To mark the approach of the new millennium, the Transportation Research Board (TRB) technical committees mounted a special effort to capture the current state of the art and practice, as well as their perspectives on future directions in their respective areas of focus. Each of these “millennium papers” provides a comprehensive view of transportation in the United States as it exists today and can be expected to evolve as the new century unfolds.

In September 1999, the Transportation Association of Canada (TAC) released “A National Agenda for Technological Research and Development in Road and Intermodal Transportation.” The agenda identifies trends, opportunities and needs, as well as specific high priority R&D projects, relevant for advancing Canadian highway transportation. The focus of the Agenda is on identifying R&D opportunities to optimize the management of the road system and intermodal transportation, and minimize the cost of road transport while maintaining or improving safety.

To further the dissemination of current North American highway technology and future research needs, C-SHRP has prepared this special series of technical briefs, called the Millennium Research Briefs, based on information published in the TRB millennium papers and the TAC agenda. One brief has been developed for each of the four original C-SHRP/SHRP technology areas - Asphalt, Concrete and Structures, Pavement Performance and Highway Operations.

### FLEXIBLE PAVEMENT DESIGN [1]

The state of the art in flexible pavement design is manifested in mechanistic, or mechanistic-empirical (M-E) based design procedures that incorporate the treatment of life-cycle costs and design reliability. State-of-the-practice methods, however, rely on empirical correlations with past performance, index-value characterizations of material properties and engineering judgment for design strategy selection. In addition, these procedures have been used for traffic load levels and environments well beyond their observational base. The AASHTO Guide for Design of Pavement Structures is commonly used to design pavements with traffic loadings greater than 50 million equivalent single axle loads (ESALs), while the basic design equations were developed from traffic loadings of less than 2 million ESALs. Mechanistic procedures can have several important advantages, including:

- Better capability to characterize material properties and assess existing pavement structural capacity (through laboratory testing, nondestructive testing, and backcalculation),
- ability to evaluate and compare different design alternatives on a fair (defensible) basis,
- ability to rigorously account for stochastic variability or uncertainty in the design process.

The Canadian Strategic Highway Research Program (C-SHRP) was established in 1987 to systematically extract the benefits from research undertaken by the Strategic Highway Research Program (SHRP) in the United States. SHRP was initiated in response to the continuing deterioration of highway infrastructure with the intention of making significant advances in traditional highway engineering and technology through the concentration of research funds in key technical areas. C-SHRP aims to solve high priority highway problems in Canada that are related to SHRP topics. The goal of both SHRP and C-SHRP is to improve the performance and durability of highways and make them safer for motorists and highway workers.
The primary disadvantage of the mechanistic procedures (as reported by the users) is that they are more complicated, time-consuming, and costly to apply because they require additional information that is not typically collected by highway agencies.

The anticipated 2002 Guide for Design of New and Rehabilitated Pavement Structures - currently under development through the National Cooperative Highway Research Program (NCHRP) under Project 1-37A - will advance the state of the art over current practices in several key areas including the use of axle load spectra for traffic modeling, the use of finite-element (FE) analysis for response prediction, and the incorporation of reliability in life-cycle cost assessment. Perhaps its greatest benefit will be the widespread introduction of M-E based design to the transportation industry.

### Analytical Models

Analytical models are used to predict the state of stress in a pavement under simulated wheel and environmental loading conditions. Most models are based on multi-layer elastic (MLE) theory and/or FE analysis. The MLE models are considered satisfactory for predicting flexible pavement response under external wheel loads and are also relatively easy to operate. However, they are not capable of predicting pavement response associated with environmental loading (i.e. that due to daily temperature changes, temperature gradients, moisture variations, etc.). FE models are capable of considering both wheel and environmental loading conditions, however, they are relatively complicated to operate and time-consuming. Prior to the 2002 Guide, FE analysis was not widely used for flexible pavement design.

### Transfer Functions

A multitude of relationships have been developed to relate the state of stress in a pavement to its overall performance. The primary transfer functions used for current flexible pavement design procedures are those that relate: (a) maximum wheel load tensile strain in the hot-mix asphalt (HMA) surface layer to fatigue cracking; and (b) wheel load compressive stress (or strain) at the top of the subgrade layer to rutting. These models are typically derived through statistically based correlations of pavement response with observed performance of laboratory test specimens, full-scale road test experiments, or both. Transfer functions are the most important component of an M-E design procedure and significant efforts are still needed to develop better and more realistic models that can predict performance.

