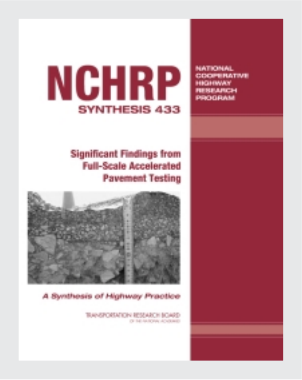

Significant Findings from Full-Scale Accelerated Pavement Testing

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 433

Significant Findings from Full-Scale Accelerated Pavement Testing

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Cover figure: Asphalt rut APT Test.

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Wynand JvdM Steyn Pr Eng, PhD, University of Pretoria, was responsible for the collection and preparation of this synthesis. The assistance, comments, and support of the Topic Panel is acknowledged. This study was managed by Jon Williams, Program Director, IDEA and Synthesis Studies, who worked with the consultant, the Topic Panel, and the Project 20-05 Committee in the development and review of the synthesis.

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation
Research Board

Full-scale accelerated pavement testing (f-sAPT) is the controlled application of a wheel loading, at or above the appropriate legal load limit, to a pavement system to determine pavement response 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, and thus shorter design lives or a combination of these factors. This synthesis study has the objective of expanding the foundation provided by *NCHRP Syntheses 325* and *235* on f-sAPT by adding information generated between the years 2000 and 2011 and identifying gaps in knowledge and future research needs.

This synthesis is based on two major sources of information. A questionnaire was distributed to 43 known U.S. and international operators and owners of f-sAPT devices, the 50 U.S. state departments of transportation representatives, and a group of specialists active in the field of pavement engineering. The second source of information is the conference and journal papers published from 2000 to 2011.

Wynand JvdM Steyn, University of Pretoria, Pretoria, South Africa, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. 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 progress in research and practice continues, new knowledge will be added to that now at hand.

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APPENDIXES C AND D ARE WEB-ONLY AND CAN BE FOUND AT WWW.TRB.ORG,
SEARCH ON NCHRP SYNTHESIS 433

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SIGNIFICANT FINDINGS FROM FULL-SCALE ACCELERATED PAVEMENT TESTING

SUMMARY

Full-scale accelerated pavement testing (f-sAPT) forms a vital link between the laboratory evaluation of materials used in pavement layers and the field behavior of these materials when combined into pavement structures. For many years f-sAPT provided pavement engineers with knowledge that improved their understanding of pavement materials and structures, as well as their behavior under typical traffic and environmental loading. It formed the basis for developing various theories about pavement behavior and supports most of the current pavement design methods.

This third NCHRP synthesis on f-sAPT contributes to the body of knowledge by evaluating current developments and advances around f-sAPT. Its objective is to expand on the foundation provided in *NCHRP Syntheses 325* and *235* on f-sAPT by adding information generated between 2000 and 2011, and identifying gaps in knowledge and future research needs. To address these objectives, the synthesis covers evaluation of the operational f-sAPT programs; discussion of material-related issues as researched through f-sAPT; discussion on pavement structure-related research using f-sAPT; application of f-sAPT in the evaluation and validation of new Mechanistic–Empirical pavement design methods; and identification of the future needs and focus of f-sAPT. Research and developments conducted outside the focus period of this synthesis (pre-2000) are excluded as this has been covered extensively in the previous syntheses.

For the purposes of this synthesis, the definition of f-sAPT covers the controlled application of full-scale wheel loads to layered, structural pavement systems to determine pavement response and performance under controlled, accelerated, accumulation of damage loading in a compressed time period. This is done while environmental effects on the pavement are typically controlled and measured.

This synthesis is based on two major sources of information. A questionnaire covering relevant aspects of f-sAPT was distributed by an online system to 43 known U.S. and international operators and owners of f-sAPT devices, the 50 U.S. state departments of transportation representatives, and a group of specialists active in the field of pavement engineering. The questionnaire focused on the perceptions of the respondents around various f-sAPT issues, as well as information on their own activities in the field. The second source of information is the conference and journal published papers over the last decade. The synthesis specifically covers the period 2000 to 2011, and thus information before this period was not included in the source material, although the work covered in the synthesis is based on the history of f-sAPT that essentially started in the 1960s. Thirty-eight U.S. state departments of transportation, 29 f-sAPT programs and 5 specialists responded to the questionnaire, for a total of 72 unique responses.

The overall finding of this synthesis is that the judicious use of f-sAPT contributes to and supports the body of knowledge regarding the way that pavement materials and structures react to controlled traffic and environmental loads. Through well-planned studies the f-sAPT work conducted over the last decade highlighted the following strategic findings that provide important information to the pavement engineering community to ensure the sustainable and efficient supply of cost-effective pavement-related infrastructure.

The importance of f-sAPT is perceived as high, with a major role to be played in pavement structure and basic materials research. The future of f-sAPT is primarily perceived as growing and being a normal part of pavement research operations, benefiting improved structural and material design methods, performance modeling, and evaluation of novel materials and structures.

It was evident from both the questionnaire and the published literature that many programs share their facilities and data in order to expand the database that their specific research is founded upon. In this regard the formation of associations of f-sAPT users with the general objective of improving the cost-effectiveness of the overall programs through cooperative efforts of program planning, data analysis, and device improvements is evident.

A wide scope of topics is addressed in the research conducted by the various programs, with traditional focus areas such as hot mix asphalt (HMA) response to applied loads still quite evident. However, the data also show that topics related to environmental issues, such as the increased use of warm mix asphalt and recycled asphalt products are receiving increasing attention. The trend derived from the questionnaire indicating that f-sAPT focuses on materials used closer to the surface was confirmed through the evaluation of the published literature. Another focus is on the extension of pavement life through the application of HMA overlays and ultra-thin whitetopping. Evaluation of materials models for newer pavement design methods [such as the Mechanistic Empirical Pavement Design Guide (MEPDG) and California Mechanistic Empirical design method (CalME)] is also quite common.

F-sAPT aims to evaluate pavement sections under a range of loading and environmental conditions to improve the knowledge of the potential performance of the pavement layers and structure under a full range of operational conditions. The majority of respondents relate their f-sAPT data to pavement temperature and ambient air temperature, while also actively managing these parameters during tests. This trend may be related to the majority of tests being conducted on temperature-sensitive HMA materials. New focus was placed by a number of researchers on the major effects that tire contact stresses and loading conditions have on pavement response, and the active management of this parameter is visible in the published literature originating from many programs.

The improved characterization of loading conditions is mirrored by the use of more complicated materials models that can react to these input conditions and provide improved models of the materials' load responses. Many programs actively focus on the validation of the models incorporated in the MEPDG and CalME pavement design processes, thereby reducing the risk involved in pavement design as more appropriate parameters are incorporated into the design and the effect of each of the parameters are better understood. The increased use of finite element modeling for analysis of moving loads (as opposed to static load analysis) where factors such as mass inertia and stress rotation are incorporated into the model; the increased use of materials models that are not simply linear elastic, but that incorporate the effects on nonlinearity and viscosity; the increased use of detailed definition of the applied loads in terms of both load history and contact stress patterns; and the increased cognizance given to the effects of the environment on pavement response are prominent in terms of f-sAPT modeling.

It appears that a virtual process is driven on several fronts where improved computing technology allows the complexity of calculations to increase without becoming too time- and resource-consuming, while the understanding of materials properties are improving with the parallel development of appropriate laboratory and field instruments and tests to obtain these parameters for different materials, and the subsequent modeling is improved through the combination of these factors.

A major part of the modeling is still focused only on the surfacing layers and that the effect and contribution of lower materials layers are generalized and simplified, although these effects may sometimes significantly affect the surfacing and other upper layers. It is specifically the strength-balance of the pavement that often appears to be ignored in test planning and modeling.

Respondents viewed improved structural and material design methods, evaluation of novel materials, improved performance modeling, and the development of performance-related specifications as the major benefits of f-sAPT, while perceptions regarding the way that f-sAPT has changed the pavement engineering world focused on proving new techniques, materials, and development of a fundamental understanding of pavement structures. In the last decade the most significant strategic level findings from f-sAPT have focused on materials characterization, pavement modeling, pavement behavior and performance, pavement design method development and calibration, benefits of specific materials and technologies, economic impacts of f-sAPT programs, calibration of pavement design methods, development of databases of information on pavement performance that are shared between different pavement research programs, cost savings through implementing f-sAPT, and the development of improved instrumentation and analysis methods. In terms of more practical examples, issues such as an improved understanding of failure mechanisms of top-down cracking, critical strain limits in HMA, the effect of adequate layer compaction, variability of materials and layer properties, improved understanding of the links between various materials' laboratory and field behavior, and the effect of various real environmental conditions and traffic on pavement behavior and performance are seen as major international findings.

Evaluation of the economic benefits of f-sAPT has come to the forefront during the past decade with more programs reporting attempts at performing benefit–cost ratio (BCR)-type evaluations of their research programs. It appears that the general international economic conditions force researchers to prove the benefit of their research much more and identify, analyze, and quantify the direct and indirect benefits obtained from f-sAPT. The majority of programs are still only conducting BCR analyses after the research has been completed (43.5%), while 17.4% of respondents indicated that they perform BCRs as an input in the research planning. Estimates of BCRs from respondents ranged broadly between 1.4 and 11.6, although some respondents to the questionnaire indicated that their perception of the BCR for their programs is greater than 30.

It is evident that the f-sAPT community is moving forward by focusing on calibration of f-sAPT outputs with in situ pavement data, specifically with the view of incorporating environmental and real traffic issues that cannot be modeled using f-sAPT. The potential exists for evaluating the effects of novel research questions around climate change on pavements through the judicious application of artificial temperature and moisture changes (based on expected weather conditions) during f-sAPT. Many of the trends identified in the synthesis are old issues that have been known to the pavement engineering community for a long time, but which did not receive the required attention in the research and testing environment.

Questionnaire respondents indicated that issues such as a more detailed focus on vehicle–pavement interaction (including improved load and contact stress models), environment–pavement interaction (including climate change issues), development of and improvements in performance-related specifications, improved MEPDG validation, evaluation of sustainable pavement solutions (energy efficient technologies and re-use of available infrastructure), and improved reliability in pavement design are important future focus areas.

CHAPTER ONE

INTRODUCTION

BACKGROUND

This chapter provides background, the study objectives and scope, a definition of full-scale accelerated pavement testing (f-sAPT), a summary of the perceived impacts and benefits of f-sAPT, a review of previous syntheses, and a summary of the questionnaire responses from f-sAPT stakeholders.

The focus of this synthesis is f-sAPT. Much of the source material refers to accelerated pavement testing (APT) in general, and the convention followed in the synthesis is to use the term f-sAPT for all references to APT, except where the reference is specifically not related to full-scale work, and where it would then be indicated as such.

The aim of this NCHRP synthesis is to collate and analyze the research conducted in the area of f-sAPT from 2000 to 2011. *NCHRP Synthesis 235* (Metcalf 1996) and *NCHRP Synthesis 325* (Hugo and Epps Martin 2004) reported on information pertaining to APT projects until early 2000. Since then, f-sAPT programs in the United States and abroad have expanded and research findings have been published on a wide range of topics. More than 30 f-sAPT programs are currently active in the United States and internationally. There have been three international conferences dedicated solely to APT—1999 Reno (Nevada), 2004 Minneapolis (Minnesota), and 2008 Madrid (Spain), with the 4th International Conference on Accelerated Pavement Testing planned for 2012 in Davis (California). Presentations and publications stemming from TRB annual meetings, other conferences, and journals have also added to the increase in APT research findings. It is clear that f-sAPT research has generated significant findings, and that the application of these findings has expanded into the broad field of pavement engineering.

The f-sAPT narrative over the last decade is well-defined through a focus on the keynote addresses and syntheses of the three International APT conferences held since 1999 (Mahoney 1999; Hugo 1999, 2004; Prozzi et al. 2007; Dawson 2008).

Mahoney (1999) posed a number of questions on the impact and applications of APT relating to technology, cost, products and value to customers, and international collaboration. Expectations for the future of APT were identified as:

- Improved analytical data analysis techniques;
- More APT devices in service;
- New and improved non-destructive testing equipment complementing APT;
- Improved practices (design procedures, specifications, etc.) resulting from APT;
- More services and options from the private sector;
- Increased use of the Internet for a variety of pavements and APT activities; and
- Formation of APT consortia.

Hugo (1999) identified the reasons for success for long-term/mature APT programs as part of a multifaceted effort that includes an extensive laboratory program and a cooperative approach that results in rapid and extensive implementation. Technical similarities between the various APT programs include the validation of design procedures, consideration of material performance, consideration of alternative or marginal materials, and measurement and instrumentation. It is acknowledged that APT is an expensive tool that must support the management of pavement infrastructure. Partnering and cooperation to ensure economic use of APT is important and the achievements of APT in evaluation of both traditional and new materials and their properties should be published and marketed. Supplemental tools for APT have become useful and indeed valuable as diagnostic tools in their own right. On a technological level, it is important that the incorporation of improved understanding of loading conditions be supported. The improved modeling of all pavement response modes to enable a better link between APT and long-term pavement performance and real life should be a focus area. Data need to be consolidated and utilized for design and management purposes. The necessity for and power of laboratory material testing in conjunction with APT is well-documented and guidelines are emerging and should be maintained. APT could serve as a proving ground for newly developed models over the full spectrum of pavement engineering. Environmental conditions for tests need to be improved and understood. The level of application of models in day-to-day pavement design and analysis should drive the level of sophistication. The need to move from elastic layer theory to more sophisticated finite element models (FEMs), also accounting for visco-elastic and nonlinear response, was highlighted.

Hugo (2004) opened the 2nd APT conference by noting that the overall goal of APT programs is to improve performance and economics of pavements. To achieve this APT is used to simulate behavior of an equivalent in-service pavement under conventional traffic and prevailing environmental conditions. In the process, knowledge is gained over the full spectrum of pavement engineering. Closer linkage is still required between pavement management systems (PMS), in-service highways, and long-term monitoring (LTM) programs. Careful formulation and execution of new APT studies with due regard to the impact of the extensive volume of significant findings from completed APT studies is required. Better national and international collaboration is also required. [Improvement of the understanding and quantification of environmental effects through specifically structured studies based on what is already known.] Many reports of application of significant APT-related findings leading to increased pavement quality and performance life are available and should be communicated in a well-structured manner to executive decision makers to ensure sustainability of APT as a field of pavement engineering.

Prozzi et al. (2007) focused on the long standing link between APT and the history of pavement design and highlighted the close relationship between TRB and APT and the importance of international collaboration in transportation research. The differences between APT and LTM, long-term effects, the need for improved modeling, and showing the taxpayers the benefits of what is done were highlighted. The importance of international collaboration, the low political profile of APT, and the need for a focus on efficient, safe, sustainable roads was emphasized. Roads agencies identified the major needs as upgrading of the transportation system, accurate performance predictions, focus on marginal materials, and the performance of rehabilitated pavements, while emphasizing international collaboration. The importance of conducting pre-project benefit–cost ratio (BCR) analyses to define goals and to communicate with the public (“address tomorrow’s problems not today’s”) is highlighted. Materials producers see new responsibilities, new global environmental challenges, and availability of private-sector funding for APT as the most important issues. A summary synthesis indicated that:

- APT covers all major pavement response modes, materials, and pavement types;
- APT needs advance modeling and quantitative methods to be beneficial to practitioners;
- APT pays off through producing significant savings in pavement life-cycle costs, and
- Opportunities exist for private funding and international collaboration.

Based on the keynotes and syntheses the importance of technical research excellence to enable the most economical use of scarce natural resources to enable a sustainable transportation network supported by international cooperation is visible through f-sAPT over the last decade.

DEFINITION OF FULL-SCALE ACCELERATED PAVEMENT TESTING

Metcalf (1996) defined f-sAPT 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 increased repetitions, modified loading conditions, imposed climatic conditions (e.g., temperature and/or moisture), the use of thinner pavements with a decreased structural capacity 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.” Saeed and Hall (2003) stated the definition of APT to be “the application of wheel loads to specially constructed or in-service pavements to determine pavement response and performance under a controlled and accelerated accumulation of damage in a short period of time.”

Hugo and Epps (2004) stated that “For this report, accelerated pavement testing was defined as the controlled application of wheel loading to pavement structures for the purpose of simulating the effects of long-term in-service loading conditions in a compressed time period.” They defined the scope of *NCHRP Synthesis 325* as “designed to capture significant findings from full-scale APT, which is defined as the application of wheel loading, close to or above the legal load limit(s) to a prototype or actual, layered, structural pavement system (Metcalf 1996). The intent of the APT is to determine pavement response and performance under a controlled, accelerated accumulation of damage in a compressed time period. Accordingly, full-scale test tracks and roads; for example, the Minnesota Road Research Project (MnROAD) were included. However, experimental road sections such as those from the LTPP [Long-Term Pavement Performance] studies were excluded, except where they form an integrated part of an APT program.”

The minutes of the TRB Full-Scale Accelerated Pavement Testing Committee [AFD40 (2)] (January 2005) state, “It is decided by all attendees that APT facilities include only those that test pavement structures and not individual pavement layers. Therefore, the Hamburg Wheel tester and the Asphalt Pavement Analyzer are not considered APT facilities” (Appendix B, Minutes AFD40 meeting, January 11, 2005).

Following this line of reporting this synthesis therefore also focuses on full-scale APT as originally defined by Metcalf (1996).

STUDY OBJECTIVE

The specific objective of this synthesis is to expand on the foundation provided in *NCHRP Syntheses 325* and *235* on f-sAPT by adding information generated between 2000 and

2011, and identify gaps in knowledge and future research needs for f-sAPT.

STUDY SCOPE

The study scope incorporates information on all aspects of f-sAPT since 2000. In this regard, the following topics are specifically included:

- Evaluation of the operational f-sAPT programs
- Discussion of material-related issues as researched through f-sAPT
- Discussion on pavement structure-related research using f-sAPT
- Application of f-sAPT in the evaluation and validation of new Mechanistic-Empirical (M-E) pavement design methods
- Identification of the future needs and focus of f-sAPT.

Research and development conducted outside the focus period (pre-2000) are excluded from this synthesis. This work has been covered extensively in the previous syntheses. The inadequate information on some topics, as well as the lack of discussion on early developments by various f-sAPT programs in this synthesis, is the result of this limited period focus. For an understanding of developments in f-sAPT it is thus strongly suggested that the various syntheses on f-sAPT and relevant NCHRP reports be read as a series of documents, and vital developments will be missed if the focus is only on selected documents.

It is also important to appreciate that the synthesis is based on published information. There is always work underway on many novel developments that readers may expect to be covered in the synthesis, but that is missing; if such research has not yet been published it would not be covered in this synthesis.

IMPACTS AND BENEFITS OF ACCELERATED PAVEMENT TESTING

The purpose of f-sAPT is to provide a more cost-efficient answer to questions regarding pavement and materials response and performance. The major topics that can be answered cost-effectively using f-sAPT include (Harvey 2008):

- Identification and highlighting of deficiencies in current practices
- Evaluation of materials, designs, materials specifications, or construction standards before full-scale implementation
- Comparison between alternatives for materials, designs, materials specifications, or construction standards under controlled conditions
- Assessment of the impact of changes in vehicle technology on pavement performance
- Development of insight regarding pavement mechanics and damage mechanisms and validation and calibration of models for pavement analysis and design.

Over the last decade more knowledge and responsibility is moving from the road authority to the road contractor. F-sAPT offers the potential for reducing the risks of using new and innovative materials in pavements, but only if it is well-coordinated with laboratory work, field testing, and computer modeling as it provides a link between laboratory tests and long-term pavement performance.

F-sAPT typically fills the gap between the uncertainty of the design model and the real, long-term pavement performance. New materials or concepts can be tested under heavy traffic and an equivalent of approximately 15 years of traffic within a short period. F-sAPT provides a good tool for the determination of the effects of special vehicles with complex loading configurations such as the Boeing 777 (specifically with the advent of airfield-loading scaled f-sAPT). The impacts of f-sAPT can thus be observed in improved understanding of pavement behavior in general and pavement performance in particularly (Beuving 2008).

SUMMARY OF PREVIOUS SYNTHESES

Three major documents have been prepared on APT since 1996 of which two are syntheses (Metcalf 1996; Hugo and Epps Martin 2004) and one is an NCHRP report (Saeed and Hall 2003). The major trends and outcomes of these documents are summarized to form the basis of the current synthesis. It was deemed important to use these as the starting point for this project, as various issues have already been investigated, evaluated, and sufficiently covered in the previous studies. Highlights from these reports are used to indicate trends and to define the major topics and contents for this document. Major information that did not change over the last decade is summarized in this chapter and not repeated elsewhere. The trends and planned future applications identified in the previous synthesis (Hugo and Epps Martin) are addressed to evaluate to what extent these occurred. Details on specific issues are addressed further in upcoming chapters.

Metcalf (1996)

Metcalf (1996) identified the increasing pressures to effectively and economically manage the road systems across all countries within a context of increasing numbers of vehicles and applied loads, requiring continuing efforts to understand and improve the design, construction, maintenance, and rehabilitation technologies for pavements and provision of robust evidence for the regulation of traffic loadings as the basis for f-sAPT. The basis for the traditional pavement design procedures and the understanding of the behavior of layered systems is an historic attempt to physically model pavement response under load with the aim of understanding pavements so that their performance under increased traffic loads can be predicted accurately within an environment of constrained funding for infrastructure and the demand for cost-effective rehabilitation of pavements that have reached or exceeded their original design life.

The main goal of f-sAPT is to help develop a methodology to allow for exploration of new pavement configurations with controlled traffic load parameters that can accumulate damage faster than the anticipated growth of or changes in vehicle technology, with control of nontraffic load factors such as material variability and environmental variation. The first laboratory studies used static loads on pavement materials within a tank to measure the strains and deformations in a partial simulation of a road pavement. This evolved to using repeated loading on multilayer pavements and the use of rolling wheel loading to better simulate the traffic. The next evolution entailed the use of full-scale loads on plates or wheel assemblies applied with static or repeated load systems. Construction of test roads over which a load was provided by ordinary vehicles driven repeatedly over the pavement and at about the same time followed. Full-scale test tracks appeared where fully loaded wheel assemblies were running on circular or linear full-size pavement sections.

Four basic f-sAPT methods were identified; test roads, circular tracks, linear tracks, and pulse or static loading. Close correlation between results from the different facilities was viewed as unlikely because of the different operational principles. Limitations in terms of the effect of the combination of environmental factors and time are acknowledged. Although traffic load can be more closely controlled, varied, and measured, the full-load spectra have not yet been applied to test pavements. The primary application of f-sAPT is viewed as an empirical comparison of different pavement configurations, materials, and loading configurations. The secondary application is viewed as the validation of theoretical pavement response and material behavior models. The application of f-sAPT for determining load equivalencies of different tires, wheel assemblies, and axle groups yielded load factors for use in design and demonstrated that such factors are also dependent on pavement configuration.

Early f-sAPT experiments led to major benefits in validating and calibrating theoretical models of pavement behavior, while f-sAPT allowed for further refinement of these models and supported the development of performance models.

Initial f-sAPT applications focused on assessment of full-scale pavement configuration and material performance and response to full-scale loads with an emphasis on goal-specific results. The limited provision of the major influence of environmental factors on pavements simulated in f-sAPT is acknowledged, with temperature effects being partially controlled. The effects of environmental change, moisture and temperature variation, and curing or aging of materials still exist and these can only be addressed to a limited extent using existing f-sAPT facilities. It was determined that a future strategy should incorporate a strategic approach to pavement research wherever possible and attempt to better coordinate the various f-sAPT programs so that each can build on the experiences of the others; building on improved models of pavement response with compatible material behavior and pavement performance criteria so that the results can be applied across a number of programs.

Improvements in instrumentation enabled strain, deflection, and deformation measurements to be possible in accordance with theoretical predictions on pavement tests while temperature can be measured and the effects incorporated in analyses. Moisture changes were less well determined.

The literature on the costs and benefits of f-sAPT were still very limited, although the benefits were regarded as substantial and effective. Specific benefits are visible in terms of improved design procedures and life estimates; validation of existing, new, nontraditional, and modified materials usage under a range of loading conditions; development and evaluation of rehabilitation techniques; improved understanding of the theory of road pavements and general increased confidence in pavement designs. The few BCRs calculated ranged between 1.2 and 11.6.

Application of f-sAPT results is evident in terms of improved pavement design procedures, modifications of design catalogues, development and validation of mechanistic pavement and overlay design, and an improved understanding of existing and innovative material behavior. Load-related phenomena using aircraft load effects, super single tires, multi-wheel axle groups, and suspension dynamics are being considered as part of research actions. The development of theoretical models has been limited to relatively few facilities, with most concentrating on shorter-term, empirically based, comparative evaluations of materials and pavement layer configurations.

Although f-sAPT is viewed as costly, the following possible alternatives provide justification for f-sAPT programs:

- Waiting for results to accumulate at a low rate under actual traffic;
- Potential cost of failures under actual traffic;
- Lack of control of major experimental, traffic, and environmental variables; and
- Difficulties in extrapolating results to other than local applications.

The cooperative nature of f-sAPT was already evident with programs selecting appropriate approaches to its particular circumstances within a broader strategy for pavement research. As it was recognized that no device was ideal for all tasks, a number of different philosophies were embodied in the different international facilities. The expectation of advances in telecommunications to facilitate a better link between international f-sAPT programs was evident, with the newly formed TRB Committee on Full-Scale and Accelerated Testing (AFD40) expected to bring f-sAPT experts together to share ideas. Major international research programs with the focus on in-service performance monitoring were developed where f-sAPT, laboratory materials characterization, and mechanistic models of pavement behavior were combined to better understand road pavement performance.

The primary requirement of f-sAPT programs is to be part of a coherent pavement research strategy as a component of an integrated program of laboratory materials characterization, f-sAPT, and long-term monitoring (LTM) within which the laboratory program could focus on characterization of materials for use in mechanistic design procedures to be used confidently in the field to refine existing designs and generate new ones. F-sAPT studies should support credible pavement response and performance data that can be used to validate the laboratory materials and theoretical models of pavements in advance of ever-increasing traffic demands and changing vehicle designs. Specific needs for further study included:

- Load rate dependency of pavement and material response and performance
- Effects of construction and maintenance factors
- Extent and effects of environmental changes
- Dynamic traffic load parameters.

Saeed and Hall (2003)

The increased use of f-sAPT by highway agencies as a means of evaluating potential construction materials, pavement designs, and other pavement-related features was identified. This research was concerned with APT where full-scale wheel loads are applied to full pavement structures by machines or vehicles in a test facility, at a test track, or on an in-service pavement. The research focused on identification and development of definitions of data elements associated with APT and recommendation of guidelines for data collection, storage, and retrieval. The data guidelines developed delineate data elements related to APT and their definitions, describe information on state-of-the-art data storage and retrieval systems, provide recommendations and specifications for a database, and propose data collection frequencies. The various data elements were categorized as follows:

- Administrative (details of a particular APT facility or study/experiment being conducted at the facility).
- Load application (wheel loadings applied to test pavement and the characteristics of the applied loads).
- Pavement description (pavement type, construction, and geometric details).
- Material characterization (material type, composition, stiffness, strength, and test methods).
- Environmental conditions (primarily temperature and moisture data affecting external and internal pavement conditions).
- Pavement response (deflections, stresses, or strains measured at the pavement surface and within the pavement structure when subjected to a given load or changes in temperature and moisture).
- Pavement performance (various types of pavement surface distress, smoothness, and longitudinal and transverse profiles).

Data can be collected manually, semi-automatically, or automatically. Electronic text files and spreadsheets are used for small data amounts, whereas dedicated databases were mostly used for large quantities of data. Storage capacity, cost, performance, reliability, and manageability are considered when selecting a data storage and retrieval system.

The cooperative nature of APT was demonstrated with APT operators indicating a willingness to share data generated at their facility with other APT operators and researchers. However, nonuniformity in climatic conditions, pavement materials, and construction practices were considered a hindrance to cooperative use of data. They recommended that existing facilities should make their databases more compatible with the proposed guidelines, and new facilities should adopt these guidelines to facilitate use of data among APT facilities, researchers, and other interested parties, which could generate maximum benefits from APT studies.

Hugo and Epps Martin (2004)

In *NCHRP Synthesis 325*, Hugo and Epps Martin (2004) focused on programs operational during the period from 1984 to 2004, identifying 28 active programs of which 15 were located in the United States. The development of a new generation of test devices that incorporated partial or full environmental control was specifically noted. They stated that APT has been instrumental in validating and refining agency structural design guidelines and improvements in structural design by the insight gained on the effect of the following factors on pavement performance:

- Interaction between structural composition and material characteristics,
- Importance of bond between layers and the quantification of the effect,
- Influence of concrete slab configuration,
- Influence of support under concrete slabs, and
- Influence of water on performance and related failure mechanisms.

It was shown that APT was useful for answering questions relating to the use of new materials, composite materials, and materials with complex physical characteristics. It further served as a tool for the confirmation and validation of laboratory test procedures. APT has become an important tool for developing and evaluating pavement models and assists in answering questions related to rehabilitation, construction, and maintenance. Economic gains as a result of APT were calculated with BCRs varying from 1 to greater than 20. Ancillary artifacts such as the improved understanding of tire–pavement interaction and its effect on performance have been developed within APT environments, and provided a quantitative basis for communicating issues around pavement performance with decision makers.

They concluded that APT had served as a means of improving performance and economics of pavements and improved the understanding of the factors that affect pavement performance through its ability to explore a wide variety of structural compositions and configurations; simulate mechanisms, conditions, and processes through loading and environment; test and characterize materials; and analyze and understand response and performance.

International cooperation was highlighted with an understanding between the TRB A2B09 committee on APT and the Cooperation for Science and Technology (COST) 347 committee, which focused on as much exchange of information as possible, and was viewed as paving the way for the European APT programs to share their knowledge in the 2004 survey. The cooperative and collaborative nature of APT was evident from the synthesis, and it was stated that by prudent use of the available information and collaborative research efforts APT programs could advance pavement knowledge more rapidly through planned replication of tests to improve the reliability of findings and establish confidence limits. Specific issues identified for potential collaborative efforts included:

- Tracking the performance of in-service pavements that have been tested in APT programs,
- Closer correlation with in-service pavement evaluation and long-term pavement monitoring and related PMS programs,
- Improvement of the quantification of the environmental impact on APT performance,
- Advancement in the understanding of vehicle–pavement interaction to enhance pavement performance prediction, and
- The prudent use of the available information to improve the reliability of findings.

The application of international APT facilities in supporting warranty contracts and improved management of pavement infrastructure was evident. It appears as if the U.S. APT programs entered a phase of development that should provide the tools, technology, and practices that will enable them to be well prepared for a similar situation. With the trend toward privatization and partnering, the results of APT studies are no longer naturally in the public domain, often slowing down the technology transfer through conferences and publications. In general, APT activities throughout the world have become more linked and this is enhancing exchange of data and information.

AVAILABLE INFORMATION

The information available for this synthesis consisted of responses to an extensive on-line web questionnaire; information obtained from journal and conference papers published from 2000 to 2011 (published by May 2011); discussions with interested and affected parties regarding f-sAPT, and meeting minutes and presentations of the TRB Full-Scale Accelerated Pavement Testing (AFD40) committee as available on the AFD40 website. This chapter provides a summary of collected information, whereas details on the various topics are provided in chapters two through seven.

The approach taken in this synthesis around the citation of specific models and equations is to generally refrain from highlighting specific models and equations that are limited to specific testing and materials conditions and that can be misinterpreted if the full background to the study is not available. The approach used provides a narrative description of such equations and models and refers the reader to the original reference to appreciate the context and specific details regarding aspects such as the pavement structure, environment, and load condition.

Information in chapters two through seven are provided in chronological order under appropriate subheadings. Generally, this allows for the development of more detailed research on specific topics over time. Cited references are typically stated at the beginning of relevant paragraphs to ease the reading process. Where appropriate and important for an improved understanding of the information, the state or country of origin of the information is provided. All abbreviations and acronyms are noted at the first instance in each chapter to enable independent study of separate chapters without reference to all previous chapters.

Questionnaire Analysis

The questionnaire was developed and hosted in an online format to which potential respondents were invited. Responses were captured automatically and downloaded and analyzed once all invited and interested respondents completed the questionnaire. Respondents included f-sAPT owners and operators, APT specialists (not necessarily owners or operators), and U.S. state departments of transportation (DOTs) representatives. The full questionnaire is provided in Appendix A, with the list of parties contacted for responses in Appendix B. Details on each of the f-sAPT programs identified are in web-only Appendix C, while the detailed questionnaire feedback is summarized in web-only Appendix D. General feedback from the questionnaire is provided in this chapter, with details on each of the specific topics provided in chapters two to through seven.

Feedback from the various respondents ranged in detail from the minimum to complete and detailed information and references. To keep a balanced approach in the synthesis most data were summarized in the main body of the synthesis with appropriate expanded information shown in the relevant appendix. Where comparative information was not available for the majority of the respondent programs (i.e., funding levels of f-sAPT activities) it has been excluded in the body of the report to prevent incorrect conclusions from being formed based on a very limited data sample.

Journal and Conference Literature

Journal and conference proceedings from 2000 to 2011 have been sourced for papers covering f-sAPT topics. It has become increasingly more common for conferences to host dedicated f-sAPT sessions in their programs. A number of the papers touch on more than one specific topic, whereas there are also cases where more than one paper covers the same set of tests or developments from different perspectives. The approach used in the synthesis limits the use of specific references to the main topic of the paper and combines references on a specific topic where appropriate. Most of the citations on a specific topic are provided in chronological order. References not specifically cited are included in the Bibliography.

Discussions with Affected Parties

Discussions were held throughout the project with various affected stakeholders regarding the contents supplied for the synthesis. Where the information was of a supporting or explanatory nature to the published information, these discussions are not separately referenced. Where additional information was supplied through such discussions, and no published reference existed, the source is identified as such.

TRB Full-Scale Accelerated Pavement Testing (AFD40) Minutes and Presentations

The TRB Full-Scale Accelerated Pavement Testing committee (AFD40) started as a task force (A2B09); currently, it functions as a full committee and tracks presentations and papers linked to its activities through an active website and communication with members (http://www3.uta.edu/faculty/sroman/AFD40). The public domain information from this committee has been incorporated into the synthesis where appropriate and cited as such.

QUESTIONNAIRE FEEDBACK SUMMARY

This section contains a summary of Section 2 of the questionnaire, which covered general perceptions regarding f-sAPT. The detailed information gleaned from the questionnaires is used in the various chapters of the synthesis. Where respondents provided information in the questionnaire that could not be substantiated with an official reference, the questionnaire responses and Appendix D are cited as a reference.

The questionnaire targeted three groups of respondents. First, a group of specialists who have worked in the field of f-sAPT and are not actively involved was used to ensure that "older" knowledge is not lost (five respondents).

Second, all 50 U.S. state DOTs were invited to participate through invitations sent to the staff responsible for pavements in accordance with the AASHTO Subcommittee on Design membership list (http://design.transportation.org/Pages/Directory.aspx, accessed May 4, 2011) of December 2009. As shown in Appendix A, the first question after the biographical information allows the respondent the option to immediately indicate whether or not they are interested in completing the survey (no interest in APT activities from the respondent/state). Thirty-eight responses were received from U.S. state DOTs indicating that 32 states were interested in APT and 6 were not.

Third, 43 known U.S. and international operators and owners of f-sAPT devices were invited to respond to the questionnaire. This is an increase of 15 over the number identified in the Hugo and Epps Martin synthesis (2004), although only 29 of these programs responded and completed the questionnaire in various levels of detail. Where details were not supplied by programs through the questionnaire, details of the programs have been identified through papers and websites and added to the synthesis. The total number of respondents in tables and graphs do not always add up to the total number of respondents for the survey, as some respondents did not answer all survey questions.

A total of 72 unique responses were obtained from the combination of U.S. state DOTs, specialists, and APT programs. Fifty-six (77%) of the respondents viewed the importance of f-sAPT as high, with 13 viewing it as medium and only 3 holding the view that the importance is low. The major roles seen for f-sAPT are pavement structure and basic materials research, while commercial evaluation of products is deemed as playing a smaller role (Figure 1). Thirty-nine respondents viewed the future of f-sAPT as a normal part of operations and increasing (Figure 2). The major benefits of f-sAPT are viewed as improved structural and material design methods, performance modeling, and evaluation of novel materials and structures (Figure 3).

REPORT STRUCTURE

The synthesis starts with the introduction and general project background, incorporating the general perceptions of respondents to the questionnaire. Chapter two focuses on the current f-sAPT programs and associations, as well as equipment and sensors typically used. In chapter three issues around pavement materials and pavement structure research are covered, while chapter four focuses on the interaction of loads and the environment. Chapter five evaluates modeling and analysis of data, and chapter six discusses benefits (economical and others) of f-sAPT. Chapter seven reviews expected

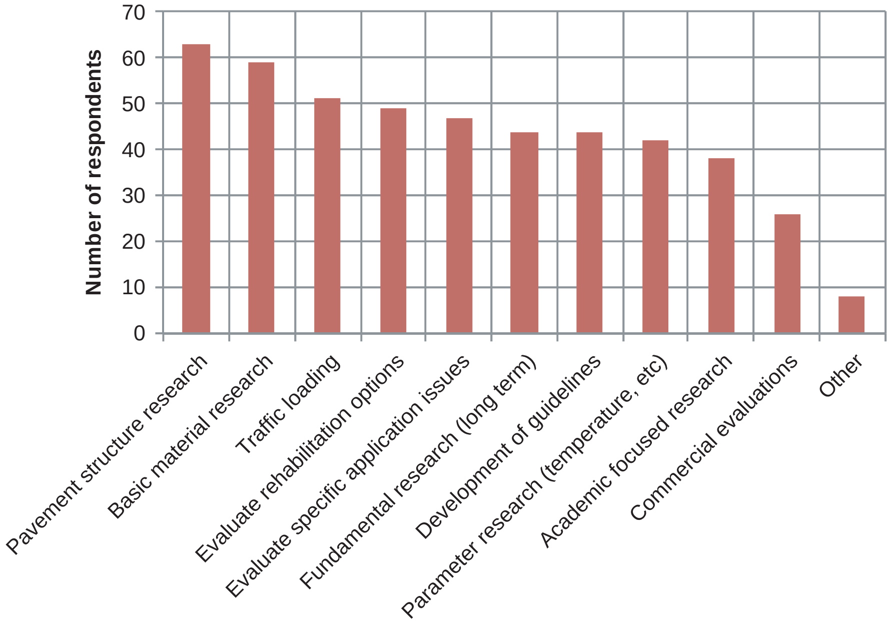

FIGURE 1 Anticipated roles of f-sAPT according to respondents.

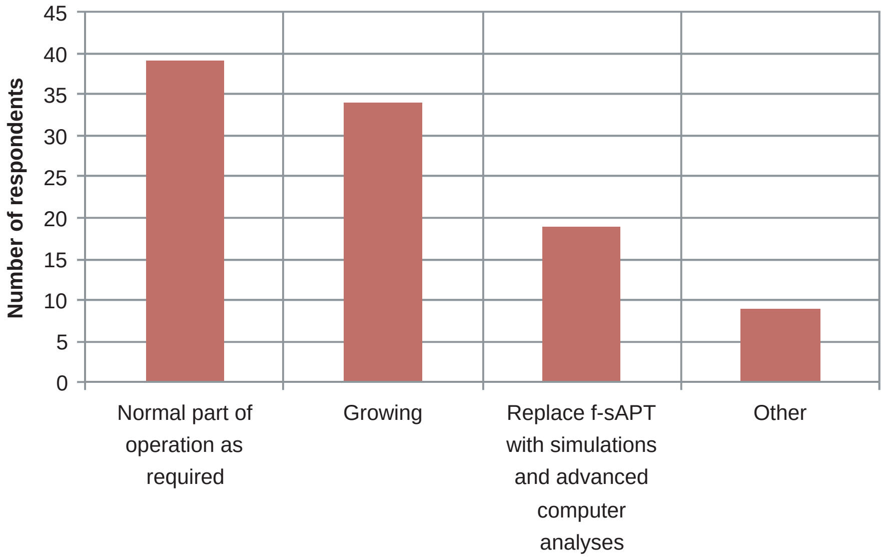

FIGURE 2 Perceptions regarding the future of f-sAPT.

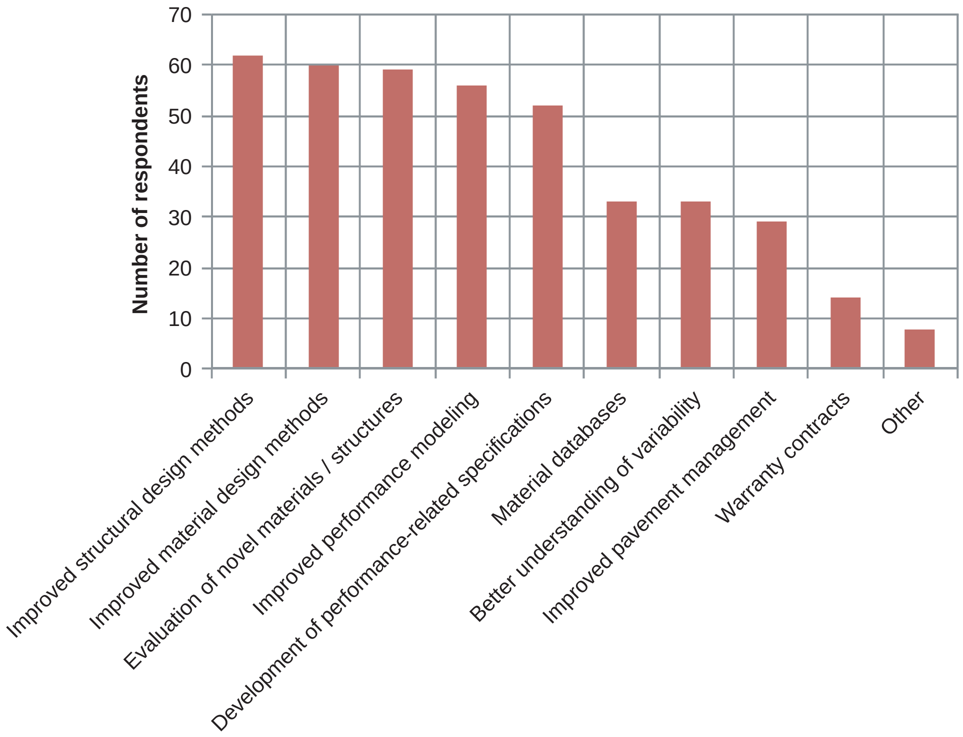

FIGURE 3 Perceptions regarding the benefits of f-sAPT.

future developments and incorporates the major conclusions of the synthesis. Full references are provided together with a Bibliography. The appendices provide detailed information obtained from the questionnaire.

CHAPTER SUMMARY

Chapter one focused on the background to the synthesis and provides the historical introduction through a timeline discussion of previous synthesis documents and the keynote addresses of the first three international APT conferences. It provides the definition used for f-sAPT as well as the origin of the information used in the synthesis. It explains the focus period of the synthesis and the importance of viewing the various f-sAPT syntheses and NCHRP documents as an ongoing and complementary series of references. Finally, it provides background on the surveyed respondents, the number of respondents providing inputs to the synthesis, and summarizes these responses on general perceptions regarding the roles, benefits, and future of f-sAPT.

CHAPTER TWO

CURRENT FULL-SCALE ACCELERATED PAVEMENT TESTING PROGRAMS AND EQUIPMENT

INTRODUCTION

Chapter two provides a summary of the current U.S. and international full-scale accelerated pavement testing (f-sAPT) programs and organizations identified in the study, as well as the sensors and instruments used by f-sAPT programs and the databases employed for data management. This includes contact details, history, major achievements, testing device information, instrumentation information, environmental control, and future plans. Detailed information is captured in Appendix C. Details on all the programs and stakeholders contacted for this synthesis are listed in Appendix B, with an indication of their respective roles (i.e., owner, sponsor, researcher, etc.). The objective of this chapter is to indicate the range of devices and test conditions used by the various programs, and how these relate to each other and test outcomes. It covers traffic loading equipment, environmental control systems, instrumentation, and analysis equipment and is based on the questionnaire survey results, literature review, and selected discussions. The chapter is structured to provide information on the f-sAPT programs, cooperative associations, instrumentation, and databases.

APT systems can be divided into full-scale systems (f-sAPT) and small-scale systems. F-sAPT systems are those where a standard truck tire (or combination of tires) applies the loads to the pavement, whereas small-scale systems are those where a scaled-down version of a truck tire and tire load is applied to the pavement (this synthesis focuses only on f-sAPT). F-sAPT can again be divided into tests tracks, circular and linear tracking devices. The objective of APT is to apply traffic loads and sometimes also environmental effects to a pavement at an accelerated rate compared with normal loading, and to determine the reaction of the pavement and its constitutive layers to this loading in a shorter time than would normally occur on a pavement under typical traffic and environmental conditions. Acceleration of traffic loading is attained through the repeated loading by a set of truck tires over a short section of pavement, most often at increased loads. These increased load levels cause the number of traffic loads applied to the pavement to be multiplied by a factor of typically between 1 and 40. Through this process the response (mostly structural) of the pavement can be quantified during a much shorter time than would be the case if a normal road was monitored under standard load applications.

FULL-SCALE ACCELERATED PAVEMENT TESTING PROGRAMS

Implementation of an f-sAPT facility and associated test program is a long-term action that requires considerable investment (Balay and Mateos 2008). The cost of such a program largely exceeds the initial price of the facility and the construction cost of the experimental pavements, as issues around activities such as laboratory testing, pavement surveys, pavement and facility maintenance, data analysis, and reporting have to be considered. A solid relationship with the academic and research environment will always be profitable and essential as it greatly facilitates access to accompanying services through cooperation with other teams. Both direct and indirect advantages of the project have to be anticipated from the beginning of the feasibility study. Road authorities need to be involved from the start to assist in defining the broad scope of the project, support during the research, and implementation of the outputs to common pavement practice. The process of developing an f-sAPT program provides information on the status quo of pavement engineering in the community and allows for a detailed analysis of needs to improve the local pavement infrastructure and knowledge.

In recent years, increased emphasis has been placed on f-sAPT with various f-sAPT facilities utilized throughout the United States and internationally. Brown et al. (2004) views the primary reason for this increase in the use of f-sAPT facilities as the need to quickly and safely develop answers to emerging pavement issues within a reasonable period of time.

Harvey (2008) evaluated the benefit of f-sAPT from an f-sAPT operator viewpoint and identifies the unique capabilities offered to rapidly move technology from computers and laboratory analysis to full-scale use at attractive BCRs. F-sAPT also offers the ability to attract and focus attention on pavement problems and their solutions. F-sAPT operators are urged to increase their attention to moving results into practice through documenting the major benefits that they produce. Opportunities exist to mine f-sAPT results to obtain additional benefits if results are fully captured and archived, allowing for the combination of f-sAPT results from different types of facilities and field studies to be combined to increase the benefits from f-sAPT experiments. Researchers should think strategically in terms of the problems they choose to invest in to be sure that they are solving future pavement problems.

In 1996, there were 35 f-sAPT facilities around the world, of which some 19 had active research programs in place (Metcalf 1996). Since then there has been an increase in interest in f-sAPT and a move to enhance national and international interaction. This has led to two broad cooperative activities: in the United States, the creation of the TRB technical committee on Full-Scale and Accelerated Pavement Testing (AFD40), and in Europe, the establishment of the COST Pavement Research with Accelerated Loading Testing Facilities Program (COST 347).

Much of the benefit from f-sAPT has been derived from comparison studies of known materials and configurations against new and innovative materials and configurations where some equivalency between the two has provided sufficient confidence to apply the novel solution. This short-term payoff has been complemented by progress in the understanding of material behavior and pavement performance.

There is a large amount of data, and efforts should focus on ensuring that these data become widely available as these outputs are related to the public investment in pavements and the outputs should benefit the public in general.

A substantial improvement in the combination of laboratory materials characterization, f-sAPT experimentation, and full-scale pavement performance observations has occurred during the last decade. Uncertainties related to f-sAPT traffic versus real traffic and the effects of real-time environmental cycles still require improved understanding and modeling.

General Questionnaire Feedback on Full-scale Accelerated Pavement Testing Programs

General feedback from the questionnaire regarding f-sAPT programs, equipment, and related issues are described here.

TABLE 1
DETAILS OF TYPE OF FULL-SCALE APT DEVICES

Description	No. of Respondents	
Type of f-sAPT device	22 Mobile	10 Fixed
Linear or nonlinear trafficking	29 Linear	3 Nonlinear
Uni- or bi-directional loading	29 Uni-directional	3 Bi-directional also
Own power or shore* power	27 Own power	5 Shore power
Field site or fixed site	28 Field site	4 Fixed site
Roads or airfields	31 Roads	1 Airfield
Fixed device or trucks	30 Fixed device	2 Trucks

*Shore power is the term indicating that the device is running off an external power source (i.e., the main electrical grid) instead of its own power supply (i.e., built-in generator).

Thirty-two of the respondents to the questionnaire own an f-sAPT device, while 38 of the respondents have some form of access to an f-sAPT device. Of those respondents who have access to an f-sAPT device, 23 own, 2 rent, and the remainder access the device through other means (i.e., sharing, part of a consortium, etc.). Selected details regarding the actual f-sAPT device characteristics are summarized in Table 1.

Analysis of the instrumentation used by the various programs indicated that most make use of the standard types of measurements (i.e., permanent deformation/strain, elastic deflection/strain) in some form, as well as basic environmental data (moisture and temperature, depending on the material and test conditions).

The nature or purpose of the various f-sAPT programs is primarily focused on state department of transportation (DOT) programs, followed by national and commercial programs (Table 2). Local and academic research needs are relatively low.

Feedback on the current research programs focused on a wide scope of all the major possible topics also reported in literature. The majority of the focus is on hot mix asphalt (HMA) as well as studies with environmentally focused topics such as warm mix asphalt (WMA) and recycling. Evaluation

TABLE 2
PRIMARY NATURE OR PURPOSE OF FULL-SCALE APT PROGRAM

Primary Nature	No. of Programs
State DOT research program or roads agency	19
National research program	11
Commercial research plan	9
International cooperative program	8
Ad hoc use of device—no specific program	8
Partnership program	6
Local research needs	6
Academic research plan	4
Other	2

TABLE 3
TYPES OF FULL-SCALE APT TYPICALLY CONDUCTED

	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	16	5	4
Dedicated constructed test sections (test pit)	9	9	5
In-service field test sections	6	9	9
Rehabilitation option comparison	10	9	5
Other	4	4	2

of materials models for the Mechanistic Empirical Pavement Design Guide (MEPDG) is also quite common. Future research programs might focus on similar topics, although some programs mentioned a decline in funding and a lack of future planning after current work is completed.

Table 3 is a summary of the types of f-sAPT experiments typically conducted by the various programs. The majority of the focus is on dedicated constructed test sections. Funding types are reported in Table 4 with the majority of the programs funded by local, state, and national governments. It was reported that 44% of the funding is short term, with 33% long term and the remainder (23%) intermittent. Respondents mainly select projects based on official research programs (19); however, there are still 7 programs selecting projects an ad hoc basis (Table 5).

Various programs are consistently upgrading and improving their f-sAPT devices and instrumentation. Examples of currently planned new developments include implementation of new f-sAPT devices (at least three programs), improvements in control and load monitoring systems and software, upgrades of data acquisition system and instrumentation packages (in-depth deflection, dynamic rutting, wireless technology, moisture and pressure sensors, fiber optic sensors, etc.), installation of camera systems for identifying and measuring cracks, commissioning of a dedicated materials testing laboratory, and f-sAPT device automatic fault finding systems.

Twenty programs use a combination of f-sAPT and laboratory testing to augment their data generation for analysis process, while selected use of LTM data [referring to both Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) sections as well as local field sections monitored over a number of years that are not part of the SHRP LTPP sections] and field studies also occur (12 programs).

F-sAPT programs use various methods to disseminate the outputs from their programs to industry. The most common

TABLE 4
BREAKDOWN OF FUNDING TYPES

Funding Type	No. of Respondents
Local/state government	8
National government	7
Commercial	6
International	4
Consortium	3
Academic	2
Other	2

TABLE 5
BASIS FOR SELECTION OF FULL-SCALE APT TESTS

Selection Basis	No. of Respondents
Official research program	19
Ad hoc test selection	7
Academic interest	4
Other	1

mechanism is conferences, meetings, and journals (21 programs), with the least common websites and news releases (8 programs). Programs view the main opportunities to disseminate f-sAPT research information as focused pavement engineering conferences and journals, with 28 respondents indicating that they have been actively involved in the various international APT conferences since 1999.

A variety of responses were received on the reasons why programs are currently continuing with their research. Most responses (18) indicated that a need still exists to generate knowledge and expand the understanding of materials and pavements in an environment where traffic demands evolve and constant improvements in performance models potentially lead to more cost-effective application of limited road infrastructure budgets.

Spreadsheet-based systems are used to store data at some stage of the research. Approximately 50% of respondents have dedicated databases where all data are ultimately stored and from where further analyses are conducted.

Sixteen of the f-sAPT device owners make data available to non-APT users for analyses, whereas 12 programs share their data with other f-sAPT programs. Consequently, 52 of the respondents use data from their own f-sAPT programs or databases for research, whereas 19 use data from other organizations. The majority of respondents (50) combine data from more than one test section in their research.

United States Programs

The U.S. f-sAPT programs included in this synthesis are listed in this section with a summary on each of their capabilities (Tables 6 to 17 and Figures 4 to 16). These programs are listed alphabetically. The information supplied by each of the respondents regarding their f-sAPT devices is reflected in the summaries. Where no feedback was received from a specific facility, no details are supplied, except where such details may have been available through public domain literature, where a short summary is provided. Where additional information was available through papers, this is also added in the summary. The full responses received from each of the facilities are provided in Appendix D.

The California DOT (Caltrans) together with the University of California, Davis and Berkeley, Dynatest, and the Commonwealth Scientific and Industrial Organization (CSIRO; South Africa), have conducted a three-phased program combining the results of analytical developments, laboratory testing of pavement materials, and f-sAPT to assist Caltrans in moving toward its goal of improved pavement performance on the approximately 80 000 lane-km of the California highway system since 1994 (Figure 4 and Table 6). The key elements identified through this process as vital for achieving a cost-effective f-sAPT program include adequate funding, commitments for long-term operations and analysis, long-term goals, an overall strategic plan, and well-planned partnering to leverage funds and knowledge (Monismith et al. 2004; Harvey et al. 2007).

The FAA's National Airport Pavement Test Facility (NAPTF) was commissioned in 1999 with the first construction cycle consisting of three rigid and six flexible pavement test items (Figure 5 and Table 7). This was followed by the second construction cycle consisting of a rigid pavement test strip, a free-standing test slab, and three rigid pavement test items, as well as four flexible pavement test items. Uniformity of construction and reliability of the apparatus for applying the loads to the pavements have been good enough to allow the results of the traffic tests to be incorporated in the FAA layered elastic flexible pavement design procedure. Test results are also being used to establish appropriate factors for four- and six-wheel landing gears in the California Bearing Ratio method of flexible pavement design (Hayhoe 2004).

The need for faster and more practical evaluation methods under closely simulated in-service conditions prompted the Florida DOT (FDOT) to initiate an f-sAPT program in 2000. The f-sAPT facility is housed within the State Materials Research Park in Gainesville (Figure 7 and Table 9). The testing site consists of eight linear test tracks, each being 150 ft (6 m) long and 12 ft (3.7 m) wide. Two additional test tracks have water table control capabilities within the supporting base and subgrade layers. A heavy vehicle simulator (HVS) Mark IV is used for the f-sAPT. The development, planning, and execution of the program have been conducted with support from the FDOT central offices and districts and partnerships with the Florida University system, industry, and FHWA. The primary objective of the program is to continuously improve the performance of Florida's pavements through acquiring and implementing knowledge and technology to extend the useful service life of pavements and prevent premature distress cost-effectively. The FDOT f-sAPT program has investigated flexible, rigid, and composite pavements over the last decade with a focus on HMA mixture gradation, the use of polymer-modified binders, damage resulting from tire types, the effect of stress-absorbing layers, HMA aging, and early strength gain of concrete.

Thirteen full-scale pavement testing projects were conducted at the Kansas State University (KSU) APT facility between 1998 and 2008 (Figure 9 and Table 11). The Midwest States Accelerated Pavement Testing Pooled Funds Program sponsors the APT program at this facility. The f-sAPT program continues to be a cost-effective method of evaluating pavement performance as evidenced by the sponsors' continuous commitment to fund the program. The lessons learned during the first ten years helped to ensure continued success (Lewis 2008).

FIGURE 4 Caltrans/UCPRC HVS.

The original vision for MnROAD was a facility that would facilitate pavement research in a real world laboratory with research results that would change the way engineers design, construct, and maintain the highway system. Although many of these changes may be incremental when looked at individually, large savings may result when these improvements are spread out over a massive national highway network (Worel and Eaton 2004). MnROAD was constructed in the early 1990s to contribute to the development of an M-E pavement design method for Minnesota. Nine of the test sections were located on an interstate highway, while the remaining five test sections were low-volume road designs (Figure 11 and Table 13). The test cells were exposed to natural weather conditions experienced daily and seasonal stresses from slab warping and curling. Longer exposure to the environment also revealed potential tendencies toward loss of support and pumping in the designs. MnROAD is trafficked by a wide variety of actual vehicles and therefore the performance of the test cells truly represents the behavior of pavements in Minnesota. The continuing archive of ride quality, distress, and load response data from the MnROAD project is valuable in calibration of the MEPDG designs (Burnham 2005).

MnDOT intended MnROAD as a site for collaboration on the state, local, and federal levels in the study of pavement and pavement technologies. This desire for collaboration was first realized in planning and later the construction of MnROAD, which was funded by MnDOT, FHWA, and the Minnesota Local Road Research Board, a consortium of members interested in research of municipal and county roads, and

TABLE 6
CALIFORNIA DOT (CALTRANS)/UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER (UCPRC)

Located in Davis, California	
Parameter	Selection
Mobile/fixed	Mobile
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Both
Number of axles	1
Own power (diesel/electric/other)/shore power	Both
Field site/fixed site	Both, UC Davis and various locations in California
Roads/airfields	Roads, can do airfields but not the focus
Fixed device/trucks (automated or manually driven)	Fixed
Load range (range in kN—indicate full load for all tires as well as range per tire)	6.7 to 45 kip (30 to 200 kN) for two tires
Tire details (size, type, inflation pressure range, other)	Truck (Goodyear G159) and aircraft 101 psi (700 kPa)
Tire wander options	Yes, programmable
Suspension (present or not, types possible, permanent or not, etc.)	No
Temperature control options	Heating and cooling. 50°F to 122°F (10°C to 50°C) pavement temperature
Speed range	2 to 12.4 mph (3 to 20 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	http://www.ucprc.ucdavis.edu/

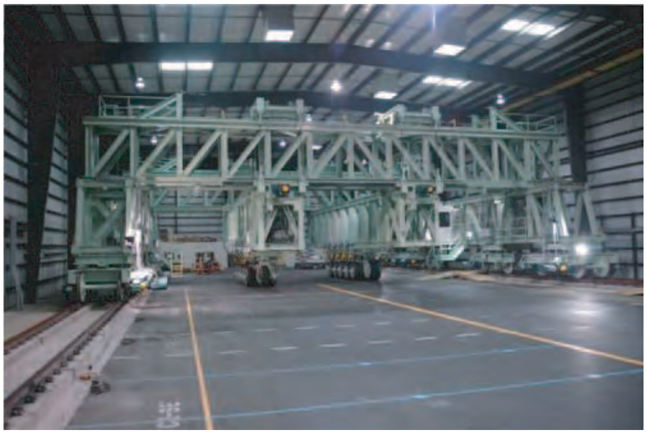

FIGURE 5 FAA NAPTF.

the early spirit of partnership in full-scale pavement testing has continued to this day through MnROAD's participation in Transportation Engineering and Road Research Alliance (TERRA) and various pooled fund studies (Tompkins et al. 2008).

Several research projects were initiated that necessitated the reconstruction of pavement test sections as MnROAD entered Phase II of its existence. This included study plans to test various configurations of heavy farm equipment and assess the resulting damage in comparison with a typical truck. A second study plans to stabilize a full-depth reclamation base material with out-of-specification fly ash and compare its performance with both a nonstabilized full-depth reclamation and conventional aggregate base. A third study is a field validation of previous laboratory work on polyphosphoric acid-modified HMA binders. Finally, a field validation of an innovative diamond grinding pattern for concrete pavements developed by Purdue University has been evaluated. These projects are the result of partnerships between MnDOT and private industry, government agencies, and other state DOTs through the Transportation Pooled Fund Program (Clyne et al. 2008a, b).

The second generation of the Minnesota Accelerated Loading Facility (Minne-ALF-2) constitutes a laboratory-based loading pavement test stand that simulates the passage of heavy wheel loads moving over a small full-scale pavement test strip. In addition to testing of long-term performance of concrete pavement joints, Minne-ALF-2 may be used for an investigation of the fundamentals of concrete joint behavior to support the development of improved M-E models of pavement joints (Khazanovic et al. 2005).

TABLE 7
FEDERAL AVIATION ADMINISTRATION

Located at Atlantic City International Airport	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional loading
Number of axles	10
Own power (diesel/electric/other)/shore power	Shore power
Field site/fixed site	Fixed site
Roads/airfields	Airfields
Fixed device/trucks (automated or manually driven)	Fixed device (automated)
Load range (range in kN—indicate full load for all tires as well as range per tire)	901 kip (4 008 kN) [75 kip (334 kN) per wheel]
Tire details (size, type, inflation pressure range, other)	Radial tires, 52 x 21.0R22 Inflation pressure depends on wheel load and rated deflection, can go up to 250 psi (1723 kPa)
Tire wander options	Wander can be programmed
Suspension (present or not, types possible, permanent or not, etc.)	No
Temperature control options	No
Speed range	15 mph (24 km/h) maximum
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	http://www.airporttech.tc.faa.gov

FIGURE 6 FHWA ALF.

Mississippi Department of Transportation

Mississippi DOT f-sAPT is conducted at National Center for Asphalt Technology (NCAT) (Figure 12 and Table 14).

Texas Department of Transportation

The Texas DOT (TxDOT) evaluated a modification of the Rolling Dynamic Deflectometer (RDD) for use as a super-accelerated pavement tester where the truck-mounted dynamic loading system was operated in a stationary mode (Figure 14). The servo-hydraulic actuator is used to apply harmonic loading to a wheel footprint on the pavement surface, applying hundreds of thousands of load repetitions in a matter of hours. This system may allow TxDOT to increase cost-effectively the number of accelerated tests that can be performed. Initial tests indicated similar results with the Texas Mobile Load Simulator (MLS) (Stokoe et al. 2000).

TABLE 8
FEDERAL HIGHWAY ADMINISTRATION

Located in McLean, Virginia	
Parameter	Selection
Mobile/fixed	Fixed Has mobile capabilities but has only rarely been used in the very beginning of the program
Linear/nonlinear (circular, elliptical)	Linear ALF, Australian designed system
Uni-/bi-directional	Uni-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed Has mobile capabilities but has only rarely been used in the very beginning of the program
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Wheels are self-powered and driven rather than the wheel carriage pulled or pushed
Load range (range in kN—indicate full load for all tires as well as range per tire)	9.9 to 16.6 kip (44 to 74 kN) Uses steel plates (dead weight) on suspension
Tire details (size, type, inflation pressure range, other)	Dual 11R22.5 Super single 425 Typically between 100 and 120 psi (690 kPa to 827 kPa)
Tire wander options	Lateral wander with three options. No wander (channelized), random tables with normal distribution for 2 in. (50 mm) standard deviation and 5.2 in. (133 mm) standard deviation
Suspension (present or not, types possible, permanent or not, etc.)	Standard air bags and shock absorber suspension Requires landing of wheel to be tuned and minimize or eliminate load spike
Temperature control options	Radiant heaters connected to temperature controllers and thermocouples can control pavement temperature at 0.8 in. (20 mm) depth. Rutting can be performed any time of year as high as 169°F and intermediate temperatures [50 to 82°F (10 to 28°C)] loading for fatigue cracking can be conducted when ambient temperatures allow radiant heaters to heat pavement up to intermediate temperature; usually spring, winter and fall.
Speed range	As low as 2.5 to 3 mph (4 to 5 km/h) and high as 10 to 11 mph (16 to 18 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Speed, position and load can be measured during operation Pavement layer instrumentation is independent from ALF operation (not integrated)
APT webpage link	http://www.fhwa.dot.gov/research/tfhrc/labs/pavement/index.cfm

FIGURE 7 Florida DOT HVS.

A fixed location f-sAPT center opened in January 2004. Work began on the program in January 2002, when the Texas Accelerated Pavement Testing (TxAPT) Center was funded by TxDOT at The University of Texas at Austin. The primary test equipment was a refurbished MLS that TxDOT used on its field highway system for six years, but with a test program at the fixed site.

