REINVENTING THE (PAVEMENT MANAGEMENT) WHEEL

Distinguished Lecture

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By

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ABSTRACT
Pavement management has progressed from a concept in the 1960's to current, widespread and successful application in many countries around the world. The reasons include a sound, underlying framework, an extensive base of technology and foresight on the part of individuals and agencies. However, a range of institutional, data, engineering and systems issues remain to be resolved. As well, there are "reinvention/invention" needs involving succession planning, integration, adaption to privatization, longer lasting pavements, performance models, quantification of benefits, incentive programs and very long term life cycle analysis which have to be addressed if progress in pavement management is to continue. By the same token, these issues and needs can also be seen as opportunities; for example, the integration of well established pavement management systems into the development of asset management systems. Finally, there are realistic expectations for the future of pavement management, such as incremental advances in technology. There are also more idealistic but achievable expectations such as widespread adoption of effective succession planning, quantum increases in pavement service lives, a new SHRP program which targets innovation, grant funding for high risk ideas, and comprehensive protocols for very long term life cycle analysis and for long term performance specifications.

1. INTRODUCTION

1.1 A Distinguished Lecture Is An Honour, and An Opportunity

According to the Transportation Research Board (TRB), a Distinguished Lecture provides (to those honored) …. "The opportunity to present overviews of their technical areas, including evolution, present status, and prospects for the future".

Certainly I am honored, and will attempt to take advantage of the opportunity offered through my background in pavement and infrastructure management, my participation in all five International Conferences on Managing Pavements, and the chance to express some opinions which may well be provocative.

It should be noted that this Distinguished Lecture is presented on behalf of the International Society For Asphalt Pavements, which I have served in various capacities since its founding in 1987.

1.2 A Title of "Reinventing the Wheel"?

The wheel was invented for efficiency, mobility, and productivity, among a variety of reasons, and we can't conceive a society without the wheel in its many forms. By the same token, we are admonished in almost every endeavour to not try and reinvent the wheel. In other words, don't waste your time redoing something that has already been done.

So what about pavement management? Well, there is a pretty solid "wheel" of achievements, technology, practice and benefits to the users, but there is also some reinventing needed. This Lecture attempts to highlight the positives; at the same time, it points out that there are unresolved issues, and there are things that need to be done and/or done better for pavement management to realize its future potential.

1.3 What This Lecture Tries To Do and Not To Do

A look at the past can be useful and instructive. However, dwelling on it, at the expense of informing, communicating, and providing ideas and challenges is not useful. This Lecture does reflect on the past but the emphasis is on what exists today, what needs to be done better in the future and on encouraging the advancement of pavement management.

More specifically, the following topics are addressed:

- A look back at the evolution of pavement management
- Successes which characterize the current strengths and status of pavement management (what doesn't require reinventing)
- Key issues and major reinvention/invention needs
- Future expectations and opportunities

2. A LOOK BACK AT THE EVOLUTION OF PAVEMENT MANAGEMENT

2.1 A Long Look Back

Those agencies, both public and private, who are responsible for roads, airfields and off-road pavements, accept the necessity of modern, up-to-date, pavement management systems. Over 2000 years ago, however, the Romans constructed and managed a system of roads throughout Europe. In the late 1700's Tresaguet managed French roads for King Louis XVI, and McAdam became famous as a road builder in England in the early 1800's. Sir Thomas Telford, founder of the Institution of Civil Engineers, wrote a treatise in 1820 on management of the King's Highways.

2.2 Early Efforts in North America

While there were many early trails in Canada, the United States and Mexico, the first paved surfaces started to appear in the late 1800's [Guillet, 1966], and in fact one of the first road organizations formed was the Ontario Good Road Association in 1894. These coincided with early pavements and were responding to the rapid growth of the automobile. In 1920, the Highway Research Board was formed in the United States, and this provided a focus for major ensuing efforts in pavement design and construction.

2.3 The Modern Era

Although perhaps arguable, the modern era began with the explosion of Post World War II road building in the late 1940's and continuing on for the next several decades. The AASHO Road Test, 1958-61, and researchers associated with it, made an enormous contribution to the technology base of pavement management. Included are the serviceability-performance concept, roughness modelling, equivalent axle load concept, and materials and structural analysis.

The initiation of pavement management as a process began in about the mid 1960's. It was based on the integration of systems principles, engineering technologies and economic evaluation. Among the early published contributions were those involving a systems approach to pavement design [Hudson et al 1968, Scrivener et al 1968], a management system for the Canadian Good Roads Association's Pavement Committee [Wilkins 1968] and a management system for highway pavements [Haas and Hutchinson 1970]. These were followed by major advances in developing the component technologies of pavement management, and by the mid 1970's much of the available knowledge was summarized in the first books on pavement management [RTAC 1977, Haas and Hudson 1978].

These books also reported on the first pavement management system (PMS) implementation projects. The following years saw literally an explosion of interest in PMS and further implementation in many countries around the world. Much of that experience was summarized in the first two conferences on pavement management in Toronto in 1985 and 1987 [MTC 1985, MTO 1987]. The Third International Conference on Managing Pavements, in San Antonio in 1994 [TRB 1994] reported further major advances, as did the Fourth International Conference in 1998 in Durban, Republic of South Africa [Visser 1998].

Now the Fifth Conference in the series, Seattle 2001, illustrates in its many contributions that pavement management is dynamic and continually evolving with new and better technologies and real efforts to achieve integration with the broader spectrum of asset management.

2.4 Value and Evolution of the International Conferences

The five international conferences provide a truly comprehensive repository of information and practice in pavement management. They are a valuable resource for researchers and practitioners, ranging from entry level to experiences and senior.

Looking at the evolution or progression of these conferences, there are distinct themes and challenges which can be summarized as follows:

- First (1985) was largely directed to "teaching"; e.g., what is the state of practice and who are the players.
- Second (1987) was largely concerned with implementation; e.g., what is involved, how and who has actual working systems.
- Third (1994) was described in the opening address (Mr. Dean Carlson, Federal Highway Administration, United States) as emphasizing the widespread use of pavement management systems.
- Fourth (1998) met the challenges of illustrating the major advances made in pavement management technology and practice.

- Fifth (2001) illustrates clearly that major advances continue to be made, and that the relationship or integration between infrastructure or asset management and pavement management is progressing.

While the value of these conferences is largely represented by the documented record, the contributors also represent a veritable "who's who" of past and current key players. Naming even a few would leave out equally deserving people. There was a semi-serious suggestion in the Keynote address in the Fourth Conference (Haas 1998) that perhaps we should establish a "Pavement Management Hall of Fame" to properly recognize outstanding contributors.

2.5 Has the Definition and Scope of Pavement management Remained Consistent?

While there has often been a tendency to view pavement management as dealing primarily with data and data management, and/or excluding design, construction and maintenance, and/or meant for administrators, and/or not applicable to small agencies, the original definition and scope of [RTAC 1977] was comprehensive and has stood the test of time; e.g.,

> "A pavement management system --- encompasses a wide spectrum of activities including the planning of programming of investments, design, construction, maintenance and the periodic evaluation of performance ---. The function of management at all levels involves comparing alternatives, coordinating activities, making decisions and seeing that they are implemented in an efficient and economical manner".

This definition is essentially the same as in [Haas and Hudson 1978 and Haas et al 1994] and was retained in [TAC 1997]; it is also entirely consistent with the 1993 AASHTO Guide [AASHTO 1993], which states: "Pavement management in its broadest sense encompasses all the activities involved in the planning, design, construction, maintenance, evaluation and rehabilitation of the pavement portion of a public works program --- a pavement management system provides an organized coordinated way of handling the pavement management process".

2.6 And Is the Scope and Definition Consistent With Asset Management?

Asset management has received literally an explosion of interest in the latter part of the 1990's and at the start of this century. What this means to the future of pavement management is subsequently discussed, but it is worthwhile at this point to look at definitions that have been put forward; e.g.,

> "Total Asset management (TAM) is a comprehensive and structured planning process for developing capital and recurrent programs and budgets. It aims to focus on customer and community needs, provide quality services and a commitment to excellence to ensure that assets remain productive" [RTA 1996].

> “Asset management is a systematic process of maintaining, upgrading and operating physical assets cost-effectively. In the broadest sense, the assets of a transportation agency include physical infrastructure such as pavements, bridges, and airports, as well as human resources (personal and knowledge), equipment and materials, and other items of value such as financial capacities, right-of-way, data, computer systems, methods, technologies and partners” [FHWA and AASHTO 1997].

> “Asset management is a comprehensive business strategy employing people, information and technology to effectively and efficiently allocate available funds amongst valid and competing asset needs” [TAC 1999].

Additional definitions are provided in [FHWA 1999]. In essence, however, asset management is defined by the framework or structure and its component activities, as subsequently described.

2.7 And What About Infrastructure Management?

Before going further, it is useful to consider the other widely used term, which is infrastructure management. Is this different than asset management and/or pavement management? In [Hudson et al 1997] it is stated that the titles Infrastructure Management, Asset Management, and Facilities Management were considered as titles for their book. They found a large degree of commonality among all three but chose the first as “more descriptive of the process that covers public infrastructure assets”. Nevertheless, asset management seems to be the term of choice today for many transportation agencies.

2.8 Milestones in the Modern Era

The modern era of pavement management was previously suggested as being post World War II. There are numerous milestones which have occurred during these five decades, with some of the particularly noteworthy ones listed in Figure 1.

The first category, (A) ROAD NETWORK EXPANSION, contains two indirect but very important milestones. First, the road building boom of the 1950’s and 1960’s in the developed countries represented large increases in asset value of the road infrastructure. When any investment or asset becomes large, there is usually accompanying pressure to manage it wisely. In the case of the developing countries, road network expansion is generally more recent but the same need for good management exists.

In the category of TECHNOLOGY (B), one of the early and most significant milestones was the application of systems methodology to design [Hudson et al 1968, Scrivener et al 1968].

