NATIONAL & INTERNATIONAL PRACTICES IN DECISION SUPPORT TOOLS IN ROAD ASSET MANAGEMENT

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PREFACE

This report is written under the research project entitled “Investment Decision-making Framework for Civil Infrastructure Assets Management”. The project has commenced at the CRC for Construction Innovation at RMIT University, with the collaboration several public and private industry partners.

Chapter 1 gives objectives and scope of the report and the background of decision-making in Road Asset Management. Investment goals, decision hierarchy, decision-making framework and classification of the tools are introduced. Chapter 2 reviews current practices in the use of single economic criterion decision support tools. The use of Benefit Cost Analysis in supporting Triple Bottom Line decision-making is also discussed. Chapter 3 investigates the use of Multiple Criteria Analysis in Road Asset Management. Key issues in applications of the approaches are presented. Chapter 4 outlines the main findings and conclusions drawn from the review.

In the preparation of this report, the author has drawn liberally from many publications written by individuals and organisations, and they are the first to be acknowledged. The author is also indebted to Professor Arun Kumar, Dr. Sujeeva Setunge, Dr. Anthony Piyatrapoomi, Dr. Saman De Silva, and Mr. Shah Ashish for their generous assistance and constructive advice.

EXECUTIVE SUMMARY

This document provides a review of international and national practices in investment decision support tools in road asset management. Efforts were concentrated on identifying analytic frameworks, evaluation methodologies and criteria adopted by current tools. Emphasis was also given to how current approaches support Triple Bottom Line decision-making.

Benefit Cost Analysis and Multiple Criteria Analysis are principle methodologies in supporting decision-making in Road Asset Management. The complexity of the applications shows significant differences in international practices. There is continuing discussion amongst practitioners and researchers regarding to which one is more appropriate in supporting decision-making. It is suggested that the two approaches should be regarded as complementary instead of competitive means. Multiple Criteria Analysis may be particularly helpful in early stages of project development, say strategic planning. Benefit Cost Analysis is used most widely for project prioritisation and selecting the final project from amongst a set of alternatives.

Benefit Cost Analysis approach is useful tool for investment decision-making from an economic perspective. An extension of the approach, which includes social and environmental externalities, is currently used in supporting Triple Bottom Line decision-making in the road sector. However, efforts should be given to several issues in the applications.

First of all, there is a need to reach a degree of commonality on considering social and environmental externalities, which may be achieved by aggregating the best practices. At different decision-making level, the detail of consideration of the externalities should be different. It is intended to develop a generic framework to coordinate the range of existing practices. The standard framework will also be helpful in reducing double counting, which appears in some current practices.

Cautions should also be given to the methods of determining the value of social and environmental externalities. A number of methods, such as market price, resource costs and Willingness to Pay, are found in the review. The use of unreasonable monetisation methods in some cases has discredited Benefit Cost Analysis in the eyes of decision makers and the public. Some social externalities, such as employment and regional economic impacts, are generally omitted in current practices. This is due to the lack of information and credible models. It may be appropriate to consider these externalities in qualitative forms in a Multiple Criteria Analysis. Consensus has been reached in considering noise and air pollution in international practices. However, Australia practices generally omitted these externalities.

Equity is an important consideration in Road Asset Management. The considerations are either between regions, or social groups, such as income, age, gender, disable, etc. In current practice, there is not a well developed quantitative measure for equity issues. More research is needed to target this issue.

Although Multiple Criteria Analysis has been used for decades, there is not a generally accepted framework in the choice of modelling methods and various externalities. The result is that different analysts are unlikely to reach consistent conclusions about a policy measure. In current practices, some favour using methods which are able to prioritise alternatives, such as Goal Programming, Goal Achievement Matrix, Analytic Hierarchy Process. The others just present various impacts to decision-makers to characterise the projects.

Weighting and scoring system are critical in most Multiple Criteria Analysis. However, the processes of assessing weights and scores were criticised as highly arbitrary and subjective. It is essential that the process should be as transparent as possible. Obtaining weights and scores by consulting local communities is a common practice, but is likely to result in bias towards local interests. Interactive approach has the advantage in helping decision-makers elaborating their preferences. However, computation burden may result in lose of interests of decision-makers during the solution process of a large-scale problem, say a large state road network.

Current practices tend to use cardinal or ordinal scales in measure in non-monetised externalities. Distorted valuations can occur where variables measured in physical units, are converted to scales. For example, decibels of noise converts to a scale of -4 to +4 with a linear transformation, the difference between 3 and 4 represents a far greater increase in discomfort to people than the increase from 0 to 1. It is suggested to assign different weights to individual score.

Due to overlapped goals, the problem of double counting also appears in some of Multiple Criteria Analysis. The situation can be improved by carefully selecting and defining investment goals and criteria. Other issues, such as the treatment of time effect, incorporating risk and uncertainty, have been given scant attention in current practices. This report suggested establishing a common analytic framework to deal with these issues.

1 INTRODUCTION

Road infrastructure assets are drivers of economic development and social equity. They also have significant impact on the natural and man-made environment. The complex nature of decision-making requires practitioners to select investment options based on a wider variety of policy considerations in addition to Benefit Cost Analyses and pure technical considerations.

The Green paper (DOTARS 2002), which is Australian National Land Transport Plan to develop and fund an integrated national land transport infrastructure network, identifies many weakness of current decision-making framework, such as:

- A short-term focus
- Poor coordination on intermodal planning and funding
- Ignorance on cooperation between governments or with the private sector
- Poor integration of land use and transport planning
- Insufficient focus on new technology-based solutions
- Ad hoc approaches to rail and port access investments

It concludes that, without major reform of current decision-making framework, Australians over the next twenty years will have a transport system that fails increasingly to meet their needs. It identified that there is an increasing demand for establishing a wholistic Investment Decision-making Framework for Road Asset Management, which brings all social, environmental, economic, and political factors to bear in a logical and systematic. The main focus of this report is reviewing current decision-making support tools for Road Asset Management.

1.1 Objective and Scope of the Report

This study was conducted on an extensive review of international sources on decision-making support tools in Road Asset Management (both published and research in progress). The objectives of this report are to:

- Investigate evaluation methodologies of current decision-making support tools in Road Asset Management.

- Review current applications of the identified evaluation methodologies.

- Identify merits and limitation of the identified evaluation methodologies.

- Identify areas of improvement.

Decision support tool is only one of several key components of an Investment Decision-making Framework. Other key components of the framework, such as strategic goals, valuation of assets, budget process, stakeholder participation, and feedback procedures, are not covered in this report.

1.2 Nature of Decision-Making in Road Asset Management

1.2.1 Goals of decision-making in Road Asset Management

Road transport services society's economic and social functions. It is assumed that decision-making situations in Road Asset Management are coordinated by a pre-determined, socially optimal strategy concerning the direction of different sectors towards government goals (Bein

1997). Ideally, government goals that reflect the social, economic and environmental aspirations of society are at the top of the hierarchy of goals to guide decision-making in Road Asset Management. A international survey (OECD 1994) outlined the common considerations in decision-making process as regional economic and social policies, unemployment, poverty, stay in budget, provide desired level of service, satisfy travel demand, car ownership, technology innovation, environment, etc.

According to Cox (1997), Australian community expects that road infrastructure policy can achieve:

- Economic growth
- Ecological sustainability
- Social cohesion and equity

The Australian State Road Authorities have been taking Triple Bottom Line concept (economic, social, environmental) into consideration in their decision-making process (DMR-QLD 2002, DMR-WA 2001, RTA-NSW 2001, VicRoads 2001). In Australia, the goals of Road Asset Management can be generalised as:

- Promote national and regional economic growth
- Improve access to service
- Improve road safety
- Improve movement of people and freight
- Responsibly manage environment
- Integrate with other transportation modes

Therefore, decision-making in Road Asset Management has broad economic, social, economic and environmental goals. In addition, through bureaucratic process, the decision is also required to meet political objectives of the government.

1.2.2 Hierarchy of decision-making in Road Asset Management

According to the United States Federal Highway Administration (FHWA 1999), decision-making in Road Asset Management can be considered at two levels:

- *Executive Level* (policy/strategic/programming)
- *Operational Level* (project development)

The first level develops a long-term strategic plan and a short-term program of projects intended for funding. The second level provides evaluating and selecting projects in different parts of the network. The two levels of decision-making take place within political and technocratic processes. Generally, at the more detailed planning levels, more weight is given to technical decisions.

A more detailed decision-making hierarchy was given by Robertson (2001):

- *Planning* intends to analyse the whole road network in order to prepare long-term strategic planning estimates of expenditure under various budgetary and economic scenarios.

- *Programming* involves the development of multi-year roadwork and budget programs, under budget constraints.

- *Preparation* involves the evaluation of one or more road projects or investment options.

- *Operation* covers the on-going operation of an organization.

- *Policy Research* investigates the impacts of funding policy for competing needs, user charge, axle load limits, and maintenance standards.

In this report, decision-making activities in a road agency are categorised into two levels:

- ***Strategic level*** includes *Planning*, *Programming* and *Policy Research.*

- ***Operational level*** includes *Preparation* and *Operation.*

Moving downward from the top of the hierarchy, the set of decision criteria narrows down from a broad social, economic, environmental and political basis at the strategic level, to mostly technical parameters and design and maintenance standards at the operational level, which reflects the different complexity of each level of decision-making. At strategic level, the set of decision criteria usually contains a larger number of qualitative factors than at operational level, because social, political, some economic, and many environmental aspects cannot easily be quantified.

1.2.3 Investment Decision-Making Framework for Road Asset Management

Decision-making of Road Asset Management is expected to be supported by an *Investment Decision-making Framework* which can accommodate social, economic and environmental considerations. The political goal can be taken into consideration through a combination of political, consultative and prescriptive processes. The *Investment Decision-Making Framework* is an integration of management policies, standards, decision-making procedures, asset data bank and decision support tools.

