

4.2. **Annual Operating Cost**

machine $__________ operating staff $__________

4.3. **Source of funds** ____________________

B. PURPOSES AND APPLICATIONS

B.1. PRIMARY PURPOSE

Improve Pavement Design : new ☐ rehabilitated ☐
overlay ☐ recycled ☐

Comparative evaluations: pavement configurations ☐
materials ☐ both ☐
other ____

B.2. SPECIFIC APPLICATIONS

Please append a list of references (publications, reports, specifications and contact persons) related to specific applications of Full-Scale Accelerated Pavement Testing in practice. Where possible, supply information on (or references to) the development of the program of full-scale testing, justification of the selected facility, strategy for use, technical and administrative organization. Information on the development of objectives for each specific trial and outcomes and benefits in relation to those objectives is particularly sought.

C. PAVEMENT CONFIGURATIONS TESTED

1. **Pavement types tested** flexible ☐ stabilized ☐
JPCP ☐ CRCP ☐ JRCP ☐ other______________

2. **Test section**
thickness min.____________ max.____________
Edge type curb ☐ shoulder ☐
Shoulder type ___________ width_________ thickness_________

3. **Drainage** drainable layer ☐ material______________
separation layer ☐ material______________
piped ☐ material______________
moisture control provision ☐ material______________

SKETCH TYPICAL CROSS-SECTIONS

Agency: ____________________

4. **Subgrade** in situ, natural ☐ material______________
select borrow ☐

5. **Subbase course** Thickness range_______to________
asphalt concrete ☐ granular ☐
stabilized with bitumen ☐ stabilized with cement ☐
Other____

6. **Base course** Thickness range_______to________
asphalt concrete ☐ granular ☐
stabilized with bitumen ☐ stabilized with cement ☐
Other____

7. **Surface course** Thickness range_______to________
asphalt concrete ☐ chip seal ☐
Other____
cross slope _________%

SKETCH TYPICAL PAVEMENT SECTIONS

Agency: ____________________

8. **Construction**
normal plant / equipment used ☐
special plant / equipment used ☐

D. **LOAD CONFIGURATION USED**

1. **Standard axle load in the state / country**
single tire axle _______ dual tire axle_______

2. **Loading pattern**
one way ☐ two ways ☐ transversal distribution ☐

3. **Operating speed** min._______ usual_______max._______
Pass frequency min._______ usual_______max._______

4. **Total load** min._______ usual_______max._______

5. **Wheel/Axle type** single wheel ☐ dual wheel ☐
single axle ☐ dual axle ☐ other______________

6. **Wheel suspension**

Type of suspension airbag ☐ steel spring ☐

driven axle ☐ towed axle ☐ other______________

7. **Tire pressure** min.______ usual______max.______

Tire size ____________________

E. DATA RECORDED

E.1. ON SITE COLLECTED DURING TRAFFICKING

1.1. **Recoverable deflection**

Benkelmann Beam ☐ FWD ☐ Other______________

1.2. **Permanent deformation** faulting ☐

surface profile ☐ rut depth ☐ multidepth ☐

1.3. **Pavement profile**

1.3.1. Longitudinal ☐ measuring method______________

measuring distance interval______________

measuring frequency______________

1.3.2. Transversal ☐ measuring method______________

measuring distance interval______________

measuring frequency______________

1.3.3. Roughness meter ☐ type______________

measuring step__________measuring interval__________

4. **Strain gauges** surface/base interface ☐

base/subbase interface ☐ subbase/subgrade interface ☐

5. **Pressure gauges** surface/base interface ☐

base/subbase interface ☐ subbase/subgrade interface ☐

6. **Temperature** controlled heating ☐ freezing ☐

Temperature measured

air ☐ continuous ☐ intermittent ☐

surface ☐ continuous ☐ intermittent ☐

in pavement ☐ continuous ☐ intermittent ☐

7. **Moisture measurement** annual rainfall______________

water table level ☐ method______________

capillarity ☐ method______________

moisture content ☐ method______________

relative humidity ☐

8. **Other instrumentation** ______________________________

____

E.2. CONSTRUCTION / MONITORING / POST MORTEM TESTING

2.1. **Laboratory characterization**	Construction	Post mortem
modulus	☐	☐
compressive strength	☐	☐
tensile strength	☐	☐
stability	☐	☐
other	☐	☐

2.2 **Field characterization**	Construction	Monitoring	Post mortem
in-situ dynamic cone	☐	☐	☐
in-situ nuclear density/moisture	☐	☐	☐
coring : for strength	☐	☐	☐
density	☐	☐	☐
layer thicknesses : by levels	☐	☐	☐
by cores	☐	☐	☐
by radar	☐	☐	☐
visual condition rating	☐	☐	☐
crack pattern	☐	☐	☐
other	________	________	________

F. ANALYSIS PROCEDURE USED

1. Empirical equation (eg. rut depth vs passes) ☐
2. Empirical/Theoretical equation(eg.calculation of modulus) ☐
3. Fundamental/theoretical/mechanistic behavior modelling ☐
4. Related laboratory program ☐
5. Related Long Term (Field) Pavement Performance Monitoring ☐

****

THANK YOU FOR YOUR ASSISTANCE!

Please send your response to:

Professor John B. Metcalf
College of Engineering
Louisiana State University
Baton Rouge, LA 70803

If you have any questions, please call Professor Metcalf on (504) 388-4911. If you would like to submit your questionnaire response by facsimile, please do so on (504) 388-4945.

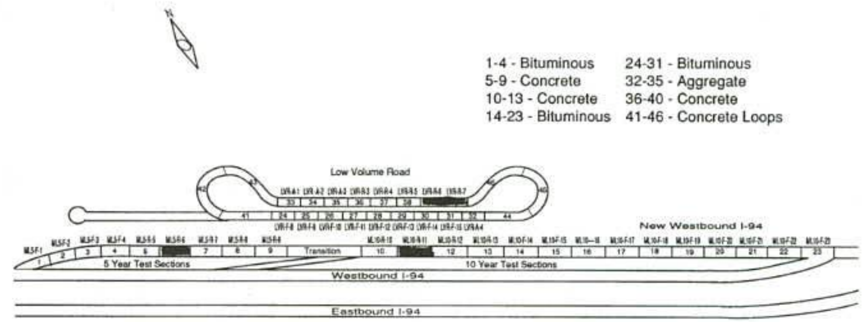
We would appreciate your response by April 7, 1995

****

APPENDIX B

B1

ACRONYM:	MnRoad
LOCATION:	Minnesota Department of Transportation Minneapolis, Minnesota , U.S.A.
Commissioned:	1993
Costs:	US$ 25 million
PAVEMENT CONFIGURATION	
Testing length/Diameter:	9.6 km (2 test roads)
Wheel path width:	N.A
Size of test section:	40 sections (8 types of pavement)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	143 m each section
LOAD CONFIGURATION	
Wheel configuration:	Normal vehicle + specialized vehicle + live traffic
Wheel load:	356 & 453.9 kN
Wheel suspension:	Normal vehicle types
Wheel velocity:	56 - 104 km/hr
Wheel passes:	N.A
Load propulsion:	Driven towed wheels
Power:	N.A
Housing:	Outside
ENVIRONMENTAL CONTROL:	None
Instrumentation:	Biaxial strain and embedment strain Steel strain gauges Moisture block Accelerometer Horizontal clip gauge Neutron probe Pressure cell and pore pressure cell Thermocouple Vibrating wire strain gauge Tipping bucket Resistivity probe Time domain reflectometer



Test cell locations at Mn/ROAD facility.

B2

ACRONYM:	NARDO
LOCATION:	Brindisi, Italy
Commissioned:	1979
Costs:	N.A
PAVEMENT CONFIGURATION	
Testing length/Diameter:	12.5 km (D=4 km) + 1.8 km inside test pavement
Wheel path width:	Channelized to pass over gages
Size of test section:	40 m x 4 m (two lanes)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	N.A
LOAD CONFIGURATION	
Wheel configuration:	3X2-axle vehicles
Wheel load:	N.A
Wheel suspension:	N.A
Wheel velocity:	30 km/hr
Wheel passes:	2.2 passes/hr
Load propulsion:	N.A
Power:	Diesel engine
Housing:	Outside
ENVIRONMENTAL CONTROL:	Partial
Instrumentation:	This experiment was directed specifically at measuring strain in bituminous layer. The following gages were used: KYOWA HBM DA 3 HBM LP 21 60-120

B3

ACRONYM:	PTI
LOCATION:	The Pennsylvania Transportation Institute The Pennsylvania State University University Park, Pennsylvania, U.S.A.
Commissioned:	1971
Costs:	N.A

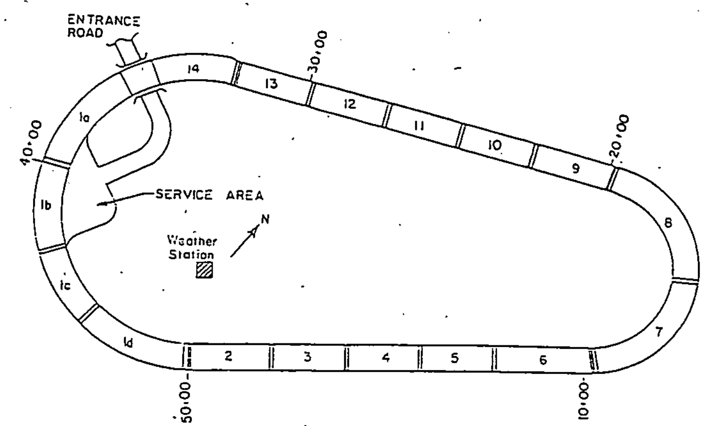
PAVEMENT CONFIGURATION

Testing length/Diameter:	1.6 km (test road)
Wheel path width:	N.A
Size of test section:	17 sections in original facility
Gantry length:	N.A
Shed size:	N.A
Length of test area:	N.A

LOAD CONFIGURATION

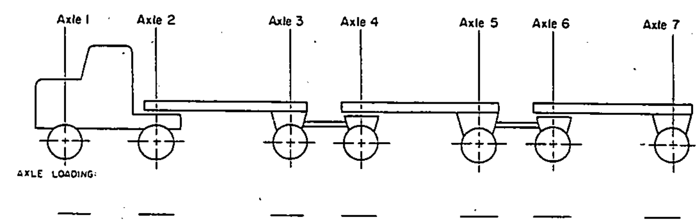
Wheel configuration:	Semi and full trailer in tow (tandem amd triple axle)
Wheel load:	Varying between 71 - 120 kN
Wheel suspension:	N.A
Wheel velocity:	36 km/hr
Wheel passes:	22.5 passes/hr (7 x 22.5 axle cycles/hr)
Load propulsion:	Truck
Power:	N.A
Housing:	Outside

ENVIRONMENTAL CONTROL:	None
Instrumentation:	Strain Stress Moisture Temperature Frost penetration



Plan of the Pennsylvania Transportation Research Facilities

AXLE LOADING ARRANGEMENT



	Axle Loading, kips						
	Axle 1	Axle 2	Axle 3	Axle 4	Axle 5	Axle 6	Axle 7
11/15/82-12/14/82	8.70	12.35	18.10	10.80	20.90	7.00	19.25
12/15/82-01/27/83	8.70	12.20	18.25	20.85	26.10	20.35	19.30
01/31/83-06/09/83	8.70	18.54	18.25	20.85	26.10	20.35	19.30
06/20/83-07/18/83	8.61	21.92	24.22	21.49	18.93	21.75	23.18
07/19/83-05/09/84	8.88	21.60	18.00	19.97	23.07	20.58	23.93
05/10/84-08/09/84	8.40	23.88	18.48	21.10	27.54	18.99	20.17

Axle loading used during accelerated loading

B4

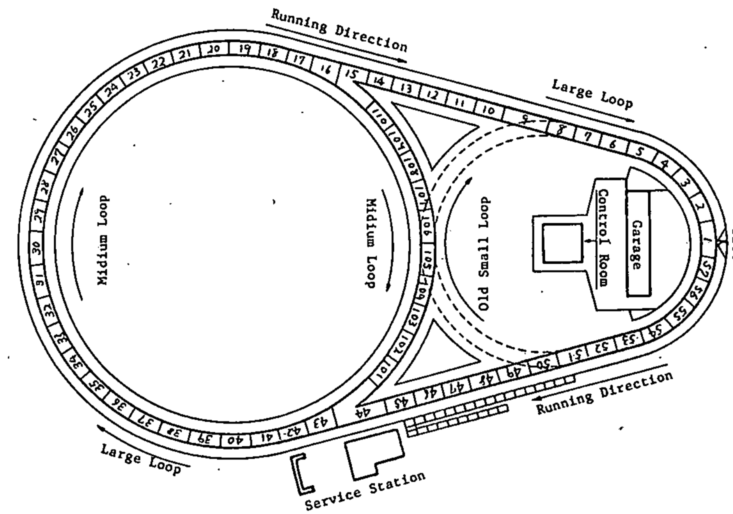
ACRONYM:	PWRI
LOCATION:	Public Works Research Institute Tsukuba Science City, Japan
Commissioned:	1979
Costs:	US$ 0.5 million

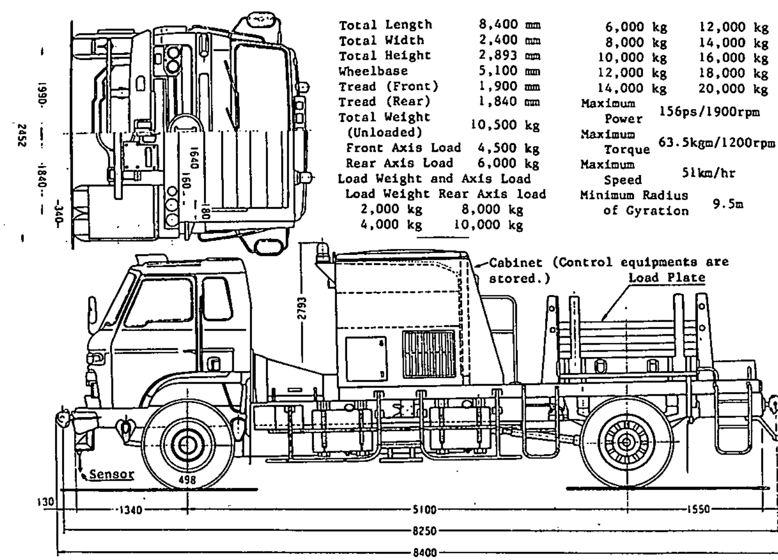
PAVEMENT CONFIGURATION

Testing length/Diameter:	870 m + 628 m (test road loops)
Wheel path width:	±0.25m
Size of test section:	67 sections
Gantry length:	N.A
Shed size:	N.A
Length of test area:	N.A

LOAD CONFIGURATION

Wheel configuration:	Loading vehicle with rear axle load
Wheel load:	60 - 160 kN
Wheel suspension:	Steel spring
Wheel velocity:	40 km/hr (max.)
Wheel passes:	N.A
Load propulsion:	Truck loading
Power:	156 ps / 1900 rpm
Housing:	Outside
ENVIRONMENTAL CONTROL:	None
Instrumentation:	N.A





B5

ACRONYM: WesTrack

LOCATION: FHWA at Nevada Automotive Test Center
Reno, Nevada, U.S.A.