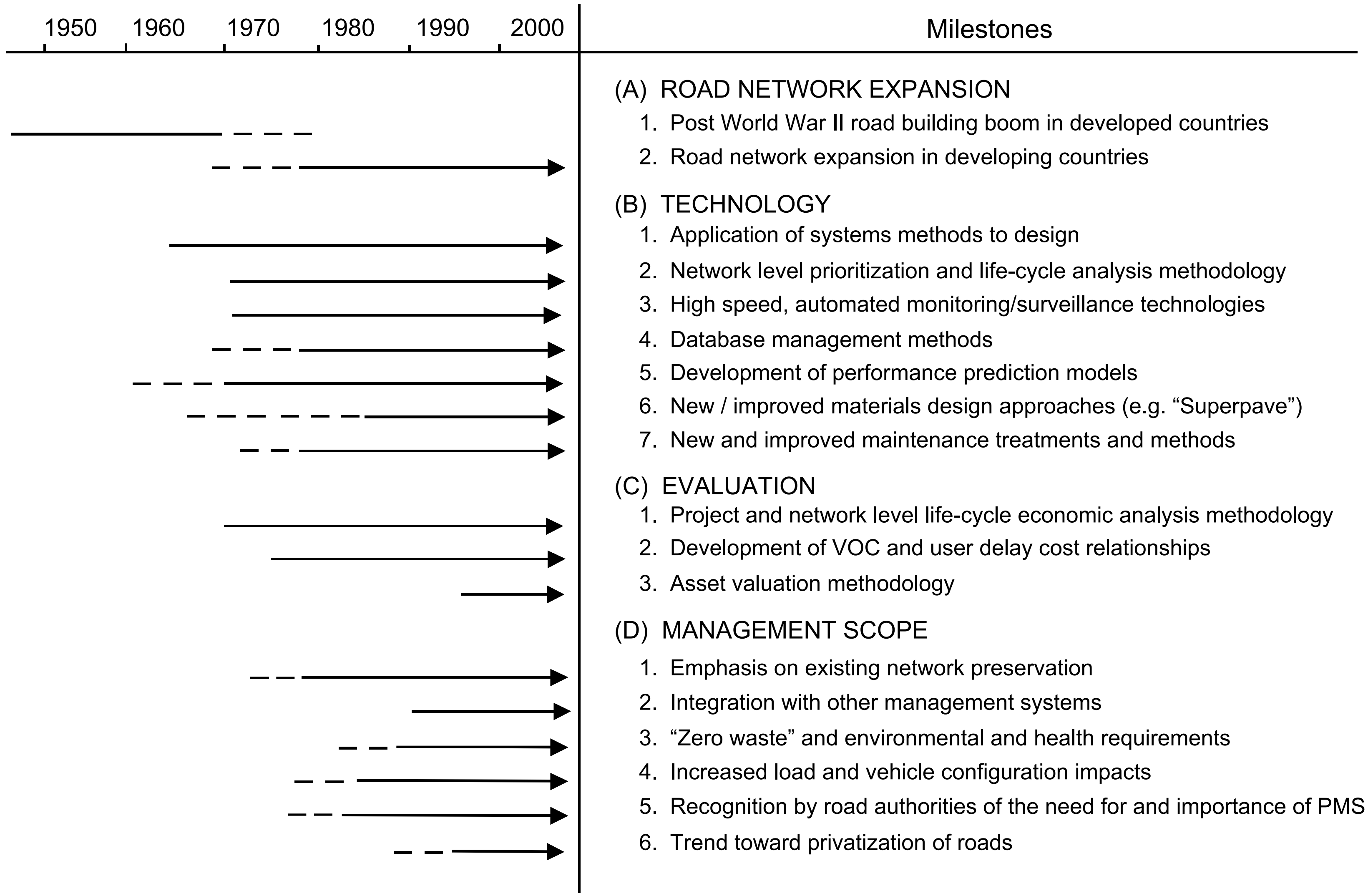


Figure 1 Some key milestones in the evolution of pavement management systems (adapted from Haas 1996)

The identification of two major operational levels of pavement management first appeared in about the late 1960's [Haas and Hutchinson 1970] and led to the development of network level prioritization methods, including life cycle analysis.

A third major milestone on the technology side has been the development of high speed, automated surveillance or data capture technologies. This includes longitudinal and transverse profile measurements, imaging methods and analyses for surface distress evaluation, measurement of geometry, etc., along with global positioning systems (GPS) to record locations.

A fourth major milestone in this category has been the development of highly flexible and versatile relational database management systems using a geographic information system (GIS) platform. This facilitates integration with other management systems for water and sewer, structures, etc.

Performance prediction modelling is one of the most important elements of pavement management, and has been for many years a key challenge facing pavement engineers. Since the 1960's, major emphasis has been placed on developing better performance prediction methodology, as illustrated by the Long Term pavement Performance (LTPP) part of the Strategic Highway Research Program (SHRP).

Good materials technology plays a vital role in project and network level pavement management, particularly with regard to effects on performance. Consequently, a significant milestone has been new/improved materials design approaches, as illustrated by the SHRP "Superpave" asphalt mix design [SHRP 1994].

The seventh milestone listed in Fig. 1 under (B), is that of new and improved maintenance treatments and methods. It was in about 1980 that realization occurred of how important this area was to pavement performance and preservation. Most agencies now place major emphasis on maintenance, which was, for example, given a prominent role in SHRP [SHRP 1993 a and b and FHWA 2001 a to d].

Under (C), EVALUATION in Fig. 1, one of the most noteworthy milestones is the widespread adoption of life-cycle economic analysis methodology at both the project and network levels, beginning in about 1970.

At about the same time, in the 1970's, quantitative relationships between vehicle operating costs (VOC) and pavement conditions, and user delay costs associated with maintenance and rehabilitation interruptions, began to be developed. Many pavement management systems now incorporate such relationships.

The importance of asset valuation in pavement management is quite a recent realization, beginning in about the mid 1990's [Yeaman 1997, Cowe Falls et al 2001].

Regarding (D) MANAGEMENT SCOPE, one of the first major milestones was the changing emphasis to preservation of the existing network, particularly in developed countries where the road system expansion had tailed off and it was realized that timely and cost-effective maintenance and rehabilitation strategies were now required.

Integration of pavement management with other management systems, a second milestone in (D), Fig. 1, began in earnest in about 1990 [Hudson and Hudson 1994]. While such integration will undoubtedly continue to progress, it can be strongly argued that pavement management systems have led the way to development of other systems and to integration [Hudson et al 1997].

The initiation of “zero waste” policies plus stringent environmental and health requirements in many countries started to have a profound effect on pavement management beginning in about 1990. In particular, the effect is on maintenance and rehabilitation strategies, construction procedures and life-cycle economics.

A fourth milestone listed under (D) is increased load and vehicle configuration impacts, which seemed to have become more dominant starting in about the mid 1980’s. There are many effects on pavement management, including structural design strategies, life-cycle economics, etc.

The fifth milestone listed under (D) is perhaps self-evident but has been extremely important to the advancement of pavement management in terms of implementation and technology development.

Finally, there seems to be a worldwide trend to privatization of both individual road links and whole networks. Because pavement management has been developed largely for public sector/owner needs, there may well be some changes of concept/philosophy/ approach and priorities of component PMS activities to adapt to this changing environment.

3. KEY INGREDIENTS FOR SUCCESSES IN PAVEMENT MANAGEMENT, OR WHAT DOESN’T NEED TO BE REINVENTED

3.1 In General

There are many ingredients or factors involved in the successes of pavement management. Indeed, they largely characterize its present status. Included are the following groups:

1. Basic lessons learned from developing and implementing pavement management systems
2. Development of a comprehensive, generic framework which explicitly recognizes the network and project levels of pavement management.
3. Widespread local, state/provincial and federal agency initiatives to implement PMS.
4. Development and application of key component technologies within the framework of 2.

These groups represent the "good news". The "bad news" (issues and reinvention needs) are to come.

3.2 Some Basic Lessons Learned

It is important to recognize what we have learned from pavement management, and what we haven't yet learned or resolved, in order to provide better and enhanced systems in the future.

Table 1 provides a summary listing of some of the key things learned from over three decades from developing and implementing pavement management systems.

Table 1 Basic Lessons Learned From Developing and Implementing Pavement Management Systems

A. Pavement Management Framework

- The P.M. process can be characterized by a generic framework
- The framework allows flexibility for incorporating different models, methods and procedures
- Two basic levels exist in P.M.: network/program/system wide and project/section/ link

B. Technological Base

- A sound base of technology is fundamental to P.M.
- Sufficient and reliable data is essential to a PMS
- Capability of evaluating alternative strategies, including life-cycle analysis, should be embedded in any PMS

C. Implementation

- Public sector users of a PMS can be categorized into three basic levels: legislative (indirect), administrative and technical
- Implementation of a PMS should be staged, with usable products after each stage
- Successful PMS implementation relies on key players and top level commitment

There is a strong case to be made that what we have learned from pavement management development and implementation has led the way for other infrastructure management systems, and for much of the overall concept of asset management [Hudson and Hudson 1994]. A cynic might say that's because pavements deteriorate faster and consequently there was an earlier need for systematic management of the asset. Well, that may be partially correct, but it can also be argued that pavement engineers had the foresight to not only develop the concept of systems based management but also to put it into practice.

3.3 Generic Framework For Pavement Management

Pavement management began to take on a more coherent and comprehensive form when it was dimensioned into two basic operating levels: network/program/system wide and project/section/link. The basic elements and activities comprising a pavement management system can be organized within these two levels, as illustrated in Figure 2.

Also shown in Fig. 2 is the interface with overall asset management, which operationally, would be through some sort of integration platform (probably Geographic Information System (GIS, based). Other management systems (e.g., Bridge Management System, BMS, etc.) are listed in Fig. 2 to illustrate a similar integration with the overall asset management system. As well, Fig. 2 lists factors which would not normally be part of the PMS itself (e.g., financing, budgets, policies at the network level, and standards and specifications, budget limit and environmental regulations at the project level) but would impact on the PMS.

The generic nature of the framework of Fig. 2 makes it amenable to a myriad of different individual models and procedures. Any agency-specific models, (or contractor-specific in the case of privatization) from simple to complex can be incorporated.

3.4 Agency Initiatives Toward PMS Development and Implementation

When the concept of pavement management began to be formulated in the mid 1960's, no agencies anywhere had a working PMS. Certainly many had developed or adopted a design method, and they built and maintained pavements. In fact, maintenance management systems were well established in various agencies around the world, but the integration or coordination of all these activities into a working PMS, covering both the network and project levels, did not really occur until the mid to late 1970's. In fact, the first two books on pavement management [RTAC 1977, Haas and Hudson 1978] describe design systems and the principles of network level pavement management, but they have no examples of an actual, implemented PMS.

The initiatives (and risks) subsequently undertaken by a number of pioneering agencies were most instrumental toward expanded acceptance and further development of pavement management. Some of the first published records of implemented PMS began to appear about 1980, and by 1982, for example Session IV of the Fifth International Conference on the Structural Design of Asphalt Pavements [UMICH 1982] was devoted to pavement management systems. It provided descriptions of implemented, working systems in the Netherlands, United Kingdom, City of Amsterdam, Washington State, Arizona State, U.S. Forest Service and the Region of Ottawa-Carleton in Canada.