### Traffic Loading Simulation Models

Currently the variety of wheel loads in the traffic stream and their cumulative applications are converted into a single number of 80-kN ESAL applications using a load equivalency factor (LEF) concept that was developed over 40 years ago. This methodology still has validity, however, it has several weaknesses when considering the impacts of new tire types, higher tire pressures and axle configurations. Furthermore, the current AASHTO LEFs were developed solely on the basis of how wheel loads affected overall pavement serviceability and not individual distresses. The new axle load-spectra approach is expected to replace the ESAL concept in the 2002 Guide to address some of these problems.

### Material Characterization Methodologies

One of the benefits of M-E methodologies is that they rely upon one or more fundamental engineering properties of the individual pavement and soil layers to determine the state of stress and predict pavement performance. One of most important properties is the elastic modulus. The elastic modulus has many benefits over other index properties such as AASHTO layer coefficients, R-value, and CBR since it has a direct effect in the analytical models used to predict the state of stress. Despite this key advantage, there are some significant problems associated with its use. First, bituminous pavement materials are not elastic. Accordingly, a surrogate for elastic modulus (resilient modulus) is used to characterize a given layer material's bending resistance under the state of stress that it will experience in-situ. Another problem concerns the difficulty in accurately measuring resilient modulus in the laboratory. Although improvements to the laboratory-based resilient modulus test method are anticipated, a second method involving the use of nondestructive testing and backcalculation analysis also holds promise. In this latter approach, measurements of surface deflection are obtained nondestructively in the field and then evaluated mechanistically (using a computerized process known as backcalculation) to determine each layer's in-situ resilient modulus. This process is especially useful for rehabilitation design, but also has some application for new pavement design if the nondestructive test measurements are obtained along the planned road alignment.
Life-Cycle Cost Model

Life cycle cost (LCC) analysis is considered a state-of-the-art component in a pavement design procedure, although it is not at all tied to the M-E design principles discussed thus far. LCC analysis provides a sound basis for economically evaluating a number of feasible pavement design alternatives.

Reliability Model

Reliability is a feature that was incorporated into the 1986 AASHTO Guide in order to account for the uncertainty in determining design inputs and predicting pavement performance. Like LCC analysis, it is not a process that is related to the M-E pavement design principles. However, it is a process that complements M-E design well and is planned for use in the 2002 Guide. The process associated with reliability involves an assessment of stochastic variability of the design inputs as well as prediction error within the transfer functions so that a structural design can be established with an associated level of confidence.

FUTURE DIRECTIONS IN PAVEMENT DESIGN

Incorporation of LTPP/C-LTPP Findings

Under the current schedule, field data collection associated with the Long-Term Pavement Performance (LTPP) studies in the United States will be completed within the next seven or eight years, while the Canadian counterpart (C-LTPP) will be completed in April 2004. Some preliminary data analyses are under way or envisioned and the eventual completion of field monitoring and finalization of the databases will set the stage for more comprehensive data analyses. These research efforts will have a variety of different goals, including the development of new transfer functions, prediction models, and M-E design procedures that would likely be incorporated into future pavement design guides.

Vehicle-Pavement Interaction

Vehicle-pavement interaction has received some attention over the years but has not significantly impacted flexible pavement design. Past studies have focused either on the effect of vehicle dynamics toward accelerated pavement deterioration or the effects of rough pavements on truck damage. Considering the hundreds of billions of dollars that are spent every year on both the preservation of the highway infrastructure and trucking activities, one approach is to determine the combination of maximum axle load (or gross vehicle load) and the cost of infrastructure restoration to optimize the overall benefits to the taxpayer.

PAVEMENT MANAGEMENT [2]

Support for pavement management among transportation agencies continues worldwide; however, recent changes in (US) legislation that no longer mandates the use of pavement management systems have reduced the support of senior management personnel. Many practitioners have expressed the need to regain or maintain the support of top-level management through increased communication and technology transfer.

Other challenges surround the technical aspects of pavement management, including more standardization in data collection procedures and more training for pavement management personnel. Broader challenges that have been identified include:

♦ The need for increased standardization in the data collection processes to facilitate communication of data between agencies on a more consistent basis.