Commissioned: 1995
Costs: N.A

PAVEMENT CONFIGURATION
Testing length/Diameter: 2800 m (oval track)
Wheel path width: Trucks wander in the wheel path, mimicking real-world conditions
Size of test section: 26 test sections, each includes two 3.7m x 70m lanes with outside lane as test lane
Gantry length: N.A
Shed size: N.A
Length of test area: 1820 m

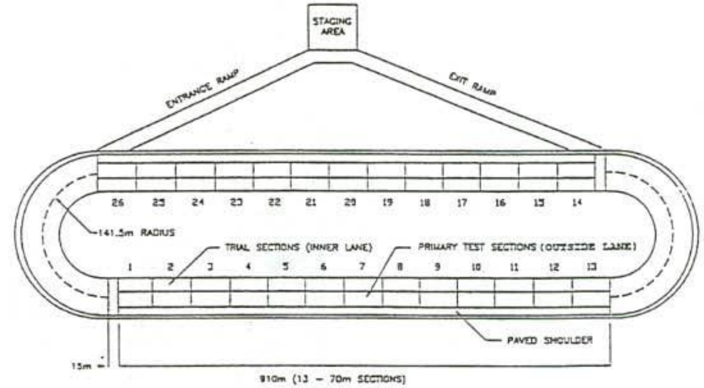
LOAD CONFIGURATION
Wheel configuration: Triple-trailer (front axle + tandem axle + five single axles
Wheel load: 53.4 kN + 178 kN + 5 X 89 kN
Wheel suspension: Steel spring
Wheel velocity: 65 km/hr
Wheel passes: 23 passes/hr

Load propulsion: Driven axle and towed axles
Power: Truck engine

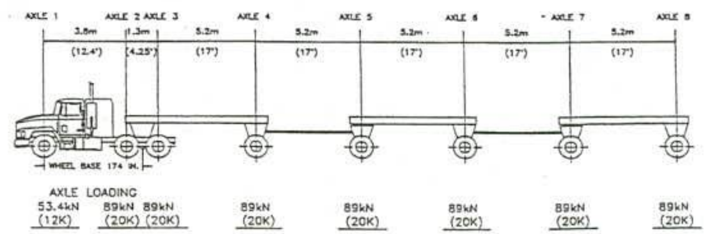
Housing: Outside

ENVIRONMENTAL CONTROL: None

Instrumentation: N.A



Layout of Test Track (not to scale)



Truck Configuration (not to scale)

B6

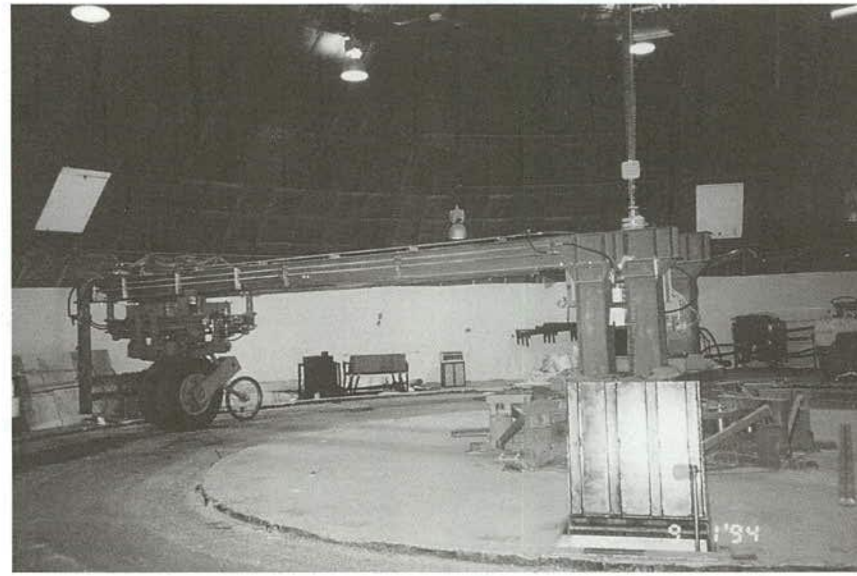
ACRONYM:	C-TIC
LOCATION:	Canadian Transportation Innovation Center Regina, Saskatchewan, Canada
Commissioned:	1978
Costs:	US$ 0.4 million

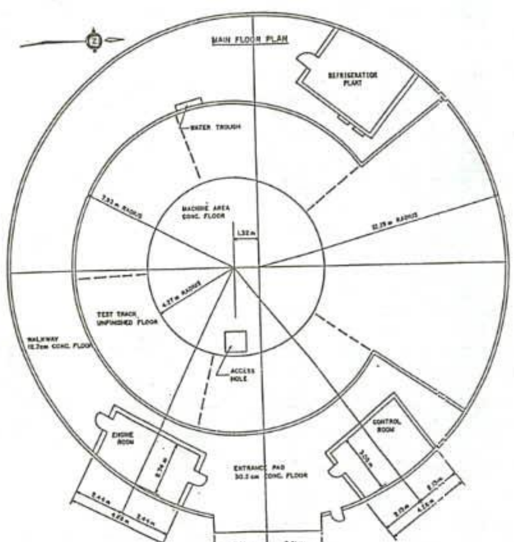
PAVEMENT CONFIGURATION

Testing length/Diameter:	D = 12 m
Wheel path width:	Typical wheel path = 1.2 m
Size of test section:	5 test sections (7.54 m long and 3.66 m wide)
Gantry length:	6.1 m from pivot to center of lane
Shed size:	24.4 m diameter
Length of test area:	N.A

LOAD CONFIGURATION

Wheel configuration:	Any commercial truck tire, free rolling, non-breaking, dual wheels
Wheel load:	40 kN - 60 kN, continuously monitored using load cells
Wheel suspension:	Disc springs
Wheel velocity:	18 km/hr (nominal), 28.8 km/hr (max.)
Wheel passes:	500 passes/hr (at nominal speed), programmable lane
Load propulsion:	Free rolling at center pivot
Power:	CGE 22 kW motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Temperature, freeze/thaw cycling, soil moisture, and road surface humidity, and ponged water against open slope can be simulated
Instrumentation:	Soil strain Temperature Time Domain Reflectometry (TDR) monitoring soil moisture Soil suction





B7

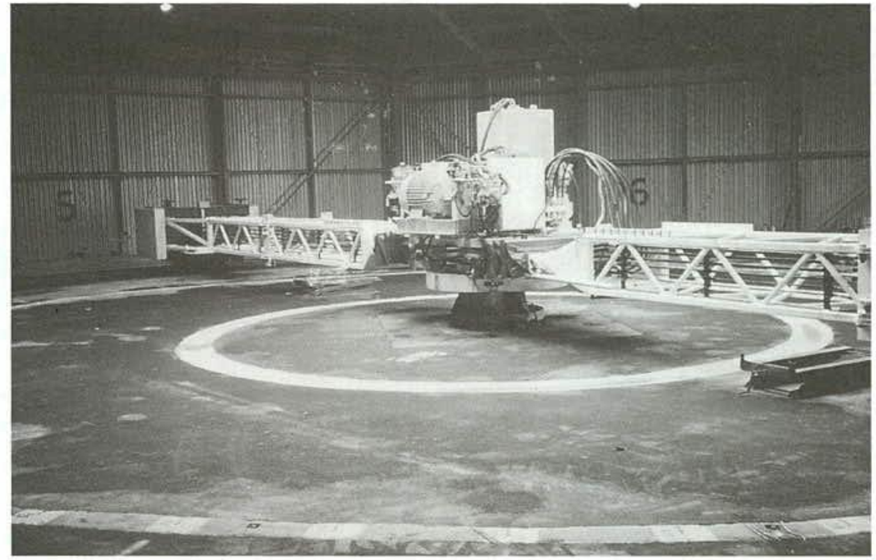
ACRONYM:	CAPTIF
LOCATION:	Department of Civil Engineering University of Canterbury Christchurch, New Zealand
Commissioned:	1987
Costs:	US$ 0.3 million

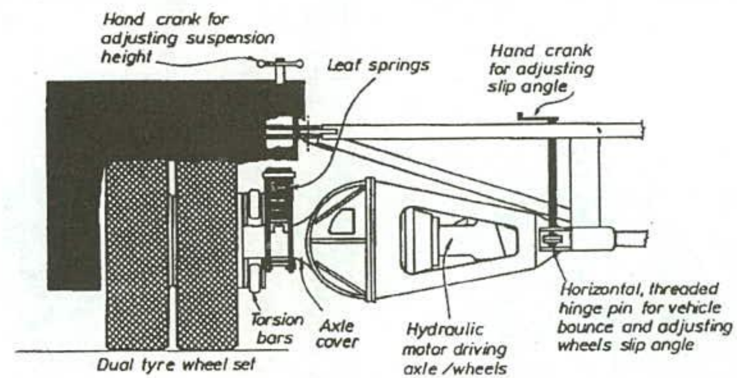
PAVEMENT CONFIGURATION

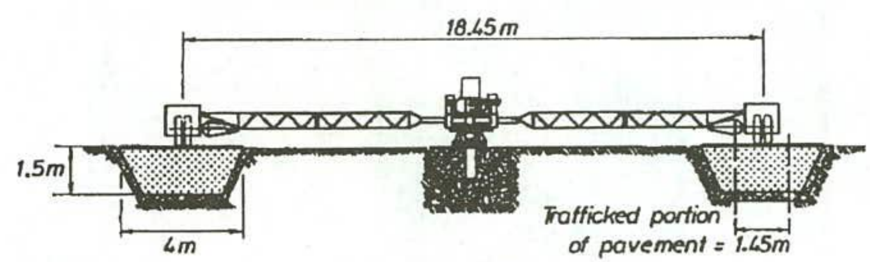
Testing length/Diameter:	D= 18.4 m
Wheel path width:	1.45 m
Size of test section:	4 m wide and 45 m long (number of sections varying)
Gantry length:	N.A
Shed size:	28m x 28m
Length of test area:	N.A

LOAD CONFIGURATION

Wheel configuration:	Half axle: one or two wheels
Wheel load:	21 -60 kN
Wheel suspension:	Leaf spring, airbag or single-unit
Wheel velocity:	1 - 50 km/hr
Wheel passes:	Depends on speed - up to 1700 passes/hr
Load propulsion:	Driven wheels
Power:	55 kW motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial
Instrumentation:	Strain (surface/base, base/ subbase, subways/subgrade) Pressure (subbase/ subgrade) Temperature Moisture







ELEVATION

B8

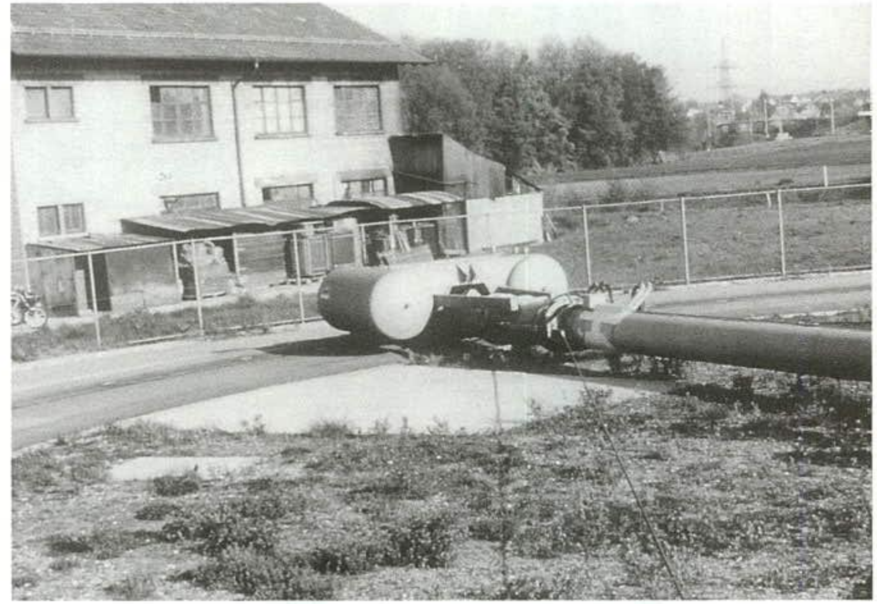
ACRONYM:	ISETH
LOCATION:	Federal Institute of Technology Zurich, Switzerland
Commissioned:	1979
Costs:	US$ 0.75 million

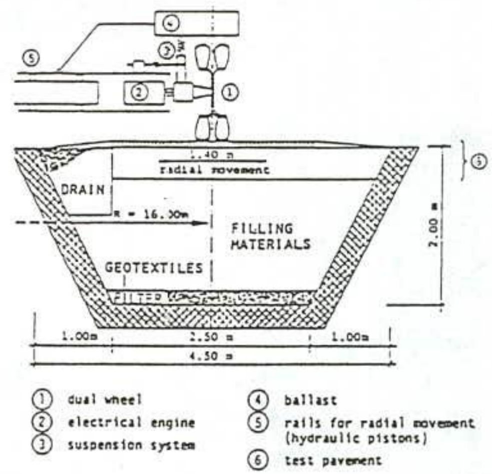
PAVEMENT CONFIGURATION

Testing length/Diameter:	D=32 m
Wheel path width:	1.3 m
Size of test section:	1.3 m wide, typically 100m long
Gantry length:	N.A
Shed size:	N.A
Length of test area:	32 m x 32 m

LOAD CONFIGURATION

Wheel configuration:	Three arms with dual wheels
Wheel load:	50 - 80 kN
Wheel suspension:	None
Wheel velocity:	80 km/hr (max.), 60 km/hr (average)
Wheel passes:	800 passes/hr
Load propulsion:	Driven wheels
Power:	Electrical motor
Housing:	Outside + fixed
ENVIRONMENTAL CONTROL:	Partial (heating and cooling elements)
Instrumentation:	N.A





B9

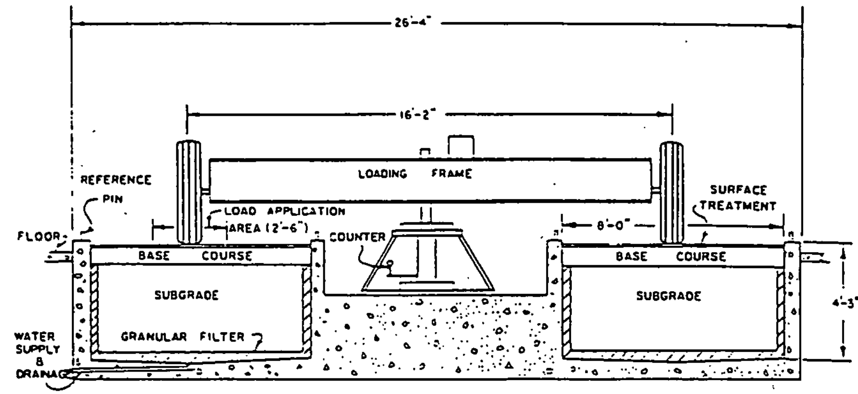
ACRONYM:	IUT
LOCATION:	University of Illinois Urbana, Illinois, U.S.A.
Commissioned:	1963 - 1983
Costs:	N.A

PAVEMENT CONFIGURATION

Testing length/Diameter:	D=4.8 m
Wheel path width:	0.76 m (max.)
Size of test section:	2.4 m wide and 15.3 m long (6 sections)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	16.8 m x 16.8 m

LOAD CONFIGURATION

Wheel configuration:	Single wheel
Wheel load:	29.51 kN (max.), 14.53 kN (normal)
Wheel suspension:	None
Wheel velocity:	3 - 15 km/hr
Wheel passes:	6000 passes/hr
Load propulsion:	Free rolling wheel
Power:	Electrical motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	None
Instrumentation:	LVDT - measuring deflection



Sectional View of the University of Illinois Circular Test Track.

