TECHNICAL AND ECONOMIC BASE REQUIREMENTS
FOR EFFECTIVE ASSET MANAGEMENT

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ABSTRACT

Effective asset management depends on adequate and reliable data, sufficient resources, good decision making and implementation and very importantly the technical and economic base that underlies these activities.

Life cycle analysis is the umbrella for this technical and economic base and incorporates three major levels: strategic, network or system wide and project or site specific. The major components within these levels are described in the paper, as are the essential technical requirements. In particular, the structural and mechanistic-empirical analysis methodology for long life pavement design is addressed.

The basic considerations in life cycle analysis, as well as the objectives, stakeholders involved, methods and a framework for short to long term life cycle analysis are then described. An example is provided of a rate-of-return analysis on a long life asphalt pavement design for an electronic toll road.

Innovations and continuing advancements area also considered essential to maintaining a sound technical and economic base for asset management. Examples of highly innovative technologies are provided in the paper as well as the role of research in advancing the state of pavement engineering. Finally, forward looking opportunities for advances in pavement management which focus on data, the process itself and institutional improvements are discussed in the paper.

INTRODUCTION

Roads and pavements represent a vital public asset and preservation of the asset through adequate resources and effective management is essential. Effective management, in turn, requires a sound and comprehensive base of technology and life cycle/whole-of-life economic analysis tools.

The development of such tools for planning, design, construction and maintenance has been ongoing for the past five or more decades in the pavement area, certainly aided by the initiation of the concept of pavement management in the 1960’s. In fact, a management system for highway pavements was reported to the Australian Road Research Board as early as 1970 (Haas and Hutchinson 1970). Since that time, pavement management, and more broadly asset management has evolved to a widely accepted process by road authorities worldwide.

Definitions of asset management have been put forward in Australia, the United States, Canada and other countries. The 1997 Canadian “Pavement Design and Management Guide”
(TAC 1997) made good use of these definitions, and, for example by earlier work in Australia and New Zealand (Vessey and Hutchinson 1994).

A key aspect of the evolution of asset management, and its application to life cycle management of road networks, has been the formulation of a comprehensive framework. This framework, as subsequently described, explicitly recognizes the essential technical and economic analysis requirements for effective asset management. As well, the objective of the paper is to emphasize the need for innovations and continuing advances in pavement and asset management. In essence, the latter need can also be viewed in terms of sustainable pavement engineering and ensuring the technical and economic base requirements are in fact met.

LIFE CYCLE MANAGEMENT OF ROAD ASSETS

A core activity in road asset or infrastructure management systems is life cycle analysis. In the following discussion, the basic principles and framework for road asset management are first described; and then further elaboration is subsequently provided on the technical and economic aspects of life cycle analysis, including examples.

Life cycle management is also a key part of public-private-partnerships (often termed “P3’s”) for long term, performance based contracts (PBC’s) in the roads sector. This is quite a comprehensive subject within itself and a large amount of information on PBC’s can be accessed on the World Bank’s website (see http://www.worldbank.org/transport/roads/resourceguide/index.html). Canadian, Australian and other international initiatives in the area are also reviewed in (Haas, et al 2008).

Road asset management systems (AMS) have evolved over the past few decades to the extent that many countries now have at least reasonably well developed component systems in place. These include pavement management systems (PMS), bridge management systems (BMS), traffic management systems (TMS), right-of-way features management systems (ROWMS), maintenance management systems (MMS), and others. Because pavements comprise a major part of the total road asset value, PMS have generally seen a greater degree of development and incorporate a considerable amount of technological advancement. While the component systems should function within an AMS umbrella, coordination and integration is not an easy task. For example, many excellent conferences, technical articles and several books exist re pavements, bridges, etc., but there are very few broader, AMS oriented, similar forums.

While the structure of AMS varies from agency to agency, examination of actual best practice reveals that a comprehensive AMS functions at three distinct but interrelated levels, all of which should exist within the agency’s corporate business plan:
• Strategic level where the business plan’s mission statement, level of service and safety targets and policy objectives plus various economic, social, political, environmental and public or stakeholder group input factors are taken into account, where long range financial forecasts and investment needs are carried out, and cost estimates are prepared to meet the defined targets. Current and future expected asset values should be included.

• Network or system wide level where alternative programs of asset preservation and network expansion are considered, performance estimates are made and life cycle cost analysis (LCCA) are used to determine an optimal program for given budget(s) or funding levels.

• Project level where detailed LCCA and other relevant inputs are used to identify and implement the most economically effective alternative for a project/link/site specific area.

Figure 1 puts the foregoing into a framework, with the main elements at each level identified within boxes, and various selected or applied factors, models, constraints, forecasts, time horizons, etc. listed at the right of the boxes. An integration platform is also shown, which is a mechanism for tying the road asset types, condition, etc. together through location as a requisite, plus asset value, level of service provided and risk exposure if possible.

A key factor in both the road authority’s business plan and in the AMS itself is explicit recognition of stakeholder group interests through provision of service. Providers of the service can range from the road authority to investor/concessionaires to managers on behalf of the road authority. Regulators, enforcement, standards, etc. are also associated with provision of service. Finally preservation and efficiency requirements and measurable performance indicators are necessary to a properly functioning provision of service environment.

Business Plan

Road authorities operate within some sort of business plan or business environment, which may be formally articulated (e.g., a mission statement followed by, for example, a 20 year vision of broad goals related to safety, environmental stewardship, mobility and accessibility, stakeholder group interests, etc.) or which may be in the form of an implicit operating environment of policies, standards, regulations, etc. What is important to recognize is that the business plan or business environment reflects the political, social and economic responsibilities of those appointed or elected to act on behalf of the public.

General Principles of Asset Management

Figure 1 indicates that the general principles of asset management are applicable to all levels, which is a self-evident requirement, and that a decision support process plus training and knowledge management/succession planning functions should be included.
The decision support process should be based on the corporate data base and the executive information system derived from the data base. Essentially, decision support provides the necessary graphs, tables, forecasts, recommendations, etc. appropriate to the key elements identified in the strategic level of Fig. 1, and similarly to the key elements in the network level. For example, at the strategic level, the major decision would likely be one of determining the tolerable shortfall between investment needs and financial forecasts; in other words a likely funding for the network level. At the network level, the major decision would involve approval of the works and associated programs.