♦ Allowances for flexibility in the customization of pavement management programs so that agencies can tailor their systems to the management philosophy and resources available.

♦ The lack of practical pooled-fund studies to address research concerns that are common to several agencies.

♦ Continuous turnover in pavement management personnel, requiring the need for more training and innovative forms of training.

♦ The need for a better link between network-level and project-level management decisions.

♦ The increased need to sell pavement management results to the individuals responsible for making program, policy, and budget decisions.

Future Directions

Several goals and objectives for taking pavement management into the new millennium have been identified:
♦ The program development process, which includes pavement management system recommendations, should become more formalized within transportation agencies, with decisions made on a more objective basis.

♦ The use of pavement management systems should be expanded beyond large transportation agencies to include cities, counties, and airports.

♦ A clearinghouse for pavement management information should be developed so that agencies have immediate access to information that documents best practices and the use of new technology in pavement management.

♦ Processes and procedures should be developed to facilitate improved coordination between transportation agencies in pavement management through shared activities and pooled-fund studies.

♦ Research is needed in order to improve the status of existing pavement data collection technology.

♦ Additional training programs should be developed for both practitioners and top-level managers. Innovative approaches to training should be considered because of restrictions on travel and the ongoing nature of the need for technology transfer programs.

♦ Efforts should focus on linking asset management components, which include pavements, into an integrated decision-making model that can be used by transportation agencies for all infrastructure assets.

PVEMENT MONITORING, EVALUATION, AND DATA STORAGE [3]

There is a need to collect pavement performance data more expeditiously and reliably. Automation technology continues to advance at an exponential rate of growth, with current technologies capable of collecting structural capacity information, ride quality data, and surface distresses. Advances in computer technology have facilitated the volumes of data that can be collected and stored. Similarly, greater access to positioning satellites has made the location of data in the field more accurate, which has assisted in making the storage, retrieval, or both, of the increasing volumes of data much more manageable and user friendly. However, only pavement ride quality and rut depth data can be collected with acceptable levels of accuracy, resolution, and precision in real time (at normal highway speeds). Research and development are under way to advance the state-of-the-art in the collection of structural capacity data, while the automated collection of pavement surface condition data remains at an unacceptable level.

Information Gaps

Many agencies have yet to determine when structural capacity data are truly needed. For example, should structural capacity data be obtained for project designs alone, or can such data be used to supplement management decisions? Can the cost of collecting such data at a network level be justified? How should the data be summarized and represented in such a network-level application?

Needs for surface condition assessment continue to be a source of uncertainty for agencies. For example, what level of detail is required for network-level surface condition assessments? How many different distresses and severity levels are truly required? Are the locations of the distresses important or just average quantities? What kinds of decisions require severity levels and additional distress types?

Similarly, analysis of visual distress data collection for pavement management remains a significant abstraction to many agencies. For example, should a threshold value be incorporated? Should rehabilitation be completed when the rate of deterioration increases? How detailed should the data collection be to ensure that the analysis is meaningful? Do composite scores maximize the value of data collection efforts? Will programs such as pavement preservation require additional data? The ability to store and process large volumes of data has advanced considerably, however this may simply be fostering significant inefficiencies.

Data Consistency

Consistency of data across individual transportation agencies remains a significant problem to this industry. Although research is being conducted on the optimum strategies for collection of data, agencies must make interim decisions. As they address their current needs, trends are established that cannot easily be redirected. The challenge of persuading agencies to convert to new or universal systems grows larger with each passing year.
Looking Ahead

The desire to have an “all-in-one” pavement-monitoring vehicle remains. Profile data can already be collected in real time and structural capacity data will likely be obtainable in a similar fashion within the next decade. Steps must be taken, however, to produce a clearer set of objectives for collection of surface condition data to allow for its automation. If extremely detailed pavement surface distress data are truly needed, advances in image resolution will be required. If a standard set of critical distresses can be agreed upon (with a specified tolerance for accuracy), industry should be able to focus on those distresses and develop some consistency in their collection. The quality and accuracy of the data appear to be of greater concern than the ability to collect these data rapidly. However, the industry as a whole continues to struggle without a definitive statement of minimum data quality and accuracy. Until these issues are adequately addressed, pavement monitoring will not be able to capitalize on the advancements in automation technology.

