TITLE: **The Highway Development and Management Tool - HDM-4**

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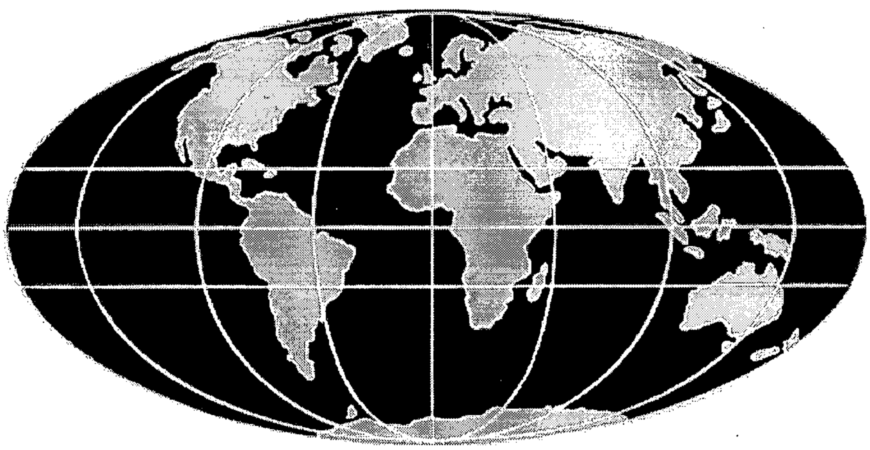

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THE HIGHWAY DEVELOPMENT AND MANAGEMENT TOOL – HDM-4

by

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1. INTRODUCTION

Over the past thirty years economic road investment and maintenance models have been developed to assist countries with road investment planning. The main models used have been TRL's Road Transport Investment Model (RTIM) and the World Bank's Highway Design and Maintenance Standards Model (HDM). HDM-III (Watanatada, ,et al, 1987 and Paterson, 1987) has been used for over two decades to combine technical and economic appraisals of road projects, to prepare road investment programmes and to analyse strategies and standards.

The International Study of Highway Development and Management (ISOHDM) is an internationally funded and executed project managed by the ISOHDM Project Secretariat within the World Road Association (PIARC) based in Paris. The study has been carried out to extend the scope of the HDM-III model and to provide a harmonised systems approach to road management, with adaptable and user-friendly software tools. This has resulted in the development of the Highway Development and Management Tools, a new suite of engineering/economic analysis software known as HDM-4, and the associated knowledge and models which make up what is termed HDM Technology.

The scope of HDM-4 has been broadened considerably beyond traditional project appraisals, to provide a powerful system for the analysis of road management and investment alternatives. Emphasis was placed on collating and applying existing knowledge, rather than undertaking extensive new empirical studies, although some limited data collection was undertaken. Wherever possible, creative new approaches were developed for applying up-to-date knowledge to the technical problems and management needs of different countries.

2. BACKGROUND

2.1 Past Developments

The first move towards producing a road project appraisal model was made in 1968 by the World Bank. The first conceptual model was produced in response to terms of reference for a 'highway design study' produced by the World Bank in conjunction with the Transport and Road Research Laboratory (TRRL) and the Laboratoire Centrale des Ponts et Chaussées (LCPC). Thereafter, the World Bank commissioned the Massachusetts Institute of Technology (MIT) to carry out a literature survey and to construct a model based on information available. The resulting Highway Cost Model (HCM) produced by MIT (Moavenzadeh, 1971) was a considerable advance over other models used for examining the interactions between road construction costs, maintenance costs and vehicle operating costs. However, the HCM model highlighted areas where more research was needed to provide a model that was more appropriate to developing country environments with additional relationships specific to that environment.

Following this, TRRL, in collaboration with the World Bank, undertook a major field study in Kenya to investigate the deterioration of paved and unpaved roads as well as the factors affecting vehicle-operating costs in a developing country. The results of this study were used by TRRL to produce the first prototype version of the Road Transport Investment Model (RTIM) for developing countries (Abaynayaka, et al, 1977). In 1976, the World Bank funded further developments of the HCM at MIT which produced an extended version of the model that was capable of carrying out economic analysis directly, and performing automatic sensitivity analysis of key variables such as discount rate and traffic growth. The work resulted in the first version of the Highway Design and Maintenance Standards model (HDM) (Harral, et al, 1979).

Further work was undertaken in a number of countries to extend the geographic scope of the RTIM and HDM models:

- **The Caribbean Study** (by TRRL). Investigated the effects of road geometry on vehicle operating costs (Morosiuk and Abaynayaka, 1982; Hide, 1982).
- **India Study** (by the Central Road Research Institute - CRRI). Studied particular operational problems of Indian roads in terms of narrow pavements and large proportions of non-motorised transport (CRRI, 1982).
- **Brazil Study** (funded by UNDP). Extended the validity of all of the model relationships (Geipot, 1982).