A new TxDOT f-sAPT research project was initiated in September 2011. It is envisaged that Project 0-6682 (Validation of the Maximum Allowable Amounts of Recycled Binder, RAP & RAS Using Accelerated Pavement Testing)

TABLE 9
FLORIDA DEPARTMENT OF TRANSPORTATION (FDOT)

Located in Gainesville, Florida	
Parameter	Selection
Mobile/fixed	Mobile (HVS)
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Diesel CAT Generator/480V Electric Shore Power
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed
Load range (range in kN—indicate full load for all tires as well as range per tire)	7 to 45 kip (31 to 200 kN)
Tire details (size, type, inflation pressure range, other)	Dual—(11R22.5) Super single—(425/65R22.5) New wide-base tires—(445/50R22.5 and 455/55R22.5)
Tire wander options	0 to 30 in. (0 to 762 mm)
Suspension (present or not, types possible, permanent or not, etc.)	Hydraulic front suspension for turning and raising the front while moving to different test sections
Temperature control options	Radiant heaters installed on both sides of test beam Insulated panels maintain temperature. No cooling device
Speed range	Up to 8 mph (12.8 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Typically collect load, speed, tire location. Also collect HVS system information
APT webpage link	http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/index.shtm
Other	Report on loading assessment (http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/researchreports/pavement/03-463.pdf)

TABLE 10
INDIANA DEPARTMENT OF TRANSPORTATION

Located in West Lafayette, Indiana	
Parameter	Selection
Mobile/fixed	Fixed (Accelerated Pavement Testing Facility—APTF)
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	20 kip (89 kN) for half axle
Tire details (size, type, inflation pressure range, other)	Dual, 11R22.5, 100 psi (689 kPa); Dual, 11R24.5, 100 psi (689 kPa); Super single, 425/65R22.5, 120 psi (827 kPa)
Tire wander options	5 in. (0.13 m) left and right
Suspension (present or not, types possible, permanent or not, etc.)	Not
Temperature control options	Yes, radiant heater and air conditioner
Speed range	5 to 10 mph (8 to 16 km/h) Dedicated operational
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	http://rebar.ecn.purdue.edu/APT/

FIGURE 8 Indiana DOT APTF.

will be used to develop an f-sAPT facility. The f-sAPT device is funded by the University of Texas at Arlington, while TxDOT is funding the testing.

International Programs

The non-U.S. f-sAPT programs included in this synthesis are listed in this section with a summary on each of their capabilities (Tables 18 to 37 and Figures 17 to 37). These programs are listed alphabetically. A similar process was followed in the summaries as that for the U.S. programs.

For some countries, questionnaire responses lacked the facilities current activities and information on f-sAPT devices (Table 18 and Figure 17). Where it was apparent that facilities were still active during the past decade, information for these facilities has been extracted from their websites and the summary of f-sAPT facilities provided as part of the 2008 3rd International Conference on Accelerated Pavement Testing.

Since 1996, a linear traffic simulator has been loading full-scale test sections in an f-sAPT facility built at the Federal

FIGURE 9 Kansas APT device.

University of Rio Grande do Sul in Porto Alegre, Brazil (see Figure 18 and Table 19). The facility includes the traffic simulator, test sections, and a control center and is part of a cooperation agreement between the University and the Rio Grande do Sul State Roads Department. Output highlights during this process include a design equation for low-volume roads, improvements in the specification for dry-bound macadam, evaluation of the influence of soil suction in subgrades, evaluation of the benefits of paving fabrics between cracked HMA pavements and HMA overlays, and evaluation of the efficiency of asphalt rubber overlays. Two additional mobile traffic simulators have been designed and built since 2003 (Núñez et al. 2008).

The School of Transportation at Southeast University owns an f-sAPT device (see Tables 20–24 and Figures 19–23). It has a 7.9-ft (2.4-m)-deep circular trough with an outer diameter of 31 ft (9.5 m) and an inner diameter of 18 ft (5.5 m). The circular test section is 6.5 ft (2 m) wide. The load is provided through two arms with a standard axle with full-sized dual tires on the outer edges of the arms. The speed is adjustable up to 12.4 mph (20 km/h). A load of 11.2 kip (50 kN) can be applied per side. The maximum tire inflation pressure is 101 psi (700 kPa). No wander can be applied. Infrared radiation is used to increase pavement temperature to a maximum of 140°F (60°C) (Jun et al. 2008).

China Changsha CSUST (Changsha Science and Technology University)

The linear accelerated loading system is located in Changsha CSUST. It is a full-scale linear test track consisting of a test pit, loading vehicle, artificial rain device, and a control and monitor console. Tests are conducted in uni- or bi-directional

TABLE 11
KANSAS DEPARTMENT OF TRANSPORTATION

Located in Manhattan, Kansas at KSU	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Bi-directional
Number of axles	One or two
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	1 to 5 kip (5 to 22 kN) single axle Double for tandem axle
Tire details (size, type, inflation pressure range, other)	Conventional over the road
Tire wander options	Yes, up to 6 in. (0.15 m)
Suspension (present or not, types possible, permanent or not, etc.)	Conventional air bag
Temperature control options	Radiant heat and cooling panels
Speed range	5 to 6.8 mph (8 to 11 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Dedicated data collection, speed, load, position, and strain
APT webpage link	http://www.k-state.edu/pavements/

TABLE 12
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

Located in Louisiana	
Parameter	Selection
Mobile/fixed	Mobile—ALF
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni-D
Number of axles	1
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	
Roads/airfields	Road
Fixed device/trucks (automated or manually driven)	Automated
Load range (range in kN—indicate full load for all tires as well as range per tire)	9 to 13.5 kip (40 to 60 kN)
Tire details (size, type, inflation pressure range, other)	11R22.5 Dual
Tire wander options	Yes
Suspension (present or not, types possible, permanent or not, etc.)	Not applicable
Temperature control options	No
Speed range	10 to 12 mph (16 to 19 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	None

mode with a wheel load of between 6.7 and 22.5 kip (30 and 100 kN). Traffic wander can be defined (Cui et al. 2007).

China Harbin Institute of Technology

F-sAPT has been recognized as the most important and direct way to obtain structural behavior information on pavements subjected to traffic loading; therefore, a new f-sAPT facility has been designed in China as part of the Eleventh Five-Year National Grand Technology Infrastructure Program. The final design is based on 3-dimensional (3-D) analysis of different types of test tracks, and is to be located at the Harbin Institute of Technology in Harbin, China (Dong et al. 2009).

Colombia Universidad de Los Andes

This test track consists of an 11.5-ft (3.5-m)-wide ring and is 115 ft (35 m) long (measured at the center of the lane). The carousel equipment can load the pavement at a rate of 200,000 repetitions per week using a dual-tired, single axle. The carousel can apply loads of up to almost 33.7 kip (150 kN). The wheel speed can be set up to 24.9 mph (40 km/h), and wheel wander is adjustable within a range of 39.4 in. (1.0 m) (Reyes and Kohler 2006).

FIGURE 10 Louisiana DOTD ALF.

In Japan, a systematic change from recipe-based to performance-based specifications has been progressing since 2001. As a result, f-sAPT has experienced increased significance and opportunity, particularly in the development of innovative pavement materials. The importance of performance evaluation of the entire pavement layer system increased, and f-sAPT is used for proofing evaluations of structural designs as well as the final evaluation of new pavement materials and functions. Based on this background, demand for f-sAPT increased significantly. A linear (reciprocating)-type f-sAPT facility has been built at the Public Works Research Institute (PWRI) to supplement the existing circular-type facility, while the circular-type facility has been upgraded (Sasaki and Nishizaki 2004).

South Korea, Korea Highway Corporation Test Road

The Korea Highway Corporation (KHC) initiated the KHC Test Road construction project in 1997 with the objective of development and validation of the Korean Pavement Design Guide. It consists of 4.8 miles (7.7 km) of two-lane highway next to the Jungbu Inland Expressway. It is made up of 25 concrete and 15 HMA test pavement sections and contains numerous

FIGURE 11 MnROAD test track.

sensors to capture the behavior of pavement systems under traffic load and environmental change. The design parameters of the portland cement concrete (PCC) sections are concrete slab thickness, base type, base thickness, and pavement type, while the parameters for the HMA sections are base type, base thickness, subbase thickness, and wearing course type. The new M-E design guide will optimize pavement design and improve pavement performance in Korea and will also reduce pavement construction and maintenance costs. It is anticipated that the effort will strengthen the pavement research infrastructure and that the test road database will provide valuable research resources to the pavement community (Kim et al. 2004).

The South African HVS Program has had a major technological and economic impact on the design, construction, and maintenance of South African roads since the 1970s. It has impacted the development of national and regional pavement design standards and guidelines, the development of material specifications and guidelines, the development of human resources, capacity building in the road construction industry, the development of innovative products and designs, and the provision of cost-effective infrastructure engineering solutions (Verhaeghe et al. 2006; Du Plessis et al. 2008a).

Switzerland has a tradition of f-sAPT since the beginning of the 1970s when the Swiss Codes for road design were affected by the outcomes of seven test campaigns on more than 35 pavement structures tested with the Rundlauf circular test track. This device has recently been replaced with the MLS10 (mobile lad simulator full-scale), which represents a reliable substitute (Rabaiotti et al. 2008).

TABLE 13
MINNESOTA DEPARTMENT OF TRANSPORTATION (MNROAD)

Located in Maplewood, Minnesota	
Parameter	Selection
Mobile/fixed	Not applicable
Linear nonlinear (circular, elliptical)	Not applicable
Uni-/bi-directional	Not applicable
Number of axles	Mainline—Live traffic
	Low volume road—5 axle semi-tractor trailer
	Farm loop and other studies—different equipment types
Own power (diesel/electric/other)/shore power	Not applicable
Field site/fixed site	MnROAD
Roads/airfields	Mainline interstate and low volume road, farm loop
Fixed device/trucks (automated or manually driven)	Manual driven
Load range (range in kN—indicate full load for all tires as well as range per tire)	Mainline—Live traffic up to 88 kip (391 kN) gross vehicle weight
	Low volume road—80 and 102 kip (355 kN to 450 kN) gross vehicle weight
Tire details (size, type, inflation pressure range, other)	Real traffic tires http://www.dot.state.mn.us/mnroad/data/pdfs/semidescription.pdf
Tire wander options	Live traffic
Suspension (present or not, types possible, permanent or not, etc.)	Real traffic suspension http://www.dot.state.mn.us/mnroad/data/pdfs/semidescription.pdf
Temperature control options	None
Speed range	Low volume road—40 mph (64 km/h) Mainline—70 mph (112 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Not applicable
APT webpage link	http://www.dot.state.mn.us/mnroad/

FIGURE 12 NCAT pavement test track.

ASSOCIATIONS AND COMMITTEES

Formation of associations of f-sAPT programs has occurred actively during the last decade. These associations are formed around specific loading devices or funding programs with the general objective of improving the cost-effectiveness of the overall programs through cooperative efforts of program planning, data analysis, and device improvements. This section provides details around activities in these associations. NCAT is excluded from this section because it is treated as a program in this synthesis, whereas the COST (Cooperation for Science and Technology) program has been included although it was officially terminated following completion of its original tasks. For each of the summaries the website address is provided as well as a short description of its background and objectives (where available).

Consortium of Accelerated Pavement Testing

In 2007, FHWA and state DOTs from nine of the 15 U.S. Pavement Testing Facilities created a pooled fund program to encourage coordination among the pavement testing facilities. The program provides resources and management for collaborative studies and support and sharing of f-sAPT technologies (http://rip.trb.org/browse/dproject.asp?n=27614).

A significant number of f-sAPT programs in the United States are funded by state DOTs with the rest being federal, academic, and private facilities. The Consortium of Accelerated Pavement Testing (CAPT) consists of a group of f-sAPT facility owners and operators in the United States that seeks to generate coordinated impacts through f-sAPT. CAPT attempts to provide continuous attention to f-sAPT

TABLE 14
NATIONAL CENTER FOR ASPHALT TECHNOLOGY (NCAT) PAVEMENT TEST TRACK

Located at Opelika, Alabama	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Oval
Uni-/bi-directional	Uni-directional
Number of axles	8 axles on 5 trucks (40 axles total)
Own power (diesel/electric/other)/shore power	Diesel
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Manually driven trucks
Load range (range in kN—indicate full load for all tires as well as range per tire)	4.8 to 9.4 kip (21.5 to 41.8 kN) per tire
Tire details (size, type, inflation pressure range, other)	275/80R22.5 at 100 psi (689 kPa)
Tire wander options	Real world
Suspension (present or not, types possible, permanent or not, etc.)	Spring and air
Temperature control options	Ambient
Speed range	Up to 50 mph (80 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Climate and high speed response
APT webpage link	www.pavetrack.com

FIGURE 13 Ohio DOT APT facility.

with a forum-like structure to discuss and improve relevant issues and is operated under the Transportation Pooled Fund program (www.pooledfund.org) [Pooled Fund TPF-5(127)] sponsored by the FHWA, TRB, and AASHTO that enables technology transfer activities to be jointly funded by several federal, state, regional, and local transportation agencies, academic institutions, foundations, or private firms. CAPT's mission is to share and develop best practices and collaborate in experimental design, data acquisition, data sharing, and validation of findings. Their vision is that owners and operators will improve and economize their operations and accelerate acceptance of pavement performance findings. Through communication and collaboration it is envisaged that these facilities can make greater impacts (Gibson et al. 2008).

CAPT developed ten key emphasis areas to balance and focus efforts because the scopes and objectives of the various participants' programs vary significantly. Overall, CAPT focuses its future efforts on overall coordination of f-sAPT research in the United States, as well as day-to-day activities outlined as needs and gaps by the participants. Instrumentation needs and gaps is one of the areas that affect all participants, including common installation methods, data collection methods, and equipment and analysis of the data files.

Cooperation for Science and Technology

COST is an intergovernmental framework for European Cooperation in Science and Technology, allowing the coordination of nationally funded research on a European level; contributing to reduction in fragmentation in European research investments (http://www.cost.eu/domains_actions). It provides a

TABLE 15
OHIO DOT

Located in Columbus, Ohio	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- or bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Hydraulic
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	http://www.ohio.edu/orite/facilities/accelpaveload.cfm
Tire details (size, type, inflation pressure range, other)	http://www.ohio.edu/orite/facilities/accelpaveload.cfm
Tire wander options	Yes
Suspension (present or not, types possible, permanent or not, etc.)	Air bag
Temperature control options	http://www.ohio.edu/orite/facilities/accelpaveload.cfm
Speed range	http://www.ohio.edu/orite/facilities/accelpaveload.cfm
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	http://www.ohio.edu/orite/facilities/accelpaveload.cfm

FIGURE 14 Refurbished TxDOT MLS.

FIGURE 15 USACE CRREL HVS.

TABLE 16
US ARMY CORPS OF ENGINEERS (EDRC) COLD REGIONS RESEARCH AND ENGINEERING LABORATORY (CRREL)

Located in Hanover, New Hampshire	
Parameter	Selection
Mobile/fixed	Mobile
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Both shore and from generator
Field site/fixed site	Fixed site with option of field sites
Roads/airfields	Roads and airfields
Fixed device/trucks (automated or manually driven)	Self-drive for short distance, truck driven for long distance
Load range (range in kN—indicate full load for all tires as well as range per tire)	2.2 to 46 kip (10 to 205 kN) Range/tire depends on gear/tire configuration
Tire details (size, type, inflation pressure range, other)	Truck (super single, single axle)
Tire wander options	35 in. (0.9 m) wander
Suspension (present or not, types possible, permanent or not, etc.)	None
Temperature control options	14°F to 140°F (–10°C to 60°C)
Speed range	0.6 to 7.5 mph (1 to 12 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	http://www.crrel.usace.army.mil/facilitieslabstestsites/ferf.html

FIGURE 16 USACE WES HVS.

flexible, fast, effective, and efficient tool to network and coordinate nationally funded research activities, bringing scientists together under light strategic guidance, based on networks, centered on research projects. The goal of COST is to ensure that Europe holds a strong position in the field of scientific and technical research by increasing European cooperation and interaction in this field. COST Action 347 [Improvements in Pavement Research with Accelerated Load Testing (ALT)] was initiated in October 2000 with a scheduled duration of 3.5 years. The main objective of COST 347 was to develop a European code of good practice to optimize the use of f-sAPT facilities and improve the application of results from these facilities, leading to a more harmonized approach to f-sAPT in Europe. It had six main work packages, comprising inventory of existing ALT facilities in Europe, previous and current research in the field of ALT, comparison between ALT and RLT (real-time load testing), development of a common code of good practice for ALT, future use of ALT, and finally dissemination.

The major benefits from f-sAPT are often obtained through national research programs that tailor the research to the

TABLE 17
U.S. ARMY CORPS OF ENGINEERS (EDRC) WATERWAYS EXPERIMENTAL STATION (WES)

Located in Vicksburg, Mississippi	
Parameter	Selection
Mobile/fixed	Mobile
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	1 or 2
Own power (diesel/electric/other)/shore power	Both shore and from generator
Field site/fixed site	Fixed site with option of field sites
Roads/airfields	Roads and airfields
Fixed device/trucks (automated or manually driven)	Self-drive for short distance, truck driven for long distance
Load range (range in kN—indicate full load for all tires as well as range per tire)	2.2 to 99 kip (10 to 440 kN) Range/tire depends on gear/tire configuration
Tire details (size, type, inflation pressure range, other)	Truck (super single, single axle, dual axle) Aircraft (C17 single tire, F-15 single tire)
Tire wander options	35 in. (0.9 m) wander
Suspension (present or not, types possible, permanent or not, etc.)	Suspension for self-drive/steering
Temperature control options	14°F to 140°F (–10°C to 60°C)
Speed range	0.6 to 7.5 mph (1 to 12 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e. applied speed, load, location etc.)?	Yes
APT webpage link	http://pavement.wes.army.mil/apt/

TABLE 18
AUSTRALIA, ARRB GROUP (ARRB)

Located in Melbourne, Australia	
Parameter	Selection
Mobile/fixed	Fixed (ALF)
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni-directional
Number of axles	1, 2 or 3 axles
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Currently on fixed site
Roads/airfields	Yes
Fixed device/trucks (automated or manually driven)	Fixed
Load range (range in kN—indicate full load for all tires as well as range per tire)	9 to 20 kip (40 to 90 kN) for whole axle group Load per axle or tires is lower and dependent upon number of axles and tires in configuration
Tire details (size, type, inflation pressure range, other)	Various dual or single
Tire wander options	Yes
Suspension (present or not, types possible, permanent or not, etc.)	Yes
Temperature control options	Yes, use heaters
Speed range	0 to 12.5 mph (0 to 20 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Separate logging data dependent upon experiment Dedicated control system that automatically logs speed, longitudinal and transverse location, pavement and surface temperatures, machine specific parameters (e.g., hydraulic oil temperature, state of fans and motors, etc.), and dynamic load applied to pavement.
APT webpage link	http://www.arrb.com.au/Infrastructure/Accelerated-Pavement-Testing.aspx

FIGURE 17 ARRB Group ALF.

specific interests of the country concerned (Balay and Mateos 2004; Hildebrand 2004). Through the Pan-European approach of COST 347, a more robust outcome with wider acceptance and reduced cost to the individual countries has been attained. COST 347 accomplished its goals regarding improved and increased European and International cooperation in f-sAPT as some 20 countries worked together in the action and new professional relationships developed that are expected to be useful in the future. Europe experienced growth in cooperative projects with the Swedish–Finnish HVS being used for projects in Poland and Denmark.

Since the end of the COST 347 project the use of f-sAPT in Europe has declined, some operations curtailed or terminated (Hildebrand and Dawson 2008). The current main use of f-sAPT is special product approval and validation as well as calibration of research modeling of pavements. F-sAPT

FIGURE 18 Brazil f-sAPT device.

operators and road owners agree that the topics proposed by the COST 347 Action (i.e., new and alternative pavement materials, environmental issues, effects of maintenance treatments, effects of new types of vehicles, and pavement design methods) continue to be relevant for their countries' needs. Since the termination of COST 347 in 2004 a formal f-sAPT network in Europe has not existed.

Forum of European National Highway Research Laboratories

Forum of European National Highway Research Laboratories (FEHRL) is a registered international association with a permanent secretariat based in Brussels (www.fehrl.org). It was formed in 1989 and is governed by the directors of each of the national institutes. FEHRL provides a coordinated structure for the interests of more than 30 European national research and technical centers, together with associated institutes from around the world. It is engaged in road engineering research topics including materials, safety, environmental issues, telematics, and economic evaluation, with research capacity provided by the national institutes and their available test facilities. FEHRL and its institutes provide research services and advice to road administrators and industries for the safe and efficient operation and management of Europe's road network. FEHRL focuses its efforts on pavement and bridge engineering, construction materials, environmental issues, maintenance management, traffic loading, safety, telematics, and geotechnics.

The current (May 2011) European members of FEHRL owning f-sAPT devices are Austria, Denmark, France, Germany, Ireland, the Netherlands, Spain, Sweden, Switzerland

TABLE 19
BRAZIL

Located at Federal University of Rio Grande do Sul, Brazil	
Parameter	Selection
Mobile/fixed	Fixed, at the university campus
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	One (half axle)
Own power (diesel/electric/other)/shore power	Own electric
Field site/fixed site	Fixed
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Automated driven
Load range (range in kN—indicate full load for all tires as well as range per tire)	9.5 to 13.5 kip (42 to 60 kN) half axle 4.7 to 6.7 kip (21 to 30 kN) per wheel
Tire details (size, type, inflation pressure range, other)	Ply tires, Inflation pressure between 81 and 101 psi (560 and 700 kPa)
Tire wander options	Wanders
Suspension (present or not, types possible, permanent or not, etc.)	Permanent
Temperature control options	No
Speed range	3 to 3.7 mph (5 to 6 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	—
APT webpage link	None

TABLE 20
CHINA, CHANG'AN UNIVERSITY

Located in Xi'an, China	
Parameter	Selection
Mobile/fixed	Mobile, HVS MkVI
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Shore power (also diesel generator possible)
Field site/fixed site	Fixed, field is possible
Roads/airfields	Roads and airfields
Fixed device/trucks (automated or manually driven)	No
Load range (range in kN—indicate full load for all tires as well as range per tire)	6.7 to 45 kip (30 to 200 kN)
Tire details (size, type, inflation pressure range, other)	Single 12R22.5 Dual 12R22.5 Super single 425/65 R22.5 super single truck tire Single aircraft tire 58 to 145 psi (400 to 1 000 kPa), temperature and pressure sensors
Tire wander options	Yes, automatic indexing or tracking between passes from side to side for a total lateral coverage of 30 in. (762 mm) adjusted in 1 in. to 4 in. (25 to 100 mm) increments
Suspension (present or not, types possible, permanent or not, etc.)	No, axle mounted directly to carriage
Temperature control options	—
Speed range	1.2 to 8 mph (2 to 12.8 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	University webpage: http://www.at0086.com/chanu/

FIGURE 19 China Chang'an University HVS.

and United Kingdom. In addition South Africa (CSIRO) and the United States (FHWA) are members and own f-sAPT devices.

Heavy Vehicle Simulator International Alliance

The Heavy Vehicle Simulator International Alliance (HVSIA) is a voluntary association of HVS users, established to promote interaction between users and to coordinate testing and the dissemination of test results (http://www.hvsia.co.za). The website captures pertinent information and displays meta-data with respect to the results of tests. The objectives of the HVSIA are to promote and share knowledge related to HVS technology; establish a structure for ongoing interactions focusing on HVS technology; establish mechanisms for funding, monitoring, and completion of

TABLE 21
CHINA, LIAONING PROVINCE COMMUNICATION RESEARCH INSTITUTE

Located in Shenyang, Liaoning, China	
Parameter	Selection
Mobile/fixed	Mobile—MLS
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni-directional
Number of axles	6
Own power (diesel/electric/other)/shore power	Both
Field site/fixed site	Both
Roads/airfields	Both
Fixed device/trucks (automated or manually driven)	Fixed
Load range (range in kN—indicate full load for all tires as well as range per tire)	11 to 19 kip (50 to 85 kN) per tire
Tire details (size, type, inflation pressure range, other)	—
Tire wander options	Yes
Suspension (present or not, types possible, permanent or not, etc.)	Present
Temperature control options	Ambient to 158°F (70°C)
Speed range	1,500 to 6,000 repetitions per hour
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Applied speed
APT webpage link	—

studies on common issues through participation of members; provide expertise to expeditiously define, manage, and review studies of interest and optimize resource use through coordination of HVS-related research. All HVS owners continue with their own research programs, while the HVSIA activities complement and support the efforts of individual members.

FIGURE 20 China Liaoning Province Communication Research Institute f-sAPT device.

Membership of the HVSIA as of May 2011 was South Africa (CSIRO/Gautrans), California (UCPRC), FDOT, EDRC (CRREL), EDRC (WES), Sweden (VTI), Costa Rica, China (Chang'an University), and India (Central Road Research Institute).

Collaboration between f-sAPT programs is often suggested as a method to encourage cost efficiencies, but is usually difficult to implement (Harvey et al. 2008). The HVSIA has, with no formal budget, organized nine successful international meetings and has been effective in encouraging interaction between users of HVS equipment. It has produced a number of very useful products, including:

- The HVSIA activity matrix provides a quick reference to all research performed by HVSIA members by focus and competency area with links to access reports that are available on this research. It also includes planned HVS research projects that are likely to lead to collaboration on actual research projects by HVSIA members and, possibly, others.
- The HVSIA instrumentation matrix provides information on instrumentation used by HVSIA members.
- Workshop and specialty sessions were held on topics of interest to the HVSIA members including HVS tests

TABLE 22
CHINA, MERCHANTS CHONGQING COMMUNICATIONS RESEARCH & DESIGN INSTITUTE

Located in Chongqing, China	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Circular
Uni-/bi-directional	Uni-directional loading
Number of axles	Two
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	24.7 to 33.7 kip (110 to 150 kN) for all tires, 6.1 to 8.4 kip (27.5 to 37.5 kN) per tire
Tire details (size, type, inflation pressure range, other)	900-20-14, C856
Tire wander options	2 in. (50 mm)
Suspension (present or not, types possible, permanent or not, etc.)	No
Temperature control options	41 to 158°F (5 to 70°C)
Speed range	Up to 37 mph (60 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	—
APT webpage link	http://www.ccrdi.com/Category_96/Index_1.aspx

versus field performance, analytical and performance issues, data collection issues, evaluation and quantification of HVS test benefits, stiffness related to structural design, linkages between f-sAPT and LTM, and M-E design and calibration.

The somewhat intangible benefit of ongoing interest and interaction between HVSIA members is viewed as the HVSIA's greatest success. This interaction is actively fostered within the HVSIA as members share a focused common interest.

FIGURE 21 China Merchants Chongqing Communications Research & Design Institute f-sAPT device.

Mobile Load Simulator User Group

A MLS user group consisting of owners of full-scale and scaled MLS devices is being developed (www.mlsglobalusers.com). Feedback from the activities is typically provided during annual TRB AFD40 committee meetings.

Transportation Engineering and Road Research Alliance

TERRA is a partnership of government, industry, and academia that continuously advances innovations in road engineering and construction (http://www.terraroadalliance.org/about/index.html). It was conceived in 2004 as a new road research governance structure to facilitate a comprehensive research program, with strategic focus to take advantage of the MnROAD test facility and associated resources. In addition to MnROAD, TERRA works with researchers and facilities at the University of Minnesota and across the world to include transportation organizations in other states and in Europe. TERRA's mission is to develop, sustain, and communicate a comprehensive program of research on

TABLE 23
CHINA, SOUTHEAST UNIVERSITY

Located in Nanjing, China	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Circular
Uni-/bi-directional	Uni-directional
Number of axles	Single
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device, automated driven
Load range (range in kN—indicate full load for all tires as well as range per tire)	The facility uses dual tires single axle to simulate the load of 22.5 kip (100 kN), and axle load of each side is 11.2 kip (50 kN). Tire pressure is 101 psi (700 kPa)
Tire details (size, type, inflation pressure range, other)	Type 11.00R20 (China standard) with a diameter of 42.7 in. (1 085 mm)
Tire wander options	No
Suspension (present or not, types possible, permanent or not, etc.)	Permanent
Temperature control options	Infrared radiation
Speed range	0 to 37 mph (0 to 60 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Data are manually collected when the testing is paused
APT webpage link	None

pavement, materials and related transportation engineering challenges, including issues related to cold climates. TERRA had 22 members from government, industry, and academia in 2011.

The current strategic plan outlines five major strategic directions for the organization: definition and launch of a bold and synergistic research program, implementation of research results, setting up activities to enhance TERRA's role as a forum for research interchange, expanding TERRA's membership proactively, and developing governance and operating structures to ensure a thriving, changing, and sustainable organization.

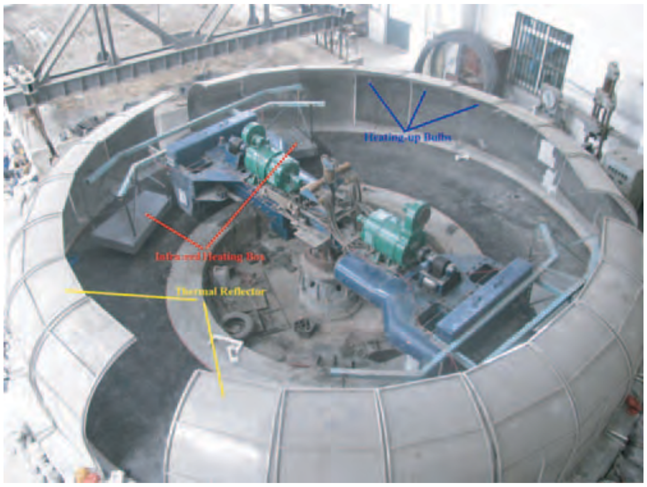

FIGURE 22 Southeast University F-sAPT device.

Midwest States Accelerated Pavement Testing Pooled Funds Program

This program consists of a consortium of the DOTs in Iowa, Kansas, and Missouri, and the Nebraska Department of Roads with the objective of supporting pooled fund f-sAPT research. No website could be found for this group for this synthesis.

Transportation Research Board Committee on Full-Scale/Accelerated Pavement Testing (AFD40)

Committee AFD40 is concerned with the full-scale testing of traditional and innovative pavement systems that reflect various construction conditions and maintenance practices (http://wweb.uta.edu/faculty/sroman/AFD40/). Testing can be performed using conventional or accelerated methods utilizing

TABLE 24
CHINA, TONGJI

Located at Tongji University, Shanghai, China	
Parameter	Selection
Mobile/fixed	Mobile (MLS)
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni-directional
Number of axles	6
Own power (diesel/electric/other)/shore power	Diesel power and shore power
Field site/fixed site	Field site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Trucks (manually driven)
Load range (range in kN—indicate full load for all tires as well as range per tire)	4.5 to 16.9 kip (20 to 75 kN) for all tires or per tire
Tire details (size, type, inflation pressure range, other)	305/70 R22.5 Maximum inflation pressure of 189 psi (1 300 kPa)
Tire wander options	−1.5 ft to +1.5 ft (–450 mm to +450 mm)
Suspension (present or not, types possible, permanent or not, etc.)	Present
Temperature control options	Yes
Speed range	3.4 to 13.4 mph (5.4 to 21.6 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Set speed, applied speed, load, location
APT webpage link	No

mobile or fixed equipment under in situ or controlled conditions. The committee is also concerned with the test results to assess long-term pavement-system performance for improved modeling, design, construction, and management of pavement systems, thereby optimizing their life-cycle costs.

FIGURE 23 Tongji MLS device.

APT is generally defined as a controlled application of a realistic wheel loading to a pavement system simulating long-term, in-service loading conditions. This allows the monitoring of a pavement system's performance and response to accumulation of damage within a much shorter time frame. Such information is critical to support informed highway planning, policy, and decision making.

General feedback on f-sAPT programs and associations as well as sensors is regularly provided during the annual TRB AFD40 committee meeting and sessions. Most of this feedback is through presentations that are available on the committee's website. A summary of the major topics on which presentations are currently available include general f-sAPT program and association feedback, calibration issues around the MEPDG models, the development of design catalogues based on f-sAPT databases, and conference feedback.

SENSORS AND INSTRUMENTATION

Background

The topic of sensors is regularly covered during conferences. In the 2008 Madrid 3rd APT conference a workshop was held on the topic. Saeed and Hall (2003) also covered the

TABLE 25
DENMARK, DANISH ROAD INSTITUTE

Located in Lyngby, Denmark	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Bi-directional
Number of axles	Single
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	9 to 29 kip (40 to 130 kN)
Tire details (size, type, inflation pressure range, other)	Truck tires
Tire wander options	±7.9 in. (200 mm)
Suspension (present or not, types possible, permanent or not, etc.)	None
Temperature control options	Indirect control
Speed range	Up to 15.5 mph (25 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	None

topic in detail. This section first focuses on sensors used directly on f-sAPT test sections, followed by complimentary instrumentation and information on databases.

Pavement parameters that are typically measured in f-sAPT include strains, stresses, deflections, moisture, and temperature (Weinmann 2004). Simulation of in-service pavement conditions, loading configurations, and loading methods, must be representative of that encountered by in-service pavements. In situ measurements during f-sAPT allow for the development of accurate performance models and the calibration of mechanistic pavement design approaches.


FIGURE 24 Danish road testing machine.

It appears that most programs conduct detailed laboratory evaluations of their materials to support the analysis of the f-sAPT data using standard laboratory tests. The complimentary use of field instruments such as the Falling Weight Deflectometer (FWD), Ground Penetrating Radar (GPR), and Portable Seismic Pavement Analyzer (PSPA) is also evident from responses, probably in an attempt to develop links between the f-sAPT responses and real pavement data.

Analysis of the instrumentation used in the various f-sAPT programs did not indicate any unexpected instruments, with a range of different instruments being used to obtain similar properties (i.e., different types of profile measurement devices, mostly being laser-based). For elastic deflection data both high frequency (i.e., FWD) and low frequency (i.e., Road Surface Deflectometer) instruments are used, which may complicate the analysis data as most of the pavement materials' elastic responses are frequency dependent. A range of typical

TABLE 26
FRANCE, FRENCH INSTITUTE OF SCIENCE AND TECHNOLOGY FOR TRANSPORT (INSTITUT FRANÇAIS DES SCIENCES ET TECHNOLOGIES DES TRANSPORTS, DE L'AMÉNAGEMENT ET DES RÉSEAUX) (IFSTTAR) [Previously Laboratoire Central Des Ponts et Chaussées (LCPC)]

Located in France	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Circular
Uni-/bi-directional	Uni-directional
Number of axles	4 x 1 (single) to 4 x 3 (tridem) combinations
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed site
Roads/airfields	Roads/airfields
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	8.9 to 31.5 kip (40 to 140 kN)
Tire details (size, type, inflation pressure range, other)	Truck
Tire wander options	±19.6 in. (500 mm)
Suspension (present or not, types possible, permanent or not, etc.)	Present
Temperature control options	Registered
Speed range	Up to 62 mph (100 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	http://www.ifsttar.fr/en/home/

strain gauges are used, as is also visible from the reported data in literature cited.

F-sAPT facilities can be used to help with the integration of the MEPDG through embedding instrumentation in pavement structures to measure pavement responses under loading (Willis 2008; Willis and Timm 2008). F-sAPT facilities have come together through CAPT to help develop practical and appropriate instrumentation uses based on positive and negative experiences at the various facilities. Using these insights ensures that an f-sAPT facility may be able to determine answers to questions such as the type of instrument required for a specific outcome before designing its instrumentation plan. Using experiences from other successful f-sAPT facilities to bolster success will increase the amount of valuable findings and improve effectiveness of these programs. Selected guidance from these experiences includes:

- Horizontal strain gauges are used to quantify pavement responses predicting pavement fatigue life.
- Vertical strain is rarely measured; however, linear variable displacement transducers can be used to measure pavement deflection.
- Pressure cells are more commonly incorporated into pavement research.
- Accurate installation of gauges is one of the most important factors in determining if a gauge is going to behave correctly.
- Sensors with appropriate working ranges and qualities for the expected parameter range should be selected.

FIGURE 25 French Manège de Fatigue.

TABLE 27
GERMANY, FEDERAL HIGHWAY RESEARCH INSTITUTE/BUNDESANSTALT FÜR STRASSENWESEN (BASt)

Located in Bergisch Gladbach, Germany	
Parameter	Selection
Mobile/fixed	Mobile and fixed, MLS and impulse generator
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	4
Own power (diesel/electric/other)/shore power	Diesel and electric
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed
Load range (range in kN—indicate full load for all tires as well as range per tire)	6.7 to 14.6 kip (30 to 65 kN)
Tire details (size, type, inflation pressure range, other)	Single/dual truck tires
Tire wander options	Yes
Suspension (present or not, types possible, permanent or not, etc.)	No
Temperature control options	Yes, indoor test section
Speed range	Creep to 13.7 mph (22 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Detailed data collection
APT webpage link	http://www.bast.de/cln_007/nn_169964/DE/Aufgaben/abteilungs/$abteilung-s-node.html?__nnn=true

FIGURE 26 BASt impulse generator device.

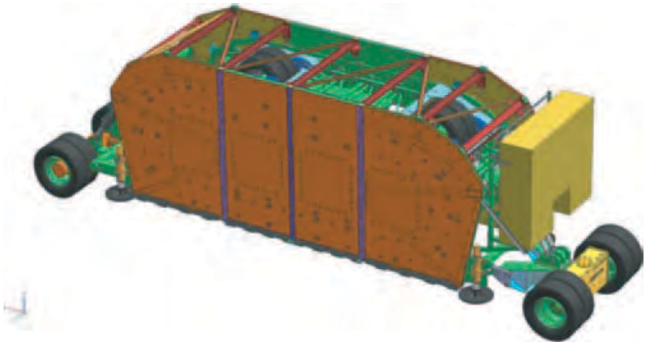

FIGURE 27 BASt MLS.

TABLE 28
INDIA, CENTRAL ROAD RESEARCH INSTITUTE (ICRRI)

Located in New Delhi, India	
Parameter	Selection
Mobile/fixed	Mobile
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Diesel generator or shore power, self-propelled also
Field site/fixed site	Fixed, field possible
Roads/airfields	Roads and airfields
Fixed device/trucks (automated or manually driven)	No
Load range (range in kN—indicate full load for all tires as well as range per tire)	6.7 to 22.5 kip (30 to 100 kN). Load levels of up to 44.9 kip (200 kN) can be achievable for short duration, special tests
Tire details (size, type, inflation pressure range, other)	Single 12R22.5 Dual 12R22.5 Super single 425/65 R22.5 truck tire Single aircraft tire, 58 to 145 psi (400 to 1 000 kPa), temperature and pressure sensors
Tire wander options	Yes, automatic indexing or tracking between passes from side to side for a total lateral coverage of 29.5 in. (0.75 m) in increments of 2 in. ± 0.2 in. (50 ± 5 mm)
Suspension (present or not, types possible, permanent or not, etc.)	No, axle mounted directly to carriage
Temperature control options	—
Speed range	Maximum wheel speed of 7.5 mph ± 1.9 mph (12 ± 3 km/h) for loads in the range of 6.7 to 22.5 kip (30 to 100 kN) and 4 mph ±1.2 mph (6.5 ± 2 km/h) for loads above 22.5 kip (100 kN) Minimum of 1.2 mph (2 km/h) (creep speed possible)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	http://www.crridom.gov.in/facilities.html

FIGURE 28 India HVS.

TABLE 29
JAPAN, PUBLIC WORKS RESEARCH INSTITUTE (PWRI)

Located in Tsukuba, Japan	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Circular
Uni-/bi-directional	Uni-directional
Number of axles	400,000 per year
Own power (diesel/electric/other)/shore power	Diesel
Field site/fixed site	Fixed
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Automated trucks
Load range (range in kN—indicate full load for all tires as well as range per tire)	7.1 to 35 kip (31.85 to 156.8 kN) wheel load
Tire details (size, type, inflation pressure range, other)	295/80R22.5
Tire wander options	Automatically controlled to wander ±9.8 in. (±250 mm) around the center
Suspension (present or not, types possible, permanent or not, etc.)	Same as actual truck
Temperature control options	None
Speed range	Less than 24.8 mph (40 km/h).
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Speed, location, and number of passes
APT webpage link	http://www.pwri.go.jp/team/pavement/eindex.html

- Gauges should be calibrated and checked before being installed in pavements for research.
- Duplication of gauges allows researchers to check the quality of the data. It is suggested that at least two strain gauges be placed in the transverse and longitudinal direction of HMA layers to allow for functionality checks, while additional gauges should be considered if wheel wander is present and uncontrolled.
- Further research is required on developing accurate and reliable devices for measuring soil moisture contents.

FIGURE 29 PWRI f-sAPT device.

Sensor Location and Installation

Burnham (2004) evaluated the load proximity correlation of dynamic strain measurements in concrete pavements at the MnROAD project. As the magnitude of a measured strain in a pavement is related to the proximity of the tire load, tire load wander is a necessary component of load testing. Best-fit curves and equations were developed for correlating dynamic strain data to tire load proximity with polynomial curves found to achieve good fit with the data. The maximum dynamic strain response did not occur when the reference point was at the location of the sensor, but rather when the tire reference point was located approximately 150 to 300 mm toward the roadway centerline.

Tracking the location of individual vehicles during load response testing is vital in operating a test track, as the location of a vehicle's tires has a profound effect on the values obtained from embedded sensors. In an effort to improve the efficiency

TABLE 30
NEW ZEALAND, CANTERBURY ACCELERATED PAVEMENT TESTING INDOOR FACILITY (CAPTIF)

Located in Canterbury, New Zealand	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Circular
Uni-/bi-directional	Uni-directional loading
Number of axles	2
Own power (diesel/electric/other)/shore power	Own power (electric)
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	4.7 to 13.5 kip (21 to 60 kN)
Tire details (size, type, inflation pressure range, other)	Truck tires
Tire wander options	39 in. (1 m) wide wander
Suspension (present or not, types possible, permanent or not, etc.)	Full suspension systems available
Temperature control options	Yes
Speed range	3 to 31 mph (5 to 50 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	None

of load response testing at MnROAD a Global Positioning System-based vehicle tracking system was developed and tested (Burnham et al. 2010). The vehicle tracking system demonstrated its capability of tracking vehicle motion with an accuracy of ±1 in. (25 mm) at speeds of up to 43.5 mph (70 km/h), at least matching the accuracy obtained with a high-definition video camera previously used. These capabilities spawned the development of a wireless triggering system (triggering data acquisition as a test vehicle passes through an area containing pavement sensor) and a vehicle guidance system (guides test vehicle drivers through various predetermined paths).

FIGURE 30 CAPTIF facility.

Sensor installation requires extreme care to ensure that the material surrounding the sensors correctly represents the material in the rest of the layer. It is desirable to have many sensors embedded in the test sections; however, too many sensors may significantly disturb the material density and moisture and thereby decrease the test data reliability. Using the assumption that stress and strain would reach maximum values at points under the center of the tire path, Cortez and Janoo (2008) installed sensors only at these locations and devised a method to create a system of virtual sensors that generated detailed contour cross sections of stress and strain without the expense of more sensors and without risking disturbance to the material layers.

Embedded instrumentation is an important tool at f-sAPT facilities as M-E pavement design and analysis methodologies are implemented. It is critical to determine the accuracy and precision of response measurements. Willis and Timm (2009b) established the practical level of within-gauge precision for HMA strain measurements at NCAT by conducting

TABLE 31
NETHERLANDS, DELFT UNIVERSITY OF TECHNOLOGY

Located in Delft, Netherlands	
Parameter	Selection
Mobile/fixed	Fixed to test area, but mobile within test area
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Bi-directional loading
Number of axles	1
Own power (diesel/electric/other)/shore power	Own power (electric)
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	5.6 to 22.5 kip (25 to 100 kN)
Tire details (size, type, inflation pressure range, other)	All types of wide base and dual tires Inflation pressure up to 130 psi (900 kPa)
Tire wander options	Any lateral wander distribution
Suspension (present or not, types possible, permanent or not, etc.)	No suspension
Temperature control options	Only heating [up to 86°F (30°C) above ambient temperature], no cooling
Speed range	0 to 12.4 mph (0 to 20 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	All available
APT webpage link	Available but not up to date

FWD testing on strain gauges and calculating the absolute differences to determine individual gauge variability. Within-gauge variability was not significantly affected by gauge orientation, load level, or pavement condition. Overall, strain readings with differences of less than 12 με were set as a practical benchmark for NCAT for within-gauge variability. During future research cycles, FWD on-gauge testing will be conducted before trafficking occurs to ensure the gauges are working properly. If more than 90% of the absolute differences within a single gauge are over the prescribed benchmark, further testing and analysis will be conducted to validate the gauge's measurements.

FIGURE 31 LINTRACK f-sAPT device.

F-sAPT facilities are typically designed to test pavements from an original condition to a failed state in a relatively short time period while utilizing embedded instrumentation to monitor pavement responses. It is important for researchers to be able to evaluate data quality obtained from the pavement. Fourteen test sections at the NCAT Pavement Test Track were investigated to better understand the interaction between pavement distress and response measurement (Taylor and Timm 2008). Prior to distress, the measured vertical pressures were typically a function of temperature. However, after major distresses were evident in many sections, the measured responses became highly erratic. Analysis of the temperature–pressure relationship data from the NCAT sections using the representative pressure value for a given day's data collection and a representative HMA temperature was used to evaluate pressure gauge behavior. It was shown that a low (<0.7) R^2 value from the relationships indicated potential gauge malfunction or pavement damage.

TABLE 32
SOUTH KOREA, HANYANG UNIVERSITY

Located in Ansan, Gyeonggi-do, South Korea	
Parameter	Selection
Mobile/fixed	Fixed
Linear /nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed
Roads airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	15.7 to 56.2 kip (70 to 250 kN)
Tire details (size, type, inflation pressure range, other)	Truck, dual
Tire wander options	±13.8 in. (±350 mm)
Suspension (present or not, types possible, permanent or not, etc.)	Yes
Temperature control options	Controlled heating
Speed range	7.5 mph (12 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	None

Traffic Loading Measurements and Control

Piezoelectric sensors used for collecting Weigh-in-Motion (WIM) data were evaluated by Alavi et al. (2001) under controlled laboratory and f-sAPT loading conditions in both HMA and PCC pavements. The HMA installation was done at the WesTrack test facility and the PCC installation at a Caltrans HVS test site. The results indicated no problems with the durability of the WIM sensors, and bonding materials performed well. The study indicated that the piezoelectric WIM sensors evaluated can withstand real loading conditions in both HMA and PCC pavements.

FIGURE 32 Hanyang Accelerated Pavement Tester (HAPT).

The Public Works Research Institute developed a new system for controlling the automatically driven trucks (four loaded vehicles with double rear axles at a time) on their pavement test field, increasing the accelerated loading test capacity by three over the previous system. When loaded vehicles are constantly operated, 8,610,000 wheel passes equivalent to 11 kip (49 kN) (250 days/year, 10 h/day) were applied. The system allows vehicles to stop and go at various points such as crossroads, and manned traveling is also possible (Kido and Ito 2004).

De Beer et al. (2004) described the development of the Stress-in-Motion (SIM) system as well as the application of the technology in f-sAPT applications. The SIM system assists in improving the definition of the tire/pavement interaction to gain an improved quantification of the shape and magnitude of the 3-D tire/pavement forces measured from real trucks. Typically, Maximum Vertical Contact Stresses (MVCS) appear to be as much as twice the inflation pressure

TABLE 33
SOUTH AFRICA, COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH (CSIR) AND GAUTENG DEPARTMENT OF PUBLIC ROADS AND WORKS (GAUTRANS)

Located in Pretoria, South Africa	
Parameter	Selection
Mobile/fixed	Mobile HVS Mk III and IV+
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni- and bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Both
Field site/fixed site	Both
Roads/airfields	Roads and airfields
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	4.5 to 45 kip (20 to 200 kN)
Tire details (size, type, inflation pressure range, other)	Dual, wide base, aircraft
Tire wander options	Yes, 0 to 4.9 ft (0 to 1.5 m) wide
Suspension (present or not, types possible, permanent or not, etc.)	No
Temperature control options	Yes, hot and cold
Speed range	0 to 5 mph (0 to 8 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	www.gautrans-hvs.co.za www.csir.co.za

(at extremely high levels of loading), while it exceeds the inflation pressure by approximately 30% for normal loading conditions. The length of the tire contact patch increases with increased loading while the width remains constant. Quantification of the horizontal interface shear stresses between the tire and the road surface could assist in understanding the horizontal stress regime of a moving tire with lateral and longitudinal stresses as high as 36.2 (250 kPa) and 23.9 psi (165 kPa), respectively.

FIGURE 33 CSIR/Gautrans HVS.

Strain Measurements

During a comprehensive f-sAPT program at Laboratoire des Voies de Circulation (LAVOC) in Switzerland (as part of COST 347), a pavement was instrumented using a range of strain sensors (Wistuba 2004). Both longitudinal and transversal signals were measured, resulting from the different strain gauges and the loading conditions. Laboratory tests were initially conducted on the different strain gauges to determine their response, and their accuracy was verified in the laboratory using a 4 point bending strain test.

Burnham et al. (2007) described a procedure developed at MnROAD to efficiently extract peak and baseline values from dynamic sensor responses. The procedure performs automated identification of peak and baseline responses and has significantly increased dynamic response data processing from MnROAD, specifically with the large volumes of data collected from the facility.

TABLE 34
SPAIN, CENTRO DE ESTUDIOS DE CARRETERAS (CEDEX)

Located in Madrid, Spain	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Linear–circular combined
Uni-/bi-directional	Uni-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Automatically driven vehicles
Load range (range in kN—indicate full load for all tires as well as range per tire)	24.7 to 31.5 kip (110 to 140 kN) axle 12.4 to 15.7 kip (55 to 70 kN) per wheel
Tire details (size, type, inflation pressure range, other)	Conventional truck wheels, typically dual wheels
Tire wander options	±14 in. (±360 mm)
Suspension (present or not, types possible, permanent or not, etc.)	Conventional trucks, air spring type
Temperature control options	No control—only shedding
Speed range	0 to 28 mph (0 to 45 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Automated system based on the following variables (or variable combinations): asphalt temperature, vehicle speed, vehicle transverse position, time, and number of cycles
APT webpage link	Not available

Kim et al. (2008) observed variations between the measured and predicted strains in compression when gauges installed on the surface of an HMA f-sAPT section underwent a significant amount of shear strain. Further analysis associated with these observations implies that the transverse strains measured in compression included approximately 20% shear strains and that the errors in the strain measurements appeared to be caused by the complexity of the strain state, occurring before and after the loading. Because the surface strain gauge was designed for measuring only axial strains, the shear strains might be the cause of the unknown strains and overestimation of compressive strains. The evaluation indicated that strain measured in the multiple-strain state may include potential errors and over- or underestimate the true strain.

FIGURE 34 CEDEX f-sAPT facility.

Literature regarding repeatability of pavement strain measurements is limited although it is necessary to have a high degree of confidence in these data. Gokhale et al. (2009) described a parametric experiment conducted by FDOT in an effort to evaluate the repeatability of strain gauges currently used in their f-sAPT facility. Strain measurements using 28 strain gauges were made at five different pavement temperatures, three levels of load, three levels of tire pressure, and three levels of speed with loading applied using the HVS (five replicate load passes per variable combination). Statistical analysis showed that the surface strain gauges are repeatable under the various conditions of temperature, load, speed, and tire pressure and that strain measurements did not vary significantly with a change in the internal tire pressure (for the specific pavement structure and materials). They concluded that, if installed properly, surface strain gauges can be repeatable and yield reliable measurements, although the strain gauges evaluated were not repeatable at operating temperatures greater than 104°F (40°C).

TABLE 35
SWEDEN, VAG-OCH TRANSPORTFORSKNINGSINSTITUT (VTI)

Located in Linköping, Sweden	
Parameter	Selection
Mobile/fixed	Mobile, HVS IV
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Bi-directional
Number of axles	One
Own power (diesel/electric/other)/shore power	Diesel or electric
Field site/fixed site	Field
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device, automated driven
Load range (range in kN—indicate full load for all tires as well as range per tire)	6.7 to 24.7 kip (30 to 110 kN)
Tire details (size, type, inflation pressure range, other)	Single or dual truck tire
Tire wander options	0 to 28 in. (0 to 0.7 m)
Suspension (present or not, types possible, permanent or not, etc.)	Hydraulic feedback
Temperature control options	Yes, pavement temp between 32 and 86°F (0 and 30°C)
Speed range	0 to 12 km/h
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Speed, load, location, number of repetitions
APT webpage link	www.vti.se

Strain magnitude increased with an increase in surface temperature and load and decreased with an increase in wheel speed.

Rutting Measurements

MnROAD developed an Automated Laser Profile System to replace the 6-foot straight edge rutting measurements conducted on the HMA test cells (Worel et al. 2004). The Automated Laser Profile System data compared well to 6-foot straight edge data when each measurement type and equipment was reviewed, although the ALPS measurements tend to be greater than straight edge measurements as a result of edge effects, the measurement increment used for straight edge measurements and straight edge wear.


FIGURE 35 VTI HVS.

The use of laser-based profiling systems has become predominant in the characterization of the permanent deformation of test pavements. FDOT developed and installed a two-laser profiler on its HVS (Byron et al. 2005). This system proved to be effective for profiling f-sAPT sections, accurately mapping the entire test surface at a reduced time and effort. FDOT employed the profiling system in a wide variety of research studies, including the measurement of rutting rate in flexible pavement systems, measurement of slab curling and faulting in rigid pavements, and determination of deformation and settlement of raised pavement markers.

Multiple-Depth Deflectometers have been implemented for measuring rutting in pavement layers by FAA during various tests (Garg and Hayhoe 2008).

Instrumented Pavements and Airfields

Twelve different flexible pavement designs have been built at the Virginia Smart Road (Al-Qadi et al. 2000). The varia-

TABLE 36
SWITZERLAND, SWISS FEDERAL LABORATORIES FOR MATERIALS SCIENCE AND TECHNOLOGY (EMPA)

Located in Empa Dübendorf, Switzerland	
Parameter	Selection
Mobile/fixed	Mobile (MLS10)
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni-directional
Number of axles	4
Own power (diesel/electric/other)/shore power	Own power (diesel/electric/other)/shore power
Field site/fixed site	Field site/fixed site
Roads/airfields	Roads/airfields
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	Up to 65 kN per axle
Tire details (size, type, inflation pressure range, other)	Dual tired 295/60 R22.5 Super single 385/65
Tire wander options	Available
Suspension (present or not, types possible, permanent or not, etc.)	Hydro-pneumatic
Temperature control options	Available
Speed range	Up to 22 km/h
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Dynamic loading, speed
APT webpage link	http://www.empa.ch/plugin/template/empa/*/71452 http://www.sf.tv/sf1/einstein/index.php?docid=20071220

tions in the 12 pavement sections include layer thickness, drainage, subgrade strength, HMA wearing surface design, and inclusion of geosynthetic materials for reinforcement and/or moisture barrier/strain energy absorption. The sections were heavily instrumented with pressure cells, strain gauges, Time Domain Reflectometry probes, thermocouples, liquid levels, and frost probes during construction and connected to a data acquisition system housed in an underground bunker. There was a need to check the response and integrity of the sensors before the completion of the road construction and a truck was driven over the instrumented sections with varying load, tire pressure, and speed. The pressure cell (located in the subgrade) response was good and the response resulting from each tire loading was symmetric, confirming the pressure cell calibration findings that there is no hysteresis. Response from the strain gauge (perpendicular to traffic direction) under the HMA base layer showed tension measured from all three axles of the truck, with the steering axle driving directly on top of the strain gauge, whereas the response from a longitudinal strain gauge under the HMA base layer showed compression in the gauge as the vehicle approaches. As the vehicle passes on top of the gauge, it causes tension at the bottom of the base layer, as would be expected. The testing plan included measuring pavement response to truck loading at different axle loading, tire pressure, and speed under different environmental conditions as well as periodic GPR, FWD, and laboratory material testing and evaluation.

FIGURE 36 EMPA MLS10.

TABLE 37
UNITED KINGDOM, TRANSPORT RESEARCH LABORATORY (TRL) PAVEMENT TEST FACILITY

Located in Crowthorne, United Kingdom	
Parameter	Selection
Mobile/fixed	Fixed
Linear/nonlinear (circular, elliptical)	Linear
Uni-/bi-directional	Uni-/bi-directional
Number of axles	1
Own power (diesel/electric/other)/shore power	Electric
Field site/fixed site	Fixed site
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed device
Load range (range in kN—indicate full load for all tires as well as range per tire)	10.3 to 45 kip (46 to 200 kN)
Tire details (size, type, inflation pressure range, other)	Truck, dual
Tire wander options	None
Suspension (present or not, types possible, permanent or not, etc.)	None
Temperature control options	Dedicated temperature control
Speed range	Up to 12.4 mph (20 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Yes
APT webpage link	http://www.trl.co.uk/facilities/pavement_testing/

Al-Qadi et al. (2008, 2010) discussed ongoing research to measure the in situ response to airplane traffic of flexible pavement on a runway at Cagliari–Elmas airport in Italy where the runway pavement layers were instrumented during construction with 149 instruments (Linear Variable Displacement Transducers, pressure cells, Time Domain Reflectometry probes, thermocouples, and HMA strain gauges). The objective of this detailed installation was measuring the pavement responses during takeoff, landing, and taxiing. Preliminary data acquired during and after the runway's construction and before opening to airplane traffic showed that the instrumentation process was a success and that data could successfully be compared with preliminary numerical simulations. It demonstrates that complicated instrumentation programs can be successfully run during f-sAPT on runways.

FIGURE 37 TRL pavement test facility.

The FAA has instrumented various runways and taxiways for APT, using commercial aircraft such as B-777, B-747, A-340, and A-380. Data from these tests were used in calibration of 3-D FEM (NIKE-3D). Valuable pavement response and performance data were collected and are continuously analyzed for heavy commercial aircraft and different climatic condition combinations (Rufino et al. 2002).

Construction Measurements

Emissions from the production and paving of HMA are constantly being scrutinized. Introduction of WMA technologies is seen as potentially leading to a reduction in some of these emissions. The University of California Pavement Research Center (UCPRC) has developed a protocol and equipment for accurately measuring surface emissions during both HMA and

WMA paving operations (Farshidi et al. 2011). The equipment consists of a transportable flux chamber to obtain direct measurements of reactive organic gas emissions and to estimate the fluxes of volatile organic compounds and semi-volatile organic compounds. The applicability of the method in characterizing organic compounds in emissions during construction was verified on an f-sAPT site during construction of test sections, and although emission reduction trends from the time of placement until after final compaction were similar for all the mixes, significant differences were noted in the alkanes' concentration of the emissions from the HMA and the WMA mixes, respectively. These preliminary results indicated that the method is appropriate for accurately quantifying and characterizing volatile organic compounds and semi-volatile organic compounds emissions during asphalt paving.

Complementary Instrumentation

Complementary instrumentation is that equipment often used in conjunction with f-sAPT, although it does not form part of the normal f-sAPT sensors and can typically be used independently. In this regard, the focus is on the FWD, GPR, Lightweight Deflectometer, PSPA, and Model Mobile Load Simulator (MMLS) as references are specifically made to these devices in the literature.

Falling Weight Deflectometer

The FWD is commonly used to evaluate structural characteristics of pavements simulating vehicular loads at typical highway speeds. The data are typically used to back-calculate layer moduli and design overlays (Howard and Warren 2008). With f-sAPT typically conducted at slow speeds, measured responses from traffic loads are typically greater than those from the FWD loads, with the extent of the difference becoming more pronounced with depth.

The release of the MEPDG generates a strong need for identifying and evaluating the way that FWD testing is operated and integrated in the new design procedure with one of the key inputs for HMA pavements the dynamic modulus ($|E^*|$) mastercurve. A more accurate prediction of its remaining service life can be achieved if the damaged $|E^*|$ mastercurve of the HMA in an existing pavement can be obtained from FWD deflections. Kutay et al. (2011) developed a methodology to backcalculate the $|E^*|$ mastercurve of the HMA pavement layer using the time history of FWD surface deflections, implementing a layered visco-elastic forward algorithm to be used in an iterative backcalculation procedure for linear visco-elastic properties of HMA pavements.

Donovan and Tutumluer (2009) presented a methodology based on analyzing FWD test data between the trafficked and nontrafficked lanes to determine degradation and rutting potential of flexible pavement unbound aggregate layers in comparison with the subgrade damage. The validity of the approach is demonstrated by analyzing Heavy Weight Deflectometer (HWD) data obtained from NAPTF flexible airport pavement test sections constructed with substantially thick unbound aggregate base/subbase courses. Clear evidence was obtained of the increased base damage induced in the NAPTF layers during trafficking resulting from the applied aircraft gear load wander through determining the modified Base Damage Index and Base Curvature Index defined from HWD pavement deflection basins.

Garg and Marsey (2004) used the HWD at the NAPTF, both on the wheel paths and pavement centerline (nontrafficked) to study the effect of traffic tests on the pavement structure. The full pavement deflection basin was characterized at three different load levels [12, 24, and 36 kip (53, 107, and 160 kN)]. Analyses of deflection data from the trafficked and nontrafficked areas showed that the HWD could be effectively used to evaluate the effect of traffic on the pavement structure.

Ground Penetrating Radar

Hugo et al. (2008) and Partl (2008) described case studies where the simultaneous evaluation of measured performance trends using GPR and seismic stiffness improved understanding and quantification of performance of pavement systems. This was supported by Vulcano-Greullet et al. (2010) who stated that more work is required to develop specific processes to detect risk areas in pavements where, for instance, trapped water is present using GPR surveying.

Light Weight Deflectometer

The use of a portable Light Weight Deflectometer (LWD) for construction quality control and material investigation for earthworks and road construction is increasing internationally. Fleming et al. (2007) reviewed the LWD as a field evaluation tool and evaluated the test variables and data quality. They concluded on its usefulness and limitations for a variety of earthwork and road assessment scenarios. They indicated that the correlation of the LWD to FWD stiffness (using the central geophone only) appears to be variable and perhaps site and layer thickness dependent.

Brill and Guo (2009) described the use of both LWD and PSPA measurements conducted for subgrade characterization, demonstrating stress-softening behavior in cohesive soils.

Portable Seismic Pavement Analyzer

De Vos et al. (2007) used the PSPA for monitoring stiffness changes resulting from trafficking under f-sAPT, successfully detecting increased distress in the pavement layers before manifestation on the surface. It was possible to discern the nature of the distress, lending support for the use of the PSPA as a nondestructive accessory tool with f-sAPT.

Gibson et al. (2011) also mentioned the use of the PSPA in evaluation changes in HMA modulus with increasing fatigue.

Dynamic Cone Penetrometer

Four forensic studies on MnROAD demonstrate that forensic investigations are valuable tools in determining the causes of premature pavement failures. Field testing methods such as Dynamic Cone Penetrometer (DCP), cores, laser profiler systems, and visual observation are quite effective in measuring pavement material properties and performance, whereas laboratory testing parameters such as asphalt binder grading, HMA performance testing, and aggregate properties provide additional information on pavement material properties. Proper compaction of all pavement layers is crucial during construction to prevent consolidation and rutting (Clyne et al. 2008a, b).

Model Mobile Load Simulator

The MMLS is a one-third scale device that is used for scaled APT. Epps et al. (2001, 2002) reported on stress analyses to explore the hypothesis of comparable stress distribution between scaled APT and f-sAPT. Application of the MMLS to predict rutting performance is based on the hypothesis that for a simple pavement structure (only a single HMA layer) and similar tire pressures, the distribution of MVCS beneath the MMLS will be comparable to that beneath a single truck tire with a standard load of one-quarter equivalent single-axle load (ESAL), considering the scaling factor and considering dimensionless depth. For the hypothetical structures evaluated, the comparable stress hypothesis was upheld. The full procedure for validating a performance prediction methodology based on stress analysis and MMLS testing is described in the cited references and not directly relevant in all details for this f-sAPT synthesis. Ebels et al. (2004) evaluated the response obtained with the MMLS and HVS on a thin HMA pavement with stabilized base and found that under ambient temperature conditions similar surface rutting was observed; however, at elevated temperatures the MMLS ruts were significantly higher. Application of the method for comparing MMLS rutting with full-scale rutting did not provide satisfactory answers, and the authors stated that "one of the main factors that influence the reliability of the Prediction Ratio method is the fact that the pavement tested on the N7 is a composite pavement with a flexible hot-mix asphalt surfacing on a rigid granular base. This type of pavement differs from the full depth HMA type of pavement structures that have been used to develop and validate the adopted theory of comparison between the two types of loading." In a comparison of the maximum vertical contact stresses of the one-third scale test tires of the MMLS with those measured for three types of full-scale test tires of the HVS using the SIM technology (De Beer et al. 2006; De Beer and Sadzik 2007), analysis indicated that the MVCS increased linearly with tire inflation pressure for the MMLS test tires and full-scale test tires. Further, the MVCSs for the diamond patterned square profile scale tires were much lower than those of the full-scale test tires as they represented, at most, only 52.5% of those measured for the 11R22.5 (full-scale HVS) test tire, 37.5% for the single 315/80 R22.5 (full-scale HVS) test tire, and 12.5% and 20%, respectively, for the smooth and rough-texture tests on the 12R22.5 (full-scale HVS) test tire. For the scaled-down tires the MVCS was roughly equal to inflation pressure, whereas for the full-scale HVS tires the MVCS was approximately 50% higher.

Databases

The Spanish Centro de Estudios de Carreteras (CEDEX) test track uses software to measure and manage the data from the six pavement sections of the facility enabling the planning of measurements for specified conditions of speed, offset, pavement temperature, date or number of cycles, and the analysis of the registered data (Ayuso et al. 2008). The system can manage up to 256 sensors and typically around 250,000 measurements are carried out in a complete test. The data acquisition system enables full-automatic sensor measurement, and all data are stored in a database together with summary data (such as maximum peak value, zero reference, etc.) for each record. The software enables analysis of the stored data allowing the response of any sensor to be plotted against test-related variables such as pavement temperature, vehicle speed, or transverse position. Evolution of data versus number of test cycles can also be displayed. Output ASCII files can be also generated so that data can be evaluated outside the database environment in statistical packages or pavement design programs.