Figure 1 Overall Framework for Road Asset Management
**Strategic Level**

The incorporation of information on classes or types of assets, locations and amount or extent is a mandatory requirement in any properly functioning AMS. Current status or condition is a similar requirement. Current asset value is desirable but not absolutely necessary. Levels of service, safety and functional targets may be part of the business plan, or stated as policy objectives, but in any case, together with performance indicators and criteria (sometimes called “trigger levels”), these provide the basis for identifying deficient or underperforming assets (e.g., pavement km on which exceed trigger levels for smoothness and/or skid resistance; bridges which are functionally or structurally inadequate, etc.) In turn, using methods of analysis for estimating performance of the assets over a stated time horizon, current and future investment needs to meet the targets or policy objectives can be calculated. If financial forecasts can be determined, then any shortfall between needs and available finances can be identified.

The structure of an AMS should directly address the elements and factors identified in Fig. 1. While the framework of Fig. 1 recognizes social/political factors and financial forecasts, these are not core functions of a management system. As well, stakeholder group interests need to be recognized in a management system but they should be defined as part of the road authority’s business plan and/or within the policy objectives.

**Integration Platform**

An integration platform, as shown in Fig. 1, is the mechanism by which the various assets are linked or tied together through the authority’s corporate data base. The essential requirement is location referencing. Other integration features, such as asset value, level of service provided and risk exposure, can also be included in an AMS.

**Corporate Data Base and Executive Information System**

The corporate/road authority’s data base is a core part of any successful AMS. Normally the software packages for such data bases are acquired from vendors who specialize in the area. There are cases where a customized data base has been developed, but the cost, time required, maintenance and upgrades are not generally justified.

For comparative, benchmarking purposes, the data base put together for the “Challenge”, (Haas, 2008) represents international state-of-the-art best practice. Examples for pavements, bridges, culverts and major signs are provided in the Challenge.

A major feature of the Challenge involves communication of the results to an informed road authority manager. In essence, this represents the Executive Information System identified in Fig. 1.
Network Level and Project Level

It is at the network level where the actual program alternatives of works for whatever time horizon or program period is applicable, are evaluated in terms of life cycle costs or cost-effectiveness and program selection is made within available budget(s). Environmental and other constraints may also be applicable. Future deficiencies should also be identified since available budgets are usually a constraint, and estimates of future asset values can be included.

Actual carrying out of the works in the program occur at the project or site specific level.

ESSENTIAL TECHNICAL REQUIREMENTS

Of the many technical requirements for effective asset management, none are more important than a sound structural analysis and performance prediction methodology. The structural base analysis, at least in recent years, has increasingly become mechanistic-empirical (ME). A comprehensive review of the evolution of long-lasting pavement design methodology has been provided in (Monismith 2004) and updated in (Haas, et al 2007).

The fundamental outputs of the mechanistic analysis part of ME design can be based on linear elastic, non-linear elastic, viscoelastic, or plasticity theory. Usually, however, linear elastic is the theory of choice in practice, with some exceptions.

Essentially, the mechanistic part of M-E design is directed to calculating one or more responses in the pavement structure as a function of material properties, layer thicknesses and loading conditions. These response(s) must then be related to observed performance (e.g., smoothness deterioration, fatigue cracking progression, rutting progression). That is the empirical part of the M-E design.

Schematically, the possible responses which can be used in design are shown in Figure 2(a), while the pavement performance to which it needs to be related is shown in Figure 2(b). In fact, establishing these relationships, in view of a wide variety of materials, loads, and environment that exists in practice has been a real and continuing challenge to pavement engineers over many years.

Not all of the responses in Figure 2(a) are used in any given design method. Most often used are horizontal strain at the bottom of the asphalt layer and vertical strain or deflection at the surface of the sub grade. The various computer based analyses subsequently listed provide the capability to calculate these responses, provided the materials properties, loading conditions and layer thicknesses are available as inputs.
Figure 2a. Fundamental Pavement Responses as a Function of Load, Material Properties and Layer Thicknesses (Mechanistic part).

Figure 2b. Pavement Performance to Which Mechanistic Response(s) Must be Related / Correlated (Empirical Part)
### Table 1 Summary of Some Computer-Based Analytical Solutions for Asphalt Concrete Pavements (Updated from Monismith 2004)

<table>
<thead>
<tr>
<th>Program and Ref.</th>
<th>Theoretical Basis</th>
<th>No. Layers (max)</th>
<th>No. of Loads (max)</th>
<th>Program Source</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEV5L Internal Rpt</td>
<td>MLE</td>
<td>5</td>
<td>1</td>
<td>Chevron Research</td>
<td>Can not calculate subgrade strain</td>
</tr>
<tr>
<td>BISAR(^1) (De Jong et al 1973, Ref. 12)</td>
<td>MLE</td>
<td>5</td>
<td>10</td>
<td>Shell International</td>
<td>The program BISTRO was a forerunner of this program</td>
</tr>
<tr>
<td>ELSYM(^4) (Ahlborn 1972, Ref. 13)</td>
<td>MLE</td>
<td>5</td>
<td>10</td>
<td>FHWA (UCB)</td>
<td>Widely used MLE analysis program</td>
</tr>
<tr>
<td>PDMAP (PSAD) (Finn et al 1977, Ref. 14)</td>
<td>MLE</td>
<td>5</td>
<td>2</td>
<td>NCHRP Project 1-10</td>
<td>Includes provisions for iteration to reflect non-linear response in untreated aggregate layers</td>
</tr>
<tr>
<td>JULEA(^1)</td>
<td>MLE</td>
<td>5</td>
<td>4+</td>
<td>USACE WES</td>
<td>Used in Program LEDFAA</td>
</tr>
<tr>
<td>CIRCLY(^4) (Wardle 1977, Ref. 15)</td>
<td>MLE</td>
<td>5+</td>
<td>100</td>
<td>MINCAD, Australia</td>
<td>Includes provisions for horizontal loads and frictionless as well as full-friction interfaces</td>
</tr>
<tr>
<td>VESYS (Kenis 1978, Ref. 16)</td>
<td>MLE or MLVE</td>
<td>5</td>
<td>2</td>
<td>FHWA</td>
<td>Can be operated using elastic or viscoelastic materials response</td>
</tr>
<tr>
<td>ILLIPAVE (Thompson &amp; Elliot 1988, Ref. 18)</td>
<td>FE</td>
<td></td>
<td>1</td>
<td>University of Illinois</td>
<td></td>
</tr>
<tr>
<td>FENLAP (Bruntun &amp; d’Almeida 1992, Ref. 19)</td>
<td>FE</td>
<td></td>
<td>1</td>
<td>University of Nottingham</td>
<td>Specifically developed to accommodate non-linear resilient materials properties</td>
</tr>
<tr>
<td>SAPSI-M (Chatti and Yun, 1996, Ref. 20)</td>
<td>Layered, damped elastic medium</td>
<td>N layers resting on elastic half-space or rigid base</td>
<td>Multiple</td>
<td>Michigan State Univ./Univ. of California Berkeley</td>
<td>Complex response method of transient analysis-continuum solution in horizontal direction and finite element solution in vertical direction</td>
</tr>
</tbody>
</table>

MLE – multilayer elastic  
MLVE – multilayer viscoelastic  
FE – finite element  
2. ELSYM5 is available from McTRANS\(^\text{TM}\) in Florida  
4. CIRCLY4 is the current version, Wardle and Rodway, Proc., Transport 98, ARRB Transport Res., Victoria, Australia, 1998. Recently, Wardle, Rickards and Lancaster have adopted/modified CIRCLY4 in developing “HIPAVE” for the M-E design of heavy duty industrial pavements (see ICAP10 Proc., Quebec, 2006)
Mechanistic Analysis Packages

The availability of computer based packages for mechanistic analysis provided a powerful tool for pavement engineers. A summary listing of some of the more well known programs is shown in Table 1.