Parallel model development continued with TRRL developing RTIM2 (Parsley and Robinson, 1982), whilst the World Bank developed a more comprehensive model incorporating the findings from all previous studies and this led to HDM-III

(Watanatada, et al, 1987). Both models were originally designed to operate on mainframe computers. As computer technology advanced, the University of Birmingham (Kerali et al, 1985) produced a microcomputer version of RTIM2 for TRRL. Later, a micro version of HDM-III was produced by the World Bank (Archondo-Callao and Purohit, 1989). Further developments of both models continued with the TRRL producing RTIM3 in 1993 to provide a user-friendly version of the software running as a spreadsheet (Cundill and Withnall, 1995). In 1994, the World Bank produced two further versions of HDM: HDM-Q, incorporating the effects of traffic congestion into the HDM-III program (Hoban, 1987): and the HDM-III Manager, to provide a menu-driven version of HDM-III (Archondo-Callao, 1994).

2.2 HDM-4 Development Objectives

Both RTIM3 and HDM-III have been used extensively, and have been instrumental in justifying increased road maintenance and rehabilitation investment in many countries, and for optimising economic benefits to road users under different levels of expenditures. They provide road investment analysis tools which are applicable in a range of climates and conditions. However, it was recognised that there was a need for a fundamental re-development of the various models to incorporate a wider range of pavements and conditions of use, and also to reflect modern computing practice and expectations.

The relationships in RTIM3 and HDM-III were based on the results of studies carried out in the late 1970's and early 1980's. Although many of the road deterioration models were still relevant, there was a need to incorporate the results of research that has been undertaken around the world in the intervening period. In the case of the vehicle operating cost relationships, it was recognised that vehicle technology has improved dramatically over the past 10 years with the result that typical operating costs are now significantly less than those predicted by the relationships.

Most of the relationships in these models are based on the results of research conducted in developing countries. Recently many industralised countries have begun to make use of HDM-III. It was therefore seen that there was a need both to update the technical relationships and to include additional capabilities such as traffic congestion effects, cold climate effects, a wider range of pavement types and structures, and environmental effects. It is against this background that the development of HDM-4 has been undertaken. An overview of the HDM-4 system has been published by PIARC (Kerali, 2000).

3. ROLE OF HDM-4 IN HIGHWAY MANAGEMENT

In the application of HDM-4, the following functions are considered in the highway management process:

- Planning
- Programming
- Preparation
- Operations

3.1 Planning

Planning involves the analysis of the road system as a whole, typically requiring the preparation of medium to long term, or strategic, estimates of expenditure for road development and preservation under various budget and economic scenarios. Predictions may be made of road network conditions under a variety of funding levels together with forecasts of required expenditure under defined budget heads. The physical highway system is usually characterised at the planning stage by lengths of road, or percentages of the network, in various categories defined by parameters such as road class or hierarchy, traffic flow/capacity, pavement and physical condition.

The results of the planning exercise are of most interest to senior policy makers in the road sector, both political and professional. Work will often be undertaken by a planning or economics unit within a road agency.

3.2 Programming

Programming involves the preparation, under budget constraints, of multi-year road works and expenditure programmes in which those sections of the network likely to require maintenance, improvement or new construction are identified in a tactical planning exercise. The physical road network is considered at the programming stage on a link-by-link basis, with each link characterised by homogeneous pavement sections defined in terms of physical attributes.

The programming activity produces estimates of expenditure in each year, under defined budget heads, for different types of road works and for each road section. Budgets are typically constrained, and a key aspect of programming is to prioritise the road works in order to find the best use of the constrained budget. Typical applications are the preparation of a budget for an annual or a rolling multi-year work programme for a road network, or sub-network of roads. Programming activities are normally undertaken by managerial-level professionals within a road agency, usually in a planning or a maintenance department.

3.3 Preparation

This is the short-term planning stage where road schemes are packaged for implementation. At this stage, designs are refined and prepared in more detail; bills of quantities and detailed costing are made, together with work instructions and contracts. Detailed specifications and costing are likely to be drawn up, and detailed cost-benefit analysis may be carried out to confirm the feasibility of the final scheme. Works on adjacent road sections may be combined into packages of a size that is cost-effective for execution. Typical preparation activities are the detailed design of an overlay scheme; the detailed design of major works such as a junction or alignment improvement, lane addition, etc. For these activities, budgets will normally already have been approved.

Preparation activities are normally undertaken by middle to junior professional staff and technicians within a design or implementation department of a road organisation, and by contracts and procurement staff.

3.4 Operations

These activities cover the on-going operation of a road agency. Decisions about the management of operations are made typically on a daily or weekly basis, including the scheduling of work to be carried out, monitoring in terms of labour, equipment and materials, the recording of work completed, and use of this information for monitoring and control. Activities are normally focused on individual sections or sub-sections of a road, with measurements often being made at a relatively detailed level. Operations are normally managed by sub-professional staff, including works supervisors, technicians, clerks of works, and others.

As the management process moves from Planning through to Operations, changes occur as summarised in Table 1.