B10

ACRONYM: JHPC

LOCATION: Laboratory of Japan Highway Public Corporation
Machida City, Japan

Commissioned: 1979
Costs: N.A

PAVEMENT CONFIGURATION
Testing length/Diameter: D=6 m
Wheel path width: ± 0.2 m
Size of test section: 12 Trapezoid test pieces. Standard test piece: long-side 1.82 m, short-side 1.34 m, width = 0.9 m, depth = 0.8 m
Gantry length: N.A
Shed size: N.A
Length of test area: N.A

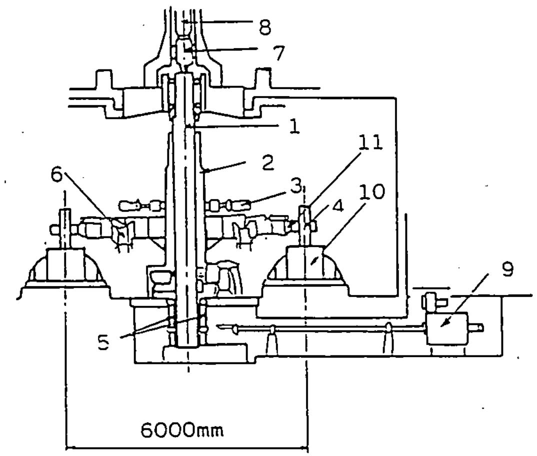
LOAD CONFIGURATION
Wheel configuration: 10.00 - 20 - 14 PR truck tires
Wheel load: 0 - 30 kN
Wheel suspension: None
Wheel velocity: 10 - 60 km/hr for Outer Orbit
Wheel passes: 3600 passes/hr (max.)

Load propulsion: Wheel arm pulled
Power: Electrical motor

Housing: Inside

ENVIRONMENTAL CONTROL: Temperature from -20 to 60 degree centigrade
Rainfall by sprinkle

Instrumentation: N.A



1·center column
2·rotating frame
3·torque motor
4·wheel
5·load adding device
6·oil cylinder
7·rotating joint
8·slip ring
9. Electrical motor
10·test piece
11·spacer

B11

ACRONYM: LCPC

LOCATION: Laboratoire Central des Ponts et Chausse'es
Nantes, France

Commissioned: 1978
Costs: US$ 5 million

PAVEMENT CONFIGURATION
Testing length/Diameter: D=38 m
Wheel path width: ±0.5 m
Size of test section: 6 m wide and 120 m long (the number of sections varying)
Gantry length: N.A
Shed size: N.A
Length of test area: 40 m x 40 m for each test site

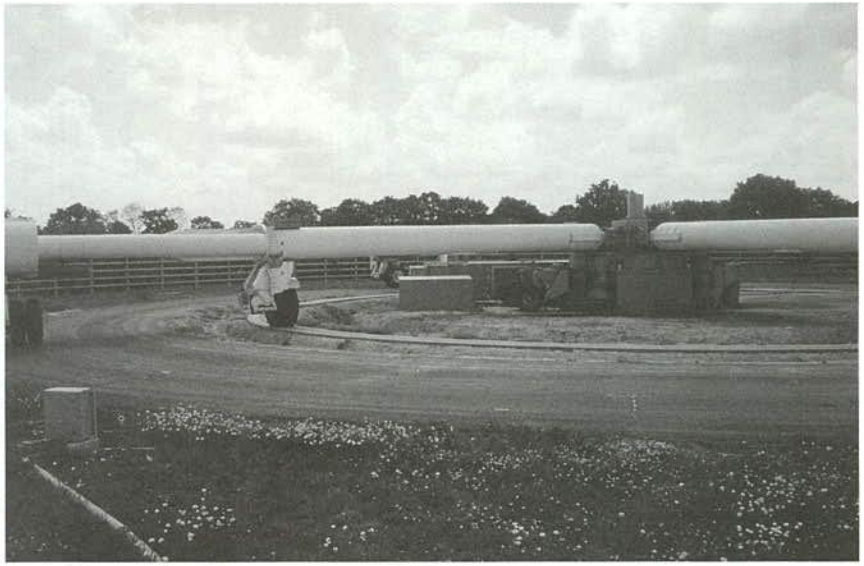
LOAD CONFIGURATION
Wheel configuration: Four arms with single or tandem axles load with single or dual wheels (40 to 140 kN)
Wheel load: 40 - 140 kN
Wheel suspension: Pneumatic suspension
Wheel velocity: 30 - 100 km/hr
Wheel passes: 1020 - 3600 passes/hr

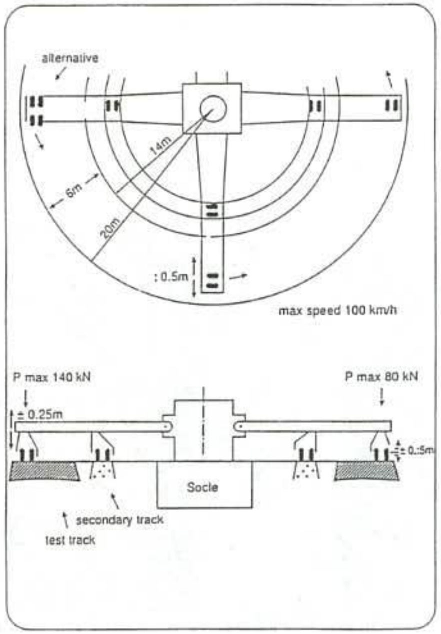
Load propulsion: Free rolling wheel
Power: 750 kW motor

Housing: Outside

ENVIRONMENTAL CONTROL: Rain falls, water level, temperature

Instrumentation: Strain (surface/base/ subways/ subgrade)
Pressure (base/subways/subgrade)
Temperature measurer
Moisture
Dynamic deflection





B12

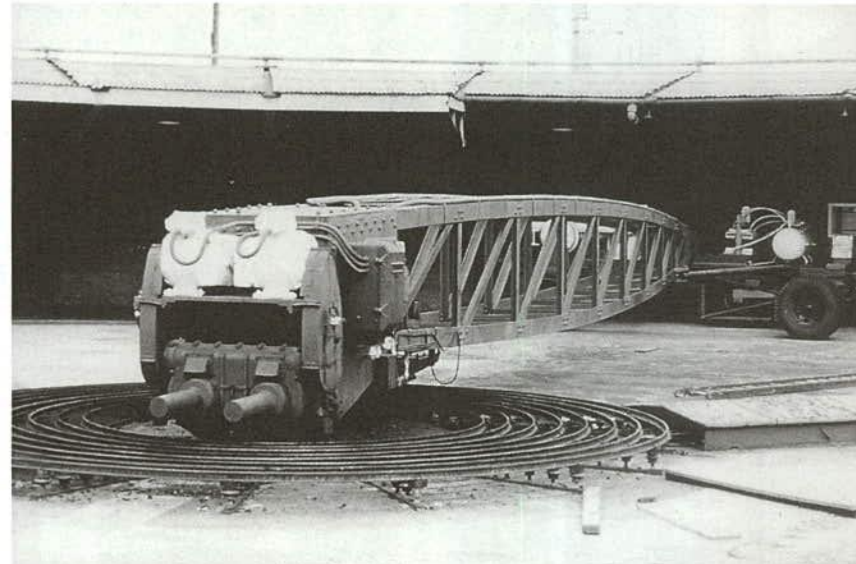
ACRONYM:	Road Machine
LOCATION:	Transport and Research Laboratory Harmondsworth, United Kingdom
Commissioned:	1963
Costs:	N.A

PAVEMENT CONFIGURATION

Testing length/Diameter:	D = 34 m
Wheel path width:	N.A
Size of test section:	N.A
Gantry length:	N.A
Shed size:	Circular roof
Length of test area:	N.A

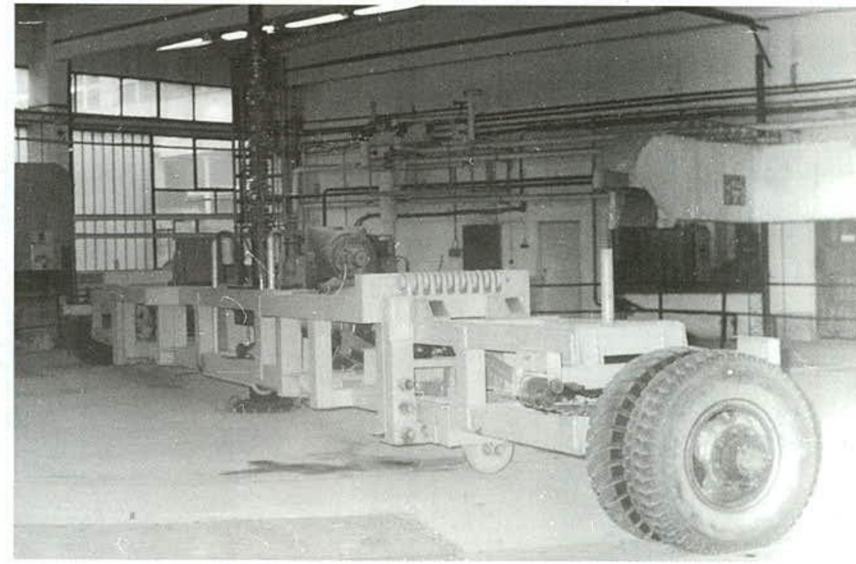
LOAD CONFIGURATION

Wheel configuration:	A pneumatically loaded single wheel
Wheel load:	49 kN and 67 kN used in the past
Wheel suspension:	N.A
Wheel velocity:	N.A
Wheel passes:	N.A
Load propulsion:	A central bearing pivot with a radius arm
Power:	Electrical motor
Housing:	Inside + fixed
ENVIRONMENTAL CONTROL:	Partial (temperature controlled)
Instrumentation:	N.A



B13

ACRONYM:	RRT
LOCATION:	Technical University Iassy, Romania
Commissioned:	1982
Costs:	US$ 0.42 million



PAVEMENT CONFIGURATION

Testing length/Diameter:	D = 16.4 m
Wheel path width:	N.A
Size of test section:	N.A
Gantry length:	N.A
Shed size:	N.A
Length of test area:	N.A

LOAD CONFIGURATION

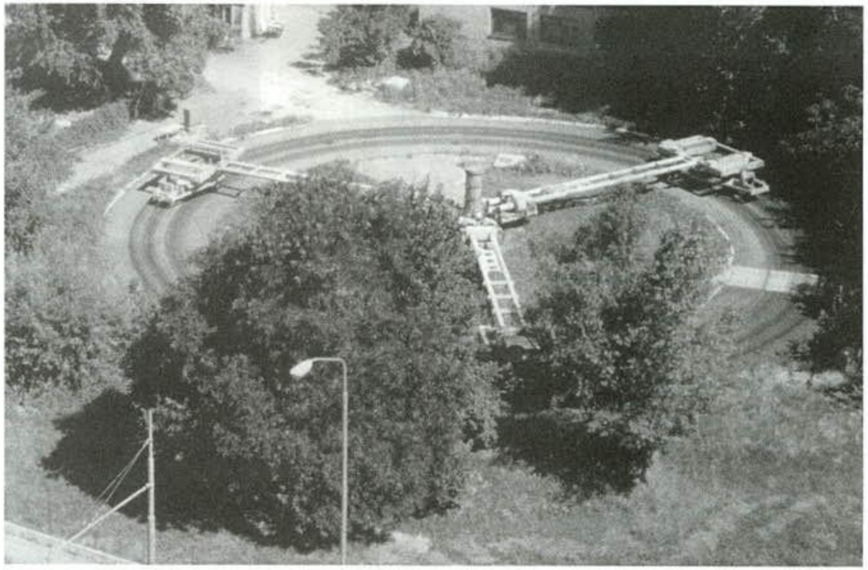
Wheel configuration:	Dual wheel
Wheel load:	45.5 kN
Wheel suspension:	Steel spring
Wheel velocity:	5.0 km/hr (min.), 21 km/h (usual), 40 km/h (max.)
Wheel passes:	333 - 410 passes/hr
Load propulsion:	Driven axle
Power:	70 kW electrical motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial (temperature controlled: heating and freezing)
Instrumentation:	Pressure (surface/base interface, base/subways interface) Temperature

B14

ACRONYM:	Shell
LOCATION:	Koninklijke / Shell-Laboratorium Amsterdam, The Netherlands
Commissioned:	1967
Costs:	N.A
PAVEMENT CONFIGURATION	
Testing length/Diameter:	D = 3 m
Wheel path width:	0.7 - 0.9 m
Size of test section:	0.9 m wide and 9.4 m long
Gantry length:	N.A
Shed size:	N.A
Length of test area:	N.A
LOAD CONFIGURATION	
Wheel configuration:	
Wheel load:	1 - 20 kN
Wheel suspension:	N.A
Wheel velocity:	1 - 20 km/hr
Wheel passes:	2123 passes/hr
Load propulsion:	N.A
Power:	Electrical motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial
Instrumentation:	Tensile strains between asphalt concrete and gravel sand asphalt

B15

ACRONYM:	S-KSD
LOCATION:	Vuis - Cesty Bratislava, Slovakia
Commissioned:	1994
Costs:	N.A



PAVEMENT CONFIGURATION

Testing length/Diameter:	D = 32 m
Wheel path width:	1.9 m
Size of test section:	100 m
Gantry length:	N.A
Shed size:	N.A
Length of test area:	N.A

LOAD CONFIGURATION

Wheel configuration:	3 arms, each with full axle (4 wheels)
Wheel load:	83 - 130 kN
Wheel suspension:	Trolley bus, 2 leaf springs
Wheel velocity:	10 - 50 km/hr
Wheel passes:	> 300 passes/hr
Load propulsion:	Drive wheel
Power:	Electrical motor
Housing:	Outside
ENVIRONMENTAL CONTROL:	None
Instrumentation:	N.A

B16

ACRONYM: UCF

LOCATION: University of Central Florida
Gainesville, Florida, U.S.A.