Federal Highway Administration (FHWA 1999) suggested that the main components of an 'Asset Management Decision-making Framework' includes: strategic goals, inventory of assets, valuation of assets, quantitative condition and performance measures, performance-prediction capabilities, consideration of qualitative issues, links to the budget process, engineering and economic analytical tools, information presentation, and continuous feedback procedures. However, it has been difficult to find a solution which brings all social, environmental, economic, and political factors to bear in a logical and systematic manner.

The various difficulties were encountered in establishing a generalised framework for supporting decision-making in Road Asset Management (Tsamboulas & Mikroudis 2000). In operational terms, the framework should be easy to understand and apply (McCoubrey 2000 & Thorpe & Kumar 2002). The efficiency criteria are generality, independence, reliability, flexibility, few data need, etc. In philosophical terms, the framework should be able to deal with challenging issues, such as uncertainty (Li, Q. *et al* 2002), time frame, network effects, model changes, while integrating cost and non-cost values into the evaluation (Pelevin *et al* 2001). The complexity also results from several other issues, such as some measures may be qualitative (Day 1998), some projects may be interdependent (Teng & Tzeng 1996), the number of feasible alternatives is often enormous (Taber 1999). In addition, due to resource limitations there are usually constraints such as government policies, finance, work force, and facilities or equipment, to be considered (Chan *et al* 2001).

1.3 Classification of Current Tools in Decision-making of Road Asset Management

The decision support tools used vary as much as the management processes in different road authorities. Much depends on professional tradition, mandate, leadership and the organisational culture of the agencies. Generally, current tools can be classified into two categories based on the use of different evaluation methodologies:

- *A single economic criterion approach*, which is primarily based on a Benefit-Cost Analysis

- *A multiple criteria approach*, which is based on ranking of decision maker's preferences using multiple criteria optimisation techniques.

2 SINGLE ECONOMIC CRITERION DECISION SUPPORT TOOLS

Generally, current decision-making in Road Asset Management is primarily supported by Pavement Management Systems (PMSs) and Bridge Management Systems (BMSs), which are based on a Benefit Cost Analysis (Hayashi & Morisugi 2000, FHWA 1999 & OECD 1994). These tools use one or more economic indicators, such as Benefit Cost Ratio, Net Present Value, Internal Rate of Return, and First Year Rate of Return, for assessing the economic efficiency of investment alternatives or impacts of policy change to all members of society.

2.1 The Methodology

2.1.1 Benefit Cost Analysis

Benefit Cost Analysis (BCA) refers to the evaluation of alternatives according to their costs and benefits when each is measured in monetary terms. This methodology is derived from Welfare Economics, which focuses on the potential for alternative uses of resources to influence the welfare of individuals. The theoretical basis of BCA was laid in the middle of 19^{th} century. In the second part of the 20^{th} century, this meaningful and practical approach has become popular and widespread in project evaluation. BCA is able to provide information to the decision-maker about (Austroads 1996):

- The economically best option out of a set of project alternatives
- Prioritisation of competing projects within a constrained budget.

Several principles applicable to BCA for infrastructure investment were identified by Hudson *et al* (1997):

- The decision-making level must be clearly identified
- The analysis only supports a decision instead of making a decision
- Criteria, rules and guides for such decisions must be separately formulated before the analysis
- The analysis itself has no relationship to the financing of a project
- The number of alternatives in the analysis should be as many as possible
- The analysis period for all the alternatives should be the same
- The analysis should include agency costs and user costs and benefits

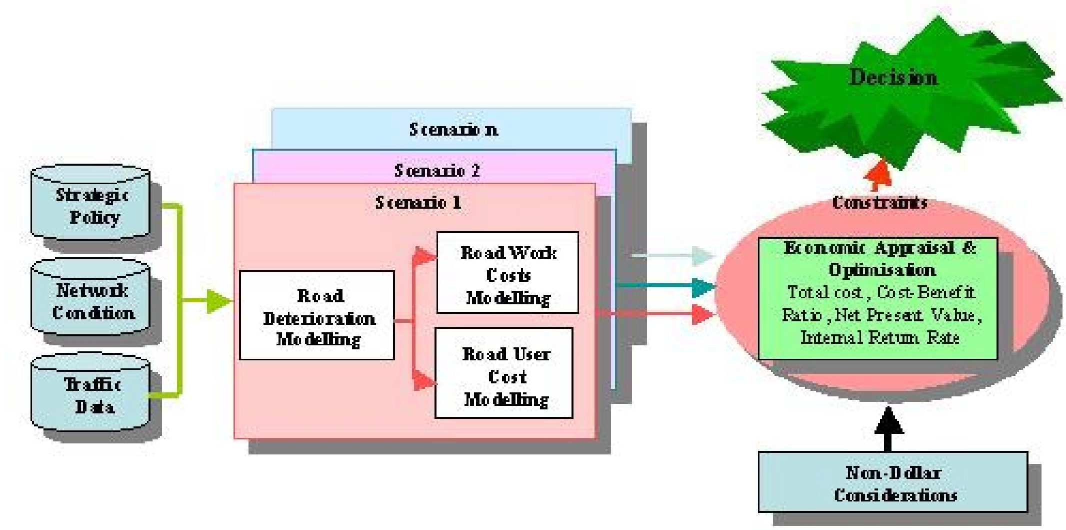
2.1.2 Analytic framework

In general, a BCA based decision support tool for Road Asset Management includes several key components:

- A comprehensive database system
- Traffic models
- Pavement/Bridge deterioration models
- Road work effect models
- Road user cost and effects models (travel time, vehicle operating cost, accident, environmental and social costs, etc.)
- Economic appraisal module
- Optimisation module

Figure 1 presents a generic decision support framework of current BCA practices in Road Asset Management.

Figure 1. Generic analytic structure of a Benefit Cost Analysis approach



2.1.3 Decision criteria

BCA attempts to find a common measure for the aggregation of costs and benefits so that the net outcome of the project is measured and that the comparison of the alternatives is based on a common measure and criterion, and, always considering the time value of money. The principal criteria used in road sector are defined below:

- *Net Present Value* (NPV) is defined as the sum of discounted net benefits over the analysis period less discounted costs. The higher the NPV, the larger the benefit from the investment alternative. When there is no budget constraint, the choice of between alternatives should be based on NPV. The criterion is widely used in evaluation of Road Asset Management. However, Hudson *et al* (1997) argued that it could not be applied to single alternatives when the benefits of those alternatives could not be estimated other than to simply calculate the NPV. It also suffers the disadvantage that it cannot reflect the intensity of benefit potential per unit of agency cost.

- *Internal Rate of Return* (IRR) is the discount rate at which NPV is zero. IRR does not indicate the size of the costs or benefits of the investment (PIARC 2002) and is not a truly economic assessment in a whole of life cycle cost context (Austroads 1996).

- *Benefit/Cost Ratio* (BCR) is the ratio between discounted community benefits and discounted total agency cost over the analysis period. The measure eliminates the bias of NPV towards larger projects. However, as IRR, it does not give indication on the size of the costs and benefits involved.

- *First Year Rate of Return* (FYRR) is defined as the ratio, in percent, of the net benefits realised in first year after construction completion to the increase of total agency costs. FYRR gives a rough guide to project timing. If it is greater than discount rate, then the project should go ahead. The measure does not provide a whole of life cycle cost approach (Austroads 1996).

2.1.4 Pavement deterioration models

Pavement deterioration model is the algorithm used to define and predict pavement deterioration, which is usually expressed in terms of a pavement condition parameter and undertaken either at the network or project level (Foley 1999). It is generally accepted that the current pavement deterioration models can be divided into two categories (Haas *et al* 1994 and Martin 1996):

- *Deterministic approaches*, which are based on statistical relationships, where various parameters such as traffic, age etc., are identified up front as attributors to the deterioration of pavement, and predict a single value of the response variable.

- *Probabilistic approaches* which reflect stochastic variance of pavement deterioration, and predict the distribution of the response variables.

In addition, with the development of artificial intelligence theories, there are growing interests in adopting Artificial Neural Networks (ANNs) (Huang & Moore 1997) to predict pavement deterioration. More detail of the above models is given in Appendix I.

2.1.5 Prioritisation and optimisation

When the serviceability or quality of a road component such as pavement or bridge deck, reaches an unacceptable or intervention level, some actions are needed. If sufficient funds are available, all actions can be taken. However, for most road authorities, the usual situation is constrained budget. In such cases, priorities have to be set to answer following questions:

- Which projects should be conducted?

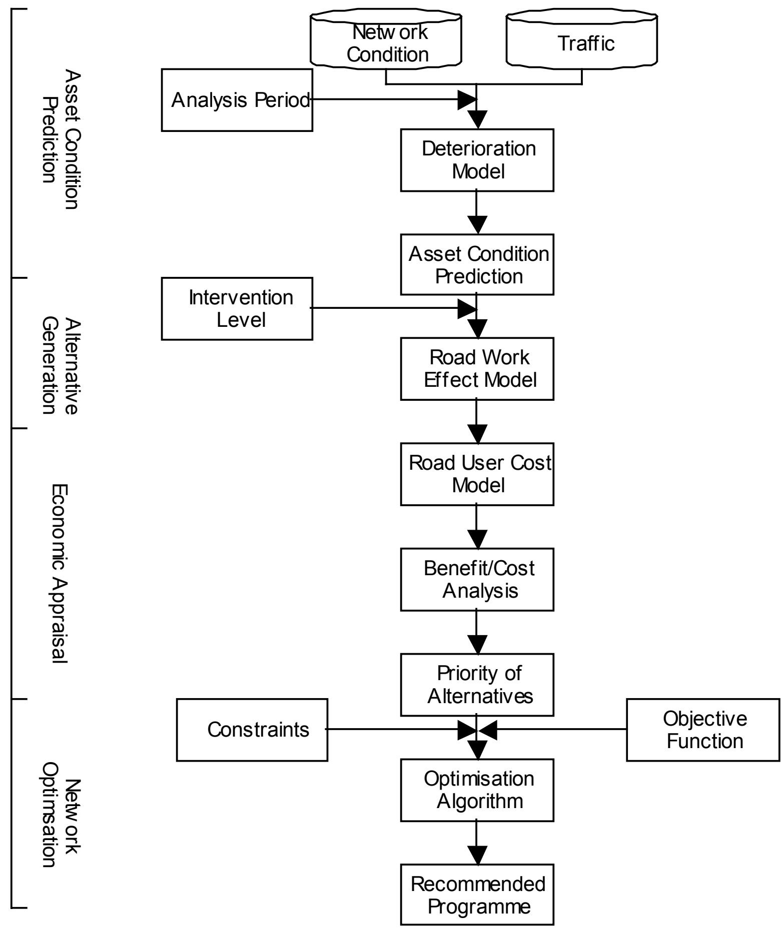
- What treatment should be applied?