Table 1
Change in management process

Activity	Time horizon	Staff responsible	Spatial coverage	Data detail	Mode of computer operation
Planning	Long term (strategic)	Senior management and policy level	Network-wide	Coarse/ summary	Automatic
Programming	Medium term (tactical)	Middle-level professionals	Network or sub-network	↓	↓
Preparation	Budget year	Junior professionals	Scheme level/sections		
Operations	Immediate/ very short term	Technicians/ sub-professionals	Scheme level/ sub-sections	Fine/detailed	Interactive

3.5 Management Cycle

Traditionally, in many highway organisations, budgets and programmes for road works have been prepared on a historical basis in which each year's budget is based upon that for the year before, with an adjustment for inflation. Under such a regime, there is no way of telling whether funding levels, or the detailed allocation, are either adequate or fair. Clearly there is a requirement for an objective needs-based approach using knowledge of the content, structure and condition of the roads in the network.

The functions of planning, programming, preparation and operations provide a suitable framework within which a needs-based approach can operate. The highway management process as a whole can be considered as a cycle of activities that are undertaken within each of these management functions. This is summarised in Table 2 and provides the framework within which HDM-4 needs to be considered.

Table 2
Role of HDM-4 within the management cycle

Management function	Common descriptions	HDM-4 Application
Planning	Strategic analysis system Network planning system Pavement management system	Strategy Analysis
Programming	Programme analysis system Pavement management system Budgeting system	Programme Analysis
Preparation	Project analysis system Pavement management system Bridge management system Pavement/overlay design system Contract procurement system	Project Analysis
Operations	Project management system Maintenance management system Equipment management system Financial management/accounting system	Not addressed by HDM-4

4. HDM-4 APPLICATIONS

There are three main areas of application for HDM-4 which can be undertaken using the following analysis tools:

- **Project analysis**
- **Programme analysis**
- **Strategy analysis**

4.1 Project Analysis

Project analysis is concerned with the evaluation of one or more road projects or investment options. The application analyses a road link or section with user-selected treatments, with associated costs and benefits, projected annually over the analysis period. Economic indicators are determined for the different investment options.

Project analysis may be used to estimate the economic or engineering viability of road investment projects by considering the following issues:

- The structural performance of road pavements
- Life-cycle predictions of road deterioration, road works effects and costs
- Road user costs and benefits
- Economic comparisons of project alternatives

Typical appraisal projects would include the maintenance and rehabilitation of existing roads, widening or geometric improvement schemes, pavement upgrading and new construction. This HDM-4 application is fundamentally the same as in HDM-III, but improved road deterioration relationships have been extended to cover a wider range of pavements and the performance of materials in temperate and cold climates. Road user cost relationships include impacts on road safety.

It is in the area of programme and strategy analysis that HDM-4 offers significant improvements over HDM-III.

4.2 Programme Analysis

Programme analysis deals primarily with the prioritisation of a defined list of candidate road projects into a one-year or multi-year work programme under defined budget constraints. In this application of HDM-4, normally a long list of candidate road projects is selected as discrete segments of a road network. When the candidate roads have been identified, programme analysis is used to compare the life cycle costs predicted under the existing regimen of pavement management (i.e. 'without' project case) against the life cycle costs predicted for the alternative maintenance, road improvement or development scenario (i.e. 'with' project case). This provides the basis for estimating the economic benefits that would be derived by including each candidate project within the budget timeframe.

The programme analysis application may be used to prepare a multi-year rolling programme, subject to resource constraints. This provides an efficient and robust index for prioritisation purposes. Two examples are given in Tables 3 and 4.

Indices such as the NPV, economic rate of return (ERR), or predicted pavement condition attributes (e.g. road roughness) are not recommended as ranking criteria. The incremental NPV/cost ratio satisfies the objective of maximising economic benefits for each additional unit of expenditure (i.e. maximise net benefits for each additional $1 of the available budget invested).

Table 3
Sample output from programme analysis (format 1)

Priority Rank	Road Section	Length (km)	Province or District	Type of Road Work	Scheduled Year	Cost $m	Cumulative S$m
1	N1-2	20.5	2	Resealing	2000	5.4	5.4
2	N4-7	23.5	7	Overlay 40mm	2000	10.9	16.3
3	N2-5	12.5	5	Reconstruct	2000	8.6	24.9
4	R312-1	30	4	Widen 4 lane	2000	31.4	56.3
5	R458-3	36.2	3	Overlay 60mm	2000	16.3	72.6
:	:	:	:	:	:	:	:
1	N4-16	32.1	6	Reconstruct	2001	22.8	22.8
2	R13-23	22.4	4	Overlay 40mm	2001	9.7	32.5
3	N521-5	45.2	2	Widen 4 lane	2001	41.3	73.8
:	:	:	:	:	:	:	:
1	N1-6	30.2	4	Resealing	2002	8.2	8.2
2	N7-9	17.8	3	Overlay 60mm	2002	9.2	17.4
3	F2140-8	56.1	1	Reconstruct	2002	34.9	52.3
:	:	:	:	:	:	:	:

Table 4
Sample output from programme analysis (format 2)