Commissioned: 1988
Costs: US$ 0.25 million

PAVEMENT CONFIGURATION

Testing length/Diameter:	D = 15.6 m
Wheel path width:	No lateral movement
Size of test section:	N.A
Gantry length:	N.A
Shed size:	N.A
Length of test area:	16 m x 16 m

LOAD CONFIGURATION

Wheel configuration:	Three arms with two wheels
Wheel load:	45.4 - 136.2 kN
Wheel suspension:	None
Wheel velocity:	24 - 48 km/hr
Wheel passes:	500 - 1000 passes/hr
Load propulsion:	Drive wheel + free wheel
Power:	163.9 kW motor
Housing:	Outside + fixed

ENVIRONMENTAL CONTROL: None

Instrumentation: N.A

B17

ACRONYM:	UNAM
LOCATION:	Institute of Engineering The Universidad Nacional Autonoma de Mexico Mexico City, Mexico
Commissioned:	1970
Costs:	US$ 0.48 million
PAVEMENT CONFIGURATION	
Testing length/Diameter:	D = 13 m
Wheel path width:	2 m
Size of test section:	3 m wide and 9 m long (3 sections)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	13 m x 13 m
LOAD CONFIGURATION	
Wheel configuration:	Dual wheels (half axle)
Wheel load:	80 - 100 kN
Wheel suspension:	None
Wheel velocity:	4 - 40 km/hr
Wheel passes:	1000 passes/hr
Load propulsion:	Three arms + drive wheel (+ free wheel)
Power:	89.5 kW motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial (temperature controlled)
Instrumentation:	Strain (surface/base) Pressure (surface/base, base/subways, subways/subgrade) Temperature Moisture

B18

ACRONYM:	WSU
LOCATION:	Washington State Department of Transportation Pullman, Washington, U.S.A.
Commissioned:	1965
Costs:	N.A

PAVEMENT CONFIGURATION

Testing length/Diameter:	D = 26 m
Wheel path width:	1.2 m
Size of test section:	4 m wide and 81 m long (12 sections)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	Varying

LOAD CONFIGURATION

Wheel configuration:	Dual tires
Wheel load:	50.5 kN
Wheel suspension:	Steel leaf spring
Wheel velocity:	N.A
Wheel passes:	N.A
Load propulsion:	N.A
Power:	N.A
Housing:	Outside + fixed
ENVIRONMENTAL CONTROL:	None
Instrumentation:	Dynamic strains (Bison coil strain sensor pairs) Temperature Vertical wheel accelerations

B19

ACRONYM:	ALF
LOCATION:	ARRB Transport Research Ltd Melbourne Australia (used in 4 states)
Commissioned:	1984
Costs:	US$ 1 million

PAVEMENT CONFIGURATION

Testing length/Diameter:	12 m
Wheel path width:	Up to 1.4 m
Size of test section:	Varying
Gantry length:	N.A
Shed size:	N.A
Length of test area:	Varying

LOAD CONFIGURATION

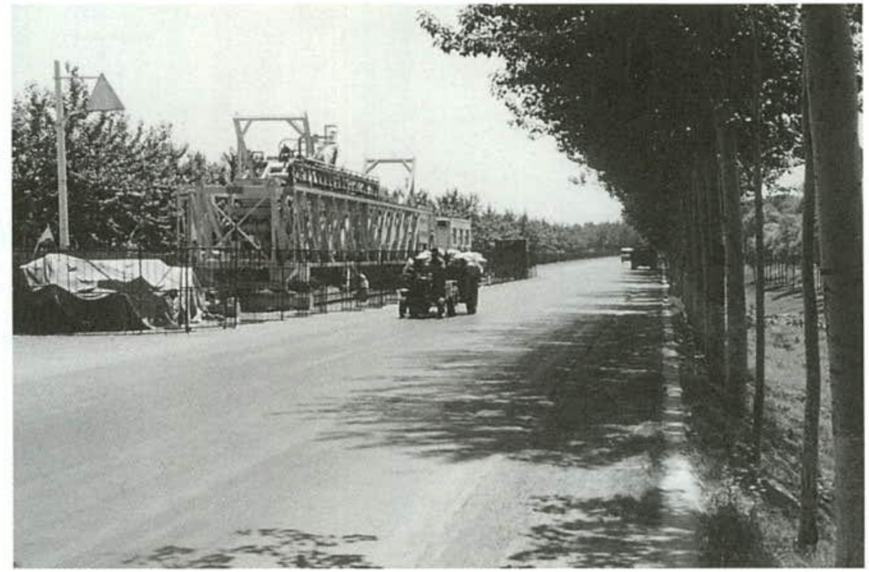
Wheel configuration:	Two wheel (half axle)
Wheel load:	40 - 80 kN
Wheel suspension:	Airbag
Wheel velocity:	1 km/hr (min.), 20 km/hr (usual and max.)
Wheel passes:	380 passes/hr
Load propulsion:	Drive wheel
Power:	40 -50 kW motor
Housing:	Outside
ENVIRONMENTAL CONTROL:	None
Instrumentation:	Multi-depth deflections Strain (surface/base/subways interface) Pressure (subways/subgrade interface) Temperature Moisture

B20

ACRONYM:	FHWA-PTF
LOCATION:	U.S. Department of Transportation Federal Highway Administration Washington D.C., U.S.A.
Commissioned:	1986
Costs:	US$ 1.1 million
PAVEMENT CONFIGURATION	
Testing length/Diameter:	12 m
Wheel path width:	Up to 1.4 m
Size of test section:	Fixed test field, 1 at one time (12 sections currently)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	Varying
LOAD CONFIGURATION	
Wheel configuration:	Dual tires (half axle)
Wheel load:	40 - 110 kN
Wheel suspension:	Airbag
Wheel velocity:	20 km/hr
Wheel passes:	380 passes/hr
Load propulsion:	Driven wheels
Power:	40 -50 kW motor
Housing:	Outside
ENVIRONMENTAL CONTROL:	None
Instrumentation:	Multi-depth deflections Strain (kyowa Hbar, Alberta research council gauge at the bottom of the laboratory-mix asphalt binder course) Temperature Moisture cell Rain

B21

ACRONYM:	RIOH-ALF
LOCATION:	Research Institute of Highway, The Ministry of Communications Beijing, China
Commissioned:	1990
Costs:	US$ 1 million
PAVEMENT CONFIGURATION	
Testing length/Diameter:	12 m
Wheel path width:	Up to 1.4 m
Size of test section:	120 m x 12 m (currently 12 sections at a site)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	Varying
LOAD CONFIGURATION	
Wheel configuration:	Dual tires (half axle)
Wheel load:	40 - 80 kN
Wheel suspension:	Airbag
Wheel velocity:	20 km/hr
Wheel passes:	380 passes/hr
Load propulsion:	Drive wheel
Power:	40 -50 kW motor
Housing:	Outside
ENVIRONMENTAL CONTROL:	None
Instrumentation:	Multi-depth deflections Strain (H-bar) Pressure Temperature (air and inside pavement)



B22

ACRONYM: PRF-LA

LOCATION: Louisiana Transportation Research Center
Louisiana State University
Baton Rouge, Louisiana, U.S.A.

Commissioned: 1995
Costs: US$ 1.8 million

PAVEMENT CONFIGURATION

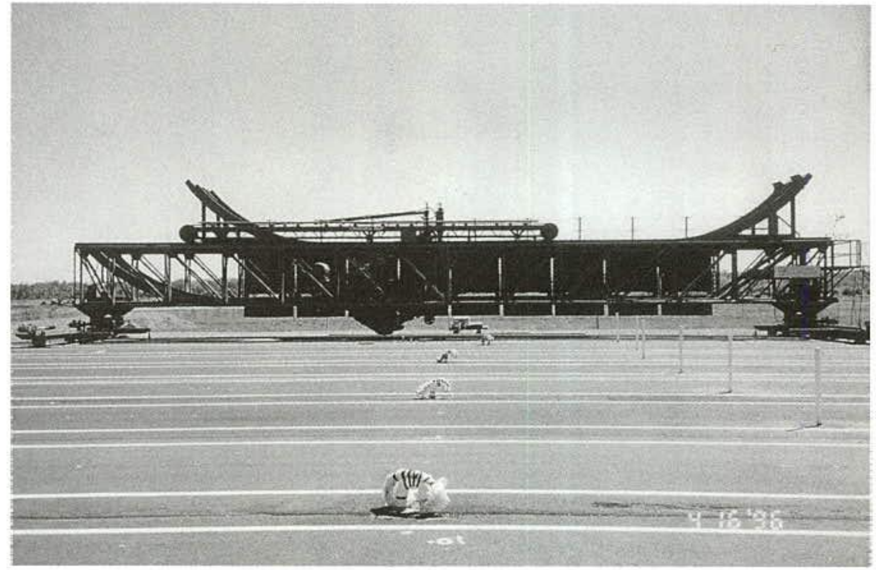
Testing length/Diameter:	12 m
Wheel path width:	Up to 1.4 m
Size of test section:	4m x 61m (currently 9 sections)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	Varying

LOAD CONFIGURATION

Wheel configuration:	Dual tires (half axle)
Wheel load:	40 - 80 kN
Wheel suspension:	Airbag
Wheel velocity:	20 km/hr
Wheel passes:	380 passes/hr
Load propulsion:	Drive wheel
Power:	40 - 50 kW motor
Housing:	Outside

ENVIRONMENTAL CONTROL: None

Instrumentation: Partial depth deflection
Strain (surface/base/subways interface)
Pressure (subways/subgrade interface)
Temperature
Moisture



B23

ACRONYM: DRTM

LOCATION: Technical University of Denmark
Lyngby, Denmark

Commissioned: 1973
Costs: US$ 0.2 million

PAVEMENT CONFIGURATION

Testing length/Diameter: 9 m
Wheel path width: N.A
Size of test section: 9 m long and 2.5 m wide
Gantry length: N.A
Shed size: N.A
Length of test area: 27.5 m long and 4 m wide

LOAD CONFIGURATION

Wheel configuration: Dural or single wheel
Wheel load: 65 kN (max.)
Wheel suspension: N.A
Wheel velocity: 25 - 30 km/hr (max.)
Wheel passes: 417 passes/hr

Load propulsion: Cable pulled
Power: Electrical motor

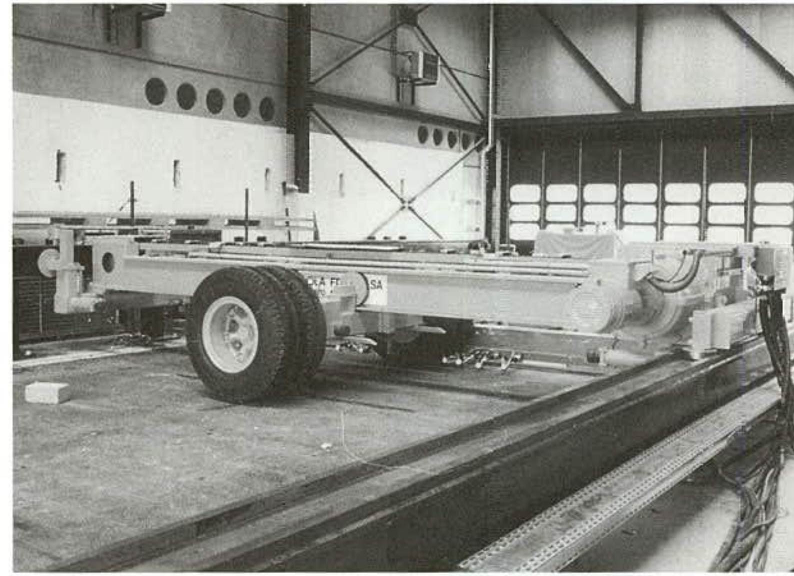
Housing: Inside

ENVIRONMENTAL CONTROL: partial (climate chamber, heat and cold controlled)

Instrumentation: Pressure
Strain
Thermocouple
Asphalt strain gauge
Deflection
Pore-water pressure

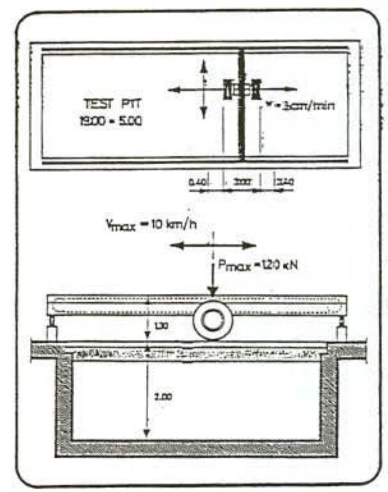
B24

ACRONYM:	EPFL
LOCATION:	Ecole Polytechnique Federale de Lausanne Lausanne, Switzerland
Commissioned:	1977
Costs:	N.A



PAVEMENT CONFIGURATION

Testing length/Diameter:	4 m (max.)
Wheel path width:	0.8 m
Size of test section:	4m x 3m (max.)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	N.A



LOAD CONFIGURATION

Wheel configuration:	A truck axle with dual wheels
Wheel load:	Up to 120 kN
Wheel suspension:	N.A
Wheel velocity:	10 km/hr (max.)
Wheel passes:	N.A
Load propulsion:	N.A
Power:	Electrical motor
Housing:	Inside + fixed
ENVIRONMENTAL CONTROL:	Partial
Instrumentation:	N.A

B25

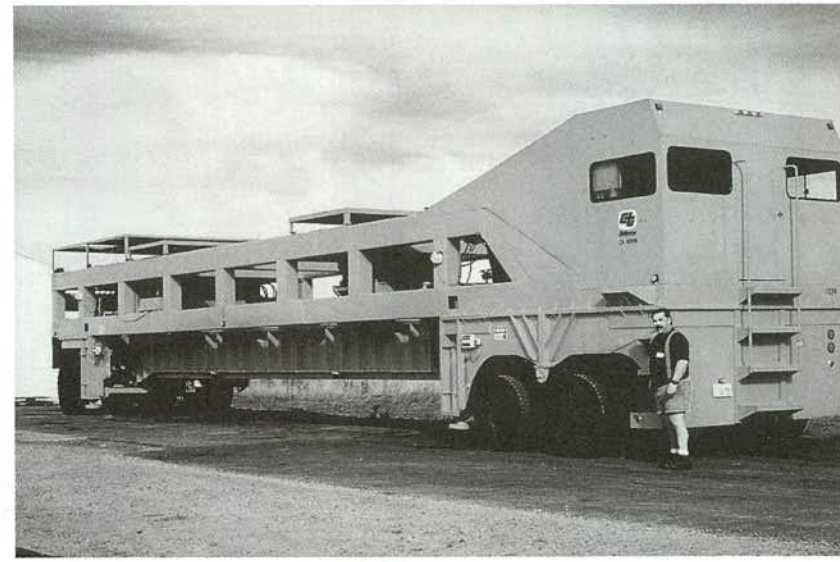
ACRONYM:	HVS
LOCATION:	CSIR, Division of Road and Transport Technology Pretoria, South Africa (used in several provinces)
Commissioned:	1971
Costs:	N.A

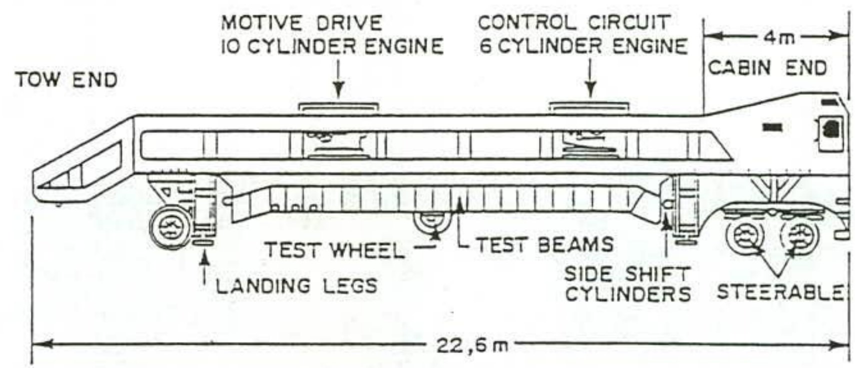
PAVEMENT CONFIGURATION

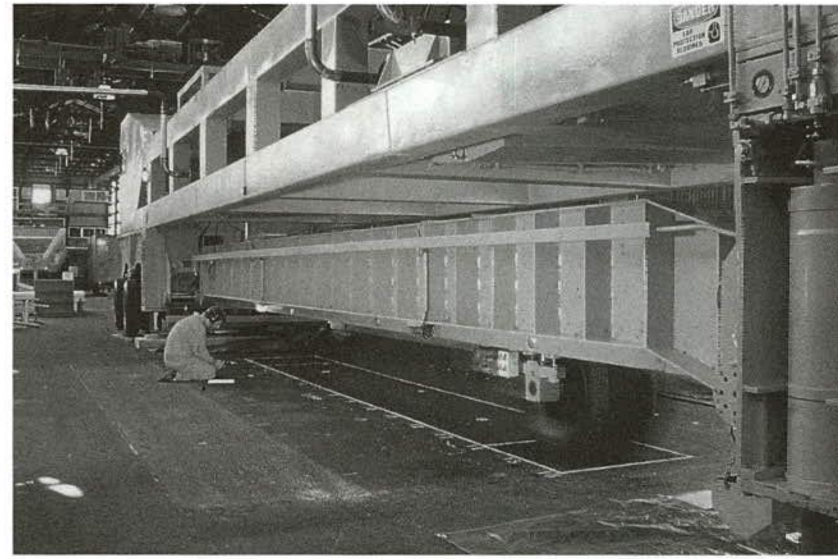
Testing length/Diameter:	8 m
Wheel path width:	1.5 m (variable)
Size of test section:	At least 8m x 1.5m, normally part of a highway
Gantry length:	N.A
Shed size:	N.A
Length of test area:	Selected lanes of highway