- When should the work be done?

2.1.5.1 Framework for prioritisation

Prioritisation is a process for assisting in the determination or selection of the preferred project from amongst a number of feasible alternatives. The actual techniques used to make the decision vary in detail and difficulty. Some techniques are simple to use and require very little mathematical analysis, such as ranking based on goals and objectives (Alkire 1998), the others are quite complicated, such as linear, non-linear and dynamic programming. There are two main priority-ranking modules used in most road asset decision support tools: economic appraisal and network optimisation. The former investigates the economic viability of investment alternatives and provides the criteria needed for economic decision-making. The latter, under constrained budget, selects the set of investment alternatives to be made on a number of road sections/categories within a network which will satisfy predefined objective function. Figure 2 presents a generic analytic framework for project prioritisation through a BCA approach.

Figure 2. Generic Prioritisation Framework by a Benefit Cost Analysis Approach



2.1.5.2 Objective functions and constraints

The use of optimisation for short/long term budget planning requires that a road authority identifies an overall investment goal. The mathematical terms of the goal is defined as an objective function. In general, objective functions fall into three categories (Mulholland 1991):

- Minimisation of total cost with set condition standards
- Maximisation of improvement of network condition within constraints
- Minimisation of life cycle cost while satisfying set network maintenance standards

Fwa *et al* (1998) listed some possible considerations of objective function used by different highway agencies:

- Maximise maintenance and rehabilitation work productivity for specified resources constraints
- Maximise overall pavement network level of serviceability for given resources constraints
- Maximise usage of yearly allocated budgets

- Maximise the Net Present Value (NPV) for a required level of service

After the objective functions are defined, the agency needs to identify any constraints to be considered in the analysis. Generally, the constraints considered (Chan *et al* 2001, Chootinan 2001 & Chen *et al* 1996) include budget, network condition, manpower, equipment, material, time, etc.

2.1.5.3 Optimisation algorithms

Optimisation algorithms are used to search the optimal strategy for any given network subjective to the predefined constraints. Zimmerman (1995) identified four predominant algorithms used in pavement management: - linear, non-linear, integer and dynamic programming. In recent decade, evolutionary programming techniques, such as Genetic Algorithms, and Neural Networks techniques, were adopted by researchers and practitioners. The selection of the appropriate algorithm depends on the type and number of decision variables, the form of the objective functions and constraints, and whether decision must be made in sequence. The main features of these techniques and their inherent advantages and disadvantages are presented in Table 1.

Table 1 Optimisation algorithm used in current practices

Method	Features	Advantages	Disadvantages
Linear Programming (Männistö et al 2001, Grivas 1993, Davis&Van 1988)	• Objective functions and constraints are formulated as linear equations • Decision variables are continuous • Most common method used in PMS	• Simple • Suitable at network level	• Can not handle large number of decision variables • Suffer from combinatorial explosion problems • Difficulty in maintaining the identity of individual pavement sections
Non-linear Programming	• Objective functions and constraints are formulated as non-linear equations	• Suitable at network level	• The same as Linear Programming
Integer Programming (Li et al 1998, Sirajuddin 1997, & Fwa et al 1988)	• Objective functions and constraints are formulated as linear and non-linear programming • Decision variable are constrained to take integer or whole number (0 or 1) values	• Suitable at project level or project-based network analysis	• Can not handle large number of decision variables • Can not handle combinatorial problems
Dynamic Programming (Smadi 2001, Feighan et al 1988)	• No existing standard mathematical formulation • The problem is divided into stage, with a decision required at each stage • Each stage has a number of states associated with it The effect of decision is to transform the current sate to a state associated with the next stage • The solution procedure is to find an optimal policy for the overall problem	• Applicable in making a sequence of interrelated decisions, say multi-year budget optimisation • Reduced computational complexity • Suitable for either network level and project level analysis	• Can not handle large number of decision variables
Genetic Algorithm (Chan et al 1994, Fwa et al 1998)	• Based on natural selection and natural genetics • Through continuous copying, swapping, and modifying of partial strings which are generated in an initial pool of solutions, to allow the solution pool to evolve toward better solutions.	• Capable of solving combinatorial problems • Can handle large number of decision variables • Flexible in defining the objective function	• Does not generate a true optimal solution
Neural Networks (Fwa&Chan 1993)	• The model is composed of a large number of nodes • Each node is associated with a state variable and an activation threshold • Each link between nodes is associated with a weight • Sate of node is determined by an activation function	• Capable of solving combinatorial problems • Can handle large number of decision variables	• Does not generate a true optimal solution

2.2 Current Benefit Cost Analysis Based Decision Support Tools

Pavement Management Systems (PMSs) generally aim to optimise the use of available funds for maintenance, improvement, and capital work. However, the decision support process has various aspects, each of them performed in various ways. Throughout the last 20 years, in almost all countries decision makers have recognised the importance of implementing a PMS system for their road networks. This leads to the development of very large number of systems. Since it is clear that each road agency has its own needs and policies, no two systems can be equal. In this study, several widely used commercial packages were reviewed. Since the purpose of the study is to investigate decision support capability of each product, the evaluation primarily focuses on methodology and main functional capabilities. ***Due to limitations in the availability of information to the author, it should be noted that the comparison might not be able to fully cover the true capacities of the products. Therefore, the results only represent author's personal judgements.***

The packages selected are:

- *HDM-4* (PIARC 2002) is the latest version of the World Bank's Highway Development and Management model. It is a commercial product of the International Study of Highway Development and Management. The system is expected to establish an international standard tool for worldwide application in road sector.

- *dTIMS^{TM} CT (DEIGHTON 2002)* was developed by Deighton Consulting Group. The system was adopted by 18 US state Departments of Transportation, 4 Canadian provinces, 4 Australian State Road Authorities, etc.

- *Micro PAVER* (KMS 2002) was developed by Construction Engineering Research Laboratory in Champaign, Illinois, the US Army Corps of Engineers. The package is currently being used by over 600 cities, counties, airports and private consulting firms. Micro PAVER's Pavement Condition Index (PCI) methodology recently received the American Society for Testing and Materials (ASTM) standard D6433-99, which is the only PMS to have received an ASTM standard designation.

- *Financial Planning Network Optimisation System (FNOS*) (RTA-NSW 1991 & Tam & Bushby 1995) was developed by the Roads & Traffic Authority, New South Wales, Australia. The system has been widely used in a number of State Road Authorities and Australian Local Government Authorities. RTA NSW no longer supports the system.

The key areas investigated are decision support levels, inventory, scope of investment, deterioration models, road user cost models, road work effect models, project prioritisation, network optimisation, non-dollar impact analysis, investment uncertainty and risk, and decision-making mechanism. The detailed results are set out in Table 2.

Although all of the packages have been used in supporting decision-making practices in road sector, it is noted that none of the packages can deal with multiple objective decision-making. HDM-4, which is able to provide limited information on environmental and social impacts, has the most comprehensive functions. FNOS is the only system using probabilistic methodology in forecasting network condition. All products except HDM-4 use scenario analysis in assessing impact of uncertainty. However, this approach cannot evaluate the probability of expected outcomes and investment risks.

Table 2 Survey of current decision support tools

Decision Support Characteristics		Product			
		HDM-4	dTIMS CT	Micro PAVER	FNOS
Decision Supporting Levels	Policy Study	●			□
	Planning	●	□	□	□
	Programming	●	●	●	●
	Preparation	●	●	●	
	Operation	●	●	●	
Inventory	Pavement	●	●	●	●
	Bridge		●		
	GIS interface		●	●	
Scope of Investment	Maintenance	●	●	●	●
	Improvement	●	●	●	
	New Construction	●			
Deterioration Model	Individual distress	●	●	●	●
	Distress Interaction	●	●	●	
Road User Cost Model	Basic		●		
	Advanced	●			
Road Work Effect Model	Basic		●	●	●
	Advanced	●			
Project Prioritisation	Rule Based				●
	LCC Analysis	●	●	●	
Network Optimisation	Priority List	●	●	●	●
	Constrained	●	●	●	●
Non-Dollar Impact Analysis	Social	□			
	Environmental	□			
	Political				
Investment Uncertainty & Risk	Scenario Analysis		●	●	●
	Probabilistic Model				●
	Sensitivity Analysis				
	Risk Analysis				
Decision-making Mechanism	Single Criterion	●	●	●	●
	Multiple Criteria				

Legend ● Present □ Present in limited

2.3 Triple Bottom Line in Benefit Cost Analysis

2.3.1 Triple Bottom Line

Triple Bottom Line is a philosophy which guides an organisation to measure and report its performance beyond the financial dimension and towards an integrated view in environmental, social and economic (including financial) domains.

The Allen Consulting Group (2002) identified several core characteristics in the Triple Bottom Line practices as followings:

- Accepting accountability
- Being transparent
- Integrated planning and operations.
- Committed to stakeholder engagement
- Multi-dimensional measurement and reporting

To some extent, an extension of traditional BCA is able to support the Triple Bottom Line decision-making (Pratt 2002). In this approach, monetised environmental and social externalities are included.

2.3.2 Environmental and Social Externalities

According to Austroads (2000a), externalities can be defined as "*the effects of economic activities which are experienced by third parties, but which are not reflected in the prices of the activities. Since producers and consumers make their decisions on the basis of prices, the external effects are not into account*". In the road transport sector, the example of externalities includes congestion, accidents, land value, employment, air and water pollution, noise, and greenhouse gas emissions, etc.