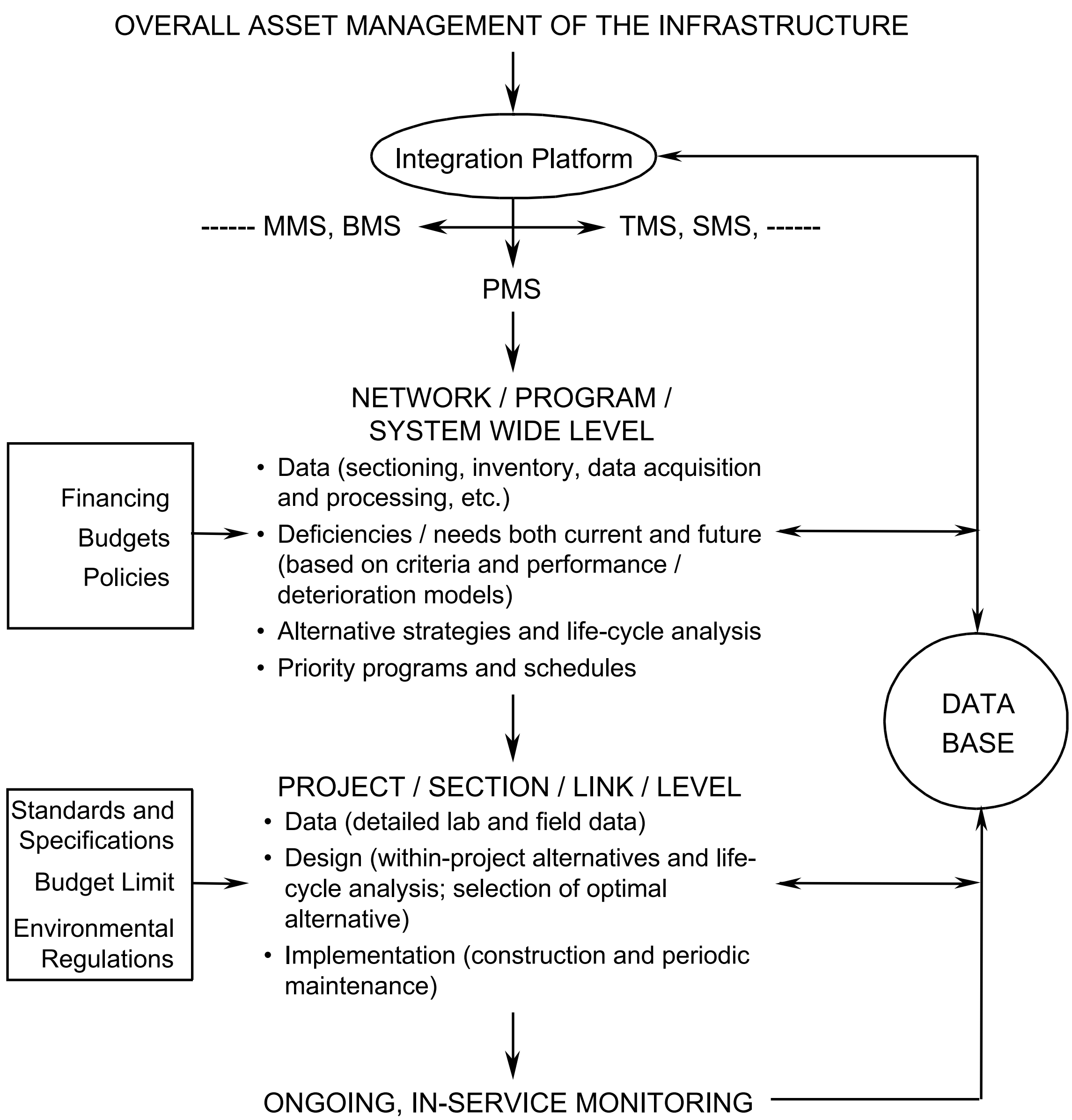


Figure 2 Generic framework for pavement management

By the time of the First and Second Conferences on Pavement Management [MTC 1985, MTO 1987], there was substantial progress evident in pavement management implementation. The Third Conference [TRB 1994] illustrated how widespread the implementation of PMS had become on all continents. The fact that such widespread acceptance had occurred in only about one decade, is in no small way attributable to the early "courage" exhibited by agencies who were willing to try something new.

3.5 Technology Highlights

The success of pavement management is largely attributable to a number of key technology developments and/or applications. Among these are the following highlights:

- Automated surveillance or data capture equipment and methods, plus highly efficient and versatile database management procedures
- Performance or deterioration model advances
- Life-cycle economic analysis methodology
- Vehicle operating cost (VOC) and user delay cost relationships
- Network level prioritization methodologies
- New and/or improved maintenance treatments and methods
- New, more fundamentally based materials characterization methods for structural design and construction
- Computing capabilities with processing speed and capacity to make effective the foregoing technologies

3.5.1 Data capture and database management

At the time the pavement management concept was first advanced, in the mid 1960's, the available technology for data capture consisted of response type car road meters for roughness, manual condition survey methods for surface distress, locked wheel skid trailers (primarily) for surface friction and the Benkelman beam for deflection. Database technology consisted of filing cabinets of records.

Today, many thousands of km of network can be surveyed annually by multifunction data capture devices with the capability of measuring one or more of the following at travel speeds:

1. Longitudinal profile (one or both wheel paths)
2. Transverse profile
3. Surface distress through keyboard entries or image acquisition (video, CCD, etc.) and analysis
4. Surface texture
5. Right-of-way features (video)
6. Pavement layer thicknesses and other properties (ground penetrating radar)
7. Location identification through global positioning system (GPS) capability

Numerous devices have been developed for the foregoing, in Japan, Europe, Australia, North America and elsewhere. Examples are provided in [Haas et al 1994, TAC 1997] and of course in the product literature of the companies involved.

The measurement of longitudinal profile enables pavement engineers to calculate International Roughness Index (IRI), and thus consistency in time and space can be maintained. In other words, engineers can make objective, consistent comparisons and they can talk the same language with regard to other regions and countries.

Transverse profile measurement has enabled engineers to determine rut depths and cross slope at a much more productive rate than with manual survey methods.

The rapid measurement of surface distress using keyboard entries at moderate speeds (semi automated method) or image acquisition and analysis (automated) at travel speeds has represented an enormous benefit to pavement management. Not only does it provide the capability to track and model composite or individual modes of distress, but it also provides the capability to better determine maintenance requirements on a network basis.

Surface texture measurements are possible with some data capture devices, primarily for the purpose of approximate or relative estimates of surface friction. As well, some devices have video cameras mounted such that right-of-way features can be recorded. While not perhaps highly important to a pavement management system per se, these additional capabilities are quite complementary and certainly of use to overall roadway management.

Ground penetrating radar (GPR) is not usually a feature of multi-function data capture devices which periodically carry out network surveys. Rather, GPR should only be needed for one-time surveys, unless it is being used to check for large voids under the pavement in urban areas; thus, it is normally in a dedicated vehicle for that purpose.

Global positioning system (GPS) capability is an optional feature available from most suppliers of data capture devices.

Database management systems have undergone enormous improvements in capacity, capability, versatility and user “friendliness”. Without these improvements, and without the availability of Geographic Information System (GIS) platforms, pavement management and more broadly infrastructure management would be far less powerful today. In essence, a database system is the heart of a pavement or infrastructure management system [Hudson et al 1997].

3.5.2 Performance modelling

One of the most profound challenges facing pavement engineers since the formulation of the serviceability-performance concept [Carey and Irick 1960] has been the development of performance or deterioration prediction models. While major advances have been made, it still represents an area where there is a need for much more improvement, as illustrated, for example, by the ongoing Long Term pavement Performance (LTPP) studies of the Strategic Highway Research Program (SHRP).

Beginning with the major advances that have been made, the concept of serviceability itself was an explicit recognition of one of the major classes of customers for pavements, the road users. Other than the concept of level of service, in terms of volume/capacity ratio, in traffic engineering, the notion of serviceability on a measurable scale represented a most important element of pavement management.

Second, the notion of developing serviceability – age or performance models represented an equally important and pioneering element of pavement management. It is noteworthy that for most other areas of infrastructure, such as bridges, underground services, building structures, etc., it was many years later before the same notion of modelling performance began to be accepted. Instead, the emphasis was primarily on service life. As a consequence, the state of performance modelling technology in these other areas is in the early stages.

The many simple to complex performance models developed around the world can essentially be grouped into classes which indicate their basis, as follows:

1. Empirical, where certain measured or estimated variables such as deflection, accumulated traffic loads, etc. are related to loss of serviceability or some other measure(s) of deterioration and pavement age, usually through regression analysis.
2. Mechanistic-empirical, where certain calculated responses, such as subgrade strain, pavement layer stresses or strains, etc., together with other variables such as accumulated traffic loads, are related to loss of serviceability or some other measure(s) of deterioration and pavement age through regression analysis or through a model which is calibrated (i.e., the coefficients are determined) by regression analysis.
3. Subjective, experience based where serviceability loss or other measure(s) of deterioration vs age are estimated, for different combinations of variables, using Markovian transition process models, Bayesian models, etc.

Examples of all three classes can be found in the proceedings of the international conferences [MTC 1985, MTO 1987, TRB 1994, Visser 1998] and in such references as [TAC 1997, Haas et al 1994].

Perhaps the major difficulty in developing performance models and attempting to keep model errors at a reasonable level is in capturing the large array of factors and their interactions. Figure 3 illustrates the complexity of the problem. There are five major classes of factors, and a number of sub factors within each class, which may also interact within classes and between factors in other classes (only overall class to class interactions have been shown by the light dotted lines).

Of course, it would be difficult, time consuming and costly to obtain data on all these factors. As a result, many are captured only implicitly or in an aggregated way in most performance models. Moreover, it is difficult for any given situation to determine the relative importance of factors; in other words, what are the sensitive factors and interactions in affecting the prediction of performance. Varying one factor at a time in a performance model can give quite misleading results and therefore a key need in performance modelling is to develop comprehensive sensitivity analysis procedures [Mrawira et al 1998]. Another key need is to develop efficient calibration procedures for regional adaption, particularly in the case of mechanistic-empirical models.

In spite of the complexities noted in the foregoing discussion, pavement engineers have done remarkably well in developing performance models with acceptable ranges of prediction errors. What is still to be achieved though is the development of models which can separate performance loss into its components: (a) traffic loads associated loss, (b) environmental factors associated loss, and (c) interaction of traffic and environment loss. The concept is shown in Figure 4.

Models have been developed which separate total loss into two components: traffic and environment associated loss, such as that reported by [He et al 1997]. This model has been used to assess the amount of pavement damage due to trucks [Hajek et al 1998]. However, part of the environment loss is in reality an interaction loss. While the development of models which separate total loss into the three components will be a difficult task, and while this would result in even more complexities in cost allocation, it is necessary if we are to have proper cost allocation assessments.

What is also still to be achieved in performance modelling is the incorporation of individual factor variances into the reliability analysis, rather than the overall variance as used for example in [AASHTO 1993]. A preliminary effort to accomplish this was reported by [He et al 1997] but Monte Carlo simulation had to be used to generate individual factor variances, the reason being that actual, as-built variance data is generally not available.

3.5.3 Life-cycle economic analysis

The application of life-cycle (or, in some countries, like Australia, 'whole of life') economic analysis was recognized as a key element at the project level of pavement management quite early [Hudson et al 1968, Scrivener et al 1968, Hutchinson and Haas 1968]. Shortly thereafter, it was also recognized as a key element of the network level [Haas and Hutchinson 1970], and the principles and methodology were comprehensively described in [RTAC 1977, Haas and Hudson 1978]. However, the actual use of life-cycle economic analysis did not become widespread among operating agencies until the 1990's.