It can be seen that multi-layer elastic (MLE) is the most widely adopted theoretical basis. Because of the assumptions involved, including homogeneous isotropic and linear elastic material properties, no shear stresses at the surface and uniformly distributed load, elastic layer theory may not be the best model of a pavement structure but it is a useful model provided the input data is properly formatted and the output is properly interpreted”.

A mechanistic-empirical pavement design procedure should incorporate a range of relevant factors or variables as inputs, and be able to predict outcomes in terms of serviceability- age history (e.g. International Roughness Index vs. age and/or accumulated traffic loads) as a minimum. In addition, it is desirable to have the capability of predicting the following measures of deterioration or damage, also as a function of age and/or accumulated traffic loads:

- Fatigue cracking
- Permanent deformation or rutting
- Thermally associated cracking

Figure 3 illustrates the range of factors and sub factors that might be considered as well as the interactions (dotted lines). Obviously it would be difficult, time consuming and literally impossible to obtain quantitative data on all these input factors for any given design situation. Thus, it is common in several design approaches to calculate fatigue cracking, rutting and thermal cracking as a design check, where the serviceability-age prediction is the main control.

The mechanistic part of the analysis of course only calculates a primary response(s), such as stress, strain and deformation at critical points in the pavement structure. Thus, a complete design analysis must relate primary response(s) to performance (e.g. IRI vs. age)and accumulated deterioration. In turn, this means an M-E design analysis must be calibrated to observed or measured field performance and this represents a major challenge, as subsequently discussed.

While the foregoing applies in general, it does not indicate, which M-E approach or methodology is most applicable for a given agency. This is also a major challenge, as discussed in the following section.
Choosing An Appropriate M-E Design Procedure

The American Association of State Highway and Transportation officials (AASHTO) has invested considerable time and resources in producing a series of pavement design guides (e.g. the 1972 Interim Guide, then the 1986 and 1993 Guides, and currently the Mechanistic-Empirical Pavement Design Guide, MEPDG, which is the outcome of NCHRP Project 1-37a. While the MEDPG represents a massive effort, expenditures of many millions of dollars and currently a group of lead States for implementation, it should be noted that most States still use some version of the earlier Guides.

The decision to choose a M-E design procedure, or to retain an existing procedure, involves a number of factors. Figure 4 summarizes the range of options and the factors that should be considered. These options, and the factors, in essence also represent a challenge.

Basically, the choices vary from retaining an existing procedure (empirical or M-E based) to updating an existing procedure to phasing into a new M-E procedure (either simplified or the new MEPDG). The new MEPDG is certainly the most comprehensive and incorporates flexibility (e.g. three levels of design), but the factors listed in Figure 4 should be carefully considered before adapting any option.
A summary listing of international mechanistic-empirical design procedures is provided in (Monismith 2004) and updated in (Haas, et al 2007).

**ESSENTIALS OF LIFE CYCLE ANALYSIS**

Conventionally, asset management and in particular component systems such as Road Asset Management Systems, pavement management systems, etc. have used life cycle cost analysis (LCCA) that discounts current and future expenditures to present worth. Benefits can be included, usually as discounted user cost savings. At the discount rates used by most agencies, generally ranging from 4% to 8%, any expenditures or benefits in the order of 30 years or more approach a small present worth value. Yet, there is a trend toward expecting a long or very long term service life from many of our infrastructure assets, including pavements and bridges.
Basic Considerations in Life Cycle Analysis

One of the fundamental premises of asset management is that it involves a life cycle. In other words, any actions and/or investments should be considered in terms of performance over some life cycle and the associated economics over that life cycle. Additional factors may be included such as environmental effects, societal impacts and the like in making decisions.

Closely coupled with the concept of life cycle analysis (LCA) is the issue of sustainability. Increasingly, we are being required to design and implement works that have explicitly incorporated the consideration of sustainability. In order to assess whether sustainability is being achieved requires the use of life cycle analysis.

Since sustainability is a long term consideration, life cycle analysis should also involve a long term approach. But this brings up the question of what constitutes a long term approach and what are the key elements. Subsequent discussion will address the question.

First, however, it is useful to review the basic purpose and components of life cycle analysis. Regarding the basic purpose, this includes the following:

- Comparison of alternative (competing) strategies over a life cycle period, using economics principles
- Identification of what strategy(s), when and where offer the best value on expenditures and/or return on investment
- Providing objectively based decision support, but not the decision itself

If the LCA is in terms of life cycle economic analysis (LCCA) it can not, however, answer questions of equity among competing infrastructure types (e.g., public housing vs. parks and recreation vs. roads vs. underground services, etc.) because of social, political and other considerations.

Nevertheless, it has been shown that a generic protocol for LCCA, covering a range of infrastructure components, is possible and applicable at the following three levels [Haas, Cowe Falls and Tighe, 2001]:

- Strategic, where cost estimates are carried out for various levels of service (LOS) targets to establish needs, for comparison to financial forecasts.
- Network or system wide where LCCA is carried out for alternative programs in order to determine an optimal program, for specified budget(s).
- Project or site specific where LCCA is used to identify the most cost-effective alternative for that project/link/site specific area.
How Far Ahead is the Future?

A time horizon for which there is a reasonably good degree of reliability in forecasting demand, calculating life cycle economics and forecasting the level of service or functional adequacy of civil infrastructure is no longer satisfactory. It is too short. The reason is that our actions today can have very long term impacts on resource conservation, environmental degradation and sustainability. In the latter case it is essential that capability is retained for periodic renewal/rehabilitation/repair of the infrastructure.

Consequently, it is useful to consider a time horizon consisting of the short, medium and long term. It has been suggested that these should be in the order of [Haas, et al 2008]:

- 10 to 30 years for short term
- 30 to 75 years for medium term
- 75 plus years for long term

The number of years appropriate to individual works or systems may fit into one, two or all three categories. For example, a software design package might only be very short term, while a long life pavement would be both short and medium term and a bridge would be short to medium to long term.