A research project conducted by European Union (EUNET 1998), which reviewed current practice across member states in appraising major transport projects and deriving monetary values for externalities, tried to develop a comprehensive methodology and model for assessing the externalities of transport initiatives. The results may be useful for future research and practice in this area. Table 3 shows a list of recommendations of externalities that should be considered in a BCA / MCA.

Models for predicting a number of externalities, such as road accident, air pollution, and traffic noise, were developed based on local conditions. Appendix II gives more details for these models.

2.3.3 International Practices

Current international practices of benefits and costs considered in a Benefit Cost Analysis evaluation of road infrastructure investment are presented in Table 4.

Table 3. Recommended EUNET Impacts

Impact		BCA*	MCA#
Direct	Investment Costs	●	●
	System Operating and Maintenance Costs	●	●
	Vehicle Operating Costs	●	●
	Revenues/User Charges	●	●
	Time	●	●
	Safety	●	●
	Service Quality		●
Environmental Externalities	Noise		●
	Local Air Pollution		●
	Regional Air Pollution	●	●
	Global Air Pollution	●	●
	Landscape		●
	Land Take	●	●
	Land Amenity		●
	Special Sites		●
	Severance		●
	Water Pollution		●
Indirect Socio-Economic Externalities	Output		●
	Employment		●
	Land Use		●
	Strategic Mobility		●
	Other Policy Synergy		●

*BCA – Benefit Cost Analysis
#MCA – Multiple Criteria Analysis
(EUNET 1998)

Table 4 International Triple Bottom Line practices by using Benefit Cost Analysis in Road Asset Management

BENEFITS/COSTS	**France** (Quinet 2000)	**Japan** (Morisugi 2000)	**Italy** (Bristow & Nellthorp 2000)	**Germany** (Rothengatter 2000)	**Sweden** (Bristow & Nellthorp 2000)	**UK** (Vickerman 2000)	**USA** (Lee 2000)
ECONOMIC							
Construction Costs	●	●	●	●	●	●	●
Disruption Costs						●	
Land and Property Costs			●	●	●	●	
Maintenance Costs	●	●	●	●	●	●	●
Operating Costs			●	●			●
Vehicle Operating Costs	●	●	●	●	●	●	●
Revenues		●					
Passenger Cost Savings							
Service Level			●				
Information			●				
ENVIRONMENTAL							
Noise	●	●	●	●			●
Air Pollution	●	●	●	●	●		●
Severance				●			
Energy Consumption		●					
SOCIAL							
Time Savings	●	●	●	●	●	●	●
Safety	●	●	●	●	●	●	●
Land Use							
Economic Development				●			
Employment				●			
International Traffic				●			
Regional Policy				●			

Value of Time

The most common approach in determining Value of Time (VOT) is based on average wage. France (Quinet 2000) and Japan (Morisugi 2000) practices fall into this category. Japan uses fix value for VOT which is based on the assumption that per capita GDP will increase in the future and the VOT will also proportionally increased. VOT for holiday is about 10% higher than weekday. However, in Germany (Rothengatter 2000), VOT of business travel is much higher than that of non-business, for example, for passenger car traffic, VOT of business is about 5 times of that of other traffic.

Noise

Sweden (Bristow & Nellthorp 2000) assigns money value to the incremental change of noise level. Japan (Morisugi 2000) converts noise to money based on different area, converting unit is (yen/dB(A)km/year). In German practices (Rothengatter 2000), the monetisation of noise is based on a cost value for equipping housing with noise-proof glazing. France (Quinet 2000) practice shows when value of noise is derived from from housing market, it is very expensive to measure and highly dependent on local conditions. The application of the approach is complicated and difficult.

Cost of accident

The methodologies used in valuing cost of accidents are as followings (EUNET 1998):

- Health and emergency service cost data (UK)
- Responses to Willingness to Pay (USA)
- Output/income data (France, Germany)
- Insurance claim data (Japan)

United Kingdom (DETR 2003a) has a very complex system in calculating the cost of accidents. Accident types are distinguished using fifteen different road types. Casualties are expressed in three categories, fatal, serious and slight. The value of life figures is based on data from current incomes, activity rates, future economic growth prediction and life expectancy forecast.

The USA Highway Economic Requirements System (HERS) (FHWA 2000) estimates the numbers of crashes and crash rates using separate procedures for three types of rural facilities and three types of urban facilities. The value of live lost is estimated by multiplying fatalities by the U.S. Department of transportation's estimation of the value of life (currently $2.7 million). These estimates are based on the willingness-to-pay concept used by HERS.

Japan practice (Morisugi 2000) is base on the payments of accident insurance policies. France (Quinet 2000) is based on the statistical value of human life. Germany (Rothengatter 2000) also adopts this approach.

Air Pollution

German practice (Rothengatter 2000) has most comprehensive form. There is a penalty factor for inner-urban pollution. The variable that describe changes in effects of air pollution from different exhaust fumes are:

- Decrease of energy consumption (of vehicles)
- Diversion of traffic away from ecologically sensitive regions
- Decreases in the distance travelled between origin and destination
- Changes of modal split to less polluting modes

The USA Federal Highway Administration considered six pollutants in its Benefit Cost Analysis package - Highway Economic Requirements System (HERS) (FHWA 2000). The costs of air pollution were derived from national wide average damage costs of human health and property damage per ton of each pollutant. France and Sweden adopt similar approach in valuing local and regional air pollution. The Values for Sweden are expressed as Skr/kg and split into rural and urban categories.

Regional Economy and Employment

Germany is the only country which incorporated regional economy and employment into its Benefit Cost Analysis procedure. The approach used four criteria in measuring externalities on regional economy and employment:

- Employment effects during the construction period.

- Employment effects related to the operation of the new road, which is a statistical estimation of relationship between regional growth and infrastructure investment.

- Benefits from improved spatial situation, which is a weighted aggregation of user cost saving and employment improvements.

- Improvement to international exchange

Generally, in international practices, there is high level of consensus as to the direct impacts, such as construction and maintenance costs and vehicle operating costs. However, agreement is rarely drawn on **WHAT** and **HOW** it should be measured with regard to environmental and social externalities/impacts.

2.3.4 National Practices

Australian practices are mainly based on Austraods Benefit Cost Analysis Manual (1996). In the manual, social and environmental externalities considered are

- *travel time costs*: the values are determined based on vehicle categories and vehicle occupancy (Austroads 1997).

- *accident costs*: standard accident cost parameters can be found in Austroads reports 2000b & 2000c)

- *noise impact costs*: it is recommended use of the differences in house prices as a measure of people's Willingness to Pay for peace and quiet. A value of 0.9% per dB is to be applied for noise reductions above 50 dBA (Austroads 1996).

2.3.5 Discussions

Benefit Cost Analysis approach can be employed to assess direct and indirect benefits and costs of a given set of choice possibilities. Through the analysis, the most favourable option, from a monetary perspective, can be identified in a straightforward way. Based on Triple Bottom Line consideration, Benefit Cost Analysis should also include costs and benefits of social and environmental externalities, and convert all of them into monetary units. Issues in applying Triple Bottom Line based Benefit Cost Analysis are identified as follows:

Externalities Considered
There is a common framework for Benefit Cost Analysis. However, different countries consider different externalities in the analysis. Some are very comprehensive, such as German practices, which cover a wide range of social and environmental externalities. Some are quite simple, for example, Australian practices (Main Roads Queensland 1999), environmental component is omitted in the analysis. There is a need to reach a degree of commonality by aggregating the best practices.

Commonality vs. Variability
Decisions have to be made based on values. Were Willingness of Pay based values are adopted, people will argue whether the value of time used for a project in Sydney, should be the same as in a rural town in Western Australia.

Methods of Monetisation
There are a number of methods for determining value of social and environmental externalities, such as market price, resource costs and Willingness to pay. Each country has

different option. For example, in determining costs of accidents, France and Germany are based on the statistical value of human life. Japan uses the payments of accident insurance policies. The United States uses statistic value of actual accident data. The use of unreasonable monetisation methods in some cases has discredited benefit cost appraisal in the eyes of decision makers and the public.

Double Counting
When only direct externalities are considered, double counting can be easily erased. However, incorporation of social and environmental externalities results in difficulties in dealing with the issue. For example, German practice tends to measure the benefits of expansion of regional economy from road investment. The method has aroused some criticism for double counting.

Unavailable Information
Due to lack of information or undeveloped techniques, models for some key social and environmental externalities are not available. For example, from government perspective, creation of employment is a major concern for investment. Estimates of the overall employment effect of a road project generally are speculative because of difficulties in modelling labour markets.

Discount Rate
The value of a discount rate is not an unambiguous parameter, but it is essential for a socio-political decision. In Australian practices (BTE 1999), the widespread practice of obtaining a discount rate by adding a risk premium to the Commonwealth bond rate is hard to defend. More sophisticated treatments of risk, while difficult, are worth pursuing.

Distributional Equity
Excluding German practice, this effect is generally omitted in international and national practices. However, it is an important consideration in road infrastructure investment decision-making. The considerations are either between regions, or social groups (income, age, gender, disable, etc.) In current practice, there is not a well-developed quantitative or qualitative measure for this distributional equity.

Level of Details
Decision Making of Road Asset Management can be made at different levels (see Section 1.2.2). Should same externalities be considered at different levels? Some detail may be not relevant to the situation. However, as practical matter, it is very difficult to handle (EUNET 1998).

Qualitative Externalities
Some social and environmental externalities cannot be quantified. Such as service quality and reliability, landscape, etc. Benefit Cost Analysis is not able to handle these externalities. Therefore, a Multiple Criteria Analysis should be employed as a complementary means.

3 MULTIPLE CRITERIA DECISION SUPPORT TOOLS

In the real world, decisions in Road Asset Management are recognised as multiple objective problems. The construction and maintenance costs, no matter how important it is in evaluating alternatives, are inadequate by themselves to support a decision convincingly and objectively. Therefore, after the popularity of Benefit Cost Analysis and related engineering-economic evaluation techniques, there was an increasing popularity of *Multiple Criteria Analysis* (MCA), which is capable of dealing with the multiple dimensions of evaluation problems. These techniques aim to solve conflicting social, environmental, political and economic issues in modern decision-making. In this chapter, the use of MCA in supporting decision-making in Road Asset Management is investigated.