				2000		2001		2002		2003	
Priority Rank	Road Section	Length (km)	Province or District	Road Work	Cost $m	Road Work	Cost $m	Road Work	Cost $m	Road Work	Cost $m
1	N1-2	20.5	2	RESEAL	5.4	R.M.	0.185	R.M.	0.185	R.M.	0.185
2	N4-7	23.5	7	OVL40MM	10.9	R.M.	0.212	R.M.	0.212	R.M.	0.212
3	N2-5	12.5	5	RECON	8.6	R.M.	0.113	R.M.	0.113	R.M.	0.113
4	R312-1	30	4	WIDEN-4	31.4	R.M.	0.180	R.M.	0.180	R.M.	0.180
5	R458-3	36.2	3	OVL60MM	16.3	R.M.	0.217	R.M.	0.217	R.M.	0.217
:	:	:	:	:	:	:	:	:	:	:	:
16	N4-16	32.1	6	R.M.	0.289	RECON	22.8	R.M.	0.289	R.M.	0.289
17	R13-23	22.4	4	R.M.	0.134	OVL40MM	9.7	R.M.	0.134	R.M.	0.134
18	N521-5	45.2	2	R.M.	0.407	WIDEN-4	41.3	R.M.	0.407	R.M.	0.407
:	:	:	:	:	:	:	:	:	:	:	:
28	N1-6	30.2	4	R.M.	0.272	R.M.	0.272	RESEAL	8.2	R.M.	0.272
29	N7-9	17.8	3	INLAY	0.240	R.M.	0.200	OVL60MM	9.2	R.M.	0.160
30	F2140-8	56.1	1	PATCH	0.202	R.M.	0.202	RECON	34.9	R.M.	0.168

Note: RM = Routine Maintenance

4.3 Strategy Analysis

The concept of strategic planning of medium to long term road network expenditures requires that a road organisation should consider the requirements of its entire road network asset. Thus, strategy analysis deals with entire networks or sub-networks managed by one road organisation. Examples of road networks include; the main (or trunk) road network, the rural (or feeder) road network, urban (or municipal) road network, etc. Examples of sub-networks include; all motorways (expressways), all paved (or unpaved) roads, different road classes, etc.

In order to predict the medium to long term requirements of an entire road network or sub-network, HDM-4 applies the concept of a road network matrix comprising categories of the road network defined according to the key attributes that most influence pavement performance and road user costs. Although it is possible to model individual road sections in the strategy analysis application, most road administrations will often be responsible for several thousand kilometres of roads, thereby making it cumbersome to individually model each road segment. The road network matrix can be defined by users to represent the most important factors affecting transport costs in the country. A typical road network matrix could be categorised according to the following:

- Traffic volume or loading
- Pavement types
- Pavement condition
- Environment or climatic zones
- Functional classification (if required)

For example, a road network matrix could be modelled using; three traffic categories (high, medium, low), two pavement types (asphalt concrete, surface treatments), and three pavement condition levels (good, fair, poor). In this case, it is assumed that the environment throughout the study area is similar and that the road administration is responsible for one road class (for example, main roads). The resulting road network matrix for this would therefore comprise (3 x 2 x 3 = 18) representative pavement sections. There is no limit to the number of representative pavement sections that can be used in a strategy analysis. The trade-off is usually between a simple representative road network matrix that would give rather coarse results compared against a detailed road network matrix with several representative sections that could potentially provide more accurate results.

Strategy analysis may be used to analyse a chosen network as a whole, to prepare medium to long range planning estimates of expenditure needs for road development and conservation under different budget scenarios. Estimates are produced of expenditure requirements for medium to long term periods of usually 5-40 years. Typical applications of strategy analysis by road administrations would include:

- Medium to long term forecasts of funding requirements for specified target road maintenance standards (see Figure 1).
- Forecasts of long term road network performance under varying levels of funding (see Figure 2).
- Optimal allocation of funds according to defined budget heads; for example routine maintenance, periodic maintenance and development (capital) budgets (see Figure 3).
- Optimal allocations of funds to sub-networks; for example by functional road class (main, feeder and urban roads, etc.) or by administrative region (see Figure 4).
- Policy studies such as impact of changes to the axle load limit, pavement maintenance standards, energy balance analysis, provision of NMT facilities, sustainable road network size, evaluation of pavement design standards, etc.