Objectives of LCCA, Stakeholders Involved and Misconceptions

Life cycle cost analysis (LCCA) uses economic principles to compare competing alternative investment strategies. It has always been an important tool in supporting decisions on the most cost-effective structure (roads, utilities, buildings, etc.) or rehabilitation treatment.

LCCA is also important in determining the affordability of a project, including both the initial construction costs and any future costs that may occur. LCCA should be used to identify where, what, and when do we get the best value/return on investment for our funds/expenditures.

Any investment or expenditure, particularly that of assuming financial liability or obligation (such as a road, purchase of a building, take-over of a business, etc.), should be accompanied by due diligence. In the private sector, this can be very rigorous, involving careful examination of the “books”, any existing litigation, any environmental cleanup liabilities, etc.

Infrastructure investments thus deserve their form of “due diligence” in terms of life cycle cost analysis. While due diligence is not (yet) a common term in the infrastructure area, a proper application of LCCA could certainly be considered due diligence.

The potential stakeholders/clients for LCCA, where public sector investments are involved, include the following:

- Elected level (Council or Legislature)
• Senior administrators
• Technical/Operating level personnel
• Taxpayers or public at large
• Interest Groups
• Contractors/Suppliers and Consultants

How these stakeholders view or use the results of LCCA, however, may well vary. For example, Interest Groups could see an LCCA as only one element toward a decision (e.g., considerations of equity, political impact, social impact, etc. may also be relevant to them).

Stakeholders can also harbour misconceptions about LCCA. Some of these are:

• LCCA can resolve equity among competing infrastructure elements. This is not correct because of social and other impacts.
• LCCA can result in distortions of budgets from one exercise to the next. In fact though, LCCA is generally used under a scenario of planned budgets. However, LCCA can explore “what if” scenarios of different budget levels.
• LCCA is a guessing game because of large uncertainties in forecasts of costs, predictions of condition or performance, expected budgets, etc. However, even with uncertainties, there is a better chance of identifying and implementing the most cost-effective strategies than by simply using judgement.
• LCCA is a substitute for the responsibility of making decisions. In fact, however, the role of LCCA is to support or enhance decision-making.
• LCCA may be able to identify the most cost-effective strategies but politics will prevail. While politicians have the ultimate responsibility of answering to the electorate, many politicians actually welcome LCCA as they can say the selected strategies are based on a fair (objective) competition for limited available funds.

**Methods for LCCA**

The basic methods for LCCA have been described extensively in the literature, including textbooks [Hudson, et al, 2007] and in particular the applicability to pavements. While the following five methods are applicable, the present worth and cost-effectiveness methods have been of primary use in the roads sector:

• Equivalent uniform annual cost method
• Benefit-cost-ratio method
• Rate-of-return method
• Present worth method for costs, or benefits or benefits minus costs, termed the net present value method
• Cost-effectiveness method
The present worth method has a number of advantages in that it is easier to comprehend value in present day terms and the method is computationally simple and straightforward.

The rate-of-return method, often termed the “internal rate-of-return” particularly in the highway field, determines the discount rate at which the costs and benefits of an investment are equal. In applying the method, it is usual practice to compare each alternative with a base alternative, in increasing order of costs. Proceeding on the basics of such paired comparisons will indicate the alternative with the highest rate of return. The rate-of-return method has a major advantage in that the results are easy to comprehend because of familiarity with business investments.

The cost-effectiveness method has been extensively used in the pavement field (Haas, et al 1994; TAC, 1997) because an appropriate measure of effectiveness exists. It is the area under the performance curve, weighted by traffic and length. Essentially, it becomes a surrogate for benefits in terms of user cost savings when comparing alternatives with different performance curves. While such user cost savings can be determined directly from vehicle operating cost and user delay costs (due to interruptions) relationships, it is difficult to establish these relationships regionally without substantive calibration effort.

**Framework for Short to Long Term LCA**

The major elements which should be incorporated into a framework for life cycle analysis of civil infrastructure, and particularly roads, include the following:

- Functional class of facility (eg., for highways this would likely be local, collector, arterial and freeway or motorway)
- Life cycle period (short, medium and long term)
- Public sector or private sector
- Most appropriate LCCA method
- Other considerations (resource conservation, environmental impacts, etc.)

Table 2 provides a framework for the applicability of LCCA method(s) according to the foregoing elements. While the preferred or likely method(s) are based largely on opinion, they can provide guidance to those having the responsibility for LCCA. It may be noted that Table 2 does not include the benefit cost ratio method, largely because it is susceptible to misleading results in certain situations, such as where benefits could also be construed as costs.
Table 2 Applicability of LCCA Methods in Likely/Preferred Order  
After (Haas, et al 2006)

<table>
<thead>
<tr>
<th>Functional Class of Highway</th>
<th>LCCA Period</th>
<th>Local</th>
<th>Collector</th>
<th>Arterial</th>
<th>Freeway</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Public Sector</td>
<td>Private Sector</td>
<td>Public Sector</td>
<td>Private Sector</td>
<td>Public Sector</td>
</tr>
<tr>
<td>Short^1 term</td>
<td>C/E PWC AC</td>
<td>-</td>
<td>C/E PWC AC</td>
<td>-</td>
<td>C/E PWC AC</td>
</tr>
<tr>
<td>Medium^1 Term</td>
<td>C/E PWC AC</td>
<td>-</td>
<td>C/E PWC AC</td>
<td>-</td>
<td>C/E PWC AC</td>
</tr>
<tr>
<td>Long^1 Term</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

Notes:
1. Short term can be up to 30 years; medium term 40 to 60 years; long term beyond 50 years in the case of pavement
2. Public sector means a public investment; private sector means private investment
3. C/E is cost-effectiveness method; PWC is present worth of costs method; AC is annual cost method; IRR is internal-rate-of-return method

Rate-of-Return Example

This example incorporates the key features of calculating a rate-of-return on highway investment alternatives, involving a multi lane urban bypass which the authority wishes to assess for its financial feasibility as an electronic toll route.

A preliminary long life pavement design is being considered, and the basic parameters are listed in Table 3. It is a heavy duty flexible pavement, with a life cycle period of 50 years.

Other costs, independent of the design under consideration, are also provided so a total cost picture can be developed. Everything is pro-rated on a per km basis.

Traffic volumes are provided, as well as toll charges. Estimates for growth rates are also given.

What is also given in the example are approximate, preliminary cost estimates for bridges, barrier walls/median dividers, grading and landscaping, drainage and interchanges. These add substantially to the total costs and certainly would have to be further assessed in more comprehensive and detailed analysis. However, the intent of the example is really to illustrate the
process and to show how alternatives can be compared for the rate-of-return that they would generate.