LOAD CONFIGURATION

Wheel configuration:	Half-axle, single or dual tyre for truck configuration Single aircraft tyre for aircraft pavement testing
Wheel load:	20 -100 kN for road pavement testing Up to 150 kN for aircraft pavement testing
Wheel suspension:	None, hydraulic load
Wheel velocity:	12 km/hr over main test section
Wheel passes:	950 passes/hr (average)
Load propulsion:	Rolling wheel propelled by hydraulic motor
Power:	166 - 189 kW diesel motor
Housing:	Outside
ENVIRONMENTAL CONTROL:	Radiant heaters enclosed around test area, surface and subsurface watering system
Instrumentation:	Strain Crack measuring transducer Crack activity meter Surface deflectometer Multi-depth deflections Thermocouples Profilometer (either laser or mechanical)



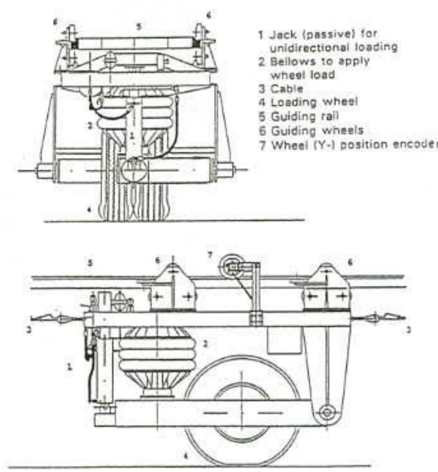




B26	
ACRONYM:	CAL-APT
LOCATION:	California Department of Transportation Richmond, California , U.S.A.
Commissioned:	1994
Costs:	US$ 1.75 million (for two heavy vehicle simulators)
PAVEMENT CONFIGURATION	
Testing length/Diameter:	8 m
Wheel path width:	1.5 m (variable)
Size of test section:	At least 8m x 1.5m, normally part of a highway
Gantry length:	N.A
Shed size:	N.A
Length of test area:	Selected lanes of highway
LOAD CONFIGURATION	
Wheel configuration:	Half-axle, single or dual tyre for truck configuration Single aircraft tyre for aircraft pavement testing
Wheel load:	20 -100 kN for road pavement testing Up to 150 kN for aircraft pavement testing
Wheel suspension:	None, hydraulic load
Wheel velocity:	12 km/hr over main test section
Wheel passes:	950 passes/hr (average)
Load propulsion:	Rolling wheel propelled by hydraulic motor
Power:	166 - 189 kW diesel motor
Housing:	Outside
ENVIRONMENTAL CONTROL:	Radiant heaters enclosed around test area, surface and subsurface watering system
Instrumentation:	Strain Crack measuring transducer Crack activity meter Surface deflectometer Multi-depth deflections Thermocouples Profilometer (either laser or mechanical) Moisture content (TDR)

B27

ACRONYM:	LINTRACK
LOCATION:	Road and Railroad Research Laboratory, Faculty of Civil Engineering, Delft University of Technology. Delft, The Netherlands
Commissioned:	1991
Costs:	US$ 1.0 million
PAVEMENT CONFIGURATION	
Testing length/Diameter:	11.5 m total: 3.5 m constant velocity
Wheel path width:	2 m
Size of test section:	18 m long, 4 m wide
Gantry length:	20 m
Shed size:	23 m long, 6 m wide, 5 m high
Length of test area:	55 m
LOAD CONFIGURATION	
Wheel configuration:	Free rolling dual or single tire truck wheel
Wheel load:	15 - 100 kN adjustable with pneumatic bellows
Wheel suspension:	Airbag
Wheel velocity:	20 km/h(max.)
Wheel passes:	About 1000 per hour, two way loading. One way loading possible with ramp and hydraulic jack
Load propulsion:	steel cable on drum
Power:	80 kW electrical motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial (temperature controlled)
Instrumentation:	asphalt strain (longitudinal and transverse) vertical soil pressure thermometers (air, surface and various depths)

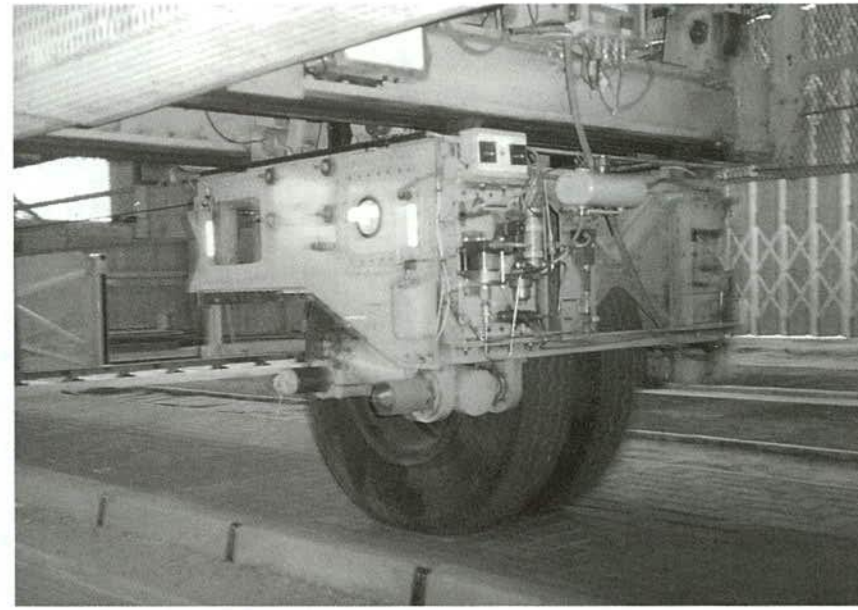


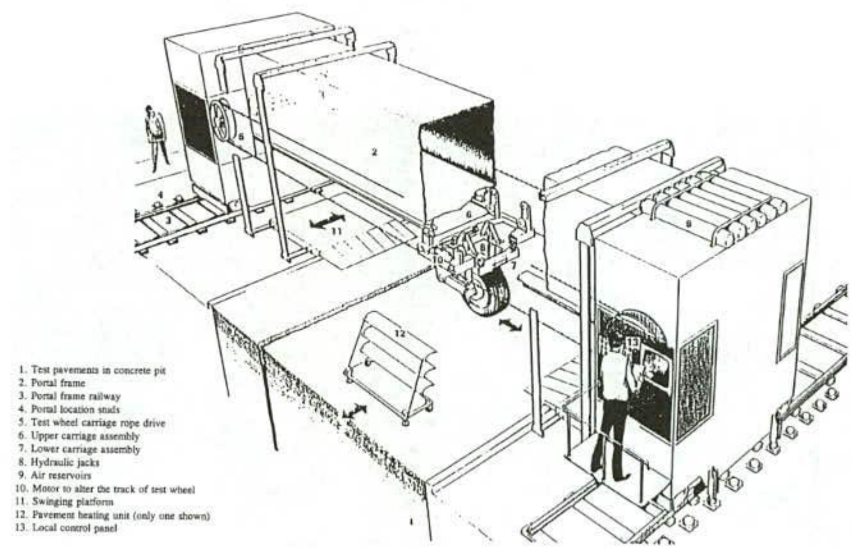
B28

ACRONYM:	Minne-ALF
LOCATION:	University of Minnesota Minneapolis, Minnesota, U.S.A.
Commissioned:	1990
Costs:	US$ 0.2 million
PAVEMENT CONFIGURATION	
Testing length/Diameter:	2.43 m
Wheel path width:	0.2 m
Size of test section:	Pavement specimen up to 4.6 m long and 3.7 m wide
Gantry length:	N.A
Shed size:	N.A
Length of test area:	>4.6 m
LOAD CONFIGURATION	
Wheel configuration:	Single tire, half-axle (expandable up to dual tire, full axle)
Wheel load:	Up to 110 kN
Wheel suspension:	None
Wheel velocity:	Variable, 88 km/hr (normal)
Wheel passes:	3600 - 7200 passes/hr
Load propulsion:	Rocking arc driven by two hydraulic actuators
Power:	150 GPM hydraulic pump
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial (simulated with heat-lamps or blankets)
Instrumentation:	Strain LVDT Temperature

B29

ACRONYM:	PTF
LOCATION:	Transport and Road Research Laboratory Crowthonne, United Kingdom
Commissioned:	1984
Costs:	US$ 1.7 million
PAVEMENT CONFIGURATION	
Testing length/Diameter:	10 m (7 m of central travel - wheel speed controllable)
Wheel path width:	1 m
Size of test section:	10 m long, 2.5 m wide (10 section)
Gantry length:	N.A
Shed size:	N.A
Length of test area:	25 m long and 10 m wide test pit
LOAD CONFIGURATION	
Wheel configuration:	Free rolling dual or single lorry wheel
Wheel load:	Up to 100 kN (in both or single direction)
Wheel suspension:	
Wheel velocity:	1 - 20 km/hr
Wheel passes:	1000 passes/hr (max.)
Load propulsion:	Cable pulled assembly
Power:	Electrical motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial (pavement temperature controlled: heat)
Instrumentation:	tensile strain Temperature Rutting





The Road Tester

B30

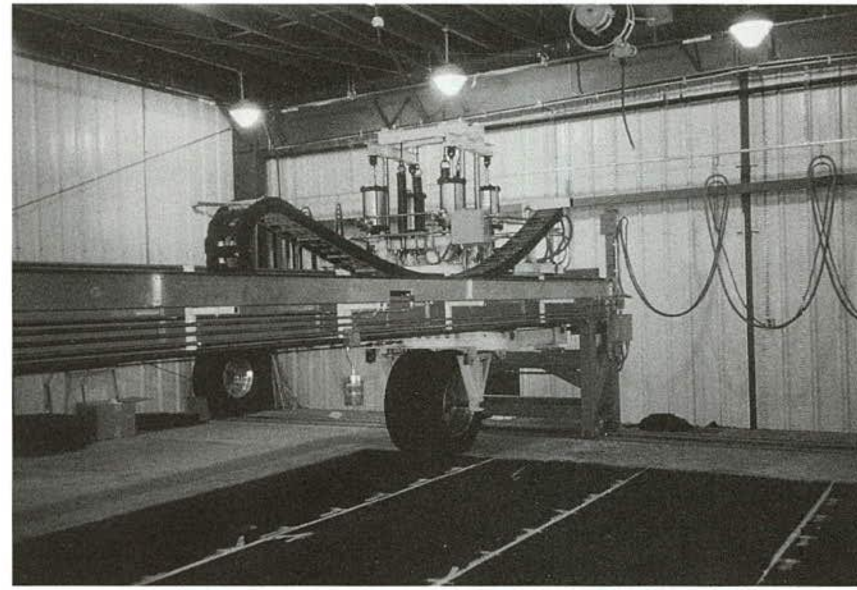
ACRONYM:	INDOT/PURDUE
LOCATION:	Division of Research Indiana Department of Transportation West Lafayette, Indiana, U.S.A.
Commissioned:	1992
Costs:	US$ 0.14 million

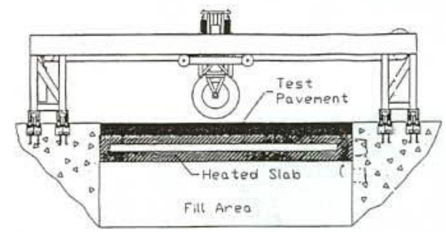
PAVEMENT CONFIGURATION

Testing length/Diameter:	6 m
Wheel path width:	± 0.2 m
Size of test section:	6 x 6 m (4 lanes) for initial tests
Gantry length:	N.A
Shed size:	N.A
Length of test area:	Varying

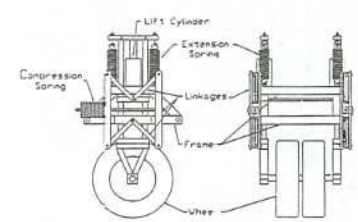
LOAD CONFIGURATION

Wheel configuration:	1 or 2 tires (half axle)
Wheel load:	Up to 90.7 kN (bi-directional or unidirectional)
Wheel suspension:	None
Wheel velocity:	8 km/hr
Wheel passes:	1333 passes/hr
Load propulsion:	Free wheel
Power:	Electrical motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial (temperature controlled from below pavement)
Instrumentation:	Strain Temperature





Schematic diagram of APT



B31

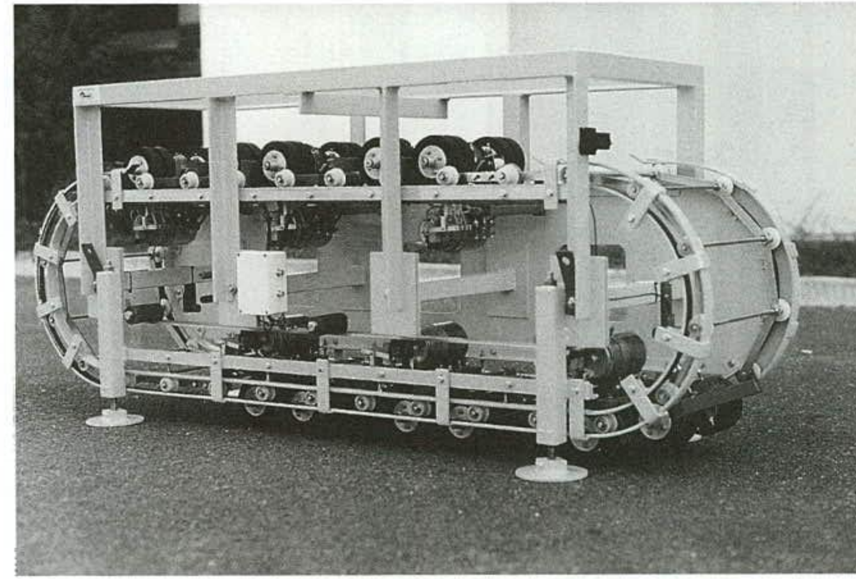
ACRONYM:	TxMLS
LOCATION:	The Texas Department of Transportation (TxDoT) U.S.A.
Commissioned:	1995
Costs:	US$ 2.5 million