Lea and Popescu (2003) described the design, implementation, and use of the UCPRC HVS database that is used to store all of the data collected directly from HVS test sections. The same database is used to store data from both flexible and rigid pavement sections. Besides the raw data files collected during testing, the database consists of a Microsoft Access® database and a Microsoft Excel® spreadsheet. The database is stored in an Oracle® database, which is used to drive an HTML site used to view the data. The database structure enforces many relationships to ensure that the data are consistent.

Worel (2006) described the MnROAD database as a collection of data originating from a number of different methods and processes and stored in a commercial database, offline data system, project reports, website, individual researcher files, and a geographical information system database. The many formats and sources impact the methods that are used to store the data (both calculated and raw). As MnROAD is a state-run public-funded facility, all data and reports are available at no cost. Although some data are available on the website, access to the MnROAD database is limited to key researchers at MnROAD. This allows controlled access to the detailed data and researchers have the opportunity to explain both methods and any quality issues that might impact the potential use of the data requested to potential users.

Lea (2008) also shared lessons learned in the design and operation of the database. Over 12 years of operation, UCPRC have operated two HVSs and tested more than 90 sections, accumulating nearly 70 million passes, resulting in a 12 GB database. The most important consideration is that the database must form an integral part of the workflow in the day-to-day running of an APT project. It is thus important that the database be adapted to the changing needs of the project, arguing against standardized databases across various APT projects. This results in the quality control of the data also being a standard part of the day-to-day operations. It is important to have the primary storage of data be in human readable and editable text files that can be used to populate a relational database, as this allows a clean separation of the data from the form of the database, and protects against database corruption and difficulties with managing a large amount of information in a relational database.

The FAA's NAPTF database (http://www.airporttech.tc.faa.gov/naptf/databases.asp) is a full-scale airfield testing database that is open for use by international researchers. Researchers from the United States, China, and France have already used data from this resource.

CHAPTER SUMMARY

Chapter two provided information on the various f-sAPT programs, associations, equipment, and instrumentation. It summarizes information obtained from the questionnaire, as well as selected public domain literature and the websites of the various associations. The information indicates that there are 19 U.S.-based and 24 international f-sAPT programs that are actively conducting f-sAPT research. Most of the programs are using sensors and instruments that were developed over a number of years, mostly well-described in previous syntheses as well as program websites. The use of complementary instruments (i.e., FWD, GPR, LWD, PSPA, etc.) forming the link between the f-sAPT sections and real pavements (where these instruments are typically used) was highlighted. Detailed information on questionnaire feedback on the topics covered in this chapter is provided in Appendix D.

CHAPTER THREE

PAVEMENT MATERIALS AND STRUCTURE EVALUATION

INTRODUCTION

This chapter provides detailed findings on the specific pavement materials being investigated with f-sAPT, as well as the responses obtained from different pavement structures and the effect of loading and environmental conditions on the test results. The chapter covers the full range of applicable materials (HMA, concrete, stabilized and granular—including novel materials) and combinations of materials (i.e., traditional pavement structures, warm mix technologies, thin reinforced concrete, etc.).

The chapter begins with a summary of the questionnaire results regarding materials and pavement structure, followed by an analysis of the available literature. The literature is divided into sections covering HMA, concrete, granular materials, pavement systems, and miscellaneous topics. Under each of the major materials, the information is grouped into subsections of similar topics (i.e., overlays, cracking, etc.).

It should be noted that all models and outputs referenced and discussed in this section are only applicable to the specific materials and conditions under which the specific testing has been conducted. Space does not allow all these conditions to be repeated for each of the references, and the reader is urged to consult with the original reference to ensure that details on these aspects are well understood before the information in this section is applied or referenced.

The most common surfacing material evaluated by respondents is HMA followed by traditional concrete, with most of the other surfacing types only being evaluated by less than 30% of the respondents (Figure 38). WMA was interestingly (as a relatively novel material) the third-most evaluated surfacing. For pavement base layers, granular materials have been evaluated the most often, followed by a group of base materials including asphaltic, cemented, and recycled (Figure 39), whereas the various unstabilized materials were most often used for subbase and subgrade materials (Figure 40).

In response to the structural distress types evaluated for HMA surfacings, the traditional cracking (incorporating all types of structural fatigue) and rutting was the most often evaluated (Figure 41), as was also observed from the topics covered in the available literature. A similar picture evolved for concrete surfacings, with cracking being most often evaluated (Figure 42). Permanent deformation was most often evaluated as the structural distress type for base and subbase layers (Figure 43).

In terms of functional distress types, fewer respondents include it in their evaluations (as may be expected with f-sAPT devices typically focusing on structural evaluation aspects of pavements), with the second-most selected option indicated that functional distress is not deemed applicable for evaluation using f-sAPT. This is probably influenced by the large number of f-sAPT devices that use short pavement sections for testing (as opposed to test tracks). Most respondents indicated rutting to be the functional safety aspect most often evaluated (similar to asphalt surfacing distress types).

Most programs used wheel load as the load characteristic to which they related f-sAPT data, with the tire-related properties (inflation pressure, type, contact stress) starting to play a more prominent role (Figure 44). The material properties used to explain performance (Figure 45) are mostly typical properties that are known to affect structural performance of materials. Respondents most commonly rated unconventional materials and compaction as the aspects of pavement engineering that may enhance construction and rehabilitation of pavements in their f-sAPT programs.

HOT MIX ASPHALT AND RELATED MATERIALS

Rutting

Mulvaney (2004) analyzed rutting on MnROAD's original 14 HMA mainline test sections, showing that cells with the softer PG58-28 binder have rutted more than the stiffer PG64-22 binder cells, with rutting forming in the upper lifts of the HMA. Fifty percent of the rutting occurred in the first two years after construction, indicating that rutting is not linear with time or traffic level. Although the driving lane has rutted 1.5 times more than the passing lane, the rutting is not linear with the number of ESALs (driving lane experienced four times the ESALs of the passing lane).

Sivasubramaniam et al. (2004) evaluated the performance of a Superpave HMA mixture from f-sAPT compared with the PURWheel laboratory wheel tracker and the Indiana DOT/Purdue University Accelerated Pavement Tester. It was observed that well-designed and constructed fine-graded mixtures may be appropriate for use with heavy traffic applications and in hot climates. The rutting performance of coarse-graded

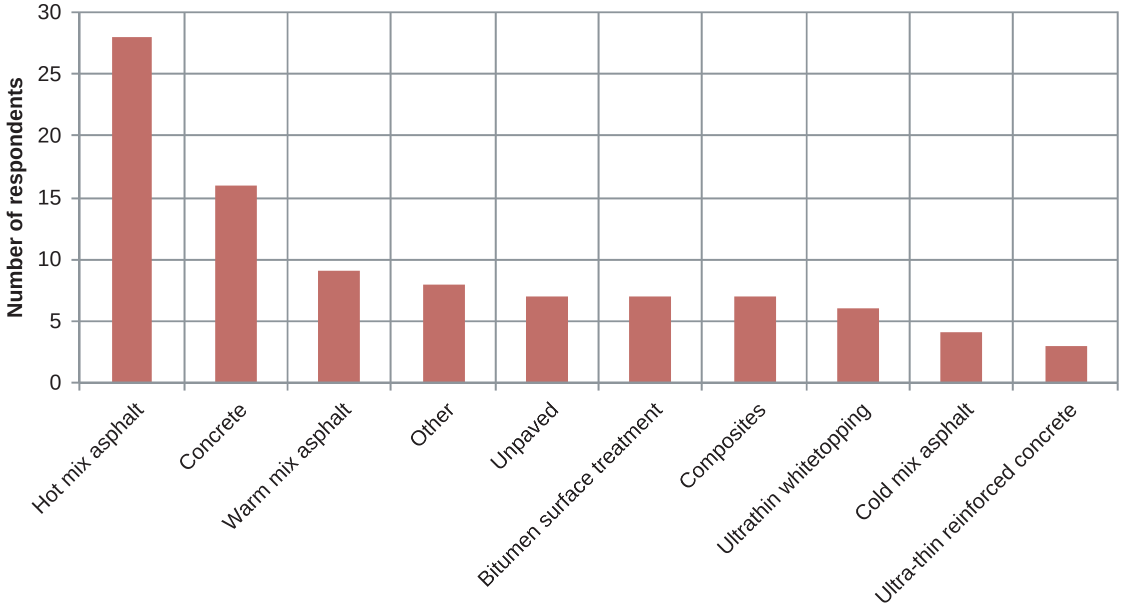

FIGURE 38 Surfacing materials evaluated with f-sAPT.

mixtures appeared to be slightly better compared with fine-graded mixtures (although no statistical difference was observed). A simple power model was successfully fitted to HMA rutting data originating from the f-sAPT and the PURWheel.

Muraya (2004) evaluated the resilient and rutting behavior of two asphalt motorway test pavements subjected to LINTRACK (Netherlands) f-sAPT loads to analyze the possibility of back-calculating the measured rutting on the basis of cyclic triaxial tests. Different trends were observed in the measured and calculated rutting behavior, with the calculated rutting (based on material characterization by resilient deformation triaxial testing) being much lower than the measured rutting in the test pavements. The poor correlation between the triaxial test results and the measured pavement response may be improved by better simulation of the stresses occurring in the pavement. The simulation of pavement stresses can be enhanced by the application of different pulse durations for both the vertical and horizontal stresses.

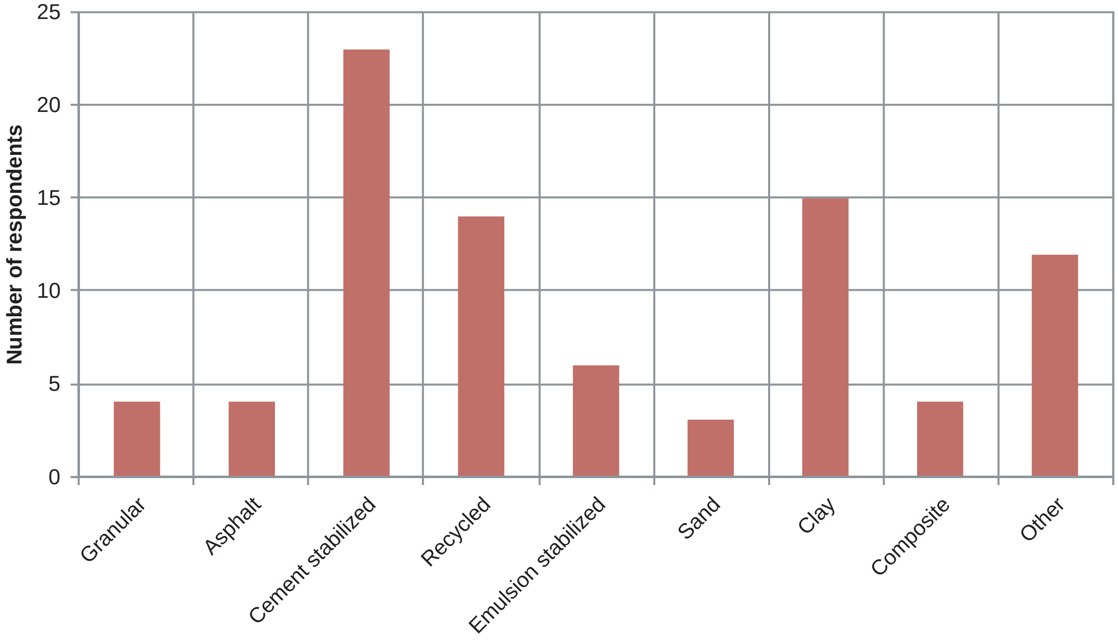

FIGURE 39 Base materials most often evaluated by f-sAPT respondents.

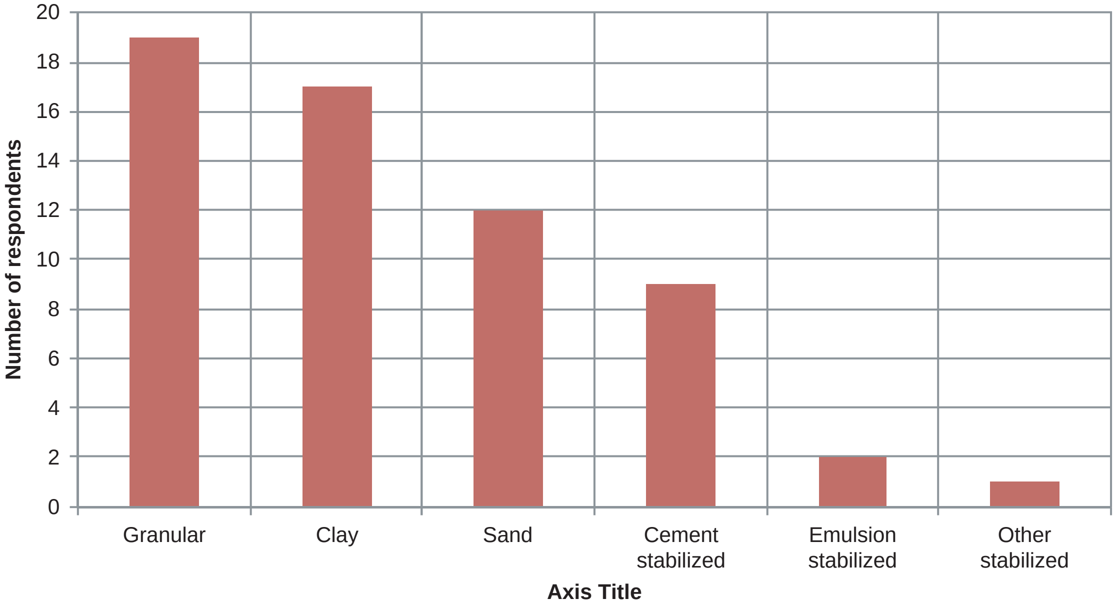

FIGURE 40 Subbase and subgrade materials evaluated by respondents.

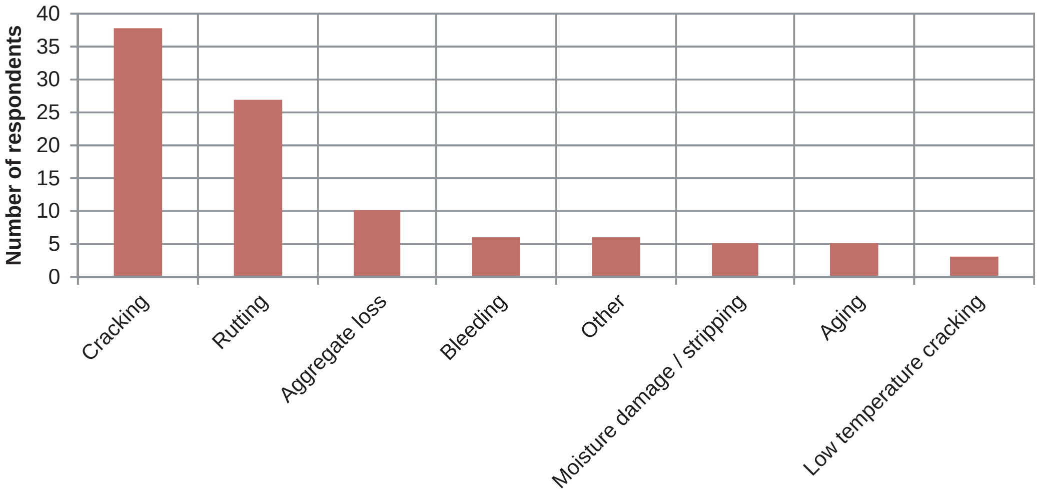

FIGURE 41 Structural distress types evaluated for asphalt surfacings.

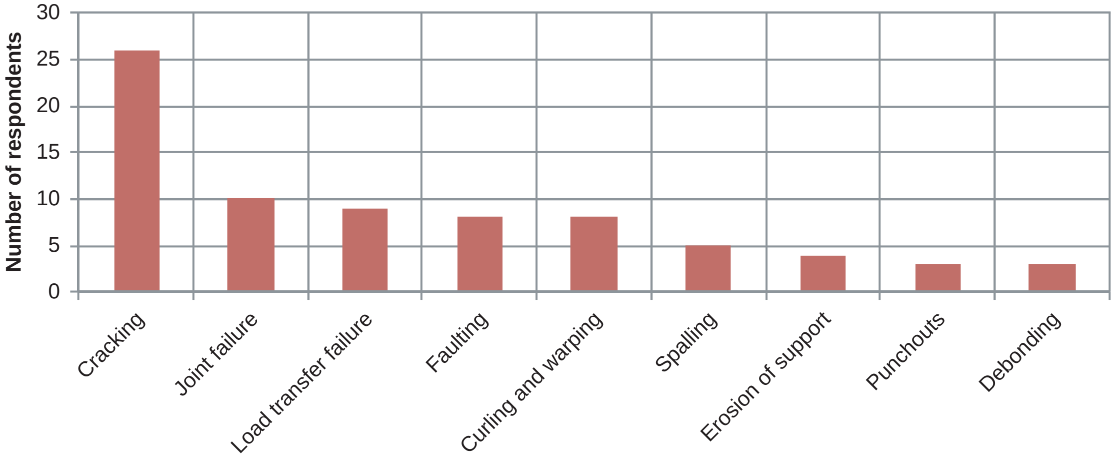

FIGURE 42 Structural distress types evaluated for concrete surfacings.

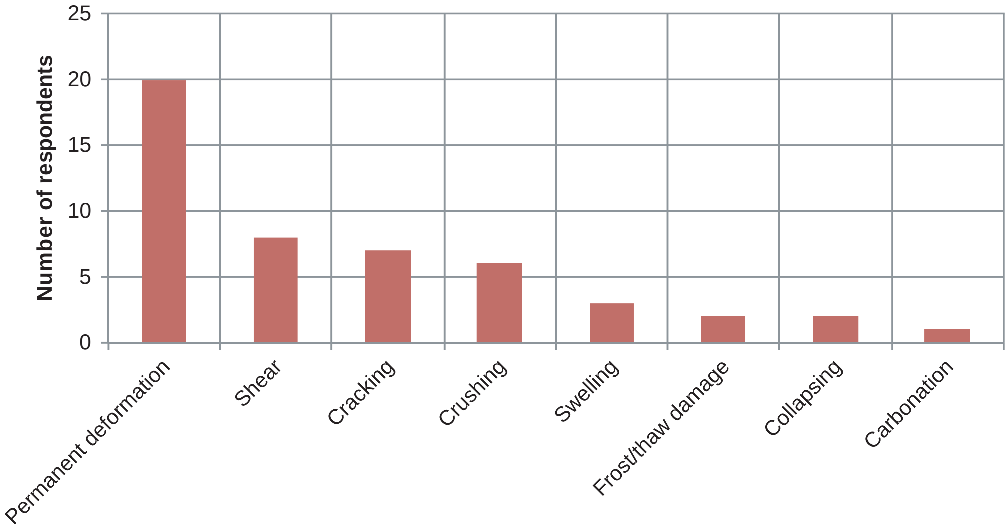

FIGURE 43 Structural distress types evaluated for base and subbase layers.

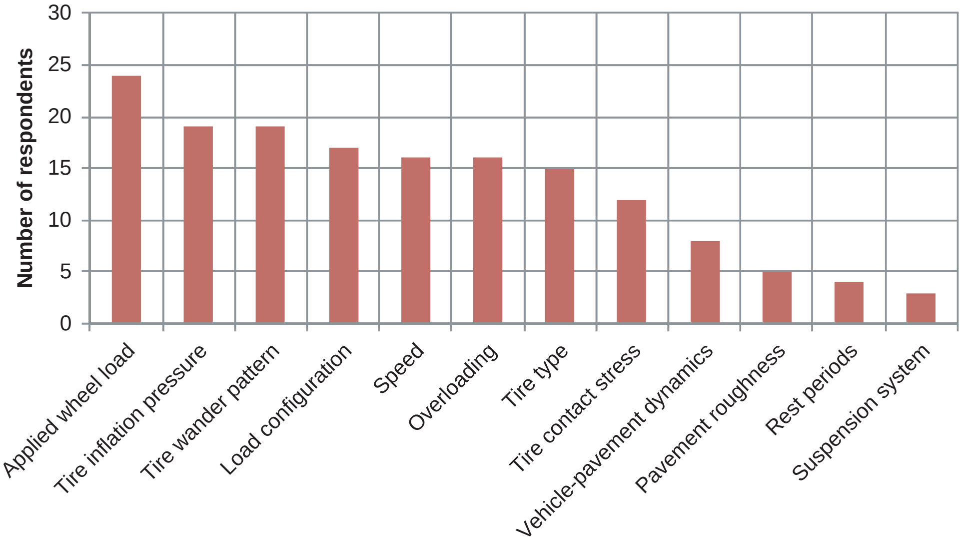

FIGURE 44 Load characteristics related to f-sAPT performance.

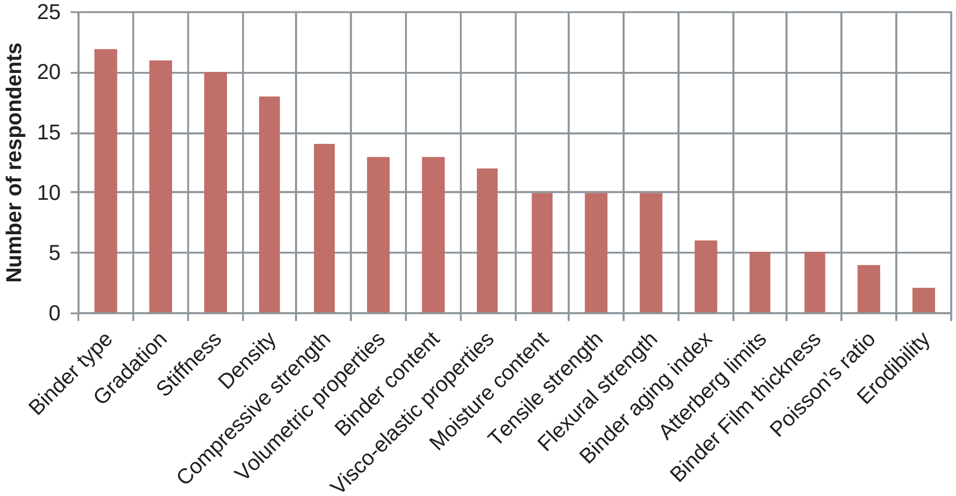

FIGURE 45 Material properties used to explain performance.

Park et al. (2004) proposed an elastic-visco-plastic continuum model based on Perzyna's visco-plastic theory and the Drucker–Prager yield function for simulation of HMA rutting at WesTrack using compressive strength test data at different strain rates and confinement pressures at a test temperature of 140°F (60°C). A Temperature Conversion Factor accounting for temperature variation in the field was developed based on repeated triaxial tests performed at 86°F, 104°F, and 122°F (30°C, 40°C, and 50°C). The Temperature Conversion Factor was used as a simple way to convert traffic loading at various temperatures to its equivalent at a standard temperature. Analysis indicated the WesTrack HMA to be a strain-dependent and pressure-dependent material at high temperature.

Wu (2004) analyzed the effects of HMA material model parameters and load assembly (tire pressure, wheel spacing) on Superpave mixture rutting. A three-parameter creep model was successfully used to capture the behavior of HMA mixtures while analyzing rutting development of the f-sAPT sections, showing that the predicted rutting depth was sensitive to all parameters of the creep model. Predicted rutting increased significantly with increasing tire inflation pressure and also with an increase in HMA layer thickness. Because the rutting depth is the summation of all creep strains throughout the depth of the pavement layer, this is a logical outflow from using the specific creep model. A set of multiple-regression equations for predicting rutting depths on Superpave mixture pavements has been developed.

Villiers et al. (2005) developed an approach to integrate FWD and core data along with transverse profile measurements to assess the contributions of different pavement layers to rutting and identify the instability within the HMA layer. Forensic data from f-sAPT trenches and laboratory test results verified the approach. The importance of evaluating rutting development from each individual layer was shown in the development.

Agardh and Busch (2006) evaluated different types of rutting depth prediction models for an incremental design process. This included a model that calculates the plastic strain through the whole pavement, and a model that is based on the critical response at a specific location in the pavement. Both models were calibrated using f-sAPT data and validated with theoretical sections and in-service roads. Both models were found to overestimate the rutting depth at the two real pavements used for the evaluation. The energy model overestimated rutting depth compared with real sections for high traffic volumes. As the comparison was done for roads located on relatively weak pavements, this may have affected the rutting model calibration.

Monismith et al. (2006) presented relationships between shear test results on field cores obtained prior to trafficking for four different mixes comprising 34 of the WesTrack sections, showing an excellent correspondence between the shear test results and rutting depths measured at specific numbers of load repetitions. These results suggest that the methodology utilizing the results of test data obtained with the Repeated Simple Shear Test at Constant Height (RSST-CH) can be used effectively for both HMA mixture design and rutting prediction in a M-E analysis/design procedure. The test appears to capture the impact of modified binders on rutting resistance.

The behavior of a flexible pavement using an elastic-visco-plastic constitutive relation that takes into consideration the influence of the temperature for the HMA has been evaluated using numerical analysis, a laboratory evaluation, and f-sAPT (Ali et al. 2006a, b). Numerical results show that the elastic-visco-plastic model reproduces the behavior of flexible pavements well, with the increase in the temperature significantly affecting the deformation of the pavement. Increasing the temperature from 68°F to 86°F (20°C to 30°C) caused an increase of 40% in the compressive strain at the top of the subgrade layer. Comparison of the numerical and f-sAPT results with laboratory data from LAVOC (France) indicated that the numerical model reproduced the pavement rutting behavior correctly.

FDOT evaluated the rutting performance of coarse and fine-graded Superpave mixtures under f-sAPT (Choubane et al. 2006) (also refer to polymer modification section—Gokhale et al. 2005). The results (supported by experience from NCAT) have shown that fine-graded mixtures can perform at least as well as coarse-graded mixtures with respect to rutting, and FDOT therefore changed the July 2005 edition of its Superpave specification, allowing fine-graded mixtures for traffic level D and E mixtures, and requiring PG76-22 modified binder in the top structural layer of traffic level D mixtures and in both structural layers for traffic level E mixtures. The information on the performance of HMA mixes under realistic loading conditions was obtained in a short time using f-sAPT, demonstrating that f-sAPT can produce cost-effectively early, reliable, and practical results while improving pavement technology and the understanding and prediction of pavement systems performance.

An effort was made to develop an HMA rutting prediction model from NCAT Test Track data (Immanuel and Timm 2007). One approach consisted of a vertical strain-based rutting model built by relating the measured rutting to the vertical strain on the top of granular layers and the traffic volume. The second approach linked rutting with maximum shear strain in the HMA layer and the traffic volume. Both approaches accurately predicted rutting on a section-by-section basis, and although the vertical strain approach could not accurately predict rutting when sections were grouped according to binder modification, the shear strain approach could do this accurately. The shear strain-based rutting prediction model is applicable only when the asphalt concrete layer rutting is the leading source of pavement rutting.

Mateos et al. (2008) (Spain) conducted f-sAPT on six sections consisting of 6 in. (150 mm) HMA on different alternatives of a high-quality subgrade to improve the understanding of mechanistic behavior of these pavements. The data were modeled using FEM where soils were assumed to be linear elastic and the HMA to be linear visco-elastic, with a constant bulk modulus and a time-dependent shear modulus. The mechanical stiffness of the HMA strongly depends on the applied load frequency, causing increases in the pavement rutting response for decreased vehicle speeds. General agreement was found between model and f-sAPT data for low temperatures; however, as the temperatures increase, the measured response increases more quickly than the model, resulting in an underestimation of the rutting at the highest temperature—probably related to the linear visco-elastic model used for the HMA mix.

Xu and Mohammad (2008) developed an M-E model for simulating HMA rutting depth under f-sAPT based on the power law of vertical strain. Total rutting depth is an integration of the individual layer rutting. Evaluating the model with Accelerated Load Facility (ALF) (Louisiana) data has shown reasonable agreement between the measured and modeled rut, with layer thickness and modulus showing significant influences on rutting development.

Azari et al. (2008) reported that HMA lanes were constructed with six different asphalt binder types and two different thicknesses and tested for rutting and fatigue cracking at the FHWA’s ALF site. Plant manufactured HMA specimens were compacted in the laboratory and subjected to dynamic modulus and flow number tests using the Simple Performance Tester (SPT) together with laboratory manufactured specimens. Good agreement was observed between permanent strains measured by the flow number test and the ALF rutting measurements for initial rutting. HMA rutting was also predicted using the MEPDG Level 1 and 3 analyses. The objective was to estimate HMA rutting using the MEPDG software and NCHRP 1-37A permanent deformation prediction models and compare the permanent strains measured during the flow number test with the measured f-sAPT rutting. The Level 3 MEPDG predictions were generally higher than measured ALF rutting (but in a similar range) while the Level 1 MEPDG predictions were significantly higher than the ALF measured rutting, and also significantly higher than Level 3 predictions. The Level 3 stiffness (from the NCHRP 1-37A stiffness prediction equation) significantly overestimated the stiffness of the ALF lanes, and it is concluded that the main reason for the overprediction of rutting (using Level 1 models) was the calibration of the permanent deformation model that was apparently performed using predicted stiffnesses from the NCHRP 1-37A stiffness equation rather than tested $|E^*|$ using the SPT. This also showed that HMA stiffness alone cannot explain field rutting sufficiently.

Gibson et al. (2009) (FHWA) further found that the SST-RSCH (at fixed air voids) and Flow Number (as-built air voids) appeared to provide the strongest indication of HMA rutting based on statistical analysis of laboratory data. When incorporating Flow Number test data into HMA rutting prediction models for the MEPDG analysis, realistic comparisons were found between f-sAPT and predicted rutting.

Coleri et al. (2008) (California) demonstrated the applicability of a two-stage Weibull approach to simulate field rutting performance of HMA mixes as a function of binder type, air-void content, shear stress level, and temperature and calibration of the model using f-sAPT results. The initial laboratory models are based on RSST-CH data and the results indicated that the approach is a reliable and promising technique for rutting performance prediction.

Korea is in the process of developing an M-E pavement design method (Cho et al. 2010). As part of this development two 0.75 in. (19 mm) dense-graded HMA sections with air-void ratios of 7.3% and 10.6% and a temperature of 122°F (50°C) at 2 in. (50 mm) depth were evaluated under f-sAPT for the development of a HMA rutting performance-based model. The rutting in the HMA was directly linked with the different air-void ratios. The surface rutting amounted to approximately 65% (10.6% air-void) and 57% (7.4% air-void).

A stone mastic asphalt mixture and a dense-graded airfield HMA mixture (both known for high shear and rutting resistance) were trafficked with 1,500 passes of a F-15E aircraft load cart at Tyndall Air Force Base, Florida, to evaluate the rutting performance of pelletized asphalt HMA (Saeed et al. 2010). The pelletized asphalt HMA section showed no rutting compared with the up to 0.9 in. (22 mm) rutting in the conventional HMA section, supporting the conclusion that it is feasible to produce airfield-quality HMA with pelletized asphalt using conventional HMA plants. Laboratory workability tests indicated that the DGA mixture compacted better with less energy than the stone mastic asphalt mixture.

Gibson et al. (2010) evaluated the similarities and differences in rutting susceptibility of HMA (FHWA APT site) fabricated by a Superpave Gyratory Compactor and field compaction rollers. The field-compacted mixtures tended to be less resistant to rutting at fewer cycles and smaller permanent strains, but exhibited more strain hardening than Superpave Gyratory Compactor samples at greater cycles and larger permanent strains. F-sAPT induced densification in the wheel paths and resulted in the characteristic upheaval humps on the side of the wheel path. None of the applied stress states or compaction methods was able to produce corresponding volumetric consolidation. Currently, reversals in stress resulting from a rolling tire are hypothesized as the reason why laboratory tests that do not have stress reversals cannot reproduce field observations accurately.

Wang and Zhou (2010) evaluated the effect of HMA pavement structures to HMA pavement rutting through f-sAPT on a circular track in Chongqing. Three test pavements with similar HMA wearing course, binder course, and subgrade, and different base and subbase layers were evaluated. Rutting was found to occur mostly in the HMA layers.

Mbakisya and Romanoschi (2010) evaluated existing mechanistic models that predict HMA rutting by comparing the computed permanent deformation to f-sAPT data from Kansas for six different asphalt mixes. The Drucker–Prager model overpredicted permanent deformation even after creep hardening was added to the model, whereas elasto-visco-plastic and creep models predicted total rutting that ranged between 95% and 102% of the f-sAPT values on the surface, subbase, and subgrade. HMA rutting was predicted to range between 28% and 78% of measured values.

Coleri and Harvey (2011) demonstrated a reliability analysis approach for prediction of HMA rutting performance by evaluating reliability through considering the variability in laboratory test results, layer thicknesses and stiffnesses, and measured in situ performance (California). Each input parameter's contribution to variability was assessed, and these variability distributions were used for rutting performance prediction and reliability evaluation of highway sections. The results indicated that distributions of calibration coefficients calculated by using measured rutting depths were very similar to calibration coefficient distributions calculated by using thickness and stiffness variability. This suggests that variability in performance can be effectively predicted by using the thickness and stiffness variability for f-sAPT sections as thickness and stiffness variability were found to be the major factors controlling the rutting variability. The variability of stiffness for bound and unbound layers was represented through lognormal distributions, whereas the variability in layer thicknesses was described by normal distribution functions. Precision of laboratory test results did not have much effect on predicted rutting performance when the effect of laboratory variability is simulated with construction or performance variability. It thus appears that a high level of variability in measured performance, thickness, and stiffness masks the effect of laboratory variability on calculated calibration coefficient distributions.

Li et al. (2011) (South Korea) developed and calibrated an HMA rutting model based on shear properties obtained from Triaxial Compressive Strength and Repeated Load Permanent Deformation tests on three types of HMA at various loading and temperature conditions. The model was calibrated using f-sAPT data conducted at various temperatures. Cohesion decreased with an increase in temperature for a given mixture, while the friction angle was not significantly affected by temperatures higher than 104°F (40°C). Deviatory stress, confining pressure, test temperature, and load frequency significantly affected the rutting of HMA and were thus incorporated in the rutting model. The proposed model has been shown to successfully predict the rutting of various HMA mixes under a range of loading and temperature conditions.

Fatigue

Hartman et al. (2001) (Ireland) performed f-sAPT on Dense Base Course Macadam (DBCM) supported by a weak subgrade. Transverse horizontal tensile strains caused longitudinal cracks in the wheel path with the single front steering tires inducing maximum strains. The measured data were modeled using a linear elastic model and lower strains were calculated, while the expected life to crack initiation was also underestimated using the linear elastic model.

The framework used for analytically based HMA pavement design methods has remained virtually unchanged for the past 40 years, utilizing the tensile strain in the HMA to deal with fatigue cracking and compressive strain on the subgrade for rutting (Brown et al. 2004). A vast amount of research has identified difficulties and shortcomings with this approach. The formation and growth of fatigue cracks causes the effective stiffness of the HMA to decrease and this effect is viewed as more important in design than details of the cracks. As an alternative approach a prediction method for stiffness deterioration can be used where the HMA stiffness modulus decreases as fatigue damage in the layer is accumulated until it reaches a terminal level when the fatigue life has been used up. This can be modeled in an exponential relationship between normalized HMA layer stiffness and accumulated fatigue damage by back-calculating HMA layer stiffness moduli from surface deflection measurements obtained at various loading stages during f-sAPT.

Rich-bottom pavements are designed to reduce the sensitivity to tensile strain in the lower layers of a pavement by the addition of an extra 0.5% binder content. The effectiveness of a rich-bottom HMA section was evaluated at NCAT (Willis and Timm 2007). Although it was expected to perform better than control sections, it failed earlier than the control sections in fatigue. Theoretical and dynamic strain data analyses showed the possibility of slippage occurring in the section. Further analysis showed that cracking initiated above the rich-bottom layer with lower strains calculated at the base of the rich-bottom. Forensic investigations indicated that debonding at the layer interfaces was most likely the cause of early cracking in the rich-bottom section, which led to early fatigue cracking.

F-sAPT conducted at NCAT showed bottom-up fatigue cracking that developed as a series of short transverse cracks that extended to the edge of the wheel path before interconnecting into the familiar alligator pattern (Timm and Priest 2008). This differs from observations on LTM sections, but is often observed in pavement experiments. Measurements showed the longitudinal strain to be higher than the transverse strain, partially owing to strain reversal before and after a given axle and between axles in an axle group. Timm and Priest (2008) recommended that strain reversal in the longitudinal direction should be included in fatigue transfer function calibration and that tandem axles could be considered separately, rather than as an axle group.

Howard and James (2009) evaluated general design guidance for bottom-up fatigue cracking of thin flexible pavements (located in Arkansas) using data collected as part of a study to evaluate geosynthetics in thin flexible pavements. All test traffic was channelized at a speed of 35 mph (56 km/h) using single-axle dump trucks (FHWA category 5). HMA strains were observed to not be normally distributed, whereas the earth pressures were normally distributed. Through FEM analysis it was determined that temperature gradients caused skew HMA strain data. After-analysis relationships were developed of damage as a function of mean strain (considering the measured temperatures) and strain distributions. The design thickness resulting from this approach does not account for any distress other than bottom-up fatigue cracking. The guidance is only valid for the low-volume roads portion of MEPDG and compliments previous work.

Kutay et al. (2009) evaluated the possibility of using small sample sizes for push-pull tests to evaluate the Visco-Elastic Continuum Damage (VECD) characteristics of HMA. The difference in characteristics for regular and small size samples was observed to be negligible. The use of the uni-axial push-pull test on cylindrical samples is viewed as a novel alternative for the costly and time-consuming bending beam test. A practical fatigue life formulation based on the VECD theory was derived and used to investigate differences in fatigue lives of different HMA layers at the FHWA's ALF site. Unlike the fatigue life formulation implemented in MEPDG, the proposed VECD equation was able to capture the f-sAPT behavior well. Since the push-pull tests are compatible with the Asphalt Mixture Performance Tester (AMPT), it is possible and practical to calibrate the VECD model by performing an additional test in the AMPT and then calculating the fatigue life of the pavements based on these equations. This fully mechanistic procedure may be used in place of the empirical fatigue life formulation implemented in the MEPDG.

Christofa and Madanat (2010) developed crack initiation models for flexible pavements by using data from the Performance Analysis for Road Infrastructure (PARIS) project database (located in the European Union), which consists of both Real-Time Load Testing data and f-sAPT data. Crack initiation models allow for optimal maintenance and rehabilitation activities and optimal pavement design. The development showed that many of the explanatory variables that are expected to play a significant role in determining crack initiation (i.e., granular layer thickness) appear to have insignificant parameter estimates, probably a result of the small number of observations used. Analysis of the model predictions indicates that they are reasonable, although they overestimate crack initiation probability in the early stages of pavement life.

Mateos et al. (2011) quantified the beneficial effect of traffic rest periods through use of a variable shift factor based on the methodology developed in NCHRP 9-38 (Endurance Limit of Hot Mix Asphalt Mixtures to Prevent Fatigue Cracking in Flexible Pavements) (Prowell et al. 2010) and NCHRP 9-44 (Developing a Plan for Validating an Endurance Limit for HMA Pavements) (Bonaquist 2008). A shift factor of 475 was calculated when laboratory fatigue life was compared with f-sAPT data from CEDEX (Spain) indicating the number of load repetitions to reach 20% alligator cracking. This variable shift factor was successfully applied to laboratory data incorporating the reduced rest period effect, followed by application of the California Mechanistic Empirical (CalME) fatigue model to adequately predict HMA deterioration in an f-sAPT experiment.

The HMA fatigue model in the MEPDG is based on the original Asphalt Institute model with modifications. Wen (2011) proposed two new fatigue models based on FHWA ALF data. Inclusion of the dynamic modulus and accounting for HMA layer thickness and construction variations in the traditional strain-based fatigue model improved the effectiveness of the applied model. A combination of critical strain energy density and dynamic modulus in the fatigue model correctly characterized the effect of HMA layer thickness on fatigue life in the analyses, and this model was proposed as being potentially effective for bottom-up cracking analysis.

Modified Binders

Sirin et al. (2003) used data from the Florida HVS to evaluate the rutting performance of unmodified and styrene butadiene styrene (SBS)-modified Superpave HMA. Analysis showed that the pavement sections with two lifts of SBS-modified mixture outperformed those with two lifts of unmodified HMA. Sections with a lift of SBS-modified HMA over a lift of unmodified HMA only showed approximately 20% higher rutting compared with the two lifts of modified mixture tested at 122°F (50°C). Two lifts of SBS-modified HMA tested at 149°F (65°C) showed high rutting resistance compared with two lifts of unmodified HMA tested at 122°F (50°C). Rutting development in the Asphalt Pavement Analyzer correlated with the f-sAPT rutting data. It was concluded that for pavements with the unmodified HMA, rutting was caused by a combination of densification and shoving, while the SBS-modified HMA experienced rutting primarily the result of densification of the HMA. The resilient modulus of the SBS-modified HMA was not significantly different from that of the unmodified HMA at 77°F (25°C). Evaluation of the viscosity at 140°F (60°C) of the recovered binders showed the binders recovered from the SBS-modified HMA to be two to three times that of the recovered binders from the unmodified HMA.

FDOT evaluated the effects of polymer modifiers on the performance of two fine-graded Superpave HMA mixes using the HVS (Gokhale et al. 2005). The sections with the SBS-modified mixture significantly outperformed those with the unmodified mixture, and it was determined that rutting in the unmodified mixture was primarily a function of shear flow while rutting in the SBS-modified mixture was due primarily to densification.

D'Angelo and Dongre (2006) evaluated the development of a high temperature performance-based binder specification to characterize both modified and unmodified HMA binders (using an HMA mixture from the FHWA ALF site). Both creep and recovery testing of the binders showed strong correlation with the mixture performance and showed the stress dependency of several polymer-modified systems. With stress dependency viewed as a key factor in determining the relationship between binder performance and mixture performance, a multistress creep and recovery test was developed that distinguishes the difference between polymer systems and simplifies the testing.

Al-Khateeb et al. (2007) conducted mechanistic analyses on the modified and unmodified asphalt HMA pavements of the FHWA's ALF using KENPAVE, WINLEA, EVERSTRS, EVERFLEX, and VESYS 5W. Load frequency impacted the tensile fatigue stress and strain at the bottom of the HMA layer and further affected the major principal stress at the surface and bottom of the HMA layer, and the minor principal stress at the bottom of the HMA layer. Insignificant effects were observed in the rutting. The mechanistic analyses indicated that Multi-Layered Elastic Theory provided reasonable predictions for the measured tensile strains. VESYS 5W provided good correlations with the measured vertical deformation within the HMA. When using the same loading frequency in the analyses, similar tensile strain outputs were obtained for the various analysis options.

Von Quintus et al. (2007) evaluated the benefits of using polymer-modified asphalt (PMA) based on field and f-sAPT data from nearly three dozen pavement sections in the United States. It was evident that the use of PMA definitely extends the service life of flexible pavements and HMA overlays, with pavements incorporating PMA mixtures found to have lower amounts of fatigue cracking, transverse cracking and rutting, and extended service lives of 5 to 10 years.

ALF testing conducted in Beijing focused on evaluation of the rutting resistance of four different modified HMA mixes (Zejiao et al. 2010). Analysis showed that the SBS-modified HMA had the best rutting resistance of the HMA mixes evaluated, and that the rutting resistance of the bottom HMA layer for semi-rigid base pavements (commonly used in China) is crucial in the performance.

The effects of binder properties on HMA mixes at intermediate temperatures were evaluated using a new materials characterization method and five binders (four modified) and five HMA mixes containing these binders with similar aggregates (Wen et al. 2011). All the HMA mixes originated from the FHWA f-sAPT facility. All the modified binders reduced the strength of the binder (except for terpolymer) but increased the failure strain and ductility of the binders (except for air-blown material). All the modification methods reduced both the dynamic moduli and indirect tensile strengths of the HMA mixes. A clear correlation was observed between the failure strain of the binders and that of the HMA, and also between the complex shear moduli of the binders and dynamic moduli of the HMA. No clear relationship could be observed between the strength and fatigue resistance of the binders and those of the HMA mixes.

Although PMA has traditionally been used in upper pavement lifts to enhance rutting performance where temperatures, vertical stresses, and shear action are extreme, the need for thinner high performing pavements provides motivation for using higher modulus, fatigue-resistant materials in the lower lifts of a flexible pavement.

Timm et al. (2011a) compared the structural responses of highly polymer modified (HPM) asphalt on the NCAT test track with a control section. The structural behavior of both HPM and the control section in response to temperature changes was well-characterized by exponential functions. At both the lowest reference temperature [50°F (10°C)] and intermediate reference temperature [80°F (27°C)] the HPM section experienced higher average strain compared with the control section (partly owing its thickness). This implies that the HPM section would have lower strain at intermediate temperatures if the thickness of the two materials is similar. At the highest reference temperature [109°F (43°C)] the control section experienced higher average strains compared with the HPM, despite a 1.4 in. (35 mm) thickness advantage over the HPM. The aggregate base experienced higher average vertical stresses in the HPM section than the control section at all temperatures. The f-sAPT data indicated that the HPM is effective at reducing HMA layer thickness without significant change in performance.

The transportation pooled fund study TPF-5(019) (Full-Scale Accelerated Performance Testing for Superpave and Structural Validation) was initiated with the construction of 12 f-sAPT lanes with various modified HMAs at the FHWA's APT site with the objective of validating and refining proposed changes in Superpave specifications to properly grade-modified HMA binders (Mitchell et al. 2004; Qi et al. 2008, 2010). Results of the first year's f-sAPT generally ranked the performance of the modified binders much differently than the results from laboratory mixture performance tests (French Pavement Rutting Tester, Hamburg Wheel Testing Device, and Superpave shear tester). None of the tests correlating to ALF-generated rutting, as the rutting depths of most of the lanes were statistically the same, as the binders were designed to have nearly identical high temperature performance grades (Gibson et al. 2011). Rutting performance throughout some mixes depended on HMA layer thickness, and correlations after sorting the data according to layer thickness were moderate between the French Pavement Rutting Tester results and the 4-in. (100-mm)-thick HMA rutting depth, and high between RSST-CH results and 6-in. (150-mm)-thick HMA rutting depth. No overall relationship was found between $G^*/\sin\delta$ of the HMA binders and rutting depth.

F-sAPT fatigue cracking performance data were compared with four binder parameters [conventional $|G^*| \sin\delta$ obtained from time or frequency sweep at low strains, $|G^*_S| \sin\delta_S$ obtained from dynamic shear rheometer (DSR) strain sweep at high strains, Essential Work of Fracture, and number of cycles to fatigue failure (N_f) obtained from a stress sweep] (Qi et al. 2006). The Essential Work of Fracture did not show a good correlation with f-sAPT data, whereas the current Superpave specification and proposed refinements showed reasonably good correlations. Although N_f from a stress sweep showed a better correlation, the trend was reversed. A total of nine binder tests were ultimately considered for fatigue cracking along with a more refined statistical selection procedure for the final report. Calculated Critical Tip Opening Displacement is a variation of binder performance test to control fatigue cracking above the eight other candidates. F-sAPT rutting performance data has been compared with four binder parameters [conventional $|G^*|/\sin\delta$, J_{NR} (nonrecovered compliance) obtained from DSR multistress creep recovery tests], $|G^*|/(1 - 1/\tan\delta \sin\delta)$ obtained from DSR time or frequency sweeps and MVR (volumetric flow rate) obtained from the flow measuring device] (Qi et al. 2006). It was found that the term $|G^*|/(1 - 1/\tan\delta\sin\delta)$ obtained from DSR time or frequency sweep showed the best correlation among the binder parameters in all cases for the thin and thick HMA pavements evaluated together and separately when outliers were removed.

In stress-controlled push-pull tests on mixtures, N_f versus field number of wheel passes to 20% crack length revealed an inverse relationship, attributed to the testing mode where it was observed that the soft mixtures performed worse in stress-controlled tests, while they performed well in the field (Qi et al. 2008). N_f based on stress-controlled push-pull tests are not recommended for fatigue characterization. Strain-controlled N_f in mixture testing generally exhibited similar trends when compared with the field; however, owing to the nature of the testing where the strain was controlled at the actuator, the field ranking was not strongly captured, and therefore N_f based on actuator strain-controlled tests may not be sufficient to understand the field fatigue behavior. Choice of stress level appears to influence the correlation between laboratory test and pavement rutting with different pavement thicknesses. High-stress ratio-unconfined friction number tests showed better relationship with rutting in thin pavements [4 in. (100 mm)] than rutting in thick pavements [6 in. (150 mm)]. Low-stress ratio-confined friction number tests provided good relationship with rutting in thick pavements [6 in. (150 mm)] and no relationship in thin pavements [4 in. (100 mm)].

Approaches to improve low temperature fracture resistance of HMA pavements were evaluated using data originating from MnROAD and other sources (Marasteanu et al. 2007). It revealed that two simple mixture tests can be used to provide relevant fracture properties of the HMA mixtures. The fracture toughness and energy obtained from these tests correlated best with the field distresses measured in the selected pavement sections. Even at low temperatures HMA mixtures were shown to be complex visco-elastic composite materials that are significantly temperature and loading rate dependent. The study demonstrated that the effect of temperature is significant as the behavior changes from brittle-ductile to brittle. When conducting low temperature tests on HMA mixtures, testing temperatures should be established relative to the expected low pavement temperature and/or relative to the low temperature Superpave performance grading (PG) grade for the location of interest. The mixture coefficient of thermal contraction was shown to be a critical parameter for estimation of field performance for low temperature cracking and it was shown that the coefficients are affected by binder grades and by mixture variables. It was recommended that a specification be developed for selecting HMA mixtures with increased fracture resistance similar to the PG system for binders, as low temperature cracking performance cannot rely entirely on the PG of the asphalt.

Hot Mix Asphalt Overlays

F-sAPT on dense-graded asphalt concrete (DGAC) and gap-graded asphalt rubber hot mix (ARHM-GG) at elevated temperatures was used to compare the rutting behavior under different tire types (Harvey and Popescu 2000). The 2.5 in. (62 mm) ARHM-GG and 2 to 3 in. (50 to 75 mm) DGAC overlays had similar performance, while the 1.5 in. (38 mm) ARHM-GG overlay had superior performance under dual radial tire loads. However, the ARHM-GG overlays had better performance than the DGACs overlay under wide-base single tire loads. Low Hveem stabilometer values obtained for the ARHM-GG mixture did not indicate the good performance of the mixture under HVS loading and indicated the need for improved methods of characterizing rutting performance of ARHM-GG mixes. The 46°F (8°C) temperature difference at 2 in. (50 mm) depth between two similar tests resulted in 140 times more load repetitions being applied before rutting failure on the cooler section compared with the hotter section, emphasizing the need to account for local pavement temperatures to be incorporated in the mixture design process.

Kumar et al. (2006) assessed whether any improvement occurs in pavement performance when incorporating a 2-in. (50-mm) HMA binder layer as part of a second generation overlay of HMA pavements, deviating from the typical 1.5-in. (38-mm) HMA surface layer overlay with leveling adopted in Pennsylvania. Dynamic modulus mastercurves for the surface and binder layer mixes revealed that for operating temperatures, both the surface and binder layer mixtures would probably lead to similar performance. F-sAPT indicated that the inclusion of the binder layer does not significantly alter the rutting resistance of the pavement structure. This was confirmed through a sensitivity study modeling both pavement structures and empirical distress prediction models using FEM. Increasing binder layer thickness appeared to offer slight improvement in rutting resistance. MEPDG analysis showed increases in top down cracking with binder layer thickness increases up to a certain thickness, after which additional thickness increase led to reduced cracking.

Bejarano et al. (2007) used the Caltrans Highway Design Manual Chapter 600 method to design an f-sAPT section to validate Caltrans overlay strategies for the rehabilitation of cracked HMA. Proper compaction of the subgrade and aggregate base layers was primarily affected by the water content in these layers. Data indicated that low aggregate base moduli were obtained in locations where low subgrade moduli were observed. The HMA layer had a significant effect on the behavior of the aggregate base and subgrade, providing a confining pressure that increased the modulus of the aggregate base and also providing additional cover to the subgrade. The HMA modulus was significantly affected by temperature. The f-sAPT data showed that the overall pavement performance appeared to be significantly influenced by the behavior of the aggregate base, with sections tested during the dry months lasting longer in fatigue and surface rutting than the sections tested during the wet months.

Jones et al. (2007a) evaluated the Caltrans overlay strategies for the rehabilitation of cracked HMA through f-sAPT to develop improved rehabilitation designs for reflective cracking. The underlying pavement incorporated a 3.5-in. (90-mm) DGAC surface on a 16-in. (410-mm) Class 2 aggregate base. All layers showed considerable variation in thicknesses. Rutting occurred primarily in the underlying DGAC and not in the overlay (rutting experiments), whereas it occurred in both HMA layers in the reflective cracking experiments. Little rutting occurred in the base, with no rutting in the subgrade. Cracks were generally clearly visible in the underlying DGAC layer. Air-void contents of cores removed from the wheel paths in the reflective cracking sections after f-sAPT were lower compared with those from cores outside the wheel paths.

Jones et al. (2007b, c) used the f-sAPT and laboratory data in CalME simulations and continuum damage mechanics analyses to develop two sets of M-E models for reflective cracking. One set of models has been incorporated into CalME (based on layer elastic theory), while the second set of models (intended as a research tool) is based on FEM analysis and continuum damage mechanics. The second model provides insight into crack propagation damage. Both models were calibrated and validated using the laboratory and f-sAPT data resulting in pavement prediction models in terms of calculated versus measured deflections, changes in stiffnesses, and ranking of reflective cracking performance. Bonding was found to be a significant variable in predicting actual performance of several HVS test sections. The models successfully predicted the performance of mixes with both modified and rubberized binders. Although the M-E rutting models predicted the overall rutting performance ranking of each section, it did not fully capture the distribution of rutting between the overlay and the underlying asphalt layers. The data indicated that the modified binder mixes have a greater risk of HMA rutting under slow, heavy loads and hot conditions compared with the full-thickness conventional DGAC overlay.

Ullidtz et al. (2008a) used CalME and data from f-sAPT and RSST-CH to perform virtual analyses on the f-sAPT section as if the supporting conditions were similar to enable a more consistent comparison of the various HMA overlays.

A comprehensive laboratory and f-sAPT experiment focuses on a comparison of gap-graded, terminal-blend-modified binder mixes with gap-graded Rubberized Asphalt Concrete (RAC-G) and conventional DGAC (Jones et al. 2008). Analysis indicated that gap-graded mixes with modified binder, and a combination of modified binder and 15% recycled rubber, will provide superior performance in terms of reflection cracking compared with the same half thickness of RAC-G and full thickness of DGAC used in thin overlays on cracked HMA pavements. Conventional dense-graded HMA was superior to all other mixes in terms of rutting performance, followed by the RAC-G and then the modified binder mixes (Jones et al. 2008).

Pérez et al. (2008) evaluated the maintenance and reinforcement of damaged pavements using HMA overlays through application of numerical analysis and f-sAPT. The reflective crack propagation was recorded and visualized on the f-sAPT section. The role of bonding interface properties in the f-sAPT was confirmed using FEM analysis with calculations matching particularly well to the measured strain data. Theoretical crack evolutions (affected by bonding interface conditions) were also confirmed in the comparison between f-sAPT data and strain field calculation data.

F-sAPT evaluation of thin HMA overlays over cracked asphalt pavement (California) illustrated the benefits of using f-sAPT for assessing these structures (Jones and Harvey 2009). It was found that clear failure criteria (related to the pavement management objectives and typical field conditions under which the treatments will be used) must be selected for good models to be developed. For thin overlays, cracking and rutting criteria were used. Much of the rutting under thin overlays may be related to the overlay stiffness and shear resistance, although much of the rutting will occur in the underlying layers if the overlays are less than 2.4 in. (60 mm) thick.

Dynamic Modulus

The dynamic modulus test has been proposed as the SPT to verify the performance characteristics of Superpave mixtures and as a potential field quality control/quality assurance parameter. Dynamic modulus (E*) is an input to MEPDG and supports the NCHRP Project 1-37A (Development of the

2002 Guide for the Design of New and Rehabilitated Pavement Structures) predictive performance models. The parameter is thus important, although the test is time-consuming. Reliable prediction of the compressive modulus of HMA mixes is essential in material characterization and pavement performance prediction. Azari et al. (2007) compared the E* values of the ALF (FHWA sections) pavement mixtures with E* values predicted from the NCHRP 1-37A and the revised Witczak models and indicated that both models made reasonably good predictions of ALF moduli at high values. However, it overestimated the predictions for the lower modulus values that correspond to low frequency and high temperatures. These are critical in rutting analysis of pavements, and failing to capture these values could increase the risk of premature rutting failure of HMA. The binder shear modulus (G^*_b) was found to be highly correlated with E* and justifies inclusion of G^*_b in the new predictive model. The phase angle of the binder was however found to be insensitive to the E* of the modified mixtures over the practical range of HMA mixture moduli.

Based on a comprehensive laboratory evaluation of actual HMA materials obtained from MnROAD, FHWA-ALF, and WesTrack (all f-sAPT sites), Zhou and Scullion (2003) recommended three SPTs for permanent deformation. These are the dynamic modulus term ($E^*/\sin\delta$), flow time, and flow number. Data from prematurely rutted sections on US-281 in Texas (used to validate the recommendation) showed that dynamic modulus (E*), $E^*/\sin\delta$, and flow number can effectively distinguish the good mixtures from the bad.

Clyne et al. (2004) evaluated the use of the complex dynamic modulus as a design and performance parameter for four of the MnROAD test cells. Master curves were constructed for each mixture and compared with FWD field data. It was observed that the dynamic modulus decreases with an increase in test temperature for the same mixture (constant load frequency), while the dynamic modulus increases with the increase of test frequency (constant test temperature). The softest binder (PG 58-40) had the lowest dynamic modulus and the mixtures with stiffer binders had higher dynamic moduli. The modulus backcalculated from FWD data correlated well with laboratory dynamic modulus data.

The accuracy and robustness of the Witczak empirical model for estimating the dynamic modulus inputs in the MEPDG methodology have been evaluated through a set of sensitivity and validation studies (Schwartz 2005). Validation of the Witczak model against an independent set of laboratory dynamic modulus data for 26 mixtures (originating from FHWA ALF, MnROAD, and WesTrack f-sAPT sections) found agreement between predicted and measured dynamic moduli nearly as good as for the calibration data set. Predicted rutting for the hypothetical pavement design using Level 1 versus Level 3 dynamic moduli inputs were in good agreement. The predicted rutting using the Level 3 inputs tended to be slightly lower than the corresponding predictions using Level 1 inputs by an average of 12% for HMA rutting and 6% for total rut, consistent with the tendency of the predictive model to overestimate dynamic modulus relative to laboratory measured values.

NCHRP 9-19 (Superpave Support and Performance Models Management) identified the confined dynamic modulus as one of three favorable indicators for evaluating the rutting potential of a mixture. Dynamic modulus testing at multiple confining pressures takes too long to be used routinely by state highway agencies. Experimental results presented by Lacroix et al. (2011) indicated that the linear visco-elastic properties of an HMA mixture are not affected by different confinements, and that all the confining stress effects manifest themselves in the elastic modulus at equilibrium. A method is proposed that uses a Prony series representation of the dynamic modulus curve and master curve shift factors obtained from unconfined testing. This method employs the elastic modulus values predicted from a modified version of the universal material model to predict dynamic modulus values at different levels of confinement. The applicability of the method was verified for the AMPT using three different mixtures that have been selected to highlight any differences in confined behavior resulting from various binder and aggregate structures. The mixture used in developing the procedure is the control mixture used at the FHWA ALF facility. This reduced testing protocol provides reasonable results, with most errors less than 20%.

Hot Mix Asphalt Modeling

A 3-D dynamic FEM procedure incorporating rate-dependent visco-plastic models was developed to predict rutting of HMA pavements under ALF (Louisiana) loading (Huang et al. 2001). The extended Drucker–Prager elasto-plastic model was used to describe the aggregate base and subgrade. Although the traditional 2-dimensional static FEM analysis was unable to simulate the dynamic nature of the traffic load and the correspondent pavement responses, the results indicated that the 3-D model described reflected pavement responses well and predicted pavement rutting with reasonable accuracy.

Seibi et al. (2001) evaluated HMA behavior under high rates of loading using uni-axial compression laboratory tests and f-sAPT (FHWA ALF). It was shown that HMA under high temperatures and high rates of loading exhibit an elastic-visco-plastic mechanical behavior reflecting the rate sensitivity of the material.

Kim et al. (2006) applied the visco-elasto-plastic continuum damage model to uni-axial compression data (FHWA ALF control mixture). The model is found to significantly overpredict the strains in the monotonic tests and the loading portions of the repetitive creep and recovery tests. Investigation suggests that the stiffening effect of aggregate interlock should be taken into account for a more accurate model of the compression behavior of HMA. This was done successfully by using the ratio of the predicted strain rate to the measured strain rate. Kim et al. (2008) subsequently compared the strain responses of a 3-D visco-elastic model with f-sAPT data and showed that the predicted strains agreed well with the field measured strains.

You and Buttlar (2006) developed a clustered distinct element modeling approach for modeling HMA microstructure in a research environment. It involves processing of high-resolution optical images to create a synthetic, reconstructed mechanical model that captures the complex morphology of the HMA. The model is applied to predict the dynamic modulus of specimens tested in cyclic, uni-axial compression. A coarse HMA mixture from the FHWA f-sAPT site and a fine-grained HMA surfacing used on Illinois highways were modeled. Both the aggregate and mastic phases were modeled. The distinct element modeling approach provided a reasonable portrayal of the force chains developed in the aggregate skeleton and is shown to be a fundamental way of looking at the complex behavior of HMA under different loading and temperature conditions.

Al-Qadi et al. (2008a, b) modeled f-sAPT responses of an HMA pavement to vehicular loading using a 3-D FEM model. The model incorporated measured 3-D tire–pavement contact stresses, a continuous moving load, and visco-elastic HMA properties. The tensile strain at the bottom of HMA decreased significantly as the HMA thickness increased, while the vertical shear strain variation was less significant. The longitudinal tensile strain at the bottom of HMA provided the critical response for thin and medium-thickness HMA layers, although the critical response for a thick HMA layer is the vertical shear strain between 3 and 4 in. (76 and 100 mm) below the HMA surface.

Underwood et al. (2010) proposed a more fundamentally appropriate method for modeling the performance of HMA based on coupling the response and material models, causing the effect of pavement degradation to be explicitly taken into account in the material response. The process requires significant computational time and effort. A numerical study of the behavior of HMA pavements subjected to f-sAPT wheel loads incorporating three pavement response tools [linear elastic analysis (LEA), linear visco-elastic analysis (LVEA), and FEM analysis] suggested that the use of the FEM for complete pavement response and performance prediction is still too computationally intensive for routine pavement design and analysis and that LEA or LVEA will be important to mechanistic pavement analysis for the foreseeable future. For pavement responses at the bottom of the HMA layers, LEA can be performed such that it yields reasonably accurate values as compared with LVEA. However, care must be taken in selecting the appropriate modulus value to use.

NCHRP 9-19 Project, Superpave Support and Performance Models Management did not propose standard triaxial testing conditions for the magnitude of the deviator and confining stresses. Hajj et al. (2010) developed recommendations for the selection of the deviator and confining stresses that best simulate the stress conditions encountered in the pavement under traffic loads through extensive mechanistic analyses (3D-Move model) of three different HMA structures subjected to moving traffic loads at a range of speeds and braking and non-braking conditions. Prediction equations for estimating the anticipated deviator and confining stresses have been developed and validated successfully on a HMA mixture from WesTrack as a function of pavement temperature, vehicle speed, and HMA stiffness. When braking conditions were incorporated into the analysis, an increase of 40% was observed for the deviator stress.

Bonding and Tack Coats

Inadequate HMA layer interface bonds typically lead to slippage cracking. The interface condition significantly affects the distribution of stresses and strains in pavement structures. Romanoschi and Metcalf (2000) proposed a constitutive model for HMA interface characterization based on laboratory-based shear-stress-displacement curves. The permanent shear displacement increases linearly with the increasing number of load repetitions under fatigue testing. The shear stress and displacement are proportional until the shear stress equals the shear strength and the interface fails under direct shear testing with normal load.

Interface bonding between HMA overlays and PCC pavements affects the service significantly. Leng et al. (2008) developed a direct shear test device to investigate the characteristics of this interface and determine the interface shear strength, including parameters such as HMA type, tack coat type, tack coat application rate, PCC surface texture, and temperature. Finely graded HMA provided better interface shear strength than coarsely graded HMA, whereas asphalt emulsion provided better interface shear strength than cutback bitumen. An optimum tack coat application rate of 0.04 gal/yd^2 (0.18 l/m^2) was found independent of tested parameters. Tining direction in the PCC did not affect the interface shear strength at 68°F (20°C). Leng et al. (2009) added f-sAPT evaluation of HMA over PCC overlays to evaluate the data obtained from laboratory tests on tack coat performance. The measured strain response data validated the laboratory findings, with the optimum tack coat application rate section providing the smallest strain responses compared with sections with higher and lower tack coat application rates. The f-sAPT section without tack coat had the highest rutting compared with other sections. Milled PCC surfaces provided lower rutting compared with a smooth and transverse tined surface, while a deep cleaned surface showed lower rutting depth than a roughly cleaned surface.

Mohammad et al. (2010) quantified the effects of tack coat type, tack coat application rate, surface type and condition (milled versus un-milled) on the interface shear strength using f-sAPT, and an experimental matrix of five tack coat materials applied at three application rates on four surface types in Louisiana. The highest shear strength was obtained at an application rate of 0.155 gal/yd^2 (0.7 l/m^2) for all tack coat types. Although higher application rates may increase interface shear strength, excessive tack coat may migrate into the HMA mat during compaction and service, causing a decrease in the air-void content of the mix. A direct relationship was observed between the existing surface roughness and the interface shear strength. The milled HMA surface thus provided the greatest interface shear strength followed by the PCC surface, existing HMA, and new HMA surface (smooth and unweathered).