Table 3 Basic Parameters for the Rate-of-Return Example

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<tr>
<td></td>
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<tr>
<td>- 40 mm surface course; 80 mm binder course, 120 mm (rich) asphalt base, 150 mm granular base, 450 mm granular subbase on clay subgrade</td>
<td></td>
</tr>
<tr>
<td>- initial service life 20 years; then mill 25 mm and add 40 mm new surface; repeat at 35 years; end of life at 50 years</td>
<td></td>
</tr>
<tr>
<td>- initial cost $282,000/lane-km; rehab. cost $88,000/lane-km at 20 and 35 years</td>
<td></td>
</tr>
<tr>
<td>- annual maint. cost $2,000/lane-km initially rising by $1,000/lane-km each year to first rehab., then back to $2,000/lane-km and rising similarly to second rehab, and so on</td>
<td></td>
</tr>
<tr>
<td>- residual value at 50 years – 0</td>
<td></td>
</tr>
</tbody>
</table>

Other Costs (independent of pavement alternative)

- electronic toll system, $228,000/lane-km on prorated basis, with major maint./upgrades at 10, 20, 30 and 40 years of $50,000/lane-km
- admin., toll collection, traffic control, etc., $42,000/lane-km initially rising by $2,500/lane-km per year through analysis period
- snow and ice control, right-of-way maint., etc., $42,000/lane-km/year throughout
- pro-rated bridge & interchange construction, medians, grading, drainage, extra ROW, etc. – initial cost $3,900,000/lane-km

Traffic Volumes and Toll Charges

- initial AADT 12,000/lane-km, rising by 2%/year (compounded); 15% commercial traffic
- initial toll charges .14/lane-km, pro-rated for commercial and peak and off-peak, rising by 2%/year (compounded)
What is also not given in Table 3 but may influence a final decision on more detailed or expanded design alternatives are the following (and these can become particularly relevant for long life designs):

- Resource conservation (e.g., aggregate consumption)
- Future recyclability
- Functionality beyond the short term
- Environmental impacts (e.g., noise, solar absorption/heat generated, energy balance)

These factors and impacts are worthy of much more study in the future, certainly beyond what could realistically be incorporated herein.

Table 4 provides calculations of costs and revenues for the example. Three discount rates, 5%, 12% and 20%, which represents quite a wide range, are used to illustrate how much variation will exist in net present value (NPV).

At the low rate of 5%, as might be expected, discounted revenues are quite substantial, while at the high rate of 20%, again as might be expected, net revenues are relatively quite small. However, total discounted costs do not vary to the same extent, primarily because of the effect of very large initial costs.

The internal rate of return (IRR) at which the NPV=0 obviously lies between i=12% and 20%, and has been calculated at 16%. This means that if the authority had to borrow money at say 6%, a net return of 10% could be realized.
Table 4 Calculations for the Rate-of-Return Example

<table>
<thead>
<tr>
<th>Costs (Per Lane-km)</th>
<th>PW for i =</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>Initial Cost, $282,000/lane-km</td>
<td>282,000</td>
</tr>
<tr>
<td>Mill 25mm, add 40mm at 20 years, $88,000/lane-km</td>
<td>33,166</td>
</tr>
<tr>
<td>Mill 25mm, add 40mm at 35 years, $88,000/lane-km</td>
<td>15,954</td>
</tr>
<tr>
<td>Maint. Costs, $2,000/lane-km, year 1……year 50</td>
<td>242,081</td>
</tr>
<tr>
<td>Residual Value at 50 Years</td>
<td>0</td>
</tr>
<tr>
<td>ETS, initial cost, $228,000/lane-km</td>
<td>228,000</td>
</tr>
<tr>
<td>Maint./upgrades of ETS @ 10, 20, 30, and 40 years, $50,000 each/lane-km</td>
<td>30,696</td>
</tr>
<tr>
<td></td>
<td>18,844</td>
</tr>
<tr>
<td></td>
<td>11,569</td>
</tr>
<tr>
<td></td>
<td>7,102</td>
</tr>
<tr>
<td>Admin., toll collec., etc., $42,000/lane-km/year 1……year 50</td>
<td>1,549,176</td>
</tr>
<tr>
<td>Snow/ice control, ROW, etc., $42,000/lane-km/year throughout</td>
<td>808,749</td>
</tr>
<tr>
<td>Pro-rated bridge &amp; interchange const., medians, grading, drainage, extra ROW, etc. initial cost, $3.9m/lane-km</td>
<td>3,900,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$7,127,337</strong></td>
</tr>
</tbody>
</table>

**REVENUES (Per Lane-km)**

<p>| | |</p>
<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Initial tolls, 12,000 X .14/lane-km x 350 days</td>
<td>$ 588,000.00</td>
</tr>
<tr>
<td>Future tolls, 12,240 year 2 x .1402/lane-km X 350 days in year 2……year 50</td>
<td>21,994,691</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$22,582,691</strong></td>
</tr>
</tbody>
</table>

**NPV (Total PW of Revenue – Total PW of Costs)**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$15,455,354</td>
</tr>
</tbody>
</table>
BENEFITS AND POTENTIAL SHORT COMINGS OF LIFE CYCLE MANAGEMENT APPROACHES FOR ROADS

It should be a logical assumption that life cycle management approaches for roads provide benefits well in excess of costs. This has in fact been quantitatively demonstrated for large scale networks, where benefit/cost ratios ranged up to 50:1 (Cowe Falls, et al, 1994).

But there are also benefits, and potential shortcomings, of a more qualitative nature. A list of the “top ten” is provided in Table 5. It should be noted that these are based mainly on the experience and perceptions of the author rather than on rigorous study.

The first three items in Table 5 focus on buy-in from: 1. The road agency, 2. The elected level, and 3. The public and other stakeholder levels. If this occurs, then the benefits should include an objective, long-term, cost-effective use of public funds. On the other hand the short comings could include less than effective management if the buy-in is not universal, if there is only lip service paid and if there is lack of a concerted, coordinated perspective.

The next three items related to understanding what constitutes a life cycle, what the life cycle management process involves and what methodology(s) are used on the benefits side, this would include acceptance of a short to long term life cycle concept, a comprehensive, coordinated, integrated application at all levels and the information needed for decision support. However, there are possible shortcomings, including the potential for lack of application over the whole life cycle spectrum, and limited availability of the necessary skills, experience and integrative thinking.

The 7th item focuses on the benefits of objective, long-term, cost-effective use of public funds if a life cycle management approach replaces a year by year planning approach. A potential shortcoming, however, could be reluctance to accept the life cycle management approach if present practice is a year by year approach.