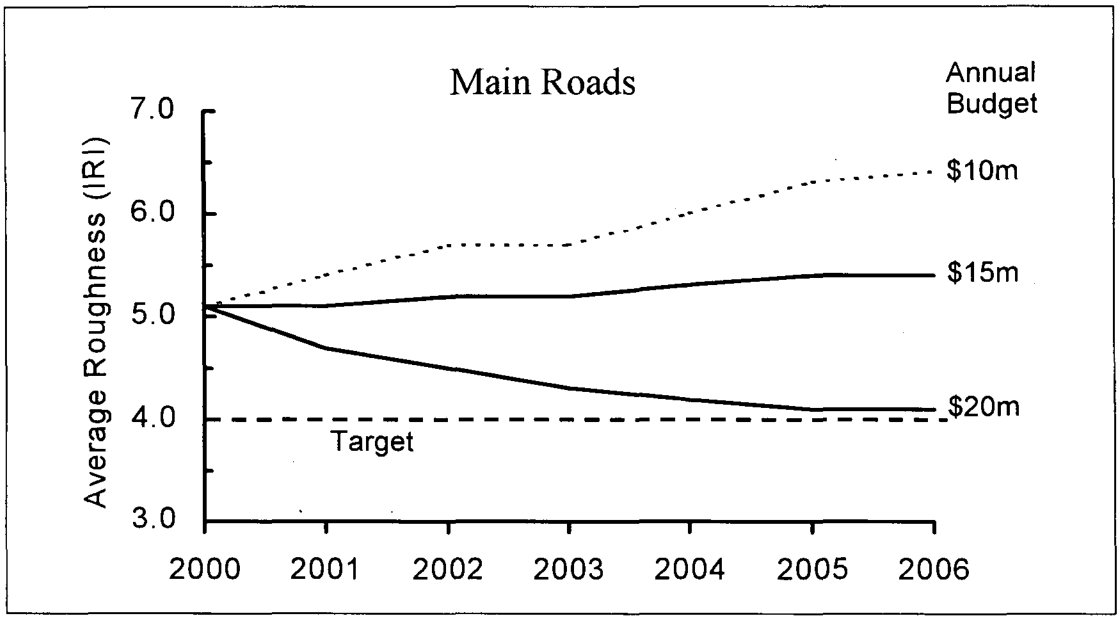

Figure 1
Effect of funding levels on road network performance

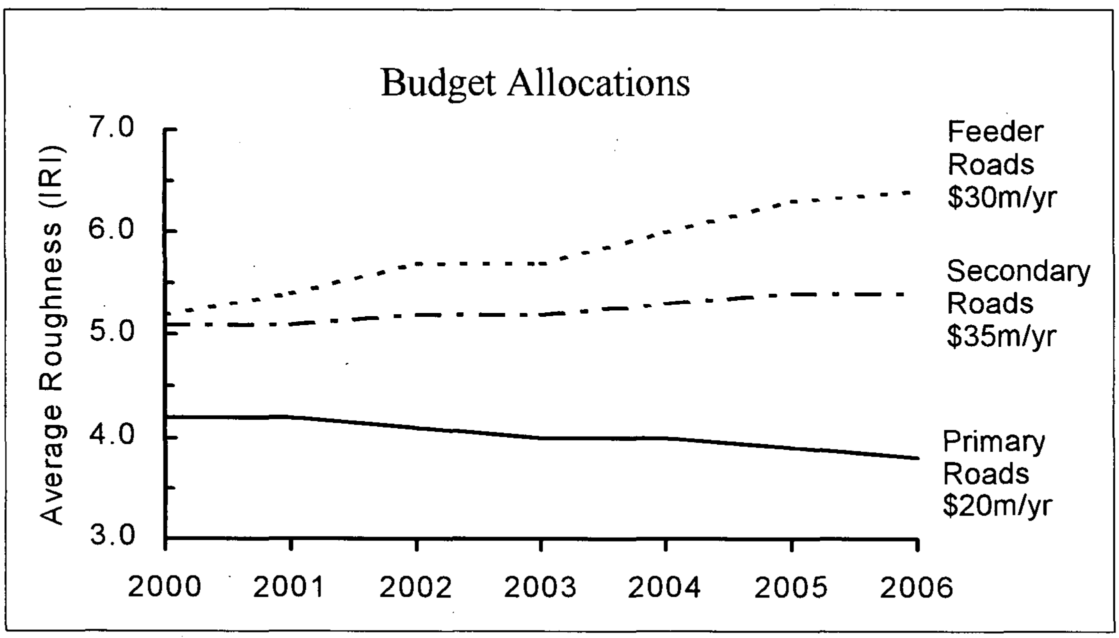

Figure 2
Effect of budget allocations on sub-network performance

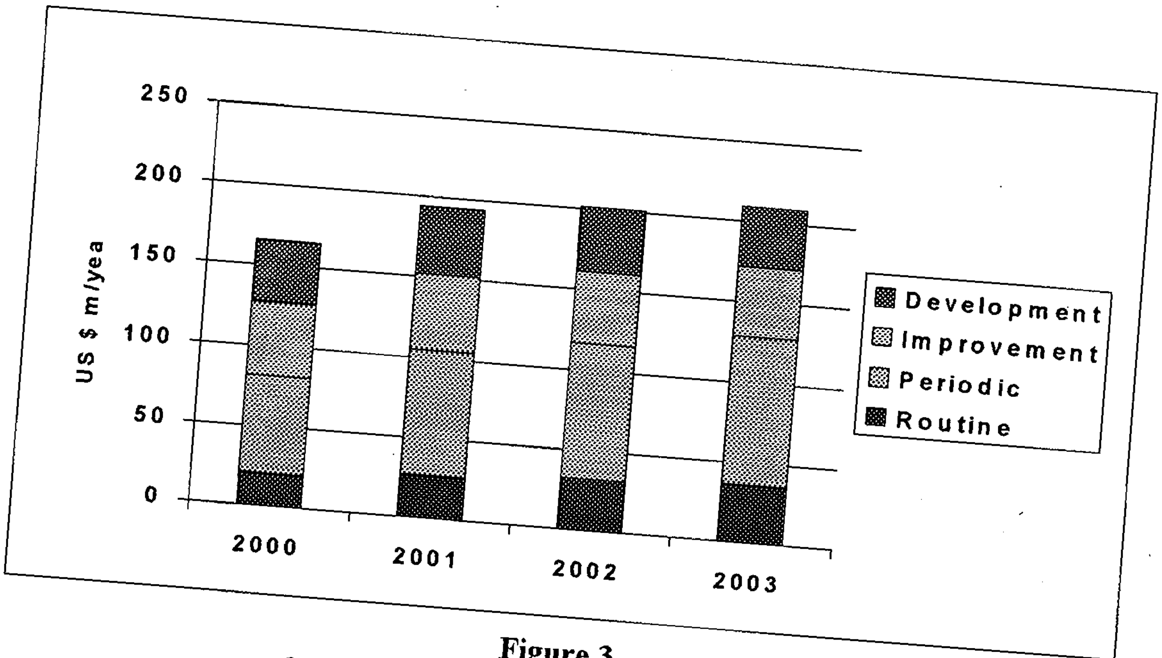

Figure 3
Optimal budget allocations to sub-heads

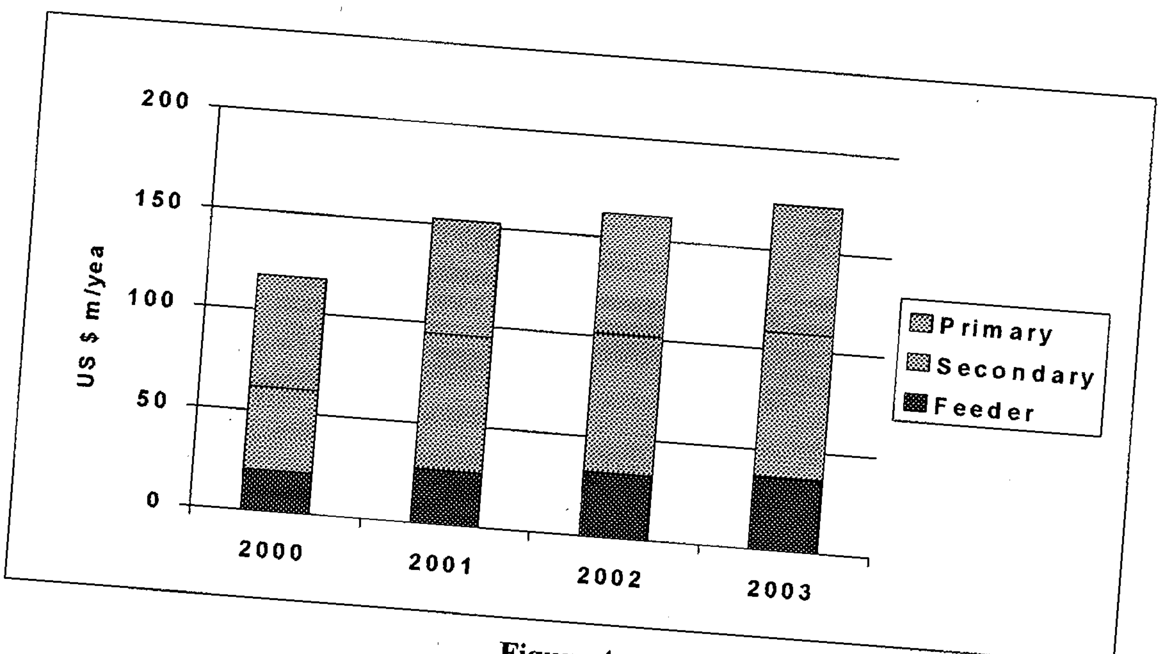

Figure 4
Optimal budget allocations to sub-networks

The main difference between strategy analysis and programme analysis is the way in which road links and sections are physically identified. Programme analysis deals with individual links and sections that are unique physical units identifiable from the road network throughout the analysis. In strategy analysis, the road system essentially loses its individual link and section characteristics by grouping all road segments with similar characteristics into the road network matrix categories.

For both strategy and programme analysis, the problem can be posed as one of seeking that combination of treatment alternatives across a number of sections in the network that optimises an objective function under budget constraint. If, for example, the objective function is to maximise the Net Present Value (NPV), the problem can be defined as: "Select that combination of treatment options for sections that maximises NPV for the whole network subject to the sum of the treatment costs being less than the budget available".

5. HDM-4 ANALYTICAL FRAMEWORK

The three analysis tools described above operate on data defined in one of four data managers:

- **Road Network**. Defines the physical characteristics of road sections in a network or sub-network to be analysed.
- **Vehicle Fleet**. Defines the characteristics of the vehicle fleet that operate on the road network to be analysed.
- **Road Works**. Defines maintenance and improvement standards, together with unit costs, which will be applied to the different road sections to be analysed.
- **HDM Configuration**. Defines the default data to be used in the applications. The default data should be modified to reflect local conditions.