High Modulus Asphalt

High modulus asphalt (HiMA) allows rutting reduction in base courses as very stiff asphalt is used in the mixture [based on the French standards for Enrobe' 'a Module E'leve' (EME) (or HiMA) regarding rutting resistance] (Perret et al. 2004). In preparation for the inclusion of HiMA into Swiss standards, three test sections (two HiMA and one reference HMA for base layer), were evaluated at Laboratoire Central des Ponts et Chaussées (LCPC) (France) using f-sAPT at 122°F (50°C). The behavior of the test sections corresponded to LCPC laboratory rutting results and the section designed to have a strong rutting resistance had no rutting in the base layer, confirming that high mastic content can strongly reduce the resistance to rutting.

HiMA is a well-known rutting-resistant solution for high-volume roads in France. Rohde et al. (2008) evaluated HiMA using f-sAPT and verified that the performance of the HiMA was superior to that of a reference HMA mixture produced with conventional binder (pen grade 50/70). The binder type was shown to be vital in the improvement of rutting resistance.

Wojciech et al. (2010) compared conventional HMA base performance with HiMA base performance, focusing on rutting development and using f-sAPT, field tests (FWD and GPR), and laboratory tests (binder content, gradation, air voids, resistance to rutting, stiffness, and fatigue). No fatigue cracking was visible and only slight rutting occurred as a result of subbase compaction.

Aging

Field cores were extracted from eight HMA pavements (two with polymer-modified and six with unmodified binders) at the FHWA's pavement testing facility (from a 1993 FHWA ALF experiment) to evaluate in situ pavement aging in the laboratory (Al-Khateeb et al. 2006). The polymer-modified HMA pavements show comparatively lower aging than the unmodified HMA pavements. For unmodified binders, the pavements with stiffer binder tended to have higher aging indices than those with lower stiffness binders. Pavements with larger nominal maximum aggregate size also experienced higher aging than those with smaller nominal aggregate size. The aging index near the surface [upper 0.3 in. (7 mm)] was four to five times higher than the aging index at a depth of 5.5 in. (140 mm).

Qi et al. (2010) evaluated the fatigue performance of HMA pavements with unmodified and modified binders using f-sAPT in early-aged and accelerated-aged conditions [originating from the TPF-5(019) (Full-Scale Accelerated Performance Testing for Superpave and Structural Validation) experiment]. The aging process decreased the fatigue performance significantly, and the overall ranking of the fatigue performance was mostly the same before and after aging. Where bottom-up fatigue cracking occurred on early-aged HMA, top-down cracking was mostly evident on the aged sections. Dynamic modulus $|E^*|$ data of the in situ HMA before and after f-sAPT indicated that the largest difference in modulus was seen between the upper layers and the bottom layers with the stiffness of the upper layers increasing. The largest increase in mixture stiffness was after more than 5 years of natural exposure, while the accelerated-aging process did not appear to cause a measurable increase in stiffness.

MnROAD (Marasteanu et al. 2008) evaluated the optimum time for applying surface treatments to existing HMA pavement structures. A detailed study on the MnROAD test track pavements included both standard and nontraditional tests on the existing HMA to determine specifically the surface condition of the pavements at different ages. The nontraditional tests included X-Ray Photoelectron Spectroscopy, Scanning Electron Microscopy, Fourier Transform Infrared Spectroscopy, and spectral analysis of the asphalt pavements. Standard Bending Beam Rheometer, Direct Tension Test, DSR, and Semi-Circular Bend Testing were also conducted on the materials. No clear single test was identified in the analysis as suitable for all purposes. The Fourier Transform Infrared Spectroscopy appeared to be the most sensitive to the binder material age with a significant positive correlation with pavement age. The DSR, Bending Beam Rheometer, and Direct Tension Test data analyses were less significant and many times led to contradictory results that could have been affected by the HMA emulsion application rates that were adjusted with the age of the pavement.

Recycled Asphalt Pavement

Hachiya et al. (2006) examined the effect of rejuvenating agents on recycled asphalt pavement (RAP) performance on airport pavement surface courses (Tokyo International Airport). Similar properties were obtained for the RAP made with different rejuvenating agents, although the recycled binder properties varied. The performance of RAP at a 70% recycling rate satisfied the specifications for use as a surface course in airport pavements.

Mohammad et al. (2006) evaluated the effectiveness of using untreated RAP as a base material in place of crushed stone in a soil cement asphalt pavement structure using f-sAPT (Louisiana ALF), FWD, and laboratory characterization. The laboratory tests results indicated similar resilient moduli for RAP and crushed stone, although there was some temperature susceptibility in the RAP. Both the field and laboratory evaluations confirmed that untreated RAP can successfully be used as base course in lieu of the conventional crushed stone base.

The performance of HMA mixes with different percentages of RAP (0, 25, and 40%) was determined using f-sAPT (LAVOC, France) and laboratory testing in relation to stiffness, fatigue cracking, water sensitivity, and permanent deformation (Bueche et al. 2008). No failure was observed in these experiments and the performance for these specific mixes, with and without RAP, was equivalent.

West et al. (2009) evaluated the performance of f-sAPT sections (NCAT) with 20% and 45% RAP, and a control section. All mixes contained the same component aggregates and RAP, while one 20% RAP mixture contained PG 67-22 binder and the other PG 76-22 binder. The 45% RAP mixes contained PG 52-28, PG 67-22, PG 76-22, and PG 76-22, plus 1.5% Sasobit. Overall binder stiffness in the RAP mixes had an impact on field compactability, showing that the 20% RAP mixes compacted easier than the 45% RAP mixes. The RAP test sections performed well in the f-sAPT despite air-voids contents that were not optimal. The data indicate that there does not appear to be a strong case to support the use of softer grade virgin binders for high RAP mixes.

The effectiveness of the use of foam asphalt-stabilized RAP from Full-Depth Reclamation (FAS-FDR) as base material for flexible pavements was evaluated through f-sAPT on four pavements with a conventional granular base and three thicknesses of FAS-FDR (Romanoschi et al. 2004, 2010). The FAS-FDR base performed well under moderate moisture conditions and supports the efficient use of the RAP material contaminated with soil and aggregates. The f-sAPT indicated that 25 mm of FAS-FDR is equivalent to 1 in. (25 mm) of conventional Kansas AB-3 granular base.

Four test sections that included both WMA and high RAP contents (50% RAP) were constructed with a control section at NCAT for evaluating the full-scale structural and fatigue characteristics in the context of M-E analysis (Timm et al. 2011c). Similar strain versus temperature behavior was observed for all sections. None of the experimental sections were statistically different from the control with respect to tensile strain at the lowest reference temperature [50°F (10°C)]. At the highest reference temperature of 109°F (43°C), three distinct groups were formed based on the average strain levels with the control section at the highest strain and the high RAP sections at the lowest strain. The WMA sections were in between these extremes. No adverse effects were visible through utilizing high RAP contents and WMA with respect to strain response relative to the control. These high RAP and WMA sections appeared to carry loads more efficiently and reduce the strain levels at higher temperatures in comparison with the control section. Combination of the temperature-corrected strain responses and laboratory-derived beam fatigue transfer functions indicated that the RAP-WMA section perform best at 68°F (20°C), with approximately 3.6 times more cycles to failure than the control. The fatigue performance estimates were made using laboratory-determined transfer functions combined with strains corrected to the corresponding laboratory temperature.

Warm Mix Asphalt

WMA test sections were constructed at the NCAT Test Track to assess the rutting performance using a chemical emulsion (Prowell et al. 2007). The sections were compacted after being stored in a silo for 17 hours, and the in-place densities were equal to or better than the control HMA surface layers, even when compaction temperatures were reduced by 46°F to 108°F (8°C to 42°C). The two WMA sections and HMA section showed excellent field rutting performance, whereas laboratory rutting susceptibility tests indicated similar performance for the WMA and HMA mixes. Increased moisture damage potential was indicated for the WMA mixes through laboratory tests.

Three WMA and one control HMA section were evaluated on the Ohio f-sAPT facility (Sargand et al. 2008). Early rutting of the WMA section was higher than the control mix, after which the rutting rate was slightly less for the WMA than for the control HMA.

The performance of an HMA control mixture was compared with three WMA mixes in California (chemical foamant, chemical emulsion, and organic wax). The WMA was produced and compacted at approximately 95°F (35°C) lower than the control (Jones et al. 2010). Acceptable compaction was achieved on all WMA mixes. The outcome of f-sAPT indicated that the use of any of the three WMA technologies will not significantly influence rutting performance. Laboratory moisture sensitivity testing indicated that all the WMA mixes were potentially susceptible to moisture damage, although no significant difference in the level of moisture sensitivity between the control mixture and mixtures with additives could be observed. Laboratory fatigue testing indicated that the WMA technologies should not influence fatigue performance.

MnDOT initiated research into WMA to specifically evaluate the performance of WMA in cold climates (MnROAD WMA 2011). As thermal cracking is the predominant distress mode of HMA pavements in Minnesota, studies at the MnROAD facility explore WMA's potential for better low-temperature cracking performance. It is anticipated that reduced oxidation levels at the mix plant should lead to enhanced long-term pavement performance. Six cells were paved with WMA on the MnROAD Mainline, carrying just under one million ESALs per year. The mix is a level 4 Superpave with PG 58-34 binder and 20% RAP from MnROAD millings. A chemical-based additive was used in the WMA production. The HMA mix was produced approximately 50°F (10°C) cooler than normal HMA production. Equal compaction was achieved than on HMA with less effort. The WMA mixes produced a good Tensile Strength Ratio, indicating this mixture is not prone to moisture damage. It is anticipated that the WMA test data will be disseminated to city and county engineers, consultants, contractors, and researchers.

Foam Bitumen

Long et al. (2004) reported on laboratory testing in conjunction with f-sAPT (South Africa) on pavements recycled with foamed bitumen-treated materials, demonstrating that f-sAPT can be enhanced by conducting a comprehensive laboratory testing project in conjunction with the f-sAPT. The testing indicated that the cement provides more strength and shear resistance than the foamed bitumen, while the foamed bitumen provides more flexibility to the mix, requiring careful selection of the foam bitumen and cement contents during design to enhance the strength and shear resistance as well as the flexibility.

Theyse and Long (2004) used the South African HVS to evaluate the performance and identify distress mechanisms of pavements that were recycled in-place and treated with foamed bitumen and emulsified bitumen. Bitumen stabilization with active filler initially increases the resilient modulus of the treated material; however, this increased resilient modulus is reduced through repeated loading to the point where the resilient modulus stabilizes at values associated with unbound materials (referred to as the effective fatigue life). The reduction rate is mainly determined by the trafficking load.

An f-sAPT test (California) on a road rehabilitated using a Full-Depth Reclamation (FDR) process using foamed asphalt (2.5%) and portland cement (1.0%) was used to develop improved mixture and structural design and construction guidelines for FDR of cracked HMA (Theyse et al. 2006). The observed mode of distress differed between favorable conditions in summer and fall and unfavorable conditions in winter and spring, with the distress mode before the onset of winter consisting of gradual rutting of the pavement resulting in a terminal surface rutting with limited fatigue cracking. After the winter, the mode changed to a more rapid rutting rate and base shear failure in certain locations. Extensive fatigue cracking was also evident, but this was probably caused by a localized weak soft base layer. The pavement structure of the HVS test track showed sensitivity to high moisture contents in terms of elastic and plastic response.

An f-sAPT experiment on foam bitumen pavements was conducted in the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to study the effects of foam bitumen on unbound granular materials. Three sections were constructed using foam bitumen contents of 1.2%, 1.4%, and 2.8%, plus a common active filler content of 1.0% cement. Two more pavements were constructed with only cement (1.0%) and only foam bitumen (2.2%) as well as a control section with untreated unbound material. Rutting development under f-sAPT showed that the addition of foam bitumen significantly improved the performance of the materials with 1% cement that were studied in this research, while little difference was observed within the sections stabilized with only foam bitumen and only cement. The existing foam bitumen design methods are overconservative. Vertical compressive strains measured at the top of the subgrade indicated that surface deflection was controlled by the subgrade elastic response (Gonzalez et al. 2009).

MnROAD is developing full depth reclamation (FDR) and cold inplace recycle processes using foamed asphalt with the intention of developing specifications for successful implementation of foamed asphalt recycling techniques in Minnesota (Eller and Olson 2009). Several foamed asphalt cold inplace recycle projects are performing well in Minnesota. MnDOT data showed that the recycled pavement layer develops a relatively uniform strength despite the high variability inherent in most low-volume roads, and that the foamed asphalt forms a cohesive matrix when mixed with the fines from the reclaimed material. It is expected that further study of these projects will add to the knowledge base regarding constructability and performance.

Crumb Rubber

Caltrans uses overlays with DGAC and overlays with ARHM-GG (Harvey et al. 2001; Harvey and Bejarano 2001). The ARHM-GG overlays are typically designed to be half the thickness of DGAC overlays. F-sAPT data indicated that the use of half thickness ARHM-GG overlays is reasonable for reflection cracking. The ARHM-GG overlays had less rutting than the DGAC overlays.

The performance of HMA with crumb rubber-modified binders (AR-HMA) as compared with similar mixes with conventional binder was evaluated under f-sAPT (Louisiana ALF) (Mohammad et al. 2000, 2004). The AR-HMA wearing course mixture showed similar rutting resistance to the conventional wearing course mixture, whereas the AR-HMA base course mixture had better rutting resistance than the conventional base mixture. No visible fatigue cracks were present during the f-sAPT. The pavement layers constructed with crumb rubber-modified binder in the base course could last almost twice as long as the conventional one.

The constructability, laboratory, and field performance of different rubber-modified HMA mixes were compared with a DGAC control mix (Cook et al. 2006). Construction using all three processes (wet, dry, and terminal blend) was successful, and f-sAPT testing (California) indicated that all asphalt-rubber-modified mixes performed at least as well as the conventional DGAC mixture.

Since the 1990s, asphalt rubber has been used in Brazil to delay reflection cracking in overlays (Núñez et al. 2006). An f-sAPT study was carried out by the Federal University of Rio Grande do Sul to quantify reflection cracking evolution in asphalt rubber and HMA overlays. Data suggested that the asphalt rubber overlay was five times more efficient than the HMA overlay in delaying reflection cracking.

Hot Mix Asphalt Aggregate Gradation

In a comparison of rutting and fatigue performance results from WesTrack with the SuperPave volumetric design method (Wen et al. 2003), it was shown that the fine-graded WesTrack HMA pavements performed better than coarse-graded HMA. The fracture energy of work potential theory was found to correlate well with the performance from WesTrack.

Particle size distribution greatly influences the rutting resistance, workability, permeability, and durability of HMA mixes. FDOT (Greene et al. 2011) developed a theoretical approach for evaluation and specification of aggregate gradations with the intent to ensure that the resulting mixes will have sufficient aggregate interlock to resist rutting. A mixture's Dominant Aggregate Size Range (DASR) and the DASR porosity is used to determine the interactive range of particle sizes and whether good contact exists between those particles, with a porosity of greater than 50% differentiating between good and poor performing gradations. The method was validated using f-sAPT.

Porous Hot Mix Asphalt

Open-graded porous asphalt (OGPA) was evaluated at CAPTIF and the outcome compared with a field trial and laboratory evaluation (Alabaster et al. 2008). The trial demonstrated that full-scale manufacture and surfacing construction with epoxy OGPA could be undertaken without significant modification to the plant or operating procedures. Trafficking resulted in early signs of surface abrasion in the control section but not in the epoxy OGPA section. Early life rutting of the epoxy OGPA is not likely to be greater than that of equivalent standard materials. The field trial results confirmed the findings of the f-sAPT test.

Research on the MnROAD test cells evaluating the correlation between tire-pavement-interaction-noise (TPIN) measured with the on-board sound intensity protocol, ESAL, Surface Rating, and age of pavement showed an increase in on-board sound intensity in bituminous segments over time. Individual models were developed for different surface types with no tenable relationship between friction number and TPIN (Khazanovich and Izevbekhai 2008).

Pavement texture is an important parameter in TPIN. As pavements carry traffic load over the years measurable degradation occurs in texture. As the pavement is exposed to environmental and traffic elements, changes occur in ride quality measured by the International Roughness Index (IRI) as well as the Surface Rating.

Thermal Cracking

Al-Qadi et al. (2005) evaluated the measured strain magnitude associated with thermal fatigue through field measurements (Virginia Smart Road) and 3-D FEM that simulates thermal fatigue in flexible pavement. The model simulates a typical interstate pavement design [less than 8 in. (200 mm) HMA]. It showed (as confirmed by the field measurements) that the pavement's response to thermal loading was associated with a very high strain range (maximum value of 350 µm/m). This confirms the hypothesis that the criticality of thermal fatigue arises from the high stress/strain level exhibited in each cycle rather than its frequency.

Hot Mix Asphalt Pavement Maintenance

Zerfas and Mulvaney (2004) evaluated the performance of preventative maintenance conducted on the MnROAD sections three months after application of micro-surfacing. The micro-surfacing did not fill the ruts as well as expected, probably because a metal strike off bar was not used during the scratch coat of the micro-surfacing, in combination with only a single pass of thin maintenance surfacing used on some sections, even though a two pass application was warranted. The primary goal of restoring the ride quality for the traveling public appeared to be met through application of the thin maintenance surfacing, with a 48% improvement in riding quality attained.

Huurman et al. (2008) initiated a project aimed at development of a Lifetime Optimization Tool (LOT) that allows the initiation and progression of HMA raveling to be predicted and the effects of mixture modifications and increasing traffic loads to be analyzed. F-sAPT (the Netherlands) was used to validate the predictions made with the FEM-based meso-mechanics model in the LOT. Data showed that the LOT model predictions were in good agreement with the observed performance and it was possible through application of the LOT to rate the f-sAPT sections' raveling performance. Analysis showed that the aggregate type appeared to be the most important factor controlling raveling.

Fiber Reinforcement of Hot Mix Asphalt

F-sAPT for performance evaluation and validation of HMA mixes (in Romania) stabilized with various fibers is described by Vlad and Andrei (2004). The rutting performance of the

HMA stabilized with various types of fibers is significantly improved in comparison with that of the control mixture without fibers. Rutting development is still affected by temperature.

CONCRETE AND RELATED MATERIALS

General

Rao and Roesler (2004b) evaluated the applicability of Miner's Law for evaluating several concrete fatigue transfer functions using f-sAPT data (California HVS). Responses resulting from trafficking were modeled with FEM over a range of temperature differences. The results indicated that although it is possible to predict the location of the crack, Miner's approach cannot be used to predict the timing or number of load repetitions corresponding to slab cracking.

Strauss et al. (2005) used a continuously reinforced concrete pavement (CRCP) inlay on a steep uphill section of an interstate highway that experienced considerable rutting damage owing to slow-moving heavy vehicles. The HMA was milled and replaced with 7 in. (180 mm) of CRCP inlay in the climbing lane. Although the test section had narrowly spaced transverse cracking prior to testing, no punch-outs could be created using the South African HVS. However, in areas where concrete was substandard, significant punch-outs occurred. Introduction of water into the supporting layers caused loss of bond between the slab and the subbase and a resulting void. Structural failure of the CRCP followed an S-curve, with a high incidence of failure occurring initially (mainly as a result of construction issues) followed by a stable period before the rate of failure increased again.

Load transfer efficiency (LTE) is commonly considered as a measure of joint quality and it plays an important role in rigid pavement evaluation and design. Wadkar et al. (2010, 2011) used data generated from the f-sAPT at the FAA National Airport Pavement Test Facility (NAPTF) to evaluate stress-based LTE [LTE(S)] and deflection-based LTE [LTE(δ)] of rigid pavement airfield joints. LTE(S) values from static loading were 45% lower than moving loads. LTE(δ) was found to be similar when measured under a single-wheel or 4-wheel gear configuration and was lower for stabilized bases compared with joints over a nonstabilized base. Field measured LTE(S) under real moving aircraft gear loading was significantly higher than the 25% value assumed in current thickness design. The f-sAPT analysis provided evidence to the theory that stiffer bases may lead to lower LTEs. LTE(δ) appears not be an indicator of joint quality and structural integrity of the pavement.

Yeh et al. (2011) examined how matched and mismatched joints affect the performance of unbounded concrete overlays under f-sAPT at the FAA NAPTF. The gauges in slabs with matched joints yielded the smallest average daily response. The peak response magnitude was inadequate to explain the timing of crack initiation, and examination of other strain response characteristics (i.e., duration and recovery) may assist in explaining the damage rate. Upon formation of the first crack, the effective modulus drops significantly. No evidence was found to state whether the slabs with matched or mismatched joint will have higher initial moduli, consistent with the behavior of new untrafficked doweled joints. The total joint stiffnesses at mismatched joints were higher than those at matched joints for most cases. This supports the hypothesis that mismatching joints take advantage of the underlying support and thus improve LTE. The benefit of mismatching joints is not as significant when the underlying slab is in good condition.

MnDOT evaluated the use of pervious concrete on porous bases for minimizing storm water intrusion from developments through evaluation on parking lots and through f-sAPT by constructing cells with porous concrete on the low-volume loop of the MnROAD facility (Izevbekhai 2008). Although the understanding of the performance of pervious concrete in northern climates is still rudimentary, the intention is to, through adequately evaluating pervious concrete in this climate, provide long-term performance monitoring through monitoring the changes in porosity and infiltration over time under standard measurable traffic loads, environmental effects, and deicing operation.

Ultra-Thin and Thin Whitetopping

Rajan et al. (2001) identified through f-sAPT (Indiana DOT) that the joint spacing of 47 in. (1.2 m) was sufficient for good performance. Measured longitudinal strains indicated that as the wheel approached a given point in the pavement, the top and bottom of the overlay experienced a tensile and compressive strain respectively that quickly reversed when the wheel was exactly over the point.

Wu et al. (2002) evaluated ultra-thin and thin whitetopping (UTW) repair and rehabilitation techniques using the FHWA ALF. As some UTW panels exhibited corner cracking distress, panel removal and replacement was selected to repair some of the distressed panels. The f-sAPT performance indicated that this panel removal and replacement is an effective repair method for UTW.

Galal et al. (2004a, b) developed models for the mechanistic design of UTW of an HMA and a PCC pavement based on f-sAPT (Indiana DOT). Initial results indicated that the equivalent thickness approach may provide a good prediction for the pavement stresses and strains. Linear-elastic analysis of the pavement stresses and strains suggested that the bond between the UTW and HMA is not uniform. Data from three sequentially placed surface strain gauges confirmed the wave effect in front of the tire and the strain reversal that exists was shown to increase with the number of load applications.

The application of UTW over composite pavements does not have an adequate mechanism to account for analysis of the in situ composite pavement (Newbolds et al. 2005) applied f-sAPT (Indiana DOT) to determine that the equivalent thickness approach to model the existing composite pavement produces reasonable results for this analysis, indicating good agreement between the calculated and measured strains.

De Larrard et al. (2005) showed through f-sAPT (France) that a thin high-performance concrete layer constructible with conventional tools and that the cracking behavior under accelerated loading is acceptable and that no damage was caused to the layer through traffic.

Research on the applicability of UTW using f-sAPT (Changsha, China) focused on the dynamic and static strains to evaluate the characteristics of different pavement structures (Cui et al. 2007). Data showed that the tensile strains are small at both the surface and the bottom of the panel when good bonding exists between the UTW and the underlying HMA layer. 3-D FEM analysis of the sections confirmed the location of maximum tensile stress as the location where cracking initiated in the pavement.

F-sAPT at Kansas State University (Romanoschi et al. 2008) focused on determining the response and the failure mode of four pavement structures: two thin concrete overlay pavements [4- and 6-in. (100- and 150-mm)-thick on top of a 5-in. (125-mm)-thick PCC pavement (PCCP)] and two thin whitetopping pavements [4- and 6-in. (100- and 150-mm)-thick PCC overlays constructed on top of 5 in. (125 mm) HMA]. Three of the four pavements performed well during f-sAPT. The 4 in. (100 mm) TWT pavement developed a crack much earlier than the other three sections. No significant joint faulting was recorded. FEM analysis conducted with all materials modeled as linear-elastic and a perfect bond between the overlays and the supporting layers, showed that the magnitude and shape of computed and measured strains matched well before any f-sAPT loading was applied. All sections experienced loss of support under the joints during trafficking, causing an increase in the maximum longitudinal strains at mid-span, and suggesting that loss of bonding may be attributed to environmental factors. The length of the loss of support can be backcalculated from the strains computed with the FEM.

The structural properties of pavement sections have a significant influence on the strain distribution and maximum strains for UTW constructed over composite pavements (Newbolds and Olek 2009). F-sAPT at the Indiana DOT indicated that the critical HMA strain location is at the top of the HMA layer. Measured strains in the bonded lanes well matched the theoretical values calculated using linear-elastic analysis.

Snyder (2009) evaluated the performance of UTW [3 to 6 in. (75 to 150 mm)] under years of heavy traffic at MnROAD. The observed performance was partly the result of the presence of good support by (and bond with) the underlying HMA layer. Joint layout should avoid placement of longitudinal joints in or near the wheel paths. The incidence of reflective cracking of well-bonded concrete placed over thermal cracks in HMA pavements appears to depend on the relative stiffnesses of the concrete and HMA layers. Reflection cracking is less likely when the HMA thickness is less than double the concrete thickness. Seasonal resilient modulus variations strongly affected load-related strains in the UTW. Reflective cracks generally occurred more quickly in the driving lane than in the passing lane. Observed distresses in the UTW confirmed that bonding of whitetopping to the underlying asphalt is essential for good long-term performance.

Vandenbossche and Barman (2010) observed in f-sAPT (MnROAD) that reflection cracking of UTW is a function of both temperature- and load-related stress, with reflection cracks developing earlier in the driving lane than the passing lane. Increasing the panel size to move the wheel path away from the longitudinal joint had the same effectiveness in decreasing reflection cracking as increasing the thickness of the overlay by 1 in. (25 mm). It was also verified that the occurrence of reflection cracking is a function of the stiffness of the concrete relative to that of the HMA layer with data indicating that reflection cracking will develop in bonded UTW if the relative stiffness of the layers falls below 1.

Ultra-Thin Continuously Reinforced Concrete Pavements

Ultra-thin CRCP (UTCRCP) [also referred to as ultra-thin heavy reinforced high performance concrete (UTHRHPC)] has been used successfully in Europe as a rehabilitation measure on steel bridge decks and reported on at the 5th International CROW [Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek (Center for Regulatory and Research in Soil, Water and the Road and Traffic Engineering)] workshop in Istanbul (2004). The concept has been explored further in South Africa for use as a road strengthening measure by constructing experimental sections of 2 in. (50 mm) UTCRCP directly on top of both natural gravel and cement-treated natural materials.

Kannemeyer et al. (2008) described f-sAPT to test the suitability of a UTCRCP overlay on a flexible pavement near the end of its life. Test sections were constructed using a different combination of support stiffnesses, construction joints in the UTCRCP layer and environment, by adding water. FEM was applied to evaluate the observed behavior numerically. Although high tensile stresses were indicated by the FEM at the bottom of the UTCRCP layer, cracking at this location of high tensile stress was not as prominent as circular surface cracks and thus tensile stress at the surface was used to simulate observed distress. The relative position of the longitudinal steel reinforcement was found not to be important, although placing it closer to the top of the UTCRCP layer reduces compressive stresses, thereby reducing the risk of spalling and the access of surface water. Debonding that occurred between the UTCRCP layer and the support resulting from water entering the pavement led to an increased stress in the UTCRCP layer with the resulting void being detrimental to the performance of the UTCRCP.

CSIRO, University of Pretoria, Gautrans, and the Cement and Concrete Institute in South Africa developed a low-cost version of the UTCRCP technology to be used in upgrading former township roads. It consists of placing a 2 in. (50 mm) layer of concrete reinforced with a 0.2 in. (5.6 mm) diameter steel mesh [grid size 8 in. (200 mm)] on top of the existing road surfacing using labor-intensive methods. F-sAPT on several of these sections showed the technology to be adequate for low-volume traffic applications (e.g., residential streets) with bus traffic. Test sections showed no deterioration after up to 700,000 equivalent 18 kip (80 kN) axles (E80s) of APT traffic, although some curling and warping was evident during the tests (Du Plessis et al. 2009a, b).

Steyn et al. (2011) demonstrated the use of a time-series analysis technique for evaluation of the influence of temperature and climate on the LTE across cracks in UTCRCP under f-sAPT. Analysis indicated that the loaded and unloaded deflections across a crack were better pavement performance predictors than LTE for the UTCRCP. It also indicated that temperature difference over the pavement influences the performance of UTCRCP.

Precast Concrete

Precast concrete slabs offer an important advantage as a pavement rehabilitation option because they can be opened to traffic immediately upon installation, making them attractive for use on heavily traveled highways and airfields where work windows for repairs or reconstruction are very short.

Tayabji et al. (2008) synthesized the results of f-sAPT evaluation of the durability of precast concrete pavements conducted in California, the Netherlands, and France. Analysis indicated that all the precast concrete slabs systems showed potential to adequately resist high traffic volumes.

Kohler et al. (2007, 2008, 2009) described an f-sAPT program in California during which the performance of a number of precast concrete slabs were evaluated. Slabs were instrumented with displacement sensors and with thermocouples and deformations caused by temperature changes measured in the ungrouted and then in the grouted condition before any load was applied to the pavement. Slab corner curl was reduced from a range of ± 0.06 in. (1.5 mm) to ± 0.02 in. (0.5 mm) by grouting the joints and the voids under the slab. LTE increased from 5% to 40% (ungrouted transverse joints) to close to 100% after grouting. F-sAPT indicated that the precast slabs can be safely opened to traffic in the ungrouted condition, so that panels can be installed in consecutive nights rather than completing the entire installation at one time. The expected life of the slab pavements was estimated to be between 140 and 240 million ESALs, equivalent to between 25 and 37 years of service. The failure mechanism was similar to that observed in cast-in-place jointed concrete pavements. Data indicate that doweled jointed plain concrete pavement and precast concrete pavement system pavement of similar thickness may be expected to have similar performance and failure mechanisms.

Nishizawa et al. (2007) evaluated long-term performance of a precast high strength fiber-reinforced concrete panel under f-sAPT (Japan) and compared the data with dynamic 3-D FEM data. Prefabricated panels 39 in. (1.0 m) by 67 in. (1.7 m) by 1.2 in. (30 mm) thick were placed over an existing HMA pavement. It was observed that an unbonded area developed at joints between panels causing weak panel support. Texturing on the bottom face of the panel effectively enhanced the bonding. No serious problems were identified under traffic loads, as long as a sound bonding was provided at the interface between the panels and HMA layer.

Ashtiani et al. (2011) investigated the feasibility and efficiency of using precast concrete panel installation techniques using high density polymer (HDP) foam and flowable fill as leveling materials for runways (Air Force Research Laboratory, Florida). The installation system impact on the performance of the repaired sections was characterized by LTE, joint stiffness, and deformation energy dissipated through the pavement foundation. Three precast concrete repair panels (conventional HDP, deep HDP injection, and flowable fill) were subjected to load applications using an F-15 loadcart. The results indicated significant increases in the deformation energy and considerable loss of joint stiffness with increasing number of load applications when flowable fill was used as leveling material, while precast panels installed with HDP foam performed better. The best performance was shown by the deep injection method.

Cracking of Concrete Slabs

JPCP test sections (California) constructed using fast setting hydraulic cement concrete developed top-down transverse cracks under environmental influences before any f-sAPT traffic was applied to them (Heath and Roesler 2000; Heath et al. 2001; Du Plessis et al. 2002, 2005; Kohler and Roesler 2004). Initial strains were most likely derived from thermal contraction after construction. Strains at the top of the slabs increased significantly after 2 months, whereas the strains in the bottom of the slab remained constant. This increase in the top of the slab was a result of drying shrinkage. The differential strains between the top and bottom of the slab resulted in slab bending stresses that exceeded the concrete strength and caused transverse cracking. The measured and FEM data showed significant curling of the slab corners owing to differential drying shrinkage. Load plus environmental stress analysis showed excessive differential drying shrinkage resulting in the critical failure location being at the corner of the slab, indicating either corner or longitudinal cracking as failure modes.

Evangelista and Roesler (2009) evaluated critical gear positions that produce maximum tensile stresses on the surface of rigid airfield pavements given no initial curling using four individual aircraft gear geometries (dual, dual tandems, and two types of triple dual tandems) and four aircraft types (B-777, A-380, MD-11, and B-747). F-sAPT on rigid pavements at the FAA NAPTF and Airbus PEP showed top-down cracking occurring under certain combined loading and pavement geometry configurations. A 2-dimensional finite-element analysis has shown consideration of the full aircraft gear is necessary if the position and magnitude of top tensile stresses need to be predicted. For the no joint load transfer case the full gears of the A-380 and MD-11 had top to bottom tensile stress ratios of 1.0 and 0.86, respectively. For the 85% LTE cases, the common critical aircraft position was when one gear straddles the adjacent slab at the corner and the other gear is located on the main slab producing the critical top tensile stress. Critical top tensile stresses occurred mostly at the transverse joint for almost all aircraft analyzed, promoting propagation of longitudinal or corner cracks. It was observed that the joint LTE and multiple gear load configuration relative to the slab geometry were the most significant factors affecting the critical top tensile stresses and top and bottom tensile stress ratios.

Dowel Bars

California HVS testing indicated that dowel bar retrofit significantly improved LTE and reduced deflections from loads and environment compared with un-doweled pavements (Harvey et al. 2003; Bian and Harvey 2006; Bian et al. 2006). Primary performance criteria for dowel joints are LTE and vertical deflection of the joints. Larger vertical joint deflections and lower LTE are strongly correlated with increased rate of faulting and roughness development. Three dowels per wheel path were found to have significantly lower LTE than four dowels per wheel path, whereas fiber reinforced polymer (FRP) dowels and grout filled hollow stainless steel dowels had similar performance to epoxy-coated steel dowels.

The use of de-icing salts in cold climates results in significant deterioration of steel dowels. Khazanovich et al. (2006) conducted f-sAPT (Minnesota) on two jointed test pavement specimens that incorporated stainless steel hollow tube dowel and epoxy-coated solid steel dowels. Deflections in the loaded test specimens yielded similar LTE when compared with numerical analyses of the doweled joints, indicating that the Minnesota Accelerated Loading Facility (MinneALF-2) provided good approximation of the in situ behavior of jointed pavements in terms of LTE and differential deflections. Test results illustrated that the LTE for the stainless steel dowel tubes was lower than the LTE for the epoxy-coated dowels and that the stainless steel tubes were capable of long-term performance above 70% LTE (the minimum acceptable LTE value for MnDOT). Based on the f-sAPT results, the stainless steel tubes are capable of providing sufficiently high long-term load transfer efficiency for concrete pavement joints.

Rohne and Burnham (2010) evaluated concrete pavement joint performance and observed a unique distress phenomenon in the transverse joints. It occurred where jointed concrete pavements were constructed on undrained gravel bases and presented through cores with a significant amount of concrete material missing from the middle section of the joint. The area of greatest distress was located just below the saw cut, approximately at mid-depth. From the investigation it was evident that sections with base layers that adequately drained water within the joints performed significantly better. The distress was identified as a likely combination of freeze/thaw damage and erosion resulting from fast-travelling trucks.

Curling of Concrete Slabs

Daiutolo (2008) evaluated curling through f-sAPT at NAPTF to avoid premature corner cracking of slabs in future testing using a single concrete slab with high fly ash content (added to reduce the flexural strength of the concrete) on a rigid support. When slab curl becomes excessive, premature top down cracking is likely to occur when the pavement is subjected to test loading. Keeping the pavement continually wet was found to be an effective procedure at the NAPTF where daily variations in concrete temperatures, and consequently curl, are not as severe in the indoor environment as would be expected outdoors.

Repair of Concrete Slabs

Priddy et al. (2009, 2010) examined nine rapid-setting materials for repair of PCC runway pavements through laboratory characterization and f-sAPT (USACE, Mississippi). Seven of the nine materials demonstrated the ability to sustain aircraft traffic within 3 hours of repair completion. Based on the f-sAPT, a wide variety of rapid setting material types were suitable for rapidly repairing small, full-depth sections of PCC pavement. Full repairs including removal and replacement of subgrade materials followed by placement of a rapid-setting cementitious cap and foam injection were tested comparing repairs (three different foam volumes and a control repair) under normally distributed simulated F-15E aircraft traffic. Foam-injected repairs provided more passes before failure and were generally less expensive and time-consuming than pourable foam repairs. Foam-backfilled repairs were not cost-effective. The use of debris backfill eliminated the requirement for compaction compared with the clay gravel repair, reducing the overall repair time, and also provided similar pass-to-failure numbers as compared with traditional backfill materials such as clay gravel. The foam injection methods were deemed more suitable in scenarios where quantities of high-quality debris backfill, similar to that used, are not available.

Airfields

Brill and Guo (2009) evaluated concrete slab performance under 4-wheel and 6-wheel simulated f-sAPT (FAA NAPTF) airplane loads using visual surveys, crack mapping, destructive and nondestructive testing, and observed top-down and bottom-up cracks. Analysis indicated that the bottom-up cracking initiated soon after starting trafficking at full load and only later progressed to the surface. The presence of a significant percentage of top-down longitudinal and transverse cracks in airfield pavements has implications for the future development of FAA rigid pavement design procedures as this failure mode is currently not considered. The evaluation demonstrated the importance of frequent and detailed visual observations of pavements.

GRANULAR MATERIALS

Rutting

Rasoulian et al. (2000) compared rutting performance under f-sAPT (Louisiana ALF) of an inverted (stone interlayer) pavement consisting of a 4 in. (102 mm) layer of stone base on top of 6 in. (152 mm) of in-place cement-stabilized base, with a control section consisting of 8.5 in. (216 mm) of cement-stabilized base layer on top of prepared subgrade. Both sections were surfaced with a 4 in. (99 mm) layer of HMA. The inverted design experienced only 16% of the reflective cracking experienced by the control section and had almost five times the performance life of the control section. The structural capacity, ride characteristics, and rutting of the inverted pavement was similar to that of the control pavement.

Bejarano (2004) conducted an analysis of rutting in unbound aggregate base, subbase, and subgrade layers using f-sAPT (California HVS). Pavement responses were related to rutting using a recursive rutting model that considers stress level, material condition, and number of load applications. The calculated model coefficients were dependent on stress level and material condition. Evaluation of the subgrade strain criteria indicated that subgrade plastic deformation was prevented.

Odermatt et al. (2004) examined the differences in rutting development of crushed and uncrushed layers subjected to f-sAPT (Sweden HVS) and laboratory tests. Indications are that for natural gravel the f-sAPT may cause less rutting than in real roads owing to better side support than that achieved near the edge of the roads, while the same natural gravel rutted more than the crushed rock in tri-axial laboratory tests because of improved aggregate interlock in the crushed rock samples. In f-sAPT crushed rock showed greater rutting, probably the result of insufficient compaction. The results indicated that the required degree of compaction for crushed materials in pavements may need to be increased.

Korkiala-Tanttu (2004) studied the rutting development of unbound materials in low-volume roads in Finland, focusing on the effects of different subgrades, layer thicknesses, water contents, and pavement materials. It was shown that FEM can model the stress distribution of a pavement reliably and that the selected material model drastically affects the stress distribution and therefore rutting development in the model. A conventional linear-elastic material model is not adequate for this modeling as tensile stresses may develop in the modeled unbound pavement layers, causing unrealistic stress concentrations and erroneous rutting development data. Use of the Mohr–Coulomb material model was effective for unbound materials and the results of the f-sAPT could be modeled reliably. Data confirmed the dependency of rutting development on pavement geometry, material stiffness, and stresses.

Wu et al. (2009a) developed a simplified numerical model for simulation of rutting development in granular base materials based on a conventional elastic-plastic model with linear strain hardening with empirical simplifications. The model directly uses different secant moduli for loading and unloading behavior and predicts permanent strain for each load repetition. The secant modulus is a function of load repetition, stress level, temperature, moisture content, and other material properties. FEM analyses simulating f-sAPT data (Louisiana ALF) showed satisfactory results using the model.

Hussain et al. (2011) investigated the geology, nature of fines, effect on the rutting development, and changes in gradation and moisture of unbound flexible pavement greywacke base course materials using f-sAPT at CAPTIF. Three similar sourced greywacke aggregate materials with different gradations were subjected to repeated load cycles during which it was found that the geologic properties of the aggregate and minerals present in the aggregate are important to improve the understanding of the layer performance. The aggregate geology showed that the three materials were geologically sound and therefore the rutting cannot be affected by the coarse aggregate fractions. The factor affecting the rutting behavior was the gradation. Materials with a Talbot's gradation value constant of 0.5 performed well, while a value of 0.37 indicated poor performance.

Structural Analysis

Kim and Tutumluer (2005, 2006) analyzed the effects of principle stress rotations resulting from moving wheel loads on rutting development in granular pavement granular layers, causing varying vertical, horizontal, and shear stresses on pavements. Laboratory testing was combined with f-sAPT on low-strength subgrade flexible pavement test sections at

NAPTF. By using stationary repeated wheel loading and moving wheel loading-type models, granular subbase rutting development was predicted. As these models do not account for stress rotations, neither the magnitudes nor the rutting accumulation rates could be predicted accurately. The prediction models were adapted through a simple laboratory-based approach (catering for different load pulse durations) for the actual NAPTF loading stress history. After the corrections were made, both the coal combustion products (CCPs) and VCP models showed improved predictions, with the variable confining pressure (VCP) model giving better predictions of the rutting magnitude and accumulation rate.

The flexible pavement test sections at NAPTF were trafficked while load-induced vertical subgrade stress were monitored, using a simulated six-wheel Boeing 777 landing gear and a simulated four-wheel Boeing 747 gear simultaneously until the sections failed (Gopalakrishnan and Thompson 2006b). Analysis of the vertical subgrade stresses shows that the subgrade stresses induced by the B777 and B747 did not differ significantly.

González et al. (2007) validated 3-D FEM models using data collected at CAPTIF demonstrating the feasibility of using advanced structural analysis tools such as 3D-FEM software and nonlinear-elastic models for the analysis of thinly surfaced pavement structures. Analysis results showed an accurate prediction of the behavior of the modeled pavement.

Wu et al. (2007) evaluated three f-sAPT sections (Louisiana ALF) with different base and subbase materials and observed that the cement-treated subbase possessed higher load-induced structural capacity than a lime-treated subbase (higher resilient modulus, greater load carrying capability, and lower rutting). Heavier loads caused a higher percent increase of vertical stresses on top of the subgrade than on top of the subbase and thus subgrade rutting owing to overloaded conditions should be less in real applications. Rutting analysis using MEPDG software generally overestimated the rutting development for the f-sAPT sections, and a simple rutting prediction model was proposed, relating flexible pavement rutting development to in situ surface deflections.

Kim and Tutumluer (2008) investigated the effect of multiple wheel loading scenarios on granular airport pavement structures. The traditional approach of single wheel load response superposition may not be adequate to analyze pavements subjected to such multiple wheel load cases, as these complex loading conditions require advanced pavement layered solutions to realistically consider nonliner behavior of the materials. Analysis of data from NAPTF yielded two peaks directly under the wheels for thinner sections, leading to the highest subgrade vertical deflections and computed stresses. As the granular base gets substantially thicker the two peaks merge toward the middle of the two wheels. Critical pavement responses and locations in the pavement structure were computed and shown to be significantly influenced by multiple wheel loads from single-, tandem-, and tridem-axle-type wheel arrangements and configurations. Load spreading and nonlinear modulus distributions of the granular base layers were found to significantly impact the maximum surface deflections, whereas the subgrade vertical stresses and deflections were considerably influenced by both loading and the base layer thickness.

Xu et al. (2008) presented data from a comparison of the performance of various semi-rigid (cement-stabilized crushed stone) base asphalt pavements and flexible (graded crushed stone) base HMA pavements obtained through f-sAPT in China. Although the flexible base structure was thicker than the semi-rigid base structure, it was less temperature-sensitive than similar HMA base pavements and less prone to rutting compared with the flexible base pavement structure. No surface cracks were observed during the tests. The deflection index was shown to be related to the bearing capacity of the full pavement structures and not affected by deterioration of the bearing capacity of individual pavement layers.

Chen and Abu-Farsakh (2010) evaluated the in situ performance of raw blended calcium sulfate (BCS), stabilized BCS, stabilized RAP, and stabilized soil as base–subbase materials through cyclic plate load tests and f-sAPT (Louisiana ALF). It was shown that the use of a conventional formula calculating the equivalent elastic modulus with only the individual layer thickness considered is not a good performance indicator for multilayer systems and proposed a modified formula using a position factor on the basis of Boussinesq stress distributions in soils. Successful application of the model to the tested pavement sections demonstrated that the position factor can turn the conventional equivalent elastic modulus into a good performance indicator. The f-sAPT measured rutting depth was higher than the cyclic plate load rutting depth (three to seven times larger) indicating that the rolling wheel load is much more damaging than the cyclic plate load. This phenomenon is probably linked to principal stress rotation, friction-induced tangential forces, and lateral wander during the f-sAPT. The extension–compression–extension multiple stress path-type test with principal stress rotation causes much higher rutting than the single compression stress path-type test with no principal stress rotation, whereas lateral wander most likely decreases the stability of unbound and weakly bound granular base materials. The ground granulated blast furnace slag (GGBFS)-stabilized BCS tested as a superior base material compared with the conventional stone base, while the two fly ash-stabilized RAP base materials did not perform well compared with the other sections.

A considerable amount of research focused on the development of a repeated load triaxial (RLT) test procedure for evaluating natural and marginal unbound base and subbase materials (Jameson et al. 2010). A major Australian research project was undertaken comparing the rutting of four granular bases under f-sAPT with various laboratory performance tests. Base layers were tested for rutting resistance in a RLT test using constant confining pressure based on the Austroads test method, the Department for Transport, Energy and Infrastructure South Australia test method, and the Transit New Zealand (NZ) method. The crushed hornfels rutted much more rapidly than the crushed rhyolite, and there was concern that there was no indication from any of the existing processes of this behavior with both the Department for Transport, Energy and Infrastructure and Transit NZ methods indicating allowable performance for all four tested granular bases. The findings questioned the usefulness of the permanent strains measured in the Austroads test method, as the RLT permanent strain results did not identify the hornfels as a material unsuitable for base course because of its low resistance to lateral shoving. The inability of the permanent strain test to identify the poor performance of the hornfels supports the contention that incorporation of aggregate interlock under shear stress reversals occurring under rolling wheel loads is vital for accurate rutting models. The laboratory wheel tracking results correlated well with the f-sAPT data indicating that the wheel tracking test is probably the most suitable test for the characterization of the rutting potential of unbound bases under thin bitumen-treated surfacings.

Navneet et al. (2010) described f-sAPT using the NAPTF and B777 and B747 loading on four flexible pavement test sections incorporating 5 in. (125 mm) HMA surfacings on top of a crushed stone base, varying thickness subbases, and a silty clay subgrade. A fixed wander pattern was used. Results showed nonlinear behavior (stress-softening) of the subgrade with a final surface rutting of approximately 3 in. (75 mm). Post-traffic tests showed no signs of shear failure or rutting in the subgrade, with most of the rutting contributed by the subbase layer.

Stabilization and Modification of Soils

Romanoschi et al. (2006) found cement and lime to be the most effective stabilizers for a nonsulfate-bearing clayey soil tested in f-sAPT (Kansas), resulting in the lowest vertical compressive stresses at the top of the unbound clayey subgrade. Fly ash-treated subgrade soil generated higher vertical compressive stresses at the top of the subgrade as well as higher rutting depths than both the cement- and lime-treated subgrade soils.

De Vos et al. (2007) reported on the development of guidelines for an M-E pavement design model for cement-stabilized sand bases in Mozambique based on f-sAPT, scaled APT, and laboratory tests. The maximum tensile stress at the bottom of these bases for both the scaled APT and f-sAPT were calculated and related using the 4th Power Law (exponent of 4.2). Similar performance was observed between the laboratory and field pavements in terms of distress and number of axle load applications. The dynamic deflection of the pavement progressively increased relative to the initial value and the PSPA stiffness decreased simultaneously with the stiffness ratio reaching 50% of the initial value when significant distress manifested.

Since 2005, pavement design in Denmark has been based on a three-tiered design guideline (1st level—design according to a catalog, 2nd level—automated M-E design, and 3rd level—based on pavement performance simulation and incremental-recursive methodology) (Busch 2008). The recursive-incremental models for cement-stabilized materials are based on f-sAPT data. These models should still be verified using in-service pavement performance to improve reliability, although they currently do provide credible outputs.

Yeo (2008) investigated parameters influencing the performance of unbound and cemented pavements with thin bitumen-treated surfacings to improve the understanding of fatigue performance and derive fatigue-consistent-terms relationships for cemented materials based on f-sAPT and laboratory strength, modulus, and fatigue characteristics. The most appropriate means to assess the fatigue performance was backcalculation of material moduli from FWD data. Measured fatigue life was compared with initial tensile strain in the cemented layer to develop a relationship for each material. Based on the f-sAPT and laboratory data, a load damage exponent of between 5 and 8 was calculated that does not support the current Austroads load damage exponent of 12.

Wu et al. (2009b) evaluated BCS as a pavement base layer using laboratory and f-sAPT, compared with a crushed stone base. FWD results indicated higher in situ stiffness for the BCS/GGBFS layer than for an HMA layer, which resulted in an inverted pavement structure for one test section. It was found that the multilayer elastic theory overpredicted the vertical compressive stresses developed in an unbound aggregate layer and underpredicted the stresses for other bounded base materials, because the elastic theory predicted an unrealistic tension zone inside the base layer. Most of the rutting occurred in the base layers. The 15% fly ash-stabilized BCS base performed better than the crushed stone base, probably because of a shear flow failure related to water susceptibility. It was demonstrated that the thickness of the HMA layer can be reduced significantly by using a GGBFS-stabilized BCS base instead of a crushed stone base.

In the current MEPDG, cement-stabilized layers are assumed to have no contribution to the total rutting development of the pavement. Wu et al. (2011) developed a unified rutting model to simulate the rutting behavior of a cement-stabilized pavement layer. The model was used successfully in a FEM analysis to evaluate the performance of f-sAPT sections, and a shift factor of 1.13 was obtained from calibration to account for the condition differences between laboratory permanent deformation tests and pavements under traffic load. It was demonstrated that rutting contribution from cement-stabilized layers may account for a considerable portion of surface rutting.

Geogrids

Dawson et al. (2004) assessed the potential of geosynthetics as unsealed road reinforcements in 16 test sections incorporating a variety of geosynthetics, natural reinforcement, or no reinforcement subjected to f-sAPT (United Kingdom), evaluating the influence of nonlinearity, material variability, pavement cross section, and other variables. There was strong evidence that the fundamental mechanism of reinforcement in unsealed pavements is the result of the prevention of outward shear on the subgrade. The commonly adopted 4th Power Law load equivalency approach was not valid for the pavements studied.

Perkins and Cortez (2004) found that similar rankings in terms of rutting were observed between f-sAPT and laboratory box test sections under a cyclic load for geosynthetic-reinforced pavement materials. The magnitude of reinforcement benefit (defined as Traffic Benefit Ratio) was generally lower in the f-sAPT sections (located at USACE–CRREL) compared with the box test results. A marked difference was observed in the stress and strain response measures for the f-sAPT data, including dynamic vertical stress on the top of the subgrade, dynamic vertical strain in the base and subgrade, dynamic transverse strain in the bottom of the base and top of the subgrade, and permanent vertical strain in the base and subgrade layers. Differences between reinforced sections were apparent but not significant.

Reyes and Kohler (2006) described the performance of three geogrid-reinforced sections and a control section under f-sAPT in Colombia. Failure was observed owing to fatigue on the HMA mixture instead of under compression on the subgrade with best performance evident when the geogrid is placed in the granular base. As long as the geogrid reinforcement is placed in the upper layers, the fatigue performance improved.

Nine pavement test sections were evaluated using f-sAPT to determine the effectiveness of geogrid in secondary flexible pavements (Al-Qadi et al. 2008a, b). All sections were constructed over a weak subgrade in Illinois. The geogrid was effective in reducing the horizontal shear deformation of the aggregate layer, and thus the effectiveness of the geogrid for aggregate base layers with thicknesses ranging from 8 to 18 in. (200 to 457 mm) was demonstrated. The optimal geogrid location (for a thin aggregate layer) was found to be at the unbound aggregate-subgrade interface, while another geogrid at the subgrade-base layer interface may be needed for stability of thicker base layers.

Numerical modeling and f-sAPT of geogrid base-reinforced pavement systems (located in Illinois) indicated the stiffening effect around geogrid reinforcement and its effect on improved pavement performance (Kwon and Tutumluer 2009). A stiffened zone was observed around the geogrid reinforcement, primarily the result of the aggregate particle interlock in the apertures of the geogrid, as shown through Discrete Element Modeling. The stiffened zone is located 100 to 150 mm above and below the geogrid. F-sAPT results demonstrated the performance benefits of using geogrids especially in the reduced horizontal base course movements.

PAVEMENT STRUCTURES AND SYSTEMS

The validity of material response models is important for reliable evaluation of the structural pavement condition. An instrumented field test pavement was established on top of a sandy material sufficiently thick to be considered a half space to verify predicted pavement response (Hildebrand 2003). FWD data on each layer provided elastic layer moduli, while in situ sensors registered stress and strain in three orthogonal directions. Pavement response was predicted using a wide range of response methods from a simple Boussinesq model to FEM and compared with f-sAPT data (Denmark). The comparison showed good agreement for strain response, whereas the agreement was more questionable for stress. It was concluded that although field verification is difficult, it is possible to construct an approximately homogeneous and isotropic test site suitable for pavement response verification.

Blab (2004) evaluated an existing semi-rigid pavement in Poland using laboratory testing and f-sAPT program. Design calculations indicated that the thickness of the cement-stabilized base layers could be reduced and still fulfill the performance requirements for the type of design, as the f-sAPT on the in-service pavement showed no fatigue damage at the end of the tests.

Lenngren (2004) evaluated eight f-sAPT sections (located in Sweden) to determine the influence of moisture on a pavement where mica is present in the granular materials. Results showed that the influence of moisture did affect the deterioration of the road, whereas the presence of mica had limited influence under dry conditions. There was no clear evidence in the test data that mica contents of between 6% and 34% affected the rutting during dry conditions. The top of subgrade strain rutting criterion proved to be a very good single indicator of rutting development, but could not predict initial rut. The evaluation demonstrated the importance of a good understanding of subbase and subgrade properties in pavement evaluation.

Martin (2005) evaluated refining existing road deterioration models for Australian sealed granular pavements based on f-sAPT data. Different rutting rates were observed for seemingly similar pavements with a crushed concrete blend showing 3 to 10 times as much rutting as a high-quality granular material. Relative performance factors and load damage equivalence (LDE) factors were developed based on the f-sAPT data for rutting and roughness development based on statistically significant relationships using variables for load cycles, pavement layer strengths, and wheel load. The rutting LDE of the marginal material was lower than the 4th Power Law and higher than the 4th Power Law for high-quality materials, while the roughness LDE was close to the 4th Power Law for the marginal material and significantly higher than the 4th Power Law for high-quality materials. The use of the relatively short [39 ft (12 m)] ALF test pavement to derive relative roughness estimates appears to be inappropriate.

Steyn (2008) developed guidelines for design of long-life pavements based on the experiences from mobile f-sAPT (South African HVS) on pavements that performed well after more than 30 years in the field. The basic principles of pavement engineering are fundamental to these designs, and it is thus important to keep the pavement layers dry, support the various pavement layers well, ensure good strength-balance between the various layers in the pavement, select appropriate aggregate gradations to prevent rutting and use bituminous binders that do not age quickly to prevent fatigue.

MnROAD performed maintenance treatments in 2003 to improve the riding quality before reconstruction could be scheduled and used the opportunity to evaluate different maintenance treatments and their effectiveness (Worel and Clyne 2009). The slurry seals used for the maintenance performed well in terms of restoring riding quality and also performed adequately for filling existing ruts. However, the maintenance treatments studied were not successful in preventing reflective cracking from underlying transverse or top down cracks.

Martin (2010) derived an equation for estimating load-related road wear for uncracked, reasonable, quality-sealed unbound pavements (in Australia) using a component cumulative roughness deterioration equation based on observational and experimental data. The equation differs from the HDM4 incremental component roughness model and provides varying estimates of road wear as affected by traffic load, pavement strength, and environmental conditions.

Parmeggiani (2009) developed an alternative approach for the design of pavements with infinite structural life and low maintenance using an M-E design method. The concept of long-life pavements defines structures that provide strong, thick HMA layers having the required structural capacity to provide long service lives under very heavy traffic loading conditions with only periodic surface renewal required during this period. The individual HMA layers are typically designed to resist specific modes of distress to maintain the critical strains in the HMA layers and subgrade below critical threshold levels. Although traditional perpetual pavements rely on the total HMA layer thickness together with the fatigue-resistant lower HMA layer to provide the required HMA fatigue life, the alternative approach entails provision of enhanced support to the HMA layers to comply with the same strain threshold levels in the HMA and subgrades as specified for the present perpetual pavements. The approach envisages complete elimination of HMA fatigue cracking and subgrade deformation and subsequent design of the HMA layer to maximize its rutting resistance without compromising durability.

F-sAPT experiments (Australia) on maintenance treatments were used to refine relative performance factors for cumulative rutting and roughness on uncracked and cracked seals as the performance of these seals are prone to the influence of surface water (Martin 2010).

Observational data were obtained for the development of road deterioration models from LTM, LTPP maintenance, and f-sAPT in Australia. The developed road development models are applicable for the gradual rutting, cracking, and roughness deterioration of sealed granular pavements under standard in-service conditions (Martin and Choummanivong 2010).

An f-sAPT evaluation of the behavior of full-depth HMA pavements designed using perpetual pavement concepts was conducted in Binzhou, Shandong Province, China (Timm et al. 2011b). PerRoad was used for probabilistic analysis comparison of the pavement responses and it was confirmed that the tensile HMA strains were sufficiently low to prevent bottom-up fatigue, except where full-slip conditions existed between layers. The importance of good bonds between layers was evident from the behavior of the sections.

MISCELLANEOUS TOPICS

Bridges

F-sAPT on an HMA-surfaced steel bridge indicated that HMA behavior depends on proper choices of material as well as the type of waterproof bonding layer used (Shao et al. 2004). Emphasis should be placed on ensuring that the HMA is nondeformable and stable at high temperatures.

F-sAPT research into orthotropic steel deck bridge deck behavior with HMA overlays combined with FEM analysis indicated that the assumptions upon which current design techniques are based proved not to be true (Huurman et al. 2004). FEM calculations showed that strain gradients are strongly influenced by the bridge deck geometry, loading, and the behavior of both the membrane interface and the surfacing material. A constitutive model was developed that is capable of simulating the f-sAPT observed behavior of the surfacing asphalt (Liu et al. 2006).

Jun et al. (2008) used circular f-sAPT and FEM to analyze rutting development of steel bridge decks surfaced with HMA. The HMA was modeled using a creep model in the FEM, and the data compared well to the measured tertiary rutting development on the f-sAPT test.

Coal Combustion Product

Tu et al. (2006) evaluated the performance of pavements constructed with recycled CCPs using f-sAPT. The performance of the CCP pavements was promising as potential substitutes for conventional base materials. All the pavement sections exhibited similar surface distress performance, with the CCP base/subbase mixes outperforming the control mix. Both CCP sections showed lower deformation, higher overall stiffness, and lower traffic-induced stress in the subgrade than the conventional pavement.

Edge Damage

Olson and Roberson (2003) described research on joint sealing activities at MnROAD where pavement sections were instrumented to provide automated measurements of pavement moisture and drainage changes resulting from varying climate conditions. The research included measuring changes in edge drain outflow and base moisture content in response to precipitation events. Data were collected before and after sealing of edge joints on concrete sections. Although no significant difference was observed in the volume drained between the control section and test section before sealing the joint on the test section, a significant reduction in the volume drained from the test section was observed after sealing the edge joints. It was shown that sealing the concrete pavement edge joint with a bituminous shoulder reduced the total volume of water entering the pavement system by as much as 85%.

Saleh (2006) evaluated the factors affecting the development of pavement edge failure in New Zealand using 3-D FEM incorporating shoulder width, shoulder stiffness, axle load, tire pressure and pavement thickness, and compared the output with multilayer analysis and f-sAPT. Shoulder stiffness was shown to be a significant factor affecting the lateral support and therefore pavement response in the outer wheel path with axle load being a significant factor for all responses affecting the edge damage. The use of stiff shoulders should thus help to reduce edge damage of the pavement.

Large Stone Hot Mix Asphalt

The applicability of using large stone HMA for airport pavements surface courses was evaluated using static loading, FWD tests, and f-sAPT (Tsubokawa et al. 2004). The research has shown that application of large stone HMA in the surface and binder courses of airport pavements may reduce rutting by up to 20% compared with conventional HMA. Backcalculation analysis showed the elastic modulus of large stone HMA to be 1.2 to 1.3 times larger than that of conventional HMA.

Low-Volume Roads

Snyder (2008b) evaluated the design and performance of the five original MnROAD low-volume road concrete sections. Application of MEPDG provided performance estimates that closely matched observed pavement roughness trends, although it still underpredicted project performance by about 23%. The low-volume road test cells show ride deterioration rates suggesting that the design parameters that were varied on these test cells (i.e., load transfer, drainage, foundation preparation, etc.) appear to be more significant for thinner concrete pavements. Initial road roughness on concrete pavements has a tremendous impact on the pavement life and thus the performance life may be extended significantly by simply improving construction quality. Panel cracking was mainly attributed to localized loss of support, with panel length changes not strongly linked to changes in panel cracking. The use of dowels and a thick sand-filled layer effectively reduced joint faulting.

Pay Factors

A procedure was developed to establish pay factors for HMA construction using performance models for fatigue and rutting based on a combination of M-E analyses, Strategic Highway Research Program (SHRP) developed laboratory test data, and f-sAPT data (Popescu and Monismith 2007). The models use means and variances rather than the Percent Within Limits (PWL) approach, with the influence of asphalt content, air-void content, and aggregate gradation considered for rutting, and air-void content, asphalt content, and asphalt concrete thickness considered for fatigue. The relative performance of the as-constructed HMA is determined based on its measured mean property and a reasonable standard deviation. Relative performance is defined as the ratio of off-target traffic (ESALs) to target or design traffic (ESALs). Only agency cost consequences delaying or accelerating the time to the next rehabilitation are included in the cost model. The methodology provides for a full bonus for superior construction and a full penalty for inferior construction. The approach emphasizes the importance of adhering to the target value for a specific pavement characteristic and maintaining uniformity to achieve or exceed the desired performance level.

Pipes

MnDOT conducted research on the performance of large diameter corrugated polyethylene pipes installed under highway vehicle loading to improve analysis and design methods for these conditions (McGrath 2005). Corrugated polyethylene pipe sections were installed on the MnROAD low-volume loop and instrumented. It was observed that the pipe has performed well with minimal load response under moderate live loads for a period of 3.5 years without any deterioration. Because of the high coefficient of thermal expansion and the temperature extremes in the Minnesota environment, the pipe expansion and contraction caused the pavement surface to become rough and crack the pavement over the pipes. The research lead to a recommendation that a minimum cover depth of 2 ft (600 mm) or 0.5 times the nominal pipe diameter is required.

Gaz de France developed a concept of a thin trench filled with a self-placing concrete in which polyethylene gas pipes are directly placed (Balay et al. 2008). The concept was evaluated in the LCPC f-sAPT facility through the construction of five trenches with depths ranging between 16 and 32 in. (400 and 800 mm), as well as a conventional trench, which indicated that the concept performed very well with no deterioration or damage of the structures or the adjacent pavement. Strain measurements indicated that the bending tensile loads created by rolling loads remained well below the fatigue damage limits foreseeable with this material, while no subsidence of the trenches was observed.

Farrag (2011) performed laboratory and f-sAPT on several excavatable controlled low-strength material (CLSM) mixtures in accordance with the standard specifications of several state highway agencies to evaluate its use as an alternative to traditional soil backfill materials around buried pipes. Lower settlement was observed than for other compacted soil backfills; however, CLSM with high fly ash had lower frost-heave and thawing resistance than soils. The long-term compressive strength of the CLSM with fly ash increased over time and exceeded the limits used for manual excavation. Construction quality control of CLSM is a challenge and mostly limited to characterizing the flowability of the mix.

Prefabricated Bituminous Slabs

The Dutch Ministry of Public Works and Water Management anticipates the need for future mobility evaluating by a prefabricated road surface (Van Dommelen et al. 2004). Four designs proposed by the private sector were constructed and evaluated for functional performance on pilot test sections, while structural evaluation was conducted using the LinTrack APT facility, supported by FEM and laboratory material research. This mix of research approaches provided sufficient evidence to justify decisions about wider scale application without the need for 10 to 15 years of test section evaluation. The evaluations showed that the modular road surface is cost-effective and viable relative to traditional road construction and maintenance efforts. The project demonstrated the benefits of the combination of f-sAPT, in-service test sections, modeling, and laboratory material testing to enable responsible decisions about the implementation of innovative pavement concepts.

Recycled Concrete

Reflection cracking is a common distress in asphalt overlays on cracked concrete pavements. Rubblization, which can minimize reflection cracks, has been used as an efficient rehabilitation method for aged concrete pavements in the United States. Garg et al. (2007) conducted f-sAPT on three rubblized rigid airport pavements overlaid with 5 in. (127 mm) of HMA at the NAPTF. MRC (rubblized concrete on conventional base) was observed to suffer severe structural distress, while MRG (rubblized concrete on grade) suffered severe structural deterioration toward the end of trafficking although it retained sufficient structural capacity to support the applied load. MRS (rubblized concrete over econocrete base) accumulated significant rutting and shear flow in the asphalt layer but did not appear to suffer severe structural deterioration (MRS is the most common of pavement structures encountered on commercial airports in the United States). The analyses indicated that the current design assumptions are overly conservative for the conditions evaluated. The structural performance of MRS suggests that rubblized concrete pavements with HMA overlay are a viable option for commercial airports.