3.1 Background of Multiple Criteria Analysis

3.1.1 Classifications of Multiple Criteria Analysis

MCA refers to DESCRIBE, EVALUATE, SORT, RANK, SELECT or REJECT objects (candidates, products, projects, etc.) on the basic of an evaluation (expressed by scores, values, preference intensities) according to several criteria.

The classification of MCA has been made by a number of researchers, e.g. Fandel & Spronk (1985), Vincke (1992) and Hwang and Yoon (1995). These classifications are based on the criteria that fit the respective authors' research interests. In this report, following Steuer's classification (1986), MCA problems are divided into two categories: *Multiple Objective Mathematical Programming* (MOMP) and *Multiple Attribute Decision Analysis* (MADA). MOMP is associated with the problems where alternatives are not predetermined, and the thrust of the model is "to design the best alternative given a set of conflicting objectives" Alternatively, the MADA problem has usually a limited number of predetermined alternatives, which is characterised by multiple, usually conflicting attributes. Generally, the former considers decision variables bounded by mathematical constraints, the latter deals with an enumeration of objects.

The use of MCA is usually supposed to have some or all of the following objectives (Lootsma 1999 pp3):

- Improvement of the satisfaction with the decision process. MCA urges the decision makers to frame the problem and to formulate the context explicitly. It presents the decision problem in a systematic way. The priorities and values of decision criteria which may hide in the back of decision maker's mind can be explored.

- Improvement of the quality of the decision itself. MCA enables the decision makers to break down a decision problem into manageable portions and to express a detailed judgement.

- Increased productivity of the decision makers. More decision per unit of time. The structured decision problem enables decision makers to work with a repeated procedure, so that time and energy can be saved

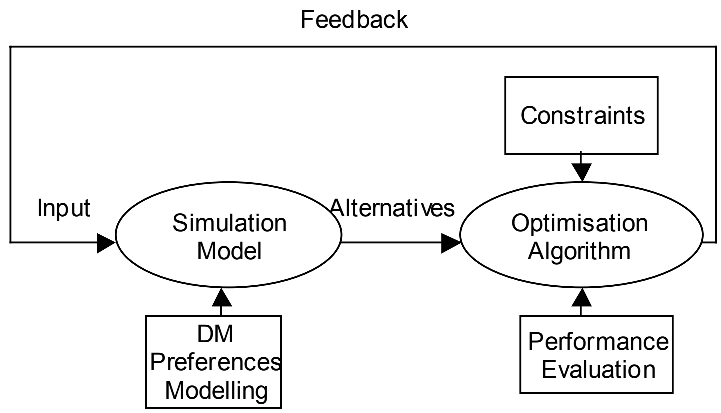
3.1.2 Construction of a Multiple Criteria Decision-Making problem

A generic MCA model is presented in Figure 3. A MCA problem generally can be described by following components:

- A set of objectives or criteria

- A set of feasible alternatives
- A number of decision constraints
- A preference structure or weights
- A set of performance evaluations of alternatives for individual objectives or criterion

Figure 3 A generic Multiple Criteria Analysis model



Preference modelling is an essential element in constructing a MCA problem. Generally, three approaches are identified:

- *A priori articulation of preferences*: Decision maker chooses an aggregating function that combines individual objective values into a single utility value, which makes the problem single-objective prior to optimisation. (De Silva & Tatam, 1996 Taplin *et al* 1996)

- *A posterior articulation of preferences*: Optimiser presents the decision maker a set of candidate solutions from which the compromise solution is then selected (Fwa *et al* 2000).

- *Interactive (Progressive) articulation of preferences*: Decision-making and optimisation occur at interleaved steps. At each step, decision-maker supplies preference information to the optimiser, which, in turn, generates better alternatives according to the information received.

After structuring the decision-making problem with preference modelling, different mathematical programming techniques can be performed for optimisation. They can be generally classified into following categories:

- *Utility Function:* which consists of assessing utility function and using the function and probabilities to come up with priorities of alternatives. Utility function is assessed by giving decision-maker a sequence of choices between alternatives. The responses are used to generate functions. The method converts the multiple objective optimisation problem into single objective problem (Bagchi 1999).

- *Goal Programming* (GP): which establishes a specific numeric goal for each of the objectives, formulating an objective function along with goals, and then seeking a solution that minimises the sum of deviations of these goals. GP is ideal for criteria with respect to which target values of achievement are of significance (Steuer 1986).

- *Compromise Programming* (CP): which determines solutions whose criteria values are close to given ideal criteria values, according to some measure of distance. The best solution minimises the sum of individual objectives' fractional deviation obtained from individual optimum values (El-gayar & Leung 2001).

- *Analytic Hierarchy Process* (AHP): which represents the decision problem as a hierarchy in which the top vertex is the main objective, and the bottom vertices are the actions and the intermediary vertices represent the criteria which should be taken into account (Saaty 1980).

- *Goal Achievement Matrix* (GAM) The Goal Achievement Matrix (GAM) identifies a set of objectives or "goals" that the project should achieve. These broad objectives are further refined to define quantifiable criteria against which the objectives can be assessed. The process allows the weighting of both the objectives and criteria to ensure that those considered most "important" are given a suitable value in the analysis. The final step in the process is to assess the level to which any particular project is able to achieve the assessment criteria (Pelevin *et al* 2001).

3.2 Applications of Multiple Criteria Analysis in Road Asset Management

3.2.1 International practices

Greece
Tsamboulas and Mikroudis (2000) compared some commonly applied MCA methods: REGIME, ELECTRE, and ADDTIVE UTILITY METHOD. Transparency, simplicity, robustness, and accountability were used as performance measures in the comparison. Three goals used in the analysis were:

- Maximum Internal Rate of Return (IRR) resulted from a Benefit Cost Analysis.

- Maximum safety, measured as % of accident reduction.

- Minimise environment damage, measured judgementally on a 1-100 scale taking into account noise, air pollution, severity, and landscape quality.

The importance of the goals are given by their weights: IRR 40%, Safety 35%, and Environment 25%. The study concludes that all methods show high degrees of flexibility, consistency, and reliability. And, the methods' performance depends on the characteristics of the decision situation.

Israel
Avineri et al (2000) proposed a multiple objectives process, which incorporates fuzzy set theory, for transportation projects selection. This methodology is able to cope with inexact information. Moreover, both quantitative and qualitative decision criteria are included in the process. Investment policy is represented by two kinds of complementary tools: Weights of criteria and noncompensatory fuzzy decision rules. The details of weights of the criteria are given in Table 5. The decision rules are developed using the concept of IF 'condition state' THEN 'decision' rules. The input variables are the fuzzy or crisp variables of the criteria. Finally, the MCA is expressed as a fuzzy multiple objective linear programming problem. The methodology was applied to 5 years Israel road investment programming. In comparison with a traditional Benefit Cost Analysis procedure, it is noted that better investment efficiency can be achieved.

Table 5 Relative weights of decision criteria of Israel practices

Criterion	Weight
Impact on traffic flow	30%
Impact on traveller's safety	25%
Impact economic growth, employment	15%
Environment impacts	10%
Land use impacts	10%
Other externalities (e.g. politics)	10%

(Avineri et al 2000)

Saudi Arabia

Ramadhan *et al* (1999) use an Analytic Hierarchy Process (AHP) to determine the weights of importance of pavement maintenance priority ranking factors. A composite maintenance priority index is used to rank the proposed projects. The index considers a number of factors: Road Class, Pavement Condition, Operating Traffic, Riding Quality, Safety, Maintenance Cost and Importance to Community. Each factor is assigned a specific weight of importance to the priority rank. AHP is used to quantify the weights from the respondents' opinions. Therefore, the priority ranking model is generated from the local experience and opinions of different people representing local perceptions regarding maintenance priority.

Singapore

Fwa *et al* (2000) developed a Genetic Algorithm based procedure for solving multiple objective network level pavement maintenance programming problem. Minimisation of maintenance costs, maximisation of work production, and maximization of network condition are considered as three objectives. Because the objectives have same weights in the decision-making, it noted that the selection of compromising solution is left to the decision-makers.

Taiwan

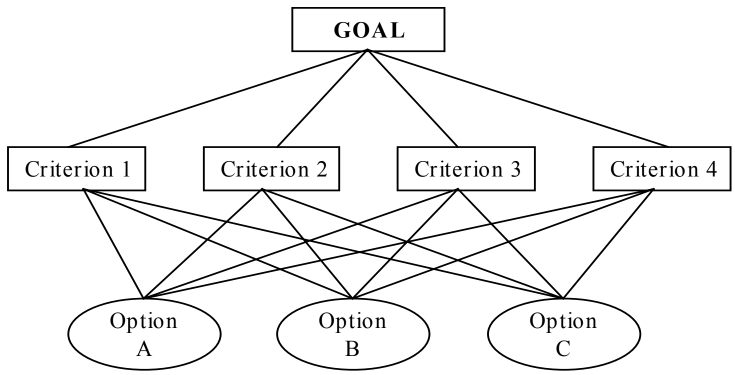
Teng and Tzeng (1996) used a multiple objective integer programming to assist transportation investment decision-making. Four objectives were expected to achieve: the increase of local government revenue, the provision of service, the promotion of industry development and the decrement of travelling time.

The USA

Frohwein and Lambert (1999) proposed a MCA model to aid the selection of road improvement projects for Virginia Department of Transportation, USA. Three factors - crash-risk reduction, performance improvement, and project cost were used as the criteria to aid the selection of competing projects. The author augured that decision could only be made by human, therefore, the approach did not assign any 'score' or 'priorities' to the projects. It used very simple chart to demonstrate information. In the project comparison chart, potential road improvement projects are depicted by circles whose areas were proportional to the anticipated total costs in dollars. The horizontal and vertical positions of the circles in the chart were determined by the anticipated total travel time saved per peak hour in vehicle minutes and total number of crashes avoided per year. The chart can help decision makers to understand the trade-offs with the respect to risk, performance and cost. Generally, this approach cannot be classified into any category of MCA approach. We may be able to say that it is a new method to demonstrate information.