The HDM-4 analytical framework is described in detail in Volume 4 of the HDM-4 series of documents (Odoki and Kerali, 2000).

Technical analysis is undertaken using four sub-models:

- **RD (road deterioration)**. Predicts pavement deterioration for bituminous, concrete and unsealed roads.
- **WE (works effects)**. Simulates the effects of road works on pavement condition and determines the corresponding costs.
- **RUE (road user effects)**. Determines costs of vehicle operation, road accidents and travel time.
- **SEE (social and environmental effects)**. Determines the effects of vehicle emissions and energy consumption.

The road deterioration and works effects (RDWE) models are described in detail in Volume 6 of the HDM-4 series of documents (Morosiuk, et al, 2001), whilst the RUE and SEE models are similarly described in Volume 7 (Bennett and Greenwood, 2001). An overview of these sub-models is given below.

5.1 Road Deterioration

The deterioration of three classes of pavements are modelled in HDM-4:

- Bituminous
- Concrete
- Unsealed

Within each class of pavement, broad definitions of the road surfacing and the base are used to define the pavement type as follows:

Bituminous surfacings – two types

- asphaltic mix (AM)
- surface treatment (ST)

Concrete surfacings – three types

- jointed plain (JP)
- jointed reinforced (JR)
- continuously reinforced (CR)

Unsealed surfacings – three types

- gravel (GR)
- earth (EA)
- sand (SA)

There are effectively five generic **base** types, including those which allow for overlays of asphalt on concrete and vice versa:

- granular base (GB)
- asphalt base (AB)
- stabilised base (SB)
- asphalt pavement (AP)
- rigid (concrete) base (RB)

The pavement classification used in HDM-4 is summarised in Table 5.

Table 5
HDM-4 pavement classification system

Surface category	Surface class	Pavement type	Surface type	Base type
Paved	Bituminous	AMGB	AM	GB
		AMAB		AB
		AMSB		SB
		AMAP		AP
		STGB	ST	GB
		STAB		AB
		STSB		SB
		STAP		AP
	Concrete	JPGB	JP	GB
		JPAB		AB
		JPSB		SB
		JPAP		AP
		JPRB		RB
		JRGB	JR	GB
		JRAB		AB
		JRSB		SB
		JRAP		AP
		JRRB		RB
		CRGB	CR	GB
		CRAB		AB
		CRSB		SB
		CRAP		AP
		CRRB		RB
Unpaved	Unsealed	GRUP	GR	UP
		EAUP	EA	
		SAUP	SA	

A series of generic deterioration relationships have been developed for each pavement type which are used to model the performance of the roads over the user-specified analysis period. Table 6 gives a summary of the individual pavement defects that are modelled in HDM-4.

Table 6
Pavement defects modelled in HDM-4

Bituminous	Concrete	Unsealed
Drainage Cracking Ravelling Potholing Edge break Rutting Roughness Texture Depth Skid resistance	Cracking Joint spalling Faulting Failures Serviceability loss Roughness	Gravel loss Roughness

5.2 Road Works

When making a life-cycle cost analysis of a road it is normally necessary to simulate in the modelling the effects of various types of roadworks during the analysis period. The option of doing nothing for a road over a period of, typically 20 years, is rarely a sensible option.

The term "roadworks" is used to embrace any change to the physical characteristics of a road and may embrace operations ranging from simple maintenance, such as cleaning detritus from the road surface, to the construction of a new road link. One of the purposes of economic analysis is to find the combination of roadworks, which over an analysis period, will deliver the optimum solution for a given funding level. For every dollar spent on roadworks there should be a corresponding benefit of a dollar or more, otherwise the works should not be carried out. Benefits of roadworks can be almost immediate or longer term and arise from reduced society costs (vehicle operation, environmental effects) and/or reduced cost to the road agency in future maintenance of the road.

HDM-4 considers the following general classes of roadworks:

- **Routine Maintenance** - works that may need to be undertaken each year or at intervals during the course of a year. Examples include sealing cracks, patching potholes, clearing side drains.
- **Periodic Maintenance** - works that are planned to be undertaken at intervals of several years and are usually classified as preventive, resurfacing, overlay and reconstruction.
- **Special** - works whose frequencies cannot be estimated with certainty in advance. Examples include clearing debris following landslides or accidents, snow removal, salting/gritting of roads in winter.
- **Improvement Works** – e.g. widening, realignment
- **Construction** – e.g. upgrading from say a gravel road to a sealed pavement; construction of a new link.

Intervention criteria are used to determine the timing and limits on the works to be carried out. The intervention criteria can be defined as either **scheduled** or **responsive**. Scheduling can be at fixed intervals of time (for example, resurface at intervals of seven years) or points in time for maintenance works, and at a fixed time (for example, widen in the year 2010) for improvement and construction works. Alternatively roadworks can be triggered in response to various critical threshold levels specified by the user. For example, when the roughness of the road reaches 5 IRI, or the area of cracking exceeds 10 per cent.