Road User Charges

Martin (2010) used data obtained from f-sAPT research to develop a model for implementation of varying heavy vehicle road user charges on Australia’s arterial roads. An equation for estimating load-related road wear was derived for uncracked, sealed, unbound pavements typical of Australia’s sealed road network using a cumulative roughness deterioration equation based on observational and experimental data for the gradual deterioration phase of sealed granular pavement life. This equation gave varying estimates of load wear with changes to the traffic load, pavement strength, and the environmental coefficient, and was also found to give different estimates of load wear than that provided by an equation based on the HDM4 incremental component roughness deterioration model.

Snow-Melting Systems

Embedding snow-melting equipment in airport HMA layers is considered an effective way of avoiding disruption from extreme weather events. Hachiya et al. (2008) evaluated the performance of two types of snow-melting equipment: a warm water heating pipe system and an electric heating wire system. Pavements were trafficked in f-sAPT fashion using a wheel configuration identical to that of a B747 aircraft. Pavement surface deflection under the aircraft loading was slightly higher when the snow-melting system was present; however, there is no clear difference arising from the type of snow-melting system and its embedded depth. The rutting development was similar with and without either of the two snow-melting systems present. 3-D FEM analysis demonstrated that the stress imposed on the heating unit when aircraft loading is applied to the pavement is much less than its strength, and it was thus concluded that snow-melting systems could be successfully introduced into airport asphalt pavements.

Pavement Markings

Choubane et al. (2006b) evaluated the viability of testing the deterioration of raised pavement markers using f-sAPT

(Florida HVS). This option allowed for the controlled application of realistic wheel loads to the installed markers, simulating long-term, in-service loading conditions. Four types of markers were evaluated and the outcome provided a relative rating between the durability of the four markers and the amount of traffic applied to the markers. Correlation to field measurements was beyond the scope of the project.

CHAPTER SUMMARY

This chapter focuses on behavior and performance of specific pavement layer materials evaluated using f-sAPT. The major focus of the chapter is on HMA materials. The questionnaire trend indicating that f-sAPT focuses on materials used closer to the surface was confirmed through the evaluation of the published literature. Apart from the major emphasis on HMA rutting, a developing trend is the evaluation of environmentally sensitive materials such as WMA and RAP, as well as the focus on pavement life extension through application of HMA overlays and various types of thin concrete overlays. Although some f-sAPT on granular materials is still being conducted, the applications are limited. A number of miscellaneous unique applications of f-sAPT were also discussed, including the testing of pipes in trenches, snow melting systems, and the use of f-sAPT data to assist in calculating road user charges and pay factors. Although the focus of this section is on the evaluation of specific materials in specific layers, most of the research incorporates the effects of the supporting layers into the pavement response analyses. The volume of research still being performed on the analysis of specific material response models indicates the importance of this work to ensure that appropriate models are developed for use on pavement design methods.

CHAPTER FOUR

VEHICLE–PAVEMENT–ENVIRONMENT INTERACTION

INTRODUCTION

This chapter provides detailed findings on specific interactions between the loading device and the pavement structure with a focus on the linkages to real traffic loading, incorporating the effects of load equivalence, tire types, real-life environmental effects, etc. F-sAPT aims to evaluate pavement sections under a range of loading and environmental conditions to improve the knowledge of the potential performance of the pavement layers and structure under a full range of operational conditions. Using this philosophy it is standard f-sAPT practice to select a range of vehicular loading conditions (i.e., load levels and tire inflation pressures) as well as environmental conditions (i.e., temperatures and moisture conditions) for different tests and obtain the response of the pavement under the specific selected conditions. The outputs of these tests are combined to develop a model of pavement response under expected field conditions.

Twenty respondents indicated that environmental aspects such as noise and dust are not applicable to f-sAPT, although seven respondents do include evaluation of the effects of road noise in their f-sAPT. The majority of respondents related their f-sAPT data to pavement temperature and ambient air temperature (Figure 46). Most respondents control the pavement and ambient temperature during tests, with moisture control being a secondary parameter that is controlled or monitored (Figure 47).

LOAD PARAMETERS

Increased Load Levels

Alabaster et al. (2004a, b) compared the potential impact of increasing the standard legal limit for a dual tired axle of 8.2 tons to 10 and 12 tons using the CAPTIF f-sAPT facility and thin pavements containing a strong dry subgrade. Data indicated that the use of subgrade strain is a poor predictor of pavement life as the basecourse aggregates significantly influenced rutting resistance. Using Vertical Surface Deformation (VSD) proved to be the most useful measure for monitoring pavement wear with 60 kN wheel loads resulting in nearly twice the VSD obtained with the 40 kN wheel load in all the pavement segments. The VSD data were modeled using a power law relationship and exponents varied between 2 and 9, depending on the pavement-type and end-of-pavement-life definition. The analysis illustrated that weaker sections in the road network that are adequate at the lower legal axle load may fail quickly under the higher legal axle load.

Tire Contact Stress Effects

De Beer et al. (2004) demonstrated the effect of tire load and inflation pressure on the shape of the tire–pavement contact stress pattern and potential implications for f-sAPT response analysis. High edge stresses develop at high tire loads (referred to as m-shape distributions). Maximum vertical contact stresses appear to be as much as twice the inflation pressure (at extremely high levels of loading). For normal loading conditions the maximum vertical stress exceeds the inflation pressure by approximately 30%. Results also show that the length of the tire contact patch increases with increased loading, whereas the tire width remains constant. Quantification of the horizontal interface shear forces (or stresses) between the tire and the surface of the road could assist in the understanding of the horizontal stress regime in the tire patch of a moving tire on a coarse surface. Lateral and longitudinal stresses could be as high as 36 psi (250 kPa) and 24 psi (165 kPa), respectively.

Park et al. (2005) compared predicted pavement response from 3-D FEM and layered elastic programs with the objective of establishing guidelines on a better approximation of pavement response parameters for pavement design and evaluation purposes. Tire–pavement contact stress data obtained from f-sAPT tests were used to predict pavement response. The horizontal strain at the bottom of the asphalt layer, compressive strain at the top of the subgrade, and the principal stresses at different depths were predicted. The decimated 3-D tire contact stresses gave computed tire loads similar to the original measured data. Incorporation of the 3-D tire contact stresses mainly influenced the pavement responses in the surface layer.

Various researchers evaluated the pavement responses of typical pavement structures under the combined actions of variable wheel loads and tire pressures using multilayer linear-elastic theory to estimate the pavement responses under uniform constant stress and actual contact stress distributions obtained from f-sAPT-based SIM measurements (Prozzi and Luo 2005; Machemehl et al. 2005; Wang and Machemehl 2006a, b). Statistical analysis found that tire inflation pressure was significantly related to tensile strains at the bottom

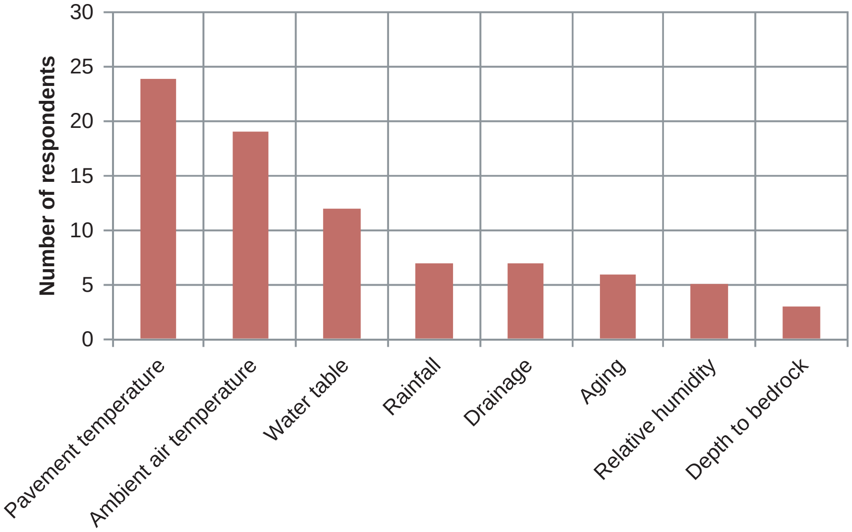

FIGURE 46 Environmental data to which f-sAPT data are related during analysis.

of the HMA layer, and stresses near the pavement surface for both the thick and thin pavement structures. However, tire pressure effects on vertical strain at the top of the subgrade were minor, especially in the thick pavement.

Steyn (2009a) reported on the effect of nonuniform tire–pavement contact stresses as measured through application of two distinct types of tire–pavement contact stresses onto the HMA pavement using a HVS. The rutting response of the pavement mirrored the contact stress shapes, indicating the direct effect that the tire–pavement stress has on rutting development in HMA layers.

Ozawa et al. (2010) derived closed form governing equations with the assumption that a rectangular load moves at a constant speed on a surface of a pavement system composed of Voigt-model-type layers using Fourier transforms to derive theoretical solutions. The theoretical results indicated that pavement response decreases in magnitude with increasing speed of the moving load. For the same speed of the moving load, a decrease was observed in the pavement response magnitude with increasing damping ratio of the materials. The effect of material density was found to be insignificant to the pavement responses.

Wide-Base Tires

Various researchers evaluated the status of wide-base tire technology specifically regarding its effects on pavement response (Elseifi et al. 2005; Timm and Priest 2006; Yeo and

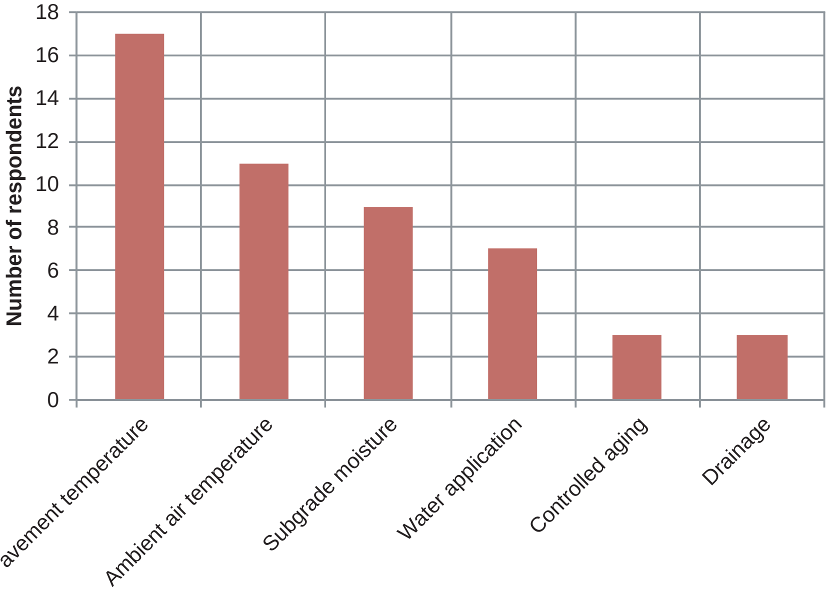

FIGURE 47 Environmental parameters controlled during f-sAPT.

Sharp 2006, 2007; Al-Qadi and Elseifi 2007; Dessouky et al. 2007; Wang and Al-Qadi 2008; Yeo et al. 2008; Greene et al. 2010; Wang and Morian 2010; Xue and Weaver 2011). Tire widths can be divided into three groups. The first group is traditional tires used as dual sets on trucks, the second group is the first generation of wide-base tires (385/65R22.5 and 425/65R22.5), and the third group is the second generation wide-base tires (445/50R22.5 and 455/55R22.5). The second generation of wide-base tires provides substantial benefits in fuel efficiency, hauling capacity, tire cost and repair, ride, comfort, and vehicle stability (Al-Qadi and Elseifi 2007). The first generations of wide-base tires were found to cause a significant increase in pavement damage compared with dual tires. Results indicated that both dual and second generation wide-base tire configurations produced similar pavement responses at the bottom of 6.7-in. (170-mm)-thick HMA, which indicates that both tire assemblies would produce similar fatigue damage. Both tire configurations also produced equal vertical stress on top of the subgrade, which indicates that the secondary rutting performance of both tire configurations would be the same. Studies also supported the notion that layered elastic theory (LET) may not be used to compare pavement response with different loading configurations as it assumes a uniform pressure distribution that is only a function of the load and a circular contact area while improvements in the second generation wide-base tires cannot be quantified using this simple method. Up to six times greater rutting and roughness damage were observed on thin HMA pavements when using first generation wide-based tires compared with dual tires, while damage resulting from second generation wide-based tires was less severe than 385/65R22.5 tires. For thick pavements and primary roads the overall effect of the second generation of wide-base tires is expected to be equivalent to dual-tire assemblies, in that the frequency of top-down cracking in the wheel path is clearly reduced. Given the relatively thick HMA layer used in these pavement classes, the probability of fatigue failure is usually low. By increasing the tire contact area, pavement damage is generally decreased.

Aircraft Tire Loading

It appears that more airfield-related work has been conducted since the previous synthesis. This may be linked to the initiation of testing using facilities with dedicated f-sAPT devices for airfield testing (i.e., NAPTF and WES). The new facility at Toulouse–Blagnac airport in France (Fabre et al. 2009) is another example of current developments of these facilities. Differences in tire and bogey configuration and tire loads necessitate a focused evaluation of these facilities.

The NAPTF was constructed to generate f-sAPT data to study the performance of airport pavements subjected to complex gear loading configurations of new generation aircraft. Comparative effects of four- and six-wheel aircraft gear loads can be evaluated and failure criteria developed for mechanistic-based airport pavement design procedures. The first construction cycle consisted of three rigid pavement test items and six flexible pavement test items, while the second construction cycle consisted of a rigid pavement test strip, a free-standing test slab, and three rigid pavement test items. The third construction cycle consisted of four flexible pavement test items. Test data from the first tests involving Boeing 777 and Boeing 747 loading gears were reported by various researchers (Garg and Marsey 2004; Hayhoe 2004; Hayhoe and Garg 2006; Gopalakrishnan and Thompson 2006a, b). FWD and HWD evaluation of the pavements before and during trafficking indicated that, among the deflections and the Deflection Basin Parameters considered, the deflection ratio (D1/D3) showed the strongest correlation with the number of load repetitions to reach functional rutting failure. Results from the f-sAPT have been incorporated in the FAA layered elastic flexible airport pavement thickness design procedure and for establishing new alpha factors for the California Bearing Ratio airport pavement thickness design procedure.

Kim and Tutumluer (2005) presented findings on predicted performance and field validations of granular base/subbase layer permanent deformation models using the NAPTF f-sAPT facility combined with a comprehensive set of repeated load triaxial tests. Both constant and variable confining pressure conditions were evaluated on a granular base and subbase material. A comparison of measured and predicted rutting indicated that a good match for the measured rutting magnitudes and the accumulation rates could only be achieved when the magnitudes and variations of stress states in the granular layers, number of load applications, gear load wander patterns, previous loading stress history effects, loading rate effects, and principal stress rotation effects owing to moving wheel loads were properly accounted for in the laboratory testing and permanent deformation model development.

Load repetition factors (Alpha factors) were calculated for NAPTF test data through a least squares quadratic curve fit procedure for four- and six-wheel configurations. Alpha factors at 10,000 coverages were compared with the International Civil Aviation Organization standard for computing Aircraft Classification Number, showing consistent relationships with the existing alpha factor of 0.825 for four-wheel gears. However, the six-wheel alpha factor at 10,000 coverages should be changed from 0.788 to a value approximately equal to the interim value of 0.72 (Hayhoe 2006).

Improvements in the Department of Defense’s flexible pavement design procedure put a renewed emphasis on the design and construction of contingency pavements prompting concerns regarding the design and evaluation of thin HMA pavements with minimum HMA thickness requirements. Bell (2008) evaluated the effects of operating cargo and fighter aircraft on representative thin HMA pavements using a C-17 and an F-15E tire in an f-sAPT evaluation. The principle failure mechanisms included rutting, polished aggregate, and surface cracking, with most of the failure gradually appearing in the subgrade. The outcome indicated that the Department of Defense's minimum HMA thickness criterion was more than adequate with sections trafficked to an equivalent of a C-17 aircraft movement on an airfield every 3 days for 20 years or six movements of an F-15E aircraft on an airfield every day for 20 years.

Leahy et al. (2008) evaluated the use of M-E analyses to predict the performance of the air-side HMA pavements at the New Doha International Airport. Data from the RSST-CH, AASHTO T-320, and mechanistic pavement analyses were used to calculate the expected rutting performance. These rutting depth estimation procedures were developed during the WesTrack f-sAPT program. Results suggest that the proposed mixture design should provide adequate rutting resistance and that the overall pavement thickness is adequate.

The concentrated effects of high tire pressure in the surface layers of the pavement structure, specifically on HMA surfaces at elevated temperatures, are being evaluated by the FAA to develop HMA mixes that can withstand these aggressive loading conditions (APWGM proceedings 2009).

Load Equivalence Factor Development

Load equivalence factors (LEFs) represent the ratio of the number of repetitions of any axle load and configuration to the number of applications of the standard 80-kN single-axle load necessary to cause a specified reduction in serviceability. The ratio between the AASHTO LEF for any two-axle loads of the same configuration is thought to be approximated by the 4th power law. When dealing with f-sAPT, it should be appreciated that there exists a difference between f-sAPT and in-service performance not only because of load differences but also because of the effects of the environment, age, and traffic mix. Most of the references on development of LEFs based on f-sAPT indicated concern about the range of values and the effect of various pavement and material parameters on the actual value for specific cases.

Dawson (2008) found that the use of the 4th Power Law cannot be recommended for predicting rutting development as a function of the number of load applications and the load magnitude for many low-volume pavements in different climates. Further, if the behavior of pavement materials is well understood, it makes power law response unlikely as materials often have a steady-state response at lower stress levels. Real pavement response cannot be modeled using the power relationship as there often appears to be a threshold stress above which large deformations result rapidly that cannot be related to the responses at lower stress levels. It is found internationally that even in controlled experiments the power law exponent varies widely as a function of material properties and pavement layer structure.

Chen and Shiah (2001) compared data from two test roads with f-sAPT data to evaluate the effect of heavy traffic loading on pavement distress. Based on Present Serviceability Index loss, a power law exponent of 8 existed for the ALF, in contrast to the 4th Power Law in full-scale test roads. This could explain why pavements tested by the ALF failed much faster. Critical loads appeared to be present for pavements tested by the ALF with pavements tested beyond the critical load failing predominantly because of traffic loading. The rut-based LEFs for the full-scale test road were closely correlated with AASHTO equivalencies, while the rut-based ALF LEF is much higher, which may be attributed to the slower speed at which the ALF operates. Crack-based LEFs were closely correlated, most probably because the terminal level of 20% cracking is reached after the terminal levels for rutting and serviceability are reached.

Chen et al. (2004) conducted a study to validate and improve the VESYS 5 pavement performance model using f-sAPT results, as well as AASHO data in the calibration. Close agreement was found among the predictions from VESYS 5, ABAQUS, and field rutting measurements from the f-sAPT results. Overload damage relationships were subsequently generated from the calibrated VESYS 5 model. The AASHO 4th Power Law relationship was shown to be valid for Pavement Serviceability Index as a pavement performance measure but not for rutting, where power values between 1.5 and 2 were found to be more appropriate. It appears as if load equivalency factors for thicker pavements do not follow the 4th Power Law.

Yeo et al. (2004, 2006) evaluated the effects of increased axle loads on the performance of thin-surfaced unbound granular pavements. The results of f-sAPT showed the lower quality material to experience much higher deformation and roughness progression compared with the high-quality materials. Load damage exponents (LDEs) were derived for each test pavement based on load cycles to equivalent surface rutting. These values ranged between 2.0 and 4.4 depending on the material quality.

Chen et al. (2006) calculated LDEs as a function of structural number, load cycles, and load levels for f-sAPT data on pavement structures with four subgrade types and three moisture conditions originating from USACE-CRREL. These effects were determined in terms of LDEs as a function of structural numbers, cycles of load, and load levels. Four test pavements had LDEs greater than 7.8, while three other pavements had LDEs greater than 4. The high LDEs were attributed to low structural capacity (structural numbers ranged between 1 and 2.6) of the test pavements. The 4th power rule may thus underestimate rutting damage for weak pavement structures. It was also observed that, based on available data, the LDE increased for an AASHTO classification of A-2-4 and A-4 soils with increasing moisture content.

Chen et al. (2008) used a data mining technique to compute rut-based LDEs through analysis of data from seven tests conducted using the CRREL HVS and one test from the Texas MLS. A rutting prediction equation using wheel load, load repetitions, and pavement structural number was developed and the LDEs computed. They were found to decrease with increasing structural number values, demonstrating that overload has a more pronounced effect on the rutting development of weaker pavements than stronger pavements.

Guler and Madanat (2011) developed a hazard rate function with data from the AASHO road test, showing that the damage exponent for fatigue crack initiation is significantly higher than the power typically assumed. Studies on marginal cost pricing typically rely on the assumption that the marginal cost prices should be based on axle loads raised to the power of 4. This power is appropriate if the agency bases its maintenance and rehabilitation decisions on serviceability. However, if the agency uses cracking as a basis, the power should be between 8 and 8.5. Erroneous selection of the load damage exponent (too low in this case) would lead to subsidies of heavier axle vehicles by the lighter ones.

Long-Term Monitoring

Various LTM studies are conducted outside the U.S. SHRP LTPP program. It has often been stated that ideally the data obtained from f-sAPT should be calibrated for real traffic and environment through LTM data. Of the respondents to the questionnaire, 36% indicated that they incorporate LTPP/LTM data in some form in their f-sAPT analyses. No explicit references focusing on this aspect could be identified. This may be attributed to the long-term nature of LTM data collection and the duration of time required before adequate data have been collected to analyze and publish.

Jones et al. (2004) developed a protocol to standardize the methodology used for establishing and monitoring LTM sections in conjunction with APT sections. The protocol focuses on issues such as the justification for the LTM sections, sustainable funding, section location layout and marking, data collection and instrument installation, laboratory and field testing requirements, and monitoring standards. A monitoring plan is discussed together with reporting criteria. Typical data requirements include visual assessments, profile measurements, density and moisture measurements, DCP logs, general environmental data, and deflection data. A dedicated traffic monitoring plan is also required.

F-sAPT Load Modes

The load mode employed during f-sAPT affects the outcome of the specific test. In this section, specific attention is given to the direction, wander, speed, and temperature effects from various f-sAPT devices.

Uni- and Bi-directional Loading

Instability or near-surface rutting of HMA surfacings is a costly form of distress. Novak et al. (2004) evaluated the nature of instability rutting observed under the HVS and specifically the response of various mixtures to rutting under one-way and two-way directional loading conditions. It was demonstrated that there are differences in rutting depth progression between these two modes of operation. A reversal of shear stress pattern occurs in two-way directional loading not seen in one-way directional loading. Although transverse shear stress patterns have no stress reversal (and thus do not differ between one-way and two-way directional loading), longitudinal shear stress patterns do differ between one-way and two-way directional loading. The lack of shear stress pattern reversal (one-way loading) produces greater strain in a visco-elastic material, even with a greater relaxation time compared with one with shear pattern reversal and less relaxation time (two-way loading). Instability rutting is manifested through lateral deformation in the transverse plane. The observed degree of rutting between one-way and two-way HVS directional loading suggest that nontransverse stresses play a role in instability rutting propagation.

A realistic f-sAPT simulation of actual in-service loading is essential to obtain accurate pavement responses. Uni-directional loading without any wheel wander is generally used in rutting evaluation using the HVS. Although this loading configuration is thought to be more efficient, its effectiveness and appropriateness to simulate actual in-service truck loading remains unclear. Choubane et al. (2004) evaluated the different possible loading combinations for f-sAPT using an HVS with the intent of determining a more realistic APT simulation of actual in-service loading. When wheel wander was not considered, the rutting developed approximately 65% faster in the uni-directional than in the bi-directional mode. However, when the wheel wander was not considered, the uni-directional mode appeared to place considerable wearing forces on both the tire and the pavement with as much as 25% of the tread depth worn away at localized locations on the tire. Each of the various wander increments considered affected the tire–pavement contact differently across the test track width when wheel wander was considered. The findings illustrated the importance of using wheel wander for more realistic and meaningful results in rutting testing.

Wheel Wander

FDOT evaluated various loading conditions under an f-sAPT device and found that when wheel wander was not considered, significantly faster rutting development was observed in the uni-directional than in the bi-directional loading mode. When wheel wander was not considered, considerable stresses were placed on both the tire and the pavement. The tire tread pattern had an impact on the pavement deformation patterns with uni-directional loading forming a pattern on the surfacing matching the general tire tread pattern, both under channelized and wandering traffic (Tia et al. 2003).

Garcia and Thompson (2008) evaluated the effect of loading speed on longitudinal and transverse tensile strain pulses measured in a HMA section of the University of Illinois ATLAS facility. The speed of loading was between 1.9 and 10 mph (3 and 16 km/h) and it is known that frequency significantly influences HMA performance. For realistic evaluations it is necessary to simulate the real loading frequency. The CalME relationship for estimating vertical stress pulse durations was successfully used to estimate the pulse durations in the f-sAPT, and it was found that the transverse strain pulse durations were about three times those in the longitudinal direction. Subsequently, the transverse tensile strains were approximately 1.5 times greater than those in the longitudinal direction and the transverse pulse was also more sensitive to the lateral position of the moving load. If considerable moving load wander is expected, the longitudinal strain pulse should be considered the most critical, because the probability that the transverse strain pulse is greater is low, and vice versa for channelized conditions.

F-sAPT using HVS to evaluate rutting performance of different HMA mixtures are typically conducted at elevated temperatures and with channelized traffic, although actual highway traffic always has a certain amount of wander. Understanding the effect of traffic wander on rutting performance of HMA under HVS loading has been evaluated using FEM of rutting development on a flexible pavement (Wu and Harvey 2008). An elasto-plastic constitutive model based on a bounding surface concept was developed to describe plastic deformation of HMA under shearing. During calibration of the model with RSST-CH test data it was found that the model can describe the accumulation of plastic strain of HMA in RSST-CH tests with high accuracy. A FEM analysis was used to simulate rutting development in flexible pavements with HMA surfacing. The effect of traffic wander on rutting performance was evaluated by comparing simulations of a HVS rutting test under both wandering and channelized traffic. The FEM simulation results were found to agree very well with typical observations under the HVS. Discrepancies between the two can be explained by the lack of plastic volumetric compression in the material model, and the actual values of the calculated total rutting were found to agree very well with measured data from HVS tests. Allowing HVS traffic to wander decreases the amount of total rutting consistently by approximately 56% (for the structure analyzed) and it is recommended that channelized traffic should be used for conducting HVS tests because it allows the same qualitative answer to be obtained much faster.

Speed

Garg and Hayhoe (2001) described asphalt strain data measured at the bottom of a 5-in. (125-mm)-thick HMA surface layer obtained at a range of speeds [0.2, 0.3, 0.5, 0.7, 1.4, 3.4, and 5 mph (0.3, 0.5, 0.8, 1.1, 2.2, 5.4, and 7.9 km/h)], with dual-wheel configurations at wheel loads of 24, 30, and 36 kip (106.8, 133.5, and 160.2 kN) and tire pressures of 200 psi (1 378 kPa) at the NAPTF. The HMA was located on top of a stabilized base. Measurements were made at asphalt temperatures of 52°F (11.1°C) and 72°F (22.2°C). Significant permanent deformations were found in the measurements, and the strains varied strongly with temperature and test speed (between 300 and 2,000 microstrains). Slower load application resulted in reduced asphalt stiffness, and increases in the amount of viscous flow and total strain within the HMA mix. Powell (2008a) described a new method of characterizing traffic (load-temperature spectra) used for weighting traffic as a function of pavement temperature. Axle loads are banded in accordance with high temperatures in the performance grading system for binders and a weight factor is developed for each band, reflecting increased rutting potential at higher temperatures. A distinct model is developed for various laboratory tests to predict field performance at an empirically determined single pavement age resulting from the application of banded, weighted traffic. Finally, a time-dependent shift factor is developed to change the model output to predict rutting performance at all other ages. Powell (2008b) applied the model when comparing rutting performance findings from HVS tests with similar findings from NCAT. A direct comparison of the NCAT and HVS data, using the load-temperature spectra method, showed generally good agreement between the different experiments with each pass on the NCAT track equivalent to 1.1 HVS wheel passes. The reduced speed of the HVS load wheel [6.2 mph (10 km/h) versus 43.5 mph (70 km/h) for the NCAT trucks] supports the finding.

Robbins and Timm (2008) evaluated methods to improve pavement response accuracy through quantification of the effects of vehicle speed and pavement temperatures on pavement response. Increasing the rate of loading (vehicle speed) caused a substantial reduction in strain levels with strain rate reduction being more sensitive to vehicle speeds at warmer temperatures. The tensile strain at the bottom of the HMA layer was found to be proportional to the natural logarithm of the vehicle speed, with the mid-depth pavement temperature correlating best with the induced tensile strain. Increasing the mid-depth temperature resulted in exponential elevations in the tensile strain induced. Regression equations were developed for the pavement test section to predict strains for various temperatures and speeds, enabling a comparison to a laboratory threshold level of 100 με. It indicated that the critical mid-depth pavement temperature for vehicle speeds of 87 mph (104 km/h) or less was approximately 79°F (26°C). The application of f-sAPT is sometimes deemed limited as factors such as the loading speed are not widely reproduced. Traffic speed on real roads is higher [generally 50 mph (80 km/h)] than that used to perform f-sAPT [less than 7.5 mph (12 km/h)] and owing to the visco-elasticity of HMA mixes, fatigue cracks appear quite rapidly in f-sAPT because of low speeds. To apply f-sAPT results on HMA to real roads, a formulation to estimate the influence of loading speed is required. Theisen et al. (2009) developed a method to do this by employing visco-elasticity theory and Schapery's work potential theory using experimental data from a HVS traffic simulator. Adaptation of Schapery's work potential theory formulation was developed and calibrated using experimental data and the effect of loading speed was estimated to speeds ranging from 2.5 to 50 mph (4 to 80 km/h). This showed results qualitatively similar to those observed in real roads.

F-sAPT devices accelerate pavement distress by applying high axle loads at high loading frequency, while the effects of high axle loads are generally computed using load factors. However, linear traffic simulators apply loads to pavements at very low speeds [generally lower than 6 mph (10 km/h)], which accelerate pavement degradation, especially on thick HMA layers. Núñez et al. (2008) developed a simplified approach to apply f-sAPT results to real pavements where trucks apply loads at speeds ten times higher than the f-sAPT device. Using Van der Poel's nomograph, the HMA binder stiffness moduli corresponding to both loading times may be estimated. Once the HMA binder stiffness moduli at both loading speeds are estimated, appropriate models can be used to estimate the corresponding HMA mixture stiffness moduli. The tensile strains at the bottom of the HMA layer may be computed. Finally, the HMA mixture fatigue life may be estimated using appropriate transfer functions. It was shown that reducing the loading speed from 50 mph (80 km/h) (trucks) to 5 mph (8 km/h) (f-sAPT) can accelerate fatigue cracking by 1.86 times. The distress acceleration resulting from high axle loads must be taken into account using load equivalence factors. A 36 kip (160 kN) axle load applied by the f-sAPT device is equivalent to 18.2 equivalent single-axle loads (using AASHTO load factors). Therefore the combined effect of high axle loads and low loading speed results in a global acceleration factor of approximately 34, and the HMA layer fatigue life, when submitted to real-time loading, may be computed as:

$N_{\text{real traffic}}$ = Loading speed × Load equivalence factor × Number of f-sAPT load applications.

Evaluation of a test on an instrumented f-sAPT section at the German Federal Highway Research Institute [Bundesanstalt für Straßenwesen (BASt)] (Rabe 2008) provides information on the basic mechanical behavior of a representative selection of pavements of different strength constructed with different materials. It was observed that vehicle speed has a decisive influence on the stiffness of HMA layers evaluated and therefore on the stress/strain level inside both the HMA and unbound materials.

ENVIRONMENTAL PARAMETERS

Temperature

Low temperature cracking is the main distress in HMA pavements in the northern United States and Canada. Li et al. (2004) described the evaluation of three HMA mixes used in the MnROAD facility under crack mouth opening displacement control using Semi-Circular Bend specimens obtained from Superpave Gyratory Compactor cylindrical samples. The results showed that neither the binder type nor the specimen location were significant for the stiffness calculated as the slope of the load-displacement curve, whereas the binder type was significant for the fracture toughness and fracture energy.

The Ministry of Transport Quebec (MTQ) and LCPC undertook a project with the objective of optimizing their frost-thaw pavement design method (Savard et al. 2004). Four test sections were constructed, representing an HMA base and a cement-treated base. The thermally un-insulated sections were designed to obtain damage within three years, while the insulated sections disassociate the effect of traffic from the thaw period loss of bearing capacity. A good correlation was obtained between the in situ f-sAPT and laboratory tests as well as the direct and indirect load strain measurements at the bottom of the pavements. FWD data showed a smaller variation in the thaw period subgrade modulus than the quasi-static tests, while the performance prediction models were validated against the measured deformation.

Kubo et al. (2006) and Kawakami and Kubo (2008) evaluated the urban heat island effect caused by street pavement temperatures and measures to decrease the effect through cool pavements that reflect solar radiation and retain water within the pavement materials. F-sAPT of the pavement structure was performed to evaluate the durability of the mixture-type heat-shield pavement. Temperature monitoring showed that the water retention pavements and the heat shield pavements reduced their surface temperatures by up to 68°F (20°C). Measured rutting was lower than that of drainage and dense-graded pavements, as the HMA temperature was suppressed because of the technology incorporated into the HMA design. Limited cracking occurred during trafficking and the in situ permeability remained good. The project proved that the mixture-type heat-shield pavement, when applied to actual roadways, is durable enough to withstand typical traffic loads for the application.

Marasteanu et al. (2007) reported on a pooled fund study on low temperature cracking in HMA pavements in the northern part of the United States and Canada. The predominant failure mode observed on HMA in these areas is cracking as a result of high thermal stresses developing at low temperatures. Both traditional and novel experimental protocols and analyses were applied to a set of laboratory prepared and field samples obtained from pavements with well-documented performance to determine the best options for improving low temperature fracture resistance of HMA pavements. Tests used included creep, strength for asphalt binders and mixtures, disk compact tension test, single-edge notched beam test, and semicircular bend test. The coefficients of thermal contraction of HMA samples were measured using dilatometric measurements and discrete fracture and damage tools utilized to model crack initiation and propagation in the pavement systems. FEM and the TCMODEL were used to predict performance of the laboratory samples and compare it to the field performance data.

Robbins and Timm (2008) evaluated the temperature effects of a perpetual pavement at NCAT. Temperature probes captured the full temperature profile of the structure. A general increase in strain resulted from increasing pavement temperatures, while the mid-depth pavement temperature correlated the best with the induced tensile strain. Increasing the mid-depth temperature resulted in drastic elevations in the tensile strain induced.

Control and management of the temperature of a HMA layer in a f-sAPT test section is important to ensure that correct inferences are drawn from the response of the layer during testing (Steyn and Denneman 2008). The effect of temperature on the loading conditions of the test (specifically through the changes in tire inflation pressure and resultant contact stresses), as well as during the measurement of pavement response parameters is important. When conducting temperature-controlled f-sAPT, actual field conditions should be incorporated into the planning of the loading conditions, HMA layer condition, and test plan to ensure that outputs are applicable to the desired application.

Velasquez et al. (2008) developed regression models to predict flexible pavement temperature profiles based on measured values for air temperature, humidity, wind speed, and calculated solar radiation at the MnROAD facility. Binder type did not affect the prediction of the maximum and minimum pavement temperature strongly. Verification of the models with a finite difference heat transfer program and data from five locations in the United States indicated that the predicted temperatures of the numerical model agreed reasonably well with the predictions from both maximum and minimum temperature regression models. Wind speed was an important factor, especially at shallow depths.

Herb et al. (2009) analyzed the HMA pavement temperature from MnROAD data and conducted simulations using a 1-dimensional finite difference heat transfer model, characterizing the diurnal and seasonal changes in pavement temperature. Information was obtained on temperature gradients inside HMA layers that assist in the characterization and analysis of temperature-related phenomena in the HMA sections.

AASHTO M 323 indicates that a blending chart should be used to determine either how much RAP can be added or which virgin binder to use when working with high RAP contents. For this process, the critical temperatures of the recovered RAP binder need to be determined. Tran et al. (2010) presented a new approach of using predictive models to backcalculate the critical temperatures of the blended binder from mixture properties, based on HMA mixtures with virgin binder and aggregate materials sampled during construction at NCAT. The Hirsch model had the tendency to underestimate the binder G* at higher test temperatures [70°F and 115°F (21.1°C and 46.1°C)]. However, the Hirsch model was calibrated based on the E* data measured using the laboratory prepared mixtures, and the mixtures used in this valuation were plant-produced. Both the un-aged and Rolling Thin Film Oven Test-aged binder physical properties are required to determine the binder critical high temperature. The Hirsch model then needs to be calibrated to backcalculate the un-aged binder physical properties. For the RAP mixture design, the binder critical high temperature can be determined solely based on the Rolling Thin Film Oven Test-aged binder physical properties. Evaluating the model showed that the procedure could be used to backcalculate the binder critical high temperature. The Hirsch model may however need to be calibrated for local materials to reduce the backcalculation errors. Leiva-Villacorta and Timm (2011) validated theoretical strain-temperature curves developed with LET with f-sAPT measured strain-temperature relationships from NCAT using LET. The results confirmed that relationships between predicted strains and mid-depth temperature can be expressed with an exponential function. Comparing different structural sections confirmed that thicker sections had lower strain levels, while mixes with stiffer binder grades had lower strain levels. Relatively soft mixes were found to be more thermally susceptible. Final analysis indicated that in the some cases LET typically overestimated pavement response at intermediate to high temperatures and underestimated it at low to intermediate temperatures.

HMA cooling rates provide important information that can help with planning operations and field decisions made during construction. MultiCool is a program that predicts cooling rates in an HMA mat during construction based on information related to start time of the paving operation, environmental conditions, existing surface, and mixture specifications. Vargas-Nordcbeck and Timm (2011) validated the cooling rates calculated by MultiCool for nonconventional mixes such as WMA, mixtures containing high percentages of RAP, and mixtures containing modified and alternative binders based on NCAT data. No evidence was found that the difference between the measured and predicted cooling curves over the entire pavement structure exceeded the 50°F (10°C) tolerance allowed. Factors such as mixture temperature, RAP content, binder type, and pavement lift were shown to have a significant effect on model fit. No need exists to adjust the existing cooling curve model in MultiCool for the nonconventional mixtures.

Moisture

Caltrans required inclusion of a 3 in. (75 mm) layer of asphalt-treated permeable base (ATPB) between the HMA and aggregate base layers of all new flexible pavements with the purpose of intercepting water entering the pavement resulting from high permeability, and transport it away from the pavement before it reaches the unbound materials. Bejarano et al. (2003, 2004a, b, c) summarized results from a study using f-sAPT to evaluate the performance of drained and undrained flexible pavements under wet (saturated base) conditions. A drained structure is a pavement section that contains an ATPB layer between the HMA and the aggregate base, whereas an undrained structure does not contain an ATPB layer. It was observed that the ATPB placed between the HMA and base stripped in the presence of water and heavy loading. Further, clogging of the ATPB with fines from the aggregate base was observed in the wheel path area. Surface rutting was the prominent failure mode because of stripping of the ATPB. For the undrained sections, fatigue cracking was the predominant failure mode. Improved compaction of the HMA layer and the use of improved structural section design suggest that consideration should be given to the elimination of the ATPB directly beneath the HMA layer.

The detrimental impact of the moisture intrusion into base and subgrade layers of pavements is well-quantified based on laboratory tests and field studies. A series of tests were carried out on small-scale specimens [40 in. (1 m) in diameter] to quantify the impact of moisture on one base and two types of subgrade using a new test set-up. The results were compared with those from two full-scale test sections made from the same materials (Amiri 2006). It was shown that if the small-scale specimens are carefully constructed to achieve similar densities and moisture contents to the pavement sections, the load-deformation responses are reasonably close, indicating that the small-scale tests can be effectively utilized to calibrate and validate the existing models under different conditions. For clayey subgrades, the moisture in the subgrade dominates the performance of the pavement, whereas for the sandy subgrades the moisture conditions within the base, as well as the subgrade, influence on the behavior of the pavement.

The test pit at LCPC's f-sAPT facility was filled with clayey-silty sand with an elastic modulus of between 12.3 and 15.9 psi (85 and 110 MPa), depending on moisture content. Four different flexible pavements and one bituminous reference structure were constructed on top of the clayey-silty sand and tested to generate information for improving the understanding of subgrade moisture content effects on flexible pavement design. It was observed that the rutting of the unbound granular subgrade significantly contributed to the overall rutting development. Although the evaluation of the behavior using the current French flexible pavement design method provided satisfactory results, it underestimated the rut resistance of the HMA surfacing (Balay and Kerzreho 2008).

Steyn and Du Plessis (2008) discussed the objectives, potential effects, and available methods for performing HVS tests on pavements where the moisture condition of the pavement is a major parameter in the experimental design test matrix. The importance of clearly defining the objective of changes in the moisture content as well as the potential outcome of the changes in moisture content to be modeled were stressed. During the tests moisture changes need to be monitored and logged to ensure accurate data analysis. The use of appropriate control sections without moisture changes are required to ensure comparison of behavior.

Erlingsson (2008, 2010a, b) investigated the response behavior and performance of a commonly used pavement structure in Sweden through f-sAPT. It was shown that raising the groundwater table during a test increased the rutting rate in all unbound layers. It further increased both the resilient and the permanent strain of all unbound layers above the groundwater table, probably because of increased moisture content in the unbound layers.

NCAT compared the construction and performance of permeable surface mixes containing two different aggregate sources that were placed with conventional and dual layer paving equipment on perpetual foundations (Powell 2009). One section contained cubical aggregates and the other more flat and elongated aggregates. The third section was built using the same slightly flat and elongated aggregates and a surface consisting of a thin 0.4 in. (9.5 mm) drainable mixture over a thicker 0.5 in. (12.5 mm) drainable mix. The field drainability exhibited by the section constructed with slightly flat and elongated aggregates appeared to be better than the section built with the more cubical aggregates after prolonged rain, while the field drainability exhibited by the dual layer pavement appeared to be better than the conventional single layer drainable surface.

Schaefer et al. (2010) described the construction and performance of a pervious concrete overlay constructed at the MnROAD low-volume road. The overlay performed well with only localized surface pavement distress and good performance and durability. The pavement provided good mitigation of splash and spray and reduction of hydroplaning through good flow characteristics.

Twelve sets of full-scale flexible pavement test sections were built inside the Frost Effects Research Facility of the U.S. Army Corps of Engineers to develop subgrade failure criteria and performance prediction models that consider the subgrade soil type and moisture condition (Cortez et al. 2007). The pavement materials and layer thickness were kept constant, while the subgrade soil type and moisture condition varied from test section to test section. The experimental data suggest that for subgrade soil type AASHTO A-2-4 and up to 15% moisture content moisture above the conventional optimum moisture content was beneficial in reducing permanent deformation. For soil types A-4 and A-6, moisture in excess of optimum had a weakening effect that gradually increased the rutting rate. For soil type A-7-5, the effect of moisture in excess of optimum was initially negligible; however, above certain moisture contents it resulted in sharp increases in rutting. With low-plasticity subgrade soils, such as types A-4 and A-6, pumping can occur under repeated loads. It has been recognized that the most important mechanism producing rutting in unbound soil materials is shear distortion and not densification. The relative contribution of the various pavement layers to the total vertical rutting varies according to subgrade soil type and moisture condition. The data suggest that the percentage deformation in the surfacing and base layers increases with stronger subgrades.

CHAPTER SUMMARY

This chapter focused on the vehicle–pavement–environment interaction that is vital for a complete understanding of f-sAPT. Respondents view pavement and ambient temperature as the most important environmental parameters to relate f-sAPT data with and to control during tests. This is probably related to the high percentage of HMA-type f-sAPT evaluations conducted (chapter three). Potential exists for evaluating the effects of climate change on pavements through the judicious application of artificial temperature and moisture changes (based on expected weather conditions) during f-sAPT.

The major effects of tire contact stresses and loading conditions on pavement response were highlighted by many researchers and are shown to be incorporated as a factor in many of the test programs evaluated for this synthesis. Improved measurement systems as well as novel analysis techniques for incorporating actual tire–pavement contact stresses into analyses allows for an improved understanding and appreciation of this parameter. The loading effects caused by wide-based and also aircraft tires are being evaluated at various f-sAPT facilities. A limited number of facilities incorporate LTM of existing pavements into their research, although it is appreciated that it is an important link between f-sAPT and real life data.

CHAPTER FIVE

MODELING AND ANALYSIS

INTRODUCTION

Chapter five provides detailed findings on the modeling and analysis methods employed by the various researchers and the benefits and limitations of different approaches. It discusses the various models conceptually and specifically comments on the application of f-sAPT in the MEPDG and other M-E pavement design methods. All the models are not repeated, as this would require substantial detail on model parameter definitions, limitations of specific models, and related details that are well covered in the various references and would add to the volume of the current synthesis without adding to the main discussion.

Most of the modeling and analysis work discussed in this chapter focuses on improving the materials models for the various M-E design models, thereby reducing the risk of design as more appropriate parameters are incorporated into the design, and the effect of each of the parameters are better understood.

The issues highlighted are the increased use of FEM for analysis of moving loads (as opposed to static load analysis), where factors such as mass inertia and stress rotation are incorporated into the model; the increased use of materials models that are not simply linear elastic, but which incorporate the effects on nonlinearity, viscosity, and environmental sensitivity (i.e., moisture and temperature); the increased use of detailed definition of the applied loads in terms of both load history and contact stress patterns; and the increased cognizance given to the effects of the environment on pavement response.

It appears as if a process is driven on several fronts where improved computers allow for increasingly complex calculations without becoming too time- and resource-consuming, the understanding of materials properties are improving with the parallel development of appropriate laboratory and field instruments, and tests to obtain these parameters for different materials and the subsequent modeling is improved through the combination of these factors. Most of the M-E methods operate on a multilevel basis, where pavements of lesser importance where higher risk can be tolerated are designed using a simplified version of the system, and pavement where very little risk can be tolerated are designed using the most complex version of the M-E method.

It does, unfortunately, appear that much of the modeling is still focused on the surfacing layers and that the effect and contribution of lower materials layers are generalized and simplified, although these effects may sometimes affect the surfacing and other upper layers significantly. It is specifically the strength-balance of the pavement (providing a pavement structure where layers are not overstrained or -stressed owing to a lack of support or protection) that often appear to be ignored in test planning and modeling.

The combination of f-sAPT data with laboratory, LTM, and field data differs between projects and depends mainly on the requirements of the specific project. F-sAPT is almost always combined with and supported by laboratory data, with field data used for calibration with real environment and traffic. It appears as if LTM data are not used by many respondents. Some respondents make use of replicate sections on public roads that become the field sections and almost play the role of LTM sections, although they are not monitored in the same way as the SHRP LTPP sections. F-sAPT is clearly viewed as one of the available tools and not as the ultimate answer to all questions. Some respondents indicated that the f-sAPT work focuses on specific materials (i.e., HMA layer testing) and that this knowledge is then combined with field response to obtain the information for typical structures.

Response regarding the types of models used for backcalculation, deflection analysis, deformation, fatigue, load equivalence, pavement serviceability, stress, and strain are summarized in Figure 48. It indicates that the majority of respondents use elastic layer theory for most applications, with usage of FEM also significant. Iterative methods are mainly used for backcalculation, whereas elasto-plastic, statistical, and visco-elastic layer theory are applied in fewer instances. This is probably because these model properties are typically material related (i.e., visco-elastic methods for asphalt materials).

MODELING AND ANALYSIS

Analysis

Romanoschi and Metcalf (2000) evaluated statistical models for the determination of the probability distribution function for time-to-failure of pavement structures using rutting data from the Louisiana f-sAPT facility. Determination of the probability distribution function for the time-to-failure is essential for the development of pavement life models as the probability distribution function reflects the variability

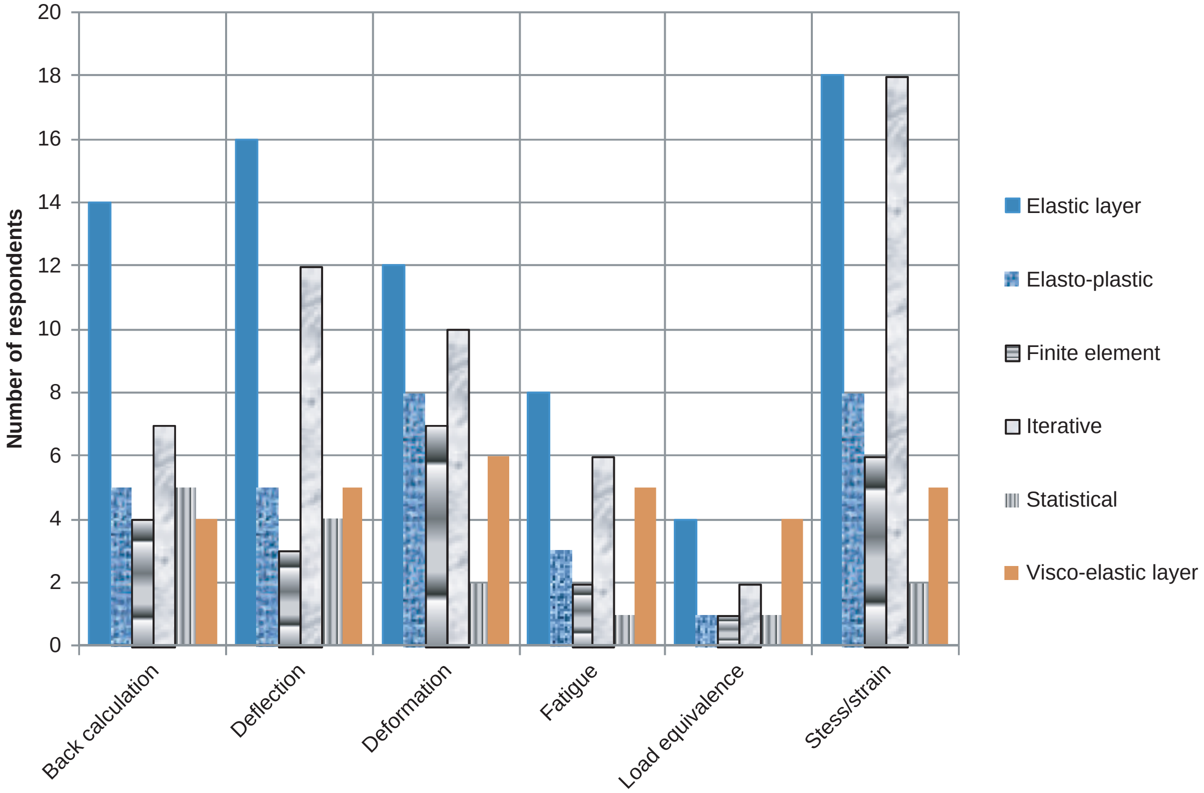

FIGURE 48 Model types used for selection of f-sAPT analysis processes.

in pavement degradation. If the pavement life model has a known form the closed form solutions and Monte Carlo algorithms can be used. Both methods use degradation data and can be employed even for degradation levels below failure levels. If the degradation model form is not known, the survival analysis method based on censored observations must be used to derive the pavement life model. This method cannot use only degradation data at levels below the failure level, because the failure of some structures must be recorded.

Saleh et al. (2003) compared the 3-D FEM technique with isotropic and anisotropic multilayer elastic solutions when the unbound base layer is assumed to behave almost elastically. The 3-D FEM was found to provide the best match for the subgrade strains as it accounts for the elastic-plastic material behavior, modeling the plasticity using the Drucker–Prager model. Data from the f-sAPT pavement at CAPTIF was used to evaluate the calculated stresses within the pavement. As backcalculation methods depend mostly on the measured deflection basin, the use of isotropic multilayer elastic solution appeared to yield unsatisfactory results if the plastic behavior of the material is pronounced. Increasing both the axle load and tire pressure will have the most damaging effect by increasing rutting significantly, with the base layer contributing about 37% of the total rutting and the subgrade layer up to 63%.

Erlingsson (2004, 2007) illustrated how f-sAPT results (obtained from two thin pavement structures) assist in increasing the understanding of thin pavement behavior, and how a bitumen stabilized base compares with an unbound base. Nonlinear analyses provided better agreement with measured data for the unbound base course while rutting prediction using a power law function showed good agreement with actual measurements of rutting development.

F-sAPT at the Virginia Smart Road allowed several hypotheses related to flexible-pavement design to be verified by Loulizi and Al-Qadi (2004). The LET overestimated the vertical compressive stress in flexible pavement layers at low and intermediate temperatures and underestimated it at high temperatures.

Onar et al. (2005) evaluated the utility of mixed-effects models in analyzing performance-type data resulting from f-sAPT experiments. Analysis of f-sAPT data indicated that both binder type and temperature are significant factors in rutting development. It was found that a sound experimental design requires the consideration of all potential interaction effects between various design parameters to prevent alteration of data inferences through unidentified interactions. By capturing the variability among test tracks separately, the mixed-effects model provided a more powerful approach to estimating the parameters of the model.

Molenaar (2006) indicated that based on work done at the Delft University in the field of f-sAPT, linear elasticity can be used to provide accurate pavement life predictions provided that ample attention is placed on the characterization of the traffic and climatic influences as well as on material characterization. Longitudinal and transverse strains measured at the bottom of the HMA layer could be predicted by a linear visco-elastic analysis, and good agreement was found between the measured peak strain values and the calculated ones using a linear elastic multilayer program.

The transfer functions in an M-E pavement design procedure are used to relate pavement structural responses (deflections, stresses, and strains) to pavement performance (cracking, rutting, etc.). NAPTF performance test results (Gopalakrishnan and Thompson 2006b) were used to investigate the relative effects of four- and six-wheel aircraft gear loads and verify failure criteria to be used for development of mechanistic-based airport pavement design procedures. It was observed that a deflection ratio (D1/D3) showed the strongest correlation with the number of load repetitions to reach functional failure, indicating the potential for developing HWD deflection-based rutting failure transfer functions for airfields.

Lee et al. (2006b) developed pavement response models for calculating the critical pavement responses in a long-life pavement. A synthetic database was developed using a FEM approach with a range of layer thicknesses and moduli. It was found that the HMA base layer should be thicker than 7 in. (175 mm) and have a modulus of at least 507 psi (3.5 GPa). F-sAPT sections were constructed for validation, and a comparison study between the computed and measured strain values indicated that the proposed procedure can predict the actual pavement responses accurately.

Bruce et al. (2007) developed a FEM approach to model thin-surfaced unbound granular pavements incorporating a nonlinear anisotropic material model for the granular material and a nonlinear material model for the subgrade. Coefficients for the material models were determined from laboratory-repeated load tri-axial tests, and the model was validated using data obtained from a test pavement at CAPTIF. Analysis results indicated the need to use a full nonlinear model to obtain realistic results when modeling FWD loading data on the f-sAPT pavement. A shift factor that depended on material properties was required to translate the results from the laboratory space to the field space. The granular stiffness values calculated in the model varied with load and depth below the surface, supporting the use of a nonlinear model.

Al-Qadi et al. (2007) developed a 3-D finite element model to simulate pavement sections at the Virginia Smart Road. Results of the finite element model were compared with the layered theory and field-measured pavement responses. To improve the FEM accuracy, a laboratory-calibrated time-hardening model was successfully incorporated into the model to simulate time retardation of HMA in the transverse direction and fast relaxation of HMA in the longitudinal direction. The finite element model was capable of predicting pavement surface damage and its partial recovery after load application. Analysis emphasized the requirement to incorporate anisotropic HMA characteristics to accurately simulate pavement responses in the lateral direction. The measured and calculated vertical stresses (FEM calculated) were in good agreement with the testing conditions, while the locations of the tensile and compressive fields were in agreement with field measurements, validating the contact conditions assumed in the modified model. Discrepancies in the strain magnitude support the anisotropic behavior of the material at high temperatures with HMA that appears to be softer in the lateral directions than in the vertical direction, probably as a result of the compaction process.

F-sAPT supplements laboratory testing and supports advances in practice and economic savings for the evaluation of new pavement configurations, stress level-related factors, new materials, and design improvements by simulating field conditions. Guo and Prozzi (2008) described a method using a bias correction factor or function to account for all quantifiable differences between f-sAPT measured response and actual field response of a pavement. The bias correction factor typically includes factors to cater for the differences between the f-sAPT and the field for the loading frequency, rest periods and loading time, lateral distribution of traffic, temperature, and subgrade moisture content. The methodology is generic, independent of the f-sAPT facility, conditions, or environment. Currently the material aging properties and actual traffic load spectrum are not addressed in the approach.

Kim et al. (2008) compared the strain responses of a pavement model with those measured in an f-sAPT experiment. The predicted strains from the 3-D visco-elastic model agreed well with the strains measured in the field, indicating that the model simulated the response of the pavement in the field well. The material properties determined from the laboratory and field tests were accurate and reliable. The time-, rate-, and temperature-dependent behavior of the HMA layer are critical to ensure good modeling of the field response of the pavement.

The energy ratio concept was evaluated as a predictor of top-down cracking performance in Florida based on f-sAPT at NCAT (Timm et al. 2009). Two f-sAPT sections were tested and both initially exhibited similar structural response as measured by embedded strain sensors, confirming that differences in as-built properties did not contribute significantly to the resulting structural response under load until after cracking became evident. The primary difference between the two sections was the binder used in the upper two lifts. The first section used PG 67-22, while the second section used PG 76-22, which resulted in approximately double the energy ratio. The section with the lower energy ratio value cracked first and more extensively, although both sections experienced top-down cracking. Field performance data were matched with the expected results, indicating that the energy ratio has the potential to reliably evaluate top-down cracking performance of HMA mixtures.

Data from an f-sAPT section were used to forecast resilient responses obtained from NCAT pavements generated under completely different loading and environmental conditions (Levenberg 2009a, b). The overall objective of the f-sAPT study was to develop an analysis approach by which pavement behavior in the f-sAPT could be used to reliably forecast the behavior of a similarly constructed pavement in the field serving different loading and environmental conditions. The f-sAPT experiment was modeled using isotropic LET using backcalculated material properties based on the entire time history of pavement response during one f-sAPT pass. This inverse analysis is vital as it minimizes systematic errors originating from the application of a rudimentary pavement model. The f-sAPT model was enhanced by adjusting the HMA model to reflect differences in loading speed and temperature relative to the calibration conditions through analysis of complex modulus data. Application of the enhanced f-sAPT model to forecast the responses generated by a moving truck in a similarly constructed pavement system at NCAT showed that the model performed relatively well.

Romanoschi et al. (2010) used f-APT and laboratory data to validate the response and distress models in the MEPDG. The revised Witczak model was found to predict the dynamic modulus of HMA mixes at a range of loading frequencies (0.1 to 25 Hz) and temperatures [68°F to 95°F (20°C to 35°C)] adequately. The MEPDG structural response model underpredicted the longitudinal strains at the bottom of the HMA layers by two to three times, while the MEPDG model predicted higher total rutting than the measured.

Models were derived for HMA modulus (as function of reduced time), unbound layer moduli (as a function of the stiffness of the layers above and as a function of the load level), HMA modulus decrease caused by fatigue, and slip development between HMA layers using laboratory data for HMA used on 13 HVS test sections (Ullidtz et al. 2008b). These models, calibrated with f-sAPT response, resulted in a relatively good prediction of the resilient deflections of the pavements at all load levels and for the whole duration of the tests.

Empirical Analysis

Chen et al. (2001) conducted more than 60 Dynamic Cone Penetrometer (DCP) tests on two f-sAPT test pavements to assess the validity of empirical equations proposed in previous literature to compute layer moduli from DCP data. Elastic moduli values for the pavement layers were obtained from the f-sAPT data. Both DCP and FWD results indicated minimal effects of f-sAPT (MLS) loading on the base and subgrade layers.

About 85% of Australia's sealed arterial road network consists of unbound granular pavements and a thin bituminous surface treatment, normally a chip seal (Martin and Sharp 2009). The feasibility of using f-sAPT to predict the influence of various surface treatments on pavement deterioration was confirmed by a pilot test. In a follow-up trial, ten experiments and various types of surface treatment on separate test pavements were undertaken under controlled environmental conditions. The observed deterioration data were used to estimate relative performance factors for rutting and roughness for a range of surface treatments under surface conditions varying from dry to continuously wet. The data are supplemented by data being collected in various long-term pavement monitoring projects, including a project directed specifically at maintenance treatments.

Steyn (2009b) evaluated the application of f-sAPT for the analysis of pavement preservation actions. It was shown that these treatments can be evaluated successfully using f-sAPT devices, if aspects such as the preparation of the test section, monitoring of pavement response for all potential failure mechanisms, and analysis incorporating information obtained from in-service pavements and laboratory test outputs are incorporated into the process. F-sAPT provides the option of simulating different types of failure conditions to ensure that the preservation treatment can be exposed to similar conditions to those expected in the field.

Mandapaka et al. (2011) described an attempt to evaluate and select an optimal maintenance and rehabilitation strategy for a flexible pavement integrating life-cycle cost analysis and M-E design procedures. Through application of CalME and life-cycle cost analysis principles, extended pavement preservation with HMA was found to be the most cost-effective M&R strategy for the case study evaluated. This result is influenced by climate region and traffic conditions.

Design Methods

The recent Danish pavement design guide includes three levels of design (Busch et al. 2005). The lower level consists of a pavement catalog, the intermediate level is a mechanistic design method, and the upper level is an incremental-recursive simulation tool allowing the long-term performance of a design to be simulated. This upper level tool is based on the Mathematical Model of Pavement Performance that has been calibrated using data from the AASHO Road Test, f-sAPT, and general experience with pavements in Denmark. It is capable of predicting longitudinal roughness, rutting, and fatigue cracking of a pavement consisting of an HMA or cement bound layer, a granular base, and subbase layer and subgrade, considering the variations in pavement layer thickness, elastic stiffness, plastic parameters, and dynamic load along the length of the road.

Tompkins et al. (2008) evaluated the effects of the MnROAD facility on pavement design methods and observed that although MnROAD was originally designed as a thickness, or structural, experiment, it was quickly observed that the environment plays a major role in pavement response (especially in this relatively cold areas). Work on MnROAD influenced the CRREL M-E model for cold regions pavements, the MnDOT rigid pavement design guidelines, the 1993 AASHTO Guide for Design of Pavement Structures (AASHTO-93), the 1984 Portland Cement Association Thickness Design for Concrete Highway and Street Pavements (PCA-84), and the MEPDG (NCHRP Project 1-37A) design procedure. The MEPDG method incorporated a large amount of MnROAD data and expertise, specifically for calibrating the MEPDG's ability to predict rutting in the lifts of an HMA pavement, and development of the MEPDG thermal cracking model.

Ullidtz et al. (2007a, b) indicated that Incremental-Recursive models provide reasonable results when predicting the response and performance of pavement under f-sAPT loading.

Ullidtz et al. (2008b) described the development of M-E models using data from 27 f-sAPT sections. Issues to address in the calibration process are the inclusion of an aging model, allowance for seasonal variation effects, traffic load rest periods, and variability of materials, structure, loads and climate.

Ullidtz et al. (2008a) described validation and calibration of CalME models using the FHWA's WesTrack project data. All the results of the WesTrack experiment were imported to the CalME database after which the experiment was simulated on an hourly basis using the incremental-recursive method with the model parameters derived from laboratory tests. Very good agreement was obtained between the measured and calculated response during the duration of the WesTrack trafficking on each section in terms of the deflection under the load plate of the FWD. Factors such as the estimated HMA temperature during the FWD test, HMA modulus versus reduced time relationship, moduli of the unbound materials, hardening of the HMA and HMA fatigue damage were significant. CalME predicted less damage for the fine, coarse, and fine plus mixes than that estimated from the FWD. Resilient deflection responses were predicted well, while the CalME-predicted damage (based on laboratory fatigue tests) was somewhat lower than the damage estimated from FWD tests.

CalBack was developed as a software tool with versatility by means of three deflection-matching search engines, three response models for flexible pavements, a Westergaard model for rigid pavements, and a large, self-contained, expandable material characterization library (Lu et al. 2008a).

Caltrans adopted the M-E pavement design methodology to replace existing pavement design methods, and a number of M-E models have been developed, tested, and collected into a design system known as CalME (Lu et al. 2009), which employs an incremental-recursive approach using the time hardening procedure and WIM load distribution data. CalME is intended to be supported by the required databases, guidelines, and test methods that will result in more cost-effective pavements (Harvey et al. 2010). CalME can be calibrated using f-sAPT data as well as test track and field section data. The incremental-recursive approach used in CalME means that the entire damage process measured by f-sAPT instruments can be used for calibration of response and damage models. This approach permits the use of pavement response data that track the damage and aging processes on sections for calibration of the damage process, even when failure has not yet manifested itself on the pavement surface. In contrast, the MEPDG and other M-E methods using Miner's Law only use the initial undamaged responses of the pavement to temperature and load, and assume the entire damage process to the end failure state.