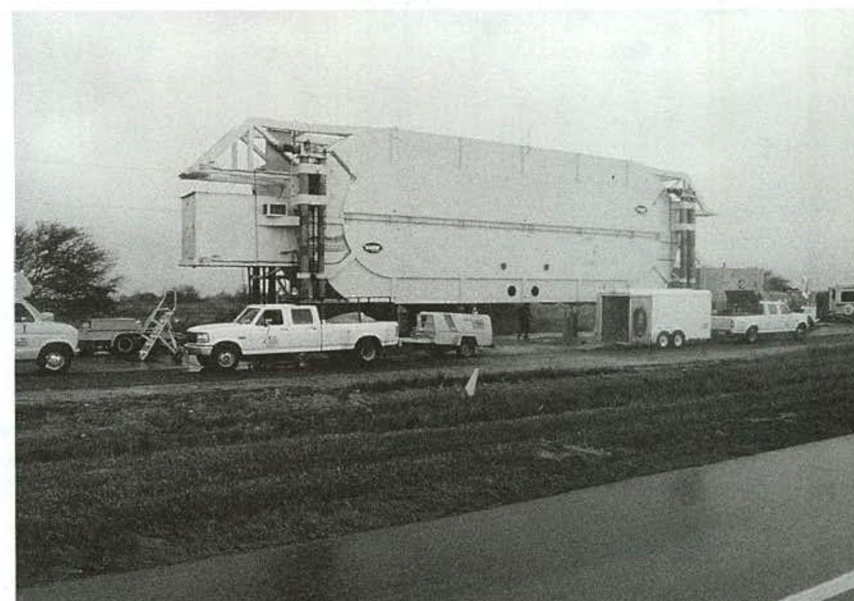
PAVEMENT CONFIGURATION

Testing length/Diameter:	11.1 m traffic length, 26.4 m other testing length
Wheel path width:	0.6 m
Size of test section:	1 or 2 wheel paths at a time
Gantry length:	40m x 3.8m x 4m
Shed size:	N.A
Length of test area:	As needed

LOAD CONFIGURATION

Wheel configuration:	6 bogies, 12 axles
Wheel load:	Single wheel: 22.2 - 111.2 kN, Dual wheels: 35.6 - 191.3 kN
Wheel suspension:	Standard truck suspensions
Wheel velocity:	32.2 km/hr (usual), 41.5 km/hr (max.)
Wheel passes:	8800 passes/hr (average)
Load propulsion:	Driven axle
Power:	Electrical motor (on two drive bogies)
Housing:	Outside + fixed or mobile
ENVIRONMENTAL CONTROL:	Partial (closed chamber, temperature controlled)
Instrumentation:	N.A





B32

ACRONYM: CEDEX

LOCATION: Road Research Center
Madrid, Spain

Commissioned: 1987
Costs: US$ 2.1 million

PAVEMENT CONFIGURATION
Testing length/Diameter: Two linear straights with 150 m, plus two curves and road 1.1 m
Wheel path width: 1.1 m
Size of test section: 6 sections with 25 m, plus two curves with 150m for testing surface courses and road paintings
Gantry length: N.A
Shed size: N.A
Length of test area: 305 m

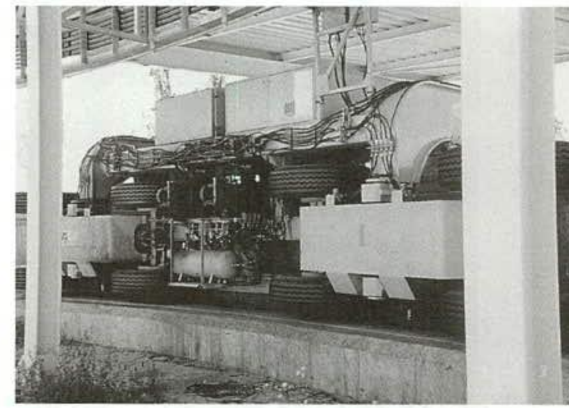
LOAD CONFIGURATION
Wheel configuration: Single half axle (Tandem half axle for modified one)
Wheel load: 55 - 75 kN per single half axle
Wheel suspension: Steel leaf spring
Wheel velocity: 1 - 60 km/hr
Wheel passes: About 200 passes/ hr/vehicle (2 vehicles)

Load propulsion: Driven wheels
Power: Electrical motor

Housing: Outside + sheltered test sections

ENVIRONMENTAL CONTROL: Partial (Ambient)

Instrumentation: Vertical strain (granular layers)
Horizontal strain (treated layers)
Pressure
Temperature
Moisture
Total deflectometer (LVDT)



B33

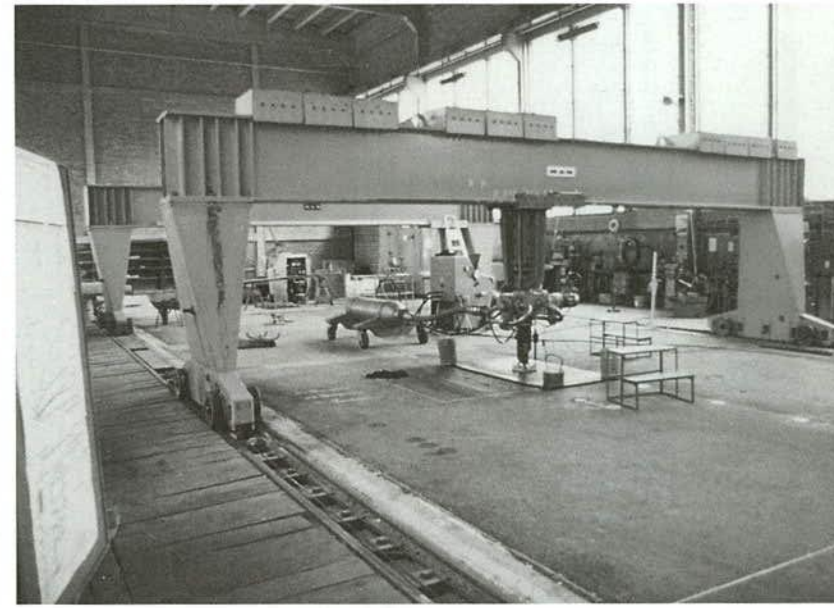
ACRONYM:	BASt
LOCATION:	Bundesanstalt fur Strassenwesen (BASt) Bergisch Gladbach, Germany
Commissioned:	1963
Costs:	N.A

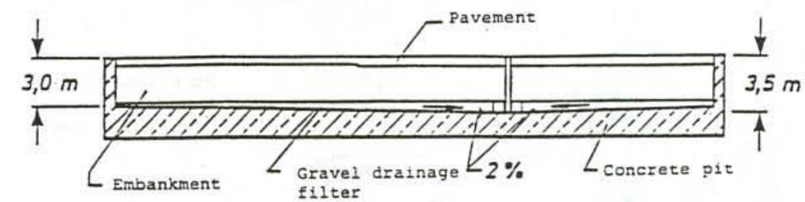
PAVEMENT CONFIGURATION

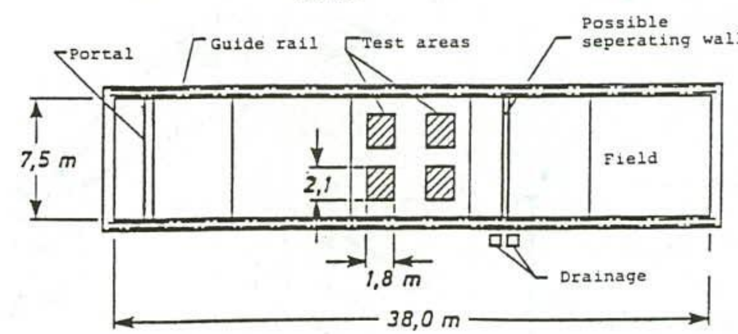
Testing length/Diameter:	1.8 m x 2.1 m
Wheel path width: plate	A circular plate of 0.3 m in diameter (1/2 width of moving laterally)
Size of test section:	5 pavement structure pits each with four test area of 1.8 m wide and 2.1 m long
Gantry length:	N.A
Shed size:	N.A
Length of test area:	38 m

LOAD CONFIGURATION

Wheel configuration:	A circular plate of 0.3 m in diameter
Wheel load:	20 - 100 kN
Wheel suspension:	N.A
Wheel velocity:	2 pulses/ sec.
Wheel passes:	8985 pulses/hr (1452 passes/hr)
Load propulsion:	Hydraulic system
Power:	Electrical motor
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial (drainage control, heating and freezing control)
Instrumentation:	Strain (base/subbase interface) Pressure (subbse/subgrade interface) Temperature (air, pavement surface and inside pavement) Water table







B34

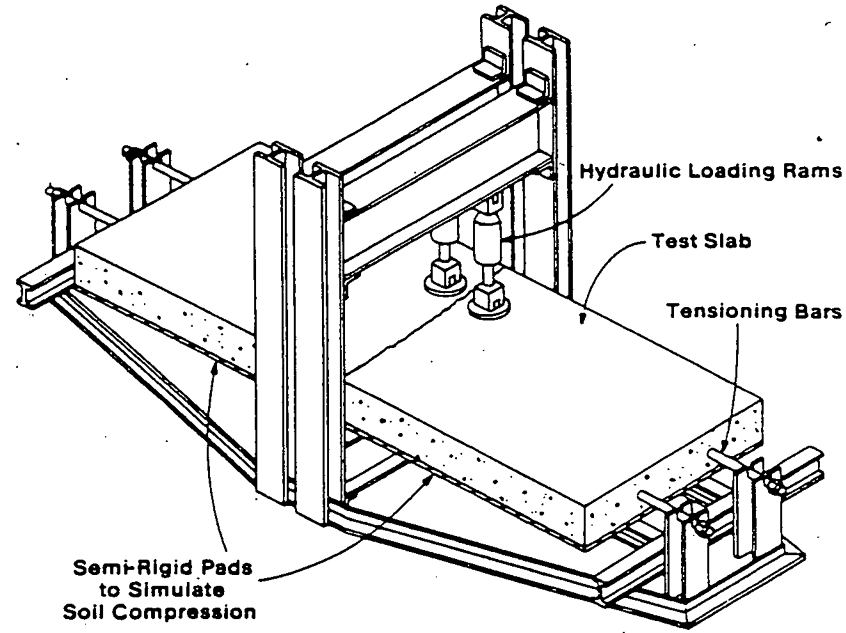
ACRONYM:	MSU
LOCATION:	Michigan State University East Lansing, Michigan, U.S.A.
Commissioned:	1990
Costs:	US$ 0.1 million

PAVEMENT CONFIGURATION

Testing length/Diameter:	3 m
Wheel path width:	0.3 m
Size of test section:	1.4 m x 3.1 m
Gantry length:	N.A
Shed size:	13.7 m x 6.1 m
Length of test area:	3 m

LOAD CONFIGURATION

Wheel configuration:	One wheel - half axle
Wheel load:	Up to 45 kN
Wheel suspension:	None
Wheel velocity:	88 km/hr
Wheel passes:	15,120 passes/hr
Load propulsion:	A composite sinusoidal load profile is generated by 2 autuators to simulate a wheel crossing a crack
Power:	As need for MTS hydraulic and data acquisition equipment
Housing:	Inside
ENVIRONMENTAL CONTROL:	Partial (moisture and temperature)
Instrumentation:	Controller for collecting loading histories Vertical deflection on each side of joint/crack Crack/joint opening Slab tension Air temperature and humidity



B35

ACRONYM: PHRI

LOCATION: Port and Harbor Research Institute
Yokosuka City, Japan

Commissioned: 1969
Costs: N.A

PAVEMENT CONFIGURATION
Testing length/Diameter: 12 m
Wheel path width: N.A
Size of test section: 12 m long, 10 m wide, and 4 m deep
Gantry length: N.A
Shed size: N.A
Length of test area: N.A

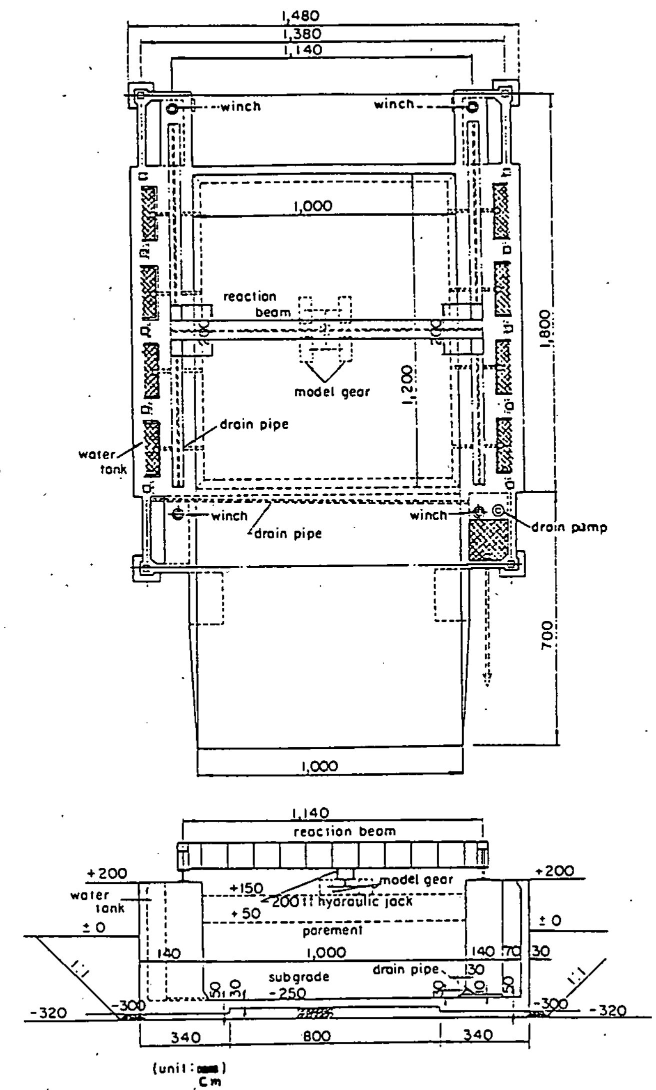
LOAD CONFIGURATION
Wheel configuration: 1 model gear having a dual - tandem wheel assembly and a 200 ton hydraulic jack for static loading, a 50 ton actuator with the frequency range of 0.001 to 5 cycle/sec. for repeated loading
Wheel load: Varing
Wheel suspension: N.A
Wheel velocity: 0.001 - 5 cycle/sec for repeated loading
Wheel passes: N.A

Load propulsion: N.A
Power: N.A

Housing: Outside

ENVIRONMENTAL CONTROL: Partial (water level controlled)

Instrumentation: N.A



APPENDIX C

INSTRUMENTATION

Almost without exception, APT facilities have instrumented test pavements to measure the known critical parameters:

- horizontal and vertical strain at various interfaces in the surfacing base and subbase,
- vertical pressures at base, subbase and subgrade interfaces, displacement; deformation and deflection, of the surface and at multiple depths in the various pavement layers,
- temperatures, at the surface and at depth and,
- moisture movement.

The most widely used technique for horizontal strain measurement is the 'H-bar' gauge. If properly installed, reliable results can be obtained. The life of an H-bar gauge is closely related to the bond between the gauge and the surrounding material; a good bond will result in strains close to theoretical estimates. However, high pavement temperatures can affect the bond and thus the results. Moisture entry and cable problems are encountered. Bison gauges have also been used to measure long-term static and dynamic vertical strains, but a high failure rate was reported at high temperatures. Various forms of pressure cells have been used, usually at subgrade level, but they have a low rate of survival of the construction process, even lower survival was experienced under asphalt layers. Displacement transducers are widely used to measure deflection and deformation at the surface and, less often, at various depths within pavements.

Temperature, ambient and in pavement, was measured at all but two sites. Moisture movement is less frequently measured or reported.