5.3 Road User Effects

The modelling of Road User Effects (RUE) in HDM-4 comprises analysis of the following:

- Motorised vehicle (MT) speed, operating costs and travel time
- Non-motorised transport (NMT) speed and operating costs
- Road safety

Separate relationships are used for the different vehicle classes specified by the user. The main classes of motorised vehicles are:

- Motor cycles
- Passenger cars
- Utilities
- Trucks
- Buses

There are 16 base motorised vehicle types pre-defined in HDM-4. For example, for passenger cars, small, medium and large types are defined. In addition to motorised vehicle the following classes of non-motorised transport, are defined:

- Pedestrians
- Bicycles
- Cycle rickshaws
- Animal carts
- Tractors

Motorised vehicle speeds and operating resources are determined as functions of the characteristics of each type of vehicle and the geometry, surface type and current condition of the road, under both free flow and congested traffic conditions. The operating costs are obtained by multiplying the various resource quantities by the unit costs or prices, which are specified by the user in financial or economic terms. Financial costs represent the actual costs incurred by transport operators in owning and operating vehicles over the road. Economic costs represent the real costs to the economy of that ownership and operation, where adjustments are made to allow for market price distortions such as taxes, subsidies, foreign exchange restrictions, labour wage laws, etc.

The following vehicle operating cost (VOC) components are derived:

- **Fuel consumption**
- **Lubricating oil consumption**
- **Tyre wear**
- **Parts consumption**
- **Maintenance labour hours**
- **Depreciation**
- **Interest**
- **Crew hours**
- **Overheads**

Travel time is considered in terms of passenger-hours during working and non-working time, and cargo holding hours. Travel time costs are expressed more appropriately only in economic terms. Additional costs due to impassability of seriously damaged unsealed roads are also included in the total amount of motorised road user cost.

Non-motorised transport (NMT) modes play a major role in moving passengers and freight in many countries. The use of NMT is increasing in some regions mainly because of their affordability, flexibility and cost-effectiveness in providing low cost transportation. Furthermore, the increasing focus on efficiency in energy use and the environmental impacts arising from the ever-increasing use of motorised transport (MT) has highlighted the need for better provision of NMT facilities. This has led to the recognition that the full range of transport needs in many countries would not be catered for adequately by MT alone. Therefore, investment policies in the road transport sector should include NMT issues.

A formal method has been developed for calculating the operating costs incurred by NMT on roads and thereby for estimating the benefits derived by NMT from road improvements (Odoki and Kerali, 1999). The presence of NMT can influence the speed of motorised transport, thereby affecting the operating costs of motorised vehicles. In addition, policies such as road improvements influence the costs and benefits to both motorised and non-motorised road users.

The HDM-4 system allows users to define a series of look-up tables for accident rates. These are basically broad, macro descriptions of the expected accident rates defined according to a particular set of road and traffic attributes (for example, road type, traffic level and flow pattern, presence of NMT, and geometry class). For each road type or intersection type, users are required to specify the accident rate for each severity (that is, fatal, injury or damage only) in terms of the numbers of accidents per million vehicle-kilometres. When a road is improved (for example, by providing separate NMT lanes or widening road shoulders) the corresponding accident rates can be changed using the road type or intersection type. Thus it is possible to analyse the change in total numbers of accidents and the costs resulting from the improvement.

5.4 Social and Environmental Effects

The Social and Environmental Effects (SEE) models in HDM-4 are for the analysis of:

- **Energy balance**
- **Vehicle emissions**

It is widely recognised that energy and environmental effects need to be considered in the assessment of alternative investment policies and projects. By adopting projects and policies that minimise total life cycle energy use and vehicle exhaust emissions, related benefits such as reduced vehicle operating costs, reduced pollution, reduced dependency on imports of energy and reductions in the balance of payments deficits can be maximised. Planners and decision makers need to be able to understand the energy implications and environmental impacts of alternative road transport projects and policies.

Energy consumption models have been incorporated for estimating the total life cycle energy consumption due to road works, vehicle operation and vehicle production. These are calculated in terms of both national and global energy consumption totals.

Vehicle emission relationships have been developed for estimating volumes of the following; hydrocarbons, carbon monoxide, nitrogen oxides, carbon dioxide, sulphur dioxide, lead and particulates. The relationships are based on a number of parameters including pavement condition, road alignment, speed limits and road cross-section.

6. CALIBRATION

HDM-4 simulates future changes to the road system from current conditions. The reliability of the results from HDM-4 depend on two primary considerations.

- How well the data provided to the model represent the reality of the current conditions and influencing factors, as understood by the model.
- How well the predictions of the model fit the real behaviour and interactions between various factors for the variety of conditions to which it is applied.

The application of the HDM-4 model thus involves two important steps.

- A correct interpretation of the data input requirements, and achieving a quality of input data that is appropriate to the desired reliability of the results.
- Adjusting the model parameters to enhance how well the forecasts and outputs represent the changes and influences over time and under various interventions.

The relationships in HDM-4 model have individual calibration factors. The user can adjust these factors so that the predictions given by the model reflect the observations made in the local conditions under investigation. Details on calibrating and adapting HDM-4 is given in Volume 5 of the HDM-4 series of publications (Bennett and Paterson, 2000).

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