CalME was used to simulate f-sAPT conducted at CEDEX by first verifying the mechanistic pavement response models against the measured responses during the experiment, followed by calibration of the distress models (Ullidtz et al. 2010a). Master curves determined from frequency sweep testing in the laboratory and derived from FWD for the HMA, as well as resilient moduli obtained from triaxial testing and backcalculated moduli for the surfacing layer and the subgrade were in good agreement. The empirical fatigue damage model determined from flexural beam testing gave a reasonably good prediction of the fatigue of the HMA layer, whereas the relationship between cracking and fatigue damage tended to overpredict the actual cracking. Rutting was shown to be dominated by the compression of the capping layer and the default empirical model for unbound materials in CalME would have predicted much less rutting than was observed. The rutting model determined from RSST-CH provided acceptable predictions of HMA rutting.

CalBack and CalME were successfully used to predict in situ pavement performance of selected MnROAD sections (Tsai et al. 2010). The applied shift factors for fatigue cracking and rutting were based on the Caltrans HVS/WesTrack project calibration study.

M-E HMA pavement design systems consist of a mechanistic model for calculating the critical primary responses in the pavement and empirical models relating the calculated responses to the pavement distress or performance. Ullidtz et al. (2010b) demonstrated how CalME can be used to develop an effective flexible pavement design system based on the facility for importing the results of f-sAPT experiments in terms of hourly loads, temperatures, response measurements, backcalculated moduli, permanent deformations, and cracking. It is still recommended that the data be complemented by track testing to incorporate the effects of realistic loads and real climatic conditions.

Ullidtz et al. (2010c) described the successful development of an overlay design procedure for reflection cracking and rutting for CalME based on the incorporation of f-sAPT data from overlay test sections.

One of the goals of the Caltrans transition to ME design is to calibrate and update the M-E methods as innovations surface using laboratory testing, modeling, f-sAPT, and PMS data (Basheer et al. 2010; Harvey et al. 2010). The materials models include coefficients for a standard equation for stiffness, with different equations for HMA and unbound materials, as well as coefficients for performance equations for fatigue and rutting. These various coefficients for the equations are determined through laboratory and field testing.

Gibson et al. (2010) summarized the outcome of the Transportation Pooled Fund Study TPF-5(019) and SPR-2(174) Accelerated Pavement Testing of Crumb Rubber Modified Asphalt Pavements Projects. With relevance to MEPDG, it was found that additional mixture-specific characterization inputs are needed apart from the $|E^*|$ dynamic modulus, to enable improved discrimination and ranking of modified and unmodified HMA performance.

Although the MEPDG models are largely calibrated using LTPP data, there are not significant amounts of polymer-modified HMA data available, while f-sAPT data (FHWA ALF) included several different polymer-modified HMA sections. The actual MEPDG software was found not to be able to be used for HMA performance predictions, as it was not developed to accommodate specialized f-sAPT conditions. It was further found that material modulus measured at small strains did not mobilize the material into regions that force rutting or fatigue crack resistance to be revealed. The NCHRP 9-30A project is currently pursuing this type of material characterization inputs, and recalibration of the MEPDG guide will be required to ensure improved rutting prediction. Two aspects of damage and fatigue cracking that the MEPDG does not provide were highlighted in this study. PSPA tests on ALF lanes indicated that HMA modulus decreases significantly before fatigue cracks are visible on the surface. The HMA modulus applied in the MEPDG is currently not recursively updated to reflect this type of damage. Further, the pattern in which actual bottom-up fatigue cracking develops is not captured, while the surface remains crack free until surface cracking is initiated and propagates. The MEPDG was still deemed useful in analyzing the uniformity of the f-sAPT (FHWA ALF) section construction.

The FAA Advisory Circular on Airport Pavement Design and Evaluation (AC150/5320-6E 2009) provides guidelines for the thickness design of airport pavements. It is typically used together with the FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layer Design) software. The guideline is based on LET for flexible pavement design and three-dimensional finite element theory for rigid pavement design. The impact of new landing gear configurations and increased pavement load conditions can be evaluated using the guideline, and it was found to be robust and able to address novel gear configurations. The International Civil Aviation Organization made intensive use of data obtained from the various FAA NAPTF f-sAPT projects for developing this guideline.

MnDOT used data from the MnROAD experiment to develop an M-E flexible pavement design program (MnPAVE) for Minnesota. The approach is applicable to both low-volume and high-volume roads. The MnPAVE thickness design procedure is a M-E computer software program that takes into account many variables that could not be considered previously. The MnPAVE procedure is based on work done at the University of Minnesota using an elastic layered system WESLEA developed by the U.S. Army Corps of Engineers. MnPAVE is based on performance prediction equations for fatigue and subgrade rutting based on material properties and performance of test sections at MnROAD. Performance prediction equations verified using performance data from 40-year-old test sections that have been used to check the performance prediction equations used in MnPAVE. The application of an M-E design procedure allows for different local material properties to be incorporated into the design to enable performance prediction for specific roads (Skok et al. 2003; Tanquist and Roberson 2010).

CHAPTER SUMMARY

The modeling and analysis chapter focused on the various modeling approaches followed and reported for f-sAPT programs. Although attempts are made to incorporate more advanced model formulations to closer predict material behavior, in some cases the use of linear elastic layered theory still provides reasonable results. However, researchers should be careful as it was shown that in many cases specific material properties prevent the use of simplified theories to accurately predict field performance. The development of advanced pavement design methods and the use of f-sAPT data for the calibration of these methods is becoming a frequent activity. The synthesis incorporates sections on advanced modeling and design methods. The application of f-sAPT data into advanced pavement response models and improved pavement design methods is evident from the body of papers on these topics. The focus period of the synthesis (2000 to 2011) is important in this part of the synthesis, as major developments in prominent pavement design methods that incorporated f-sAPT (such as in Australian, South African, and Minnesota) have either been covered in the previous syntheses (Metcalf 1996; Hugo and Epps Martin 2004), or much of the work is only currently being completed and thus has not yet been reported in the literature. Readers are urged to consult with these documents as well as the 4th International Conference on Accelerated Pavement Testing (September 2012) proceedings to ensure that a complete picture of modeling and analysis aspects can be formed.

CHAPTER SIX

IMPACTS AND ECONOMIC ANALYSIS

INTRODUCTION

This chapter provides detailed information on the impacts and economic analysis of f-sAPT findings from 2000 to 2011. The impacts indicated by respondents to the questionnaire are discussed, followed by information on the economic analyses. Finally, the impacts of f-sAPT on general pavement engineering practice in terms of learning activities are discussed.

IMPACTS

Respondents viewed improved structural and material design methods, evaluation of novel materials, improved performance modeling, and the development of performance-related specifications as the major benefits of f-sAPT (Figure 49).

The most significant findings from f-sAPT in the last decade for respondents' own f-sAPT programs contain a vast collection of specific topics focusing on all aspects of pavement engineering. Issues around materials characterization, pavement modeling, pavement behavior and performance, pavement design method development and calibration, benefits of specific materials, and technologies and economic impacts of f-sAPT programs provide a small sample of these highlights. Aspects that do stand out is the number of respondents indicating that technologies that are viewed as environmentally friendly, such as WMA and the use of RAP, are significant in their programs. Full details of the responses are contained in Appendix C.

The most significant international findings of f-sAPT in the last decade can be summarized on a strategic level as the calibration of pavement design methods (specifically MEPDG and CalME), development of databases of information on pavement performance that are shared between different pavement research programs, cost savings through implementing f-sAPT, and the development of improved instrumentation and analysis methods. In terms of more practical examples, issues such as an improved understanding of failure mechanisms of top-down cracking, critical strain limits in HMA, the effect of adequate layer compaction, variability of materials and layer properties, improved understanding of the links between various materials' laboratory and field behavior, and the effect of various real environmental conditions and traffic on pavement behavior and performance are seen as major international findings.

Specific aspects again focused on respondents' own circumstances and included issues such as a better understanding of top-down cracking of HMA, improved understanding of shear stresses, durability of HMA layers, bituminous binder replacements, evaluation of problematic issues such as orthotropic bridge decks, quantitative benefits of geogrids, and HMA aging models.

In response to the question on major specific tests conducted by facilities and the benefits of their activities, a host of different answers were obtained. As would be expected, most of these answers are not generic as each of the programs has very specific reasons why they conduct their f-sAPT and they need to ensure that the objectives and research questions of their sponsors are addressed sufficiently. It is clear however from the feedback (details in Appendix C) that the various f-sAPT facilities are conducting focused research that addresses questions that affect the quality and performance of their sponsor's pavement infrastructure positively through an improved quantification of risks associated with the use of various technologies, as well as improving the general understanding of material and pavement behavior and performance.

ECONOMIC ANALYSIS

General Questionnaire Feedback on Economic Benefits

Respondents indicated that the BCR is mostly used to evaluate the economic benefit of their programs. However, nine programs are not conducting economic evaluations, and most of the evaluations that are conducted are performed after the research has been completed (eight respondents) and not as an input in the research planning (four respondents). Feedback from clients and sponsors are in some cases used to evaluate the benefit, albeit not in economical or objectively measured terms. The benefit of cost avoidance or avoidance of implementation of a costly action that is proven to be ineffective during f-sAPT is also seen as a strong indicator of the success of some f-sAPT programs.

Estimates of BCR from respondents (Figure 50) indicated that the majority (six respondents) estimate their BCR at between 1% and 5%. The number of respondents drops for the next two categories (6% to 10% and 11% to 20%) and increases again for the over 31% BCR group.

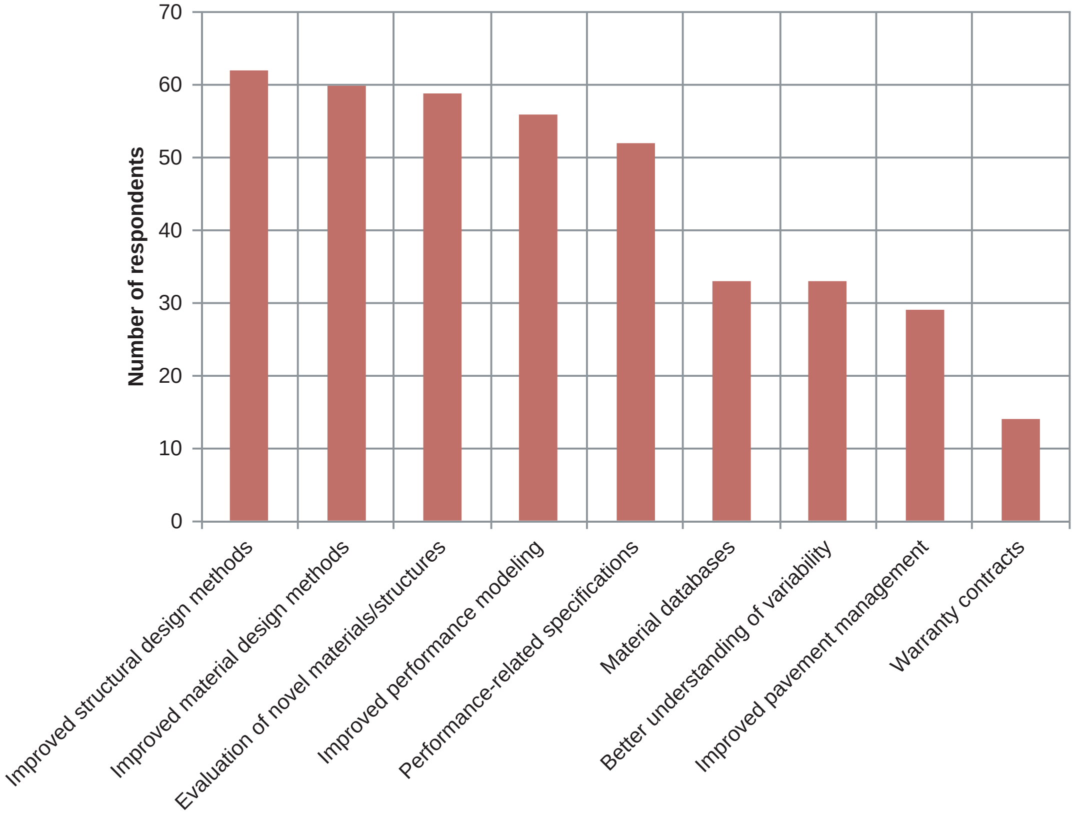

FIGURE 49 Major benefits of f-sAPT.

Background

The evaluation of economic benefits of f-sAPT has been conducted for many years. Metcalf (1996) already mentioned attempts at calculating these benefits, whereas Hugo and Epps Martin (2004) expanded on these issues with the wider reporting of economic benefits during the late 1990s. Benefits not translated to economic numbers were also included in the latter. Much work has been conducted during the last decade with the 3rd APT conference using this as a theme, as well as various TRB sessions focusing on economic aspects. It appears that the general international economic conditions force researchers to prove the benefit of their research much more and identify, analyze, and quantify the direct and indirect benefits obtained from full-scale APT. Recent studies in the United States suggest that clear justifications of costs and benefits may increase public confidence in decision makers. The COST 347 study suggested that transparency and the

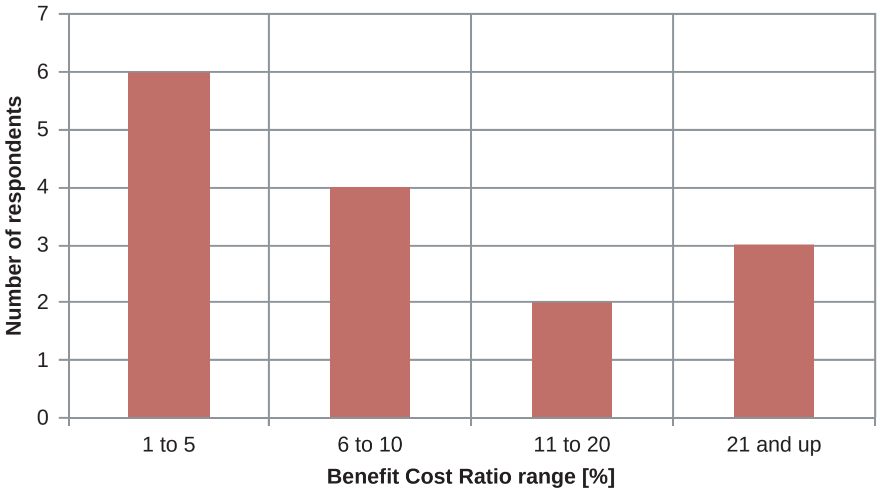

FIGURE 50 Estimates of BCR for f-sAPT facilities.

use of evaluation methods (such as cost-benefit analysis) may help increase funding by enhancing the marketing of research activities and results. Expanding global collaboration of transportation research would require establishment of evaluation techniques that are acceptable to all participating agencies (Nokes et al. 2011).

Du Plessis et al. (2008a) reported that, although significant technical breakthroughs have been made in the UCPRC full-scale program, the following questions remain:

- What is the potential impact of the research results?
- How much implementation has taken place?
- What are the practical benefits obtained from the research program?

Harvey (2008) stated that f-sAPT has been part of the development of new pavement technology for more than 60 years, offering unique capabilities to rapidly move pavement technology through the various developmental levels to full-scale use at attractive BCRs. It also offers the ability to attract and focus attention on pavement problems and solutions, and the opportunity to focus thoughts and actions on future pavement requirements and demands (i.e., higher traffic volumes and less available natural materials).

Lay (2006) stated that an “impediment in valuing research projects is the difficulty of convincing the researchers to take the valuation process seriously” and that it is “as if the researchers’ livelihoods did not depend on the value of their research output.”

Sampson et al. (2008) found a key element associated with decreases in research funding to be the relatively high cost of research and development activities conducted in the road building sector. In addition, the impacts of these activities are often of a highly technical nature with the link between applied funding and the associated benefits not always obvious. The lack of immediate, tangible benefits stemming from road-related research funding is a significant detriment when the motivation for funds has to compete with other budget demands such as those related to health and education, which have more immediate and obvious benefits. In an attempt to investigate and clarify the benefits associated with technology development work in the road sector, the Gauteng Department of Public Transport, Roads and Works initiated a study to develop and execute an appropriate methodology for quantifying the benefits stemming from road-related research and development, with specific emphasis on their HVS technology development program.

Economic Analysis Approaches

Various approaches exist for economic analysis of benefits of research investments (Du Plessis et al. 2011). Agencies typically use indicators such as the Net Present Value, Present Value of Benefits, Present Value of Costs, and BCR. The BCR is the approach primarily used and cited in full-scale APT literature. It is simply the quotient of total discounted benefits divided by total discounted costs, and projects with BCR of greater than one have positive net benefits with higher ratios translating into greater benefits relative to costs.

Du Plessis et al. (2011) demonstrated a method initially developed and applied in Australia and later enhanced and applied in South Africa to determine economic benefits of f-sAPT programs. A key part of this process consists of estimating the probability of technical advances that would have occurred if the specific APT had not been performed. The process includes evaluation of alternative scenarios of technology development through decision tree analysis taking uncertainty into account. The key elements of this methodology include the following main steps:

- Identify the situation with and without the benefit of f-sAPT;
- Accommodate the uncertainty in assumptions and outcomes by assigning a probability to each alternative outcome;
- Calculate the life-cycle cost of each alternative outcome;
- Calculate the expected value (cost) of each alternative outcome by multiplying its probability by its cost;
- Calculate the total expected value for each decision (with f-sAPT and without f-sAPT) as the sum of expected cost for alternative outcomes;
- Determine the benefit (in terms of cost savings) of the information provided by the f-sAPT by subtracting the total expected cost without the f-sAPT from the total expected cost with the f-sAPT included; and
- Derive the BCR by dividing the benefit by the total costs of the f-sAPT.

Nokes et al. (2011) stated that research project life cycles are long, monetary benefits that only accumulate late in the process and lead responsibilities to change in successive phases of the project. The eventual accumulation of benefits requires continuing actions by implementers not associated with the original research. It is accepted that agency cost savings diminish gradually over a time horizon such as 5 to 10 years, and retrospective assessment of benefits of research should wait until most or all cost savings have accumulated. Analysts who evaluate research benefits must decide what is significant to be measured, how and when to measure, and then how to interpret the results. Many impacts are difficult to quantify. F-sAPT researchers and operators might consider the following needs and potential ways to pursue them regarding economic evaluation of f-sAPT programs:

- Recognize the need for more frequent, formal, and quantitative assessments of f-sAPT research;
- Organize and perform coordinated studies of evaluation techniques for f-sAPT research;
- Investigate techniques that may be suitable for both retrospective and prospective assessments;

- Evaluate previous and existing efforts at establishing frameworks to evaluate research benefits;
- Pursue and promote systematic and consistent practices for evaluating f-sAPT research results;
- Identify conditions and criteria for assessing f-sAPT at various levels of assessment;
- Investigate the potential development of a multifaceted approach that combines many techniques and measures that complement each other and may be suitable for f-sAPT research as well as other pavement and/or transportation research;
- Develop standardized and commonly accepted (between f-sAPT programs) techniques and measures for establishing and evaluating costs and benefits of f-sAPT research; and
- Identify credible evaluation techniques that potentially are acceptable to international agencies.

In a study by Nokes et al. (2011) to determine direct economic benefits of f-sAPT using HVSs in California, it was found that the Australian/South African technique provides advantages such as quantitative, direct economic benefits (benefit/cost generally under 10:1), analysis of alternative outcome scenarios accounting for uncertainty, and validation interviews with implementers of research findings. Challenges identified in using this methodology include intensive cost, labor, and time requirements, as well as sensitivity to assumptions and subjective input.

In general, the quantification of benefits centers around the assumption of new and freely available information that will impact positively on policies, which, in turn, lead to measurable economic benefits (Sampson et al. 2008). This simple linear model fails to adequately take into account the complex relationships between development, innovation, and government policy objectives. The failure of a simple benefit quantification to take into account further downstream benefits and the impact of these on the quality of life of the population at large means that the benefits of publicly funded technology development are likely to be greatly underestimated. In an effort to provide a more accurate assessment of the benefits of technology development work, the use of direct (benefits that rely primarily on the project outcomes) and indirect (benefits that arise because of the development process) benefits should be considered.

Although indirect benefits such as the number of employment opportunities created and technical progress are important, it can be argued that at the strategic level a favorable economic indicator such as a BCR provides a more powerful motivation for continued technology development funding. Quantified estimates of the direct economic benefits arising from technology development work are difficult to obtain because of the vague and subjective nature of the task. Among the many difficulties associated with such a benefit assessment are the following three aspects:

1. Conceptual and time-related separation between project findings and benefit realization,
2. Benefits often resulting from several contributing projects and processes, and
3. Benefit assessment involving a significant subjective component.

A survey of the technical impacts of road-related technology development work, and specifically of those involving f-sAPT, showed that the technical impacts of road-related technology development work can be generalized into the following three categories:

1. Optimized materials and pavement design, which lead to reduced construction costs;
2. More reliable design and maintenance practices that reduce the likelihood of costly early failures; and
3. More cost-effective materials and pavement design that optimizes the time between maintenance interventions and reduces pavement life-cycle costs.

Direct economic benefits that are typically derived from these impacts can be evaluated in different ways. The approach described by Sampson et al. (2008) compares the life-cycle costs of viable scenarios with and without the benefit of the impacts that stem from technology development work. The approach includes the following steps:

1. The life-cycle cost for constructing and maintaining a typical road segment is calculated for scenarios with and without the benefits of technology development work.
2. A probability of occurrence is assigned to each scenario (an indication of the average long-term, network-wide likelihood of occurrence for each scenario).
3. The two life-cycle costs calculated in Step 1 are multiplied by the probabilities assigned in Step 2 and the difference between the two products calculated. This is the net benefit per road segment.
4. The net benefit per road segment is multiplied by the size of the network on which the technology development will have an impact. This provides an indication of the overall network-wide savings associated with the impact of the technology development work.
5. The overall savings calculated in Step 4 is the expected long-term benefit assigned to a specific impact stemming from technology development work.

A key aspect of the process used by Jooste and Sampson (2004) is that it relies on documented interviews with individuals involved in the implementation and use of the technology. These interviews form the basis for the critical subjective assumptions and lend consistency and credibility to the approach.

Examples and Applications

Gillen et al. (2001) presented the evaluation of the economic costs and benefits of implementation of three recommendations for changes in flexible pavement design and construction made by University of California Accelerated Pavement Testing pavement research program to Caltrans. The analysis was performed using a full-cost model developed for transportation projects including direct agency costs, user costs, and safety costs. It was shown that new pavement technologies (primarily consisting of the method of application of pavement materials) can deliver significant cost savings to Caltrans maintenance and rehabilitation efforts. Caltrans used a life-cycle costing model to minimize the sum of capital and maintenance costs. In calculating future maintenance costs, Caltrans considers the direct costs to the agency through contracts, and attempts to consider the impact on traffic flow, but not safety and the environment. The first two components reflect the conventional life-cycle cost model; however, user costs are not considered by many agencies. Once all user costs over the lifetime of the facility are taken into account, the standard to which a facility is built and the frequency of repair and rehabilitation will change. The new pavement technologies reviewed and evaluated in this research provide a means of reducing all costs, including those directly incurred by Caltrans and those incurred by users and the public. Implementing the recommended increase of the period between overlays by 1.5 years resulted in savings of more than $56 million. If the period between overlays is extended by 5 years, the statewide savings is more than $244 million (these savings exclude user and safety cost savings).

King and Morvant (2004) evaluated the Louisiana APT program and the BCR assessment of the implementation strategies for the first three experiments conducted since 1993. Results indicated that the BCR over the period (2001–2003) was 5.3. The life-cycle savings for two implemented sections evaluated was 40%. Implementation of the information from this experiment has proven to be very beneficial to the Louisiana Department of Transportation and Development. Through the BCR procedure Louisiana has proven that implementing research sections from APT testing on the nation's highways can save the motoring public both money and time.

MnROAD has led to positive economic benefits during its initial research phase (Worel et al. 2008). The Phase I research benefited Minnesota by providing insight into policies resulting in increased pavement life. Some of these areas include seasonal load policies, M-E design methods, HMA binder gradation, low temperature cracking reduction, and improved pavement maintenance operations. These benefits led to an annual savings for MnDOT of at least $33 million for six projects evaluated. Other benefits are equally important but harder to quantify. Neither national nor local privately owned pavements were included in the cost savings even though they also gain a benefit through the research findings and updated construction specifications. MnROAD Phase I (1994–2006) costs were estimated at $44 million and its benefits at $396 million [$33 million per year for six research findings over a 12-year period (2006–2012)], representing a BCR of 8.9.

Du Plessis et al. (2008b) concluded that their Australian/South African method is effective in identifying the implementation of results from HVS tests, identifying practical benefits and quantitatively determining impacts of HVS research, proving that Caltrans' investment in f-sAPT research with the HVS has been rewarding and well worthwhile.

Du Plessis et al. (2011) conducted a case study applying the Australian/South African method to HVS tests conducted for Caltrans. The case study evaluated benefits from HVS tests performed to validate innovative pavement mixes and designs proposed for the rehabilitation of a high traffic urban interstate route. Although local conditions differ significantly between these countries the method was successfully applied and showed positive results.

In addition, there are a number of other qualitative benefits from HVS testing that are difficult to quantify, such as peripheral software development and the generation of new knowledge that can be applied elsewhere (Du Plessis et al. 2008b).

Ranges of Values

Based on the questionnaire feedback and current literature, the ranges of BCRs are shown in Table 38. It is important to ensure that the same factors had been included in analyses compared with each other and that similar analysis procedures have been applied. The data in Table 38 indicates that the ranges are broadly between 1.4 and 11.6 (excluding the high Caltrans example where user costs were included in the analysis). This relates well with the 10 respondents who indicated a BCR of between 1 and 10 for their facilities (see Figure 50).

Du Plessis et al. (2008a) calculated BCRs ranging from 3.2 to 9.5 in analyses of UCPRC APT projects. These values are deemed very conservative because they do not take into account indirect benefits, savings in user delay costs and accident costs and cost avoidance. Du Plessis et al. (2011) compared various f-sAPT evaluations and BCR values for a discount rate of 4% reported in the Australian, South African,

TABLE 38
SUMMARY OF BENEFIT COST RATIOS (BCRS) FROM QUESTIONNAIRE AND LITERATURE

Origin	BCR
UCPRC 1	3.2 to 9.5
Australia	1.4 to 11.6
South Africa	2.2 to 10.2
Caltrans I710	5.3 and 32.4
Louisiana	5.3
MnROAD	8.9

and the Californian cost-benefit studies on their respective APT devices revealed the following:

- The Australian ALF program reported a BCR of 4.9 for the overall APT program and BCR values of between 1.4 and 11.6 for individual ALF tests.
- The South African HVS study on the G1 base course technology reported BCR values of between 2.2 and 5.6 (low contribution ratio) and 3.6 and 10.2 (high contribution ratio).
- The California I-710 HVS tests: BCR values of between 5.3 and 7.1 (low contribution ratio) and 22.4 and 32.4 (high contribution ratio).

Although the California studies have a larger spread of BCR values, these results are in agreement with the other two f-sAPT programs (road user costs were included in the Californian study as opposed to only agency costs in the Australian and South African studies) (Du Plessis et al. 2011). The credibility of this type of analysis lies in the acceptance of the results by road authorities and practitioners. One of the criticisms of BCR is the effect of inputs, assumptions and subjectivity on results as reflected in the sensitivity analysis. A sensitivity analysis is recommended as it enables examination of these effects for interpretation and use of BCR values.

EDUCATIONAL BENEFITS OF ACCELERATED PAVEMENT TESTING

Ten respondents indicated that f-sAPT data are used for graduate studies on selected projects, whereas five respondents indicated this to be the case for all projects. Table 39 shows that 32 degrees linked to f-sAPT data were completed in the last decade, while an additional 23 degrees of current students will be linked to f-sAPT data (linked indicates that the studies have at least made use of data from f-sAPT programs, whether or not specific new tests have been conducted for the specific degree). A listing of references to specific masters and doctorate degrees (provided by questionnaire respondents) linked to f-sAPT is provided as a separate part of the bibliography. References could not be obtained for all the degrees indicated in Table 39.

Respondents evaluated the major influence that their f-sAPT programs had on academia and industry over the past decade as a combination of contributions to national and local guidelines and specifications, opportunities and funding for academic graduate studies, and subsequent fast-track of knowledge implementation, the validation of analytical design standards, and acceptance by industry of technologies proven through f-sAPT.

A highly significant benefit of f-sAPT programs is the opportunity these programs create for staff training and learning. Pavement engineering represents only a small proportion of the curriculum at most tertiary engineering education institutions, and it is widely recognized that there is a current global shortage of skilled pavement engineers. Moffat et al. (2008) described how the Australian operation of ALF has exposed student and graduate engineers to a wide range of learning experiences, including pavement construction, instrumentation, condition measurement, laboratory testing, analysis, and report writing.

An f-sAPT facility and associated research program can create an excellent environment for staff training and increased learning. Rust et al. (1997) described the educational benefit of the long-running and extensive HVS program in South Africa. They noted that pavement engineers who have seen an f-sAPT in operation have an insight not afforded other engineers that may only rarely see badly failed pavements, and then without the benefit of truly knowing the contributing conditions. These assertions are echoed by many pavement engineers, clients, and researchers in South Africa and the United States during discussions on training and education. Engineers exposed to f-sAPT programs are typically exposed to activities such as pavement terminology and the roles of materials within pavement structures, removal of existing pavements layers, pavement construction and surfacing, construction-related testing, quality control and assessment, laboratory testing, and in situ field testing (i.e., FWD).

Although many of these activities are commonly conducted throughout the road industry, it is considered uncommon for a recent engineering graduate to be exposed to such a range activities within the first 12 months of a professional career (Moffat et al. 2008). Engineers also gained experience and skill in specialist areas such as the measurement of pavement responses to load using strain gauges, pavement trenching, and related investigations and technical

TABLE 39
DEGREES COMPLETED PARTLY OR FULLY BASED ON f-sAPT DATA BETWEEN 2000 AND 2010

Degree Type	Completed	Current	Links to Theses	Total
Masters	15	8	2	25
Doctorate	15	9	3	27
Other	2	1	0	3

photography. It also provides an excellent environment for developing skills in project management, technical writing, and communication. Within the specific research teams engineers are working they are exposed to detailed discussions on pavement performance and behavior and learn to evaluate a pavement's condition from various angles, allowing young engineers to develop a feel for pavement behavior.

Tompkins et al. (2008) evaluated various benefits of the MnROAD project and concluded that one of the benefits (among many others) was the opportunity for collaboration on the state, local, and federal levels in the study of pavement and pavement technologies with the result of an increase in the general level of technical understanding of pavement engineers in the state based on their exposure to this facility.

CHAPTER SUMMARY

This chapter evaluated the impacts and economic benefits of f-sAPT. Major impacts are viewed as improved understanding of pavement materials, structure, and general performance and behavior. The economic benefit of f-sAPT programs can be calculated objectively, and most facilities either calculate or assume BCRs of between 1 and 10. It appears as if BCR evaluations are being done by more f-sAPT owners over the last several years, although it still often happens after the testing and not as part of the planning process. The educational benefits of f-sAPT lie in the opportunity of providing students and young engineers with the funding, topics, and technical support to pursue studies in pavement engineering through detailed analyses of full-scale pavement behavior. At least 55 specific students could be identified as involved with graduate studies linked to f-sAPT in the past decade.

CHAPTER SEVEN

TRENDS AND CONCLUSIONS

INTRODUCTION

This final chapter provides information on expected future developments in full-scale Accelerated Pavement Testing (f-sAPT) with emphasis on current plans, anticipated important issues for the future, and an analysis of how the outcome of f-sAPT could guide and influence pavement engineering. Information is discussed around current gaps identified in specific projects, future research needs identified by respondents, and the level to which gaps and needs identified in the previous syntheses have been bridged over the last decade. It further provides conclusions regarding the key findings of the synthesis project, as well as recommendations for f-sAPT research in the near future. It focuses on significant findings that are deemed to influence pavement engineering.

CONTINUED TRENDS

The following four items for future research were identified by Hugo and Epps Martin in 2004:

1. In situ field performance of pavements tested in f-sAPT for future comparative studies.
2. Closer association between f-sAPT and in-service pavement evaluations from SHRP Long-term Pavement Performance (LTPP) studies and pavement management systems to validate and evaluate f-sAPT results.
3. Exploration of vehicle–pavement–environment interaction to enhance the ability to do quantitative performance prediction of different pavement structures under specific conditions.
4. Prudent use of available information and collaborative research efforts to improve the reliability of findings and establish confidence limits.

Evaluating these four items in light of the information covering the period from 2000 to 2011 contained in this synthesis it is evident that the f-sAPT community is moving in the right direction, although it may be slow, with detours in some areas. The importance of in situ sections for performance evaluation and validation of f-sAPT data (long-term monitoring section) is appreciated by most, and there are a number of cases where such validations have been attempted. The problem currently is in the linkage, with good information regarding the performance trend of the field sections. Primarily, these sections are not as well monitored as the original f-sAPT sections, and it often becomes difficult to obtain reliable traffic and environmental data for a field section. The costs of a long-term field evaluation are often a deterrent to ensuring that long-term data are collected regularly.

Vehicle–pavement–environment interaction is receiving ample attention in current programs, and most of the reports at least indicated the conditions under which specific tests were conducted. This includes tire types and conditions, temperature and moisture content at which a test was conducted, and the speed at which the test was conducted. Although not all of these parameters are necessarily controlled during the test, that the researchers appreciate their importance is already a step forward. The importance of incorporating these aspects into the modern pavement design methods also forces an improved evaluation of the methods to control and measure these parameters during f-sAPT, as well as during normal trafficking of pavements.

Collaborative research has increased significantly during the last decade. The development of associations has led to improved communications around common interests and facilities, and different facilities and programs are also using data collectively to evaluate models developed on specific facilities and validate the applicability of specific models and design methods. This allows for data originating from other programs and countries to be analyzed using a model developed under different conditions, and the robustness of models is thus evaluated. The regular international accelerated pavement testing APT conferences and the work at TRB's Full-Scale Accelerated Pavement Testing AFD40 committee also ensure constant communication between role players. Prudent use of technology such as videoconferencing allows meetings to be organized with international colleagues, fostering the relationships and the multiple uses of data.

Thirty-two respondents to the questionnaire indicated that they own an f-sAPT device, whereas 38 had access to a device. Fourteen owners of f-sAPT devices noted that they make data available to non-APT owners, whereas 11 allow APT owners access to their data. Of those respondents who have access to an f-sAPT device, 23 own the device, 2 rent the device, and the remainder access the device through other means (i.e., sharing, part of a consortium etc.).

NEW TRENDS

Many of the trends identified in the synthesis are known issues, but did not receive the required attention in the research and testing environment as would be expected. In this regard, issues such as the stress rotation within pavement layers that affects the performance as indicated in the synthesis, nonlinear, elasto-plastic, elasto-visco-plastic, and other complex models are being incorporated into research and analysis procedures more often. The active use of these models and techniques would gain further improvements in the area of pavement behavior based on f-sAPT.

Economic evaluation of f-sAPT programs is receiving more attention, and it is not clear whether all programs would prefer to enhance the profile of benefit–cost ration (BCR) analyses. It does appear that the majority of programs are satisfied that they do get good data from the programs, and that more detailed analyses are not required; rather, more attention and time are focused on the technical analyses and issues around pavement provision and maintenance.

Continuous improvements in computer technology allow for the use of more complex models that are providing data much closer to real pavement's response to loads. These more complex models also incorporate the details of tire–pavement contact stress area and magnitudes.

Respondents to the questionnaire indicated that the following future research from f-sAPT could aid in the evaluation of the following broad topics:

- A more detailed focus on vehicle–pavement interaction (including improved load and contact stress models),
- Environment–pavement interaction (including climate change issues),
- Development of and improvements in performance-related specifications,
- Improved Mechanistic Empirical Pavement Design Guide (MEPDG) validation,
- Evaluation of sustainable pavement solutions (energy efficient technologies and re-use of available infrastructure), and
- Improved reliability in pavement design.

The increased use of dedicated airfield facilities is visible in the academic literature. The special load magnitudes and bogeys used by this traffic require more specific instrument and monitoring equipment than for some of the traditional f-sAPT programs.

CONCLUSIONS

These conclusions are based on the information gained from the questionnaire as well as the published literature. This synthesis on f-sAPT contributes to the body of knowledge by evaluating developments and advances around f-sAPT between 2000 and 2011. The specific objective of this synthesis is to expand on the foundation provided in *NCHRP Syntheses 325* and *235* on f-sAPT by adding information generated between 2000 and 2011, and identify gaps in knowledge and future research needs for f-sAPT.

To address this objective, the study scope incorporates information on all aspects of f-sAPT since 2000 with a focus on:

- Evaluation of the operational f-sAPT programs,
- Discussion of material-related issues as researched through f-sAPT,
- Discussion on pavement structure-related research using f-sAPT,
- Application of f-sAPT in the evaluation and validation of new Mechanistic-Empirical (M-E) pavement design methods, and
- Identification of the future needs and focus of f-sAPT.

The overall finding from this synthesis is that the judicious use of f-sAPT contributes to and supports the body of knowledge regarding the way that pavement materials and structures react to controlled traffic and environmental loads. Through well-planned studies the f-sAPT work conducted over the last decade highlighted the following strategic findings that provide important information to the pavement engineering community to ensure the sustainable and efficient supply of cost-effective pavement-related infrastructure.

General perceptions regarding f-sAPT indicate that it is perceived as important, with a major role to be played in pavement structure and basic materials research. The future use of f-sAPT is mainly perceived as growing and being a normal part of pavement research operations, benefiting improved structural and material design methods, performance modeling, and evaluation of novel materials and structures.

It was evident from both the questionnaire and the published literature that many programs share their facilities and data in order to expand their database. In this regard, the formation of associations of f-sAPT users with the general objective of improving the cost-effectiveness of the overall programs through cooperative efforts of program planning, data analysis, and device improvements is evident. It also supports cross-fertilization of ideas and solutions to pavement engineering problems.

A wide scope of topics is addressed in the research conducted by the various programs, with the major focus on hot mix asphalt (HMA) materials. The questionnaire trend indicating that f-sAPT focuses on materials used closer to the surface were confirmed through the evaluation of the published literature. Apart from the major emphasis on HMA rutting, a developing trend is the evaluation of environmentally sensitive materials such as warm mix asphalt and recycled asphalt pavement (RAP), as well as the focus on pavement life extension through application of HMA overlays and ultra-thin whitetopping. Aging effects of HMA are addressed, although accelerated artificial aging of HMA is not necessarily providing similar results to real-time-aged HMA. A number of miscellaneous unique applications of f-sAPT have also been discussed, including the testing of pipes in trenches, snow melting systems, and the use of f-sAPT data to assist in calculating road user charges and pay factors.

Respondents view temperature as the most important environmental parameter to relate f-sAPT data with and to control during tests. This is probably related to the high percentage of HMA-type f-sAPT evaluations conducted. The potential exists for evaluating the effects of novel research questions around climate change on pavements through the judicious application of artificial temperature and moisture changes (based on expected weather conditions) during f-sAPT. The major effects of tire contact stresses and loading conditions on pavement response were highlighted by many researchers and are shown to be incorporated as a factor in many of the test programs evaluated for this synthesis

The improved characterization of loading conditions is mirrored by the use of more complicated materials models that can react to these input conditions and model the response of the various materials more realistically. Many programs actively focus on the validation of the models incorporated in the MEPDG and California Mechanistic Empirical pavement design processes, thereby reducing the risk involved in pavement design as more appropriate parameters are incorporated into the design, and the effect of each of the parameters are better understood. The increased use of the finite element method for analysis of moving loads (as opposed to static load analysis), where factors such as mass inertia and stress rotation are incorporated into the model; the increased use of materials models that are not simply linear elastic, but which incorporate the effects on nonlinearity, viscosity, and environmental sensitivity (i.e., moisture and temperature); the increased use of detailed definition of the applied loads in terms of both load history and contact stress patterns; and the increased cognizance given to the effects of the environment on pavement response are standing out in terms of f-sAPT modeling.

It appears that a virtual process is driven on several fronts, where improved computing technology allows the complexity of calculations to increase without becoming too time- and resource consuming, while the understanding of materials properties is improving with the parallel development of appropriate laboratory and field instruments and tests to obtain these parameters for different materials. The subsequent modeling is improved through the combination of these factors.

It does, unfortunately, appear that a lot of the modeling is still focused only on the surfacing layers and that the effect and contribution of lower materials layers are generalized and simplified, although these effects may sometimes affect the surfacing and other upper layers significantly. It is specifically the strength balance of the pavement that often appears to be ignored in test planning and modeling.

Respondents viewed improved structural and material design methods, evaluation of novel materials, improved performance modeling, and the development of performance-related specifications as the major benefits of f-sAPT, while perceptions regarding the way that f-sAPT has changed the pavement engineering world focused on proving new techniques and materials and development of a fundamental understanding of pavement structures. The most significant strategic level findings from f-sAPT in the last decade focus on issues around materials characterization, pavement modeling, pavement behavior and performance, pavement design method development and calibration, benefits of specific materials and technologies, economic impacts of f-sAPT programs, calibration of pavement design methods, development of databases of information on pavement performance that are shared between different pavement research programs, cost savings through implementing f-sAPT, and the development of improved instrumentation and analysis methods. In terms of more practical examples, issues such as an improved understanding of failure mechanisms of top-down cracking, critical strain limits in HMA, the effect of adequate layer compaction, variability of materials and layer properties, improved understanding of the links between various materials' laboratory and field behavior, and the effect of various real environmental conditions and traffic on pavement behavior and performance are seen as major international findings.

The evaluation of economic benefits of f-sAPT has come to the forefront during the past decade with more programs reporting attempts at performing BCR-type evaluations of their research programs. It appears that the general international economic conditions forces researchers to prove the benefit of their research much more and identify, analyze, and quantify the direct and indirect benefits obtained from f-sAPT. Most programs are still only conducting BCR analyses after the research has been completed (43.5%), whereas 17.4% of respondents indicated that they perform BCRs as an input in the research planning. Estimates of BCR from respondents ranged broadly between 1.4 and 11.6, although some respondents to the questionnaire indicated that their perception of the BCR for their programs is over 30.

It is evident that the f-sAPT community is moving toward the future with a focus on calibration of f-sAPT outputs with in situ pavement data, specifically with the view of incorporating environmental and real traffic issues that cannot be modeled using f-sAPT. Many of the trends identified in the synthesis are old issues that were known to the pavement engineering community for a long time, but which did not receive the required attention in the research and testing environment.

Questionnaire respondents indicated that issues such as a more detailed focus on vehicle–pavement interaction (including improved load and contact stress models), environment–pavement interaction (including climate change issues), development of and improvements in performance-related specifications, improved MEPDG validation, evaluation of sustainable pavement solutions (energy efficient technologies and re-use of available infrastructure), and improved reliability in pavement design are important future focus areas.

CHAPTER SUMMARY

This chapter focused on an analysis of continued trends and future trends identified through the responses to the questionnaire as well as the literature. The conclusions of the synthesis are also incorporated into the chapter. Overall it is concluded that the f-sAPT community is actively engaging with real-world pavement performance and behavior issues and real attempts are being made to ensure that appropriate f-sAPT research supports the development of improved material response models and pavement design methods.

ABBREVIATIONS AND ACRONYMS

APT	accelerated pavement testing
ATPB	asphalt-treated permeable base
CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility
CEDEX	Spanish Centro De Estudios De Carreteras test facility
COST	Cooperative Science and Technology
CRCP	continuously reinforced concrete pavement
CRREL (USACE–ERDC)	Cold Regions Research Engineering Laboratory
DOT	department of transportation
ESAL	equivalent single-axle load
FEM	finite element method
f-sAPT	full-scale accelerated pavement testing
FWD	falling weight deflectometer
HMA	hot mix asphalt
HVS	heavy vehicle simulator
IRI	International Roughness Index
LAVOC	Laboratoire des Voies de Circulation
LCPC	Laboratoire Central des Ponts et Chausses
LINTRACK (Dutch)	LINear TRACKing Apparatus
LTM	long-term monitoring
LTPP	SHRP long-term pavement performance
MLS10	mobile load simulator full-scale
MMLS3	model mobile load simulator (one-third scale)
MnROAD	Minnesota Road Research Project
NAPTF	National Airport Pavement Test Facility
NCAT	National Center for Asphalt Technology
PCC	portland cement concrete
PMS	pavement management system
RAP	recycled asphalt pavement
SBS	styrene butadiene styrene
SHRP	Strategic Highway Research Program
UCPRC	University of California Pavement Research Center
USACE	U.S. Army Corps of Engineers
UTCRCP	ultra-thin continuously reinforced concrete pavement
UTW	ultra-thin whitetopping

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Yoo, P.J., I.L. Al-Qadi, M.A. Elseifi, and I. Janajreh, "Effect of Moving Wheel Load Amplitude and Interface Condition on Flexible Pavement Responses," Preprint CD, prepared for the 85th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 22–26, 2006.

APPENDIX A

Survey Questionnaire

NCHRP Synthesis 42-08: Full-Scale Accelerated Pavement Testing
Section 1: Administrative information
Dear Full-scale APT owner, manager, researcher or interested party

The Transportation Research Board (TRB) is preparing a synthesis on Significant Findings From Full-Scale Accelerated Pavement Testing. This is being done for the National Cooperative Highway Research Program, under the sponsorship of the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration.

This questionnaire is part of the effort in NCHRP Synthesis Topic 42-08 to gather information on the respondents' perspectives on significant findings from full-scale accelerated pavement testing (APT). There are 10 sections in the questionnaire and a total of 60 questions. The sections cover general perspectives on full-scale APT, full-scale APT device owner and research program manager questions, and full-scale APT researcher and engineer questions. The first two sections should be completed by all respondents, while the remaining sections should be completed by one representative of each full-scale APT device/research program or researchers and engineers involved in the specific program.

DOCUMENTATION

If there is any specific documentation that you would like to submit to the project team, please contact the Principal Investigator (wynand.steyn@up.ac.za) for the most appropriate channel to submit these. There are several questions in the questionnaire where a text box is provided for supplying more information. Please do not use carriage returns when entering data in these text boxes, rather paste text as one large paragraph.

Where documents exist that summarize such information, you are welcome to either provide the link to the document (if it is available on a website) or indicate that you send the document via a separate e-mail. This procedure is followed to save you time on completing the questionnaire.

This questionnaire is sent to owners and managers of full-scale APT facilities, researchers using APT data, and all U.S. state departments of transportation. Your cooperation in completing the questionnaire will ensure the success of this effort. If you are not the appropriate person at your agency or facility to complete this survey, please forward it to the correct person, or send an e-mail to the Principal Investigator indicating the correct contact person.

Please complete and submit this survey by 8 April 2011. We estimate that it should take no more than 45 minutes to complete Sections 1 and 2 (information for all participants) and another *180 minutes* to complete the remainder of the questionnaire (for APT device owners and data users).

If you have any questions, please contact our principal investigator—Prof. Wynand JvdM Steyn at: wynand.steyn@up.ac.za, Tel +2712 4202171 (South Africa), Skype—wynandjvdms

QUESTIONNAIRE INSTRUCTIONS

To view and print the entire questionnaire, Click on the following link: http://appv3.sgizmo.com/users/64484/NCHRP_Synthesis_4208_Fullscale.htm; and print using “control p”

To save your partial answers, or to forward a partially completed questionnaire to another party, click on the “Save and Continue Later” link in the upper right hand corner of your screen. A link to the partial survey will be e-mailed to you or a colleague.

To view and print your answers before submitting the survey, click forward to the page following question 60. Print using “control p”

To submit the survey, click on “Submit” on the last page.

Any supporting materials can be sent directly to Prof. Steyn by e-mail or at the postal address shown at the end of the survey.

Section 1:

Please enter the date (MM/DD/YYYY):_______________________________
Please enter your contact information.
First Name: ____
Last Name: ____
Title: ____
Agency/Organization: ____
Street Address: ____
Suite: ____
City: ____
State: ____
Zip Code: ____
Country: ____
E-mail Address: ____
Phone Number: ____
Fax Number: ____
Mobile Phone: ____
URL: ____

1.) **My organization (or I in my personal capacity)** is interested **in taking part in this questionnaire based on our interest and/or involvement with full-scale APT.**

( ) Yes—this option will take you to the next section and lead you through the various questions based on your level of interest and involvement.
( ) No—this option will take you to the last page and will not require from you to answer any of the questions.

Section 2: General perspectives (all respondents)

2.) **How do you view the importance of full-scale APT?**

( ) High
( ) Medium
( ) Low
( ) None

3.) **What do you see as the roles of full-scale APT? Please indicate all the relevant roles.**

[ ] Basic materials (pavement layer) research
[ ] Pavement structure work
[ ] Rehabilitation option selection
[ ] Fundamental research (long term)
[ ] Parameter research (temperature, moisture, etc.)
[ ] Traffic loading
[ ] Development of guidelines
[ ] Academic research
[ ] Evaluate specific application issues
[ ] Commercial evaluations
[ ] Other

4.) What do you see as the future of APT? Please indicate all relevant options.

☐ Everything has been done—close it
☐ Normal part of operation when required
☐ Growing
☐ Simulations and advanced computer analyses should be used
☐ Other

5.) What do you view as the benefits of full-scale APT? Please indicate all relevant options.

☐ None
☐ Improved structural design methods
☐ Improved material design methods
☐ Evaluation of novel materials and structures
☐ Development of performance-related specifications
☐ Material databases
☐ Improved performance modeling
☐ Improved pavement management
☐ Better understanding of variability
☐ Warranty contracts
☐ Weather databases
☐ Other

6.) What are the main opportunities to disseminate full-scale APT research information? Please indicate all relevant options.

☐ General engineering conferences
☐ Focused transportation conferences
☐ Focused pavement engineering conferences
☐ Focused APT conferences
☐ General engineering journals
☐ Focused transportation journals
☐ Focused pavement engineering journals
☐ Focused APT journals
☐ Electronic journals
☐ Meetings such as TRB
☐ Other

7.) What is your perception of the way that APT has/should change the pavement engineering world? Please indicate all relevant options.

☐ Academic benefits
☐ Internal organizational training and education
☐ Fundamental understanding of pavement structures
☐ Development of new materials
☐ Proving new techniques and materials
☐ Specific examples in your area
☐ Other

8.) In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column.

TRB AFD40: ____________________________
COST: ____________________________
HVSIA: ____________________________
MLS user group: ____________________________
South African APT advisory committee: ____________________________
NCAT: ____________________________
CAPT: ____________________________
FEHRL: ____________________________
Midwest States Accelerated Pavement Testing Pooled Fund Program (states of Iowa, Kansas, Nebraska and Missouri): ____________________________
APT conferences: ____________________________
TERRA: ____________________________
Other: ____________________________

9.) **What do you view as the most significant finding of full-scale APT in the last decade (since 2000)? Please respond in terms of your own program as well as your perception of international programs. Also indicate your perception of any significant future findings required (holy grails).**

Most significant finding—own full-scale APT program: ___________________________
Most significant finding—international full-scale APT program: ___________________________
Future significant findings required: ___________________________

10.) **Do you own a full-scale APT device?**

○ Yes
○ No

11.) **Do you have access to a full-scale APT device (and therefore APT data that you can analyze)?**

☐ Yes (Continue to Question 12)
☐ No (Questionnaire completed—go to end)

Section 3: Full-scale APT device owner and research program managers

12.) **Describe the type of access that you have to a full-scale APT device.**

☐ Own
☐ Rental
☐ Borrow without financial cost
☐ Share
☐ Part of consortium
☐ Other

13.) **Provide details of the full-scale APT device that you own/use. Description according to selection of specific options. Please provide a website link to your full-scale APT device homepage where more details are available (including official photos)**

	Selection	Additional information
Mobile/fixed		
Linear/non-linear (circular, elliptical)		
Uni/bi-directional loading		
Number of axles		
Own power (diesel/electric/other)/shore power		
Field site/fixed site		
Roads/airfields		
Fixed device/trucks (automated or manually driven)		
Load range (range in kN—indicate full load for all tires as well as range per tire)		
Tire details (size, type, inflation pressure range, other)		
Tire wander options		
Suspension (present or not, types possible, permanent or not, etc.)		
Temperature control options		
Speed range		
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location, etc.)?		
APT webpage link		
Other		

14.) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table. Please provide additional information on the following aspects where appropriate—which new parameters are measured (not listed in the table), which parameters that you view as important are not measured and why (i.e., lack of instruments?). Provide links to documents/specifications used for selection, installation, calibration, and use of instruments (if it exists). Provide information on documents used to guide forensic analysis of the pavement distress observed through the various instruments (documents only). Please provide full details on sensors (i.e., names, supplier, etc.)

	Instrument used	Details—background on instrument, commercial or in-house developed (add links to documents here)
Permanent surface deformation		
Permanent surface strain		
Permanent in-depth deformation		
Permanent in-depth strain		
Elastic surface deflection		
Elastic surface strain		
Elastic in-depth deflection		
Elastic in-depth strain		
Density		
Temperature		
Moisture		
Stiffness		
New parameter (list)		
Important but not measured (list)		
Other—please provide details		

15.) Provide a description of the nature or purpose of your APT program (select all that may be applicable in the first column and indicate the primary nature in the second column).

	All applicable	Primary nature
National research program		
State DOT research program or roads agency		
Academic research plan		
Commercial research plan		
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

16.) Provide a summarized (bulleted version indicating major dates and topics only, not more than a page) history of your program by completing the table and adding explanatory notes. Please provide a link to a website or document if this information is covered elsewhere already.

	Details
Date of initiation of program	
Number of pavement sections tested	
Typical duration of APT tests in months	
Typical number of repetitions per test	
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	
Estimated capital cost of APT equipment	
Number of staff—Managerial/administrative	
Number of staff—Professional	
Number of staff—Technical	

17.) Provide information on your current research program (what are you busy with now—add information on overall focus, pavement/material types, etc.). Add links to possible planning documents with more information. ____________
____

18.) Provide information of your future research plan (5-year plan in broad terms—indication of main expected research areas. Indicate if no medium term plans are made, indicate whether this is part of an agency-wide plan or just for this facility). Add links to possible planning documents with more information. ____
____

19.) Which of the following full-scale APT types of tests are you conducting?

	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)			
Dedicated constructed test sections (test pit)			
In-service field test sections			
Rehabilitation option comparison			
Other			

20.) Provide information on your funding model and levels [if more than one source, indicate percentage per funding agency (sponsor) type in percentage].

	Model used	Funding levels (annual budget—US$ 2010)
Funding agency (sponsor)		
Local/state government		
National government		
International		
Consortium		
Commercial		
Academic		
Other		
Short-term (project linked)		
Long-term (program linked)		
Intermittent/ad hoc		
Is funding guaranteed?		
Links to reference documents		

21.) Provide typical information of cost of APT (no commercially sensitive information needs to be provided). Indicate the number of years and type of projects on which the cost is based (i.e., 10 years of dedicated long-term tests or 1 year of 8 ad hoc tests).

	Total budget (US$ 2010)	Number of years	Type of projects
Total budget			
Operational budget			
Maintenance budget			
Staff budget			
Construction budget			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short term studies)			
Links to reference documents			

22.) Provide an indication of any planned new developments on your device (updates to device, new instruments, new initiatives, etc.). ____

23.) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program (LTPP refers to both SHRP LTPP sections as well as local LTPP sections that are not part of the SHRP LTPP sections). Select all applicable options.

[ ] APT and laboratory
[ ] APT and LTPP
[ ] APT and field
[ ] APT, laboratory and LTPP
[ ] APT, laboratory and field
[ ] APT, laboratory, field and LTPP
[ ] Other
[ ] Links to reference documents

24.) Provide information on the major specific tests that were conducted during the last decade. These are your major/significant achievements. What was the effect of these programs on your department/research group/commercial activities, etc. (Objective, materials/structure, type of funding, type of outputs, etc.)? ____

25.) Provide an indication of the standard way in which full-scale APT information from your program is being disseminated into industry (provide information for academic dissemination, commercial dissemination, and industry dissemination). Please provide official links to information (official website/database with reference lists and downloadable papers/reports if available) in the text boxes.

[ ] Academic dissemination (i.e., dissertations and theses)
[ ] Commercial dissemination (i.e., reports, websites, news releases, etc.)
[ ] Funding agency (sponsor) dissemination (reports, other)
[ ] Industry dissemination (i.e., reports, websites, news releases, etc.)
[ ] Conferences, meetings, and journals
[ ] Other (i.e., organization database, organization website, wikis, etc.)

26.) What do you perceive as the major influence that your full-scale APT program had on academia/industry over the last 5 to 10 years? Did it make a measureable difference?

____

27.) How do you measure/evaluate the benefit of your program in industry—benefit/cost studies, economic analyses, seminar feedback, others? Provide indications of calculated parameters (i.e., benefit cost ratios) where applicable, or links to reports with this information.

____

28.) What is your estimate of the return on investment (cost benefit ratio) for your facility for the testing performed? Please add references to supporting literature where available.

- ○ 1 to 5
- ○ 6 to 10
- ○ 11 to 20
- ○ 21 to 30
- ○ 31 and up

29.) Why are you currently continuing with your APT program?

____

30.) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices).

____

31.) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis? What processes are followed to enable such researchers to obtain access to this data? (only relevant to owners of APT devices).

- ☐ Data available to non-APT owners
- ☐ Data shared with other APT programs
- ☐ Process used
- ☐ Links to reference documents

Section 4: Full-scale APT researcher/engineer/user (this section is to be completed by all APT data users—regardless of whether you use your own device or not)

32.) Where do the data that you use in your research originate from?

- ☐ Focused research program—own organization
- ☐ Focused research program—other organization
- ☐ Full-scale APT database—own organization
- ☐ Full-scale APT database—other organization
- ☐ Other

33.) Do you only use data from individual sections in your research or a combination of selected sections or a whole research program?

- ☐ Individual sections
- ☐ Combinations
- ☐ Others

34.) Who is your typical client (select all applicable)?

- ○ Funding agency (sponsor)
- ○ State DOT/roads agency
- ○ Academic institution
- ○ External clients (non-commercial)
- ○ External clients (commercial)
- ○ Other

35.) How do you combine full-scale APT, laboratory, field, and LTPP data in your research?

____

36.) How often are full-scale APT data used in conducting graduate studies (masters or doctorate level)?

- ☐ All projects
- ☐ Selected projects
- ☐ Only ad hoc
- ☐ Never

37.) How many Masters and Doctorate degrees were completed based on (partly or fully) full-scale APT data between 2000 and 2010 (provide links to copies of theses)?

	Completed	Current	Links to theses
Masters			
Doctorate			
Other			

38.) What is the importance of economic analyses of the investigated technology in your research program?

[ ] Conducted during test planning as motivation
[ ] Conducted afterwards as standard step
[ ] Conducted afterwards as ad hoc activity
[ ] Not done

39.) Which techniques do you use to conduct these economic analyses?

____

40.) Provide a list of your personal papers/reports on full-scale APT over the last decade (full references required as per standard TRB paper requirements). If these are located in a web-accessible database/site, please provide the address. If possible, please indicate the field of interest of each specific document (general APT, materials, pavement structure, modeling/analysis, program evaluation, instrumentation). ______________________________________

Section 5: The following questions are more detailed with respect to actual studies and detailed aspects of full-scale APT.

41.) What is the basis of the selection of full-scale APT test sections in your program?

[ ] Official research program
[ ] Ad hoc test selection
[ ] Academic interest
[ ] Other

42.) Indicate the type of surfacing pavement layers **that you evaluated using full-scale APT.**

[ ] Unpaved
[ ] Seal/bitumen surface treatment
[ ] Hot mix asphalt
[ ] Warm mix asphalt
[ ] Cold mix asphalt
[ ] Concrete (all thick concrete pavement layers)
[ ] Ultra-thin reinforced concrete
[ ] Ultrathin white-topping
[ ] Composites
[ ] Other

43.) Indicate the type of pavement base layers **that you evaluated using full-scale APT.**

[ ] Sand
[ ] Clay
[ ] Granular
[ ] Cement stabilized
[ ] Emulsion stabilized
[ ] Other stabilized (define)
[ ] Asphaltic
[ ] Composite
[ ] Recycled
[ ] Other

44.) Indicate the type of pavement subbase and subgrade layers **that you evaluated using full-scale APT.**

[ ] Sand
[ ] Clay
[ ] Granular
[ ] Cement stabilized
[ ] Emulsion stabilized
[ ] Other stabilized
[ ] Other

45.) Which are the structural distress types **typically evaluated for** asphalt surfacing layers **in your full-scale APT program [please add failure threshold if available (i.e., 20 mm rut)]?**

[ ] Raveling
[ ] Bleeding
[ ] Cracking
[ ] Rutting
[ ] Fatigue
[ ] Low temperature cracking
[ ] Moisture damage/stripping
[ ] Aging
[ ] Aggregate loss
[ ] Other

46.) Which are the structural distress types **typically evaluated for** concrete surfacings **in your full-scale APT program [please add failure threshold if available (i.e. 20 mm rut)]?**

[ ] Cracking
[ ] Stress ratio
[ ] Joint failure
[ ] Faulting
[ ] Punchouts
[ ] Erosion of support
[ ] Fatigue
[ ] Curling and warping
[ ] Load transfer failure
[ ] Spalling
[ ] Steel rupture
[ ] Debonding
[ ] Other

47.) Which are the structural distress types **typically evaluated for** base and subbase layers **in your full-scale APT program [please add failure threshold if available (i.e. 20 mm rut)]?**

[ ] Permanent deformation
[ ] Shear
[ ] Cracking (define type?)
[ ] Frost/thaw damage
[ ] Collapsing
[ ] Crushing
[ ] Carbonation
[ ] Swelling
[ ] Other

48.) Which are the functional distress types **typically evaluated in your full-scale APT program?**

[ ] Safety
[ ] Environment
[ ] User cost
[ ] Roughness
[ ] Functional distress not deemed applicable to full-scale APT
[ ] Other

49.) Which functional safety **aspects were evaluated?**

[ ] Rutting
[ ] Skid resistance
[ ] Punchouts
[ ] Delamination
[ ] Roughness
[ ] Spalling
[ ] Functional aspects not deemed applicable to full-scale APT
[ ] Other

50.) Which environmental aspects **are typically evaluated during full-scale APT?**

[ ] Noise
[ ] Dust pollution
[ ] Not deemed applicable to full-scale APT
[ ] Other

Section 6: Loading and environment questions

51.) To which of the following load characteristics **do you relate full-scale APT data?**

[ ] Applied wheel load
[ ] Tire inflation pressure
[ ] Tire contact stress
[ ] Tire type
[ ] Load configuration
[ ] Suspension system
[ ] Vehicle–pavement interaction/dynamics
[ ] Channelized/wandering traffic
[ ] Speed
[ ] Rest periods
[ ] Overloading
[ ] Pavement roughness
[ ] Other

52.) To which of the following environmental data **do you relate full-scale APT data?**

[ ] Ambient air temperature
[ ] Pavement temperature
[ ] Rainfall
[ ] Relative humidity
[ ] Aging
[ ] Water table
[ ] Drainage
[ ] Depth to bedrock
[ ] Other

53.) Which of the following environmental parameters **are** controlled **during your full-scale APT tests? Please provide typical ranges for applicable parameters in the textbox.**

[ ] Ambient air temperature (temperature ranges)
[ ] Pavement temperature (temperature ranges)
[ ] Water application (method)
[ ] Relative humidity
[ ] Aging (method)
[ ] Subgrade moisture
[ ] Drainage
[ ] Other

Section 7: Materials and tests questions

54.) Which of the following bituminous-based materials **have been tested?**

[ ] HMA continuously graded
[ ] HMA open graded
[ ] HMA semi-gap graded
[ ] HMA gap graded
[ ] HMA large stone
[ ] SMA
[ ] HMA porous
[ ] HMA RAP
[ ] Gussasphalt
[ ] HMA sand
[ ] Warm mix asphalt—Add process description
[ ] Cold mix asphalt—Add process description
[ ] Surfacing seals—Single
[ ] Surfacing seals—Double
[ ] Surfacing seals—Cape
[ ] Surfacing seals—Other
[ ] Composite with concrete—Description
[ ] Other

55.) Which of the following cement-based materials **have been tested?**

[ ] JCP
[ ] CRCP
[ ] Concrete blocks
[ ] Doweled
[ ] Other combinations
[ ] Whitetopping—Description
[ ] Ultra-thin reinforced concrete
[ ] Composite with asphalt—Description
[ ] Other

56.) Which of the following material properties **have been related to full-scale APT performance?**

[ ] Stiffness
[ ] Poisson's ratio
[ ] Density
[ ] Gradation
[ ] Strength (concrete)
[ ] Erodibility
[ ] Atterberg limits
[ ] Volumetric properties
[ ] Binder type
[ ] Binder content
[ ] Film thickness
[ ] Moisture content
[ ] Visco-elastic properties
[ ] Aging index
[ ] Tensile strength
[ ] Compressive strength
[ ] Flexural strength
[ ] Stiffness modulus
[ ] Other

57.) Which of the following laboratory tests **are used in conjunction with your full-scale APT program?**

[ ] Standard asphalt tests
[ ] Standard bitumen tests
[ ] Standard concrete tests
[ ] Standard granular/soil tests
[ ] Standard stabilized layer tests
[ ] Wheel tracking
[ ] PTF
[ ] MMLS3
[ ] French rut tester
[ ] Hamburg tester
[ ] Asphalt Pavement Analyzer
[ ] Direct tensile
[ ] Indirect tensile
[ ] Bending beam fatigue
[ ] Strain at break
[ ] Cantilever fatigue
[ ] Semi-circular bending
[ ] Triaxial
[ ] Dynamic creep
[ ] Static creep
[ ] Gyratory
[ ] Vibratory
[ ] Kango hammer
[ ] Other

58.) Which of the following field tests **are used in conjunction with your full-scale APT program?**

[ ] Penetration tests (i.e., DCP)
[ ] Density/moisture
[ ] Benkelman beam (or modified)
[ ] Rolling dynamic deflectometer
[ ] Plate load
[ ] Seismic (i.e., PSPA)
[ ] Ground Penetrating Radar (GPR)
[ ] FWD
[ ] Light FWD (LFWD)
[ ] Permeability
[ ] In situ strength/cores
[ ] Relative crack/joint movement
[ ] Scaled trafficking
[ ] Other

Section 8: Modeling and analysis questions

59.) Which of the following pavement/materials modeling aspects **do you relate to full-scale APT data?**

	Data origin (instrumentation used for data)	Model type used						
		Elastic layer	Visco-elastic layer	Elasto-plastic	Finite element	Iterative	Statistical	Other
Stress/strain								
Deflection								
Deformation								
Fatigue								
Back-calculation								
Load equivalence								
Pavement serviceability								
Other								

Section 9: Construction/Rehabilitation questions

60.) Which aspects of pavement engineering did you evaluate that may enhance construction and rehabilitation of pavements? Please provide details where applicable.