When land use, infrastructure, and social variables are taken into consideration for large scale transportation infrastructure planning, the extremely large number of alternative becomes unmanageable. Taber (1999) uses a multiobjective genetic algorithm model to tackle this problem in State of Utah. The model considers three primary objective functions: minimizing travel time, minimizing per capita cost (as related to property taxes), and minimizing land use change. A large number of constraints are also used. A Pareto fitness function is used to develop a small set of optimal solutions. More than 1.9 million alternative designs were evaluated, and 195 optimal Pareto plans were found. The Pareto set of optimal solutions indicated that solutions clustering higher-density development along existing arterials were most likely to meet the objectives.

Figure 4. Analytic Hierarchy Process structure



(Hagquist 1994**)**

Using the Analytic Hierarchy Process (AHP), a ranking procedure for selecting highway improvement projects was developed (Hagquist 1994). The approach used a performance function which was a weighted sum of nine condition factors, to determine the priority. Subjective preferences from local practitioners formed the basis of the weights of these factors. It was noted that the AHP method did not produce the numerical biases seen in the traditional single-step method, therefore, better confidence could be achieved in determining the weights. The Author also suggested that this approach could be applied to more complex situations, such as assessing competing multimodal projects. The structure of the AHP is given in Figure 4.

United Kingdom

United Kingdom (DETR 1998) developed a MCA based approach – the New Approach to Appraisal (NATA). The core of the approach is an Appraisal Summary Table, which introduces the excluded elements from BCA in a formal manner, but retains BCA as a key element. The approach has five main criteria each of which has a number of sub-criteria (Table 6). Each criterion has, where possible, both qualitative and quantitative elements. Qualitative measures are evaluated on a seven points scale. No weighting is implied between the criteria. The Appraisal Summary Table aims to provide a single sheet summary to policy and decision-makers which characterises the project.

3.2.2 National practices

Victoria

Analytic Hierarchy Process (AHP) is used to assess multicriteria environmental sensitivity of Victoria urban road networks (Klungboonkrong& Taylor 1998). The integrated system is consist of Multiple Attributes Decision-Making, environmental impact models, Knowledge Based Expert System (KBES) and GIS. KBES contains the knowledge derived from human experts. AHP is used to transfer and aggregate the knowledge. The system was applied to environmental impact evaluation of Geelong Road. Three criteria were used in the study: Difficulty of access, Noise sensitivity and Pedestrian safety.

Table 6 Criteria used in the New Approach to Appraisal, UK

Main Criteria	Sub-Criteria
Environmental Impact	Noise
	Local air quality
	Landscape
	Biodiversity
	Heritage
	Water
Safety	
Economy	Journey times and vehicle
	Operating costs
	Journey times reliability
	Scheme costs
	Regeneration
Accessibility	Access to public transport
	Community severance
	Pedestrians and other
Integration	

(DETR 1998)

Western Australia

In Western Australia, De Silva and Tatam (1996) proposed a methodology for identifying road investment proposals in a multiple objective decision environment. The methodology demonstrated the ability to assess cost-effectiveness and equity of proposed projects. A number of outcome criteria, which cover a wide range of social, environmental, economic issues, were identified in the study. The study determined criteria weights within a set of objectives required the respondents to rank the criteria to reflect the preferences rather than assign weight to them. The impact of a road project was assessed as highly detrimental, detrimental, neutral, beneficial or highly beneficial. The externalities were translated into corresponding criteria scores. The criteria and their respected weights are given in Table 7. The proposed road projects were ranked based on their scores. The author claimed that better social equity and investment efficiency could be achieved through the process. The author also suggested that a further refining of the list of project assessment criteria and the communities' perception of their relative importance was needed.

Table 7 Calculation of weighted criteria scores

Criteria	Weight	Score	Weighted score
Benefit-Cost Ratio	5.52	4.6	2.5
State & National Economy	5.36	8	4.3
Local Business Community	4.53	4	1.8
Contribution to Regional Product	4.23	2	0.8
Road Freight Transport	3.84	10	3.8
Mining and Resource Development Access	3.27	5	1.6
Tourism	3.25	7	2.3

(De Silva&Tatam 1996)

Efforts (Taplin *et al* 1996) were given to study policy-sensitive selection and phasing of road investments in Western Australia through a Goal Programming (GP). Five economic benefits and twelve environmental, developmental and accessibility objectives constituted the goals in a rural road project. The non-economic objectives were converted into money value based on the project cost. The criteria are given in Table 8. 35 projects were prioritised over 10 years time-span. Although the procedure was arbitrary and merely a starting basis, the authors observed that the project priority was sensitive to the importance weights attached to individual criterion. For example, comparing with the results of a traditional Benefit-Cost evaluation, high priority on access introduced nine new projects.

Table 8 Criteria for the road program

Criteria group	Criterion
User and supplier	Savings in travel time
	Savings in vehicle operation costs
	Value of reduced accidents
	Reduced road maintenance costs
	Other operational benefits
Access	All weather access
	Community access
Development	Benefits to state and national economics
	Tourism benefits
	Mining and resource development benefits
Environment	Decreased air pollution and dust
	Surface water impacts
	Flora and fauna impacts
	Cultural site and national parks impacts
Other	Bridge adequacy
	Other safety benefits

(Taplin *et al* 1996)

Figure 5 Western Australian multiciteria assessment table

PROJECT TITLE:	Enter Title Here	PROJECT NO:	02/xxx
PROBLEM/OBJECTIVE	What is the project/program intended to achieve?		
KEY DRIVERS			
Other options considered	List other options that have been or could be tested (independently or in conjunction with this one) and why they are regarded as less satisfactory than this one		
Status/Outstanding Issues	How ready for implementation? What issues still to be addressed?		
Policies/Strategies supported: Transport	Title(s) and specific reference(s) (eg Metropolitan Transport Strategy – Walking; Perth walking – Promote safe and secure walking environments)		
Policies/Strategies supported: Other	Title(s) and specific reference(s) (eg Sustainability Strategy – reducing car dependence)		

Part 1: Strategic Assessment

STRATEGIC DIRECTION	OBJECTIVE/OUTCOME	QUALITATIVE IMPACTS	QUANTITATIVE IMPACTS	ASSESSMENT
Integration	Impacts on whole-of-government performance measures			
	Intermodalism			
Safety	Fatalities			
	Injuries			
	Personal security			
Accessibility	Pedestrians and cyclists			
	People with disabilities			
	Access to public transport			
	Affordability			
Sustainability	Greenhouse			
	Air Quality			
	Energy			
	Congestion			
	Regional Development			

(Ker 2002)

A multiciteria assessment table (Figure 5), which is similar as UK current practices, is under development in the Department of Main Roads, Western Australian (Ker 2002).

Queensland

In Department of Main Roads, Queensland, a Goal Achievement Matrix (GAM) was applied to long term planning of state road network (Pelevin *et al* 2001). The approach identified key issues through extensive stakeholder consultation. The GAM indices and the respective weightings were established. A simple linear program was incorporated in the evaluation process to identify trade-offs between competing objectives thus allowed social, environmental, economic outcomes to appropriately influence decision-making. Using GAM, a map of the Queensland road network identifying roads which have priority, was developed at the strategic level.

Tasmania

Department of Infrastructure, Energy and Resources, Tasmania (1998) also developed a Goal Achievement Matrix approach for road project evaluation. The detail of the criteria and assigned weights are given in Table 9.

Table 9 Tasmania Goal Achievement Matrix

Objective	Wo	Criteria	Wc	W
To minimise the variation in travel time along the route.	0.25	Traffic bunching	0.5	0.13
Objective Total			1	
To improve the level of safety using state wide accident measures	0.25	Treatment reduces accident numbers	1	0.25
Objective Total			1	
To preserve significant environmental features along the route	0.2	Botanical Issues	0.35	0.07
Objective Total			1	
To maximise the opportunities for economic development between Conara and St Marys	0.15	Accessibility for Tourists	0.5	0.08
Objective Total			1	
To preserve the value of the route for inter-regional traffic.	0.15	Access Control in Rural Sectors	0.6	0.09
		Traffic Management in Towns	0.4	0.06
Objective Total			1	
Total	**1**			**1**

(Transport Tasmania 1998)

3.3 DISCUSSIONS

MCA techniques are flexible ways in optimising decision under complex environment. They are able to consider quantitative as well as qualitative factors in the decision-making process. Theoretically, the decision problem can be better formulated with respect to reality. The approach is especially useful in highlighting aspects of a project that are of particular community or other interest. However, as each MCA technique has different properties suited for different type of problems, there is no simple answer to which method to use for a particular problem. Furthermore, the use of arbitrary weights in MCA and lack of a standard methodology increases the scope for misuse and deliberate. International practices show that MCA can be complementary rather than competitive analytical tools of BCA. Issues arise from applying MCA in road sector as followings:

Lack of Common Framework
Various MCA techniques (Tsamboulas & Mikroudis 2000, BTE 1999) were adopted by road agencies around the world. There is not a generally accepted framework in the choice of modelling methods and impacts. The result is that different MCA analysts are unlikely to reach consistent conclusions about a policy measure.

Determination of Weights and Scores
MCA generally use weights and scores (Transport Tasmania 1998, De Silva & Tatam 1996, and Avineri *et al* 2000) to reflect decision makers' preferences. Despite the very considerable mathematical and statistical efforts that have been given to weighting and scoring systems, the underlying analytical framework remains highly arbitrary and subjective.

It is essential that the process of assessing weights and scores should be as transparent as possible. Obtaining weights by consulting local communities (Pelevin *et al* 2001) is a common practice, but is likely to result in bias towards local interests. Although interactive approach was developed to avoid the above situation, computation burden may result in lose of interests of decision-makers during the solution process of a large-scale problem, say a large state road network.

Double Counting
The lack of a framework for choosing impacts in MCA could lead to double counting. In practice, double counting is introduced by overlapped goals. For example, West Australian practice (Taplin *et al* 1996) nominates 'Benefits to state and national economics', 'Tourism benefits', and 'Mining and resource development benefits' as criteria, double counting is obviously involved.