What seems generally acceptable is the methodology; more specifically, present worth analysis is used by almost all agencies and is described, for example, in [Haas et al 1994, TAC 1997, Hudson et al 1997]. So there should be unanimity among agencies and individuals? But of course there is not because a number of major issues and questions impact almost any life-cycle analysis, and these include the following:

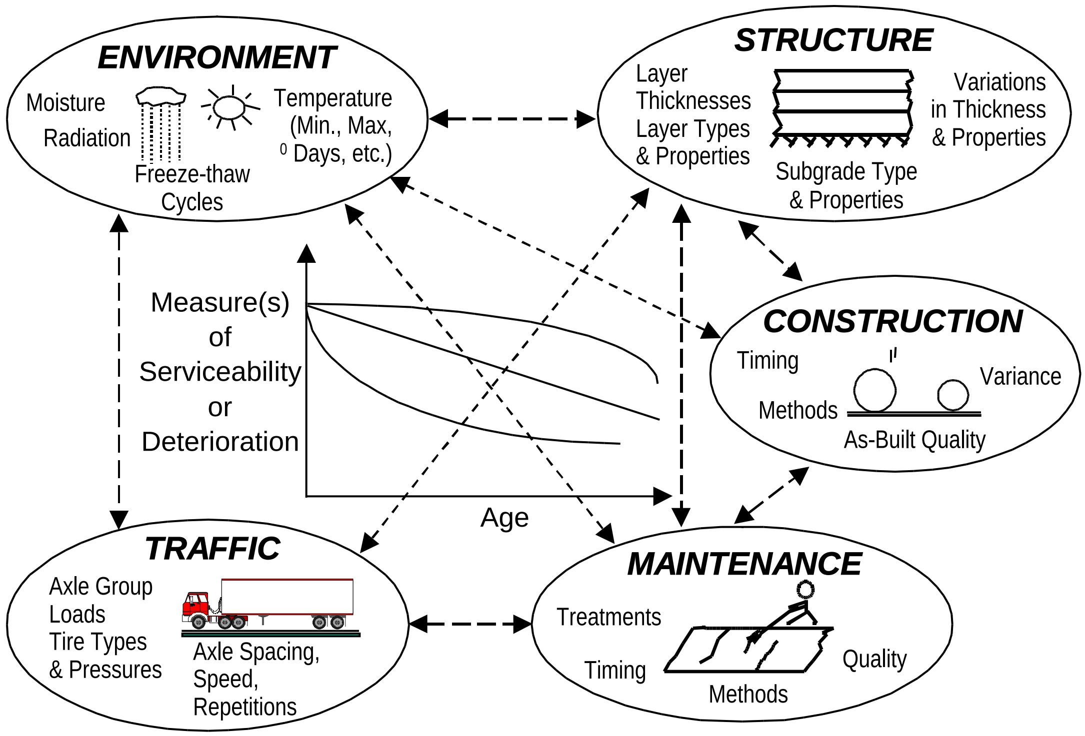


Figure 3 Factors affecting pavement performance

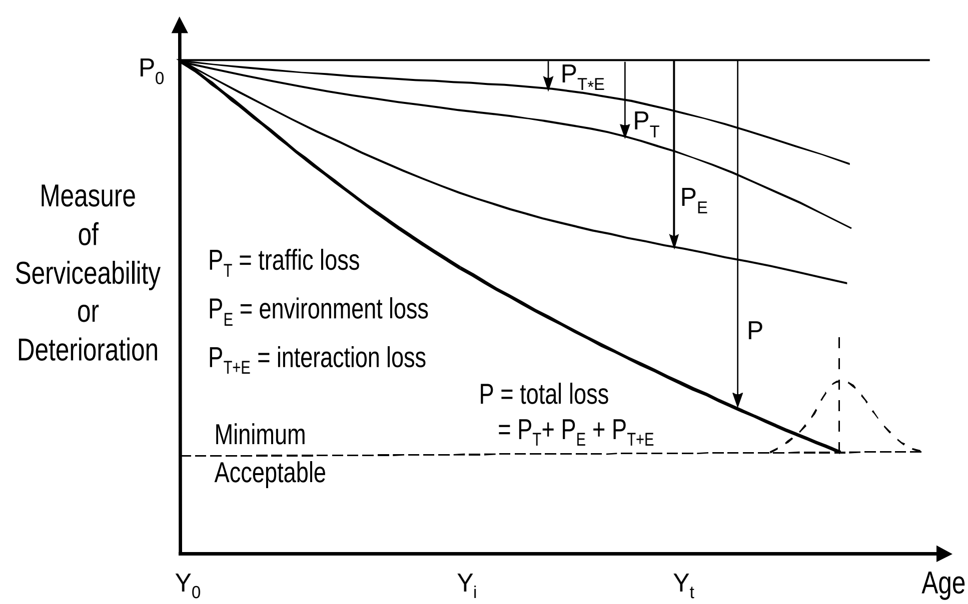


Figure 4 Separating loss of serviceability or deterioration into its major components

- discount rate to be used?
- which costs should be included?
- should benefits be included; if so, what type or form?
- reliability of the cost and benefit estimates?
- minimum acceptable or "trigger" level of serviceability?
- length of the life-cycle or analysis period?
- errors in the performance predictions (see Figure 5)
- resolving or comparing flexible vs rigid on an objective, consistent basis

Some of the foregoing are illustrated in Figure 5 (i.e., error distributions in performance prediction, life-cycle period and minimum acceptable level of serviceability), as well as possible cost and benefit factors for inclusion in the analysis.

Guidelines for establishing values for all of the foregoing issues/questions, except the last one, are available and summarized for example, in [Haas et al 1994, TAC 1997, Hudson et al 1997]. However, the issue of objective and consistent comparisons of flexible vs rigid pavement is far from settled. Most pavement engineers have been asked innumerable times "which pavement type is better, asphalt or concrete?" The response is "it depends; what answer do you want?"

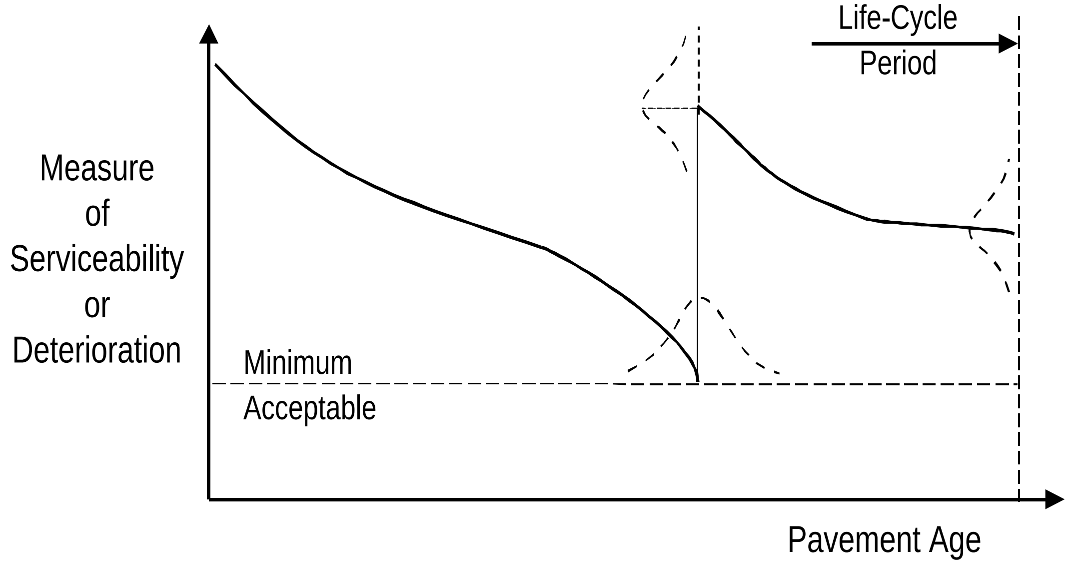
While that response may seem facetious, individuals or agencies with vested interests in asphalt pavements can give a definite answer that favours their type, and of course the same holds true for those with vested interests in portland cement concrete (PCC) pavements. This remains a truly controversial area of pavement management.

In essence, the application of life-cycle economic analysis in pavement management is widespread, which is a highly significant and positive feature. But we are a long way from resolving a number of key issues which impact the results of any analysis, including a consensus way to compare flexible and rigid pavements.

3.5.4 Vehicle operating cost and user delay cost relationships

The importance of including vehicle operating costs, as a function of pavement roughness or serviceability, and user delay costs during maintenance and rehabilitation interruptions was recognized by some quite early in the development of pavement management systems [Scrivener et al 1968]. However, whether or not they should actually be included in life-cycle economic analysis is still controversial among many agencies. The attitude seems to be that these costs don't come out of their budget; therefore they should not be included in the cost analysis. The counter argument is that we all pay, particularly road users, for all the costs; therefore all costs should be included in life cycle economic analysis.

A major advance in establishing vehicle operating cost (VOC) relationships was based on extensive World Bank studies in Brasil and elsewhere, mainly in the mid to late 1970's and 1980's. The results were "transformed" into relationships applicable to United States conditions [Zaniewski et al 1982], and were subsequently calibrated to conditions in



Possible Costs to Include

- Initial and Future construction / rehabilitation (R)
- Periodic maintenance (M)
- Residual value at end of life-cycle ("negative cost"), or disposal cost
- Vehicle operating costs (VOC)
- User delays due to M&R
- Accident costs attributable to pavement factors
- Environmental degradation

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etc.

Possible Benefits to Include

- Savings in VOC, or surrogate (i.e., "effectiveness")

others ?

Issues / Questions

- Discount rates ?
- What costs to include ?
- Inclusion of benefits ?
- Reliability of cost ad benefit estimates ?
- Minimum acceptable level ?
- Life cycle / analysis period ?
- Errors of performance predictions
- Flexible vs rigid

Figure 5 Life cycle costs and benefits, and issues in life-cycle analysis

various other countries around the world, as for example in Southern Africa [DuPlessis and Schutte 1991], Ontario, Canada [MTO 1993] and for the World Bank's HDM model series [Callao and Faiz 1991]. Calibration issues and procedures have also been discussed in the literature, as for example in a Tanzanian case study [Mrawira and Haas 1996].

Unfortunately, the calibration of vehicle operating costs for the different and changing vehicle fleet types and combinations in various regions represents a major effort. More efficient calibration and updating procedures are needed, as well as comprehensive procedures for assessing the sensitivity of VOC's to the range of factors involved. In addition, the issue of whether VOC's differ for rigid vs flexible pavements, because of different rolling resistance and other characteristics, needs to be definitively established.

User delay costs due to traffic interruptions during maintenance and rehabilitation can be enormous for high volume facilities. In fact, they can be far higher than the cost of the work itself, and thus tend to dominate the total costs in the life-cycle analysis. This is one reason why many agencies do not incorporate user delay costs. However, they should be a key component in life-cycle analysis and can indicate, for example, the benefits or total cost reductions for "premium", longer lasting pavements with less maintenance and deferred rehabilitation.

User delays are composed of two parts: slowing delay due to reduced speed in the work zone and queuing delay due to congestion when the traffic demand exceeds capacity. The traffic handling strategy thus becomes very important and can significantly affect the user delay costs, as illustrated in a comprehensive new user delay cost model in the OPAC 2000 design package [He et al 1997].