☐ Unconventional materials
☐ Gradients
☐ Joints
☐ Slippage
☐ Buried pipes and culverts
☐ Bridge deck joints
☐ Road markings
☐ Durability
☐ Traffic accommodation
☐ Compaction
☐ Patching
☐ Reinforcement
☐ Risk management
☐ Preventative maintenance
☐ Quality assurance/quality control
☐ Surface texture
☐ Surface tolerance
☐ Surface drainage
☐ Subsurface drainage
☐ Other

Section 10: References

61.) Provide any references or links to references that were not specifically covered already in this questionnaire. Please use the standard TRB reference format and add links to web-accessible databases where applicable. ____________________ ____

Thank You!

Thank you for taking our survey. Your response is very important to us. If you have any questions or comments, please feel free to contact Prof. Wynand JvdM Steyn at:

E-mail: **wynand.steyn@up.ac.za**
Skype: wynandjvdms
Post: Department of Civil Engineering, University of Pretoria, Lynnwood road, Hatfield, 0002, South Africa Phone (South Africa): +2712 420 2171

APPENDIX B

Survey Respondents and Interviewees

The list of contact people to which the request for participation in the questionnaire was sent is shown in Table B1.

TABLE B1
PROGRAMS AND FACILITIES CONTACTED TO TAKE PART IN QUESTIONNAIRE

United States	International
Alabama DOT	Australia—Australian Road Research Board (ARRB)
Alaska DOT	Germany—BAST
Arkansas DOT	Belgrade—Highway Institute
California DOT	Brazil—Federal University of Rio Grande do Sul
Colorado DOT	Spain—Centro de Estudios de Carreteras (CEDEX)
Connecticut DOT	China—Chang’an University
Costa Rica	China—Liaoning Province Communication Research Institute
Delaware DOT	China—Merchants Chongqing Communications Research & Design Institute
Federal Aviation Administration (FAA)	China Tongji University
Federal Highway Administration (FHWA)	Denmark—Danish Road Institute
Florida DOT	Netherlands—Delft University of Technology (Lintrack)
Georgia DOT	Switzerland—EMPA
Idaho DOT	South Africa—Gautrans
Illinois DOT	South Africa—Council for Scientific and Industrial Research (CSIR)
Indiana DOT	Iceland—Icelandic Road Administration
Iowa DOT	India—Central Road Research Institute
Kansas DOT	Italy—Roads Department
Kentucky DOT	Japan—Public Works Research Institute (PWRI)
Louisiana DOTD	France—Laboratoire Central des Ponts et Chausses—LCPC
Maryland SHA	Norway—Norwegian Public Roads
Massachusetts DOT	United Kingdom—University of Nottingham
Michigan DOT	New Zealand—Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF)
Minnesota DOT (MnROAD)	Romania—National Roads Department
Mississippi DOT	South Korea—South Korea Highway Corporation (ETRI)
Missouri DOT	United Kingdom—Transportation Research Laboratory (TRL)
Montana DOT	Canada—University of Waterloo
National Center for Asphalt Technology (NCAT)	Ireland—University of Ulster
Nevada DOT	Sweden—Swedish National Roads and Transport Institute (VTT)
New Hampshire DOT	
New Mexico DOT	
New York DOT	
North Dakota DOT	
Ohio DOT	
Oregon DOT	

(*Continued on next page*)

TABLE B1
(*continued*)

United States	**International**
South Carolina DOT	
South Dakota DOT	
Tennessee DOT	
Texas DOT	
US Army Corps of Engineers Research and Development Center—Cold Regions Research and Engineering Laboratory (CRREL)	
U.S. Army Corps of Engineers Research and Development Center—Waterways Experimental Station (ERDC)	
University of California Pavement Research Centre (UCPRC)	
Utah DOT	
Vermont DOT	
Washington DOT	
Wyoming DOT	

APPENDIX C

Full-Scale Accelerated Pavement Testing Programs and Facility Descriptions

This appendix contains information on each of the responding full-scale accelerated pavement testing (f-sAPT) programs. The information supplied by the respondents is the main source for these summaries. Additional information has been requested from respondents where possible. There are some facilities missing in the summary after they did not respond to the requests to take part in the project. Some of these facilities may have been terminated.

A standard reporting format is used for each of the responding programs. Where information was not supplied by the respondent, the block is left open, except where a whole section was left out, in which case the section is deleted from the specific response. Only the responses on selected questions are shown. These questions are deemed to be indicative of specific differences between the various programs. The question numbers are shown for each of the tables. A summary of responses for all questions are provided in Appendix D.

Questionnaire information—USA programs

California Department of Transportation/UCPRC

Section 1

Agency/Organization	University of California Pavement Research Center
Location (City, State, Country)	Davis

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Mobile	
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Both	
Number of axles	1	
Own power (diesel/electric/other)/shore power	Both	
Field site/fixed site	Both	UC Davis and various locations in California
Roads/airfields	Roads	Can do airfields but not the focus
Fixed device/trucks (automated or manually driven)	Fixed	
Load range (range in kN—indicate full load for all tires as well as range per tire)	6.7 to 45 kip (30 to 200 kN) for two tires	
Tire details (size, type, inflation pressure range, other)	Truck (G159) and aircraft, pressure about 700 kPa	
Tire wander options	yes	Programmable
Suspension (present or not, types possible, permanent or not, etc.)	no	
Temperature control options	Heating and cooling	50 to 122°F (10 to 50°C) pavement temperature
Speed range	1.9 to 12.4 mph (3 to 20 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	yes	
APT webpage link	http://www.ucprc.ucdavis.edu/	
Other	None	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	MDD and laser profilometer	CSIR developed
Permanent surface strain		
Permanent in-depth deformation	MDD	Developed by CSIR
Permanent in-depth strain		
Elastic surface deflection	Road Surface Deflectometer, and Joint Deflection Measurement Device	CSIR
Elastic surface strain		
Elastic in-depth deflection	MDD	CSIR
Elastic in-depth strain	Strain gauge	Commercial, CTL group
Density	Nuclear	
Temperature	Thermocouple	Omega
Moisture	Decagon sensors	Commercial
Stiffness	HWD	Dynatest
New parameter (list)		
Important but not measured (list)		
Other—please provide details	Pressure cell	GeoCon

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	yes	Evaluate new designs, new tires, new materials, develop ME models, etc.
Roads agency or state research program	yes	Same as national
Academic research plan	yes	Integral part of graduate student program
Commercial research plan	yes	Evaluate commercial technologies if requested
Partnership program	yes	Costs shared by industry and state
International cooperative program	yes	HVSIA plus other countries depending on projects
Ad hoc use of device—no specific program	yes	Various research needs for modeling
Local research needs	yes	Results shared with local government.
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1994
Number of pavement sections tested	110
Typical duration of APT tests in months	2
Typical number of repetitions per test	300,000
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	0.5 in. (12.5 mm) of total surface rut or 8.2 ft/ft^2 (2.5 m/m^2)of surface cracking
Estimated capital cost of APT equipment	$3 million (3 machines)
Number of staff Managerial/administrative Professional Technical	 1 2 4

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)		x	
In-service field test sections		x	
Rehabilitation option comparison		x	
Other		x	

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	yes no yes yes yes yes no	
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc	 yes yes yes	
Is funding guaranteed?	no	

(22) Provide an indication of any planned new developments on your device.

Information	Upgrade data acquisition system, develop new device for in-depth deflection measurement

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	Compare performance trends and use lab data to do modeling for APT Use APT to calibrate model and use model to predict field performance Direct comparison of performance trends, as well as using model to interpret all results	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	PostgreSQL database on a server, with raw data in CSV format.

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	

Federal Aviation Administration (FAA)

Section 1

Agency/Organization	Federal Aviation Administration
Location (City, State, Country)	Atlantic City International Airport

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Fixed	
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Uni and bi-directional loading	
Number of axles	10	
Own power (diesel/electric/other)/shore power	Own power (electric)	
Field site/fixed site	Fixed site	
Roads/airfields	Airfields	
Fixed device/trucks (automated or manually driven)	Fixed device (automated)	
Load range (range in kN—indicate full load for all tires as well as range per tire)	900 kip (4 008 kN)	75 kip (334 kN) per wheel
Tire details (size, type, inflation pressure range, other)	Radial tires, 52x21.0R22	Inflation pressure depends on wheel load and rated deflection, can go up to 250 psi (1 723 kPa)
Tire wander options	Wander can be programmed	
Suspension (present or not, types possible, permanent or not, etc.)	no	
Temperature control options	no	
Speed range	15 mph (24 km/h) maximum	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed,	yes	

load, location etc.)?		
APT webpage link	http://www.airporttech.tc.faa.gov	
Other		

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial, or in-house developed
Permanent surface deformation	Laser profiler, straight edge	In-house developed
Permanent surface strain		
Permanent in-depth deformation	Multiple Depth Deflectometers (MDDs)	Commercial
Permanent in-depth strain	MDDs	Commercial
Elastic surface deflection	MDDs	
Elastic surface strain		
Elastic in-depth deflection	MDDs	Commercial
Elastic in-depth strain	MDDs	Commercial
Density	Nuclear gauge (for HMA), sand cone (aggregate base and subbase), drive cylinder (subgrade)	Commercial
Temperature	Thermistor and thermocouples	Commercial
Moisture	Laboratory (on samples collected from test sections)	
Stiffness	Laboratory tests, HWD tests, field CBR, LWD, PSPA, D-PSPA, vane shear, DCP	Commercial
New parameter (list)		
Important but not measured (list)	Moisture content	
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	yes	Support development of standards and specifications for airport pavements for the FAA
Roads agency or state research program		
Academic research plan		
Commercial research plan		
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	April 1999
Number of pavement sections tested	23
Typical duration of APT tests in months	12 from construction to demolition
Typical number of repetitions per test	Varies from 100 to 30,000
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Complete structural failure
Estimated capital cost of APT equipment	$14 million just for the test vehicle, $21 million total
Number of staff Managerial/administrative Professional Technical	 3/1 3 9

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)			
In-service field test sections		x	
Rehabilitation option comparison		x	
Other		x	

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	FAA	US $10 million
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?	Depends on federal budget. Has been good so far.	

(22) Provide an indication of any planned new developments on your device.

Information	Additional load modules were added recently; always working on improving control systems.

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	APT results are used for improving failure models, laboratory testing is used for advanced material characterization, field test sections (instrumented pavements at active commercial airports) are used for studying combined environmental and load effects. All the information collected is used for improving airport pavement thickness design procedures and developing FAA advisory circulars.	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections).*

Database type	Sequel Server database.

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	Through website http://www.airporttech.tc.faa.gov

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program		
Ad hoc test selection		
Academic interest		
Other	Selected by standards team and a working group	

Federal Highways Administration (FHWA)

Section 1

Agency/Organization	Federal Highway Administration
Location (City, State, Country)	McLean, Virginia

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection
Mobile/fixed	Fixed, but has mobile capabilities—has only rarely been used in the very beginning of the program
Linear/non-linear (circular, elliptical)	Linear ALF, Australian designed system
Uni/bi-directional	Uni directional
Number of axles	1
Own power (diesel/electric/other)/ shore power	Electric
Field site/fixed site	Fixed, but has mobile capabilities—has only rarely been used in the very beginning of the program
Roads/airfields	Roads
Fixed device/trucks (automated or manually driven)	Fixed Wheels are powered and driven rather than the wheel carriage pulled or pushed
Load range (range in kN—indicate full load for all tires as well as range per tire)	9.9 to 16.6 kip (44 to 74 kN) Uses steel plates, dead weight on suspension
Tire details (size, type, inflation pressure range, other)	Dual 11R22.5 Super single 425 Typically between 100 to 120 psi (690 to 827 kPa)
Tire wander options	
Suspension (present or not, types possible, permanent or not, etc.)	Air bag suspension Requires landing of wheel to be tuned and minimize or eliminate load spike
Temperature control options	
Speed range	As low as 2.5 to 3 mph (4 to 5 km/h) and high as 10 to 11 mph (16 to 18 km/h)
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Speed, position and load can be measured during operation Pavement layer instrumentation is independent from ALF operation (not integrated)
APT webpage link	http://www.fhwa.dot.gov/research/tfhrc/labs/pavement/index.cfm
Other	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Rod and level survey Manual laser profiler	Manual laser profiler was developed in-house

Permanent in-depth deformation	Layer deformation measurement assembly (LDMA) which is a horizontal steel plate between asphalt and aggregate base and vertical collapsible tube with removable surface cap Multi Depth Deflectometer (MDD)	LDMAs are cheap, disposable items (8 per test site along the wheel path) is a simple, in-house Commercial MDD
Elastic surface deflection	LVDTs	Rarely used, once in past
Elastic in-depth deflection	MDD	
Density	Not monitored except for HMA cores for non-routine evaluations	
Temperature	Thermocouples	Embedded at different depths with 20 mm depth used for temperature control
Moisture	Time Domain Reflectometry	Eliminating older generation system and planning for a contemporary system
Stiffness	FWD Portable Seismic Pavement Analyzer (PSPA)	
New parameter (list)	Exploring the use of multiple antenna, stepped frequency Ground Penetrating Radar system with enhanced resolution to evaluation subsurface cracking and damage	In research stage

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	FHWA's Accelerated Loading Facility is one of several laboratories within the pavement materials program (e.g., chemistry, aggregates, bituminous, PCC) and addresses research needs applicable to all regions of the country	Project selection is guided by an agency-wide strategic plan
Roads agency or state research program		
Academic research plan		
Commercial research plan		
Partnership program	FHWA experiments can and are funded by pooled/partnered states	
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	Began in mid-1980s
Number of pavement sections tested	Tire study 1993 Superpave Ultrathin whitetopping 2002 Superpave
Typical duration of APT tests in months	Rutting 1–2 weeks Fatigue 1–4 months
Typical number of repetitions per test	One out of about 12 test sections in each experiment will be duplicated
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	15 to 25% cracked area 1 in. (25 mm) rutting

Estimated capital cost of APT equipment	1986 ALF1 1991 ALF2
Number of staff Managerial/administrative Professional Technical	1 FHWA managerial 1 technical (contract support) 2 to 3 operational (contract support)

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	yes		Dedicated constructed test sections (normal construction)
Dedicated constructed test sections (test pit)		A test pit is on site but can be loaded by pulsing actuator that does not meet definition of full-scale APT	Dedicated constructed test sections (test pit)
In-service field test sections		Never, but very early in program one ALF unit traveled to several field sites	In-service field test sections
Rehabilitation option comparison	Recently begun utilizing used/tested sections with thin overlay		Rehabilitation option comparison
Other		x	

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funder/sponsor Local/state government National government International Consortium Commercial Academic Other	Combination; mostly federal funds with state participant funds used for construction of test sections	
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc	Program-linked	
Is funding guaranteed?	No, but with tractable lead times between critical time periods	

(22) Provide an indication of any planned new developments on your device.

Information	Electronic control systems are of the late 1980s to early 1990s vintage and are becoming increasingly more difficult to find service and spare parts. Planning for control system upgrade with modern electronics Early 1990s vintage instrumentation data acquisition system has been replaced with contemporary multi-channel.

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory	APT and laboratory	APT and laboratory
APT and LTPP	APT and LTPP	APT and LTPP
APT and field	APT and field	APT and field
APT, laboratory, and LTPP	APT, laboratory, and LTPP	APT, laboratory, and LTPP
APT, laboratory, and field	APT, laboratory, and field	APT, laboratory, and field
APT, laboratory, field, and LTPP	APT, laboratory, field, and LTPP	APT, laboratory, field, and LTPP
Other		

Florida Department of Transportation

Section 1

Agency/Organization	Florida Department of Transportation
Location (City, State, Country)	Gainesville

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Mobile	
Linear/non-linear (circular, elliptical)	linear	
Uni/bi-directional	uni	
Number of axles	half	
Own power (diesel/electric/other)/ shore power	electric	
Field site/fixed site	fixed site	
Roads/airfields	roads	
Fixed device/trucks (automated or manually driven)	fixed	
Load range (range in kN—indicate full load for all tires as well as range per tire)	7 to 45 kips	
Tire details (size, type, inflation pressure range, other)	Dual (11R22.5), Super Single (425/65R22.5), and two new wide-base tires (445/50R22.5 and 455/55R22.5)	Dual and new
Tire wander options	0 to 30 in.	http://materials.dot.state.fl.us/sm
Suspension (present or not, types possible, permanent or not, etc.)	None	
Temperature control options	Radiant heaters installed on both sides of test beam. Insulated panels maintain temperature No cooling device	
Speed range	up to 8 mph	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Typically collect load, speed, tire location	Also collect HVS system information
APT webpage link	http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/index.shtm	
Other	Report on loading assessment	http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/researchreports/pavement/03-463.pdf

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Laser profiler	http://www.dot.state.fl.us/statematerialsoffice/pavement/research/reports/smo/rutmeasurement-r.pdf
Permanent surface strain		
Permanent in-depth deformation		
Permanent in-depth strain		
Elastic surface deflection		
Elastic surface strain	Tokyo Sokki PFL-20-11-5L and 30-11-5L gauges	Have also used other size gauges—http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/documents/instrumentation.pdf

Elastic in-depth deflection		
Elastic in-depth strain	Tokyo Sokki KM-100HAS H-gauge	
Density	Non-nuclear density device	
Temperature	Thermocouple	http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/documents/instrumentation.pdf
Moisture	Moisture probes	http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/documents/instrumentation.pdf
Stiffness	FWD, PSPA, DCP	
New parameter (list)	Have also measured strain and temperature of concrete pavements Recently used LVDTs to measure concrete joint movement	http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/documents/instrumentation.pdf http://www.dot.state.fl.us/statematerialsoffice/pavement/research/reports/smo/uf/slabreplacement.pdf
Important but not measured (list)		
Other—please provide details	Semi-automated cracking analysis	http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/documents/instrumentation.pdf

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program	All research is performed to solve Florida-specific problems.	
Academic research plan		
Commercial research plan		
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	2000
Number of pavement sections tested	More than 200; more than 22 million loaded passes
Typical duration of APT tests in months	Less than 1 month for rutting tests at elevated temperatures, up to 3 months or more for cracking tests
Typical number of repetitions per test	Minimum of 3, often 4 to 5 or more
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Rutting is stopped after achieving 0.5 in. (12.5 mm). Currently, there are no criteria for cracking tests. Cracking tests are conducted until cracks initiate and progress or it is decided to terminate the test.
Estimated capital cost of APT equipment	N/A
Number of staff Managerial/administrative Professional Technical	 1 3 3

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)		x	
In-service field test sections			x
Rehabilitation option comparison	x		
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	Funded by Florida DOT	N/A
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?		

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction	N/A		
Average operational cost per test	N/A		
Annual APT budget (US$)	N/A		
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)	N/A		

(22) Provide an indication of any planned new developments on your device.

Information	Recently installed camera system to identify/measure surface cracks and other surface damage. Will continue to improve this system. (http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/documents/instrumentation.pdf). Recently completed extending test tracks—extension consists of six 13-ft-wide lanes extended an additional 300 ft (total length of 450 ft).

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	Always coordinate APT and lab testing. Typical lab tests include construction QA, dynamic modulus, indirect tensile, Hamburg wheel tracker, and asphalt pavement analyzer (rut measurement). When available, will compare APT results with field results.	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	We have a web-based database where all APT information is stored (reports, photographs, instrumentation data, HVS maintenance files, etc.). Typically, information is stored here after a project is complete. APT information is also stored on a network drive that is backed up nightly. This network is primarily used for active projects.

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	No formal process is in place. Any information will be made available upon request.

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program		
Ad hoc test selection		
Academic interest		
Other	Coordinated effort with pavement/ construction offices and districts.	

Indiana Department of Transportation

Section 1

Agency/Organization	Indiana Department of Transportation
Location (City, State, Country)	West Lafayette

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Fixed	
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Bi-directional	
Number of axles	1	
Own power (diesel/electric/other)/shore power	Electric	
Field site/fixed site	Fixed site	
Roads/airfields	Roads	
Fixed device/trucks (automated or manually driven)	Fixed device	
Load range (range in kN—indicate full load for all tires as well as range per tire)	20 kip (89 kN)	Per axle, two tires
Tire details (size, type, inflation pressure range, other)	255/70R22.5, 90 psi (620 kPa)	Super single
Tire wander options	6 in. (150 mm)	Left and right
Suspension (present or not, types possible, permanent or not, etc.)	Not	
Temperature control options	yes	Heater and air conditioner
Speed range	5 to 10 mph (8 to 16 km/h) edicated operational	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	yes	
APT webpage link	http://rebar.ecn.purdue.edu/APT/	
Other	http://rebar.ecn.purdue.edu/APT/Pages/photos.htm	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Laser and LVDT	Commercial
Permanent surface strain	Strain gauges	Commercial
Permanent in-depth deformation	Laser	Commercial
Permanent in-depth strain	Strain gauges	Commercial
Elastic surface deflection	Laser profiler and LVDT	Commercial
Elastic surface strain	Strain gauges	Commercial
Elastic in-depth deflection	Strain gauges	Commercial
Elastic in-depth strain	None	
Density	Nuclear gauge	Commercial
Temperature	Infrared	Commercial
Moisture	None	
Stiffness	None	
New parameter (list)	Pressure, using pressure meter	Commercial
Important but not measured (list)		
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	yes	
Roads agency or state research program	yes	yes
Academic research plan		
Commercial research plan		
Partnership program	yes	
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	Summer 1992
Number of pavement sections tested	7 projects with numerous sections
Typical duration of APT tests in months	6 to 12
Typical number of repetitions per test	Varied
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Failure
Estimated capital cost of APT equipment	$1 million
Number of staff	
Managerial/administrative	1
Professional	1
Technical	1

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)			x
Dedicated constructed test sections (test pit)	x		
In-service field test sections			
Rehabilitation option comparison	x		
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other		
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc	Contribution from projects	$70,000
Is funding guaranteed?	no	

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction	$70,000 $20,000 $10,000 $40,000 Depends on projects	1 1 1 1	Short term
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)			

(22) Provide an indication of any planned new developments on your device.

Information	http://rebar.ecn.purdue.edu/APT/Pages/newfacility.htm

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	In one office, in one section	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	Hard drive and DVD

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	Only by request

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program	Close to the actual field testing Better control of testing parameters	
Ad hoc test selection		
Academic interest		
Other		

Kansas Department of Transportation

Section 1

Agency/Organization	Kansas Department of Transportation
Location (City, State, Country)	Topeka

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Fixed	
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Bi-directional	
Number of axles	One or two	
Own power (diesel/electric/other)/shore power	Electric	
Field site/fixed site	Fixed site	
Roads/airfields	Roads	
Fixed device/trucks (automated or manually driven)	Fixed device	
Load range (range in kN—indicate full load for all tires as well as range per tire)	1.1 to 5 kip (5 to 22 kN) single axle; double for tandem axle	
Tire details (size, type, inflation pressure range, other)	Conventional over the road	
Tire wander options	yes, up to 6 in. (150 mm)	
Suspension (present or not, types possible, permanent or not, etc.)	Conventional air bag	
Temperature control options	Radiant heat and cooling panels	
Speed range	5 to 7 mph (8 to 11.5 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Dedicated data collection, speed, load, position and strain	
APT webpage link	http://www.kstate.edu/pavements/	
Other	None	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	yes	In-house rut bar
Permanent surface strain		
Permanent in-depth deformation	yes	Commercial gauges
Permanent in-depth strain		
Elastic surface deflection	yes	FWD
Elastic surface strain		
Elastic in-depth deflection		
Elastic in-depth strain		
Density	yes	Nuclear meter
Temperature	yes	Conventional
Moisture	yes	Conventional, TDR
Stiffness		
New parameter (list)		
Important but not measured (list)		
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program	yes	Pavement
Academic research plan		
Commercial research plan	Some	Pavement products
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1993
Number of pavement sections tested	16
Typical duration of APT tests in months	12–15
Typical number of repetitions per test	250,000 to over 1 million
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Rutting or cracking failure
Estimated capital cost of APT equipment	$1.5M
Number of staff Managerial/administrative Professional Technical	 2 3 2

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)			x
Dedicated constructed test sections (test pit)	x		
In-service field test sections		x	
Rehabilitation option comparison	x		
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	 Pooled Fund Direct compensation	 $300,000 $100,000
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?		

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction	$4.5 million 40% 5% 50% 5%	16 year dedicated	Yearly projects
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)	Typical one direction applications are 250,000 to 500,000 per year.		

(22) Provide an indication of any planned new developments on your device.

Information	None

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	Measure material properties. Material characteristics and field measurements of shadow pavements	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	Databases are established for each experiment. Take the form of tables, graphs, and charts.

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	Share based on request for data

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program		
Ad hoc test selection		
Academic interest		
Other	KTRAN program	

Louisiana Department of Transportation and Development

Section 1

Agency/Organization	Louisiana Transportation Research Center
Location (City, State, Country)	Louisiana

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	mobile	ALF
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Uni-D	
Number of axles	1	
Own power (diesel/electric/other)/shore power	Electric	
Field site/fixed site		
Roads/airfields	Road	
Fixed device/trucks (automated or manually driven)	Automated	
Load range (range in kN—indicate full load for all tires as well as range per tire)	9 to 13.5 kip (40 to 60 kN)	
Tire details (size, type, inflation pressure range, other)	11R22.5	Dual
Tire wander options	yes	
Suspension (present or not, types possible, permanent or not, etc.)	N/A	
Temperature control options	no	
Speed range	10 to 12 mph (16 to 20 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	yes	
APT webpage link	N/A	
Other	N/A	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation		
Permanent surface strain		
Permanent in-depth deformation	MDD	SnapMDD
Permanent in-depth strain		
Elastic surface deflection		
Elastic surface strain		
Elastic in-depth deflection	MDD	
Elastic in-depth strain	Strain gauge	
Density		
Temperature		
Moisture	TDR	
Stiffness		
New parameter (list)		
Important but not measured (list)		
Other—please provide details	Pressure cell	Geokon 3500

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program	yes	
Academic research plan		
Commercial research plan		
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1994
Number of pavement sections tested	>15
Typical duration of APT tests in months	12
Typical number of repetitions per test	500,000
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	rutting/cracking
Estimated capital cost of APT equipment	$1.5 million
Number of staff Managerial/administrative Professional Technical	1 2

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)			
In-service field test sections			
Rehabilitation option comparison			
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	State	Varied
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?		

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction	$500,000	1 year	pavement
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)			

(22) Provide an indication of any planned new developments on your device.

Information	1 year pavement

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory	x	
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other		

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections).*

Database type	Hard drive

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	upon request

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program		
Ad hoc test selection		
Academic interest		
Other		

Minnesota Department of Transportation (MnROAD)

Section 1

Agency/Organization	Minnesota Department of Transportation
Location (City, State, Country)	Maplewood

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	N/A	
Linear/non-linear (circular, elliptical)	N/A	
Uni/bi-directional	N/A	
Number of axles	5-axle semi, live traffic, other specific vehicles/ equipment testing	
Own power (diesel/electric/other)/ shore power	N/A	
Field site/fixed site	MnROAD	http://www.dot.state.mn.us/mnroad/
Roads/airfields	Mainline interstate and low volume road, farm loop	
Fixed device/trucks (automated or manually driven)	Manual driven	
Load range (range in kN—indicate full load for all tires as well as range per tire)	80 to 102 kip (360 to 450 kN)	Gross vehicle weight
Tire details (size, type, inflation pressure range, other)	See report	http://www.dot.state.mn.us/mnroad/data/pdfs/semidescription.pdf
Tire wander options	Live traffic	
Suspension (present or not, types possible, permanent or not, etc.)	See Report	http://www.dot.state.mn.us/mnroad/data/pdfs/semidescription.pdf
Temperature control options	None	
Speed range	LVR 40 mph (65 km/h) Mainline 70 mph (113 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	N/A	
APT webpage link	See website	http://www.dot.state.mn.us/mnroad/
Other	See website	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	ALPS, PATHWAYS	http://www.dot.state.mn.us/mnroad/data/pdfs/alps.pdf
Permanent surface strain	N/A	
Permanent in-depth deformation	LVDT	assume this is HMA—http://www.dot.state.mn.us/mnroad/instrumentation/
Permanent in-depth strain	Dynatest, CTL, Geomechanics, Tokyo Sokki	http://www.dot.state.mn.us/mnroad/instrumentation/
Elastic surface deflection	LVDT	http://www.dot.state.mn.us/mnroad/instrumentation/
Elastic surface strain	Dynatest, CTL, Geomechanics, Tokyo Sokki	http://www.dot.state.mn.us/mnroad/instrumentation/
Elastic in-depth deflection	LVDT	http://www.dot.state.mn.us/mnroad/instrumentation/

Elastic in-depth strain	Dynatest, CTL, Geomechanics, Tokyo Sokki	http://www.dot.state.mn.us/mnroad/instrumentation/
Density	DCP, LWD, Intelligent Compaction, sand cone, Humboldt SSG	http://www.dot.state.mn.us/mnroad/data/pdfs/dcp.pdf, http://www.dot.state.mn.us/materials/research_lwd.html, http://www.dot.state.mn.us/materials/researchic.html
Temperature	Thermocouple, thermistor attached to assorted gauges, weather station	http://www.dot.state.mn.us/mnroad/instrumentation/pavementsensors.html#tc
Moisture	Decagon, Irrometer, Campbell Scientific, Sensirion	http://www.dot.state.mn.us/mnroad/instrumentation/sub-surface-sensors.html
Stiffness	See Density	
New parameter (list)		
Important but not measured (list)	Pavement surface temperature, HMA surface strain	
Other—please provide details	Dynamic pressure gauges	http://www.dot.state.mn.us/mnroad/instrumentation/sub-surfacesensors.html#pg

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	x	
Roads agency or state research program	x	x
Academic research plan	x	
Commercial research plan	x	
Partnership program	x	
International cooperative program	x	
Ad hoc use of device—no specific program		
Local research needs		
Other	x	

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1994
Number of pavement sections tested	~125
Typical duration of APT tests in months	Variable (34 days to 17 years)
Typical number of repetitions per test	N/A
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Failure and performance of materials over time
Estimated capital cost of APT equipment	$25 million to build in 1994 and roughly $1 million to operate/year, test cell (500 ft) construction cost vary but is roughly 100K–150K each—U.S. dollars
Number of staff Managerial/administrative Professional Technical	State DOT staff—2 managers Many at the state making it hard to count but 5 MnROAD operations Many at the state making it hard to count but 5 MnROAD operations

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)			x
In-service field test sections	x		
Rehabilitation option comparison	x		
Other	x		

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/State Government National government International Consortium Commercial Academic Other	MnDOT LRRB FHWA, pooled funds TERRA TERRA Partnerships Industry (associations, private companies) University of Minnesota yes	
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?	no	

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction	$1,000,000 part of operations $100,000–150,000 per test section	17	assume for HVS type of cost plus the cost of sensors/monitoring
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)	$15,000/cell/year		Not HVS numbers

(22) Provide an indication of any planned new developments on your device.

Information	Investigation into fiber optic sensors, other surface mounted sensors (temp, strain), new monitoring systems/tools

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		

Other	Use some LTPP data for model validation—MnROAD has LTPP test sections; MnROAD is our APT, lab performance testing like APA, SCB and have public roadways to also collect data	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	Oracle Database along with auxiliary data (pictures, video, some raw data not enter into the database)—one TB data http://www.dot.state.mn.us/mnroad/data/pdfs/databaseguide.pdf Working to get data onto the web in the next 2 years—data product 1.0 currently is being developed in-house and used by internal staff

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	http://www.dot.state.mn.us/mnroad/data/requestspecial.html MnROAD data product 1.0 developed

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program	all the above plus industry needs	
Ad hoc test selection		
Academic interest		
Other		

NCAT

Section 1

Agency/Organization	NCAT Pavement Test Track
Location (City, State, Country)	Opelika

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	fixed	
Linear/non-linear (circular, elliptical)	oval	
Uni/bi-directional	unidirectional	
Number of axles	8 axles on 5 trucks (40 axles total)	
Own power (diesel/electric/other)/shore power	diesel	
Field site/fixed site	fixed site	
Roads/airfields	roads	
Fixed device/trucks (automated or manually driven)	manually drive trucks	
Load range (range in kN—indicate full load for all tires as well as range per tire)	5.3 to 9.4 kip (23.6 to 41.8 kN) per tire	
Tire details (size, type, inflation pressure range, other)	275/80R22.5 at 100 psi (689 kPa)	
Tire wander options	real world	
Suspension (present or not, types possible, permanent or not, etc.)	spring and air	
Temperature control options	Ambient	
Speed range	up to 50 mph (80 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	climate and high speed response	
APT webpage link	www.pavetrack.com	
Other	N/A	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Dipstick	
Permanent surface strain	Dipstick	
Permanent in-depth deformation	N/A	
Permanent in-depth strain	CTL strain gauges	
Elastic surface deflection	FWD	
Elastic surface strain	N/A	
Elastic in-depth deflection	N/A	
Elastic in-depth strain	N/A	
Density	nuclear and impedance	
Temperature	thermistor	
Moisture	N/A	
Stiffness	FWD & PSPA	
New parameter (list)		
Important but not measured (list)		
Other—please provide details	Inertial profiler for roughness and macrotexture	

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	M-E pavement design	validation/calibration
Roads agency or state research program	compare materials and methods	reduce life-cycle cost of pavements
Academic research plan		
Commercial research plan	product evaluation	new technology
Partnership program	pooled fund	research cooperative
International cooperative program	support for Chinese APT	optimized pavement design
Ad hoc use of device—no specific program	surface treatments	wear and abrasion
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	2000
Number of pavement sections tested	183
Typical duration of APT tests in months	36
Typical number of repetitions per test	10 million ESALs
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	predetermined number of repetitions
Estimated capital cost of APT equipment	US $8M
Number of staff Managerial/administrative Professional Technical	13 1 2

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)			x
In-service field test sections	x		
Rehabilitation option comparison	x		
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	public and private pooled fund cooperative agreement individual projects at coop rate	$2.4M $80k $800k
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?	in 3-year cycles	

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction	$10M $4.0M part of operations $3.5M $2.5M	3	
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)	$1		

(22) Provide an indication of any planned new developments on your device.

Information	Rebuild test oval in 2012 and traffic with same heavy triple trailer trains

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other		

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	Data QC via spreadsheet, permanent storage in Access database

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program	Meet sponsors' individual research needs while guiding program to address broad issues	
Ad hoc test selection		
Academic interest		
Other		

Ohio Department of Transportation

Section 1

Agency/Organization	Ohio Department of Transportation
Location (City, State, Country)	Columbus

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	fixed	
Linear/non-linear (circular, elliptical)	linear	
Uni/bi-directional	uni or bi	
Number of axles	1	
Own power (diesel/electric/other)/ shore power	hydraulic	
Field site/fixed site	fixed site	
Roads/airfields	roads	
Fixed device/trucks (automated or manually driven)	fixed device	
Load range (range in kN—indicate full load for all tires as well as range per tire)	http://www.ohio.edu/orite/facilities/accelpaveload.cfm	
Tire details (size, type, inflation pressure range, other)	http://www.ohio.edu/orite/facilities/accelpaveload.cfm	
Tire wander options	yes	
Suspension (present or not, types possible, permanent or not, etc.)	air bag	
Temperature control options	http://www.ohio.edu/orite/facilities/accelpaveload.cfm	
Speed range	http://www.ohio.edu/orite/facilities/accelpaveload.cfm	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	yes	
APT webpage link	http://www.ohio.edu/orite/facilities/accelpaveload.cfm	
Other	none	

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	

U.S. Army Corps of Engineers (EDRC) WES

Section 1

Agency/Organization	U.S. Army Corps of Engineers, ERDC
Location (City, State, Country)	Vicksburg

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	mobile	
Linear/non-linear (circular, elliptical)	linear	
Uni/bi-directional	uni and bi	
Number of axles	1 or 2	
Own power (diesel/electric/other)/shore power	Both shore and from generator set	
Field site/fixed site	Fixed site with option of field sites	
Roads/airfields	Roads and airfields	
Fixed device/trucks (automated or manually driven)	Self-drive for short distance/ truck driven for long distance	

Load range (range in kN—indicate full load for all tires as well as range per tire)	2.2 to 100 kip (10 kN to 440 kN)	Range/tire depends on gear/tire configuration
Tire details (size, type, inflation pressure range, other)	Truck (super single, single axle, dual axle. Aircraft—C17 single tire, F-15 single tire	
Tire wander options	3 ft (930 mm) wander	
Suspension (present or not, types possible, permanent or not, etc.)	Suspension for self–drive/steering	
Temperature control options	14 to 140°F (–10°C to 60°C)	
Speed range	0.6 to 7.5 mph (1 to 12 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	yes	
APT webpage link	N/A	
Other	N/A	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	None	
Permanent surface strain	foil strain gauges applied to surface of pavement	
Permanent in-depth deformation	SDD—Single Depth Deflectometer (LVDT)	
Permanent in-depth strain	asphalt or concrete strain gauge	
Elastic surface deflection	None	
Elastic surface strain	foil strain gauge applied to surface of pavement	
Elastic in-depth deflection	SDD	
Elastic in-depth strain	concrete or asphalt strain gauge	
Density	Nuke gauge	
Temperature	I-button	
Moisture	Campbell SCI water content sensor	
Stiffness	Earth pressure sensor	
New parameter (list)		
Important but not measured (list)		
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program		
Academic research plan		
Commercial research plan	yes	Construction products
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other	Military	Airfield research for Air Force, roads and airfields for Marines and Army

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1940
Number of pavement sections tested	Thousands

Typical duration of APT tests in months	3
Typical number of repetitions per test	100,000
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Failure
Estimated capital cost of APT equipment	$20 million
Number of staff Managerial/administrative Professional Technical	6 30 10

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)		x	
In-service field test sections			x
Rehabilitation option comparison		x	
Other		x	

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International	95%	$5 million annual budget
Consortium Commercial Academic Other	5%	$250k
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?	no	

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction	$5 million 500K 500K 3 million 1 million	1 1	HVS/various load carts
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)			

(22) Provide an indication of any planned new developments on your device.

Information	New version of HVS software just installed. New computers planned.

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		

APT, laboratory, field, and LTPP		
Other	Structural design/mix design structural and mix design work	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections)*.

Database type	No standard database or storage is being used.

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program		
Ad hoc test selection		
Academic interest		
Other		

Questionnaire information—International programs

Australia—ARRB

Section 1

Agency/Organization	ARRB Group
Location (City, State, Country)	Australia

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Fixed	
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Bi	
Number of axles	1	
Own power (diesel/electric/other)/shore power	Electric	
Field site/fixed site	Fixed	
Roads/airfields	yes	
Fixed device/trucks (automated or manually driven)	Fixed	
Load range (range in kN—indicate full load for all tires as well as range per tire)	HGV	
Tire details (size, type, inflation pressure range, other)	Various dual or single	
Tire wander options	yes	
Suspension (present or not, types possible, permanent or not, etc.)	yes	
Temperature control options	yes	use of heaters
Speed range	0 to 12.5 mph (0 to 20 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Separate logging data dependent upon experiment	
APT webpage link	no	
Other		

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Primarily precise leveling	
Permanent surface strain		
Permanent in-depth deformation	slab extraction	
Permanent in-depth strain	Various	

Elastic surface deflection	Various	
Elastic surface strain		
Elastic in-depth deflection	Various	
Elastic in-depth strain	Various	
Density	Gauge or sample	
Temperature	Thermocouples	
Moisture	unbound layers	
Stiffness	In situ or material sampling—tested separately	
New parameter (list)		
Important but not measured (list)		
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program		
Academic research plan		
Commercial research plan	Y	
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program	Y	
Local research needs	Y	
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1984
Number of pavement sections tested	too many to catalogue here
Typical duration of APT tests in months	1 to 3
Typical number of repetitions per test	specific to project
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	specific to project
Estimated capital cost of APT equipment	N/K
Number of staff Managerial/administrative Professional Technical	

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)			x
Dedicated constructed test sections (test pit)	x		
In-service field test sections			x
Rehabilitation option comparison		x	
Other	x		

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state governments National government International Consortium Commercial Academic Other	 Y Y Y Y	

Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc	 Y Y	
Is funding guaranteed?	N	

(22) Provide an indication of any planned new developments on your device.

Information	Always looking at new ways of instrumenting experiments

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	product comparison/developments of guidelines	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections).*

Database type	No single database. Project specific data. Electronic.

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program	client driven	
Ad hoc test selection	client driven	
Academic interest		
Other		

Brazil—Federal University of Rio Grande do Sul

Section 1

Agency/Organization	Federal University of Rio Grande do Sul
Location (City, State, Country)	Brazil

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Fixed	At the University Campus
Linear/non-linear (circular, elliptical)	Linear	Only
Uni/bi-directional	Uni-directional	Might be bi-directional
Number of axles	one half-axle	That is two wheels
Own power (diesel/electric/other)/shore power	Own	Electric
Field site/fixed site	Fixed	At the University Campus
Roads/airfields	Roads	
Fixed device/trucks (automated or manually driven)	Automated driven	
Load range (range in kN—indicate full load for all tires as well as range per tire)	9.5 to 13.5 kip (42 to 60 kN) half axle; 4.7 to 6.7 kip (21 to 30 kN) per wheel	

Tire details (size, type, inflation pressure range, other)	ply tires, inflation pressure ranging from 81 to 100 psi (0.56 to 0.70 kPa)	
Tire wander options	Wanders	
Suspension (present or not, types possible, permanent or not, etc.)	Permanent	
Temperature control options	no	
Speed range	3 to 5 mph (5 to 8 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?		
APT webpage link	None	
Other	Nothing else	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	We use a profilograph	
Permanent surface strain		
Permanent in-depth deformation		
Permanent in-depth strain		
Elastic surface deflection	Measured with a Road Surface Deflection and Benkelman beam. FWD is very rarely available	
Elastic surface strain		
Elastic in-depth deflection	Wish we had MDD	
Elastic in-depth strain	In unbound layers sometimes we install vertical strain gauges	Kyowa K-120
Density	Non-nuclear	
Temperature	yes	
Moisture		
Stiffness		
New parameter (list)		
Important but not measured (list)		
Other—please provide details	Sometimes we install tensiometers to measure soil suction	Jet-fill tensiometers

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program	Sometimes	
Academic research plan	Always	
Commercial research plan	Sometimes	
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs	Always	
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1996
Number of pavement sections tested	20
Typical duration of APT tests in months	Variable from 3 months to years
Typical number of repetitions per test	From 100,000 to 1,000,000
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Sometimes we aim at a failure criterion. In a few cases we limit the number of repetitions

Estimated capital cost of APT equipment	US$ 1,000,000
Number of staff	
Managerial/administrative	2
Professional	4
Technical	2

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)		x	
In-service field test sections			x
Rehabilitation option comparison	x		
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	The DOT funded the assembling of the traffic simulator and paid for the first ten to twelve test sections, but that was 15 years ago. Some enterprises have funded researches The university pays the researches salaries and scholarships and provides basic infrastructure	$150,000 $200,000
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?		

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget			Academic
Operational	$250,000	15	Academic
Maintenance	$200,000	15	Academic/commercial
Staff	$50,000	15	
Construction	$30,000		
Average operational cost per test	US$ 1		
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)			

(22) Provide an indication of any planned new developments on your device.

Information	The traffic simulator has just been updated. An automated driven system for moving from one test section to other has been added.

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory	Materials characterization and performance tests (fatigue, resilient modulus, etc.)	
APT and LTPP	Very little experience (paving fabrics)	
APT and field	Very little experience (paving fabrics)	
APT, laboratory, and LTPP	Very little experience	
APT, laboratory, and field	Very little experience	

APT, laboratory, field, and LTPP	Very little experience	
Other		

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selection*s).

Database type	Very basic: computer files, sheets and the resulting papers

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	Whoever wants may access the data

China—China Merchants Chongqing Communications Research & Design Institute

Section 1

Agency/Organization	China Merchants Chongqing Communications Research & Design Institute Co., Ltd.
Location (City, State, Country)	Chongqing

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	mobile	
Linear/non-linear (circular, elliptical)	nonlinear	
Uni/bi-directional	bi-directional loading	
Number of axles	two	
Own power (diesel/electric/ other)/shore power	electric	
Field site/fixed site	fixed site	
Roads/airfields	roads	
Fixed device/trucks (automated or manually driven)	Fixed device	
Load range (range in kN—indicate full load for all tires as well as range per tire)	24.7 to 33.7 kip (110 to 150 kN) for all tires, 6 to 8.4 kip (27.5 to 37.5 kN) per tire	
Tire details (size, type, inflation pressure range, other)	900-20-14, C856	
Tire wander options	2 in. (50 mm)	
Suspension (present or not, types possible, permanent or not, etc.)	The precision and survival rate of the sensor are all too low	
Temperature control options	41 to 158°F (5 to 70°C)	
Speed range	37 mph (60 km/h) (max)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?		
APT webpage link	http://www.ccrdi.com/Category_96/Index_1.aspx	
Other	The max vertical slope is 6%	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	displacement sensor	
Permanent surface strain		
Permanent in-depth deformation	displacement sensor	

Permanent in-depth strain		
Elastic surface deflection		
Elastic surface strain		
Elastic in-depth deflection		
Elastic in-depth strain		
Density		
Temperature	temperature sensor	
Moisture		
Stiffness		
New parameter (list)		
Important but not measured (list)		
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program	the client	
Academic research plan		
Commercial research plan		
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	
Number of pavement sections tested	eight
Typical duration of APT tests in months	eight
Typical number of repetitions per test	1,000,000
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	test to predetermined number of repetitions
Estimated capital cost of APT equipment	3,000,000 RMB
Number of staff Managerial/administrative Professional Technical	 One Three Two

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)		x	
Dedicated constructed test sections (test pit)			
In-service field test sections		x	
Rehabilitation option comparison		x	
Other			

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	The deformation of the APT, the depth of the rutting test	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	through some process of my company, the other researchers can get the data

China—Liaoning Province Communication Research Institute

Section 1

Agency/Organization	Liaoning Province Communication Research Institute
Location (City, State, Country)	Shenyang

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Mobile	
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Uni-directional	
Number of axles	6	
Own power (diesel/electric/other)/shore power	both	
Field site/fixed site	both	
Roads/airfields	both	
Fixed device/trucks (automated or manually driven)	fixed	
Load range (range in kN—indicate full load for all tires as well as range per tire)	11.2 to 19 kip (50 to 85 kN) per tire	
Tire details (size, type, inflation pressure range, other)		
Tire wander options	yes	
Suspension (present or not, types possible, permanent or not, etc.)	present	
Temperature control options	Ambient temperature to 158°F (70°C)	
Speed range	1,500 to 6,000 times load per hour	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	applied speed	
APT webpage link		
Other	None	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Profilometer	
Permanent surface strain	Sensor	
Permanent in-depth deformation	FWD	
Permanent in-depth strain		
Elastic surface deflection		
Elastic surface strain		
Elastic in-depth deflection		
Elastic in-depth strain		
Density		
Temperature	Thermocouple	
Moisture	Sensor	
Stiffness		
New parameter (list)		
Important but not measured (list)		
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program	yes	
Academic research plan		
Commercial research plan		
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs		
Other		

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)	x		
In-service field test sections			
Rehabilitation option comparison			
Other			

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	

China—Tongji University

Section 1

Agency/Organization	Tongji University
Location (City, State, Country)	Shanghai

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	mobile	
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Uni-directional	
Number of axles	6	
Own power (diesel/electric/other)/shore power	Diesel power and shore power	
Field site/fixed site	field site	
Roads/airfields	roads	
Fixed device/trucks (automated or manually driven)	Trucks (manually driven)	
Load range (range in kN—indicate full load for all tires as well as range per tire)	5 to 16.8 kip (20 to 75 kN) for all tires or per tire	
Tire details (size, type, inflation pressure range, other)	305/70 R22.5	Maximum pressure: about 189 psi (1 300 kPa)
Tire wander options	–18 in. to +18 in. (–450 to +450 mm)	
Suspension (present or not, types possible, permanent or not, etc.)	Present	Its suspension theory is not clear for me
Temperature control options	yes	
Speed range	3.3 to 13.4 mph (1,500 to 6,000 mm/s)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	set speed, applied speed, load, location	
APT webpage link	no	
Other	no	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	profilometer	
Permanent surface strain		
Permanent in-depth deformation	strain gauge	http://www.geokon.cn/en/?p=3&a=view&c=5&r=9
Permanent in-depth strain	strain gauge	
Elastic surface deflection	FWD	
Elastic surface strain	strain gauge	
Elastic in-depth deflection	strain gauge	
Elastic in-depth strain	strain gauge	
Density	cores measured in lab	
Temperature	thermal couple	http://www.geokon.cn/en/?p=3&a=view&c=5&r=7
Moisture	moisture gauge	
Stiffness	PSPA	
New parameter (list)		
Important but not measured (list)		
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	yes	fundamental research
Roads agency or state research program		
Academic research plan		
Commercial research plan		
Partnership program		
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs	yes	performance of specified pavement structures
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	2009-9-30
Number of pavement sections tested	2
Typical duration of APT tests in months	3 months
Typical number of repetitions per test	1 million
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	rutting or fatigue cracking
Estimated capital cost of APT equipment	170,000 US$
Number of staff Managerial/administrative Professional Technical	 2 10 2

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)	x		
In-service field test sections			
Rehabilitation option comparison			
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor)		
Local/state government	80%	$140,000
National government		
International	20%	$30,000
Consortium		
Commercial		
Academic		
Other		
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?		

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget	$170,000	1	1 year of two ad hoc tests
Operational	$40,000		
Maintenance	$20,000		
Staff	$20,000		
Construction	$90,000		
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)			

(22) Provide an indication of any planned new developments on your device.

Information	Improve the ability to collect the dynamic rutting information

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	Compare the results from APT testing and lab testing	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	No special database.

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	Need to apply

Germany—BASt

Section 1

Agency/Organization	Federal Highway Research Institute (BASt)
Location (City, State, Country)	Germany

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Mobile and fixed	MLS and impulse generator
Linear/non-linear (circular, elliptical)	linear	MLS and impulse generator
Uni/bi-directional	Uni/bidirectional	MLS and impulse generator
Number of axles	4	MLS
Own power (diesel/electric/other)/shore power	Diesel and electric	MLS and impulse generator
Field site/fixed site	fixed site	
Roads/airfields	Roads	
Fixed device/trucks (automated or manually driven)	Fixed	
Load range (range in kN—indicate full load for all tires as well as range per tire)	6.7 to 14.6 kip (30 to 65 kN)	
Tire details (size, type, inflation pressure range, other)	Single/twin truck tires	MLS
Tire wander options	yes	MLS and impulse generator
Suspension (present or not, types possible, permanent or not, etc.)	no	
Temperature control options	yes	Indoor test section
Speed range	Creep—13.6 mph (22 km/h)	MLS
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Detailed data collection	MLS and impulse generator
APT webpage link	www.bast.de	http://www.bast.de/cln_007/nn_169964/DE/Aufgaben/abteilungs/abteilung-s-node.html?__nnn=true
Other		http://www.bast.de/cln_005/nn_43710/EN/e-publikationen/epublikationen__node.html?__nnn=true

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Laser profiler	For all: http://www.bast.de/cln_005/nn_43710/EN/epublikationen/epublikationen__node.html?__nnn=true
Permanent surface strain		
Permanent in-depth deformation		
Permanent in-depth strain	Strain gauges	in-house development
Elastic surface deflection	FWD, accelerometer, geophones	Carl Bro, commercial
Elastic surface strain		
Elastic in-depth deflection		
Elastic in-depth strain	Strain gauges	in-house
Density	Nuclear gauge	Troxler
Temperature	Thermocouples	in-house
Moisture		
Stiffness	FWD backcalculation	Carl Bro
New parameter (list)	Pavement velocity and acceleration	commercial
Important but not measured (list)	Strain in unbound layers	commercial
Other—please provide details	Pressure in unbound layers	in-house

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	yes	
Roads agency or state research program		
Academic research plan		
Commercial research plan		
Partnership program		
International cooperative program	not yet	
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1997 “Sieben Stufen Plan” “Seven Stage Program”
Number of pavement sections tested	8
Typical duration of APT tests in months	Depending on research objective
Typical number of repetitions per test	>1 million load impulses and/or tire passing
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Depending on research objective
Estimated capital cost of APT equipment	
Number of staff Managerial/administrative Professional Technical	2 3

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)			
Dedicated constructed test sections (test pit)	x		
In-service field test sections			
Rehabilitation option comparison			
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	Funding	
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc	Budget per project National research funding	“Innovation Program”
Is funding guaranteed?	yes	

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction			

Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)			

(22) Provide an indication of any planned new developments on your device.

Information	Implementation of a new APT device (MLS 10)

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	Coring, determination of fatigue and stiffness	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	EXCEL files (among others)

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	

Japan—PWRI

Section 1

Agency/Organization	Public Works Research Institute
Location (City, State, Country)	Tsukuba

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Fixed	
Linear/non-linear (circular, elliptical)	Circular	
Uni/bi-directional	Uni	
Number of axles	400,000/year	
Own power (diesel/electric/other)/shore power	diesel	
Field site/fixed site	fixed	
Roads/airfields	roads	
Fixed device/trucks (automated or manually driven)	automated trucks	
Load range (range in kN—indicate full load for all tires as well as range per tire)	7 to 25 kip (31.85 to 156.8 kN) wheel load	
Tire details (size, type, inflation pressure range, other)	295/80R22.5	
Tire wander options	automatically controlled to wander ±10 in. (250 mm) around the center	
Suspension (present or not, types possible, permanent or not, etc.)	Same as actual truck	
Temperature control options	None	
Speed range	Less than 24.8 mph (40 km/h) Dedicated operational	

Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	speed, location and number of passengers	
APT webpage link	http://www.pwri.go.jp/team/pavement/eindex.html	
Other	None	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Manual	
Permanent surface strain	None	
Permanent in-depth deformation	None	
Permanent in-depth strain	None	
Elastic surface deflection	FWD	
Elastic surface strain	FWD	
Elastic in-depth deflection	FWD	
Elastic in-depth strain	FWD	
Density	Manual	
Temperature	Occasionally by manual	
Moisture	None	
Stiffness	None	
New parameter (list)	Skid resistance	
Important but not measured (list)	Inside temperature	
Other—please provide details	None	

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	applicable	
Roads agency or state research program		
Academic research plan	applicable	
Commercial research plan	applicable	
Partnership program	applicable	
International cooperative program		
Ad hoc use of device—no specific program		
Local research needs	applicable	
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	since 1970s
Number of pavement sections tested	more than 10
Typical duration of APT tests in months	20 days
Typical number of repetitions per test	1,000,000
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	predetermined number or failure
Estimated capital cost of APT equipment	5,000,000 US$
Number of staff Managerial/administrative Professional Technical	1 1 2

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)		x	
In-service field test sections		x	
Rehabilitation option comparison			x
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	200,000 US$	
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?		

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget Operational Maintenance Staff Construction	$200,000 $150,000 $50,000 no specific staff 0 (changed every year)		
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)			

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	

Netherlands—Delft University of Technology

Section 1

Agency/Organization	Delft University of Technology
Location (City, State, Country)	Netherlands

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Fixed	Fixed to test area, but mobile on that test area
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Bi-directional loading	
Number of axles	1	
Own power (diesel/electric/other)/shore power	Own power (electric)	
Field site/fixed site	Fixed site	
Roads/airfields	Roads	
Fixed device/trucks (automated or manually driven)	Fixed device	
Load range (range in kN—indicate full load for all tires as well as range per tire)	5.6 to 22.5 kip (25 to 100 kN)	
Tire details (size, type, inflation pressure range, other)	All types of wide base and dual tires, inflation pressure up to 130 psi (900 kPa)	
Tire wander options	Any lateral wander distribution	
Suspension (present or not, types possible, permanent or not, etc.)	No suspension	

Temperature control options	Only heating [up to 86°F (30°C) above ambient temperature], no cooling	
Speed range	0 to 12.4 mph (0 to 20 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	All available	
APT webpage link	Available, but not to date	
Other	None	

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	Early nineties
Number of pavement sections tested	Around 20 (including orthotropic steel deck bridge)
Typical duration of APT tests in months	Ranging from 0.25 to 4
Typical number of repetitions per test	Ranging from 10,000 to millions
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	Depends, sometimes predefined number of load repetitions, sometimes failure (e.g., rut depth, cracking of asphalt or concrete pavement)
Estimated capital cost of APT equipment	1 million Euros
Number of staff	
Managerial/administrative	0.2
Professional	0.4
Technical	1

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)		x	
Dedicated constructed test sections (test pit)			x
In-service field test sections			x
Rehabilitation option comparison		x	
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor) Local/state government National government International Consortium Commercial Academic Other	Irregular/ad hoc commission of funding projects	
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?	no	

(22) Provide an indication of any planned new developments on your device.

Information	No planned new developments.

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		

APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	Was done with APT rutting research of asphalt pavement and laboratory triaxial testing of applied asphalt mixes Was done with APT research on modular pavement structures, orthotropic steel deck bridges and silent joints between bridge and abutment	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections)*.

Database type	Project-based computer database (CD-ROMS etc.)

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	no
	On request

South Africa—CSIR

Section 1

Agency/Organization	CSIR Built Environment
Location (City, State, Country)	South Africa

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	HVS Mk III & IV	www.dynatest.com
Linear/nonlinear (circular, elliptical)	linear	
Uni-/bi-directional	yes	
Number of axles	1	
Own power (diesel/electric/other)/shore power	both	
Field site/fixed site	both	
Roads/airfields	roads	
Fixed device/trucks (automated or manually driven)	no	
Load range (range in kN—indicate full load for all tires as well as range per tire)	4.5 to 45 kip (20 to 200 kN)	
Tire details (size, type, inflation pressure range, other)	dual, wide base, aircraft	
Tire wander options	Yes, 0 to 59 in. (0 to 1.5 m) wide	
Suspension (present or not, types possible, permanent or not, etc.)	No	
Temperature control options	yes, hot and cold	
Speed range	0 to 4.9 mph (0 to 8 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location, etc.)?	Yes	
APT webpage link	www.gautrans-hvs.co.za www.dynatest.com	
Other	None	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	Wireless laser Profilometer	in-house developed.www.Dynatest.com
Permanent surface strain	No	

Permanent in-depth deformation	MDD	In-house developed.www.Dynatest.com
Permanent in-depth strain	No	
Elastic surface deflection	MDD, JDMD, RSD	In-house developed.www.Dynatest.com
Elastic surface strain	No	
Elastic in-depth deflection	MDD	In-house developed.www.Dynatest.com
Elastic in-depth strain		
Density	Nuclear density gauge	troxler
Temperature	thermocouples temperature buttons	National instruments
Moisture	No	
Stiffness		
New parameter (list)		
Important but not measured (list)	in situ moisture, horizontal strain, vertical stress	
Other—please provide details		

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program		
Roads agency or state research program	x	
Academic research plan	x	
Commercial research plan		
Partnership program	x	
International cooperative program	x	
Ad hoc use of device—no specific program		
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1976
Number of pavement sections tested	480
Typical duration of APT tests in months	6 months
Typical number of repetitions per test	1 million
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	failure determination
Estimated capital cost of APT equipment	
Number of staff	
Managerial/administrative	2
Professional	2
Technical	10

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)	x		
Dedicated constructed test sections (test pit)			x
In-service field test sections	x		
Rehabilitation option comparison	x		
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor)		
Local/state government	95% funder/sponsor	$0.7 million
National government		
International		
Consortium	External project based	$500,000
Commercial		
Academic		
Other	5% asphalt and concrete associations	$50,000

Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?	no	

(22) Provide an indication of any planned new developments on your device.

Information	Wireless technology, moisture sensors, pressure sensors.

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	APT verification on lab designs; lab investigates more variables than APT. LTPP sections identified next to field APT sections. Evaluations 2x per year. APT tests compared with full-scale field trail sections.	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	MS access, XLS-based

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	Through websites, published reports and conferences Through websites, published reports and conferences www.gautrans-hvs.co.za;www.hvsia.co.za

(41) What is the basis of the selection of full-scale APT test sections in your program?

Description	Selection	Details
Official research program		
Ad hoc test selection		
Academic interest		
Other	APT steering committee	

Sweden—VTI

Section 1

Agency/Organization	VTI—The Swedish Road and Transport Research Institute
Location (City, State, Country)	Linköping

(13) Provide details of the full-scale APT device that you own/use.

Parameter	Selection	Comment
Mobile/fixed	Mobil	
Linear/non-linear (circular, elliptical)	Linear	
Uni/bi-directional	Bi-direction	
Number of axles	One	
Own power (diesel/electric/other)/shore power	Diesel or electric	
Field site/fixed site	Field	
Roads/airfields	Roads	
Fixed device/trucks (automated or manually driven)	Fixed device	automated driven

Load range (range in kN—indicate full load for all tires as well as range per tire)	6.7 to 24.7 kip (30 to 110 kN)	
Tire details (size, type, inflation pressure range, other)	Single/dual	truck tire
Tire wander options	0 to 27.5 in. (0 to 700 mm)	
Suspension (present or not, types possible, permanent or not, etc.)	Hydraulic	
Temperature control options	yes	Pavement temperature 32 to 86°F (0 to 30°C)
Speed range	0 to 7.5 mph (0 to 12 km/h)	
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location etc.)?	Speed, load, location, number of repetitions	
APT webpage link	www.vti.se	
Other	HVS Mark IV	

(14) Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table.

Parameter	Instrument used	Details—background on instrument, commercial or in-house developed
Permanent surface deformation	laser profile	
Permanent surface strain	LVDT	
Permanent in-depth deformation	LVDT/emu	
Permanent in-depth strain	emu	
Elastic surface deflection	LVDT	
Elastic surface strain		
Elastic in-depth deflection	emu	
Elastic in-depth strain	emu	
Density	Troxler	
Temperature	Pt100	
Moisture	TDR	
Stiffness	FWD/LWD	KUAB
New parameter (list)		
Important but not measured (list)		
Other—please provide details	Ground water table	

(15) Provide a description of the nature or purpose of your APT program.

Parameter	All applicable	Primary selection
National research program	x	
Roads agency or state research program		
Academic research plan	x	
Commercial research plan	x	
Partnership program		
International cooperative program	x	
Ad hoc use of device—no specific program	x	Tire pressure influence on performance
Local research needs		
Other		

(16) Provide a summarized (bulleted version indicating major dates and topics only, probably not more than a page) history of your program by completing the table and adding explanatory notes.

Description	Information
Initiation of program	1998
Number of pavement sections tested	20
Typical duration of APT tests in months	2 months
Typical number of repetitions per test	500,000
End-condition objective (i.e., test to predetermined number of repetitions, failure, something else)	rut exceeds critical value
Estimated capital cost of APT equipment	?
Number of staff Managerial/administrative Professional Technical	 2 2 4

(19) Which of the following full-scale APT types of tests are you conducting?

Parameter	Often	Infrequently	Never
Dedicated constructed test sections (normal construction)		x	
Dedicated constructed test sections (test pit)	x		
In-service field test sections			x
Rehabilitation option comparison			x
Other			

(20) Provide information on your funding model and levels.

Parameter	Model used	Funding levels (annual budget)
Funding agency (sponsor)	Research program	Swedish Transport Administration
Local/state government		
National government		
International	Application	EU projects
Consortium		
Commercial	Contracts	Contractor
Academic		
Other	Contracts	International Road Administrations
Type of funding Short-term (project-linked) Long-term (program-linked) Intermittent/ad hoc		
Is funding guaranteed?		

(21) Provide typical information of cost of APT.

Parameter	Budget	Number of years	Type of projects
Breakdown of budget	$500,000	3	Research project
Operational	$50,000		
Maintenance	$50,000		
Staff	$350,000		
Construction	$50,000		
Average operational cost per test			
Annual APT budget (US$)			
Average US$ per standard repetition (one direction) for a typical 1 year program (not short-term studies)	0,5		

(23) Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program.

Parameter	All relevant	Number of cases/reference to tests/reports
APT and laboratory		
APT and LTPP		
APT and field		
APT, laboratory, and LTPP		
APT, laboratory, and field		
APT, laboratory, field, and LTPP		
Other	stiffness, fatigue, RLTT etc. stiffness, fatigue, RLTT etc.	

(30) Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices) (*Only space to add own information—no automatic selections*).

Database type	Microsoft Access database

(31) Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis?

Data available to non-APT owners	yes/no
Data shared with other APT programs	yes/no
Process/vehicle used	on request

APPENDIX D

Response Analysis

Copy of Summary Report—June 5, 2011
Survey: NCHRP Synthesis 42-08 Full-Scale Accelerated Pavement Testing
My organization (or I in my personal capacity) is interested in taking part in this questionnaire based on our interest and/or involvement with full-scale APT.

Value	Count	Percent
Yes—this option will take you to the next section and lead you through the various questions based on your level of interest and involvement.	75	92.6%
No—this option will take you to the last page and will not require from you to answer any of the questions.	6	7.4%

Statistics	
Total Responses	81

How do you view the importance of full-scale APT?