PAVEMENT MAINTENANCE [4]

There is a shortage of data that reflect the effectiveness (cost and performance) of pavement maintenance treatments. Although data may be collected, documentation is sparse, and the data is not often analyzed in an organized fashion. The various management systems that currently exist (pavement management, maintenance management, project management, etc.) must be integrated to effectively manage pavement information and to improve pavement maintenance planning, programming, and scheduling. Some agencies are already integrating management systems, but more emphasis is needed. Integrated systems will also promote the implementation of effective pavement preservation programs.

Quality assurance for pavement maintenance activities has been relatively slow to evolve. While some agencies have adopted quality assurance programs for maintenance, much work remains to be done. As more agencies outsource maintenance activities to contract workers, better specifications and quality assurance will become more important.

FULL-SCALE/ACCELERATED PAVEMENT TESTING [5]

A renewed interest in FS/APT programs has been observed worldwide. In the United States alone, major investments in FS/APT programs have been committed by FHWA, the US Army Corps of Engineers, and several states. In addition, the Federal Aviation Agency (FAA) is currently commissioning the largest APT machine in the world. The state of Florida and the National Center for Asphalt Technology (NCAT), in collaboration with the Alabama Department of Transportation, have both initiated major FS/APT efforts, which are likely to be the first new APT programs of the 21st century. In Canada, the Université Laval has established an accelerated test facility for low volume roads, and efforts are underway at the University of Waterloo to establish a roads and pavements test facility. FS/APT affords rapid evaluation of potential solutions in a number of current and enduring problem areas including asphalt concrete rutting, quality control and assurance procedures, warranty construction, performance-based specifications, improved maintenance procedures, and nondestructive pavement evaluation procedures.

In the immediate future, the most beneficial development for FS/APT would be improved coordination of effort to ensure the most effective application of resources without duplication. This goal requires significant standardization of distress definition and data collection procedures.

PAVEMENT REHABILITATION [6]

The achievement of longer-lasting pavement rehabilitation while efficiently managing heavy traffic through construction zones is an ongoing challenge. As such, continuous improvements in technology are needed to improve the entire process of pavement rehabilitation. The key areas that will benefit from such improvements include the following:

♦ Assessment of the in-situ condition of existing pavements. Use of ground-penetrating radar, seismic techniques, and other nondestructive techniques needs to be expanded to complement FWD testing. There is a need to standardize pavement evaluation and testing protocols,

♦ Use of durable paving and repair materials that can carry truck traffic within a few hours after placement.

♦ Use of zero-clearance paving equipment that will minimize extensive lane closures.
♦ Development of rehabilitation design procedures that clearly address mitigation of specific distress types and rationally account for future truck traffic loading.

♦ Concrete pavement restoration techniques (e.g., dowel bar retrofit technique) and reflection cracking mitigation techniques.

**JOINT- AND CRACK-SEALING [7]**

Pavement joint and crack sealants are designed to prolong pavement life by minimizing water infiltration and preventing the accumulation of debris. Research has indicated that, in conjunction with maintenance techniques such as slurry seals and chip seals, crack sealing will extend the life of a flexible pavement. A major challenge facing the sealant industry is to quantify the effectiveness of joint sealing in rigid pavements and its cost-to-benefit ratio when considering the life cycle cost. Another challenge is to identify the appropriate sealant for a specific job. The third challenge is training of contractors and users concerning the types of materials, the correct installation geometry, and the procedures that are required to clean the joint or crack and install the sealant.

**Materials and Specifications**

Different kinds of pavement (from both the material and use perspectives) require different sealant materials. Hot-applied modified asphalt-based sealants are the most effective and widely used sealant materials for use on flexible pavements. Other materials—such as emulsified, cutback, and chemically curing products—will continue to be used in specific applications where the costs or material characteristics of the products are justified. Sealant materials used for rigid pavement applications vary more widely than those used for flexible pavements. Historically, the hot-applied asphalt-based materials have been the most commonly used materials for these applications. However, silicone-based sealants and preformed compression-seal materials have gained increased acceptance and have become the preferred choice of a significant number of US agencies.