One of the major issues is the determination of cost or value of time for the road users who are delayed. Economists and engineers have argued extensively about the value of travel time, and the literature is replete with papers which present the various arguments [Kazakov et al 1993]. There is a real need for a definitive set of guidelines

3.5.5 Network level prioritization

The development of multi-year, network level priority programming methodology represents a most significant achievement in the pavement management field. In fact, it represents a feature of pavement management still far in advance of most management systems for other infrastructure elements.

By the mid 1970's, the principles of prioritization based on ranking, or benefit maximization or cost minimization based on linear programming, were established [RTAC 1977]. During the ensuing decade, as reported in the first international conference [MTC 1985], the applications of multi-year prioritization, using techniques ranging from ranking to near optimization to mathematical programming based models, were extensive. In 1990, the United States Federal highway Administration incorporated multi-year prioritization methods in their advanced course on pavement management [FHWA 1990].

While the principles and applications of network level prioritization have been well described, it is important that any method used is able to give the following answers:

1. Recommended maintenance and rehabilitation treatments for the prioritized sections for each year of the program period, as well as section characteristics, costs and other indicators such as B/C ratio, cost-effectiveness, etc. (depending on the basis of the prioritization).
2. Average network "quality", using some indicator such as Pavement Quality Index (PQI), International Roughness Index (IRI), Pavement Condition Index (PCI) etc., and/or network asset value, over the program period and for different budget or funding levels.
3. Amount or percent of deficient km (i.e., the sections falling below the minimum acceptable or "trigger" level of serviceability, or other measures of deterioration) over the program period and corresponding to the budget or funding levels of 2. above.

The concept of the latter two of these key requirements is shown schematically in Figure 6. A numerical example was provided in [Haas 1998].

The next generation of network level prioritization methodology should incorporate a reliability concept, and some initial progress has been made toward this objective; for example, as reported by [Li and Haas 1998]. But this is also a quite complex task which will require a considerable amount of additional work.

3.5.6 New and improved maintenance treatments and methods

Pavement engineers have for many years faced the question of what are the effects on performance of various preventive and corrective maintenance treatments, the methods of application and the timing. While the answers are far from complete, the question has been addressed in the Strategic Highway Research Program (SHRP) and by various researchers and practitioners.

As a result, repair manuals of practice are available from a variety of sources, such as [SHRP 1993a and 1993b and FHWA 2001a,b,c and d], and a substantial amount of literature has been developed on the effects of maintenance treatments and timing. One of the best examples is contained in TRB's award winning paper of 1995 [Ponniah and Kennepohl 1995], where a life-cycle cost analysis was carried out on a two-lane, 21 km road in Ontario for the following alternative strategies:

- 50 mm overlay at years 11 and 21, with no crack sealing
- crack routing and sealing at years 4 and 8, 50 mm overlay at year 13, crack routing and sealing at years 17 and 21, 59 mm overlay at year 25, and crack routing and sealing at year 29.

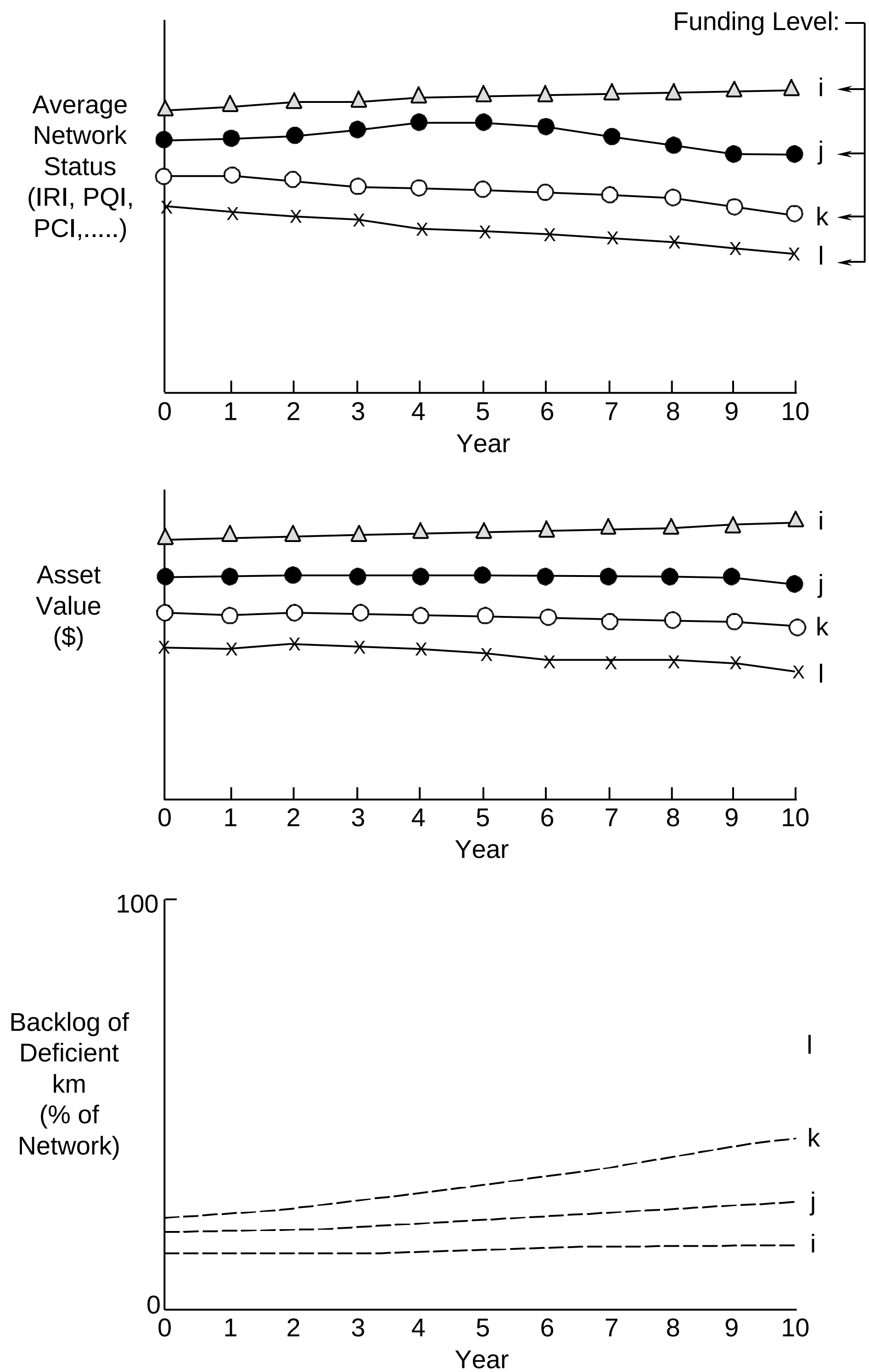

Figure 6 Report results from network level, multi-year prioritization

Details of the traffic volumes and growth rates, pavement structure, cost details of the routing and sealing and overlays, user delay costs and residual value at the end of 30 years are provided in [Ponniah and Kennepohl 1995]. The "bottom line", however, using a discount rate of 5%, is:

- present worth of costs for no crack sealing ≈ $24,000/lane-km
- present worth of costs with crack sealing ≈ $17,000/lane-km

The savings represented by the preventive maintenance treatment, crack sealing, are about $7,000/lane-km, or about $300,000 over the whole project.

It is not only these types of documented data on timely maintenance effectiveness which need to be brought into pavement management but also the rapidly emerging area of automated maintenance technologies.

3.5.7 Materials characterization for structural design and construction

A vast body of literature and experience base exists on properties of asphaltic, granular and portland cement materials. Much of it is empirical. The "Superpave" part of SHRP was designed in part to provide a more fundamental or mechanistic materials characterization base, particularly for asphaltic materials. The results were: (a) a new binder test and classification system where performance grades (PG) are designated for expected high and low in-service temperatures, (b) a volumetric mix design using the gyratory shear compactor, and (c) mix characterization methods and models to establish the non-linear elastic, viscoelastic, plastic, fracture and other properties under stress states which simulate traffic and/or environmental loads.

In turn, the properties established in (c) were used in: (d) an environmental effects model to calculate pavement temperature with depth, (e) pavement response models to calculate stresses and strains in the pavement layers and subgrade due to wheel loads and environmental effects, and (f) pavement distress models to predict low-temperature cracking, fatigue cracking and rutting in newly constructed pavements. Various reports are available on the foregoing, including [Kennedy et al 1994], and extensive research and implementation efforts have been underway for several years.

However, it is primarily the PG system, including the various tests involved, and the volumetric mix design procedure, that have received the most widespread acceptance. Implementation seems to be continually increasing and in fact, many agencies, researchers, consulting firms and suppliers have purchased the necessary equipment. Very few, though, have purchased the equipment for mix characterization of (c) above, partly due to the cost involved and partly due to difficulties with the distress models in (f) above. Consequently, the Federal Highway Administration initiated a study to carry out a comprehensive, unbiased evaluation of the models. A summary of the findings has been reported by [Witczak et al 1997]. Essentially, it indicated that the SHRP materials characterization methods and prediction models need to undergo major reworking, including the development of a simple strength test for the volumetric mix design procedure.

But Superpave is not the only approach. There are significant developments in other countries, such as, for example, the AUSTROADS methodology where mixes are designed using gyratory compaction and evaluated in a MATTA (MATerials Testing Apparatus) device for resilient modulus and dynamic creep response [Oliver 1994]. In fact, a comparative study between Superpave and AUSTROADS designed mixes in new Zealand included that "The AUSTROADS mix design method – is a less expensive (relative to SUPERPAVE) mechanistic method that allows the design of bituminous mixes from specific properties" [Pidwerbesky and Devine 1996].

For construction, fundamentally based materials characterization, per se, is generally not thought to be necessary. Rather, as-built properties such as density, voids, binder content, etc. are considered as essential information. It is possible, of course, to carry out deflection tests, and "backcalculate" to estimate layer moduli, but this is normally done for strengthening or overlay design purposes and not at the construction stage. However, a recently developed in-situ shear strength test method [Abdelhalim et al 1997, MTO 2001] shows promise not only as a construction monitoring tool but also for updating design estimates on future distresses such as permanent deformation.

3.5.8 Computing capabilities

One simply has to look back at the mid 1960's, when the pavement management concept was formulated, and the manual processing of information combined with laborious, time consuming and limited analysis capabilities, to realize how computing power has shaped the scope of modern pavement management to a very large degree.

This computing capability has made it possible to do numerous tasks, including the following:

- acquire, process and make available large amounts of high speed surveillance data, deflection data, laboratory test data, construction and maintenance data, etc.
- develop relational databases, including integration with other management sysstems and including the use of a GIS platform
- carry out network level optimization and priority analyses
- develop performance prediction models, visual displays of data and/or analysis results for easy comprehension and/or interaction, structural analysis models, life-cycle economic analysis models, multi-media presentations, etc.
- carry out multi-factor sensitivity analyses of complex models

However, the caveat remains that just because exponentially increasing computer capabilities are available, bad data, bad analyses and mistakes can still just as easily occur. Nevertheless, there is a tremendous opportunity to use this computing power to advance the technology, and in turn, the power of pavement management systems, by orders of magnitude over the next decades.