STRAIN GAUGES

A strain measurement device in early use in full-scale pavement tests is the inductive coil strain gauge, first developed at the Illinois Institute of Technology Research (IITR). The technique had been further developed by Bison Instrument Inc., Minneapolis, Minnesota. These gauges were applied to research on asphalt concrete pavement at the Washington State University Test Track (*1,2*) and at the University of Canterbury, New Zealand (*3*), Delft University of Technology (*4*), TRL (*5*), Saskatchewan Highways and Transportation, and other agencies.

The Bison coil strain gauge consists of two flat coils embedded in the soil or a pavement layer in near concentric and parallel orientation. They operate on the differential transformer principle so that a change in the spacing of the coils, caused by soil strain, is recorded as a change in the mutual inductance of the coils. One coil is connected to an oscillator to produce an electromagnetic field in the pavement and soil surrounding the buried coil, driven by a high frequency alternating current signal that causes "pickup" in the other coil. For a small change in spacing of the coils, the induced voltage is nearly linearly related to the gauge length. The magnitude of measured current is a function of the spacing between two coils. The multiple Bison strain gauge (Figure C1), can measure horizontal strain (longitudinal and transverse), at the bottom of the pavement structure,

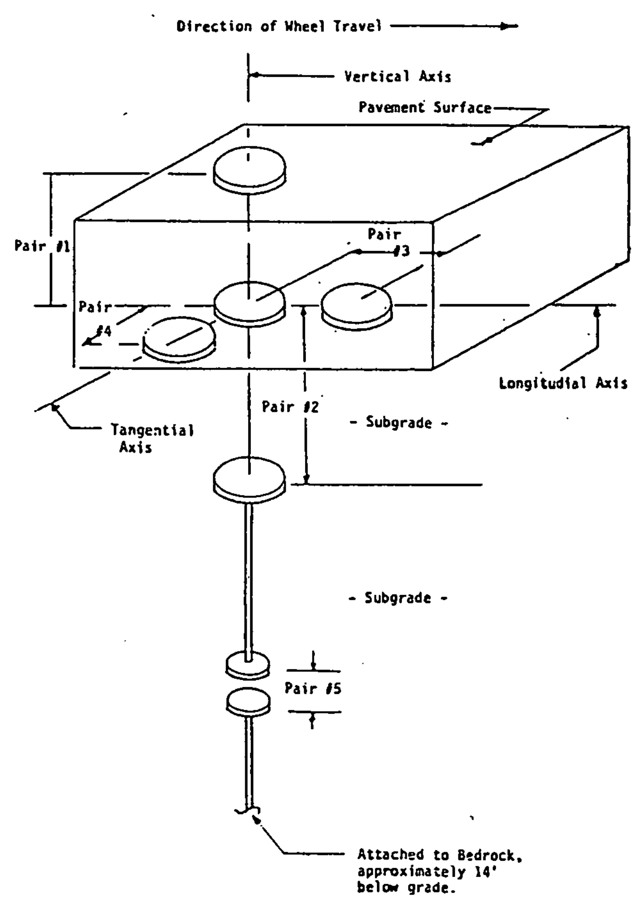


FIGURE C1 Bison strain coil gauge at Washington State University (*2*).

vertical strain in the pavement structure, and vertical strain at the top of the subgrade (*6*). The larger the coil diameter, the greater the possible coil spacing. The extensometer, coil pair 5, was able to measure the total pavement deflection under moving loads.

Test results from the University of Canterbury show that accuracy of the measurement depends on two factors: signal noise and the accuracy of the location of coils. Most of the measurements had an accuracy better than 10 percent, although the worst error was about 25 percent for small strains of the order of 50×10^{-6}. Permanent strain could only be estimated from the calibration of "amplitude" readings, and the dynamic instrument did not have a high long-term stability. The results from Washington State University experiments showed that the lateral position of the tires, environmental factors, and the depth of coils, greatly affected the magnitude, mode, and reversal of strains. Tests by the Delft University of Technology, with Bison coils incorporated at the bottom of an asphalt layer, were not very successful. The asphalt test sections were built with a regular asphalt paver and a vibratory compactor at a laying temperature of approximately 160°C. It was concluded that the insulation inside the coils could not resist that temperature.

At TRL, Bison strain gauges arranged in vertical stacks, were used to determine the variation of permanent strain with depth. A pair of large diameter strain coils are situated at the asphalt surface and the interface between the surface and base layer to directly measure the permanent strain (*5*). The comparison between the measured and predicted values showed that the theoretical values calculated by an elastic model for one pavement were distinctly different from the measurements, but closely resembled those measured in a second pavement. It was concluded that Bison gauge measurements can provide invaluable assistance to the development of reliable theoretical models for pavements.

Small size strain gauges of the rosette type were also used (*7*). Horizontal strain gauges (600-Ohm type, 3 mm (1.2 in.) active length) were cemented to the surface of successive 50 mm (2 inches) layers in both transverse and longitudinal directions. Vertical strain gauges (10 mm (0.4 in.) active length) were connected between pairs of small prefabricated blocks of sand asphalt, which were then incorporated into the layers. Gauges for measuring horizontal strains at the asphalt/sand subgrade interface were mounted on carriers made of sand sheet, which were embedded in the sand subgrade, or on carriers of asphaltic concrete, which were placed in the asphalt layer. In both cases the gauges were flush with the asphalt/subgrade interface. The test result showed that (1) the shape of the strain signal at various levels was only roughly in agreement with that predicted by elastic theory, with the measured signal being asymmetric and, (2) the measured strain values were not in agreement with the calculated values, whether a rough or a smooth interface was assumed.

The strain transducer now most widely used in full-scale pavement testing is the so-called 'H-bar' embedment strain gauge: the KM -100-HB, T. M. L., KM-100-HAS (modified KM-100-HB), the Kyowa KM-120 series and ML-60 made by Tokyo Sokki Kenkujo Co., Ltd; Dynatest PAST-2AC, PAST-2PCC made by Dynatest Consulting, Inc., and other similar types for measuring strains in asphalt pavement structure—Netherlands (*1*), FHWA-PTF (*8*), MnRoad - (*9*), OECD - (*10*), Finland - (*11*), Denmark (*12*), Australia (*13*). Other gauges are similar. They are normally encapsulated in a plastic strip to which two brass anchors are attached, forming the so called H-bar, which ensure a proper fixation in the asphalt layer for measuring the horizontal tensile, or compressive strain at the bottom of the lower asphalt layer. Another type of H-bar, used occasionally, is slightly different in that the gauge is cemented to an aluminum plate and protected by a resin coating (*10*). It is important to select a suitable plate thickness to prevent the gauge from acting as a reinforcing element in the pavement layer to avoid the measured strain being less than the correct value.

The Delft University of Technology developed an installation specification for KM-100-HB gauges, modified to a 5000 micro-strain capability. Much attention is paid to a good fixation of the strain gauges on the granular base, so that the gauges are not displaced when laying down and compacting the upper layer. Thermocouples were incorporated close to the strain gauges during construction to provide for temperature correction. Test results showed that, if the specification is exactly followed, the failure rate of this H-bar can be as low as five percent. The Delft University of Technology has successfully used this type of transducer for more than 5 years (*4*).

The Australian APT program has used Kyowa gauges for many years. The gauge survival rate of one trial was low (*14*) but improved installation techniques have been developed.

The experience of Kyowa gauges at the FHWA/PTF showed that, when the asphalt concrete was warm during the summer months, the plastic strip was too stiff relative to the asphalt concrete, causing the H-bar to become loose after repeated loading. Gauges that remained tightly bonded measured values of strain that agreed well with theoretical calculations. However, the loose H-bar gauges consistently yield strains significantly less than theoretical strains. The conclusion was that better cabling and moisture protection are needed for the gauges and, the stiffness of the H-gauge should be reevaluated. In one test, two of six gauges installed at the bottom of the asphalt layer were operational during the pavement response experiment. No temperature compensating gauges were installed.

At MnRoad, Dynatest PAST-2AC gauges were installed at the asphalt concrete / base or subgrade interface immediately prior to paving. Dynatest PAST-2PCC and Tokyo Sokki PML-60 were installed with a gauge chair to measure the interior strains in concrete under loadings. Installation procedures were developed for installing various gauges in different pavements. The gauge failure rates from the paving operation are: asphalt strain gauges - 2 percent and concrete strain gauges - 8 percent.

A considerably improved H-bar strain gauge was used in Denmark. The gauge had been tested for more than 2 years in moist conditions in an asphalt specimen, and had been subjected to more than one million large strain repetitions and to several freeze/thaw cycles, without any damage.

Another strain gauge type used successfully was the Finnish-made VTT gauge (*15*), also used in the FHWA/PTF test track and the OECD FORCE full-scale pavement test, for strain measurement in bituminous layers (*16,10*).

The VTT strain measurement system consists of foil resistance strain gauges glued to laboratory-made 150-mm (6-inch) core samples that fit into a hole in the pavement with a tolerance of less than one millimeter. The samples are glued to the bituminous pavement. The gauge acts as an integral part of the bituminous layer and has no strengthening effect because it is made up of the same material as the layer and glue is very thin. The gauges have no elastic component and thus it is also possible to measure plastic and resilient deformation. The VTT technology can be used for longitudinal and transverse gauges, at the bottom, on the pavement surface, and at different depths in bituminous layers, as well as for vertical strains. The gauge can be easily replaced (*15*).

The first use of VTT gauges was in the Nantes test (*10*) in which seven out of eight gauges survived up to the end of the test (270,000 loadings) for one structure, and six from eight in another structure. Three transverse gauges survived to one million loadings.

The VTT gauges installed in the FHWA test remained operational for over one million load repetitions. Gauges were also installed at the pavement surface for a special tire pressure experiment. These gauges were bonded in 3-mm (1.2-inch) deep slots cut in the pavement surface. The gauges were removed on completion of the experiment. Many of the surface gauges failed during the response evaluation experiment (*17*).

Strain gauges adhered to, or embedded in, carrier blocks (Alberta Research Council gauges and HBM Type 20/600 XA 21 gauges) were used to measure the transverse and longitudinal strains in pavement at the Nardo Test Site, and in the FHWA program and MnRoad project (Figure C2). The gauge used in the FHWA program consisted of four wire resistance strain gauges embedded in an asphalt mastic to form a 165-mm square transducer which was approximately 20 mm (0.8 inch) thick (*17*). After installation, two of the gauges were oriented in the longitudinal direction and two of gauges in the transverse directions. The durability of this type gauge was poor at the FHWA program; in one test, two out of three gauges failed. The Delft University of Technology used similar techniques (*4*).

There are several instruments used for measuring the vertical strains in pavement. Two of them use vertical strain gauges or using multi-depth or partial-depth deflection gauges. The basic principle for both methods is to measure

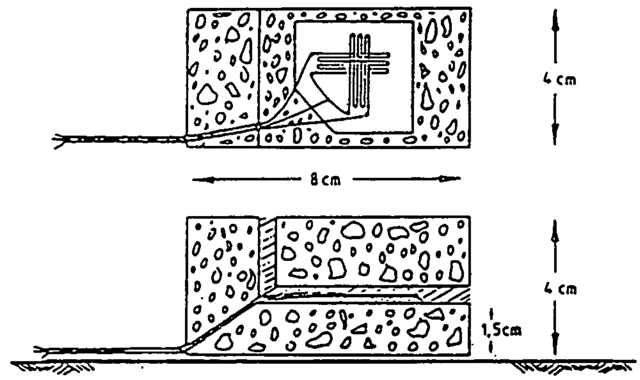


FIGURE C2 Embedment gauge configuration used by the German research team at Nardo (*19*).

relative displacement between different depths in the pavement.

The vertical strain gauges used at the Danish RTM, TRL, and the OECD FORCE full-scale pavement test are based on a linear variable differential transducer (LVDT). These gauges use short inductive displacement transducers to each end of which is secured a perforated metal disc that permits good contact with the surrounding material. These gauges measure the relative displacement of two discs, and this is then converted to strain by calibration in the laboratory.

Another strain gauge based LVDT was also used in TRL (Figure C3), and a variation of the gauge was used in the FHWA program (*8*). An LVDT measures the relative displacement between a plate bonded in the surface of the asphalt layer and a reference plate placed at the desired depth during pavement construction. Average strains are obtained by dividing by the gauge length between two plates. It required a small hole (10 mm diameter enlarged to 20 mm (0.4-0.8 inch) near the asphalt surface. This device in fact is a partial depth displacement gauge (PDDG), see following section.

At the LCPC test track in France, strain gauges and displacement transducers are used to measure strains and deformations in concrete pavements (*18*). Two longitudinal strain gauges are glued to the top and bottom surface of a

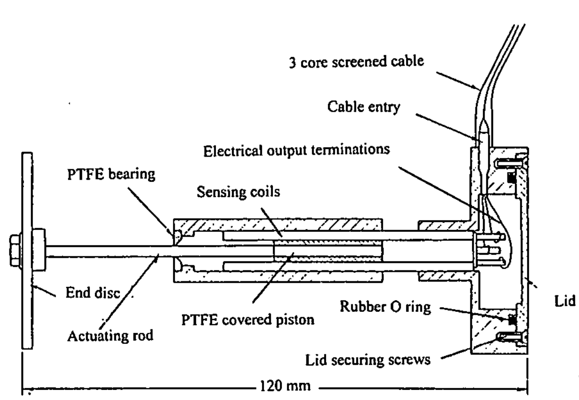


FIGURE C3 Soil strain gauge at TRL (*23*).

dowel, providing information about bending strains; two diagonal gauges, glued to the dowels at mid-height, provide information about shearing strains. Displacement sensors are installed to measure horizontal movement of joints (Figure C4).

At MnRoad, Measurements Group LWK-06-W250b-350 was used to measure dynamic strain in steel dowels. Applied Geomechanics Tiltmeter 756-1129 and Geokon VCE 4200 vibrating wire strain gauges were installed to measure concrete slab inclination, and warp and curl in the slab, respectively. These gauges are known to have good long term measurement qualities.

Other types of strain gauge used in the OECD Test at Nardo are shown in table 6 on page 23 of the text (*19*).

PRESSURE CELLS

There are many types of pressure cells for measuring the compressive stress in pavements. The diaphragm type pressure cell is the most widely used. The principle of this gauge is that the pressure on the thin diaphragm of the cell causes a deflection, which is transformed into an electrical signal by a strain gauge or a small LVDT, or a vibrating wire transducer glued on the inside diaphragm (*12,20*). Pressure cells are usually installed in the subgrade, at different depths, in aggregate material layers and, in some cases, at the interface of the base course and the asphalt concrete layer (*21*). Test data from and survival rates of pressure cells are very limited. This kind of gauge is sensitive to environmental factors, such as moisture and temperature.