Optimisation
It is noted that some MCA techniques, such as Genetic Algorithms (Fwa *et al* 2000), are not function optimiser. Their purpose is to seek 'good' solutions to the problem, rather than a guaranteed optimal solution.

Time Effect
Benefit-Cost Analysis relies on the concept of net present value to permit comparisons of costs and benefits that accrue at different points in time. The treatment of time in MCA seems to have been given scant attention in the literature.

Distorted Valuations
Distorted valuations can occur where variables measured in physical units (EUNET 1998), such as level of noise or quantity of pollutant, are converted to cardinal or ordinal scales. For example, decibels of noise converts to a scale of -4 to +4 with a linear transformation, the difference between 3 and 4 represents a far greater increase in discomfort to people than the increase from 0 to 1. Similarly, the health costs of pollution, beyond a certain threshold, are likely to rise proportionately more than with the increment of quantity of the pollutant.

Risk and Uncertainty
Comparing with practices in other sector, it is noted that there are limited practices in incorporating risk and uncertainty analysis in MCA in road sector.

Generally, the application of MCA in road sector is promising, however, the applications are in preliminary stage. Some MCA techniques, such as Goal Achievement Matrix, Analytic Hierarchy Process, Goal Programming, and Multiple Objective Genetic Algorithm are found in practices. Although efforts have been given to apply these techniques, a matured Multiple Criteria Decision-Making Framework is not available.

4 FINDINGS

4.1 Requirements on Decision Support Tools in Road Asset Management

Decision support tools are needed at each management level to support decision-making. These tools inform politicians, executive officers, engineers and stakeholders of how alternative choices will affect the attainment of goals and objectives. Moreover, in some cases, it needs to give the decision-maker an indication of a project's attractiveness to the private sector. The tools are expected to provides information for decision-makers by:

- Integrating decisions at various management levels
- Presenting past and current road asset conditions and traffic conditions
- Measuring the real-life performance of road assets
- Predicting future trends of travel demands and road asset condition
- Predicting future economic, social and environmental externalities of possible investment alternatives
- Evaluating the impacts and trade-offing alternative policies, programs, and projects
- Providing monetary and non-monetary measures of investment effectiveness
- Assessing investment uncertainties and risks

An idealised decision support tool for decision-making of Road Asset Management consists of:

- Road asset deterioration models
- Road work effect models
- Road user cost models
- Social externalities models
- Environmental externalities models
- Evaluation algorithms
- Optimisation algorithms

4.2 Benefit Cost Analysis vs. Multiple Criteria Analysis

- BCA approach is a useful tool for investment decision-making from a financial perspective. While the decision involves conflicting goals, the MCA approach is more powerful. Due to the complex natural of decision-making in Road Asset Management, there is not a single method that can satisfy all decision-making problems. The choice of evaluation technique depends on the feature of the problem at hand, on the aims of the analysis, and on the underlying information base.

- The conventional BCA approach and MCA approach should be regarded as complementary rather than competitive analytical tools. In early stages of project development, MCA may be particularly helpful. However, the BCA approach is used most widely for project prioritisation and selecting preferred project from amongst a given set of alternatives.

4.3 Issues in Use of Benefit Cost Analysis

- Most current decision-making support tools are based on a conventional Benefit Cost Analysis approach. The extension of a traditional BCA, which includes social and environmental externalities, is able to support Triple Bottom Line decision-making in road sector.

- There is a need to reach a degree of commonality on considering social and environmental externalities by aggregating the best practices.

- A number of methods for determining value of social and environmental externalities, such as market price, resource costs and Willingness to pay, are found in the review. Cautions should be given to the selection of appropriate method for specific externalities. The use of unreasonable monetisation methods in some cases has discredited Benefit Cost Analysis in the eyes of decision makers and the public.

- When only direct externalities are considered, double counting can be easily erased. However, incorporation of social and environmental externalities results in difficulties in dealing with the issue.

- Due to lack of information or undeveloped techniques, models for some key social and environmental externalities are not available. It is noted that employment and regional economic impacts are generally omitted in BCA.

- Equity is an important consideration in road infrastructure investment decision-making. The considerations are either between regions, or social groups (income, age, gender, disable, etc.) In current practice, there is not a well-developed quantitative or qualitative measure for this externality.

- The detail of consideration of social and environmental externalities should be different at different decision-making levels. It is intended to develop a wholistic framework to coordinate the practices.

- Some social and environmental externalities cannot be readily and credibly quantified or monetised. Such as service quality and reliability, landscape, etc. These externalities should be incorporated in a MCA.

4.4 Issues in Use of Multiple Criteria Analysis

- There is not a generally accepted framework in the choice of modelling methods and externalities. The result is that different MCA analysts are unlikely to reach consistent conclusions about a policy measure.

- In current practices, some favour using methods, which are able to prioritise alternatives, such as Goal Programming, Goal Achievement Matrix, and Analytic Hierarchy Process. Others just present various impacts to decision-makers to characterise the projects.

- The processes of assessing weights and scores are highly arbitrary and subjective. It is essential that the process should be as transparent as possible. Obtaining weights and scores by consulting local communities is a common practice. However, the lack of focus groups with representatives of diverse interests is likely to result in bias towards local interests.

- Interactive approach has the advantage in helping decision-makers elaborating their preferences. However, computation burden may result in loss of interests of decision-makers during the solution process of a large-scale problem, say a large state road network.

- The lack of a framework for choosing externalities in MCA could lead to double counting. In practice, double counting is generally introduced by overlapped goals.

- It is noted that the treatment of the timing of costs and benefits in MCA seems to have been given scant attention in current practices.

- Distorted valuations can occur where variables measured in physical units, are converted to cardinal or ordinal scales. For example, decibels of noise converts to a scale of -4 to +4 with a linear transformation, the difference between 3 and 4 represents a far greater increase in discomfort to people than the increase from 0 to 1. It is suggested that different weights be assigned to individual scores.

- Comparing with practices in other sector, it is noted that there are limited practices in incorporating risk and uncertainty analysis in MCA in road sector.

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APPENDIX I

PAVEMENT DETERIORATION MODELS

Pavement deterioration model is the algorithm used to define and predict pavement deterioration, which is usually expressed in terms of a pavement condition parameter and undertaken either at the network or project level (Foley 1999). It is generally accepted that the current pavement deterioration models can be divided into two categories (Haas *et al* 1994 and Martin 1996):

- *Deterministic approaches*
- Probabilistic approaches

In addition, with the development of artificial intelligence theories, there are growing interests in adopting Artificial Neural Networks (ANNs) (Huang & Moore 1997) to predict pavement deterioration.

I.1 Deterministic Approaches

Deterministic approaches, which are based on the statistical relationships, where various parameters such as traffic, age etc., are identified up front as attributors to the deterioration of pavement, predict a single value of the response variable. Over several decades, considerable studies have been undertaken in developing deterministic models. The models are widely used by highway agencies throughout the world. Present deterministic models can be further categorised into purely mechanistic, mechanistic-empirical, and empirical models.

I.1.1 Purely mechanistic models

These models are based on a theoretical analysis of primary responses of pavement under load applications. It also takes the mechanical properties of the materials and different environmental conditions into account. The primary response parameters used in the models are stress, strain, and deflection, which can be calculated by a layered-elastic or finite element analysis (Collop & Cebon 1995).

The models are widely used in mechanistic design of pavement (Wardle 1999). However, the method is lacking in prediction of roughness and surface distresses, which are important from maintenance and rehabilitation perspectives. There are several factors limiting the use of mechanistic models in pavement roughness and surface distresses prediction:

- The interactions between distress types
- The effects of different maintenance intervention strategies
- Different contributions on roughness progression from various surface distresses
- The aggregated effects of environmental conditions

I.1.2 Mechanistic-Empirical models

In mechanistic-empirical models, the response parameter can be roughness, rutting, cracking, and other individual distress. Due to influence from numerous and complex traffic and environmental factors, long-term performance of natural and treated materials in a road pavement is highly variable. Therefore, the relationships structured on theoretical consideration have to be calibrated by field observation. HDM-III and HDM-4 models fall into this category.

This approach is not only useful in identifying the effects of traffic loading and of environmental factors on pavement performance, but in quantifying developing rate of individual distress, the interaction of distress modes, the effects of different intervention timings and maintenance treatments (Paterson 1987). Al-Suleiman *et al* (1993) examined environmental effect on deterioration of pavements. The study found that most of the deterioration in lightly trafficked road was caused by environmental factors. This finding is compatible with Paterson's (1987) observations.

HDM-III and HDM-4 models require detailed data on pavement surface condition, such as cracking, potholing, ravelling, rutting. Collection of the information is difficult and costing. The ARRB model (Martin 1994) was developed to improve the situation by using roughness as only proxy for pavement condition proxy. The ARRB models focus on Australian national highways and rural arterial roads. There are four components that contribute to roughness progression, namely initial roughness, non-load related roughness changes, load-related roughness changes, and improvement due to rehabilitation activity.

The mechanistic-empirical approach uses statistical correlations to establish the relationship between distress and various pavement type, traffic and environmental factors. The results may represent only a 'fingerprint' of the local situation and not necessarily identify the true underlying relationship between variables (Paterson 1987). Another major concern is multicolinearity (Martin 1996). This problem is resulted from the correlationships between some of 'independent' variables used in formulating the models. For example, a high degree of collinearity typically exists pavement strength and traffic loading on in-service pavements.

I.1.3 Empirical models

The models are statistical relationships between observed pavement performance parameters, such as Present Serviceability Index (PSI) and Riding Comfort Index (RCI), and pavement thickness, material properties, traffic loading, and age. The approach was used in the early stage of pavement deterioration study.

Despite empirical models and mechanistic-empirical models often have similar mathematical forms, there is distinct difference underneath. The latter is calibrated from the understood or assumed engineering relationships between independent and dependent variables. On the contrary, the former is solely based on regression analysis.

I. 2 Probabilistic Approaches

In real situation, the inherent non-homogeneity of construction materials and some environmental factors, which are difficult to be quantified, contribute to stochastic variance of pavement deterioration. These uncertainties of pavement deterioration behaviour lead to the development of probabilistic models, which predict the distribution of the response variables. Probabilistic models can be classified as survivor curves, Markov, and Semi-Markov approaches.