The 8th item involves the all too common situation of a shortage of funds and a growing backlog of needs. A life cycle management approach is still the most cost effective use of available budget, but there is a potential shortcoming and it is to dismiss the life cycle approach and make ad hoc decisions.

Item 9 focuses on sustainability/continuity of people, information and programs. Commitment to a life cycle management system is the best approach, but the potential shortcoming is that this can fall by the wayside if proper succession planning is not carried out.

The 10th item is that of a national initiative at all levels of government to ensure that the infrastructure provides a sustained level of service, safety, environmental stewardship and efficiency desired by all. Again a commitment to life cycle management is the best approach, but the potential shortcoming is that of agreeing in principle but an unwillingness to actually carry through in practice.
Table 5: A Suggested “Top Ten” Benefits and Potential Shortcomings of Life Cycle Management Approaches for Roads

<table>
<thead>
<tr>
<th>Life Cycle Management Aspect or Role or Application</th>
<th>Benefits</th>
<th>Shortcomings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Buy-In by the Road Agency</td>
<td>An objective, long-term, cost-effective use of public funds</td>
<td>Need buy-in from top to bottom; if not, inefficiencies and waste</td>
</tr>
<tr>
<td>2. Buy-In at the Elected level</td>
<td>Same as above</td>
<td>Temptation for lip service only</td>
</tr>
<tr>
<td>3. Buy-In at the Public and other Stakeholder Levels</td>
<td>Same as above</td>
<td>Potential for lack of concerted, coordinated perspective, and lack of interest</td>
</tr>
<tr>
<td>4. Understanding of what constitutes a Life Cycle</td>
<td>Acceptance of short, medium and long term concepts</td>
<td>Potential for lack of application over whole life cycle spectrum</td>
</tr>
<tr>
<td>5. Understanding of the life cycle management process</td>
<td>A comprehensive, coordinated, integrated, long-term application across all levels</td>
<td>Requirement for experience, skills, integrative thinking, etc., which may be limited</td>
</tr>
<tr>
<td>6. Understanding of the life-cycle methodology</td>
<td>Proper application will provide information required for decision support</td>
<td>Same as above</td>
</tr>
<tr>
<td>7. An alternative to year by year planning approach</td>
<td>Same as 1, 2, 3 Benefits</td>
<td>Reluctance to accept if present practice is year by year</td>
</tr>
<tr>
<td>8. Shortage of funds/growing backlog</td>
<td>Still the most cost-effective use of available budget</td>
<td>Tendency to dismiss LC approach and make ad hoc decisions</td>
</tr>
<tr>
<td>9. Sustainability/continuity of people, information and programs</td>
<td>Commitment to L.C. management is the best approach</td>
<td>These can fall by the wayside especially if proper succession planning does not occur</td>
</tr>
<tr>
<td>10. A national initiative, at all levels of government to ensure the infrastructure provides sustained level of service, safety, environmental stewardship and efficiency desired by all</td>
<td>Same as 9 above</td>
<td>Easy to agree in principle but major hurdles to overcome in practice</td>
</tr>
</tbody>
</table>

NEED FOR INNOVATIONS AND CONTINUED ADVANCES

The premise of this paper is that a sound technical and economic base is needed for effective asset management. Innovations and continuing advances are also needed, however, to ensure that the technical and economic base is in fact maintained. The driving forces behind
innovations in pavement and asset management have been described in (Haas 2007) and come from such sources as individuals themselves, economic/cost-efficiency concerns, environmental issues, science and engineering problems, resource issues, knowledge needs, security issues, social/political concerns and public-private-partnership (P3) initiatives.

**Factors in and Examples of Highly Innovative Technologies**

The identification of unique and/or highly innovative technologies in pavements and transportation poses a dilemma, largely because there have been so many excellent advances but they have been largely incremental in nature. Nevertheless, perhaps no example area in pavements has had more of a far reaching sustainability than pavement management. This area has been successful in integrating a wide range of technologies, in gaining widespread acceptance by the private and public sector user agencies, in providing a robust life cycle analysis methodology and in the decision support necessary for managing networks of roads, streets and airfields. Figure 5 is a schematic representation of some of the technology and analysis highlights in pavement management, together with a list of the factors that characterize this process as unique and innovative.

**Figure 5 Some Technology and Analysis Highlights in Pavement Management, With Contributing Factors to Innovation**
Other leading edge technologies have also been suggested in (Haas 2010). Several that particularly exemplify forward looking advancements in the pavement area include the following:

- Superpave technology which provides a more scientific and engineering base to asphalt materials selection, characterization and use
- Long Term Pavement Performance Database which constitutes the most comprehensive repository of pavement performance data every assembled, over two decades and a total investment exceeding $800 million (TRB 2009).
- Mechanistic Empirical Pavement Design Guide, the result of several AASHTO projects, made available in the mid 2000’s and at the time of this paper undergoing calibration by various state, provincial, federal and local authorities
- Recycling of waste/reclaimed materials in asphalt pavements as a mature, cost-effective and widely used process toward a zero waste management policy
- Major advancements in engineered materials and processes, including polymer modified asphalt mixes, and warm asphalt mixes tailored to specific durability, strength, environmental, cost-efficiency and other requirements
- Pavement construction equipment and process advancements including infrared sensing for “hot and cold” areas (e.g., segregation), high frequency vibratory rollers, materials transfer equipment (“shuttle buggies”) the (“PRSPAC”) flat plate compactor and as-built evaluation of smoothness, density, etc.
- Micro electro-mechanical sensors (MEMS) in “smart” roads, airfields and other transportation structures
- Radio Frequency Identification (RFID) tags for materials and construction progress tracking
- Emerging nanotechnology applications in particle size and shape analysis (eg., molecular weight distributions), coatings such as titanium dioxide on concrete panels, fabrication of carbon nanotubes for concrete mixes, and many others
- Permeable asphalt and porous concrete pavements as environmentally important contributions to minimizing surface runoff and recharging ground water.

Innovations and Advances through Research

The long term viability and success of a research program is particularly dependent on how well its strategic planning is formulated and executed. The University of Waterloo’s Centre for Pavement and Transportation Technology (CPATT) research program, for example has focused on a succession planning strategy, and on linking a number of interrelated key strategic elements with program areas (Tight, et al 2008). These strategic elements included the following:
Activities within three basic knowledge types: (a) explicit knowledge in terms of documented research results and technology developments, data and information and professional involvements, (b) implicit knowledge in terms of skills and expertise resident in CPATT’s researchers and staff, and (c) tacit knowledge in terms of the innovative/creative capabilities resident in CPATT’s researchers and staff.