LTT (*22*), the Delft University of Technology (*4*) and Pennsylvania Transportation Institute (PTI) (*21*) used a diaphragm-type pressure cell developed by the University of Nottingham. PTI installed the pressure cell at the interface of the base and asphalt concrete layers. After completion of the base layer, small depressions were made at the desired points for holding the pressure cells inside. A thin layer of fine sand was placed at the bottom of each depression. Extra care was taken to place the pressure cell in the horizontal position. A slurry mixture of hot asphalt cement and fine

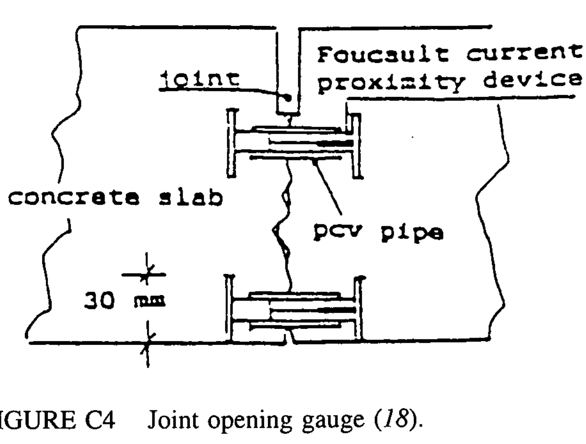


FIGURE C4 Joint opening gauge (*18*).

sand was carefully poured over the pressure cell to keep it in place. Two pressure cells were installed, one of the pressure cells failed during construction because of an excessive permanent stress at the active face of the cell, which may have been due to the direct contact of a sharp aggregate with the face of the cell. The data from the second cell indicated good repeatability; with coefficients of variation below 10 percent. The calculated static pressure was always higher than that measured and the difference became larger as the axle load increased.

Another typical diaphragm pressure cell used by the Delft University of Technology is Kulite Model 0234. The element is housed in a flat cylindrical stainless steel body and isolated from the soil by a stainless steel diaphragm. The cavity between sensor and isolation diaphragm is filled with silicone fluid giving perfect pressure transfer. A report showed that the measured stress in base materials suffered from a large dispersion and measurement of soil stress was abandoned (*4*). Australia used similar technology with a very low cell survival rate of pressure cell but 66 Kulite 0234 cells installed at MnRoad test pavement survived the paving operation.

The pressure cell used in TRL and the OECD NARDO FORCE Test (Figure C5) comprised a miniature inductive displacement sensor fixed between two diaphragms secured to a steel annulus. The direct output signal indicates the effective displacement between diaphragms, from which the soil stress is deduced by reference to the calibration curve. The pressure cells were installed in untreated materials (*10*). Not enough measurements were available for comment on the survival rate or the reliability of the measured stress values.

The diaphragm cell used in the early experiments in the Danish Road Testing Machine was made from titanium. The stiffness difference between the cell and the surrounding soil will change the stress field in the soil, thus the calibration conditions greatly affect the accuracy of this type of pressure cell. To overcome this calibration problem, a hydraulic soil cell (Figure C6) was developed and used at Danish RTM. The hydraulic cell consists of two membranes welded around the periphery. The region between the membranes is filled with oil. This gauge shows the same stress response when calibrated under hydrostatic pressure and in different soils (*12*). The hydraulic pressure cell used at MnRoad is Geokon 3500 with Ashkroft K1 transducer. The cell is approximately 152 mm (6 inches) in diameter and 13 mm (0.5 inches) thick. A total of 106 of these gauges were installed and none failed at pavement construction.

A piezo-electric gauge was used to measure subgrade stress at TRL. This gauge was used in many full-scale test pavements and proved to be durable. The disadvantage of this gauge is that it requires a charge, rather than voltage, amplifier. This type of amplifier lacks the stability necessary for accurate measurement and has other shortcomings (*23*).

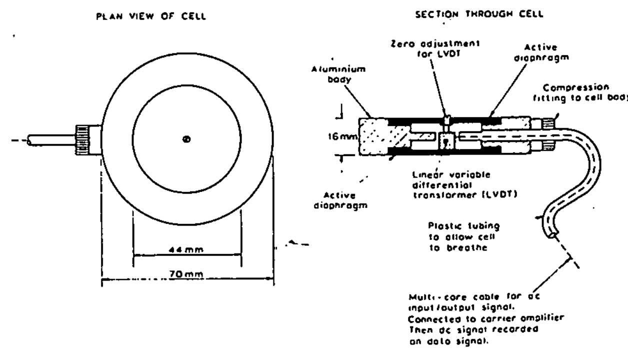


FIGURE C5 TRL/LVDT soil stress gauge (*23*).

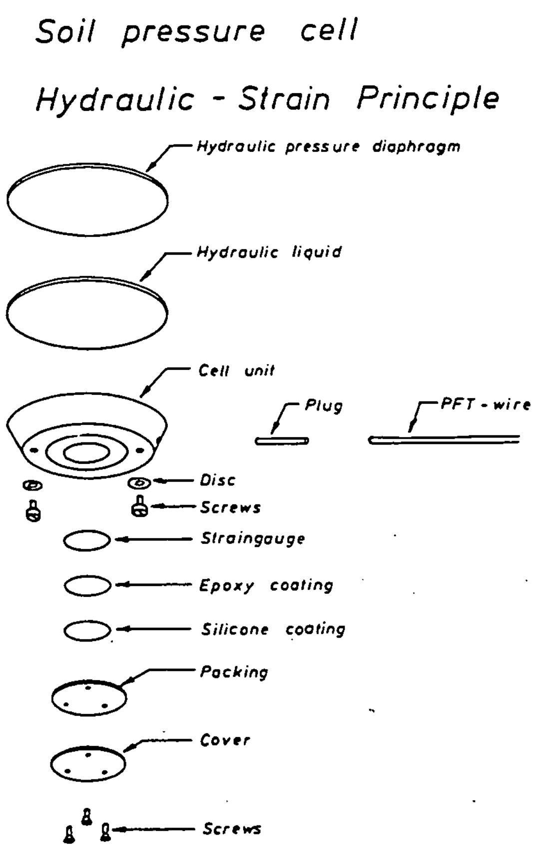


FIGURE C6 Improved hydraulic pressure cell developed for the Danish RTM (*12*).

DISPLACEMENT GAUGES

A gauge for measurement of transient and long-term displacement in test road pavement was developed for University of Illinois Pavement Test Track (*24*). An LVDT core was attached to a stainless steel anchor rod which was anchored to a base plate in the bottom of the test track pit or at a certain point under the pavement layer. The housing of the LVDT was bonded to the base or surface layer material. As the wheel load caused the pavement to deflect, the LVDT housing moved relative to the core and the displacement between the housing point and base plate was recorded. Each LVDT was individually calibrated before measuring The LVDT displacement system provided a means of measuring the deflection of the pavement at a specific point, whatever of the position of the load. In this way the deflection measured could be compared with the result predicted from theoretical response models. The deflection of the pavement at the LVDT was correlated with load position by observing the location and speed of the wheel.

A similar displacement gauge based on LVDT and anchor plates was used by TRL (*25,26*) and at the Washington State University Test Track (*1,2*). The results were used to examine the effect on pavement response of different types of gravel aggregate in bituminous bases and base courses. Comparisons of maximum dynamic deflections from different test sections show that the results are generally compatible.

Two types of displacement gauges that have been widely used in the last 10 years are the multi-depth and partial-depth displacement gauges (MDDG and PDDG) (Figure C7) and the TRL 'spring' gauge. MDDG gauges were used in South Africa in the 1970s, where much of the current technology was developed. Studies of deflections at different depths, used to estimate working stress and strain levels under vehicle loading, led to the systematic development of a series of multi-depth gauges capable of measuring displacement at up to eight depths simultaneously, to supplement surface deflection measurements (*27*). The application of MDDG data to in-situ materials characterization and load-equivalency estimation was also initiated (*28*). The Australian, FHWA, and Chinese ALF programs (*13,29*), the Texas Transportation Institute (*30*), TRL (*23*) and other organizations all use MDDG techniques to measure the vertical strain in unbound materials.

A heavy-duty deflectometer was also developed for concrete pavements (*31*) (Figure C8). Surface deflections measured by the falling weight deflectometer (FWD), or similar devices, are replacing the Benkelman beam favored in the 1970-1980s (*32*).

The crack-activity meter (CAM) was developed in South Africa to measure the relative movements of cracks, or joints,

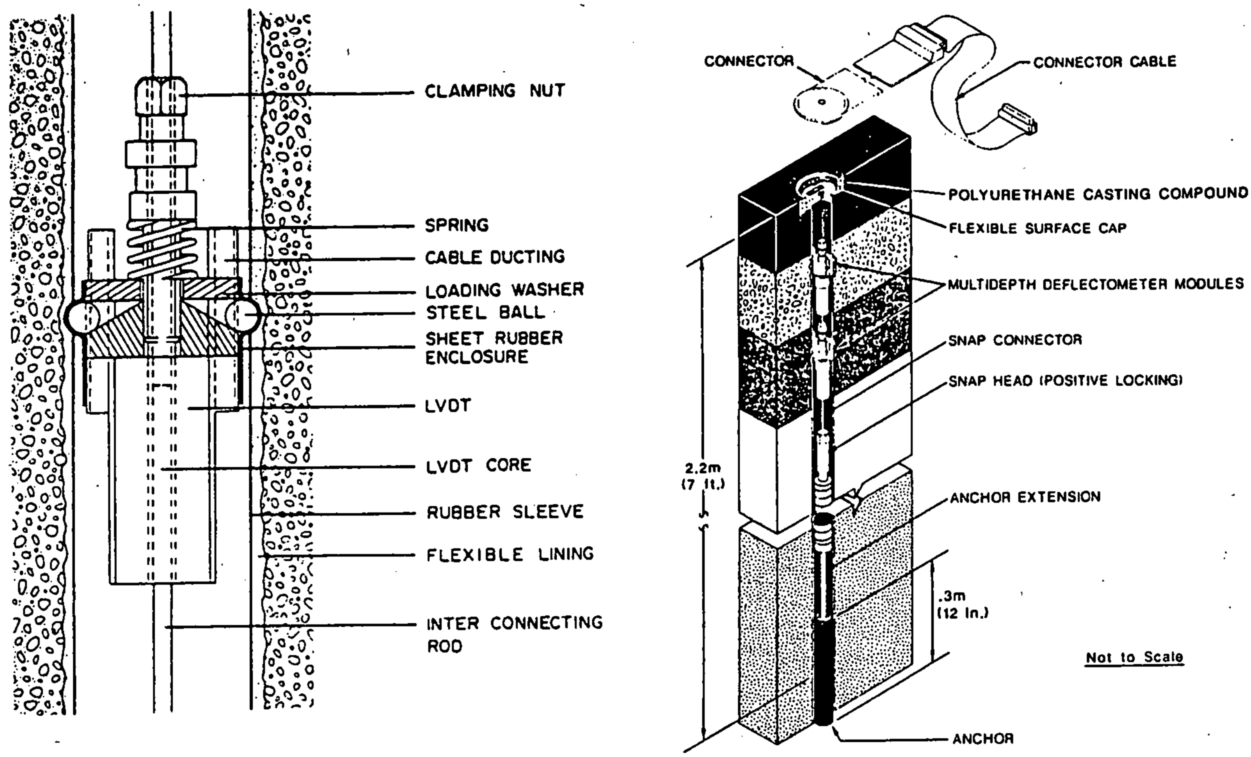


FIGURE C7 MDDG at the Texas A&M Research Annex (*30*).

in a pavement caused by moving wheel loads (*32*). The CAM has two LVDTs, one of which is positioned vertically and one horizontally to measure vertical and horizontal movements of cracks or joints simultaneously, and measure relative movements directly.

A horizontal clip gauge (Tokyo Sokki TML-PI5) was used at the MnRoad project to measure the static horizontal movement at concrete joints. The clip gauge consists of an inverted U-shaped steel strip with electrical resistance strain gauges bound to the top of the strip (*9*). The gauge measures horizontal joint movement by attaching one end of the strip to concrete on each side of a joint.

TEMPERATURE GAUGES

The most commonly used temperature gauges are thermocouples of various types (copper-constantan, type T, type K) (*33,10,23,34,4,16,9*). Thermocouples were normally installed at various depths in the different pavement structures (especially in the asphalt layers) at the time of construction to monitor pavement temperatures. TRL used many copper-constantan thermocouples installed in the pavement, with an infra-red heater, to control the temperatures at a given depth in the accelerated loading pavements.

Thermistor temperature gauges have been used but are considered less robust than thermocouples. They were successfully used at TRL where thermistor beads glued into holes drilled horizontally into cores extracted from the pavement remained active for several years.

SUBGRADE MOISTURE CELLS

Resistance type moisture cells (Soiltest Model MC-373) were used at FHWA PTF. The principle of these gauges is that the resistance of the cell changes with variations in the moisture content of the soil in which they are installed. The accuracy of the absolute moisture content measured with these gauges is questionable because of the uncertainties associated with calibration and installation. The measured data with the moisture gauges were supplemented with oven-dried moisture contents obtained after test completion (*16*).

Time domain reflectometry (TDR) is a new technology to measure soil moisture content being used in the Minnesota Road Research Project (*9*). The gauge consists of two parallel wave guides that are buried in the soil. The principle of operation is that a high-frequency wave is sent down the wave guides and the water content is determined by the time it takes the wave to move through the soil and be reflected back. The wave guides were oriented horizontally at distinct depths in a hole augured through the base and subgrade. The principal advantage of the TDR is that it is insensitive to the effects of temperature, salinity, and bulk density, which distinguishes it from the instruments based on changes in soil electrical properties. A neutron probe is used in con-

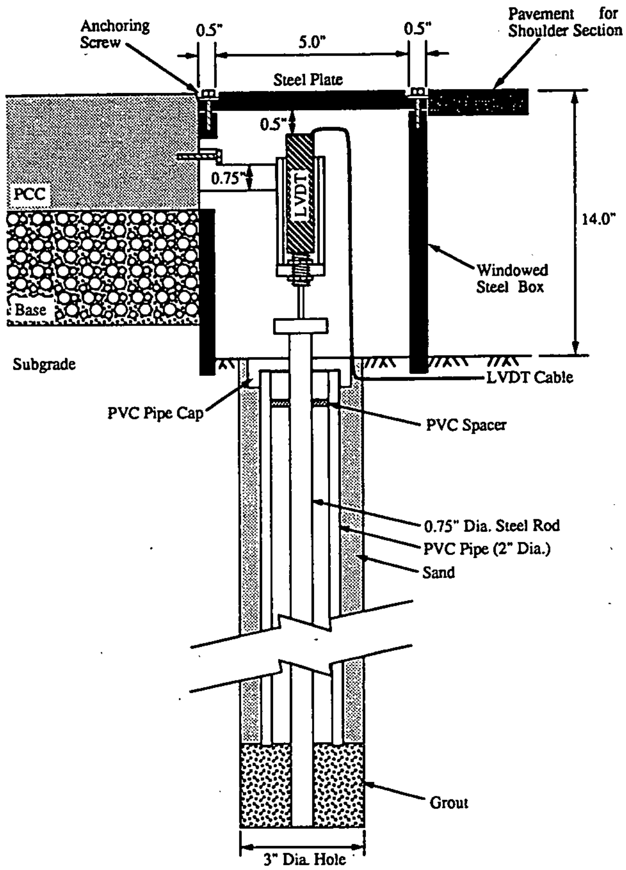


FIGURE C8 Slab edge joint single layer deflectometer for concrete pavement (*31*).

cert with the TDR to measure soil moisture. The neutron probe measures total water content regardless of the state (frozen or liquid), while the TDR measures only the liquid water content.

Other types of gauges used at MnRoad are open standpipes to measure water table, dynamic and static pore water pressure cells to measure positive pore water pressure, resistivity probes to measure frozen soil location, and the tipping bucket to measure subsurface drainage run-off.

The MnRoad project is one of the most comprehensively instrumented full-scale accelerated pavement research facilities of the last 20 years. More than 4,500 electronic gauges, including 1,151 pavement load response gauges and 3,421 environmental gauges, were installed in 40 pavement test sections.

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