4. FACING KEY ISSUES, OR REDUCING THE NEED FOR REINVENTION

The development and implementation of a pavement management system by any agency invariably faces a number of key issues or questions. A fairly comprehensive list is provided in Table 2. If these are not resolved, successful application of the system can be jeopardized. Moreover, they are not just issues to be resolved at the start and then go away; they will re-occur as the system is used and periodically upgraded. A lot of "reinvention" may well be the result for those agencies, both public and private, who ignore the items of Table 2 which are relevant to their situation.

Most of the institutional/administrative issues can be resolved with success if the agency addresses them directly, although the driving force behind the implementation, resources available and degree of commitment at the senior/policy level can certainly change with time. However, the last issue of succession planning is one that has basically been an abysmal failure with many agencies and indeed needs "invention" as much as "reinvention". More about that later.

Data issues can also be resolved with reasonable success if addressed directly and periodically. The periodic review is particularly important with regard to what data to collect and its frequency, its integrity and quality production rates, and calibration procedures. An inherent commitment to good, reliable data is absolutely essential as this is fundamental to any management system, including pavements.

Database issues of course are directly tied to data issues and it is essential that these are addressed as an ongoing part of the PMS use. Changes in the technology, such as upgrades to software and operating systems, higher speed computing power, etc. occur rapidly and in turn successful pavement management systems must similarly upgrade their software, hardware, application programs, etc. fairly frequently.

Engineering issues also require reasonably frequent reassessment, particularly those involving improvements to prediction models and analysis models. The degree of integration between network and project levels of pavement management, however, is an issue that has not been well addressed or resolved in a lot of PMS applications. Additionally, periodic assessment of the effectiveness of maintenance and rehabilitation strategies should be a key issue or requirement for any PMS.

Systems issues are closely tied to all the foregoing issues and again, because of rapid changes in the technology, fairly frequent upgrades to the system platform, computer functions, networkability, ongoing system support, etc. will be an ongoing requirement for any PMS.

Table 2 Key issues facing PMS development and implementation -Adapted from (Haas 1998)

Category	Issues/Questions
Institutional/Administrative Issues	· Degree of commitment at senior/policy level? · Customized or off-the-shelf PMS? · Driving force behind the PMS implementation? · Scope of PMS (network only, or network and project, integration with other systems, etc.)? · Resources available (people, money, equipment, hardware, etc.)? · In-house PMS, or consultants? · "Home" of the PMS within the agency? · Degree of succession planning?
Data Issues	· Performance data: what data, frequency, integrity and quality, variation with class of road, etc.? referencing system (GIS, km posts, etc.)? production rates for collection, and costs? calibration procedures? · Attribute data: availability (traffic, structural, geometric. etc.)? use of default values for missing data?
Database Issues	· Software (integrity, accuracy, validity, security, identification) · Hardware (speed, capacity, network, flexibility, compatibility) · Incorporating software and hardware improvements · Avoiding redundancy and inconsistency · Rigorous adherence to standards · Skilled and trained personnel · Versatility of database management systems and application programs · Ensuring good documentation
Engineering Issues	· Engineering functionality/scope (network and project levels? degree of integration between levels? maintenance and rehabilitation strategies) · Development of prediction models (performance, surface distress, surface friction, traffic loads and growth, etc.) · Development of analysis models (prioritization, structural response, etc.)
Systems Issues	· Type of system being implemented (customized/tailored, or structured, flexibility, scope, etc.) · System platform (Windows, UNIX, etc.)? · Computer language(s) and function(s) involved (database manipulation, graphics, engineering calculations, etc.) · Modularity and networkability · Ongoing system support, back-up procedures and anti-piracy measures · System access (degree of security, people, procedures, etc.

5. MAJOR REINVENTION/INVENTION NEEDS

To start, what does not need reinvention is the rediscovery by researchers, and practitioners, of technology, procedures, behavior, etc. as so often illustrated in published literature. The reasons are threefold: ignorance per se; laziness (e.g., not reviewing the past literature) and deliberately ignoring what is available. Rectifying that problem is not the objective of this lecture; rather, it has to be the concern of our peer community and the rediscoverers employers.

On a more positive note, there are several major reinvention/invention needs which also present opportunities, as subsequently discussed, but which certainly are glaring deficiencies and/or areas for improvement in current pavement management practice. They include the following:

1. Institutional
   a) Succession planning (people and technology) and dealing with frequent turnover of key personnel
   b) Integrating PMS with asset management overall and with other management systems
   c) Adapting PMS to privatization

2. Technical
   a) Interfacing/integrating the network and project levels of pavement management
   b) Longer lasting, better quality pavements
   c) Performance models which identify the separate effect of traffic, environment and the interaction of traffic and environment on deterioration

3. Economic and Life Cycle
   a) Quantifying benefits (PMS implementation, technology development and research products)
   b) Development of incentive programs for better and/or new technologies
   c) Very long term life cycle analysis protocols (e.g., up to 75 years or more)

5.1 Succession Planning

Observation of agencies and their usage of pavement management over the past several decades reveals that few if any agencies, federal, state and local, have any kind of succession plan in place. Rather, the approach is almost invariably ad hoc, response to crisis based (only when people quit or retire, or the data is inadequate or can't be found, or the new people don't know how to apply the technology, or the "corporate memory" has disappeared, or …), and casual. Indeed, there is little or no guidance in the pavement management literature on proper succession planning. Technology transfer initiatives and training programs such as those conducted by the National Center for Asphalt Technology (NCAT) in Auburn, Alabama are extremely important and valuable to the industry (public and private sectors) and its people, but they do not fill the gap of proper succession planning.

Several key ingredients are involved in succession planning and they include the following:

1. Recognizing the need and obtaining top level commitment
2. Developing a plan which involves timing of replacements, including sufficient training and overlap, provides for contingencies (e.g., sudden resignations) and contains mentoring responsibilities
3. Making the necessary investments
4. Keeping the plan dynamic by periodic updating and periodic assessment of its effectiveness
5. Documenting the plan and procedures, its ongoing activities and accomplishments and the lessons learned.

The latter ingredient would contribute substantially to a real overall need and that is a "Primer on Succession Planning", to complement the various Primers appearing on Asset Management.

5.2 Integrating PMS With Asset Management and Other Management System

Among the reasons for widespread interest in asset management is the perception that applying corporate business principles, including proper financial and management accounting methods, will lead to more efficient and cost effective transportation program delivery. Of course this has to be reconciled with the profit motives of the private sector vs the plethora of objectives and demands facing public sector agencies.

Another dimension is the well-established existing management systems for pavements, bridges, traffic congestion, safety, maintenance, etc. While it is generally recognized that these component systems must be integrated into an overall asset management strategy, actually carrying out that integration has not yet occurred to any extent [Haas et al 2001].

While [Haas et al 2001] have demonstrated that the framework for asset management, as put forth in [FHWA 1999], is very similar to that for network level pavement management, and that the basic principles are also very similar, there are some key issues to be resolved and they include the following:

1. Asset management to date has been defined almost exclusively as a network level process. However, the component systems, pavement management, bridge management, etc. operate at both the network and project levels. The issue and/or challenge for asset management is whether it needs to operate at both levels, or only at the network level. If the latter prevails, then there is an associated buy-in issue from other than senior administrative levels in an agency.
2. It should be clearly recognized that an asset management system in no way replaces component or individual management systems. For example, almost every state or provincial DOT in Canada and the U.S., as well as most local agencies, currently

have some form of pavement management system in place and most have a bridge management system. About half use a maintenance management system. An asset management system must effectively integrate these existing systems into a broader corporate strategy of obtaining maximum return on investment yet not lose their accuracy.

3. Comprehensive, integrated asset management systems are not likely to replace (component) management systems for specific types of infrastructure. However, the appropriate role of transportation system level asset management in managing these specific types of assets, and vice versa, need to be resolved.
4. While the concept of asset management is based largely on private sector business principles, it should also be recognized that the profit motive drives the private sector, whereas delivery of services for which users pay indirectly or not at all is paramount in the public sector. On the other hand, there is an increasing trend to long term, performance based privatization of whole systems such as road networks in countries like New Zealand and Australia [Haas and Yeaman 2001]. This may well require some changes to the way asset management systems and individual systems, like pavement management, which have been developed for public sector application, are used by the private sector.

It has also been suggested [Haas et al 2001] that further development of asset management can benefit from pavement management experience, particularly with regard to explicit recognition of the various levels of users of the system, learning from the basic lessons (see Sec. 3.2), taking advantage of opportunities for innovations and advancements and using established implementation guidelines.

5.3 Adapting PMS to Privatization

Management systems for pavements and bridges have been primarily developed for and implemented by the public sector agencies. There has been a growing trend, however, to privatize maintenance and recently to long term performance based contracting of entire road networks. In the latter case, particularly in Australia and New Zealand (NZ), contractors have partnered with firms who have specialized expertise in asset management, including component management systems for pavements, bridges, etc [Haas and Yeaman 2001].

Most contracts for road networks in North America (NA) to date have involved only maintenance, as compared to the combined capital and maintenance spending in the Australian and NZ contracts. Moreover, these NA contracts have generally been end-result based and short term; e.g., commonly 3 years. The definition of maintenance in Australia and NZ, and many other European, Asian, etc. countries is much broader than in NA. It is all-inclusive and covers rehabilitative, preventive and corrective maintenance.

In adapting PMS to privatization, the contract approach used is an extremely important element. The alternative contract approaches have been categorized and described by [Haas and Yeaman 2001], including their key features and their pros and cons. Particular attention, with examples, has been given to the long term performance based contracts. They have suggested that in order to maximize the benefits in this approach, the recommendations summarized in Table 3 are relevant.

Table 3 Recommendations for maximizing benefits of going to privatized road management

	Recommendation	Applicable to Agency	Applicable to Contractor
1.	Obtain clear and unequivocal commitment of politicians and senior agency staff	x	
2.	Establish rigorous, objectively based pre-qualification criteria	x	x
3.	Define the work and/or performance requirements in clear, objective terms	x	x
4.	Perform an accurate inventory of the assets and assessment of their condition	x	x
5.	Don’t mix end-result requirements with performance requirements (let the contractors do their QC and the agency only do the QA on the performance)	x	x
6.	Understand and define the relative assumptions of risk involved in the contract	x	x
7.	Review the experience of others including frank disclosures of what went right and wrong	x	x
8.	Utilize any existing agency management system (bridge, Pavement, sign, etc.) if possible		x
9.	Utilize any “surplused” personnel from the agency who bring appropriate skills and knowledge		x
10.	Provide on-line access for agency to contractor data base	x	x
11.	Develop a reward procedure for innovation		x
12.	Develop a clear, well defined dispute resolution procedure	x	x
13.	Clearly understand the political climate and motivations	x	x
14.	Harmonize the agency and contractor ongoing performance measurement methods and procedures	x	x

5.4 Integrating the Network and Project Levels of Pavement Management

Integration of the network and project levels of pavement management has been talked about but, with some exceptions [Pilson and Hudson 1998], it has not yet become a reality for most pavement management systems. The problem is twofold: first, decisions made at the project level are often quite at variance with what was recommended in the network priority program; second, the intensity and extent of data acquired for the project level is normally prohibitive in terms of time and cost if that level of detail were carried to the network level. For example, the project level design data requirements in [AASHTO 1993] would not be feasible for network programming. However, other project level design systems, such as OPAC 2000, because of the more limited data input requirements, are capable of being extended to the network level as demonstrated by [He et al 1997]. Future pavement management systems will be much improved in an operational and cost-effectiveness sense when they are able to function on a more integrated basis.