Mentoring, both formal and informal, involving a commitment to advising and encouraging students, the promotion of pavement engineering and research and assistance to newer researchers and staff by more senior and experienced people. In essence, a concerted team approach to mentoring is a cornerstone to the long term sustainability of a research program.

Training and skills development is one of the most critical elements to ensuring sustainability of CPATT’s research program. It involves hands-on work in the laboratories and field test sites, as well as regular instruction.

Succession planning as an integral part of knowledge management, where this involves a process for the orderly planning/continuity of renewal and upgrading of the resources behind a research program, including people, technology and information.

The latter element has an underlying rationale of cost-effectiveness, promoting organizational cohesiveness, preserving investment and basically good business practice. It also requires top level commitment, providing the necessary resources, periodic assessment of effectiveness and documentation of activities and accomplishments. But obstacles also exist, including high staff turnover, a culture of “we can simply buy what we need”, and a lack of balance between outsourcing and being a knowledgeable buyer.

The use of key performance indicators (KPI’s), which are objectively based and measurable, became important in the long term performance and/or warranty based contracts, starting in about the early 1990’s. The use or application of this approach to forward looking research programs, without being constraining, has been described in (Haas 2010).

Forward Looking Opportunities for Advances in Pavement Engineering and Management

The US FHWA initiative on developing a “Roadmap” for the future of pavement management provides an excellent context for identifying forward looking opportunities to advance pavement engineering and management. In the following, a number of such opportunities are suggested. Extensive use has been made of (APT 2010), supplemented by the author’s own perspective and background in the area. Issues and challenges associated with these opportunities are also identified, together with the short, medium and long term prospects for realizing the opportunities. It may be noted that the intent is to examine some, but certainly not all possible, opportunities rather than describe the many state-of-the-art existing technologies and practices.
Table 6 is a consolidated but certainly not exhaustive listing, which categorizes the opportunities as follows:

A. Pavement Data (Needs and Cost-Effectiveness; Collection Technologies; Quality Assurance; Storage and Integration)

B. Pavement Management (Structural Design and LCAA; Performance Modeling; Treatment Selection; Quantifying Benefits; Decision Support)

C. Institutional Improvements (Organizational Structure; Location of PMS and AMS; Technology; Skills; Public-Private-Partnerships)
TABLE 6 Forward Looking Opportunities for Advances in Pavement Engineering and Management