Materials resistant to jet fuel and aircraft exhaust are commonly required for airfield pavements. The use of silicone-based materials for airfield pavements that are exposed to intermittent or limited fuel spillage is increasing for civil and military applications. The U.S. military typically uses preformed compression seals, which are believed to provide a long-lasting seal in new pavements, during the new construction of airfield pavements.

New materials will continue to be developed for sealing cracks and joints in flexible and rigid pavements in an effort to provide a more effective seal. As new products become available, it will be important to verify their performance in specific applications. The real challenge will be to identify material properties and develop testing procedures that can assess sealant performance in the field. Procedures and concepts developed during the Strategic Highway Research Program (SHRP) for performance grading of asphalt cements, as well as adhesion (to substrate) tests may allow the development of performance-based specifications. Performance-based specifications provide two advantages. First, the performance of newly developed materials could be more rapidly assessed against the known performance of existing sealants. Second, the most appropriate sealant could be objectively selected for a specific set of conditions. However, new material specifications alone will not improve the performance of crack and joint sealants in the field. Application procedures and equipment also play a vital role in the field performance of materials.

**PAVEMENT TECHNOLOGY ISSUES AND OPPORTUNITIES IN CANADA [8]**

The following pavement technology issues were identified in the TAC National Agenda through an extensive consultative process.

**Pavement Preservation**

Until recently, decisions concerning how and when to rehabilitate pavements were essentially based on expert judgement. The rapid emergence of pavement management technologies and systems have assisted the decision-making processes greatly, however, these systems and technologies have evolved unevenly over the past few years. A few key technologies have still not reached industry expectations and are restricting the potential of modern pavement management tools. The key issues and opportunities are related to pavement data, pavement management, and contracting methods.

**Durability of Pavement Materials**

Increased traffic loads and the deterioration and aging of materials used in pavement construction in the 1960’s and 70’s have promoted the need to develop
more resistant and durable pavement materials. Recent developments in engineered asphalts, Superpave binder and mix specifications, and high performance concrete have helped to resolve several pavement performance problems. Improvements are still needed in many aspects of material performance in the Canadian context. The growing preoccupation with environmental considerations and sustainable development during the last decade has forced the rapid development of technologies and procedures for recycling pavement and other materials in road construction. Research is still needed to refine the existing recycling processes and to develop new ones. The key issues and opportunities in this area are the development of surfacing materials resistant to reflective cracking, developing performance-based specifications for pavement materials, and recycling methodologies.

**Design procedures for new and rehabilitated pavements**

Major developments are currently underway led by TRB-NCHRP, FHWA and C-SHRP. These developments will produce improved technologies for the design of new and rehabilitated pavements based on mechanistic principles and distress-specific empirical transfer functions calibrated to local conditions. It is expected that significant improvements will result from these ongoing research endeavours. Important efforts will, however, be required in order to adapt and calibrate research results to Canadian conditions.

**Variability of pavement design factors**

The AASHTO and the OPAC 2000 design methods have incorporated the concept of reliability in pavement design. This concept, based on the quantification of the variability of significant design factors, is likely to be incorporated in other design methods in the future.

**Policies and procedures for spring load restrictions**

Bearing capacity loss during spring thaw period has long been recognized as a major factor toward pavement deterioration. Most Canadian highway agencies use springtime load restrictions to mitigate the detrimental effect of heavy vehicles during spring thaw. However, procedures and criteria to establish the beginning, the duration, and the magnitude of the restrictions vary considerably from one agency to the other. The development and promotion of a standard approach to spring load restrictions would greatly benefit both the highway agencies and the transportation industry.

**CONCLUDING REMARKS**

This brief highlights the state of the art and some of the critical issues facing the pavement design and performance fields as identified by the Transportation Research Board and the Transportation Association of Canada. The interest and awareness of this field have grown progressively over the last fifty years. Most notably, the LTPP/C-LTPP initiatives and SHRP/C-SHRP research focused the attention on the challenges of the pavement industry in the past decade. The majority of issues identified in the pavement design and performance field relate to data quality and management, standardization of distresses, practices and quality control procedures, and performance based specifications. There is an evident need for increased research and development in this area. Continued collaboration and partnerships between the pavement industry, research institutes, and transportation agencies will provide solutions to many of these issues.
REFERENCES


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ISBN 1-55187-064-9