Application of the reliability concept at the network level of pavement management is important to the advancement of the process, but also presents a very challenging task. Project level application of the reliability concept is in the relatively early stages; thus, it must be recognized that full extension to the network level will be a longer term effort.

5.5 Longer Lasting, Better Quality Pavements

There is an increasing demand by road users and clients (public and private owners) for longer lasting, better quality pavements. This should be achievable through better or new technologies, better QC/QA and construction, improved materials, etc. A study for FHWA claims, for example, that "--- switching to the Superpave binder specification could increase the service life of an asphalt overlay by 25 percent ---" [FHWA 1997]. The term "perpetual pavements" has come into recent use by the Asphalt Pavement Alliance to represent designs which are supposed to remain structurally adequate for the foreseeable future and will only need periodic maintenance of the surface [Frecker 2000]. Long term performance monitoring will determine whether these and other claims are in fact valid.

5.6 Separating Performance Models Into Deterioration Components

Almost all performance modelling efforts have been directed to characterizing the total performance loss; e.g., what is actually experienced or measured on the road, airfield, etc. So why separate or disaggregate into traffic associated, environment associated and traffic-environment associated deterioration, as shown schematically in Figure 4? The answer is that this is the only rational or objective way to carry out cost allocation analysis; e.g., determining the amount of damage caused by trucks and developing a charging scheme accordingly. Of course there are other truck impacts on safety, congestion, etc. which might be relevant but these are beyond the scope of this Lecture.

While the development of models which separate loss into three components is a difficult task, it is worthwhile if we are to have defensible cost allocation assessments.

5.7 Long Term Performance Specifications

A variety of short term, performance based contracts, as implemented by various agencies, have been described by [Haas and Yeaman 2001]. Generally, these are for 2 to 5 year terms. However, they point out that long term contracts, involving long term performance specifications and 10 year terms have seen more limited implementation and this has occurred primarily in Australia and New Zealand.

One of the really pioneering initiatives is the 10 year, long term performance guaranteed contract for 2,000 lane-km in the Hornsby and Warringah area of New South Wales, Australia [Yeaman 1997, 2000]. In essence, the contractor's specifications on this $170 million (Australian) contract are to result in an increase of up to 4% annually from the 1996 benchmark asset value of $700 million (Australian) for the pavement portion of the network. As well, it is intended to have an annual decrease of up to 0.4% in road user costs, based on no flexible pavement section with an IRI greater than 4.5 and no rigid/ composite section greater than 5.5. Additionally, there are limits on cracked surface area and on rut depths. Data collection is carried out by the contractor and the Road Transport Authority (RTA) is on line to the contractor's data base.

A second major long term (10-year) performance based contract was awarded in July, 1998 for 1,200 km of state roads and 470 bridges in Tasmania [TEACC 1998]. It is $80 million (Australian) fixed price and includes pavements, shoulders, drainage systems, bridges and right-of-way features. As in the NSW contract, the contractor must meet a set of defined performance standards, and must assume all risk for planning, programming and financing the work, as well as the risks associated with natural forces such as minor floods, snow and landslides.

The first NZ long term performance based contract (also 10 years) started in Jan., 1999, covering a network of 850 lane-km state highways in the New Plymouth, Ruapchu, Waitomo, Otorohanga, Waipa and Waikato Districts of the North Island. Within a total contract amount of $75 million (NZ), the major performance requirement is that the average roughness will be no greater in 10 years than the March, 1999 benchmark value from Transit New Zealand's survey. In reviewing the project, it was observed that prior experience in data collection, database management, project scheduling and network optimization, as well as prior investments in technology development, were proving to be of substantive value overall and particularly in the pavement management system [Haas 1999].

Another major initiative in long term performance based contracting is represented by Main roads, Western Australia [W. Austr. 1998]. It involves 8 network contracts, each 10 years in duration. The first two were awarded in 1999, and two others were awarded in late 2000. These four are fully outcome based (termed Road Outcome Based Maintenance and Rehabilitation Contracts – "ROB MARCS"), while three of the remaining four will be a combination of outcome based and client scheduled works. In total, 17,000 km of highways will be involved. Regarding the pavement asset, the key performance indicators (KPI's) include roughness, rutting, texture, skid resistance, cracking and strength. An interesting feature in the contracts is bonus provisions as an incentive to achieve better results on the KPI's than required.

The key features of long term performance specifications in these contracts include objective, clear and consistent measures, refraining from the imposition of end-result specifications and a well thought out monitoring plan and schedule. However, there is very little published guidance on developing and implementing long term performance based specifications. This is a clear and major need which should be addressed in the short term.

5.8 Quantifying Benefits

The payoffs and/or benefits from PMS implementation and from technology development can fairly easily be qualitatively identified. However, it appears increasingly that administrators in transportation agencies are demanding benefit and cost estimates for research and development, as well as PMS implementation, in monetary terms. While the SHRP program was originally “sold” largely on the estimate of very substantial payoffs, and while the previously noted study on SHRP results [FHWA 1997] is an example of R&D payoff estimation, much more similar work is needed for other areas of pavement technology and it is important that the quantifications are credible and that they are verified.

Regarding PMS implementation, it has been shown [Cowe Falls et al 1994] that very high benefit-cost ratios can be achieved. Again, however, the literature in this area of quantifying payoffs is very sparse.

5.9 Incentive Programs

The idea of advancing pavement management through incentive programs for public and private agency players and researchers to create new and better technologies is certainly not new. To date, however, there seems to be little if any formal programs of this sort. Rather, the incentive is indirect for the private sector and researchers in terms of commercialization of products and services; public sector people are essentially excluded. While SHRP, for example, has an “IDEAS” program, and while it is an excellent component of the overall program, it does not really fit the notion of direct incentives for innovations. There are numerous monetary awards for distinguished service or achievements by foundations, etc.; as well, many private sector firms provide monetary prizes to employees for ideas. A similar concept for innovations in pavement technology could prove to be valuable to the next generation of pavement management.

Another, related concept that certainly could benefit from “reinvention” is that of grant funding for high risk, innovative ideas. Most funding agencies prefer the contract approach, where tasks, schedules and deliverables are defined in great detail, almost like a method specification. This results in incrementalism rather than breakthroughs, and while efficient for controlling individual projects this “--- R&D model will provide limited returns --- and less likely to discover breakthrough technologies” [Johnston 1996, TRB 1995]. The advancement of pavement management would be much enhanced by at least some portion of R&D funding, both private and public sector, being designated as grant money where the researchers are allowed to explore their ideas without the shackles of micro managed research contracts.

5.10 Very Long Term Life Cycle Analysis Protocols

The methodology for life cycle cost analysis (LCCA) has been well documented in various textbooks and manuals. Almost without exception, however, the analysis period used does not go beyond 30 to 35 years [FHWA 1998]. The rationale is that any costs or benefits beyond this period, when discounted back to present worth terms, are insignificant; as well, the error of forecasting up to this period of time, particularly regarding traffic, is substantial.

However there are considerations today and in the future which suggest we should go beyond LCCA to a very long term life cycle analysis (VLTLCA) that involves more than immediately quantifiable economic costs and benefits. Specifically, these considerations include long term, future resource conservation and availability, number of times recycling of materials can be carried out and any associated disposal or decomissioning impacts, long term effects of waste products and/or hazardous materials which have been put into the pavement, and various long term environmental imapcts.

Consequently, we need the "invention" of a new or extended VLTLCA concept which might incorporate the following periods:

1. Short to medium term, up to 40 years, which would concentrate on LCCA aspects,
2. Long to very long term, up to 75 years or more, which would add the considerations or impacts of resource conservation and availability, future recycling, long term effects of waste products, long term environmental impacts, etc., to the LCCA.

6. FUTURE EXPECTATIONS, AND OPPORTUNITIES

This lecture is a part of the 5th International Conference on Managing Pavements. It is useful to look at this and past conferences as providing a progressive road map to the future.

At the 1994 Conference in San Antonio, Mr. Dean Carlson, then Executive Director of FHWA, said in his opening address that the focus of the 1985 Conference was to teach, that of the 1987 Conference was to implement and that of the current Conference was to use. The closing remarks to the 1994 Conference suggested the biggest challenge for the future was to advance [Haas 1994], and that was realized to a considerable degree by the 1998 Conference. If there is a single word that would characterize this 5th Conference it would be 'integrate'. So what does this indicate for the future? Again, a single word might be 'reinvent'. This not only relates to the needs described in the previous section but also builds on the challenge posed in the 1994 Conference closing remarks [Haas 1994]:

> "---seize the opportunities and advance the process, technology, and use of pavement management. Keep pavement management dynamic; innovate; resolve your institutional barriers; educate the new people, including new administrators; strive for quality; communicate; take risks; be proactive, not reactive; and make pavement management a truly effective decision support tool for all agency levels".

But it is now seven years later. Have the needs and challenges changed? Are there new ones? Do the same opportunities remain; have they changed? What are the pitfalls? The answer to all of these is yes and no! In fact though, a lot of what was relevant in the past still remains with us; by the same token, there are certainly some realistic expectations and new opportunities, as discussed in the following sections.

6.1 Realistic Expectations

Realistically, the expectations for pavement management over the next decade or more are that dramatic changes will not likely occur; rather in a broad sense:

- Pavement management will see increasing integration with other infrastructure management systems and/or overall asset management. The basic generic structure of Fig. 2 will remain, at least for public sector pavement management systems.
- Most, if not all of the institutional, data, database, engineering and systems issues identified in Table 2 will continue to varying degrees, although the emphasis may shift particularly where privatization occurs.
- There will be progress on the reinvention/invention needs described in Sec. 5. To what degree, however, and the amount of quantum vs incremental advances that will occur, remain open to speculation.
- The Strategic Highway Research Program will certainly provide technological benefits to pavement management, but it should not be expected to meet more than a portion of the needs previously identified.
- Pavement management will increasingly be challenged by administrators and by private sector players, where applicable, to justify the cost-effectiveness of data acquisition and processing, PMS development and operational costs and the effectiveness of PMS toward increasing or preserving the asset value of the pavement network.
- The globalization of pavement management technology transfer, marketing of products and services, etc. will continue to increase, as will the provision of web based information and technology.

6.2 More Idealistic Expectations

Reality is what we deal with, but there is nothing wrong with raising the expectations to a level which is perhaps more idealistic but not unachievable. These would include the following:

- Quantum increase in pavement life, with substantially less maintenance and rehabilitation interruptions, and significantly lower user cost
- Widespread adoption of both private and public sectors of meaningful and effecive succession planning strategies
- New SHRP program which targets innovation, minimizes the short term emphasis on number of “products” as the primary evidence of success and which includes construction technologies

- Substantial grant funding for high risk, innovative ideas and incentive programs for high payoff, new technologies
- Comprehensive protocols for very long term life cycle analysis
- Comprehensive guide on long term performance specifications and on privatization of networks and individual projects or links
- Objectively based and widely accepted protocols for comparing rigid and flexible pavement designs for a range of conditions and situations

6.3 Future Opportunities

All of the key issues of Sec. 4 and the needs of Sec. 5 also represent opportunities. While a comprehensive discussion on realizing these opportunities might be worthwhile, a selection of just two for illustrative purposes, has been selected, as follows:

1. Incorporating safety into pavement management, and
2. Ensuring that asset management development is consistent and/or effectively incorporates existing, well established Pavement Management Systems, Bridge Management Systems, etc.

The first area, safety, is of course an enormous and costly problem with many dimensions beyond pavements. For example, the past decade has seen 500,000 people die on North American highways. However, there are contributions toward safety which can be made by pavement management. A study by [Haas and Tighe 2000] first identified the classes of pavement factors associated with safety (see Table 4). It also incorporated the results of a general public and technical people survey on the effects of various types of shoulders, along with an economic analysis of the benefits [Tighe and Haas 1998]. The latter revealed positive economic benefits of partially paved shoulders.

It has also been suggested that a safety management system (SMS) can and should be effectively integrated with an agency's overall asset management system on both the network and project levels [Cowe Falls and Ibrahim 1999]. Figure 7 provides an example framework for an integrated management of transportation system assets, including the SMS, for the Province of Nova Scotia in Canada. Bridge, pavement and safety data are entered in the Database (TMIS) and supported by Traffic Census Data. All data is on a GIS platform and is used as input to asset-specific Condition Analysis (current and future) and then Treatment Selection Analysis. In this analysis, feasible alternatives are evaluated and entered into the Programming and Planning Analysis. While these are shown as asset-specific, they are integrated and all assets are finalized through Bridge, Pavement and Safety Management Application (BMA, PMA and SMA).

Turning to asset management (see Sec. 2.6), this is a term that began to appear in about the early 1990's and it is likely that current and future generations of engineers and administrators will increasingly become exposed to the principles and practices of asset management.

Why is this occurring, particularly when pavement management systems, for example, have served so well? A major reason lies with traditional highway agencies now having to manage a variety of transport assets. In doing so, they have to seek improved efficiency through increased attention to congestion, safety, environmental impacts and user costs, factors previously outweighed by the more easily-understood financial expenditure for highway construction and maintenance. As well, vigorous economic growth in the private sector has influenced public opinion toward greater reliance on private-sector principles as the preferred basis for managing public systems. The consequence is that public agencies have found themselves faced with the need to justify how they do business and even their mission.

In adjusting to these changes, departments of transportation (DOT's) are embracing management concepts from the private sector. This is neither simple or straightforward, however, because DOT's are expected to meet a plethora of objectives and are subjected to the scrutiny of the many groups with diverse perspectives comprising the "public" to which the agency must be responsive and responsible. In contrast to private-sector enterprise where profitability is the ultimate "bottom line", many of the benefits the public derives from the transportation system are not easily measured and compared.

An overall asset management framework has been described by [Cowe Falls and Haas 1999] as shown in Figure 8. It is generic in nature and allows flexibility to accommodate individual agency needs, resources and policies. The framework is based on first identifying or inventorying the classes/types of assets, locations and amount or extent, and establishing their current status or condition. To do this requires evaluation methods and models. Also shown in Figure 8 is future asset values, based on the programs, their costs and return on investments. An essential requirement for estimating these future asset values is models or estimates of future performance of the assets (e.g., performance prediction models for pavements, remaining life estimates for bridge components, etc.). Particular attention to the methodology and applications of asset valuation is provided in [Cowe Falls et al 2001].

A second level framework for the individual management systems (e.g., pavements, bridges, sidewalks, signs, drainage structures, etc.), within the overall framework, has also been described by [Cowe Falls and Haas 1999]. It represents the more traditional management approach for these individual systems, an approach that has served very effectively for many highway agencies. Again, asset valuation is a key component of the framework.

It should be clearly recognized that an asset management system in no way replaces the component or individual management systems. For example, almost every state or provincial DOT in Canada and the U.S. currently has some form of pavement management system in place and most have a bridge management system. About half use a maintenance management system. These three existing systems manage the engineering aspects of about 80% of the assets of the typical department of transportation. An asset management system must integrate these existing systems into a

Table 4 Classes of factors associated with safety attributes

Type of Factor	Safety Element Measures or Indicator	Sensitivity to Drivers
Surface Texture or Friction	· Macrotexture and microtexture characteristics, such as International Friction Index (IFI) · Skid resistance or skid number measures · Vehicle tire type standards	Low
Pavement Roughness or Riding Quality	· Riding comfort rating, International Roughness Index (IRI), etc. · Roughness and speed relationship	Higher
Pavement Surface Distress	· Severity and extent of surface distresses, such as ruts, faults, potholes, cracks, spalls, etc. · Distress index	Middle
Pavement Geometric Design and Location	· Widths of lanes and shoulders, median, and pedestrian paths · Cross slopes of pavement surface	Middle
Visibility of Pavement Surface Features	· Pavement surface color and reflectivity · Lane markings and signings · Visibility at night and bad weather conditions	Higher
Paving Materials and Pavement Mix Design	· Type of pavement · Texture and color of paving materials · Mineralogy and anti-resistance properties	Low
Road Safety Measures and Facilities	· Safety warning signs · Safety protection facilities	Higher
Environmental and Weather Conditions	· Place and time of accident occurrence · Roadside obstacles and safety facilities · Overall precipitation, such as fog, rain, snow and wind, etc.	Highest

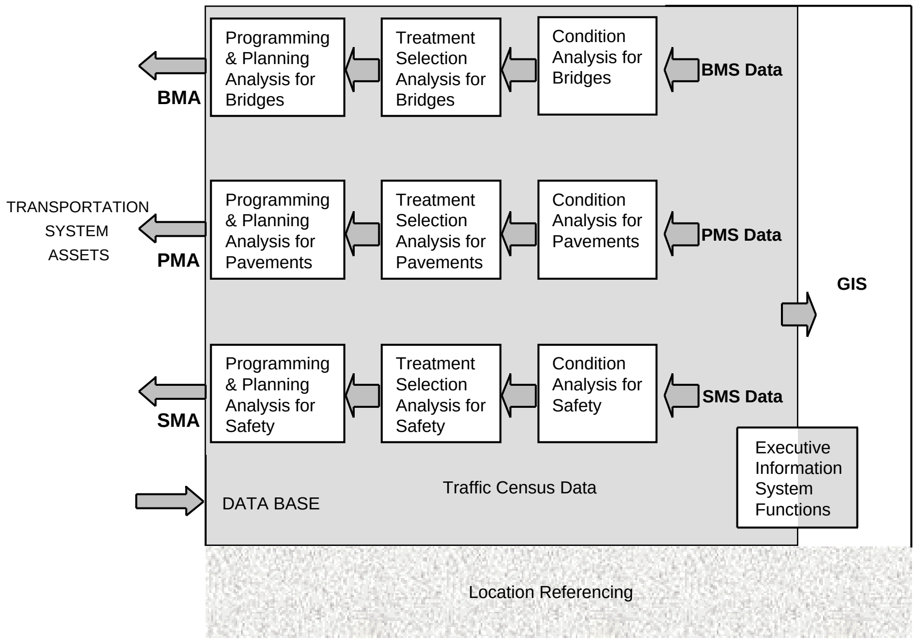

Figure 7 Integrated management of transportation system assets
(Cowe Falls and Ibrahim 1999)

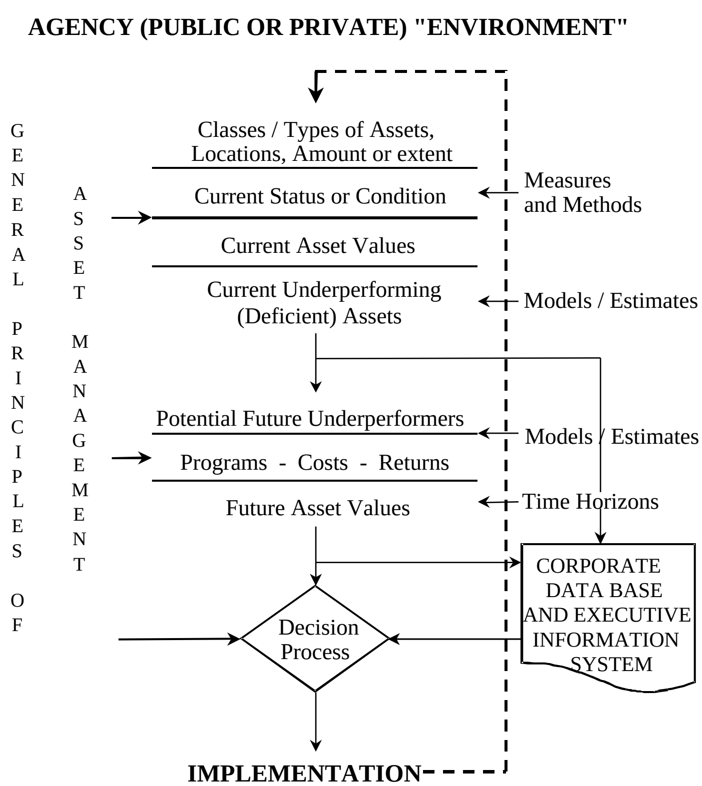

Figure 8 Overall framework for asset management
(Cowe Falls and Haas 1999)

broader corporate strategy of obtaining maximum return on investment yet not lose their accuracy.

Agency personnel will need new or updated skills and education for asset management. These include financial management; micro and macro-economic analyses; accounting; broader knowledge of integrated databases; easier and more accurate ways of obtaining, managing, and analyzing data; statistical applications; data collection; and more.

Finally, it should also be clearly recognized that the profit motive drives the private sector whereas delivery of services for which users pay indirectly or not at all is paramount in the public sector. Consequently, measures of management effectiveness other than “profit” must be considered in the public sector.

7. CONCLUSIONS

This Lecture has covered considerable background, current status and needs and a look at the future. Hopefully this will be of interest and use to both practitioners and researchers. In a nutshell, the message of the Lecture is:

> Pavement management has seen widespread and successful application. Key ingredients for this success include a sound concept, learning from implementation experience and the development of technologies which provide the foundation for pavement management systems. But there are institutional, data, engineering and systems issues still to be resolved and there are major reinvention/invention needs, which, if turned into opportunities can substantially strengthen pavement management. The future lies in continuing advances of the technology, risk taking and innovation and effective integration with overall asset management.

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