<table>
<thead>
<tr>
<th>FORWARD LOOKING OPPORTUNITY AREAS</th>
<th>EXAMPLE ISSUES/CHALLENGES</th>
<th>PROSPECTS FOR MAJOR ADVANCES (Short Term 1-5 Yrs; Med. Term 6-10 Yrs; Long Term 10 Yrs. Plus)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Pavement Data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Needs and Cost-Effectiveness</td>
<td>• Responding to advancements in technology</td>
<td>• Needs will remain short to long term</td>
</tr>
<tr>
<td>(comprehensive protocols/guidelines</td>
<td>• Consistency over time</td>
<td>• More comprehensive guidelines likely in short term</td>
</tr>
<tr>
<td>for types of data required, frequency</td>
<td>• Amount (s) and types required for different uses</td>
<td>• Advances will be constrained by cost concerns short to long term</td>
</tr>
<tr>
<td>of collection, level (strategic,</td>
<td>• Value of and compatibility with historical data</td>
<td>• Widespread standardization not likely in short to medium term</td>
</tr>
<tr>
<td>network or project), use (MEPDG,</td>
<td>• Role of standardization and comparison across agencies</td>
<td>• Competition will continue to drive advances short to long term</td>
</tr>
<tr>
<td>overall asset management, etc.)</td>
<td>• In-house or outsourcing data collection?</td>
<td>• Image quality will continue to improve (eg. 3D photogrammetry) short to long term</td>
</tr>
<tr>
<td></td>
<td>• Commitment to and amount of resources required</td>
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<tr>
<td></td>
<td>• Coordination with other data collection (traffic, etc.)</td>
<td></td>
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<tr>
<td></td>
<td>• Optimization of data collection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Needs will remain short to long term</td>
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<tr>
<td></td>
<td>• More comprehensive guidelines likely in short term</td>
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<td></td>
<td>• Advances will be constrained by cost concerns short to long term</td>
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</tr>
<tr>
<td></td>
<td>• Widespread standardization not likely in short to medium term</td>
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<tr>
<td></td>
<td>• Competition will continue to drive advances short to long term</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Image quality will continue to improve (eg. 3D photogrammetry) short to long term</td>
<td></td>
</tr>
<tr>
<td>2. Collection Technologies</td>
<td>• Implementation of high speed deflection (eg. Rolling Wheel Deflectometer)</td>
<td>• QA procedures in LTPP can be used advantageously for short to long term</td>
</tr>
<tr>
<td>(precision required, automation of</td>
<td>• Evaluation of new/improved equipment</td>
<td>• Prospects for impact of quality level of data on pavement design, maintenance, preservation, etc. likely to be better established in medium term</td>
</tr>
<tr>
<td>condition measurement, sensors,</td>
<td>• Equipment costs, reliability and service life</td>
<td></td>
</tr>
<tr>
<td>image quality, speed, referencing,</td>
<td>• Degree of integration capabilities required in a vehicle vs. use/optimization of data</td>
<td></td>
</tr>
<tr>
<td>integrated collection capabilities,</td>
<td>• Agency procurement of equipment vs. contract/outsourcing</td>
<td></td>
</tr>
<tr>
<td>equipment reliability and robustness)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Cost may delay under spread use of high speed deflection in short to medium term</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Competition will continue to drive advances short to long term</td>
<td></td>
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<tr>
<td></td>
<td>• Image quality will continue to improve (eg. 3D photogrammetry) short to long term</td>
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<tr>
<td></td>
<td>• Level of accuracy needed for various data elements?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Volume of low-quality data vs less but higher quality data?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Technical expertise required to develop QC/QA plans</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Impact of staff turnover (vendors and clients)?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Impact of data quality on engineering and management decisions?</td>
<td></td>
</tr>
<tr>
<td>3. Quality Assurance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(validity, consistency, accuracy,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>completeness, management of data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>quality, audits, effect of collection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>method, automation of quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>checks, QC and QA plans</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• QA procedures in LTPP can be used advantageously for short to long term</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Prospects for impact of quality level of data on pavement design, maintenance, preservation, etc. likely to be better established in medium term</td>
<td></td>
</tr>
<tr>
<td>FORWARD LOOKING OPPORTUNITY AREAS</td>
<td>EXAMPLE ISSUES/CHALLENGES</td>
<td>PROSPECTS FOR MAJOR ADVANCES (Short Term 1-5 Yrs; Med. Term 6-10 Yrs; Long Term 10 Yrs. Plus)</td>
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<tr>
<td>-----------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| 4. Storage and Integration        | • Limits to storage capacity, offsite backup, purging old and/or redundant data  
• Reluctance to share information/preservation of “silos”?  
• Distribution, format and level of reports  
• Sufficiency of available technology and agency resources to meet storage and integration demands                                                                                                             | • Benefits from well designed and managed storage systems and integration platform can be substantial in the short term  
• A constraint on storage capacity; however, is already a short term problem                                                                                                           |
|                                  |                                                                                                                                                                                                                           |                                                                                                                                                          |
| B. Pavement Management           | **1. Structural Design and LCCA** (input variables, type of facility, design method, component models, design options, LCCA method, constructability and maintainability)  
• Probabilistic vs deterministic approach  
• Adoption of the MEPDG method, or …..?  
• Defining and incorporating sustainability and “green” aspects  
• In-house vs outsourced design (within a P3)  
• Communication of finalized design to other areas (construction, maintenance, etc.)                                                                 | • More probabilistic short term  
• Extensive calibration on MEPDG short term  
• Comprehensive attention to sustainability and “green” roads short to medium term  
• More P3’s short to long term                                                                                                                                            |
|                                  | **2. Performance Modeling** (Direct part of evaluating design options, models), predictions (IRI vs Age, and/or…..), reliability, periodic updating, accuracy, etc.)  
• Probabilistic vs deterministic basis  
• Impact of new materials on predictions (warm mixes, etc.)  
• Groups/families vs individual sections  
• Calibrating MEPDG performance models  
• Use of performance models in predicting remaining service life (RSL) – functional and structural                                                                 | • Continual move to probabilistic short to long term  
• Continued work on improved accuracy of models, and in MEPDG calibration, short to long term  
• Advances in RSL protection capability short to medium term                                                                                                                   |
|                                  | **3. Treatment Selection** (Fundamental component of a PMS, selection process for network and project, interface with other project elements, sensitivity to timing, safety, constructability and future rehabilitation)  
• Flexibility in selection vs change upon implementation  
• Clarifying preservation vs preventative vs rehabilitative vs maintenance treatments  
• Estimating treatment costs in rapidly changing prices  
• Types and extent of information needed for selection                                                                                                                        | • Better, more comprehensive models/processes likely over long term  
• Integration of preservation and preventive treatments into PMS likely in short term  
• More emphasis on long term impacts of treatments likely over short to long term                                                                                           |
<table>
<thead>
<tr>
<th>FORWARD LOOKING OPPORTUNITY AREAS</th>
<th>EXAMPLE ISSUES/CHALLENGES</th>
<th>PROSPECTS FOR MAJOR ADVANCES (Short Term 1-5 Yrs; Med. Term 6-10 Yrs; Long Term 10 Yrs. Plus)</th>
</tr>
</thead>
</table>
| 4. Quantifying Benefits (Cost side of people, equipment, data collection, etc. represents the investment; impacts on decisions) | • What benefits and how to quantify?  
• Demonstrating changes in network condition vis a vis cost side  
• How to communicate benefits and to whom? | • Increasing demand likely from stakeholders to quantify benefits, short to long term  
• Improved communication tools also likely, short to long term |
| 5. Decision Support (information needed at all levels for policy, strategic network and project level decisions; optimization approach; feedback) | • Incorporating risk exposure into the decision process  
• Balancing practicalities with recommendations  
• Incorporating user costs and benefits?  
• Transparency of the decision process | • Increasing use of risk analyses in decisions, short to long term  
• Increased requirement from senior levels to demonstrate value of PMS in decision support, short term |
| C. Institutional Improvements 1. Organizational Structure (Centralized vs regional decisions; simple (small) vs comprehensive (large); use of performance indicators) | • Impact of funding (amount, sources) on organizational structure  
• Capability of adapting to change (downsizing, asset management, retirements, information, politics, technology, etc.)  
• Ability to compete for pavement dollars | • Many types of changes will occur, even in short term, and adaption will be crucial to survival of pavement management  
• Continued erosion of institutional knowledge likely in short to medium term |
| 2. Location of PMS and AMS (Distinct or combined offices for pavement management and asset management; communication channels) | • PMS as a “silo” or component subsystem of AMS?  
• Rationale for PMS in traditional location (materials, planning, maintenance, etc.)  
• Pavement preservation in the PMS, or separate budget? | • Smooth interpretation of PMS, BMS, etc. into AMS likely to be a struggle over short to medium term  
• Risk of losing distinct benefit and features of PMS, short term |
| 3. Technology (State-of-the-art technologies today, and periodically upgraded, for data acquisition and processing, sensors, maintenance, etc.) | • Developing and maintaining in-house expertise on a fast moving world of technology  
• Assessing capabilities and limitations of new technologies  
• Investment in new or improved technologies | • Effective acquisition, understanding and use of new/improved technologies will continue as a long term need |
<table>
<thead>
<tr>
<th>FORWARD LOOKING OPPORTUNITY AREAS</th>
<th>EXAMPLE ISSUES/CHALLENGES</th>
<th>PROSPECTS FOR MAJOR ADVANCES (Short Term 1-5 Yrs; Med. Term 6-10 Yrs; Long Term 10 Yrs. Plus)</th>
</tr>
</thead>
</table>
| 4. Skills (Experience, teaching and training base; periodic upgrades; technical plus administrative and other skills) | • Determining what skills the “leaders of tomorrow” will need (see TAC Briefing Note of Nov., 2009, Ref. 8)  
• In-house skills/knowledge requirements vis a vis outsourced/purchased skills  
• Losses through retirements and resignations | • Maintaining the continuing skill sets requirements for effective PMS and AMS will continue at a long term priority need |
| 5. Public-Private-Partnerships (Use ranges from maintenance outsourcing to finance, design, build and operate) | • Achieving a true partnership with measurable key Performance Indicators on warranties, source delivery, allocation of risk, etc.  
• Achieving positive benefits for all stakeholders | • Adoption of P3”s in PMS and AMS will be a growing trend over the long term (See Ref. 6) |
Conclusions

The major conclusions derived from the paper are:

- Effective management of road assets depends on a sound technical and economic base which underlies the various activities that go into providing roads and pavements
- Life cycle analysis is the umbrella for the technical and economic base, and is comprised of three basic levels: strategic, network or system wide and project or site specific
- An essential technical requirement for long life pavement design is the structural and mechanistic-empirical analysis methodology.
- An essential economic requirement is life cycle analysis, which is complementary to the structural design.
- Continuing advancements and innovations are also essential to maintaining a sound technical and economic base. Examples are provided in the paper, as well as forward looking opportunities for advances in pavement engineering and management.

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