I.2.1 Survivor Curves

Survivor curves are empirical accumulative probability functions that used to predict the percentage of pavement length of a specific age (or number of traffic application) that will need rehabilitation in the future. Survivor curve of pavements under a given condition can be developed by historical records (Vepa *et al* 1996).

I.2.2 Markov approach

Markov process assumes that conditional probability of any future event, any past event, and present state, is independent of past event and depends on only present state of the processes (Wang *et al* 1994). In Markov process of, future pavement condition is dependent only on current pavement condition. Under a certain maintenance treatment, the probability of a segment changing from one state to another after specific time units can be calculated by multiplying matrices of one-step transition probabilities.

The approaches are ideal for pavement prediction at a network-level and where little observational data is available (Smith *et al* 1996 and Tam & Bushby 1995). However, due to its questionable assumption, the model is not capable to consider effects of changeable traffic and environmental factors. Although semi-Markov method (Li *et al* 1996) was attempted to overcome this deficiency, it was only applicable to a few pavement categories under local conditions due to problems in building Transition Probability Matrix.

One literature is available for studying the relationship between deterministic and probabilistic prediction models (Li *et al* 1997). The study focused on the principle of system conversion from a deterministic model to a probabilistic one. The study showed that the formulation of the system conversion gave good results, compared with those obtained by the traditional Markov process.

APPENDIX II

MODELS FOR SOCAIL AND ENVIRONMENTAL EXTERNALITIES

II.1 Accident Model

II.1.1 Australia

Austroads (2001) published two improved accident models for rural and urban roads under Australian condition. In the models, the traffic and road attributes affecting crash costs have been regarded as primarily acting through either crash rates or crash severities. This model has the form:

$$A_R = K_1 \ldots K_i \ldots K_n \, A_{BR}$$

Where:

A_R = predicted crashes
K_i = a factor representing the effect of attribute i; and
A_{BR} = a base crash rate corresponding to a defined set of base case attributes.

Inputs for the rural model include data on road inventory (road type, surface type, width, horizontal alignment, and overtaking lanes), traffic mix (proportion of cars, rigid trucks, and articulated trucks), crash costs, and crash mix (e.g. fatal, injury, and property damage). The rural model includes adjustments for the effects of traffic mix on crash severity, horizontal alignment, overtaking lanes, and remote roads.

For the urban model, Inputs include road type, intersection type, frontage access control, and crash mix. Adjustments are available for the effects of traffic mix on crash severity and frontage access control on divided arterial roads.

The main outputs of the models developed are rates of casualty crashes.

II.1.2 The USA

The US Federal Highway Administration (FHWA 2000) used separated procedures to estimate the number of crashes and crash rates for three types of rural roads and three types of urban roads. The road categories distinguished were freeways, multi-lane roads and two lane roads.

The procedure for rural two-lane roads has most comprehensive form, which estimates crashes within 250 feet of an intersection and crashes on segments between intersections. For non-intersection crashes, the explanatory variables of the exponential equation included Section Length, Lane Width, Shoulder Width, Road Hazard Rating, Driveway Density, Degree of Curvature, Length of Curves, Grade, and Length of Grades. For Intersection crashes, three models were adopted for intersections with traffic signals, intersections with stop signs, and all other intersections. The explanatory variables included Number of Signalised Intersections, AADT and fraction of AADDT on the inventoried section, number of driveway within 250 feet of a given intersection, degree of curvature, speed limit, roadside hazard rating, and probability that a three-legged intersection has a right-turn lane.

The procedures for rural multilane roads, rural freeways, urban freeways, urban multilane roads, and urban two-lane roads did not distinguish crashes in segments and in intersection. AADT and Lane Width were two key explanatory variables for the equations.

The number of fatalities and nonfatal injuries was estimated as directly proportional to the number of crashes, with sperate ratios used for each functional class.

II.1.2 United Kingdom

In the latest United Kingdom Cost Benefit Analysis Manual (DETR 2003a), road link accidents could be predicted separately from or combined with junction accidents. The accidents were classified into fatal, serious and slight accidents.

The models for road link accidents and link and junction combined accidents were distinguished using 15 road types. The models used power function to reflect the declining trend in accident rates, which was observed by TRL Report 382.

Based on junction characteristics, 95 models were developed for predicting junction accidents. As with links, accident rates and their severity at junctions were also declining over time.

II.1.3 Denmark

Separate models for various accident modes at road links and junctions were developed for urban roads in Denmark (Greibe P 2003). The models were structured in exponential forms. Explanatory variables are AADT, land use, number of minor junctions, parking, speed limit, road width, number of exits, and number of lane. The most powerful variable for the models was vehicle traffic flow AADT, particularly for junctions. For road links, additional explanatory variable were needed.

II.1.4 Egypt

Time series data collected over 10 years period, was utilised in developing road accident models for Egyptian rural roads (Abbas K A 2003). Accidents were expressed in four categories - accidents, fatalities, injuries, and causalities. AADT was used as only explanatory variable. The Author used several functional forms, such as linear, exponential, power, logarithmic and polynomial, in exploring the dataset. It was noted that power function fitted the data best.

II.2 Emission Models

II.2.1 The USA

The USA Benefit Cost Analysis took air pollution into consideration. Six pollutants, Carbon Monoxide, Volatile Organic Compounds, Nitrogen Oxides, Sulphur Oxides, Particulate Matter, and Road Dust, were calculated in Highway Economic Requirements System (HERS) (FHWA 2000). The estimated costs of human health and property damage per ton of each pollutant were derived by national wide average damage costs per ton of each pollutant. The models provided the option of using either midpoint or the upper limit of the range for cost per ton of each pollutant.

Five consolidated groups of road types were used to estimate the air pollution. The groups were Rural Interstate, Rural Arterial, Rural Collector, Urban Interstate, and Urban Other. For each group, the typical mix of vehicle classes was used as an input to models to predict average emission per vehicle-mile of travel for each of six air pollutants.

In the models, Carbon Monoxide, Volatile Organic Compounds and Nitrogen Oxides varied in response to changes in the average effective speed of travel. Therefore, the three pollutants on one group of road types were calculated as the functions of the average effective speed of travel. The other three pollutants, Sulphur Oxides, Particulate Matter, and Road Dust, did not vary significantly with travel speed.

The likely effects of including air pollution costs were discussed in HERS. In most cases, the proposed improvements to a sample section tended to increase air pollution costs by raising the level of travel on the section. Thus including air pollution reduced the net benefits from typical improvements.

II.2.2 United Kingdom

Air pollution effects were considered in the Multiple Criteria project appraisal approach – *A New Approach to Appraisal* (NATA) (DETR 1998a, 1998b, & 2003b). The quantitative elements are global carbon emission and local air quality. The former was expressed in terms of ton of Carbon Dioxide and the latter was expressed relative to the number of properties experiencing better or worse air quality in terms of Nitrogen Oxides and Particulate Matter. The quantities of the pollutants could be calculated by the procedures developed in *Environmental Assessment* (DETR 2003b). The procedures include models for Carbon Monoxide, Volatile Organic Compounds, Nitrogen Oxides, Hydrocarbons, Particulate Matter, and Carbon Dioxide.

Generally, the procedures were structured with two sub-models: vehicle emission models and atmospheric dispersion models. The former was expressed as a function of speed for a number of broader vehicle categories. The latter was originally developed to forecast only carbon monoxide concentrations. It has been assumed that the dispersal of other pollutants will be equivalent to that of carbon monoxide, so that their concentrations will be in the same proportions as their rates of emission.

Once the quantities and dispersion of the pollutants were determined. The number of properties affected by the proposed scheme could be counted, and split into several distance bands. The results were accompanied by a qualitative comment indicating whether the proposal causes a significant increase in concentrations.

III.3 Noise Model

III.3.1 The USA

Menge *et al* (1998) developed the Traffic Noise Model (TMN), to assist modelling highway noise and design of effective, cost-efficient highway noise barriers. In 2002, an updated version TNM 2 has been released. The model contained five standard vehicle types, including automobiles, medium trucks, heavy trucks, buses, and motorcycles, as well as user-defined vehicles. Both constant-flow and interrupted-flow traffic were modeled. Several different pavement types were appeared in the model. Sound level computations were based on a one-third octave-band data base and algorithms. Multiple diffraction analysis, parallel barrier analysis and contour analysis which includes sound level contours, barrier insertion loss contours, and sound-level difference contours, can be conducted by the model.

The model is currently adopted by the Federal Highway Administration (FHWA) as a means for aiding compliance with policies and procedures under FHWA regulations.

III.3.2 Unite Kingdom

Noise impact from proposed road project was considered in United Kingdom road project appraisal approach (DETR 1998a & 1998b). The impact was expressed in terms number of properties with increases or decreases in noise. The noise model used was appeared in the Design Manual for Roads and Bridges (DETR 1994).

The model predicted noise levels at a distance from a highway, taking into account factors such as traffic flow, speed and composition, road configuration, intervening ground cover between source and listener, screening (barriers, buildings and land form), angle of view of the traffic and reflections from facades.

The noise impact assessment would then be conducted for properties where existing traffic is likely to be increased by at least 25% or reduced by at least 20%. The assessment should show predicted noise changes and noise nuisance changes. The assessment noise levels classified locations according to their ambient levels, in bands of below 50 dB(A), 50-<60 dB(A), 60-<70 dB(A) and > 70 dB(A). For each ambient noise band, the number of properties subject to the following increases or decreases were included: <3 dB(A), 3-<5 dB(A), 5-<10 dB(A), 10-15 dB(A) and over 15 dB(A).

III.3.3 Thailand

Pamanikabud and Vivitjinda developed a model of highway traffic noise based on vehicle types for Thailand. The Calibrating data were collected from highway with free-flow traffic conditions. In the model, there were six vehicle types – automobile, light truck, medium truck, heavy truck, semi-trailer and full-trailer, and bus and motorcycle. The noise volume of each vehicle type was the function of the average travel speed, distance, angle, pavement condition, and barrier adjustments.

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