Value	Count	Percent
High	56	77.8%
Medium	13	18.1%
Low	3	4.2%

Statistics	
Total Responses	72

What do you see as the roles of full-scale APT? Please indicate all the relevant roles.

Value	Count	Percent
Basic materials (pavement layer) research	61	84.7%
Pavement structure work	65	90.3%
Rehabilitation option selection	51	70.8%
Fundamental research (long-term)	46	63.9%
Parameter research (temperature, moisture, etc.)	44	61.1%
Traffic loading	53	73.6%
Development of guidelines	46	63.9%
Academic research	40	55.6%
Evaluate specific application issues	49	68.1%
Commercial evaluations	28	38.9%
Other	8	11.1%

Statistics	
Total Responses	72

What do you see as the future of APT? Please indicate all relevant options.

Value	Count	Percent
Normal part of operation when required	41	56.9%
Growing	35	48.6%
Simulations and advanced computer analyses should be used	20	27.8%
Other	10	13.9%

Statistics	
Total Responses	72

What do you view as the benefits of full-scale APT? Please indicate all relevant options.

Value	Count	Percent
Improved structural design methods	64	88.9%
Improved material design methods	62	86.1%
Evaluation of novel materials and structures	60	83.3%
Development of performance-related specifications	54	75%
Material databases	35	48.6%
Improved performance modeling	58	80.6%
Improved pavement management	31	43.1%
Better understanding of variability	35	48.6%
Warranty contracts	14	19.4%
Weather databases	9	12.5%
Other	8	11.1%

Statistics	
Total Responses	72

What are the main opportunities to disseminate full-scale APT research information? Please indicate all relevant options.

Value	Count	Percent
General engineering conferences	22	30.6%
Focused transportation conferences	33	45.8%
Focused pavement engineering conferences	64	88.9%
Focused APT conferences	53	73.6%
General engineering journals	16	22.2%
Focused transportation journals	32	44.4%
Focused pavement engineering journals	58	80.6%
Focused APT journals	39	54.2%

Electronic journals	21	29.2%
Meetings such as TRB	49	68.1%
Other	14	19.4%

Statistics	
Total Responses	72

What is your perception of the way that APT has/should change the pavement engineering world? Please indicate all relevant options.

Value	Count	Percent
Academic benefits	27	37.5%
Internal organizational training and education	13	18.1%
Fundamental understanding of pavement structures	64	88.9%
Development of new materials	48	66.7%
Proving new techniques and materials	65	90.3%
Specific examples in your area	15	20.8%
Other	5	6.9%

Statistics	
Total Responses	72

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. TRB AFD40.

Count	Response
1	Attend/member
1	Attended
1	Co-chair, presenter, review panel
1	Committee member
1	Emeritus member. Chaired A2B52, A2B09 (now AFD40) 1994–2002
1	Involved in the start of this committee
2	Member
1	Member since 2010
1	Member since inception
1	Myself—attend when I can—others at the state are active members
1	Participate
2	Participate in meetings
1	Participate through active members.

Count	Response
1	TRB, but not necessarily this committee
1	Active, current friend, past member (8 years)
1	Ex not at present
1	Guest
4	Member
1	Occasionally attended committee meeting
1	Participate
1	Committee member
1	yes

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column). COST

Count	Response
1	1-year testing/evaluation of different rehabilitation techniques
1	347
1	Ad hoc
1	COST 347
1	Chair
1	Invited speaker and participated in meetings on several occasions
1	Ad hoc, not for over a decade
1	Participate
1	COST 333 on pavement design models; COST 347 on APT; member of COST technical domain of transport and urban development

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. HVSIA

Count	Response
1	Ad hoc
1	Attended
1	Member since inception
1	Participate
2	Participate in meetings
1	Ex-member
1	Member and part of the EXCO
1	Member early on

Count	Response
1	Participate
1	Regular permanent member since 1990s

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. MLS user group

Count	Response
1	Participant
1	Active
1	Attend TRB user group meeting when possible
1	Ex-member
1	In future
1	Two years, user

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. South African APT advisory committee

Count	Response
1	Ad hoc
1	Attended
1	Ex-member
1	Member, co-author of the strategic 5-year plan

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. NCAT

Count	Response
1	Close friends—someone in our office is on the technical advisory group
1	Florida has funded test sections
1	Funded test section
1	Member state
1	Member of research Project Advisory Committees
1	Member, ex sponsor
1	Monitor research and results
1	NCAT Test Track Pooled Fund
1	Participate in meetings, Florida has funded two sections
1	Participated on advisory panels
1	Read publications

Count	Response
1	Test track sponsor since inception
1	Instrumentation support (2000–2006)
1	Past employee
1	Project manager since 1999

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. CAPT

Count	Response
1	Active member
1	Lead state chair. Involved since inception
1	Member since inception
1	Participate
2	Participate in meetings
1	pooled fund member
1	one of participation states

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. FEHRL

Count	Response
1	From member organization
1	Member
1	Monitor research and results
1	Research coordinator
1	Working with to develop relationship with
1	Yes, but not in specific APT forum
1	Participate
1	Participated in SPENS project (FP6) and TITaM (Marie Curie)
1	Yes

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. Midwest States Accelerated Pavement Testing Pooled Fund Program (states of Iowa, Kansas, Nebraska, and Missouri)

Count	Response
1	Chairman of pooled fund effort
1	Iowa participates as a pooled fund state

Count	Response
1	Missouri tech rep
1	Pooled fund tech rep for Missouri

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc) in the additional details column. APT conferences

Count	Response
1	Active
1	Attend when I can. Co-authored papers
1	Attend. Host and Committee Co-Chair for APT 2012
1	Attend/present
1	Attended
1	Attended last one, ARRB has attended all three
1	Have been in the past
1	Occasionally
2	Participant
1	Participate
1	Participate
1	Participated/wrote/presented papers
1	Presentation of papers at the 1st and 3rd International APT Conference
1	Served in first two USA-based APT conferences
1	USACE—sponsor
1	Various papers on various APT Conferences
1	Was co-chair with Jon Epps for the 1st APT Conference in Reno, NV
1	Attended conference; reviewed papers for conference
1	Attended all, papers accepted
1	Member of TPF-5(070)
1	Occasional participant
1	Papers, presentations
1	Part of technical review committee
1	Participant
1	Participate
1	Presentation in 2008
1	2004 conference
1	yes

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. TERRA

Count	Response
1	Friend
2	Member

In which local/international APT forums are you active? Indicate those forums and please provide more details on the forums that you are active in next to the section [level of involvement, duration of involvement (history), role in program, permanent or ad hoc] in the additional details column. Other

Count	Response
1	China
1	China
1	FHWA ETGs
1	FWD User’s Group
1	I’ve never taken part in relevant local or international APT forums
1	Korean Society of Road Engineers
14	N/A or none
1	SPTC (with TxDOT, MnDOT, and Caltrans, with COE and NCAT) and FDOT
1	Transportation Association of Canada Pavement Standing Committee
1	U.S./French governments’ Memorandum of Understanding for airport pavements
1	Collaborative studies with both Indiana APT and Florida HVS
1	CEDR—Conference of European Directors of Roads: from member organization; Nordic Road Association: from member organization

What do you view as the most significant finding of full-scale APT in the last decade (since 2000)? Please respond in terms of your own program as well as your perception of international programs. Also indicate your perception of any significant future findings required (holy grails). Most significant finding—own full-scale APT program

Count	Response
1	Project-specific and some commercial in confidence
1	AC in long-life applications, approving WMA and R-WMA products
1	B/C ratios and COST results (see Du Plessis et al. papers)
1	Behavior (response and performance) of thin pavement structure
1	Bottom Ash Performance Evaluation
1	Confirmed rutting resistance of 4.75 mm
1	Construction impacts
1	Determination of structural coefficient for Full Depth Reclamation of HMA pavement
1	Dowel Bar Retrofit study with Caltrans
1	Evaluate rehab options

Count	Response
1	Evaluation of polymer modified binder due to cost savings
1	Evaluation of polymer modified binder due to cost savings
1	Improved asphalt pavement structure and materials design at the high temperature
1	Improved materials selection and design methods
1	Improved performance
1	Long-term rutting potential of our HMA mixes compared to others
1	Measured pavement response due to traffic loading → guidelines
1	Minimum Flexible Pavement Criteria
1	Modified binder research implemented into Florida design specifications
1	Moisture effects on pavement structures
1	Performance of materials
1	Quantifying the benefits of asphalt rubber in overlays
1	RAP and PFC performance
1	Reduced costs for pavement rehab
1	Saving time and funds on pavement structure or material comparison and verifying area
1	South African mechanistic design method update
1	To improve performance modeling
1	Understanding of the materials and structural responses
1	Validate lab material characterization and development of performance models
1	Validate lab material characterization and development of performance models
1	Validation of the use of rubberized asphalt concrete, calibration of ME models, WMA
1	Evaluation of warm-mix asphalt, verification of perpetual pavement design
1	Evaluation to specified pavement structure
1	Practical use of porous asphalt concrete
1	Program has not been active
1	Revised AASHTO layer coefficients
1	Subgrade performance
1	Understanding pavement behavior and deterioration models
1	Determination of new alpha factor for six-wheel landing gears in flexible airport pavement design and recalibration of rigid airport pavement failure model for design
1	Helped in development of New Pavement Design procedure, failure model update, developed new Alpha factors for 6-wheel gears for ICAO
1	Poor correlation of performance of unbound granular materials in RLT testing with field performance
2	Confirmation of the qualitative benefit of polymer-modified asphalts. Also, the durability of thin whitetopping
1	Calibration of the South African Concrete Pavement Mechanistic Design Method CnCPAVE, Bearing capacity determination of old structures
1	Quick comparison of competing materials and verification of materials used or design methodologies

Count	Response
1	The effect of the environment on pavement performance rather than the traditional load related deterioration
1	Evaluation of new structural concepts such as modular pavement structures and new types of “silent joints” between bridge and abutment
1	In the asphalt pavement, the main distortion under high temperature happens in 7 cm position under the pavement surface, not in the surface of the pavement.
1	Analysis of fine particles in pavements: MLS as a tool to distinguish between the emissions due to abrasion and resuspension of PM10 from road surfaces
1	Importance of long life pavement design and construction through proper selection of materials, use of analytically based methods for layer selection and proper construction practices
1	The NCAT Test Track facility has allowed MDOT to do rapid, full-scale testing of Mississippi-specific asphalt mixtures. Results from previous test track cycles have resulted in specification changes and implementation of new (special) mixture types.
1	Recalibration of AASHTO pavement structural coefficient, validation of MEPDG, validating high RAP content mixes

What do you view as the most significant finding of full-scale APT in the last decade (since 2000)? Please respond in terms of your own program as well as your perception of international programs. Also indicate your perception of any significant future findings required (holy grails). Most significant finding—international full-scale APT program.

Count	Response
1	Calibration of MEPDG
1	Calibration of mechanistic models
1	Classifying benefits of asphalt modifiers
1	Databases established from WesTrack and the HVS program
1	Development of design methods and instrumentation methods and tools
1	HMA cracking models
1	Huge cost savings in terms of implemented HVS verified innovative designs
1	Input for MEPDG
1	Interchange of information to expedite improved pavement design and rehabilitation
1	MEPDG
2	Materials/designs/construction
1	New pavement systems
1	Pavement modeling
1	Performance models
1	Role of geosynthetic reinforcement
1	The South African Mechanistic Design Method
1	Too many to select one single one
1	Top-down cracking research on Florida sections at NCAT—these are important for Florida
1	Validation of response and performance models
1	Verification of critical strain limit for HMA

Count	Response
1	Better performance models
1	Effects of compactions on bases and pavements
1	Performance of pavement structures
1	Structural performance models
1	Variability of mix responses and sensitivities
1	In a broad sense, full-scale testing of pavements yields quick indication of actual field performance.
1	Impact on various Caltrans research projects on concrete as well as asphalt pavements (see UC–Irvine research output).
1	Impossible to mention just one finding. I believe that many APT projects are extremely important to the understanding of pavements behavior. I would mention: the early works at Nottingham University (Brown & Pell), FORCE (OCDE) Project in France in the late 1980s; CAL-APT Program in the 1990s; MnROAD; the non-uniformity of stress distribution by SA researchers.
1	Databases of well documented performance data to assist with validation of design, theory, and to understand in situ failure mechanisms. WesTrack and the HVS program have been particularly good.
1	Shift factors for fatigue equations; layer equivalency between rubber-HMA and conventional HMA; performance of WMA vs. HMA; subgrade soil characterization/deformation/modeling CRREL
1	Difference in material performance index between the lab and the field, validation to design principle and design method
1	Relative long-term performance, obtained in a limited period of time, of potential long-life pavement structures.
1	The relationship between the performance of pavement and the traffic or temperature or moisture, and so on

What do you view as the most significant finding of full-scale APT in the last decade (since 2000)? Please respond in terms of your own program as well as your perception of international programs. Also indicate your perception of any significant future findings required (holy grails). Future significant findings required

Count	Response
1	Performance-related specification and verification. 2. Vehicle–pavement interaction
1	Aging/top-down cracking evaluation
1	An understanding of fatigue in asphalt mixes
1	Clearly understand and measure shear stresses near the surface of pavements
1	Developing much more method or instrument for environment stimulation for APT
1	Effect of aging/top-down cracking
1	Expanded use of RAP
1	Fully validated pavement performance model (you did say grail!)
1	How can we test pavement fatigue in the APT?
1	Improvement of response and performance models
1	Long lasting pavement materials and structures
1	Modeling, validate MEPDG, evaluate mixes with high % RAP
1	More MEPDG validation, inertial profiler certification
1	Qualification of WMA technologies

Count	Response
1	Sustainable pavement research
1	Test new materials before introducing them to common practice
1	To make more reliable performance modeling
1	Verification of materials performance
1	Weather and environmental aspects simulation
1	Bitumen alternatives
1	Develop damage models for new materials and construction techniques
1	Durability of open-graded mixes
1	Environmental issues, climate change consequences
1	Improved design methods for changing climate and traffic loading
1	New asphalt binder replacement materials
1	Relation of APT results and actual pavement performance
1	Structural performance models including rehabilitation
1	Full-scale testing is providing and will provide data to mathematically model anticipated performance as it relates to the selected materials.
1	Evaluation of new pavement concepts or problematic existing structures (e.g., orthotropic steel deck bridges) as an intermediate step between laboratory testing and/or computer simulations and field application.
1	Relationship between rigid airport pavement life and concrete strength, models for reflection cracking in airport pavements.
1	Most tests to date by Florida have been rutting based; future tests should focus on crack development. Most pavements in Florida fail due to excessive cracking.
1	Validation of lab materials' characterization; development of performance prediction models, performance-based specs; QC/QA procedures, preservation treatment life, warranty issues...
1	Verification of cheaper more cost-effective designs, testing of nontraditional binders & materials
1	HMA aging (effect of the environment on design)—Construction variability (how to reduce so thinner designs can be done)—verification of new non-traditional designs
1	We need to establish assigned quantitative benefit of geogrids and/or fabrics for base course reduction. Also, I am curious to see if APT can show any performance issues for warm-mix asphalt, especially relating to moisture-induced stripping.
1	Continued development of new materials, improved analyses for their utilization, effects of environment particularly combinations of aging, moisture and traffic

Do you own a full-scale APT device?

Value	Count	Percent
Yes	32	44.4%
No	40	55.6%

Statistics	
Total Responses	72

Do you have access to a full-scale APT device (and therefore APT data that you can analyze)?

Value	Count	Percent
Yes (Continue to Question 12)	37	51.3%
No (Questionnaire completed—go to end)	35	48.6%

Statistics	
Total Responses	72

Describe the type of access that you have to a full-scale APT device.

Value	Count	Percent
Own	22	71%
Rental	2	6.5%
Share	2	6.5%
Part of consortium	2	6.5%
Other	9	29%

Statistics	
Total Responses	31

Provide details of the full-scale APT device that you own/use. Description according to selection of specific options. Please provide a website link to your full-scale APT device homepage where more detail are available (including official photos).

	Selection	Additional information	Total
Mobile/fixed	70.5% 31	29.5% 13	100% 44
Linear/non-linear (circular, elliptical)	90.9% 30	9.1% 3	100% 33
Uni/bi-directional loading	90.9% 30	9.1% 3	100% 33
Number of axles	85.7% 30	14.3% 5	100% 35
Own power (diesel/electric/other)/shore power	83.3% 30	16.7% 6	100% 36
Field site/fixed site	88.2% 30	11.8% 4	100% 34
Roads/airfields	96.8% 30	3.2% 1	100% 31
Fixed device/trucks (automated or manually driven)	93.8% 30	6.3% 2	100% 32
Load range (range in kN indicate full load for all tires as well as range per tire)	81.1% 30	18.9% 7	100% 37

Tire details (size, type, inflation pressure range, other)	76.3% 29	23.7% 9	100% 38
Tire wander options	83.3% 30	16.7% 6	100% 36
Suspension (present or not, types possible, permanent or not, etc.)	87.9% 29	12.1% 4	100% 33
Temperature control options	78.4% 29	21.6% 8	100% 37
Speed range	87.9% 29	12.1% 4	100% 33
Dedicated operational data collection on full-scale APT device during operation (i.e., applied speed, load, location, etc.)?	90.6% 29	9.4% 3	100% 32
APT webpage link	87.9% 29	12.1% 4	100% 33
Other	90.3% 28	9.7% 3	100% 31

Provide details of the instrumentation that you typically use during full-scale APT tests by completing the table. Please provide additional information on the following aspects where appropriate, which new parameters are measured (not listed in the table), which parameters that you view as important are not measured and why (i.e., lack of instruments?). Provide links to documents/specifications used for selection, installation, calibration and use of instruments (if it exists). Provide information on documents used to guide forensic analysis of the pavement distress observed through the various instruments (documents only). Please provide full details on sensors (i.e., names, supplier etc.).

	Instrument used	Details—background on instrument, commercial or in-house developed (add links to documents here)	Total
Permanent surface deformation	69.2% 27	30.8% 12	100% 39
Permanent surface strain	81.3% 13	18.8% 3	100% 16
Permanent in-depth deformation	66.7% 22	33.3% 11	100% 33
Permanent in-depth strain	77.3% 17	22.7% 5	100% 22
Elastic surface deflection	74.1% 20	25.9% 7	100% 27
Elastic surface strain	73.7% 14	26.3% 5	100% 19
Elastic in-depth deflection	75.0% 18	25.0% 6	100% 24
Elastic in-depth strain	75.0% 21	25.0% 7	100% 28
Density	75.0% 21	25.0% 7	100% 28
Temperature	71.4% 25	28.6% 10	100% 35
Moisture	82.6% 19	17.4% 4	100% 23

Stiffness	78.9% 15	21.1% 4	100% 19
New parameter (list)	66.7% 6	33.3% 3	100% 9
Important but not measured (list)	88.9% 8	11.1% 1	100% 9
Other—please provide details	64.7% 11	35.3% 6	100% 17

Provide a description of the nature or purpose of your APT program (select all that may be applicable in the first column and indicate the primary nature in the second column).

	All applicable	Primary nature	Total
National research program	66.7% 12	33.3% 6	100% 18
State DOT research program or roads agency	63.0% 17	37.0% 10	100% 27
Academic research plan	81.8% 9	18.2% 2	100% 11
Commercial research plan	68.8% 11	31.3% 5	100% 16
Partnership program	72.7% 8	27.3% 3	100% 11
International cooperative program	66.7% 8	33.3% 4	100% 12
Ad hoc use of device—no specific program	63.6% 7	36.4% 4	100% 11
Local research needs	72.7% 8	27.3% 3	100% 11
Other	66.7% 2	33.3% 1	100% 3

Provide an indication of main expected research areas. Indicate if no medium term plans are made, indicate whether this is part of an agency wide plan or just for this facility. Add links to possible planning documents with more information.

Count	Response
1	Airfield research for DOD (Department of Defense—mainly Air Force).
1	Currently developing a 10-year research plan
1	Depends on research approved by committee
1	Funding is getting scarce so long-term plans are on hold.
1	Geogrids, concrete (RCC, whitetopping, etc.)
1	No medium research plan
1	Practical use of FWD and RWD

Count	Response
1	Recycled materials, full-depth recycling, partial depth recycling
1	Two projects. One for concrete pavement saw cutting guidelines and one for warm-mix asphalt
1	Under progress
1	Rehabilitation and secondary materials
1	The development of new materials
1	Always looking for ideas and partners. TERRA is one area that is helping develop these new partnerships along with other contacts our staff has. Five main research themes are innovative construction, green roads, preservation/rapid renewal, surface characteristics, and non-pavement research. Our 5-year plan includes finishing many pooled fund studies that were initiated during our phase two construction that took place in 2007–2010.
1	Future research plan is dependent on each research group. Now I don’t know other group’s plan. My main expected research areas include the verification to design parameters and indexes.
1	Currently establishing plan. Interlayers, RAP, high-performance aggregate and sub-bases and full-depth reclamation are ranked high.
1	Validation of pavement performance models, determination of pavement structural substance/residual lifetime, validation of methods for evaluation of the structural substance, testing and evaluation of new/innovative pavement structures
1	Plan to rebuild for next research cycle in 2012 with expected focus on pavement preservation, PFC durability, GTR binders, and high recycle content mixes
1	No detailed plan beyond two to three years. See above for projects over the next two to three years. After that expect to be running tests on full-depth (perpetual-type) asphalt pavements and to investigate reflective cracking failure mechanisms in asphalt overlays on deteriorated concrete pavements.
1	The following plan of action is proposed for the HVS Program, completion of the investigation into the structural strength and performance of Ultra-Thin Reinforced Concrete Pavements (UTRCP) for use on low-volume urban township roads, and the launching of a new study by which this technology will be adapted for use on provincial roads (inclusive of a study on the likely impacts of vehicle overloading on the performance of UITRCP). Drafting of guidelines and specifications on the design, construction and maintenance of UTRCP for use on low-volume urban township roads and, on completion of its development, also for use on provincial roads; launching of a new study to investigate the construction (by means of labor-intensive construction methods) and performance of roller-compacted concrete; launching of a capacity building, mentorship and technical support program dedicated to departmental staff that would include the following: Dedicated training courses (tendering and contract administration; geometric road design; structural design of pavements (new and rehabilitation); design of road pavement materials; construction; maintenance; quality control/assurance; and asset management); structured as well as ad-hoc (hot-line) technical support program in aspects such as short-, medium-, and long-term road maintenance planning; financing of roads; asset management (pavements/bridges/drainage structures); geometric design; pavement and bridge design; infrastructure performance predictions; road construction materials design; stabilization of slopes and maintenance/protection of retaining structures; road classification; contract management (technical specifications as well as design reviews); tender prizing (reasonability thereof); quality control/assurance; revision of departmental documentation (i.e., guidelines, standards, and specifications); evaluation of non-standard products for road construction and maintenance (assessment of fitness-for-purpose of unconventional products and provision of technical advice to department); launching of a new study into the stabilization of (marginal) materials with polymers, which can potentially be used for various pavement applications, including the stabilization of unsealed (gravel) roads, as well as for base and sub-base stabilization; enhanced focus on sustainable development and the environment; to evaluate the suitability and performance of warm and half-warm mixes; to develop alternative, non-bituminous binders; and to investigate the use of waste materials and by-products for road construction; HVS testing in support of the development of a new South African Pavement Design Method (SAPDM), including the simulation of traffic loading/stresses and creating a better understanding of the effects thereof on pavement performance (in association with SANRAL); construction and testing of High Modulus Asphalt (HiMA) to develop and validate mix design and structural design protocols, and to develop appropriate specifications for South Africa (in association with Sabita); Assessment of the fatigue resistance of hot-mix asphalt in support of the development of national guidelines for the design of hot-mix asphalt (in association with SANRAL and Sabita). The 2010–2015 strategic agenda for the HVS Program is fully aligned with the overall objectives of the Gauteng Government and supports the development of appropriate pavement engineering solutions aimed at generating significant savings in road building and rehabilitation, and augmenting the use of labor in these activities.

Count	Response
1	We will keep on working with WMA until the end of 2012. We haven’t still defined the research plan from 2013 on.
1	Research cycles are typically 1 year and are planned starting in the fall (Sept.–Oct.) based on FDOT needs.
1	General focus of last five years, and next three or so is on using APT to validate (or improve) laboratory assessment techniques.
1	Continued research into special, high performance asphalt mixtures (SMA/OGFC), high RAP mixtures, preventative maintenance asphalt mixtures, and warm-mix asphalt.
1	Typically plan research projects one year in advance. Planning is coordinated with state materials office, district materials engineers, construction office, and pavement management/design office. Research projects are divided into APT, field or laboratory (in-house), and contracted research efforts.
1	Future research is dependent on customer needs. As a private company there is no specific 5-year testing plan for the APT.

Which of the following full-scale APT types of tests are you conducting?

	Often	Infrequently	Never	Total
Dedicated constructed test sections (normal construction)	65.4% 17	19.2% 5	15.4% 4	100% 26
Dedicated constructed test sections (test pit)	41.7% 10	37.5% 9	20.8% 5	100% 24
In-service field test sections	25.0% 6	37.5% 9	37.5% 9	100% 24
Rehabilitation option comparison	41.7% 10	37.5% 9	20.8% 5	100% 24
Other	40.0% 4	40.0% 4	20.0% 2	100% 10

Provide information on your funding model and levels [if more than one source, indicate percentage per funding agency (sponsor) type in percentage].

	Model used	Funding levels (annual budget—US$ 2010)	Total
Funding agency (sponsor)	56.3% 9	43.8% 7	100% 16
Local/state government	55.0% 11	45.0% 9	100% 20
National government	58.8% 10	41.2% 7	100% 17
International	55.6% 5	44.4% 4	100% 9
Consortium	66.7% 4	33.3% 2	100% 6
Commercial	56.3% 9	43.8% 7	100% 16

Academic	50.0% 3	50.0% 3	100% 6
Other	42.9% 3	57.1% 4	100% 7
Short-term (project-linked)	66.7% 4	33.3% 2	100% 6
Long-term (program-linked)	60.0% 3	40.0% 2	100% 5
Intermittent/ad hoc	66.7% 2	33.3% 1	100% 3
Is funding guaranteed?	84.6% 11	15.4% 2	100% 13
Links to reference documents	50.0% 1	50.0% 1	100% 2

Provide an indication of any planned new developments on your device (updates to device, new instruments, new initiatives, etc.).

Count	Response
1	Additional load modules were added recently; always working on improving control systems.
1	Always looking at new ways of instrumenting experiments
1	Implementation of a new APT device (MLS 10)
1	Load monitoring system
1	New HVS Mark 6 arriving in April 2012
1	New version of HVS software just installed. New computers planned.
1	No planned new developments
1	Upgrade data acquisition system, develop new device for in-depth deflection measurement
1	http://rebar.ecn.purdue.edu/APT/Pages/newfacility.htm
1	Improve the ability to collect the dynamic rutting information
1	Rebuild test oval in 2012 and traffic with same heavy triple trailer trains
1	Wireless technology, moisture sensors, pressure sensors
1	The traffic simulator has just been updated. An automate driven system for moving from one test section to other has been added.
1	Investigation into fiber optic sensors, other surface mounted sensors (temp, strain), new monitoring systems/tools
1	Recently installed camera system to identify/measure surface cracks and other surface damage. Will continue to improve this system (http://www.dot.state.fl.us/statematerialsoffice/pavement/research/apt/documents/instrumentation.pdf). In the process of extending test tracks—extension consists of six 13-ft-wide lanes, 300 ft long.
1	Regenerative braking. New hydraulic load control components such as digital servo valves and digital controllers. Added four new load modules two years ago. Currently commissioning a dedicated materials testing laboratory.
1	Minor refinements to control system to better trap potential systems faults (we run largely unattended, so the system needs to be smart enough to halt trafficking if any issue occurs).

Provide information on the way in which you combine full-scale APT, laboratory testing, field testing, and long-term pavement performance (LTPP) in your program (LTPP refers to both SHRP LTPP sections as well as local LTPP sections that are not part of the SHRP LTPP sections). Select all applicable options.

Value	Count	Percent
APT and laboratory	20	80%
APT and LTPP	4	16%
APT and field	12	48%
APT, laboratory, and LTPP	3	12%
APT, laboratory, and field	12	48%
APT, laboratory, field, and LTPP	2	8%
Other	1	4%
Links to reference documents	1	4%

Statistics	
Total Responses	25

Provide information on the major specific tests that were conducted during the last decade. These are your major/ significant achievements. What was the effect of these programs on your department/research group/commercial activities etc. (objective, materials/structure, type of funding, type of outputs, etc.)?

Count	Response
1	All published reports may be found at: http://www.ltrc.lsu.edu/publications.html
1	Commonly built Swedish pavement structures have been tested.
1	Minimum Asphalt Thickness—Air Force
1	Porous asphalt concrete durability test
1	See summary reports on www.ucprc.ucdavis.edu
1	http://rebar.ecn.purdue.edu/APT/Pages/research.htm
1	Validation of 4th power law for unbound granular pavements with tin bituminous surfacings. Poor ranking of RLTT performance of crushed rocks (not characterization) to APT results—now considering shifting lab performance assessment to wheel tracking (have seen similar results, and similar use of wheel tracking, for asphalt a little over a decade ago). Improved understanding of the effect of tire type (mainly width) on rutting of crushed rock pavements.
1	Threshold effects/high modulus layers/grids/buried pipes/access covers etc. Reports specific to client.
1	AASHTO layer coefficient recalibration, fine gradations perform as well as coarse, reducing design gyrations, field performance prediction, increasing aggregate availability, implementation of SMA and PFC surfaces, identification of polishing aggregates, expanded use of 100% gravel mixes, PG67 in high RAP mixes, full-depth high RAP pavements, high-performance screenings mixes, and rehabilitation of failed pavements with high polymer inlays all resulted in changes to state DOT specifications.
1	Use MnROAD data to calibrate local and national design models, demonstrate material use for construction and performance, support the development of new tools to develop specification, provide training to partners, and provide a forum for discussion/demonstrations. These are the top areas but we have many more.
1	Full-scale traffic tests to failure on rigid and flexible pavements with 4-, 6-, and 10-wheel loading. Results incorporated in the FAA's airport pavement thickness design computer program, FAARFIELD, which is required for design by the FAA's Advisory Circular AC 150/5320-6E when pavement construction is funded from the Airport Improvement Program. Full-scale traffic tests on conventional flexible pavements with 4- and 6-wheel loading. Results used to revise the numerical values of empirical factors in the failure model of the CBR method of airport pavement thickness design. The revised factor values were adopted by ICAO in its ACN-PCN standard for airport pavement evaluation. The revised factors were also incorporated in the FAA's computer program for airport pavement evaluation, COMFAA.

Count	Response
1	Full-scale loading of the following asphalt mixture types: High Traffic, Gravel, Dense Graded Superpave Mixtures. Thin (3/4 in.) 4.75 mm gravel/limestone asphalt mixture; 45% High RAP, gravel/limestone mixture gravel/limestone SMA with an all gravel OGFC wearing surface.
1	Superpave and Marshall mix design parameters, material type, and thickness. Cold in-place recycling. Rigid pavement load transfer devices. Calibration of SHA's mixes for MEPDG. Geo-cell for surfaced and unsurfaced pavements. Rehabilitation of concrete and hot-mix asphalt surfaces. Experiments verified our specifications, caused us to use certain types of materials, verified design procedures. Either saved us funds that might have been used on an unsuccessful product or verified that funds were being properly used.
1	1. Study the effect of 6-wheel landing gear on the performance of flexible and rigid pavements and update 6-wheel Alpha factor for ICAO. 2. Develop advanced pavement design procedure for airport pavements (both flexible and rigid). 3. Study performance of HMA overlay over rubblized PCC pavements under heavy aircraft loads. 4. Study the effect of high aircraft tire pressure on flexible pavement performance.
1	Rutting in asphalt pavements (together with triaxial testing on asphalt mixes) and into different asphalt pavement rehabilitation techniques: no direct effect. Wearing courses on orthotropic steel deck bridges: together with computer simulations implemented in practice. Structural evaluation of modular pavement structures and silent joints between bridge and abutment: APT played major role in selection of alternative(s) applied or to be applied in practice.
1	Tests on WMA allowed field sections to be built. Currently testing R-WMA for field applications at $1.5M/year.
1	Suitability of recycled materials as base course materials. Pavement response measurements in different pavement structures due to heavy vehicle loading. Accelerated pavement testing of different pavement structures with impulse generator loading. Achievements: Equivalency of different types of pavement structures; classification of different pavement construction classes; comparison of measured and calculated response data; determination of pavement performance until failure under repeated impulse loading.
1	1. Evaluation of Superpave mixtures with and without modified binder. Specifications changed to show that modified binders should be used only in top surface lift for high volume roadways. APT showed that using modified binder in entire asphalt structure was not significantly better than using in top lift only. 2. Evaluation of Coarse and Fine-Graded Superpave Mixtures. APT showed that fine-graded mixtures performed just as good as or better than coarse graded mixtures. Specifications changed to allow fine-graded mixtures. 3. Assessment of wide-base tires. Compared performance of new wide-base tires with standard dual tires. Recommended use of the 455-mm-wide base tire in Florida. 4. Evaluation of Strain Gauge Repeatability. Provided confidence in instrumentation. As a result, use instrumentation more often than in the past.
1	Evaluation on innovative road building technology. Research and roll-out of UTCRCP, UTRCP, calibration of CNCPave, characterization of the load transfer efficiency in plain jointed concrete pavements through aggregate interlock.
1	Please, read our paper at the 3rd International Conference on APT ("Twelve years of accelerated pavement testing in Southern Brazil: achievements, lessons learned and challenges"). The available information is there.
1	In 2010, Tongji University conducted APT testing with MLS66 on a highway test track in the Congming Island. The purpose of MLS66 trafficking was to understand the permanent deformation characteristic and long-term performance of asphalt pavement with fine sand subgrade. There were two test tracks, low-filling subgrade (1.5-m thickness) and high-filling subgrade (3-m thickness) with the same asphalt pavement. The pavement included three asphalt layers (total thickness 20 cm) and two cement-treated aggregate layers (total thickness 54 cm). The low-subgrade test track was subject to one million two-wheel load repetitions with controlled temperature and the high-subgrade test track has 1.2 million loading in air temperature. The researcher collected the information of strain gauges, moisture sensors, and thermal couples. Other equipment such as PSPA, FWD, and profilometer also were used to monitor the performance before and during MLS66 trafficking. Core samples were obtained to compare material change. After MLS66 trafficking, test pits were cut to investigate the pavement structure.
1	Evaluation of polymer modified binder (changed design guide/specs to allow use of binder and specify which layer). Evaluation of coarse and fine-graded Superpave mixtures (changed specifications to allow fine-graded mixtures). Repeatability of strain gauges (determined strain gauges were repeatable, increased confidence in use). Evaluation of wide-base tires (recommended use of wide-base tires in Florida, specifically the 455-mm tire). Evaluation of a gradation-based performance evaluation method (validated a method developed by the University of Florida/FDOT, currently evaluating methods to implement). Evaluation of PCC slab replacement requirements (recommended temperature ranges and PCC strength to resist cracking) These reports can be found here: http://www.dot.state.fl.us/statematerialsoffice/pavement/research/reports/experimentalprojects.shtm

Provide an indication of the standard way in which full-scale APT information from your program is being disseminated into industry (provide information for academic dissemination, commercial dissemination and industry dissemination). Please provide official links to information (official website/database with reference lists and downloadable papers/reports if available) in the text boxes.

Value	Count	Percent
Academic dissemination (i.e., dissertations and theses)	17	65.4%
Commercial dissemination (i.e., reports, websites, news releases, etc.)	8	30.8%
Funding agency (sponsor) dissemination (reports, other)	17	65.4%
Industry dissemination (i.e., reports, websites, news releases, etc.)	8	30.8%
Conferences, meetings and journals	21	80.8%
Other (i.e., organization database, organization website, wikis, etc.)	8	30.8%

Statistics	
Total Responses	26

What do you perceive as the major influence that your full-scale APT program had on academia/industry over the last 5 to 10 years? Did it make a measureable difference?

Count	Response
1	Contribution in the National Transport Administration guidelines and recommendations
1	Development of specs for materials. Comparative performance of systems and products
1	Numerous graduate degrees. Faster implementation of new technologies
1	The program is still in progress and the influence is not clear.
1	Mainly on government normative
1	Participation by academia through the FAA's Center of Excellence program and the FAA's Grants program. Ph.D. and Master's dissertations as well as support for faculty and post-doctoral workers. The effect has been significant at those institutions specializing in airport work.
1	In Brazil, thanks to APT researches, the knowledge of pavement materials, design, and performance has been highly improved. We must intensely work to enhance data interpretation. Traffic simulators accelerate pavement distress by applying high axle loads at high loading frequency. The effects of high axle-load are generally computed using loading factors, as those derived from the results of AASHO Road Test. However, linear traffic simulators apply loads to pavements at very low speeds (generally lower than 10 km/h) and this also accelerates pavements degradation, especially when they include thick asphalt mixes. Loading speed has a strong effect on asphalt layers strains, and therefore on asphalt mixes fatigue life. In order to apply APT results to real pavements on which trucks apply loads at speeds many times higher than linear traffic simulators do, we will have to advance in the field of visco-elastic behavior of asphalt binders and mixes. Meanwhile, we propose a simplified approach in another paper [25] addressed to this Conference. It is highly desirable to more thoroughly integrate climate effects in the analysis of pavements performances under accelerated traffic. We already know the influence of soil suction in the resilient modulus of our APT facility subgrade and have succeeded to model temperature propagation across the thickness of asphalt layers. But we still have to develop a reliable model for correcting deflections according to pavements temperatures. We still make assumptions that we know are not completely true. In spite of the efforts carried out by our colleagues from South Africa and California, we still assume that wheel loads are uniformly distributed on circular surfaces. We need to improve pavement instrumentation and develop software to overcome gaps like that. More than anything else we have to strive to make TT more than a meaningless abbreviation.

Count	Response
	We sadly admit that many Brazilian pavement engineers and roads authorities still see APT as a worthless sophistication. Notwithstanding, in recent years two mobile traffic simulators were designed and built, based in our old good traffic simulator. One of them has continuously tested in-service pavements in Rio de Janeiro and Sao Paulo states since 2003. In National Conferences on Pavements held in the last twelve years, new results of APT researches have been reported. The idea that APT is essential when developing innovative pavement materials, such as high modulus asphalt mixes [26] is growing. We must think of technologic transfer as a mantra we should recite at every moment. If we succeed in shortening the distance between APT results and paving practices, more than improving the interactivity between researchers and practitioners, we will bring new partners to support our facility, to provide funds to graduate students and to help us advertise what such a facility could make for better pavements. As anticipated in the beginning of this paper we have intentionally defied the principles of scientific publication to let the reader know how happy we are for having a history, perhaps neither long nor bright, to tell; a history of concerns and hopes of people who dared trying to follow in the steps of notable pavements engineers and researchers of the most developed countries.
1	Tremendous influence on the evolution of specifications in the southeastern US over the last 10 years
1	A measurable difference for the Ministry of Transport, Public Works, and Water Management in the evaluation of new structures.
1	Had a huge impact on academia by providing funding for continued research and funds for graduate programs. Influenced the paving industries based on materials used.
1	Yes, development of the labor-intensive guideline document for road building materials, calibration of the South African Mechanistic Design Method, calibration of CnCPave, successful roll-out of UTCRCP and UTRCP road building technology.
1	Assessment of empirical standards on the basis of measured response. First validation of analytical design methods.
1	People attach importance to the high temperature stability to the other asphalt layers, not only to the course layer as before.
1	Full-scale rapid loading of pavements has allowed state DOTs to modify mixture design procedures and construction specifications in a very timely manner as opposed to waiting for performance distresses to occur on existing state highway facilities.
1	Two examples, see brochure: http://www.dot.state.mn.us/mnroad/pdfs/MnROAD%20Brochure%20_Aug%202010_.pdf APT Paper: http://www.cedex.es/apt2008/html/docs/TS07/Economic_Benefits_Resulting_from_Road.pdf
1	The results obtained from research at NAPTF have widely accepted nationally and internationally. 1. Developed a new airport pavement design procedure (FAARFIELD), which is the current FAA standard and an Advisory Circular. 2. New Alpha-factors were adopted by the International Civil Aviation Organization (ICAO). 3. ICAO is in the process of modifying tire pressure requirements under ACN-PCN methodology.
1	1. Evaluation of Superpave mixtures with and without modified binder. Specifications changed to show that modified binders should be used only in top surface lift for high volume roadways. APT showed that using modified binder in entire asphalt structure was not significantly better than using in top lift only. 2. Evaluation of Coarse and Fine-Graded Superpave Mixtures. APT showed that fine-graded mixtures performed just as good as or better than coarse graded mixtures. Specifications changed to allow fine-graded mixtures. 3. Assessment of Wide-Base Tires. Compared performance of new wide-base tires with standard dual tires. Recommended use of the 455-mm-wide-base tire in Florida.
1	The target is the industry. It makes a very significant difference in the performance of the pavement, especially HMA.

How do you measure/evaluate the benefit of your program in industry benefit/cost studies, economic analyses, seminar feedback, others)? Provide indications of calculated parameters (i.e., benefit cost ratios) where applicable, or links to reports with this information.

Count	Response
1	Benefit/cost investigation on the success of the APT program
1	I don't know
1	Improved knowledge, understanding and skill
1	No benefit/cost ratios have been calculated yet.
1	Now it's not available.
1	Value of research and benefit/cost ratio
1	Economic analysis or benefit cost analysis has not been conducted.
1	http://www.ltrc.lsu.edu/pdf/2007/riu_347.pdf
1	Not calculated
1	Cost benefit analyses. Feedback from client and industry. Monitor rate of implementation of recommendations.
1	Our sponsoring organization has adopted tests results and incorporated them in standards documents. Significant amount of non-financial support from industry (Boeing and Airbus) and from foreign governments. Cannot calculate benefit-cost ratios to any degree of accuracy because our test results are not disseminated commercially. Most of the monetary benefit is in cost avoidance and by this measure the benefit-cost ratio has been estimated to be in excess of 100. Documentation of this result has not been published.
1	A benefit/cost study has not been performed. In general, the benefit is the accelerated evaluation of methods and materials of interest to our districts and Pavement and Construction offices. Implementation of successful research is accelerated and unsuccessful materials/methods are not allowed.
1	Benefit/cost. Can calculate cost of making incorrect decision on one time or multiple time basis. Can show cost saving because one action is less than another and more effective or longer performance. Each experiment has a calculated B/C ratio.
1	We measure our success through feedback during interaction with state DOTs and industry, but more benefit/cost studies are needed
1	Any cost benefit analysis would have been small elements of the work (or done separately outside of the APT project) and would need to review past repeats to extract this information. benefits
1	This is a need that we have not been able to do in a lot of ways. We have good feedback from customers both paying and non-paying. Some of the small "just using the facility" people also have found benefit. The lessons learned cover some of these success stories. Mistakes are also benefits but we have a hard time quantifying them.

What is your estimate of the return on investment (cost benefit ratio) for your facility for the testing performed? Please add references to supporting literature where available.

Value	Count	Percent
1 to 5	6	40%
6 to 10	4	26.7%
11 to 20	2	13.3%
31 and up	3	20%

Statistics	
Total Responses	15
Sum	145.0
Average	9.7
Std. Dev.	11.18
Max	31.0

Why are you currently continuing with your APT program?

Count	Response
1	APT owned by company. Program specific to customer requirements.
1	Continued interest and financial support from local government
1	Mainly to support the Department of Defense and to protect our military.
1	Pursuing increased knowledge
1	Still have active customers and funding required to keep moving forward.
1	To rapidly monitor/measure the performance of pavement mixtures.
1	I think it is an important and effective approach to research the performance of pavement.
1	Public and private demands
1	Respond to market needs
1	Pavement materials and technologies evolve every day. We have to utilize the greatest materials and technologies available, but their performance should be tested first. Policies in pavement design and materials are changing very often. To write better policies (specifications, manuals, etc.) they have to be based on data-driven decision. APT can give us the “data driven decision.”
1	The APT program is one part of FDOT’s research program. It is performed in coordination with contracted and other in-house research efforts. These efforts answer problems faced by our districts and pavement/construction offices.
1	Hoping that someday the government will understand what are the uses of APT. I was the first Brazilian to fall in love with APT. Merci les amis du LCPC/Nantes.
1	Cost-effective means of evaluating new technologies. Peace of mind for road authorities to implement new technologies.
1	It answers questions that we could not get unless we placed the experiments on the road. The road is the wrong place for experiments to go bad.
1	Further support and development of the FAA’s airport pavement design and evaluation standards. Particularly new materials, changing aircraft operating specifications and landing gear configurations, and changing airport pavement maintenance activities.
1	Further validation of pavement response and performance models. Face challenges like significant increase of road transport volume, shortage of resources (e.g., bitumen), climate change.
1	1. To constantly improve design procedures, study failure mechanisms, advanced material characterization. 2. Provide support to the aviation community.
1	The Florida program is an essential part of our research effort. The goal is to implement the findings when feasible.
1	Currently no program; it will be very difficult to maintain the APT facility in the (near) future because of lack of funding/research program.

Provide information on the type of database or storage method that is used to store data in your APT program (only relevant to owners of APT devices).

Count	Response
1	Data bases are established for each experiment. Take the form of tables, graphs, and charts.
1	EXCEL files (amongst others)
1	Excel and Access
1	Hard drive
1	Hard drive and DVD
1	MS access, XLS-based
1	Microsoft Access database
1	No single database. Project specific data. Electronic.
1	No special database
1	No standard database or storage is being used.
1	PostgreSQL database on a server, with raw data in CSV format.
1	Project-based computer database (CD-ROMS, etc.)
1	Sequel Server database.
1	Very basic: computer files, sheets, and the resulting papers
1	Data QC via spreadsheet, permanent storage in Access database
1	Microsoft SQL Server database posted online. Raw data are archived on hard disks, DVDs, and magnetic tape.
1	We have a web-based database where all APT information is stored (reports, photographs, instrumentation data, HVS maintenance files, etc.). Typically, information is stored here after a project is complete. APT information is also stored on a network drive that is backed up nightly. This network is primarily used for active projects.
1	A dedicated database is used to store all APT-related data. We also have a dedicated network drive that we store all current files on. This drive is backed up nightly.
1	Oracle Database along with auxiliary data (pictures, video, some raw data not entered into the Database)—one TB data http://www.dot.state.mn.us/mnroad/data/pdfs/databaseguide.pdf. Working to get data onto the web in the next 2 years—data product 1.0 currently is being developed in-house and used by internal staff.

Do you make data from your APT program available to other researchers (not directly linked to your APT program) for analysis? What processes are followed to enable such researchers to obtain access to this data? (Only relevant to owners of APT devices.)

Value	Count	Percent
Data available to non-APT owners	14	82.4%
Data shared with other APT programs	11	64.7%
Process used	9	52.9%
Links to reference documents	5	29.4%

Statistics	
Total Responses	17

Where do the data that you use in your research originate from?

Value	Count	Percent
Focused research program—own organization	21	75%
Focused research program—other organization	7	25%

Full-scale APT database—own organization	17	60.7%
Full-scale APT database—other organization	5	17.9%
Other	2	7.1%

Statistics	
Total Responses	28

Do you only use data from individual sections in your research or a combination of selected sections or a whole research program?

Value	Count	Percent
Individual sections	10	35.7%
Combinations	23	82.1%
Others	1	3.6%

Statistics	
Total Responses	28

Who is your typical client (select all applicable)?

Value	Count	Percent
Funding agency (sponsor)	7	25.9%
State DOT/roads agency	15	55.6%
Academic institution	3	11.1%
External clients (commercial)	1	3.7%
Other	1	3.7%

Statistics	
Total Responses	27

How do you combine full-scale APT, laboratory, field, and LTPP data in your research?

Count	Response
1	Already answered
1	Combined research projects covering all different aspects
1	Compare different results and try to establish their relationship
1	Completely depends on the specific research project but LTPP data are rarely involved
1	Depends on the study—each has its strengths and weaknesses
1	Evaluate field and test results of same materials

Count	Response
1	They are organized and managed by one office, one section, and one manager.
1	We do combine full-scale APT and laboratory data, but very rarely field and LTPP data.
1	We use laboratory and field, APT and LTPP together to improve our understanding of pavement performance.
1	Only APT and Lab fundamental testing
1	Phase II Track studies are typically designed based on Phase I laboratory studies with modeled prediction of various research alternatives. Stockpiles, binders, bases, and subgrades are long hauled from remote locations to build track sections that are representative of open roadways in various states throughout the U.S. Replicate sections are also built on open local roadways for comparison purposes.
1	With skill and dexterity! All aspects are combined to present the whole picture. We use APT as a tool, not as the whole answer.
1	Laboratory data are often used to corroborate APT data. We have full-scale laboratories that characterize the materials used in the APT research and also conduct performance tests. When possible, field data are also used to corroborate APT data.
1	Laboratory tests are commonly conducted to reinforce or corroborate APT findings. FDOT has fully equipped asphalt, soils, and concrete labs. Field experimental projects are sometimes constructed to evaluate materials/ methods. These projects are longer term, but the performance may be used in conjunction with APT if available. LTPP data have not been used in FDOT’s APT program.
1	During my research work, I combine the three factors through modifying the test methods, modifying design methods, and so on.
1	Depends on research program but could be APT only, APT plus Lab, APT plus Field, or APT plus Field plus Lab.
1	Full-scale APT testing is very focused on specific asphalt mixture types. Field performance and laboratory testing are analyzed to make changes to existing state specifications.
1	Measure the characteristic of the properties used in the full-scale test. Compare full-scale measurements with field performance.

How often are full-scale APT data used in conducting graduate studies (masters or doctorate level)?

Value	Count	Percent
All projects	5	21.7%
Selected projects	10	43.5%
Only ad hoc	8	34.8%

Statistics	
Total Responses	23

How many masters and doctorate degrees were completed based on (partly or fully) full-scale APT data between 2000 and 2010 (provide links to copies of theses)?

	Completed	Current	Links to theses	Total
Masters	60.0% 15	32.0% 8	8.0% 2	100% 25
Doctorate	55.6% 15	33.3% 9	11.1% 3	100% 27
Other	66.7% 2	33.3% 1	0.0% 0	100% 3

What is the importance of economic analyses of the investigated technology in your research program?

Value	Count	Percent
Conducted during test planning as motivation	4	18.2%
Conducted afterwards as standard step	2	9.1%
Conducted afterwards as ad hoc activity	8	36.4%
Not done	9	40.9%

Statistics	
Total Responses	22

Which techniques do you use to conduct these economic analyses

Count	Response
1	According to experience and cost analysis
1	B/C
1	Modified CSIR/Jooste approach
1	None
1	Not formalized method—see APT 2008 report
1	Practical analysis periods and basic present value methodology using conservative costs
1	See Bennett and Rose TRB paper.
1	Value of research and benefit/cost ratio
1	Various
1	Bibliometrics, life-cycle cost analyses, cost/benefit analysis
1	Life-cycle cost

What is the basis of the selection of full-scale APT test sections in your program?

Value	Count	Percent
Official research program	20	74.1%
Ad hoc test selection	7	25.9%
Academic interest	4	14.8%
Other	1	3.7%

Statistics	
Total Responses	27

Indicate the type of surfacing pavement layers that you evaluated using full-scale APT.

Value	Count	Percent
Unpaved	7	24.1%
Seal/bitumen surface treatment	8	27.6%
Hot-mix asphalt	29	100%
Warm-mix asphalt	10	34.5%
Cold-mix asphalt	5	17.2%
Concrete (all thick concrete pavement layers)	16	55.2%
Ultra-thin reinforced concrete	3	10.3%
Ultra-thin white-topping	6	20.7%
Composites	8	27.6%
Other	8	27.6%

Statistics	
Total Responses	29

Indicate the type of pavement base layers that you evaluated using full-scale APT.

Value	Count	Percent
Sand	4	14.8%
Clay	4	14.8%
Granular	24	88.9%
Cement stabilized	15	55.6%
Emulsion stabilized	7	25.9%
Other stabilized (define)	3	11.1%
Asphaltic	16	59.3%
Composite	5	18.5%
Recycled	13	48.1%
Other	4	14.8%

Statistics	
Total Responses	27

Indicate the type of pavement subbase and subgrade layers that you evaluated using full-scale APT.

Value	Count	Percent
Sand	12	44.4%
Clay	17	63%
Granular	20	74.1%

Cement stabilized	10	37%
Emulsion stabilized	3	11.1%
Other stabilized	1	3.7%

Statistics	
Total Responses	27

Which are the structural distress types typically evaluated for asphalt surfacing layers in your full-scale APT program [please add failure threshold if available (i.e., 20 mm rut)]?

Value	Count	Percent
Raveling	6	21.4%
Bleeding	6	21.4%
Cracking	21	75%
Rutting	28	100%
Fatigue	19	67.9%
Low temperature cracking	3	10.7%
Moisture damage/stripping	5	17.9%
Aging	5	17.9%
Aggregate loss	4	14.3%
Other	6	21.4%

Statistics	
Total Responses	28
Sum	167.8
Average	13.9
Std. Dev.	8.37
Max	30.0

Which are the structural distress types typically evaluated for concrete surfacings in your full-scale APT program [please add failure threshold if available (i.e., 20 mm rut)]?

Value	Count	Percent
Cracking	18	90%
Stress ratio	5	25%
Joint failure	10	50%
Faulting	8	40%
Punchouts	3	15%
Erosion of support	4	20%
Fatigue	8	40%

Curling and warping	8	40%
Load transfer failure	9	45%
Spalling	5	25%
Steel rupture	1	5%
Debonding	3	15%
Other	3	15%

Statistics	
Total Responses	20
Sum	3.0
Average	3.0
Max	3.0

Which are the structural distress types typically evaluated for base and subbase layers in your full-scale APT program [please add failure threshold if available (i.e., 20 mm rut)]?

Value	Count	Percent
Permanent deformation	20	87%
Shear	8	34.8%
Cracking (define type?)	7	30.4%
Frost/thaw damage	2	8.7%
Collapsing	2	8.7%
Crushing	6	26.1%
Carbonation	1	4.3%
Swelling	3	13%
Other	3	13%

Statistics	
Total Responses	23

Which are the functional distress types typically evaluated in your full-scale APT program?

Value	Count	Percent
Safety	6	26.1%
Environment	3	13%
User cost	3	13%
Roughness	13	56.5%
Functional distress not deemed applicable to full-scale APT	10	43.5%
Other	3	13%

Statistics	
Total Responses	23

Which functional safety aspects were evaluated?

Value	Count	Percent
Rutting	25	92.6%
Skid resistance	10	37%
Punchouts	3	11.1%
Delamination	4	14.8%
Roughness	11	40.7%
Spalling	3	11.1%
Functional aspects not deemed applicable to full-scale APT	1	3.7%
Other	2	7.4%

Statistics	
Total Responses	27

Which environmental aspects are typically evaluated during full-scale APT?

Value	Count	Percent
Noise	5	20.8%
Dust pollution	2	8.3%
Not deemed applicable to full-scale APT	16	66.7%
Other	4	16.7%

Statistics	
Total Responses	24

To which of the following load characteristics do you relate full-scale APT data?

Value	Count	Percent
Applied wheel load	25	96.2%
Tire inflation pressure	20	76.9%
Tire contact stress	13	50%
Tire type	16	61.5%
Load configuration	17	65.4%
Suspension system	3	11.5%
Vehicle-pavement interaction/dynamics	9	34.6%

Channelized/wandering traffic	20	76.9%
Speed	16	61.5%
Rest periods	5	19.2%
Overloading	17	65.4%
Pavement roughness	6	23.1%

Statistics	
Total Responses	26

To which of the following environmental data do you relate full-scale APT data?

Value	Count	Percent
Ambient air temperature	20	76.9%
Pavement temperature	25	96.2%
Rainfall	8	30.8%
Relative humidity	6	23.1%
Aging	7	26.9%
Water table	12	46.2%
Drainage	7	26.9%
Depth to bedrock	3	11.5%
Other	2	7.7%

Statistics	
Total Responses	26

Which of the following environmental parameters are controlled during your full-scale APT tests? Please provide typical ranges for applicable parameters in the textbox.

Value	Count	Percent
Ambient air temperature (temperature ranges)	11	52.4%
Pavement temperature (temperature ranges)	18	85.7%
Water application (method)	8	38.1%
Aging (method)	3	14.3%
Subgrade moisture	9	42.9%
Drainage	3	14.3%
Other	1	4.8%

Statistics	
Total Responses	21
Sum	133.0

Average	26.6
Std. Dev.	18.98
Max	58.0

Which of the following bituminous-based materials have been tested?

Value	Count	Percent
HMA continuously graded	24	92.3%
HMA open graded	11	42.3%
HMA semi-gap graded	5	19.2%
HMA gap graded	7	26.9%
HMA large stone	6	23.1%
SMA	13	50%
HMA porous	8	30.8%
HMA RAP	7	26.9%
Gussasphalt	3	11.5%
HMA sand	3	11.5%
Warm-mix asphalt—Add process description	9	34.6%
Cold-mix asphalt—Add process description	3	11.5%
Surfacing seals—Single	6	23.1%
Surfacing seals—Double	5	19.2%
Surfacing seals—Cape	1	3.8%
Surfacing seals—Other	2	7.7%
Composite with concrete—Description	3	11.5%
Other	2	7.7%

Statistics	
Total Responses	26
Sum	11.8
Average	5.9
Std. Dev.	1.13
Max	7.0

Which of the following cement-based materials have been tested?

Value	Count	Percent
JCP	11	55%
CRCP	2	10%

Concrete blocks	5	25%
Doweled	8	40%
Other combinations	2	10%
Whitetopping—Description	4	20%
Ultra-thin reinforced concrete	2	10%
Composite with asphalt—Description	5	25%
Other	7	35%

Statistics	
Total Responses	20
Sum	106.0
Average	35.3
Std. Dev.	45.73
Max	100.0

Which of the following material properties have been related to full-scale APT performance?

Value	Count	Percent
Stiffness	20	80%
Poisson’s ratio	4	16%
Density	18	72%
Gradation	21	84%
Strength (concrete)	14	56%
Erodibility	2	8%
Atterberg limits	5	20%
Volumetric properties	13	52%
Binder type	22	88%
Binder content	13	52%
Film thickness	5	20%
Moisture content	10	40%
Visco-elastic properties	12	48%
Aging index	6	24%
Tensile strength	10	40%
Compressive strength	13	52%
Flexural strength	10	40%
Stiffness modulus	17	68%
Other	2	8%

Statistics	
Total Responses	25

Which of the following laboratory tests are used in conjunction with your full-scale APT program?

Value	Count	Percent
Standard asphalt tests	25	100%
Standard bitumen tests	19	76%
Standard concrete tests	13	52%
Standard granular/soil tests	19	76%
Standard stabilized layer tests	13	52%
Wheel tracking	11	44%
PTF	1	4%
MMLS3	2	8%
French rut tester	1	4%
Hamburg tester	10	40%
Asphalt Pavement Analyzer	11	44%
Direct tensile	5	20%
Indirect tensile	15	60%
Bending beam fatigue	11	44%
Strain at break	5	20%
Cantilever fatigue	2	8%
Semi-circular bending	5	20%
Triaxial	15	60%
Dynamic creep	9	36%
Static creep	8	32%
Gyratory	14	56%
Vibratory	4	16%
Kango hammer	2	8%
Other	3	12%

Statistics	
Total Responses	25

Which of the following field tests are used in conjunction with your full-scale APT program?

Value	Count	Percent
Penetration tests (i.e., DCP)	15	57.7%
Density/moisture	24	92.3%

Benkelman beam (or modified)	7	26.9%
Rolling dynamic deflectometer	2	7.7%
Plate load	8	30.8%
Seismic (i.e., PSPA)	13	50%
Ground Penetrating Radar (GPR)	11	42.3%
FWD	24	92.3%
Light FWD (LFWD)	14	53.8%
Permeability	8	30.8%
In situ strength/cores	19	73.1%
Relative crack/joint movement	10	38.5%
Scaled trafficking	1	3.8%
Other	2	7.7%

Statistics	
Total Responses	26

Which of the following pavement/materials modeling aspects do you relate to full-scale APT data?

Model type used—Back-calculation

Value	Count	Percent
Elastic layer	14	87.5%
Visco-elastic layer	5	31.3%
Elasto-plastic	4	25%
Finite element	7	43.8%
Iterative	5	31.3%
Statistical	4	25%

Statistics	
Total Responses	16

Model type used—Deflection

Value	Count	Percent
Elastic layer	16	84.2%
Visco-elastic layer	5	26.3%
Elasto-plastic	3	15.8%

Finite element	12	63.2%
Iterative	4	21.1%
Statistical	5	26.3%

Statistics	
Total Responses	19

Model type used—Deformation

Value	Count	Percent
Elastic layer	12	80%
Visco-elastic layer	8	53.3%
Elasto-plastic	7	46.7%
Finite element	10	66.7%
Iterative	2	13.3%
Statistical	6	40%

Statistics	
Total Responses	15

Model type used—Fatigue

Value	Count	Percent
Elastic layer	8	80%
Visco-elastic layer	3	30%
Elasto-plastic	2	20%
Finite element	6	60%
Iterative	1	10%
Statistical	5	50%

Statistics	
Total Responses	10

Model type used—Load equivalence

Value	Count	Percent
Elastic layer	4	66.7%
Visco-elastic layer	1	16.7%
Elasto-plastic	1	16.7%

Finite element	2	33.3%
Iterative	1	16.7%
Statistical	4	66.7%

Statistics	
Total Responses	6

Model type used—Other

Value	Count	Percent
Elastic layer	2	100%
Finite element	1	50%

Statistics	
Total Responses	2

Model type used—Pavement serviceability

Value	Count	Percent
Elastic layer	1	50%
Finite element	1	50%

Statistics	
Total Responses	2

Model type used—Stress/strain

Value	Count	Percent
Elastic layer	18	90%
Visco-elastic layer	8	40%
Elasto-plastic	6	30%
Finite element	18	90%
Iterative	2	10%
Statistical	5	25%

Statistics	
Total Responses	20

Which aspects of pavement engineering did you evaluate that may enhance construction and rehabilitation of pavements? Please provide details where applicable.

Value	Count	Percent
Unconventional materials	15	65.2%
Gradients	3	13%
Joints	4	17.4%
Slippage	1	4.3%
Buried pipes and culverts	4	17.4%
Bridge deck joints	2	8.7%
Road markings	3	13%
Durability	6	26.1%
Traffic accommodation	3	13%
Compaction	13	56.5%
Patching	4	17.4%
Reinforcement	5	21.7%
Preventative maintenance	4	17.4%
Quality assurance/quality control	4	17.4%
Surface texture	8	34.8%
Surface tolerance	2	8.7%
Surface drainage	1	4.3%
Subsurface drainage	2	8.7%
Other	1	4.3%

Statistics	
Total Responses	23
Sum	60.0
Average	60.0
Max	60.0

Agency/Organization

Count	Response
1	ARRB Group
1	Alabama Department of Transportation
1	Alaska DOT&PF
1	Arkansas Highway and Transportation Department
1	CEDEX Transport Research Center
1	CSIR
1	CSIR Built Environment

Count	Response
1	CTR
1	Caltrans
1	China Merchants Chongqing Communications Research & Design Institute Co., Ltd.
1	Chongqing Communications Research & Design Institute
1	Colorado Department of Transportation
1	ConnDOT
1	Danish Road Directorate, Danish Road Institute
1	Delaware DOT
1	Delft University of Technology
1	Dynatest Consulting Inc.
1	ESJ Pavement Consulting Engineers
2	Empa
1	Expressway & Transportation Research Institute
1	Federal Aviation Administration
1	Federal Highway Research Institute (BASt)
1	Federal University of Rio Grande do Sul
3	Florida Department of Transportation
1	Georgia DOT
1	Icelandic Road Administration
1	Idaho Transportation Department
1	Illinois DOT
1	Indiana Department of Transportation
1	Iowa DOT
1	Kansas DOT
1	Kansas Department of Transportation
1	Kentucky Transportation Cabinet
1	Liaoning Province Communication Research Institute
1	Louisiana Transportation Research Center
1	MT Department of Transportation
1	Maryland SHA
1	MassDOT—Highway Division
1	Michigan Department of Transportation
1	Minnesota Department of Transportation
1	Mississippi Department of Transportation
2	Missouri DOT

Count	Response
1	NCAT Pavement Test Track
1	NCE
1	NDDOT
1	NYSDOT
2	National Laboratory of Materials and Structural Models of the University of Costa Rica
1	Nevada DOT
1	New Hampshire Department of Transportation
1	New Mexico Department of Transportation
1	Norwegian Public Roads Administration
1	ODOT
1	Ohio Department of Transportation
1	Public Works Research Institute
1	South Carolina Department of Transportation
1	South Dakota DOT
1	TRL
1	Tennessee Department of Transportation
1	The Highway Institute—Belgrade
1	The University of Texas
1	Tongji University
1	TxDOT
1	U.S. Army Corps of Engineers, ERDC
1	U.S. Army Corps of Engineers, CRREL
1	U.S.DOT, Federal Aviation Administration
1	University of California Pavement Research Center
1	University of California, Berkeley
2	University of Nottingham
1	University of Washington
1	University of Waterloo—Civil and Environmental Engineering
1	Utah Department of Transportation
1	VTI—The Swedish Road and Transport Research Institute
1	Vermont Agency of Transportation
1	WSDOT
1	Wyoming DOT

Country

Count	Response
1	Australia
1	Brazil
1	Canada
1	China
2	Costa Rica
1	Denmark
1	Germany
1	Iceland
1	Japan
1	Korea
1	Norway
2	P.R. China
1	Pulaski
1	RSA
1	Serbia
3	South Africa
1	Spain
1	Sweden
2	Switzerland
52	United States
3	United Kingdom
1	the Netherlands

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation