Contents

Volume 4 - Analytical Framework & Model Descriptions: Part G

Part G Road Map

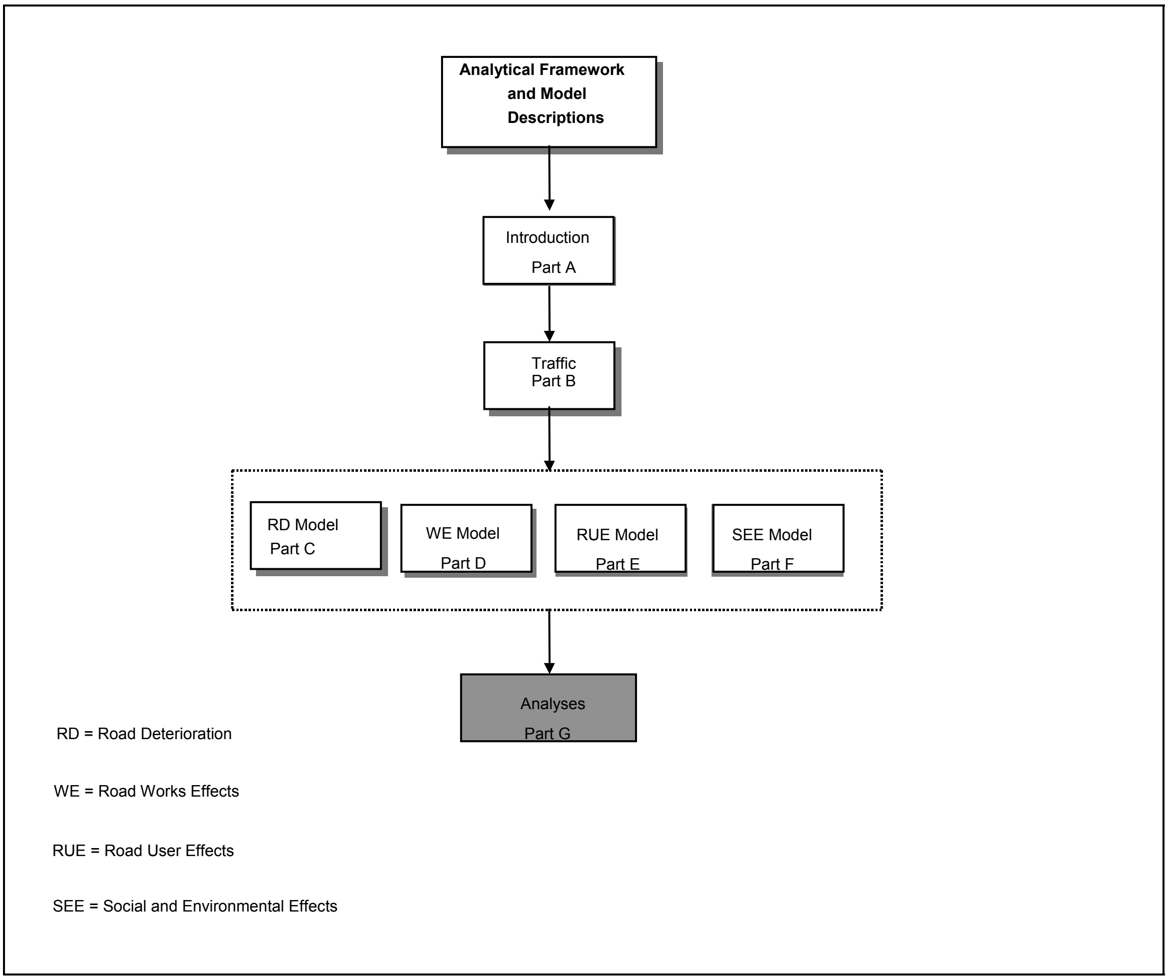

Figure G Analytical Framework and Model Descriptions Road Map

G1 Economic Analysis

1 Introduction

HDM-4 caters for three applications levels commonly used in decision making within the road sub-sector. The different applications, which are described in more detail in the Applications Guide, are:

1 **Strategic planning**

For estimating medium and long-term budget requirements for the development and preservation of a road network under various budgetary and economic scenarios.

2 **Programme analysis**

For preparing single or multi-year work programmes under budget constraints, in which those sections of the network likely to require maintenance, improvement, or new construction, are identified in a tactical planning exercise.

3 **Project analysis**

For estimating the economic or engineering viability of different road investment projects and associated environmental effects. Typical projects include the maintenance and rehabilitation of existing roads, widening or geometric improvement schemes, pavement upgrading and new road construction.

For all the three applications, the underlying operation of HDM-4 is based on the concept of life cycle analysis under a user-specified scenario of circumstances. This involves the analysis of pavement performance, road works effects and costs, together with estimates of road user costs and environmental effects, and economic comparisons of different project alternatives.

This chapter describes how HDM-4 is used to determine the benefits and costs associated with a road investment, and how these are applied in economic analysis and optimisation procedures to find the best use of available resources.

2 Background

2.1 Economic analysis

Economic analysis of the time stream of costs and benefits is used to compare the economic viability of different alternatives, and to provide the criteria needed for economic decision making. Decisions can be made about which option to implement, and when is the most favourable time for implementation. Economic analysis can also be used to investigate the technical standards and strategies to be followed by a particular investment decision. Economic analyses involves the following tasks:

1 Identification of the problem to be solved and the formulation of alternatives.

2 Identification and quantification of the life-cycle costs to be incurred and benefits to be realised.

3 Modelling future impacts of the proposed alternatives on road performance and traffic flow.

4 Economic comparison of the different alternatives, involving:

   (a) discounting the annual costs and benefits streams to a chosen base year

   (b) Comparing the time stream of costs for each pair of alternatives

   (c) Calculating the economic indicators such as the net present value, internal rate of return, benefit-cost ratio, and first year benefits

A project analysis usually involves a small number of road links or sections and the results of economic analysis would provide adequate information for decision making, since a budget would normally already have been approved for these activities.

2.2 Optimisation

The purpose of the Strategy and Programme applications is to calculate the economic benefits derived from maintenance or improvement options, and to select the set of investments to be made on a number of road sections within a network which will optimise an objective function.

Programme analysis is concerned with short to medium term planning and preparation where budget levels are known with reasonable certainty and the objective is to select a set of road sections and road works within the budget constraint.

Strategy analysis involves the analysis of an entire road network (or sub-network). The objective is either to determine which types of road works should be applied in order to maximise economic benefits, or it may also be applied to determine the budget required for a given long term target road network condition. Thus, the problem can be posed as one of searching for the combination of investment alternatives that optimises the objective function under a budget constraint or a road network condition constraint. Note that the set of investment options to be optimised is user-defined and is not the set of all possible options for the particular network; hence the problem is not true optimisation since all possible solutions are not normally considered. Note also that the investment options on any one road section are mutually exclusive.

The three alternative objective functions provided for the Strategy and Programme applications are:

1 **Maximisation of economic benefits** (that is, NPV)

This option is used when the problem can be defined as the selection of a combination of investment options applied on several road sections which maximises the NPV (net present value) for the whole network subject to the sum of the financial costs being less than the budget available.

5 **Maximisation of the improvement in network condition**

The roughness reduction on each road section multiplied by the section length (ΔIRI*Length) is used instead of NPV. Consequently, the arithmetic procedure is similar to that used for maximisation of economic benefits.

6 **Minimise costs of road works to achieve a given target road network condition**

This option is used mainly in the Strategy analysis application. The target road condition defined in terms of the long-term average roughness (IRI) over the whole analysis period must be specified for each road section. The optimisation procedure is then reduced to a simple selection of the road work options for which the average IRI (over the analysis period) is equal to or just below the target IRI and has the lowest total financial cost.

2.3 Classification of benefits and costs

Costs and benefits due to road investments may be classified into the following three broad categories:

1 **Benefits and costs expressed in monetary terms**

For example, vehicle operating costs, savings in travel time, accident costs.

2 **Quantified benefits and costs not expressed in monetary terms**

For example, road safety, pollution from vehicle emissions and traffic noise.

3 **Non-quantified benefits and costs**

For example, better social welfare, ecological impacts.

An economic analysis considers directly only benefits and costs expressed in monetary terms. Other costs and benefits may also need to be considered, and this is sometimes done within the framework of a multi-criteria analysis.

3 Benefits and costs considered in HDM-4

3.1 Summary of benefits and costs

HDM-4 considers quantified benefits and costs that can be expressed in monetary terms, and has some scope for considering those that cannot be expressed in this way. The benefits and costs considered are:

- **Costs incurred by the road administration** (see Section 3.2)
- **Road user costs** (see Section 3.3)
- **Environmental effects** (see Section 3.4)
- **Other benefits and costs** (see Section 3.5)

3.2 Costs incurred by the road administration

These costs are also referred to as road agency costs and include the following:

- **Road development**
- **Pavement maintenance**
- **Road-side or off-carriageway activities**

The cost of works is derived from the product of the physical quantities involved in the activity and the unit cost. These are determined for each road section and investment option, and for each year of the analysis period. The resulting costs are assigned to budget categories that are user-definable. The following default categories are used in HDM-4:

- **Capital (or periodic)**
- **Recurrent (or routine)**
- **Special**

Budget constraints can be applied separately to each category when required by the economic analysis and optimisation.

3.3 Road user costs

The following components of Road User Costs are modelled:

- **Motorised vehicle operating costs**

  These costs include:

  - Fuel and lubricant consumption
  - Tyre and parts consumption
  - Labour
  - Capital
  - Crew
  - Overheads

- **Travel time costs**

  These costs include passenger travel time costs, and cargo holding time costs.

- **Non-motorised transport (NMT)**

  These costs include time and operating costs.

- **Accident costs**

  These costs are evaluated both in monetary and non-monetary terms, and separated into several different types (for example, fatal, injury, and damage only). Note users are allowed the flexibility to include or exclude accident costs from an economic analysis.

3.4 Environmental effects

The following environmental impacts are determined:

- **Vehicle emissions**
- **Energy use**
- **Traffic noise** (not included in this release)

3.5 Other benefits and costs

The user can specify those benefits and costs that are not modelled for each year of the analysis period. These benefits and costs are discounted and added to those that are calculated internally. These other benefits and costs are sometimes termed **exogenous**. Social benefits and costs of road investments are typical examples of exogenous benefits and costs *(TRL, 2004)*.

3.6 Unit costs

Unit costs are applied to the calculated physical and operational quantities to produce the cost estimates used in investment decisions and budget preparation. Unit costs should be expressed in economic terms when economic analysis is being undertaken, and in financial terms for financial analysis. Financial unit costs are the market prices of resources. Economic unit costs are the real value or opportunity costs of resources, and they are found by removing distortions such as taxes, subsidies and other miscellaneous costs from the market prices.

Unit costs are required for the following:

- **Road development, maintenance and road-side activities**

  These unit costs are specified by the user (see Part D).

- **Road user costs**

  These unit costs include vehicle resources, travel-time values, and road accident resources (see Part E).

In most cases, unit costs are specified in units-per-quantity. However, some costs are specified as a proportion of other costs, or as a lump sum.

In addition to calculating economic costs, financial costs are also computed if the user gives appropriate inputs (for example, unit costs in financial terms).

4 Outline methodology

4.1 Basic unit of analysis

The basic unit of analysis in HDM-4 is the **homogeneous** road section. Several investment options can be assigned to a road section for analysis. One or more vehicle types that use the road must also be defined together with the traffic volume specified in terms of the annual average daily traffic (AADT).

4.2 Life cycle analysis

The underlying operation of HDM-4 is common for the project, programme or strategy applications. In each case, HDM-4 predicts the life cycle pavement performance and the resulting user costs under specified maintenance and/or road improvement scenarios. The broad concept of the life cycle analysis is illustrated in Figure G1. The agency and user costs are determined by first predicting physical quantities of resource consumption and then multiplying these by the corresponding unit costs.

Two or more options comprising different road maintenance and/or improvement works should be specified for each candidate road section with one option designated as the **do minimum** or **base case** (usually representing minimal routine maintenance). The benefits derived from implementation of other options are calculated over a specified analysis period by comparing the predicted economic cost streams in each year against that for the respective year of the base case option. The discounted total economic cost difference is defined as the net present value (NPV). The average life cycle riding quality measured in terms of the international roughness index (IRI) is also calculated for each option.

INPUTS	MODEL	OUTPUTS
Vehicle type, volume, growth, loading, physical parameters, terrain, precipitation, road geometry, pavement characteristics, unit costs	Start of analysis loop	
Pavement type, strength, age, condition, and ESAL	Road Deterioration	Cracking, ravelling, pot-holes, rut depth, faulting (paved); gravel thickness (unpaved); roughness
Road geometry and roughness; vehicle speed, type; congestion parameters; unit costs	Road User Effects	Fuel, lubricant, tyres, maintenance, fixed costs, speed, travel time, road user costs
Road works standards and strategies	Works Effects	Reset cracking, ravelling, pot-holes, rut depth (paved); gravel thickness (unpaved); roughness, works quantities and agency costs
Road geometry and surface texture, vehicle characteristics	Social and Environmental Effects	Levels of emissions and energy used, and number of accidents
Developmental, accident, environmental, and other exogenous costs and benefits	Economic Analysis	Costs and benefits, including exogenous benefits
	Return to start of analysis loop	Total costs by component; net present values and rates of return by section

Figure G1.1 Life cycle analysis procedure in HDM-4

4.3 Models

Total life-cycle conditions and costs of sections or road networks can be simulated over a user-defined period into the future. The inter-dependence between the costs incurred by the road administration and the road user is recognised, and models are used to predict cost streams under the various headings.

The models incorporated in HDM-4 contain technical relationships for the following purposes:

1 Calculation of traffic volumes and flows, and vehicle loading over the road section.

2 Prediction of road deterioration, and works effects and costs, that are incurred in response to traffic flows, time and the surrounding environment.

3 Prediction of the costs of road use incurred as road condition and traffic flow change over time.

4 Prediction of accident rates as a function of the road and traffic characteristics, and the evaluation of accident costs.

5 Evaluation of vehicle emissions and energy use due to different road investment projects.

6 Economic analysis by comparison of the impacts or effects of different road investment project alternatives.

7 Calculation of road asset value of individual road section as a function of the level of investment.

4.4 Analysis sequence

The overall logic sequence for economic analysis and optimisation is illustrated in Figure G1.2a and represented below by pseudo codes. The analysis mode assumed for this illustration is analysis by project. To perform the analysis using ‘analysis by section’ mode, the section and alternative loops are interchanged. This illustration shows the following:

1 **The outer analysis loop**

Enabling economic comparisons to be made for each pair of investment options, using the effects and costs calculated over the analysis period for each option, and indicates that generated and diverted traffic levels may vary depending on the investment option considered.

2 **Costs and asset values**

How annual costs to the road administration and to the road users, and asset values are calculated for individual road section options.

3 **Optimisation procedures and budget scenario analysis**

These are performed after economic benefits of all the section options have been determined.

4 **Multiple criteria analysis**

Providing a means of comparing projects using criteria that cannot easily be assigned an economic cost.

The pseudo code that represents the outer analysis loop is given below:

START

- Define input data
- Loop for each scenario
  - Loop for each alternative
    - Loop for each section
      - Loop for each analysis year
        - Calculate traffic, effects, costs and asset values (see Figure G1.2b)
        - Store results for evaluation and reporting phase
      - End loop
    - End loop
  - End loop
  - Loop for each pair of alternatives to be compared
    - Loop for each analysis year
      - Loop for each section
        - Calculate non-discounted net benefits
        - Calculate discounted net benefits
        - Calculate net environmental effects and energy used
      - End loop
      - Calculate total non-discounted net benefits over all the sections (see Figure G1.2c)
      - Calculate total discounted net benefits over all the sections (see Figure G1.2c)
      - Calculate total environmental effects and energy used over all the sections (see Figure G1.2c)
    - End loop
    - Calculate economic indicators (NPV, IRR, BCR, and FYB see Section 5.3.1 and Figure G1.2c)
  - End Loop
  - Perform budget optimisation and budget scenario analysis (for strategy and programme analysis)
  - Perform multiple criteria analysis (for project analysis see Part G5)
- End Loop
- Output results

END

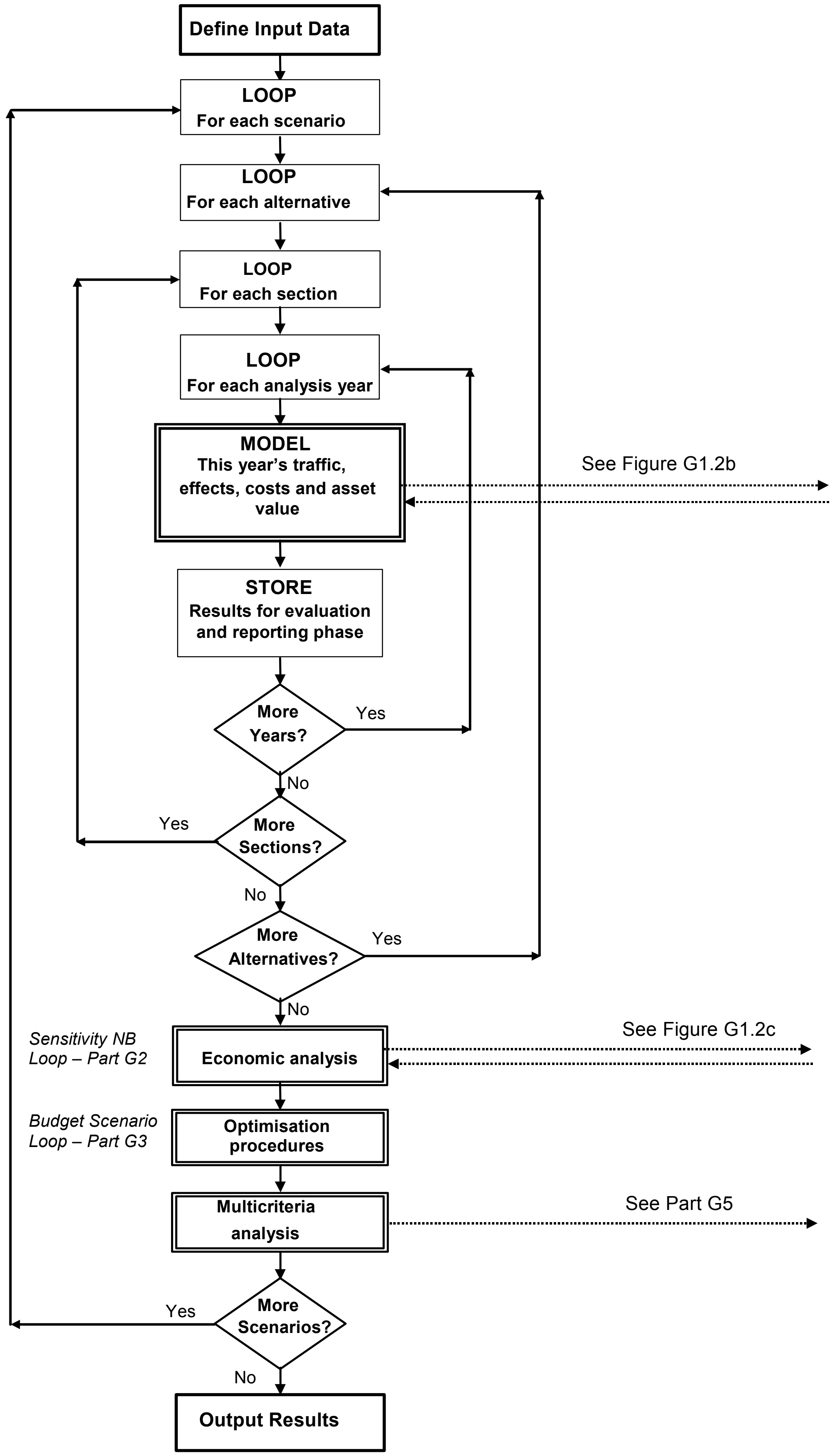

Figure G1.2a Overall Analysis Sequence – Part A

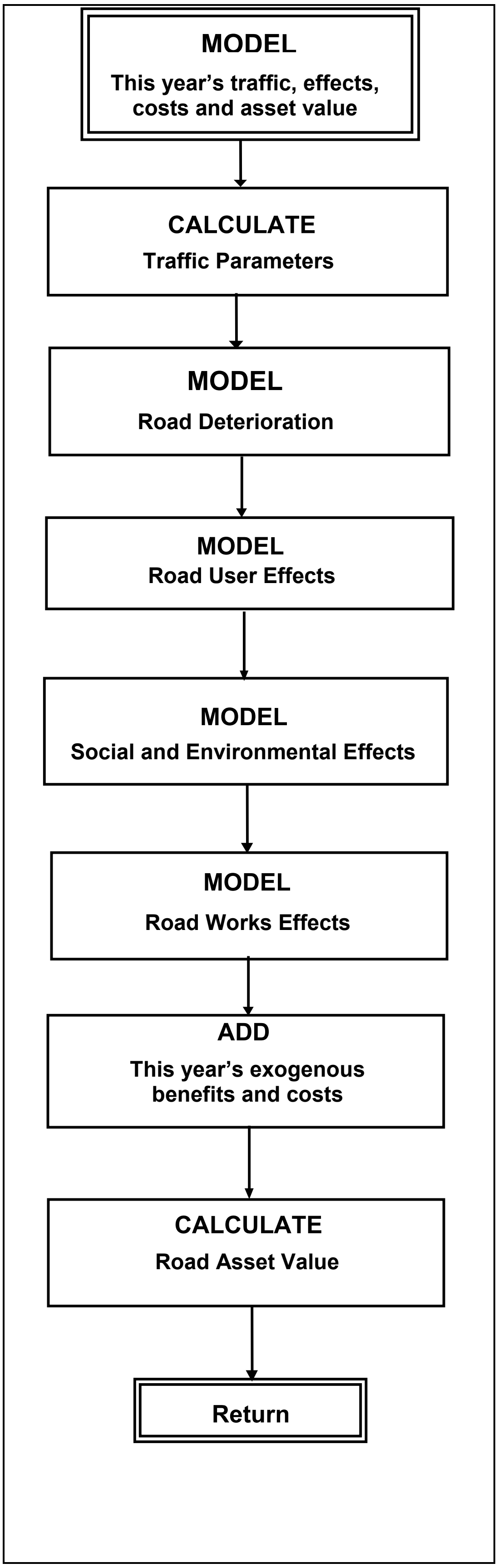

Figure G1.2b Overall Analysis sequence logic - Part B

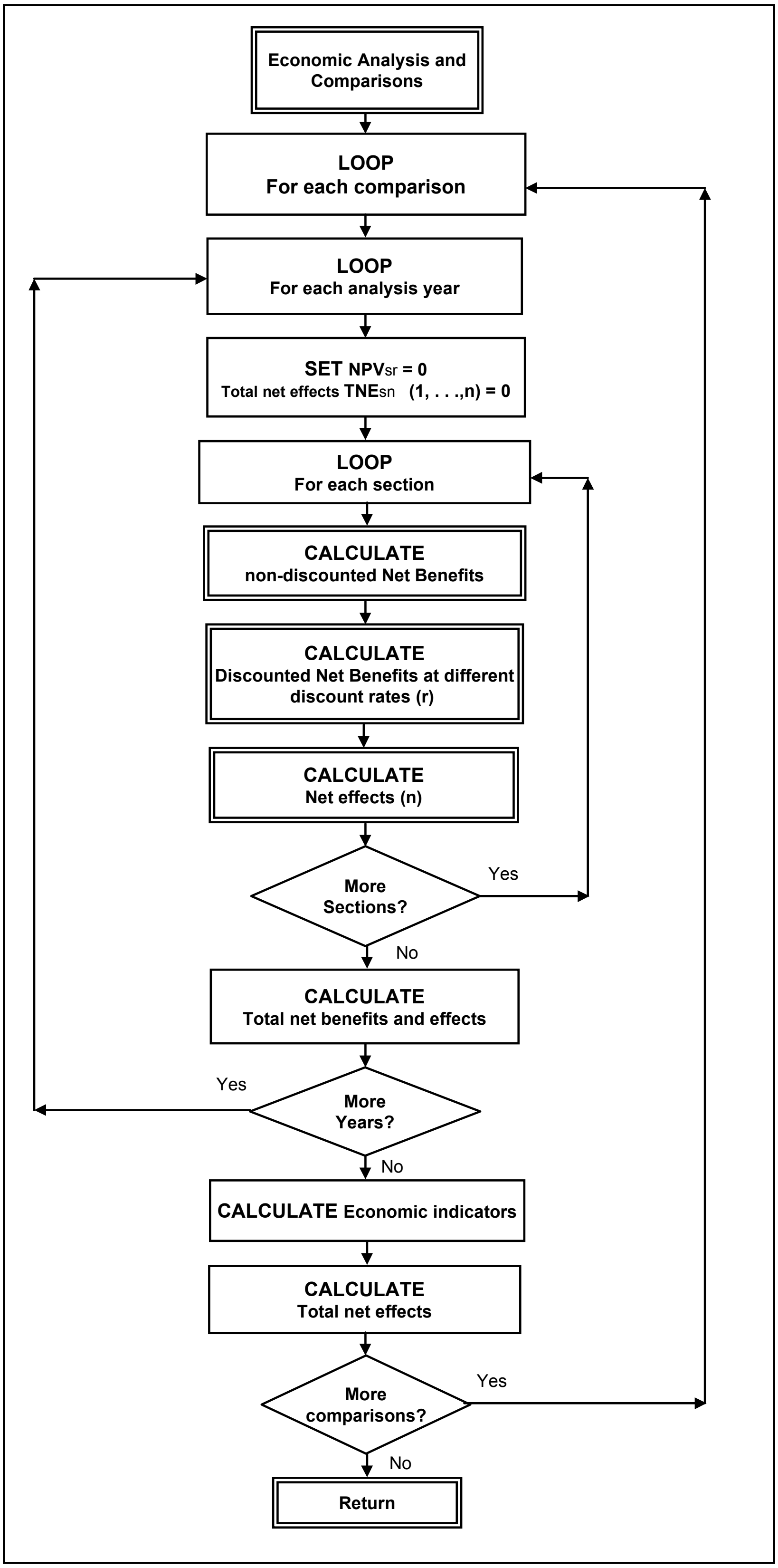

Figure G1.2c Overall Analysis sequence logic - Part C

The procedure for calculating annual road agency costs and road user effects for individual section options is illustrated in Figure G1.2b and summarised by the following steps:

1 **Calculate road deterioration** - in the RD module (see Part C)

2 **Calculate road user costs**

VOC, travel time costs, NMT time and operating costs, and accident costs - in the RUE module (see Part E).

3 **Calculate quantities and costs for road works** - in the WE module (see Part D)

4 **Calculate environmental effects**

For example, emissions and energy use - in the SEE module (see Part F).

5 **Add exogenous benefits and costs**

6 **Calculate road asset value** - (see Part G4)

Figure G1.2c illustrates the inner analysis loops for economic analysis and comparison of each pair of road alternatives.

5 Economic analysis

5.1 Comparison of investment options

Economic indicators are computed at different user-specified discount rates using the time streams of benefits or costs resulting from the various comparative pairs of investment options. The term **investment options** has been used in this document to refer to both project options (or alternatives) and section options (or alternatives).

For each pair of investment options to be compared, the net benefits (or costs) of implementing one option relative to the other is calculated year by year. The various methods of comparison are described in sub-sections within Sections 5.2 and 5.3. In all cases, investment option *m* is compared against option *n* (that is, option *n* is the base case).

5.2 Determination of costs and benefits

5.2.1 Costs to the road administration

The cost differences between a pair of investment options, *m* and *n*, in a given year, are calculated as follows:

$$\Delta C_{(m-n)i} = \left[\sum_s C_{mis} - \sum_s C_{nis}\right] \qquad \text{...(5.1)}$$

where:

$\Delta C_{(m-n)i}$ the difference in road administration cost of investment option *m* relative to base option *n* for budget category *i*

C_{jis} the total costs to road administration incurred by investment option *j* (where *j* = *n* or *m*) for budget category *i*, for road section *s* (see Part D)

The difference in annual costs to road administration is given by the expression:

$$\Delta RAC_{(m-n)} = \sum_i \Delta C_{(m-n)i} \qquad \text{...(5.2)}$$

where:

$\Delta RAC_{(m-n)}$ the difference in annual costs to road administration of investment option *m* relative to base option *n*. (The summation is over all the budget categories)

These cost differences provide a relative measure of the increase in costs to the road administration, of implementing investment option *m* over base option *n*.

The difference in the salvage values of works performed under investment options *m* and *n* is a component of the net economic benefits to be included in the last year of the analysis period (see Section 5.2.4), and is given as:

$$\Delta SALVA_{(m-n)} = \left[SALVA_m - SALVA_n\right] \qquad \text{...(5.3)}$$

where:

$\Delta SALVA_{(m-n)}$ the difference in salvage value of implementing investment option *m* relative to base option *n*

$SALVA_j$ salvage value of the works performed under investment option *j* (where *j* = *n* or *m*) (see Part D)

5.2.2 Savings in road user costs

The annual economic benefits in terms of savings in road user costs are calculated separately by components and traffic categories as follows:

- **Savings in motorised vehicle operating costs**

Vehicle operating benefits due to normal and diverted traffic is calculated as follows:

$$\Delta VCN_{(m-n)} = \left[\sum_s VCN_{ns} - \sum_s VCN_{ms} \right] \quad ...(5.4)$$

$$VCN_{ns} = \sum_k TN_{nsk} * UC_{nsk} \quad ...(5.5)$$

$$VCN_{ms} = \sum_k TN_{msk} * UC_{msk} \quad ...(5.6)$$

Vehicle operating benefits due to generated traffic is calculated as follows:

$$\Delta VCG_{(m-n)} = \left[\sum_s \sum_k \{0.5 * [TG_{msk} + TG_{nsk}] * [UC_{nsk} - UC_{msk}]\} \right] \quad ...(5.7)$$

The summations are over all the motorised vehicle types (*k* = 1, 2, ..., K) specified by the user, and all road sections (*s* = 1, 2, ..., S) being analysed.

The annual saving in vehicle operating costs is given by the expression:

$$\Delta VOC_{(m-n)} = [\ \Delta VCN_{(m-n)} + \Delta VCG_{(m-n)}\ ] \quad ...(5.8)$$

where:

$\Delta VCN_{(m-n)}$ vehicle operating benefits due to normal and diverted traffic of investment option *m* relative to base option *n*

VCN_{js} annual vehicle operating cost due to normal and diverted traffic over the road section *s* with investment option *j*

TN_{jsk} normal and diverted traffic, in number of vehicles per year in both directions on road *s*, investment option *j*, for vehicle type *k*

UC_{jsk} annual average operating cost per vehicle-trip over road section *s*, for vehicle type *k* under investment option *j* (where *j* = *n* or *m*)

VCG_{js} annual vehicle operating cost due to generated traffic over road section *s* with investment option *j*

$\Delta VCG_{(m\text{-}n)}$	vehicle operating benefits due to generated traffic of investment option *m* relative to base option *n*
TG_{jsk}	generated traffic, in number of vehicles per year in both directions on road *s*, for vehicle type *k*, due to investment option *j*
$\Delta VOC_{(m\text{-}n)}$	savings in vehicle operating costs due to the total traffic of investment option *m* relative to base option *n*

- **Savings in travel time costs – motorised vehicles**

Vehicle travel time benefits due to normal and diverted traffic are calculated as follows:

$$\Delta TCN_{(m-n)} = \left[\sum_{s} TCN_{ns} - \sum_{s} TCN_{ms}\right] \quad ...(5.9)$$

$$TCN_{ns} = \sum_{k} TN_{nsk} * UT_{nsk} \quad ...(5.10)$$

$$TCN_{ms} = \sum_{k} TN_{msk} * UT_{msk} \quad ...(5.11)$$

Vehicle travel time benefits due to generated traffic are calculated as follows:

$$\Delta TCG_{(m-n)} = \left[\sum_{s}\sum_{k}\{0.5 * [TG_{msk} + TG_{nsk}] * [UT_{nsk} - UT_{msk}]\}\right] \quad ...(5.12)$$

The annual savings in travel time costs are given by the expression:

$$\Delta TTC_{(m-n)} = [\Delta TCN_{(m-n)} + \Delta TCG_{(m-n)}] \quad ...(5.13)$$

where:

$\Delta TCN_{(m\text{-}n)}$	travel time benefits due to normal and diverted traffic of investment option *m* relative to base option *n*
TCN_{js}	annual vehicle travel time cost due to normal and diverted traffic over road section *s* with investment option *j*
UT_{jsk}	annual average travel time cost per vehicle-trip over the road section *s*, for vehicle type *k*, under investment option *j* (where *j* = *n* or *m*)
TCG_{js}	annual vehicle travel time cost due to generated traffic over road section *s* with investment option *j*
$\Delta TCG_{(m\text{-}n)}$	travel time benefits due to generated traffic of investment option *m* relative to base option *n* on the given road section in the given year
$\Delta TTC_{(m\text{-}n)}$	savings in travel time costs due to total traffic of investment option *m* relative to base option *n*

- **Savings in NMT time and operating costs**

Non-Motorised Transport (NMT) time and operating benefits due to normal and diverted traffic are calculated as follows:

$$\Delta TOCN_{(m-n)} = \left[\sum_s TOCN_{ns} - \sum_s TOCN_{ms} \right] \quad ...(5.14)$$

$$TOCN_{ns} = \sum_k TN_{nsk} * UTOC_{nsk} \quad ...(5.15)$$

$$TOCN_{ms} = \sum_k TN_{msk} * UTOC_{msk} \quad ...(5.16)$$

NMT time and operating benefits due to generated traffic are calculated as follows:

$$\Delta TOCG_{(m-n)} = \left\{ \sum_s \sum_k [0.5 * (TG_{msk} + TG_{nsk}) * (UTOC_{nsk} - UTOC_{msk})] \right\}$$

...(5.17)

The summations are over all the NMT types (*k* = 1, 2, ..., K) specified by the user, and all road sections (*s* = 1, 2, ..., S) being analysed.

The annual savings in NMT time and operating costs are given by the expression:

$$\Delta NMTOC_{(m-n)} = [\Delta TOCN_{(m-n)} + \Delta TOCG_{(m-n)}] \quad ...(5.18)$$

where:

$\Delta TOCN_{(m-n)}$	NMT time and operating benefits due to normal and diverted traffic of investment option *m* relative to base option *n*
$TOCN_{js}$	annual NMT time and operating costs due to normal and diverted traffic over the road section *s* with investment option *j*
TN_{jsk}	NMT normal and diverted traffic, in number of vehicles per year in both directions on road *s* investment option *j*, for vehicle type *k*
$UTOC_{jsk}$	annual average NMT time and operating cost per vehicle-trip over road section *s*, for vehicle type *k*, under investment option *j* (where *j* = *n* or *m*)
$TOCG_{js}$	annual NMT time and operating costs due to generated traffic over road section *s* with investment option *j*
TG_{jsk}	NMT generated traffic, in number of vehicles per year in both directions on road *s*, for vehicle type *k*, due to investment option *j*
$\Delta TOCG_{(m-n)}$	NMT time and operating benefits due to generated traffic of investment option *m* relative to base option *n*
$\Delta NMTOC_{(m-n)}$	annual savings in NMT time and operating costs due to total traffic of investment option *m* relative to base option *n*

- **Reduction in accident costs**

The benefits from reduction in total accident costs are given by the expression:

$$\Delta ACC_{(m-n)} = [AC_n - AC_m] \quad ...(5.19)$$

where:

$\Delta ACC_{(m-n)}$	the accident reduction benefits due to implementing investment option *m* relative to base option *n*
AC_j	the total accident costs under investment option *j* (where *j* = *n* or *m*)

- **Road user benefits**

The annual savings in road user costs are given by the expression:

$$\Delta RUC_{(m-n)} = \left[\Delta VOC_{(m-n)} + \Delta TTC_{(m-n)} + \Delta NMTOC_{(m-n)} + \Delta ACC_{(m-n)}\right] \qquad ...(5.20)$$

where:

$\Delta RUC_{(m-n)}$	the total road user benefits of investment option *m* relative to base option *n*

5.2.3 Other benefits and costs

The difference in other (exogenous) benefits and costs, for each pair of investment options *m* and *n* in a given year, is calculated as follows:

$$\Delta NEXB_{y(m-n)} = \left[EXB_{ym} - EXC_{ym} - EXB_{yn} + EXC_{yn}\right] \qquad ...(5.21)$$

where:

$\Delta NEXB_{y(m-n)}$	the annual net exogenous benefits of investment option *m* relative to base option *n*, in year *y*
EXB_{jy}	exogenous benefits for investment option *j*, in year *y*, (where *j* = *n* or *m*)
EXC_{jy}	exogenous costs for investment option *j*, in year *y*

5.2.4 Annual net economic benefits

For each pair of investment options, the annual net economic benefits of implementing option *m* relative to option *n* is obtained by combining the differences in costs to the road administration, road user costs, and other benefits and costs, as follows:

$$NB_{y(m-n)} = \left[\Delta RUC_{y(m-n)} + \Delta NEXB_{y(m-n)} - \Delta RAC_{y(m-n)}\right] \qquad ...(5.22)$$

where:

$NB_{y(m-n)}$	net economic benefit of investment option *m* relative to base option *n* in year *y*, and the parameters on the right-hand side are as defined earlier, but with subscript *y* added to indicate year

In the last year of the analysis period, the net economic benefits of implementing option *m* relative to option *n* is calculated as:

$$NB_{Y(m-n)} = \left[\Delta RUC_{Y(m-n)} + \Delta NEXB_{Y(m-n)} - \Delta RAC_{Y(m-n)} + \Delta SALVA_{(m-n)}\right] \quad ...(5.23)$$

where:

$NB_{Y(m-n)}$ net economic benefit of investment option *m* relative to base option *n* in the last year of the analysis period *Y*, and the parameters on the right-hand side are as defined earlier, but with subscript *Y* added to indicate the last year of the analysis period

5.2.5 New road sections (or links)

For the analysis of a new road section, the following variables used in the equations given in Sections 5.2.1 to 5.2.3 are set to zero: C_{nis}, $SALVA_n$, UC_{nsk}, TN_{nsk}, TG_{nsk}, UT_{nsk}, $UTOC_{nsk}$, AC_n, EXB_{yn}, and EXC_{yn}.

5.3 Economic decision criteria

5.3.1 Indicators determined

The following economic indicators are computed from the time streams of benefits or costs at the user-specified discount rate:

- **Net Present Value** - NPV (see Section 5.3.2)
- **Internal Rate of Return** - IRR (see Section 5.3.3)
- **Net Benefit/Cost Ratio** - BCR (see Section 5.3.4)
- **First Year Benefits** - FYB (see Section 5.3.5)

The determination of these indicators is described in the sections referenced.

5.3.2 Net present value

The Net Present Value (NPV) of investment option *m* relative to base option *n* is the sum of the discounted annual net benefits or costs, calculated from the relationship:

$$NPV_{(m-n)} = \sum_{y=1}^{Y} \frac{NB_{y(m-n)}}{[1+0.01*r]^{(y-1)}} \quad ...(5.24)$$

where:

$NB_{y(m-n)}$ net economic benefit of investment option *m* relative to base option *n* in year *y*

r discount rate (%)

y analysis year (y = 1, 2, ..., Y)

The higher the NPV, the greater the benefits from investment option *m* relative to base option *n*. If there are no budget constraints, then the choice between the two alternative investments should be based on NPV. Larger investments will tend to have larger NPVs.

5.3.3 Internal rate of return

The Internal Rate of Return (IRR) is the discount rate at which NPV is zero. It is calculated by solving the implicit relationship for $r°$:

$$\sum_{y=1}^{Y} \frac{NB_{y(m-n)}}{[1+0.01*r°]^{(y-1)}} = 0 \qquad ...(5.25)$$

This equation is solved for $r°$ by evaluating the NPV at 5 percent intervals of discount rates between -95 and +900 percent, and determining the zero(es) of the equation by linear interpolation of adjacent discount rates with NPV of opposite signs. Depending on the nature of the net benefit stream, $NB_{y(m-n)}$, it is possible to find one solution, multiple solutions, or none at all.

The IRR gives no indication of the size of the costs or benefits of an investment; it acts as a guide to the **profitability** of the investment - the higher the better. If the computed IRR is larger than the planning discount rate, then the investment is economically justified.

5.3.4 Benefit cost ratio

The Benefit Cost Ratio (BCR) of investment option *m*, relative to base option *n*, is the ratio is calculated as follows:

$$BCR_{(m-n)} = \frac{NPV_{(m-n)}}{C_m} + 1 \qquad ...(5.26)$$

where:

$BCR_{(m-n)}$	benefit cost ratio of investment option *m* relative to base option *n*
$NPV_{(m-n)}$	discounted total net benefit of investment option m relative to base option *n*. This is the Net Present Value at discount rate *r*
C_m	discounted total agency costs of implementing investment option *m*

If the $NPV_{(m-n)}$ is zero, then $(NPV/C)_{(m-n)}$ is zero. These ratios give an indication of the **profitability** of investment option *m* relative to base option *n* at a given discount rate. These measures eliminate the bias of NPV towards larger project options but, like the IRR, they give no indication of the size of the costs or benefits involved.

5.3.5 First-year benefits

The First-Year Benefits (FYB) is defined as the ratio, in percent, of the net benefit realised in the first year after construction (or improvement) completion to the increase in total capital cost:

$$FYB_{(m-n)} = \frac{100 * NB_{y°(m-n)}}{\Delta TCC_{(m-n)}} \qquad ...(5.27)$$

where:

$FYB_{(m-n)}$	first-year benefits of investment option *m* relative to base option *n* (%)
$NB_{y°(m-n)}$	net economic benefit of investment option *m* relative to base option *n* in year *y°*, where:
	y° is the year immediately after the last year in which the capital cost for improvement or construction is incurred in option *m*
$\Delta TCC_{(m-n)}$	the difference in total capital cost (non-discounted) of investment option *m* relative to base option *n*

FYB gives a rough guide to project timing: if it is greater than the discount rate, then the project should go ahead; otherwise it should be delayed until it satisfies the criterion.

This indicator is not calculated in this version of HDM-4.

5.4 Comparison of environmental effects

Where it is not possible to model costs directly, the **effects** of alternative investments can be evaluated. This information could be used as a decision tool for screening projects. For example; investment alternatives can be selected that are more effective in reducing the number of fatal accidents, or which are more effective in reducing the number of persons disturbed by a high level of traffic noise. Effects may also be a useful input for multi-criteria analysis.

The approach to carrying out a **comparative study** of environmental effects, for a pair of investment options, is similar to that used for economic analysis (see Section 5.2). The annual net quantities of vehicle emissions, number of accidents, and levels of traffic noise that are determined are compared with the benefit of implementing one investment option relative to the other.

5.5 Diverted traffic

Traffic diversion reduces or increases traffic on the roads that are affected. Therefore, in a situation where a road works causes traffic to divert significantly to a new or improved road section, a direct economic comparison of section options is not valid since the normal traffic flows on the road with and without the works are not identical.

Economic comparisons of investment options involving diverted traffic can only be performed meaningfully at the project analysis level, if the following conditions are met:

- All the road sections from and to which traffic diverts must be analysed together with the section(s) being considered under the investment analysis; this implies that a study area be defined to comprise all the sections that are affected significantly by traffic diversion as a result of carrying out the road works.

- In any given analysis year, the total traffic volume entering the study area equals the total traffic volume exiting the area; this implies a fixed trip matrix.

The analysis of a new road section (or link) in an entirely new location always involves diverted traffic. The **normal** traffic in the first year of road opening is diverted traffic from nearby routes (and from other transport modes, which may complicate matters further). The economic analysis and comparison involving a new road section, therefore, should always comply with the conditions described above.

6 Optimisation

The two methods for budget optimisation provided for road works programming and network strategic analysis are:

1 **Total enumeration**

2 **Incremental benefit/cost ranking**

[Further methods may be added in later versions of the HDM-4 software.]

If the number of roads to be analysed is less than 100, and there are no more than five budget periods and 16 alternatives per road, total enumeration (see Section 6.1) can be used. This will be externally done in the EBM-HS model of HDM-III. If the above mentioned constraints are exceeded, incremental benefit/cost ranking (see Section 6.2) will be used.

6.1 Total enumeration

This is the method used by the EBM-HS model of HDM-III. It requires the user to specify the following parameters:

- **Name of data set**

  For example, **CAPROG97**.

- **Length of analysis period**

  For example, 20 years.

- **Budget periods**

  For example, 1, 2, 3, 4-20 years.

- **Objective function**

  Either: maximise NPV or maximise the improvement in roughness.

- **Constraints on resources for each budget period**

  For example, 10, 10, 10, 200.

The analysis period is given in terms of the number of years over which the overall analysis should be performed, together with the initial calendar year. Budget periods are shorter time periods for which the budget constraints are given. The objective function defines which parameter is to be optimised. The default is the maximisation of NPV over the analysis period, but the user can also choose the maximisation of the improvement in roughness.

The program is run for all the road sections defined with positive economic return, and for all budget and investment options. The budget requirements from any committed projects will be deducted from the available budget and the balance is used for optimisation.

The optimisation problem is then defined as an integer programming problem of maximising the total objective function (TOBJ) for the network (*extracts from EBM documentation*):

$$\text{Maximise } TOBJ[X_{sm}] = \sum_{s=1}^{S} \sum_{m=1}^{M_s} OBJ_{sm}\, X_{sm} \qquad ...(6.1)$$

where:

s	a road section (s = 1, 2, ... , S)
M_s	the number of alternatives for road section *s*
m	an investment alternative on a road section
OBJ_{sm}	the objective function to be maximised which may be the discounted net present value of economic benefits, or the average reduction in roughness due to the investment alternative
sm	subscript denoting alternative *m* for road section *s*
X_{sm}	the **zero-one** decision variable:

X_{sm}	1 if alternative *m* of investment unit *s* is chosen
X_{sm}	0 otherwise
m	1,...,M_s

The above is subject to the following resource constraints:

$$\sum_{s=1}^{S}\sum_{m=1}^{M_s} R_{smqt}\ X_{sm} \le TR_{qt},\ q = 1,....,Q;\ \ t = 1,....,T \qquad ...(6.2)$$

where:

R_{smqt}	Non-discounted amount of resource of type *q* incurred by the sectoral agency within a budget period *t*
TR_{qt}	maximum amount of resource type *q* available for budget period *t*
Q	the total number of resource types
T	the total number of budget periods (the duration of *t* may be one or more years and need not be equal for different budget periods)

The above is subject to the constraint of mutual exclusivity:

$$\sum_{m=1}^{M_s} X_{sm} \le,\ s = 1,....,S \qquad ...(6.3)$$

that is, for each road section *s*, no more than one alternative can be implemented.

If *M* is the average number of alternatives for the roads, the problem then has SM (= S x M) zero-one variables, *QT* (= Q x T) resource constraints and *S* interdependency constraints. The parameters that define the problem size are *S*, *M* and *QT*. Depending on the solution method used, different problem-size parameters determine whether the method is suitable for the problem in terms of the computational effort needed.

The **total enumeration** method provides the user with an unconditionally optimal solution. It computes the total net present values of all feasible programme selections, and chooses the one with the highest value. The computational effort required for this may be considerable, so the method is only feasible when the number of alternatives per investment unit is relatively small.

Total enumeration is performed internally within the HDM-4 software provided the problem size is small, *i.e.*, less than 6 road sections each with less than 5 alternatives. The AHMED method of *effective gradients* is generally used within HDM-4 as coded in the EBM-32 version, provided the problem size is within the following limits:

- Maximum number of sections: 400
- Maximum number of alternatives: 17
- Maximum number of years: 20
- Maximum number of budget periods: 12

The effective gradient method (see appendix 8B in *Watanatada et al, 1987*) proceeds in two stages: first, it finds a feasible solution based on the concept of effective gradients; and second, it searches for better solutions that would improve the total NPV obtained after the first stage . The computational procedure is described below:

Stage I: Find feasible solution

Step 1: For each road section k, consider the alternative that has the maximum net present value. Check whether the capital budget constraints are satisfied. If so, go to step 10. Otherwise, proceed to step 2.

Step 2: For each road section, rank the alternatives according to the ranking index RI_{km}, defined as:

$$RI_{km} = \left[\frac{(NPV_{km})}{\sum_{q=1}^{Q} \sum_{t=1}^{T} \frac{R_{kmqt}}{TR_{qt}}} \right] m = 1,\ldots,M_k \qquad \ldots(6.4)$$

where:

R_{km}	the ranking index
NPV_{km}	the net present value of the selected road section alternative *km*
R_{kmqt}	the required financial capital budget of type *q*, for road section *k*, alternative *m*, in budget period *t*.
TR_{qt}	the total financial capital budget of type *q*, available within budget period *t*.
Q	the number of budget types available
T	the number of time periods specified
M_k	the total number of road sections to be prioritised.

Note that Q = 1 in HDM-4, i.e. only the capital budget constraint is used.

Step 3: For each road section, select the alternative that has the greatest ranking index, RI_{km}

Step 4: Add the budget requirements for all the selected alternatives and check whether all the budget constraints are satisfied. If so, go to step 8. Otherwise, go to step 5.

Step 5: Consider the road section alternatives selected in step 4. Calculate the effective gradients EG_k of the selected section alternatives, defined as:

$$EG_k = \left[\frac{\left(NPV_{km}\right)}{\sum_{(q,t.. \in ...Q'T')} \sum R_{kmqt} \sum_{k=1}^{K} R_{kmqt} - TR_{qt}} \right] \qquad ....(6.5)$$

where:

k = 1, …, K and Q'T' is the set of exceeded budget periods.

Step 6: Consider the road section with the smallest effective gradient and, if possible, exchange the selected alternative with the next best one for that road section which satisfies the criterion that it should not be uniformly worse in terms of requirement of exceeded budgets. The next best alternative is defined in terms of the next higher ranking index (RI_{km}). If all the alternatives for the road section are exhausted, go to step 7. Otherwise, return to step 4.

Step 7: Consider the road section with the next higher effective gradient EG_k. Return to step 4.

Stage II: Search for better solutions

Step 8: For each road section, look for an alternative that has the highest net present value other than the one currently selected, and which would be feasible if the currently selected alternative is replaced. If there is at least one alternative that meets this condition, go to step 9. Otherwise, go to step 10.

Step 9: From all the road sections that have at least one better feasible alternative, select the one that gives the maximum increase in the net present value. Return to step 8.

Step 10: Stop. A final solution has been obtained.

It is possible that the algorithm can fail to find a solution in Stage I. If this happens, then it is recommended that the user should pre-select an alternative for one or more road sections and re-run the optimisation.

[The above text was extracted from: Watanatada et al, 1987, Appendix 8B.]

6.2 Incremental benefit/cost ranking

With many applications of HDM-4, a large number of road sections will need to be prioritised. In these cases, the incremental benefit/cost method is the most appropriate. This involves searching through investment options on the basis of the incremental NPV/cost ratio of one alternative compared against the base case. The incremental NPV/cost is defined as:

$$E_{ji} = \left[\frac{\left(NPV_j - NPV_i\right)}{\left(cost_j\right)} \right] \qquad \text{...(6.6)}$$

where:

E_{ji}	the incremental NPV/cost ratio
NPV_j	the net present value of the selected project alternative *j*
NPV_i	the net present value of the designated base alternative *i*
$cost_j$	the **financial capital** cost of the selected project alternative *j*

In Equation 6.6 above, the incremental NPV/cost can be replaced by the incremental ΔIRI*Length/cost where ΔIRI*Length is the weighted average change in roughness obtained by comparing the project alternatives using IRI instead of NPV.

The objective of the incremental method is to select road sections successively starting with the largest NPV/cost ratio (E_{ji}), since this maximises the NPV (net present value) for any given budget constraint. Where there is more than one investment option on any individual road section, that with the lowest discounted investment costs is designated the **base case** alternative. This method considers all possible options, and compares these incrementally starting against the base case, by using the incremental algorithm to select the combination that maximises the selected objective function.

An incremental search technique is used to select the options with successively lower incremental NPV/cost ratios, ensuring that at any time there is no more than one option per road section. The process continues until the budget is exhausted for each budget period. The method is often referred to as the **efficiency frontier**, which is a **line** that joins investments with the highest NPV along the cost axis in a plot of NPV against investment cost (*Harral and Faiz, 1979*). In essence, the method seeks out those options that are close to the boundary of the efficiency frontier. The algorithm is illustrated in Figure G1.3, and is defined in the following steps:

1. Determine the pre-defined investment options for pre-selected sections and deduct the **financial** costs of these options from the available budget in corresponding years. Exclude these sections from any further optimisation.

2. Determine possible investment options for the remaining sections. If the life cycle analysis option is being used, set the user-defined base alternatives as the **do minimum** for each road section. For the multi-year forward programme, the **do minimum** option is that with the delayed capital works.

3. If the total **financial** cost of the **do minimum** investment alternatives on each section is greater than the available budget for any period, then the investment options or budget constraints must be redefined.

4. Deduct the **financial** cost of the **do minimum** investments from the available budget to determine the remaining budget for each period. Set the **do minimum** as the first **Base option** for each section.

5. Calculate the incremental NPV/Cost ratio for all remaining section-options compared against the Base option, and all other option pairs with higher **economic** cost. For example, consider the following investment options for a particular section arranged in the ascending order of discounted total **economic** costs:

   options: A, B, C, D, E

   The incremental NPV/Cost ratios for these are given by:

   Eba Eca Eda Eea ; Ecb Edb Eeb ; Edc Eec ; Eed

6 Delete incremental NPV/cost ratios that are less than the user specified minimum incremental value (MIV).

7 List the remaining incremental NPV/cost ratios in decreasing order (with the associated section-option pair codes) and, within each incremental NPV/cost, in the order of decreasing **economic** cost. For example, if $E_{eb} = E_{db}$ then E_{eb} is ranked higher.

8 Select the next incremental NPV/cost ratio from the top of the list. If the lower cost section-option is not the current Base Option for that section, continue searching until one is found.

9 If the remaining budget is insufficient in any of the periods for the **financial** costs of works required for the section-option selected in Step 8 above, then the selected option should be rejected, and continue searching by repeating Step 8.

10 If the section-option can fit within the remaining budgets for all periods, deduct the net **increase in financial** cost of capital works from all corresponding budget periods. Set the Base option for this section to be that corresponding to the lower cost option for the incremental NPV/Cost ratio chosen in Step 8. Providing that the remaining list is not empty, return to Step 8.

The process described above continues until the budget is exhausted or there are no more section-options remaining in the list. The resulting list of selected section-alternatives constitutes the optimal work programme.

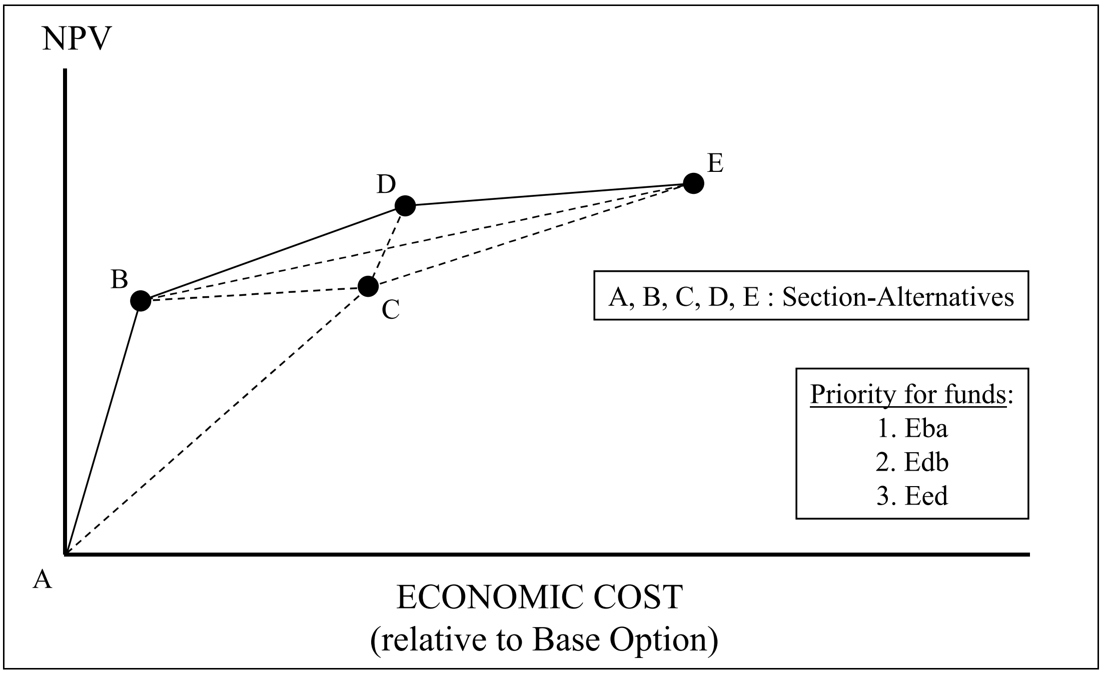

Figure G1.3 Efficiency frontier concept

7 References

Harral, C.G. and Faiz, A. (1979)

The highway design and maintenance standards model (HDM): model structure, empirical foundations and applications. PTRC Summer Annual Meeting, University of Warwick, 13-16 July 1979. PTRC Education and Research Services, London, UK

PIARC, (1991)

Methods for Selecting Road Investment, Economic and Finance Committee of PIARC, Paris, France

TRRL Overseas Unit, (1988)

A guide to road project appraisal, Road Note 5
Transport and Road Research Laboratory
Crowthorne, Berkshire, UK

TRL Limited, (2004)

A guide to pro-poor transport appraisal. The inclusion of social benefits in road investment appraisal, Overseas Road Note 22
Transport Research Laboratory
Crowthorne, Berkshire, UK

G2 Sensitivity and Scenario Analysis

1 Introduction

Sensitivity analysis is used to study the effects of changes in one parameter on the overall viability of a road project as measured by various technical and economic indicators. This analysis should indicate which of the parameters examined are likely to have the most significant effect on the feasibility of the project because of the inherent uncertainty.

Scenario analysis is used to determine the broad range of parameters which would affect the viability of the road project. For example, a review of government long-term development plans could yield alternative economic growth rates. Investment projects should be chosen on their ability to deliver a satisfactory level of service across a range of scenarios. In this way, the economic return of a project need not be the sole criterion since social and political realities can also be taken into account.

Network level analyses within (i.e. Programme and Strategy analysis) usually involve a large number of road sections, and therefore require large amounts of time to complete even a single run without sensitivity or scenario analysis. To include sensitivity and scenario analysis at network level analysis would extend the run time excessively. Therefore, sensitivity and scenario analysis has been implemented only within the Project analysis application of HDM-4.

For all the three applications, the underlying operation of HDM-4 is based on the concept of life cycle analysis under a user-specified scenario of circumstances. From their definitions, sensitivity analysis may be conceptualised to be a special case (or a subset) of scenario analysis in which only one rather than a broad range of variables is adjusted at a time. The core HDM-4 run that uses the initial user-defined input data is called *base scenario*. Subsequent HDM-4 runs may be conducted as sensitivity or scenario analysis using different sets of user-defined parameters required to adjust the initial data used in the base scenario. Each of these subsequent runs should be given a name and referred to as a scenario. A scenario analysis is therefore the basic unit of an HDM-4 run.

This Section describes the implementation of sensitivity and scenario analysis in HDM-4. It provides details of the following:

- Important variables on which sensitivity analysis can be performed
- Methodology used, input data requirements, data flow and, analysis procedure and the outputs/reports

2 Variables for sensitivity analysis

The important variables considered for sensitivity analysis in HDM-4 are grouped under the following:

- Traffic levels – baseline flows and future growth rates
- Vehicle use - loading and utilisation
- Net benefits streams – reflecting variations in transport costs

The choice of which variables to test will depend upon the kind of study being conducted and it is a matter of judgement on the part of the user.

2.1 Traffic levels

The economic viability of most road investment projects will depend significantly on the traffic data used. However, it is difficult to obtain reliable estimates of traffic and to forecast future growth rates, (*TRRL, 1988*). Thus sensitivity analysis should be carried out, both of baseline flows and of forecast growth.

In HDM-4, traffic is considered in three categories as normal, diverted and generated. Baseline flows are specified separately for motorised transport (MT) and for non-motorised transport (NMT) in terms of the annual average daily traffic (AADT) by vehicle type. Future traffic is expressed in terms of annual percentage growth rate or annual increase in AADT for each vehicle type.

2.1.1 Normal traffic

For normal traffic, sensitivity analysis should be conducted on the baseline flows by specifying a multiplication factor which is then applied to the baseline traffic to obtain a new initial AADT value for each vehicle type used in the study. Both sensitivity and scenario analysis can be applied to test future traffic growth. For sensitivity analysis, the user is required to specify a multiplication factor that can be used to adjust the specified future traffic growth rates.

2.1.2 Generated traffic

Generated traffic indicates the level of economic development associated with a road project. In HDM-4, sensitivity analysis should be conducted on the levels of generated traffic by applying a multiplication factor to adjust the initial amounts specified.

2.1.3 Diverted traffic

The method of using multiplication factors for conducting sensitivity analysis is not appropriate for diverted traffic. It is advised that to carry out sensitivity/scenario analysis on diverted traffic the user should first determine the levels of traffic diversion externally, import the data into HDM-4, and then perform the required number of runs.

2.2 Vehicle use

In HDM-4, there are several parameters related to vehicle loading and annual utilisation which are difficult to estimate and may therefore be considered as candidate variables for sensitivity analysis. The vehicle use parameters include the average vehicle operating weight, equivalent standard axle load factor, baseline annual number of vehicle kilometres, and baseline annual number of working hours. All of these parameters are classified under HDM-4 sensitivity class II with impact elasticity ranging from 0.2 to 0.5 see A Guide to Calibration and Adaptation - Volume 5. The inclusion of these parameters for sensitivity and scenario analysis would also enhance the capability of HDM-4 for carrying out special research studies, for example the determination of road use cost. To conduct sensitivity analysis, the user will need to specify multiplication factors to adjust the 'base' values of these parameters.

2.3 Net benefits streams

In HDM-4, total net benefits stream is considered under three components namely:

- Net benefits from savings in road agency costs
- Net benefits from savings in road user costs
- Net benefits related to savings in exogenous costs

2.3.1 Savings in road agency costs

It is important to investigate sensitivity of output parameters to uncertainties in the costs of road works since these costs are always difficult to estimate accurately. The costs incurred by road agencies are analysed in HDM-4 for the following budget heads: capital, recurrent, and special. To conduct sensitivity analysis it is required that a multiplication factor be specified for each of these budget heads.

2.3.2 Savings in road user costs

In HDM-4, road user costs are modelled separately by component as follows: MT vehicle operation, MT travel time, NMT time and operation, and accidents. To conduct sensitivity analysis it is required that a multiplication factor be specified for each type of cost.

2.3.3 Savings in exogenous costs (and benefits)

These are costs that are not modelled endogenously in HDM-4. Examples include developmental and other environmental or social costs and benefits. It is useful to test the project's sensitivity to variations in exogenous costs and benefits since their estimation are usually not accurate. A multiplication factor will be applied to adjust the amounts of costs and benefits specified in order to perform this analysis.

3 Methodology

3.1 Input data requirements

The list of the variables for sensitivity and scenario analysis in HDM-4 is given in Table G2.1. Each variable is effectively a multiplication factor, which is used to calculate new values of the variables to be analysed within each scenario. A multiplication factor is a real number, and is used to increase or decrease the initial values of traffic, vehicle use and costs variables. It is also possible to define the time period over which a particular multiplication factor is valid. By default a multiplication factor will apply over the whole analysis period.

A 'scenario' is defined by the name, a list of the variables to be tested, and input data required to adjust the initial value of each variable.

Table G2.1: HDM-4 Variables for Sensitivity and Scenario Analysis

Type	Variable	Required Input Data
Traffic Levels	Baseline total AADT for MT normal traffic	A single multiplication factor
	Baseline total AADT for NMT normal traffic	A single multiplication factor
	Future growth rates for MT and NMT normal traffic	A single multiplication factor
	Future growth rates after traffic diversion (for MT and NMT)	A single multiplication factor
	Levels of generated traffic (for MT and NMT)	A single multiplication factor
Vehicle Use	Operating weight (WGT_OPER)	A single multiplication factor
	Equivalent standard axle load factor (ESALF)	A single multiplication factor
	Annual number of kilometres (AKM)	A single multiplication factor
	Annual number of working hours (HRWRK)	A single multiplication factor
Net Benefits	Capital	A single multiplication factor
	Recurrent	A single multiplication factor
	Special	A single multiplication factor
	MT vehicle operation	A single multiplication factor
	MT travel time	A single multiplication factor
	NMT time and operation	A single multiplication factor
	Accidents	A single multiplication factor
	Exogenous benefits and costs	A single multiplication factor

3.2 Analysis sequence

As described above, the analysis in HDM-4 will be performed on a ‘scenario’ basis. The analysis procedure for each scenario will follow the data flow chart given in Figure G1.2a. Different scenarios would comprise different combinations or configuration of user-selected variables to be analysed. The run time for completing a sensitivity analysis will therefore depend on the number of scenarios defined and the types of variables chosen. Figure G1.2a shows the outer analysis loop which is used whenever a scenario includes variables related to traffic and vehicle use. To reduce run time, a sensitivity analysis that involves only net benefits variables will be carried out following the net benefits loop illustrated in Figure G1.2c.

3.2.1 Selection of traffic variables

Whenever a scenario to be analysed includes traffic variables, this will require the analysis to be re-run to re-compute the traffic data in order to obtain new annual traffic data, which are then used to re-calculate the annual effects and costs. The resulting new streams of annual costs and benefits will be used for calculating new economic indicators for each scenario.

For normal traffic, the user-defined multiplication factors will be used to adjust the values of baseline AADT and future growth rates defined for the ‘base scenario’. The generated traffic levels for all section alternatives will be increased or decreased by applying a single user-defined multiplication factor.

In cases where the ‘base scenario’ includes alternatives with traffic diversion effects, the diverted traffic AADT specified on each road section should be adjusted by applying the same multiplication factor used to increase or decrease the baseline AADT for normal traffic. This will be done separately for MT and NMT.

3.2.2 Selection of vehicle use variables

Sensitivity and scenario analysis that involves the variables related to vehicle use will require adjusting vehicle fleet characteristics, and this will have impacts on annual traffic data (e.g. equivalent standard axle loads) and the annual effects and costs for all road sections. A complete re-run of HDM-4 will need to be performed to generate new sets of outputs.

A set of multiplication factors will be used for each scenario to adjust the initial values of the selected variables that have been defined in the 'base scenario'.

3.2.3 Selection of net benefits variables

Sensitivity analysis on net benefits involves using the multiplication factors defined for each scenario to increase or decrease the streams of net benefits generated from the '*base scenario*'. The resulting new streams of benefits are then used to calculate new economic indicators. Note that the net benefits streams contain positive and negative values. Positive values indicate benefits (savings) and negative values indicate negative benefits (increases) in relation to the base investment alternative.

3.3 Outputs and reports

The reports for sensitivity analysis should include both inputs and outputs. The input reports will show what sensitivity variables have been tested in each scenario and the respective multiplication factors used. The output reports will depend on whether or not a full HDM-4 re-run was performed for the particular scenario. As described earlier, sensitivity analysis involving variables related to traffic, vehicle use or delay of works will require a re-run of the HDM-4 analysis. In these cases a complete set of HDM-4 outputs will be produced and all the current HDM-4 reports should be generated. For analyses involving changes in net benefits streams, the output reports to be reproduced are for the new streams of net benefits and the economic indicators.

Apart from the sensitivity scenario input report described above, no new reports are required specifically for sensitivity analysis. Rather, all existing reports (where appropriate) should be adapted to group results not just by section and alternative, but by sensitivity scenario also.

4 References

TRRL Overseas Unit, (1988)

A guide to road project appraisal, Road Note 5
Transport and Road Research Laboratory
Crowthorne, Berkshire, UK

G3 Budget Scenario Analysis

1 Introduction

The amount of financial resources available to a road agency determines what road investment works can be affordable. The level of budget is not always constant over time due to a variety of factors including competing demands from other sectors, changes in a country's macro economic performance, etc. This variation of budget levels over time affects the functional standards as well as the size of road network that can be sustainable. It is therefore important to study the effects of different budget levels or budget scenarios on the road network performance.

Many HDM-4 users have indicated the need for several budget scenarios to be specified and optimised simultaneously. This feature has been implemented in HDM-4 and it permits comparisons to be made between the effects of different budget scenarios and to produce desired reports.

This part describes the methodology for budget scenario analysis in HDM-4. It describes how to define budget scenarios, the analysis procedures and the outputs.

2 Methodology

For all the three applications (project, programme and strategy analysis) the underlying operation of HDM-4 is based on the concept of life cycle analysis under a user-specified scenario of circumstances. As explained in Part G2, a scenario will constitute the basic unit of an HDM-4 run. A scenario is represented by a complete set of HDM-4 input data. The user may specify several scenarios to be run simultaneously. In Project analysis application of HDM-4, scenarios will be defined based on the requirements to conduct sensitivity analysis, whereas in Programme and Strategy analysis applications of HDM-4 scenarios will be defined based on the different budget levels to be optimised.

The overall HDM-4 analysis procedure is illustrated by Figure G1.2a, where the outer analysis loop enables economic analysis and optimisation procedures to be performed for each scenario separately. Note that budget levels inputs are not required in project analysis and therefore budget optimisation procedures are excluded. On the other hand, both programme and strategy analysis applications will not incorporate dedicated facilities to perform sensitivity analysis.

Facilities to allow users to input different budget scenarios have been implemented within the Programme and Strategy analysis applications of HDM-4 as described below.

2.1 Defining budget scenarios

A budget scenario could be described as low, average or high; initially low and steadily increasing, initially high and steadily decreasing, stable annual expenditure or any configuration of different levels. HDM-4 allows for a maximum number of 5 budget scenarios to be analysed simultaneously in a run.

A budget scenario should be defined by the following:

- Name (or description)
- Budget periods – in terms of start year and end year (it is possible to define a budget period of one year or multiple years)
- Budget constraints – the amount of budget available in the particular period

The budget constraints defined for each budget period are the total capital budget only, without any division to recurrent and special budget headings. Therefore these budget constraints do not include the costs of annual routine maintenance (recurrent budget heading) and special works (special budget heading). Only works assigned to the capital budget heading will be optimised.

2.2 Analysis procedure

The analysis procedure for each scenario will follow the data flow chart given in Figure G1.2a. In Programme and Strategy analysis applications of HDM-4, different scenarios would comprise different specifications of budget levels. Figure G1.2a shows that optimisation procedures are performed after economic analysis. Budget scenario analysis involves optimisation procedures for different budget scenarios and this will be performed within the optimisation module. A budget scenario analysis loop has been implemented within the optimisation module for this purpose.

Each budget scenario will be optimised separately, and the optimisation procedures are given in Section 6.2 of Part G1. [This was extracted from *Watanatada et al, 1987, Appendix 8B*].

There are two analysis methods provided in HDM-4: analysis by section and analysis by section grouping (or projects). Analysis by section analyses, individually, each of the road sections that has been included in programme or strategy analysis. Several alternatives can be defined for each section (for example, three alternatives for section A, four alternatives for section B, etc.), with one alternative designated as the *base case* against which all the other alternatives will be compared. Economic indicators (for example, NPV, IRR and NPV/C) are calculated for each section alternative.

2.3 Outputs and reports

The most important aspect of budget scenario analysis is the presentation of results. This should be given at two levels as follows:

1 At detail level – to include parameters for each section alternative analysed and the performance indicators. These detail parameters will be used to generate aggregate level results and ad hoc user-designed reports.

2 In aggregate terms – to present performance indicators for the whole road system, with trends by analysis interval over the analysis period for each budget scenario. Reports on the results of comparison between the effects of different budget scenarios should also be presented in terms of aggregate data.

HDM-4 provides a standard presentation of the following types of reports:

- Aggregated quantity and cost of road works by works class.
- Space-mean distribution of performance indicators, for example length (in km) or road space (in lane-km) and percentages in VCR (volume-to-capacity ratio), PCR (pavement condition rating), PSA (pavement strength adequacy) classes.
- Space-mean and Travel-mean values of key road system condition indicators e.g., average roughness IRI, travel speed, VOC per vehicle-km.
- Vehicle travel distribution in *vkt* (vehicle kilometres travelled) and percentages in VCR, PCR classes.
- Network size, in km and lane-km

Typical examples of budget scenario analysis are given in Overview of HDM-4 - Volume 1.

3 References

Watanatada T., Harral C.G., Paterson W.D.O., Dhareshwar A.M., Bhandari A., and Tsunokawa K., (1987)

The highway design and maintenance standards model volume 1: description of the HDM-III model. The Highway Design and Maintenance Standards Series. Baltimore: Johns Hopkins for the World Bank.

G4 Asset Valuation

1 Introduction

The purpose of preparing annual asset valuations for a road network is to provide a means of checking on the success or otherwise of the road authority in preserving the assets it holds on behalf of the nation. All public assets should have associated with them a current capital value.

The concept of asset valuation has been both well known and used for many years to justify works in the private sector. Assets can be valued in a number of ways. Most kinds of asset are included in the balance sheets of commercial firms at historical cost less depreciation. When an asset is acquired and paid for, the amount paid is added into the firm's balance sheet. The value of the asset is then reduced annually, by the depreciation, an amount representing the consumption of the asset during each year. This valuation method is referred to as the depreciation method.

This part describes the methodology used for road asset valuation that has been implemented in HDM-4. It describes the data requirements, the valuation procedure and the reports required.

2 Road asset valuation methodology

2.1 Road asset components

For the implementation of road asset valuation in HDM-4, only the following components are relevant:

- Road formation, drainage channels, and sub-grade, i.e. earthworks
- Road pavement layers
- Footways, footpaths and cycle-ways
- Bridges and structures
- Traffic facilities, signs and road furniture

Other components of road assets not considered in HDM-4 include the following: land, buildings, plant and equipment, materials and supplies, existing plans and designs, and financial assets.

2.2 Basis of valuation

Certain components of the road asset may be valued by conventional means such as the value of the land upon which the road corridor lies, and the value of the works to produce, or to reproduce, a cutting or an embankment. The problem however is with the valuation of the pavement from the top, or formation level, of earthworks, upwards. Depreciation accounting, which is based on the assumption that depreciation of the network equals the sum of the depreciation of all of the asset components making up the network, can be applied to road asset valuation. The basis of valuation used is as follows (*International Infrastructure Management Manual, 2002*):

1 The *Optimised Replacement Cost* (ORC) of each component of the road asset, which is defined in general terms as the cost of a replacement asset that most efficiently provides the same utility as the existing asset. This can be estimated as equivalent to the initial financial cost of construction, adjusted to current year prices.

2 The *Optimised Depreciated Replacement Cost* (ODRC) of each component; ODRC is the replacement cost of an existing asset after deducting an allowance for wear or consumption to reflect the remaining useful life of the asset

The relevant basis of valuation and method for the road components considered is given in Table G4.1. The following ODRC methods are used for valuation of the road components: the straight-line method, production-based method, and condition-based method.

Table G4.1: Valuation methods for road assets considered in HDM-4

Feature/component	Basis of valuation	Depreciation method
Road formation and sub-grade (RFS)	ORC	
Road pavement layers (RPL)	ODRC	Production or Condition-based
Footways, footpaths and cycle-ways (NMT lanes)	ODRC	Straight Line
Bridges and structures (BS)	ODRC	Straight Line
Traffic facilities, signs and road furniture (TSF)	ODRC	Straight Line

The relevant valuation methods for some of the road asset components that are not considered in HDM-4 are given in Table G4.2.

Table G4.2: Appropriate valuation methods for other road assets

Feature/component	Basis of valuation
Land	Market value
Buildings	Market value
Plant and equipment	Market value
Materials and supplies	Market value
Existing plans and designs	ORC
Financial assets	Financial value

The backbone of HDM-4 analysis is the ability to predict the life cycle pavement performance and the resulting user costs under specified road works scenarios. The asset valuation methodology used links the capital value of the asset with its condition, which is predicted annually using the road deterioration (RD) and works effects (WE) models in HDM-4. This methodology provides a smooth relationship between road condition and asset value, thus avoiding the problem of using “stepped” methods in which pavements in different conditions can be assigned the same capital value.

The ODRC is particularly useful for capital valuation of the pavement layers. The following three ODRC methods are used in HDM-4:

- Straight-line depreciation
- Production-based depreciation
- Condition-based depreciation

2.3 Straight line depreciation

Figure G4.1 illustrates the method used to estimate the ODRC for a component of a road asset using the straight line depreciation method. The method yields a fixed annual loss in the value of an asset. For many purposes, this approach, though crude, is an adequate practical approach that can be used if there is no better deterioration/depreciation model is available. It can be upgraded to take account of major maintenance expenditures and rehabilitation, by capitalising such works and depreciating them over an appropriate time period.

As given in Table G4.1, this method will be used for valuation of bridges and structures; footways, footpaths and cycle-ways; and traffic facilities, signs and road furniture.

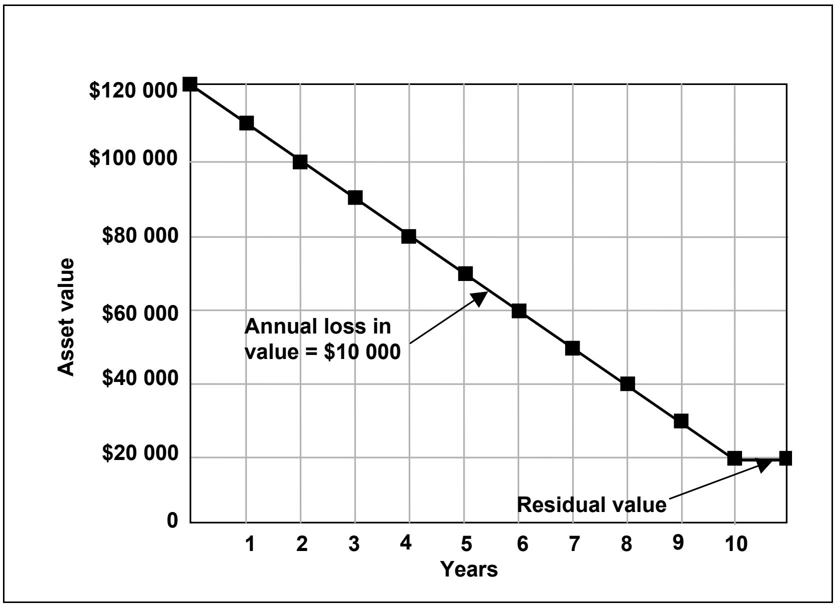

Figure G4.1: Straight Line Depreciation

(Source: National Asset Management Steering Committee, 1996)

2.4 Production-based depreciation

This estimates the annual economic benefit or consumption of the asset component (see Figure G4.2). For paved roads, the annual consumption can be measured in terms of the cumulative annual equivalent standard axle loads (CESAL) at the year of analysis compared to the design equivalent axle loads (DESAL). For gravel roads, this can be estimated from the cumulative annual gravel loss (CGL) compared to the initial gravel thickness (IGT).

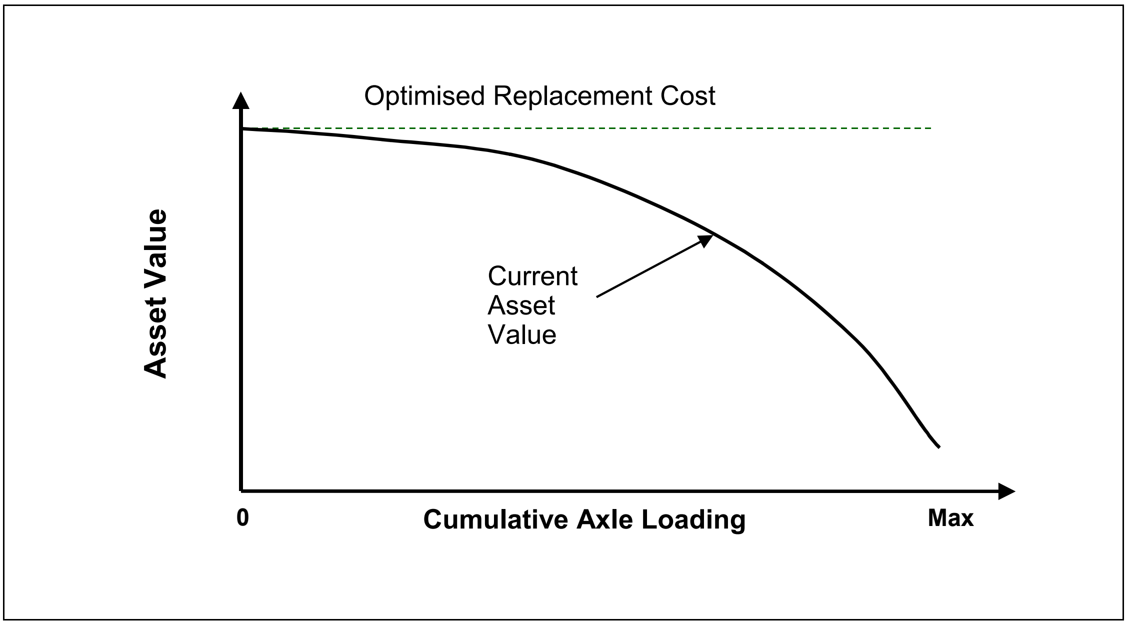

Figure G4.2: Production-based Depreciation

This method will be provided in HDM-4 as an option for valuation of road pavement layers.

2.5 Condition-based depreciation

The condition-based method is based on the estimated terminal condition and the current year condition of the asset (see Figure G4.3). For both paved and unsealed roads, the suggested condition indicator can be roughness (IRI) as its calculation combines almost all other forms of pavement defect. It is necessary to provide the Terminal IRI (TIRI) and the Initial condition (IRI0) in order to estimate the asset value. This corresponds to the need for reconstruction of the pavement layers.

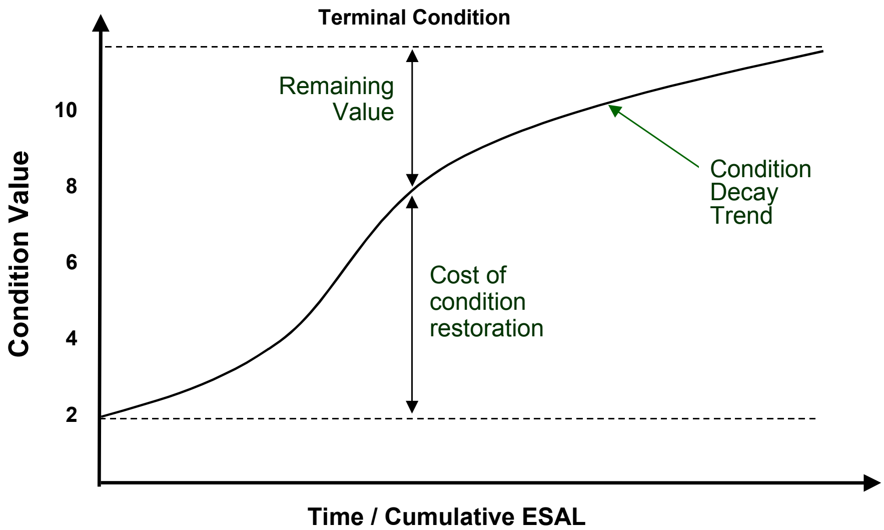

Figure G4.3: Condition-based Depreciation

3 Valuation procedure

3.1 Outline

Asset valuation can be performed in all the three HDM-4 applications: project, programme and strategy analysis. The user should define all the required input data and select the option for asset valuation in order to do this analysis.

The overall HDM-4 analysis procedure is illustrated in Figure G1.2a. This shows that asset valuation is performed annually for each section alternative. The analysis procedure can be summarised by the following steps:

1 For each section alternative and analysis year, initialise the required input data.

2 Determine the asset value of each component as follows:

   i. Calculate the useful life and the optimised replacement cost (ORC). This can be estimated as equivalent to the initial financial cost of construction, adjusted to current year prices.

   ii. Calculate the "remaining useful life".

   iii. Calculate the ODRC value of the asset component.

3 Sum the ODRC values of all the asset components to obtain the annual total asset value of the road section for the given investment alternative.

4 Reset parameters for asset valuation to reflect any changes that might have occurred due to implementation of road works.

5 Output analysis results

The asset components modelled for each road section alternative are given in Table G4.1.

3.2 Data requirements for valuation

The input data required for road asset valuation in HDM-4 can be considered as follows:

- *Inventory*: physical attributes of asset components
- *Standard unit costs*: for estimating component replacement values
- *Useful life*: service period when asset delivers benefits to users, expressed in appropriate units, see Table G4.3
- *Current condition*: this affects remaining life and estimated asset value

The input variables required for the calculation of asset component values are given in Tables G4.3 and G4.4.

Table G4.3: Input variables for Section

Variable	**Comments**
Replacement cost (CONCST)	Equivalent to construction cost
Component age at year (CAYEAR)	The reference year against which component ages are calculated
Proportion of asset component cost (PCTi)	User input as a percent of replacement cost
Residual value of asset component *i* (RESPCTi)	User input as a percent of replacement cost at end of component life
Useful life (USFLIFEi) of asset component *i*	User input in years or million equivalent axle loads (MESAL) or mm of gravel thickness
Component age of asset component i (CAi)	User input in years or MESAL. The unit will be determined by the unit used for (USFLIFEi)
Cumulative ESAL (CESAL)	Initial value obtained from CAi (expressed in MESAL), values for subsequent years will be calculated using YE4
Terminal roughness (TIRI)	User input, default = 12 for paved roads, and 22 for unsealed roads. Default values will be stored in the road network
Initial roughness (IRI0)	User input, default value = 2 for AM, 2.8 for ST pavements
Current roughness (CIRI)	Calculated annually from Road Deterioration model
Initial gravel thickness (IGT)	User input in mm

Table G4.4: Input variables for road works

Variable	**Comments**
Proportion of the cost of new work (PCTWi) for component *i*	User input as percent of capital cost (or improvement cost) of the new work. For maintenance work, only road pavement layers will be affected and the value for this input will always be 100%
Residual value of new work (RESPCTWi) for component *i*	User input as percent of capital cost of the new work.
Useful life of new work (USFLIFEWi) for component *i*	User input in both years and MESAL for road pavement layers and in years for other asset components
Proportion of existing asset decommissioned (PCTDISP)	User input for an improvement standard. PCTDISP is the percentage of the total asset value of the road, adjusted construction cost of the section (CONCST), which is decommissioned as a result of the improvement.
Capital cost of new road works (CAPCST)	Calculated annually from Works Effects model

3.3 Determination of asset value

3.3.1 Road formation and subgrade

The valuation of road formation and subgrade is based on ORC approach. The optimised replacement cost will be calculated as follows:

$$ORC = \frac{PCT * CONCST_{bw}}{100} \quad ...(1)$$

where:

ORC	Optimised replacement cost for road formation and subgrade, (currency)
PCT	Cost of road formation and subgrade expressed as a percentage of the adjusted construction cost of the section, (%)
$CONCST_{bw}$	Adjusted construction cost of the section, before works (currency)

The useful life of road formation and subgrade (in years) is considered to be unlimited (10,000 years) by default. The remaining life can be calculated as follows:

$$REMLIFE = USFLIFE - CA \quad ...(2)$$

where:

REMLIFE	Remaining life in years
USFLIFE	Useful life in years (user-specified, default value = 10,000 years)
CA	Component age in years

The asset component age can be user-specified in years. At the start of analysis period component age will be calculated as follows:

$$CA_{ai} = CA_{ui} + (STARTYEAR - CAYEAR) \quad ...(3)$$

where:

CA_{ai}	Age of component ‘i’ at the start of analysis
CA_{ui}	Age of component ‘i’ at the reference year (CAYEAR)
STARTYEAR	Analysis start year

For subsequent analysis years, the calculation of asset component age is as follows:

$$CA_{yi} = CA_{(y-1)i} + 1 \quad ...(4)$$

where:

CA_{yi}	Age of component 'i' at year 'y'
$CA_{(y-1)i}$	Age of component 'i' at year '(y-1)'

For each analysis year, the value of this asset component (ODRC) will be equal to the ORC value calculated using Equation (1).

3.3.2 Road pavement layers

This will be valued on the basis of ODRC approach. The optimised replacement cost will be calculated as follows:

$$ORC = \frac{PCT * CONCST_{bw}}{100} \qquad ...(5)$$

where:

ORC	Optimised replacement cost for road pavement layers, (currency)
PCT	Cost of road pavement layers expressed as a percentage of the adjusted construction cost of the section, (%)
$CONCST_{bw}$	Adjusted construction cost of the section, before works (currency)

The asset value of a given asset component (ODRC) will be obtained from the following equation:

$$ODRC = \left[\frac{(ORC - RESVAL) * MAX(0, REMLIFE)}{USFLIFE}\right] + RESVAL \qquad ...(6)$$

where:

ODRC	Optimised depreciated replacement value of road pavement layers, (currency)
RESVAL	Residual value of road pavement layers, (currency)
REMLIFE	Remaining useful life of pavement layers, (in years, or ESAL, or IRI or mm of gravel thickness as described below)
USFLIFE	Useful life of pavement layers, (in years, or ESAL, or IRI or mm of gravel thickness as described below)

The residual value of road pavement layers at the end of its useful life is given by the following expression:

$$RESVAL = \frac{RESPCT * ORC}{100} \qquad ...(7)$$

where:

RESVAL	Residual value of road pavement layers at the end of its useful life, (currency)
RESPCT	Residual value of road pavement layers at the end of its useful life expressed as a percentage of the ORC, user-specified (%)

The useful life (USFLIFE) and the remaining useful life (REMLIFE) of pavement layers are defined according to the pavement type and the ODRC method to be used for asset valuation (i.e. production-based method or condition-based method).

For paved roads

The user has the options of using production-based method or condition-based method.

Production-based method

For production-based method the user input for useful life and component age can be in MESAL or years.

- If useful life/component age is specified in MESAL

The useful life of road pavement layers will be defined in terms of traffic loading, i.e. the design equivalent axle loads (DESAL), in millions per lane. This value can be obtained from pavement design information. Thus,

$$USFLIFE = DESAL \qquad \text{. . . (8)}$$

The remaining useful life will be determined from the following expression:

$$REMLIFE = MAX[0, (DESAL - CESAL)] \qquad \text{. . . (9)}$$

where:

REMLIFE	Remaining useful life of road pavement layers (MESAL)
DESAL	Design traffic loading of road pavement layers (MESAL), provided by the user
CESAL	Component age expressed in terms of cumulative traffic loading

The asset component age will be defined in terms of cumulative annual equivalent standard axle loads (CESAL) and calculated as described below.

At the start of analysis period:

$$CESAL_a = CESAL_u + (STARTYEAR - CAYEAR) * YE4 \qquad \text{. . . (10)}$$

where:

$CESAL_a$	Cumulative equivalent standard axle load at the start of analysis, in million per lane

$CESAL_u$	Cumulative equivalent standard axle load at the reference year (CAYEAR), in million per lane
YE4	Annual number of equivalent standard axles in millions per lane, calculated within HDM-4
STARTYEAR	Analysis start year

Calculation of CESAL for each year of analysis:

$$CESAL_y = CESAL_{y-1} + YE4_y \quad ...(11)$$

where:

$CESAL_y$	Cumulative equivalent standard axle load at analysis year y, in million per lane
$CESAL_{y-1}$	Cumulative equivalent standard axle load at analysis year (y-1), in million per lane
$YE4_y$	Annual total number of equivalent standard axles in year y, in million per lane

- If useful life/component age is specified in years

Then the remaining useful life will be determined from the following expression:

$$REMLIFE = MAX[0, (USFLIFE - CA)] \quad ...(12)$$

where:

REMLIFE	Remaining useful life of road pavement layers, in years
USFLIFE	Design life in years
CA	Component age in years

The asset component age will be calculated as described below.

At the start of analysis period, the asset component age will be calculated as follows:

$$CA_{ai} = CA_{ui} + (STARTYEAR - CAYEAR) \quad ...(13)$$

where:

CA_{ai}	Age of component *i* at the start of analysis, in years
CA_{ui}	Age of component *i* at the reference year (CAYEAR), in years
STARTYEAR	Analysis start year (Calendar year)

For subsequent analysis years, component age will be obtained from the following expression:

$$CA_{yi} = CA_{(y-1)i} + 1 \quad ...(14)$$

where:

CA_{yi} Age of component *i* at year 'y'

$CA_{(y-1)i}$ Age of component *i* at year '(y-1)'

Condition-based method

If the user selects the condition-based method then useful life of road pavement layers will be defined in terms of terminal roughness value (TIRI). This value should be user-specified. The default value is 12 IRI m/km.

$$USFLIFE = MAX[0,(TIRI - IRI0)] \quad ...(15)$$

The remaining useful life will be determined from the following expression:

$$REMLIFE = MAX[0,(TIRI - CIRI)] \quad ...(16)$$

where:

REMLIFE Remaining useful life of road pavement layers (IRI, m/km)

TIRI Terminal roughness, (IRI, m/km)

CIRI Current roughness, (IRI, m/km)

IRI0 Initial roughness, (IRI, m/km)

For gravel roads

The user has the options of using production-based method or condition-based method.

Production-based method

For production-based method the user input for useful life and component age can be in years or initial gravel thickness (mm).

- If useful life is given in IGT (mm)

The useful life of road pavement layers will be defined in terms of initial gravel thickness, (IGT), in mm. This value can be obtained from pavement design information.

The remaining useful life will be determined from the following expression:

$$REMLIFE = MAX[0,(IGT - CGL)] \quad ...(17)$$

where:

REMLIFE	Remaining useful life of road pavement layers
IGT	Initial gravel thickness (mm)
CGL	Cumulative gravel loss (mm) calculated annually

The cumulative gravel loss (CGL) will be calculated as described below.

At the start of analysis period CGL will be calculated as follows:

$$CGL = MAX[0, (IGT - CGT)] \quad ... (18)$$

where:

IGT	Initial gravel thickness, (mm)
CGT	Current gravel thickness, in mm (i.e. gravel thickness at the start of analysis)

For subsequent analysis years, CGL will be obtained from the following expression:

$$CGL_y = CGL_{y-1} + MATLOSS_y \quad ... (19)$$

where:

CGL_y	Cumulative gravel loss at analysis year y, (mm)
CGL_{y-1}	Cumulative gravel loss at analysis year (y-1), (mm)
$MATLOSS_y$	Gravel material loss in year y, (mm)

- If useful life/component age is given in years

Then the remaining useful life will be determined from the following expression:

$$REMLIFE = MAX[0, (USFLIFE - CA)] \quad ... (20)$$

where:

REMLIFE	Remaining useful life of road pavement layers in years
USFLIFE	Design life in years
CA	Component age in years, provided by the user

The asset component age will be calculated using Equations (13) and (14).

Condition-based method:

If the user selects the condition-based method then useful life of road pavement layers will be defined in terms of terminal roughness value (TIRI). This value should be user-specified. The default value is 22 IRI m/km.

$$USFLIFE = MAX[0, (TIRI - IRI0)] \quad ...(21)$$

The remaining useful life will be determined from the following expression:

$$REMLIFE = MAX[0, (TIRI - CIRI)] \quad ...(22)$$

where:

REMLIFE	Remaining useful life of road pavement layers, (IRI, m/km)
TIRI	Terminal roughness (IRI, m/km)
CIRI	Current roughness (IRI, m/km)
IRI0	Initial roughness, (IRI, m/km)

For earth roads:

The user will be provided with only one option: the condition-based method.

The useful life of road pavement layers will be defined in terms of terminal roughness value (TIRI). This value should be user-specified. The default value is 22 IRI m/km.

$$USFLIFE = MAX[0, (TIRI - IRI0)] \quad ...(23)$$

The remaining useful life will be determined from the following expression:

$$REMLIFE = MAX[0, (TIRI - CIRI)] \quad ...(24)$$

where:

REMLIFE	Remaining useful life of road pavement layers, (IRI, m/km)
TIRI	Terminal roughness (IRI, m/km)
CIRI	Current roughness (IRI, m/km)
IRI0	Initial roughness, provided by user

3.3.3 Other road asset components

The other asset components considered in HDM-4 will be valued on the basis of ODRC straight-line depreciation method. These asset components are:

- Footways, footpaths and cycle-ways
- Bridges and structures
- Traffic facilities, signs and road furniture

For each asset component, the optimised replacement cost will be calculated as follows:

$$ORCi = \frac{PCT_i * CONCST_{bw}}{100} \qquad \ldots (25)$$

where:

ORCi	Optimised replacement cost of asset component *i*, (currency)
PCTi	Cost of asset component *i* expressed as a percentage of the adjusted construction cost of the section, (%)
$CONCST_{bw}$	Adjusted construction cost of the section, before works (currency)

The value of each asset component *i* (ODRCi) will be obtained from the following equation:

$$ODRCi = \left[\frac{(ORCi - RESVALi) * MAX(0, REMLIFEi)}{USFLIFEi}\right] + RESVALi \qquad \ldots (26)$$

where:

ODRCi	Optimised depreciated replacement value of road asset component *i*, (currency)
RESVALi	Residual value of road asset component *i*, (currency)
REMLIFEi	Remaining useful life of asset component *i*, (in years)
USFLIFEi	Useful life of asset component *i*, (in years)

The residual value of road asset component *i* at the end of its useful life is given by the following expression:

$$RESVALi = \frac{RESPCTi * ODRCi}{100} \qquad \ldots (27)$$

where:

RESVALi	Residual value of road asset component *i* at the end of its useful life, (currency)
RESPCTi	Residual value of road asset component *i* at the end of its useful life expressed as a percentage of the ODRCi, user-specified (%)

The useful life (USFLIFEi) is equal to design life (DLi) of road asset component *i* and will be user-specified in years.

The remaining useful life will be determined from the following expression:

$$REMLIFEi = MAX[0, (DLi - CAi)] \qquad \text{. . . (28)}$$

where:

REMLIFE	Remaining useful life of road asset component *i*, (years)
DLi	Design life of road asset component *i*, (years)
CAi	Current age of road asset component *i* (years)

3.3.4 Total asset value

For each analysis year, the total asset value of each section alternative will be derived from the sum of the values of the asset components that comprise the section alternative.

3.4 Reset of parameters after roadworks

3.4.1 Maintenance works:

In HDM-4, it is considered that in periodic maintenance will affect the asset value of only road pavement layers component. Routine maintenance works will not change the asset value.

After a periodic maintenance work the parameters for asset valuation will be reset as described by the equations below.

The construction cost after works will be given by:

$$CONCST_{aw} = CONCST_{bw} + CAPCST \qquad \text{. . . (29)}$$

$$PCT_{aw} = \frac{PCT_{bw} * CONCST_{bw} + PCTW * CAPCST}{CONCST_{aw}} \qquad \text{. . . (30)}$$

$$RESPCT_{aw} = \frac{RESPCT_{bw} * ORC_{bw} + RESPCTW * CAPCST}{(ORC_{bw} + CAPCST)} \qquad \text{. . . (31)}$$

For production-based analysis of paved roads the following equation will be used to reset the useful life:

$$USFLIFE_{aw} = REMLIFE_{bw} + USFLIFEW \quad ...(32)$$

where:

$USFLIFE_{aw}$	Useful life after work
$REMLIFE_{bw}$	Remaining life before work
USFLIFEW	Useful life of new work

For production-based analysis of gravel roads the above equation will be used only if the useful life has been specified in years.

The parameters $CESAL_{aw}$, CGL_{aw}, CA_{aw} will be reset as described below.

Production-based method

- If useful life/component age is given in MESAL then

$$CESAL_{aw} = MAX[0, (CESAL_{bw} - DESALW)] \quad ...(33)$$

where:

$CESAL_{aw}$	Cumulative ESAL after work
$CESAL_{bw}$	Cumulative ESAL before work
DESALW	USFLIFEW expressed in terms of MESAL

- If useful life is given in IGT (mm) then

$$CGL_{aw} = MAX[0, (CGL_{bw} - \Delta THG)] \quad ...(34)$$

where:

CGL_{aw}	Cumulative gravel loss after works, in mm
CGL_{bw}	Cumulative gravel loss before works, in mm
ΔTHG	Increase in gravel thickness specified in the works design, in mm

The increase in gravel thickness is calculated as follows:

$$\Delta THG = THG_{aw} - THG_{bw} \quad ...(35)$$

where:

THG_{aw} Gravel thickness after work

THG_{bw} Gravel thickness before work

- If useful life is given in years then

The component age CA_{aw} will be set to zero.

Condition-based method

The initial roughness IRI0 will be reset to a new value specified by the user.

The component age CA_{aw} will be set to zero.

The terminal roughness TIRI will not change over time; CIRI will be calculated annually from the road deterioration model.

3.4.2 Improvement works:

After an improvement work, the values of the following asset components will be affected:

- Road formation and subgrade
- Road pavement layers
- NMT lanes

Following an improvement the valuation parameters will be reset as described below.

The construction cost will be given by:

$$CONCST_{aw} = CONCST_{bw} * \left(1 - \frac{PCTDISP}{100}\right) + CAPCST \qquad ...(36)$$

where:

$CONCST_{bw}$ Construction cost before work

$CONCST_{aw}$ Construction cost after work

CAPCST Capital (financial) cost of the improvement work, (currency)

PCTDISP Proportion of existing asset decommissioned, (%)

For road formation and subgrade:

The parameter PCT (i.e. the asset component cost as a percentage of replacement cost of the section) and USFLIFE will be reset as follows:

$$PCT_{aw} = PCT_{bw} * (CONCST_{bw} / CONCST_{aw}) \qquad ...(37)$$

where:

PCT_{aw}	Proportion of cost for the component after works
$CONCST_{bw}$	Construction cost before work
$CONCST_{aw}$	Construction cost after work

$$USFLIFE_{aw} = REMLIFE_{bw} + USFLIFEW \quad ...(38)$$

where:

$USFLIFE_{aw}$	Useful life after work
$REMLIFE_{bw}$	Remaining life before work
USFLIFEW	Useful life of new work

For road pavement layers:

The valuation parameters will be reset as follows:

$$PCT_{aw} = \frac{PCT_{bw} * \left[CONCST_{bw} * \left(1 - PCTDISP/_{100}\right)\right] + PCTW * CAPCST}{CONCST_{aw}} \quad ...(39)$$

$$RESPCT_{aw} = \frac{RESPCT_{bw} * \left[ORC_{bw} * \left(1 - PCTDISP/_{100}\right)\right] + RESPCTW * CAPCST}{\left[ORC_{bw} * \left(1 - PCTDISP/_{100}\right)\right] + CAPCST} \quad ...(40)$$

For production-based analysis of paved roads the following equation will be used to reset the useful life:

$$USFLIFE_{aw} = REMLIFE_{bw} + USFLIFEW \quad ...(41)$$

where:

$USFLIFE_{aw}$	Useful life after work
$REMLIFE_{bw}$	Remaining life before work
USFLIFEW	Useful life of new work

For production-based analysis of gravel roads the above equation will be used only if the useful life has been specified in years.

The parameters $CESAL_{aw}$, CGL_{aw}, CA_{aw} will be reset as described below.

Production-based method:

- If useful life/component age is given in MESAL:

$$CESAL_{aw} = MAX[0, (CESAL_{bw} - DESALW)] \quad ...(42)$$

where:

$CESAL_{aw}$ Cumulative ESAL after work

$CESAL_{bw}$ Cumulative ESAL before work

DESALW USFLIFEW expressed in terms of MESAL

- If useful life is given in IGT (mm):

$$CGL_{aw} = MAX[0, (CGL_{bw} - \Delta THG)] \quad ...(43)$$

where:

CGL_{aw} Cumulative gravel loss after works, (mm)

CGL_{bw} Cumulative gravel loss before works, (mm)

ΔTHG Increase in gravel thickness specified in the works design, in mm

The increase in gravel thickness is calculated as follows:

$$\Delta THG = THG_{aw} - THG_{bw} \quad ...(44)$$

where:

THG_{aw} Gravel thickness after work (mm)

THG_{bw} Gravel thickness before work (mm)

- If useful life is given in years:

The component age CA_{aw} will be set to zero

Condition-based method:

The initial roughness IRI0 will be reset to a new value specified by the user.

The component age CA_{aw} will be set to zero.

The terminal roughness TIRI will not change over time; CIRI will be calculated annually from the road deterioration model.

For NMT lanes:

The asset valuation parameters will be reset as follows:

The parameter PCT_{aw} will be computed using Equation (39), where CAPCST is the capital cost for lane addition.

The parameter $RESPCT_{aw}$ will be computed from Equation (40), where CAPCST is the capital cost for lane addition, and RESPCTW is the residual value of the work done (i.e. lane addition).

The parameter $USFLIFE_{aw}$ will be reset equal to the design life of the work done (DLW or USFLIFEW).

The asset component age CA_{aw} will be reset to zero.

$$USFLIFE_{aw} = USFLIFEW \qquad ...(45)$$

where:

$USFLIFE_{aw}$	Useful life after work
USFLIFEW	Useful life of new work

3.5 Outputs

The most important aspect of asset valuation is the presentation of results, in terms of long term trend of asset value.

The following reports are particularly useful and should be produced for each budget scenario and investment alternative:

1 Graph of annual total asset values versus time (in years) i.e. over the analysis period

2 Tabulated annual total asset values

4 References

National Asset Management Steering Committee, (1996)

Asset Valuation and Depreciation Guidelines
The NAMS Group, New Zealand

The Institute of Asset Management, (2002)

International Infrastructure Management Manual, International Infrastructure Management Manual Version 2.0, United Kingdom Edition, UK

G5 Multiple Criteria Analysis

1 Introduction

Multiple criteria analysis provides a systematic framework for breaking a problem into its constituent parts in order to understand the problem and consequently arrive at a decision. It provides a means to investigate a number of choices or alternatives, in light of conflicting priorities. By structuring a problem within the multiple criteria analysis framework, road investment alternatives may be evaluated according to pre-established preferences in order to achieve defined objectives *(Cafiso et al., 2002)*.

The analytical framework of HDM-4 needs to be extended beyond technical and economic factors to consider explicitly social, political and environmental aspects of road investments. It should also take into account the opinion of others interested in the condition of the road network, such as road users, industrialists, environmental groups, and community leaders. There are instances where it is important to consider these factors when evaluating road investment projects, standards and strategies. For example, the evaluation of the following:

- a low trafficked rural road that serves a politically or socially sensitive area of the country
- the frequency of wearing course maintenance for particular road sections for which the economics are secondary to the minimisation of noise and intrusion from traffic (e.g. adjacent to hospitals)
- cases where national pride is deemed paramount, for example, the road leading between a main airport and the capital city
- roads of strategic/security importance to the country

In many situations, the definition of investment standards and strategies for cases similar to the examples described above is usually effected on an ad hoc basis. A systematic approach, that is auditable, for the definition of road investment standards and strategies, which takes into account not only the expertise of the road engineer and economic considerations, but also environmental, social and political aspects, is therefore required.

Economic analysis requires that all impacts should be quantified in monetary terms. Although a number of monetary valuation techniques are available for quantifying environmental and social impacts, most of these impacts, and in particular political impacts of road investment may be extremely difficult to quantify in such a manner. In addition, it is extremely difficult in practice to obtain information on the monetary values for the whole range of parameters which may have to be considered.

An alternative available tool, which does not require monetary valuation and which caters for the requirements of the issues described above, is Multicriteria analysis (MCA). This Section describes the MCA method implemented in HDM-4 that considers a number of impacts within a unified decision-making framework.

2 Components of MCA

MCA basically requires the clear definition of possible alternatives, together with the identification of the criteria under which the relative performance of the alternatives in achieving pre-established objectives is to be measured. Thereafter it requires the assignment of preferences (i.e. a measure of relative importance, or weighting) to each of the criteria *(Cafiso et al., 2002)*.

2.1 Investment alternatives

Several investment alternatives can be analysed to determine, for example, which is the most cost-effective to implement. An alternative is one of a set of mutually exclusive works alternatives specified as options to be analysed for a road section. It could consist of different works options applied to various sections making up the study. A section option (or section alternative) consists of one or more works standards combined logically. For example, the resurfacing of a road section constitutes a section option. Similarly the existing maintenance practices would constitute another option for the same section. Standards refer to the targets or levels of conditions and performance that a road administration aims to achieve. Road agencies set up different standards that can be applied in practical situations in order to meet specific objectives that are related to functional characteristics of the road network system

2.2 Objectives and criteria

Perhaps the most important component of the MCA process is the identification of the objectives relevant to the problem of defining investment alternatives, together with their associated criteria. A general objective may be specified from several viewpoints; for example economic, environmental, social and political.

From the economic viewpoint, the main objective in highway development and management studies could be the minimisation of the total transport costs, or the maximisation of NPV. This aims at balancing the costs borne by the road administration and road users. These costs are computed endogenously within the HDM-4 system. Other economic impacts that are not internally modelled in HDM-4 (e.g., increase in agricultural productivity, increase in commercial activities, etc) could be quantified externally and input into the MCA framework.

The main objective from the environmental viewpoint is the minimisation of all the unwanted effects on the environment caused by traffic and road works. The following effects are modelled internally in HDM-4: pollution from vehicle emissions and energy use. Other environmental effects that may be included in the MCA framework include ecological impact, vibration caused by traffic, dust pollution (on unsealed roads); visual intrusion and aesthetic impacts; and possibly water and ground contamination due traffic and road works. These would constitute a set of criteria to measure the performance of the alternatives in achieving the general environmental objective.

The social impact of road investment include access to better education and health facilities, safety of road users and those living in the vicinity of roads, improvement of quality of life as measured by accessibility, equity and property value; and the promotion of tourism and workplace activity.

With respect to the political viewpoint several objectives may be identified depending on local, regional and national situations. These may include consideration of minorities to ensure that there is a perception of fairness in providing road access, the promotion of political stability, etc.

2.3 Attributes and measurement scales (Performance)

Attributes are surrogate measures of performance, and they may measure the achievement of objectives directly or indirectly. The attributes from HDM-4 outputs are mostly direct measures of the achievement of objectives.

The measurement scale for an attribute is referred to as the performance index, which on the economic objective may be an economic indicator such as the net present value (NPV). This indicator is normally calculated by comparing the economic impact of the implementation of each alternative set of standards against the economic impact of the 'do minimum' scenario. In this application the alternatives with higher NPV would be preferred to alternatives with lower NPV.

2.4 Preferences (weightings)

The selection of a particular set of investment alternatives will greatly depend on the relative importance (or weights) assigned to each criterion. The identification of those responsible for defining the weights will depend on the extent of the applicability of the investment alternatives being defined, whether they are local, regional, national, or whether the standards defined are legally binding or are simply guidelines. Ideally, all stakeholders together with those involved in the identification of objectives and the measurement scales for quantifying attributes should be involved in the process of deciding the relative importance. Consequently, the different views of environmentalists, social scientists, representatives of the community, engineers and politicians may be combined in a rational way to reach weightings that are acceptable to all.

3 MCA framework

3.1 Outline of the MCA framework

3.1.1 Analytic Hierarchy process

The Analytic Hierarchy Process (AHP) method has been selected for implementation in HDM-4 because it systematically transforms the analysis of competing objectives to a series of simple comparisons between the constituent elements. In particular, the approach does not require an explicit definition of trade-offs between the possible values of each attribute (i.e. it is not necessary to build utility functions), and it allows users understand the way in which outcomes are reached and how the weightings influence the outcomes. Hence, the approach is useful when the decision maker needs to decide whether an alternative option is better than another option on the basis of all the criteria and to easily determine the relative importance of these criteria. It is an attractive methodology as the decision makers may focus, in turn, on each small part of the problem. AHP is based on “pairwise” comparisons of alternatives for each of the criteria to obtain the ratings *(Saaty, 1990)*.

3.1.2 Analysis sequence

The overall analytical framework can be illustrated as in Figure G1.2a, where the outer analysis loop shows that economic analysis and MCA procedures can be performed for each scenario separately. MCA has been implemented in project analysis application of HDM-4 to select the best or most efficient investment alternative from a set of user-defined choices in meeting pre-established objectives.

The overall analysis procedure for multicriteria analysis within HDM-4 can be summarised by the following steps:

1 Define all the input data required for HDM-4 analysis including investment alternatives to be compared.

2 Run HDM-4 to produce outputs that can be used as attributes for each road section and investment alternative (i.e. the average IRI values, energy use, volume-capacity ratio, emission quantities, NPV, RAC, RUC, and accident numbers).

3 Define all the input data required for MCA: objectives/criteria, relative importance (weight) of each criterion, parameters for calculating the performance indices for each criterion and for each investment alternative.

4 Establish a criteria hierarchy matrix (HM) using the relative weights of the criteria. Derive a normalised hierarchy matrix (NHM) and compute the total vector of priorities (TPV). In mathematical terms, the principal eigenvector of HM is computed, and when normalized, becomes the vector of priorities. Verify the consistency of NHM. (See Section 3.3)

5 Determine the performance index for each criterion, using HDM-4 output or exogenous data. For each criterion define the reference value, on which basis every investment alternative will be compared, and compute the performance vector (PV). For each criterion, the HDM-4 default reference value will be either the maximum or minimum value that characterises all the investment alternatives defined in the study. The user may change this reference value if necessary. (See Section 3.4)

6 Build the matrix of comparisons (MC) from the performance vectors (PV) calculated for each criterion as described in Section 3.4. (See Section 3.5)

7 Determine the ranking vector for all the investment alternatives considered in the study. The ranking vector is obtained from the product of the matrix of comparisons (MC) and the total vector of priorities (TPV). (See Section 3.6)

8 Output a list of sections with the ranking index of each investment alternative.

3.2 Input data requirements

There are four major inputs for carrying out MCA: investment alternatives, criteria/ objectives and the attributes under which the alternatives are to be compared, and a statement of preferences on the set of criteria/objectives.

3.2.1 Alternatives

A clear definition of mutually exclusive investment alternatives to be compared is required from the user. Any number of investment alternatives may be specified for a HDM-4 run. However, it should be noted that when the number of criteria and alternatives is large this results in a large number of pair-wise comparisons, which reduce the practicability of MCA.

3.2.2 Criteria and objectives

Table G5.1 shows the set of criteria that is supported in the current version of HDM-4. This is considered under the following categories: economic, safety, functional level of service, environment, energy use, social impacts and political impacts. The user is able to select the criteria they wish to include in the multicriteria analysis.

It is important that the user selects the criteria logically in order to avoid the problem of double counting in some situations. For example, if accident is considered both in the road user cost criterion in monetary terms and in the safety criterion as number of accidents this would lead to double counting. In this particular case, the HDM-4 system will automatically use only the vehicle operating cost (VOC) and travel time cost components of RUC. Another example that leads to double counting of effects relates to inclusion of travel time in monetary terms within the road user costs criterion and in the congestion level criterion (measured in terms of volume-capacity ratio). In this case the HDM-4 system will adopt the VOC and accident cost components of RUC.

Table G5.1: Criteria Supported in HDM-4 Multicriteria Analysis

Category	Criteria/Objectives	Attributes
Economic	Minimise road user costs (RUC)	Total road user costs are calculated internally within HDM-4 for each alternative.
	Maximise net present value (NPV)	Economic net benefit to society is calculated internally within HDM-4 for each alternative.
Safety	Reduce accidents	Total number and severity of road accidents. These are calculated internally within HDM-4.
Functional service level	Provide comfort	Provide good riding quality to road users. This is defined on the basis of average IRI (international roughness index). The average IRI is calculated internally within HDM-4.
	Reduce road congestion	Delay and congestion effects. Level of congestion is defined in terms of volume-capacity ratio (VCR). VCR values are calculated internally within HDM-4.
Environment	Reduce air pollution	Air pollution is measured in terms of quantities of pollutants from vehicle emissions, which are computed internally within HDM-4.
Energy	Maximise energy efficiency	Efficiency in both global and national energy use in the road transport sector. Energy use is calculated internally within HDM-4.
Social	Maximise social benefits	Social benefits include improved access to social services (e.g. schools, health centres, markets, etc.). A representative value is externally user-defined for each alternative.
Political	Consider political issues	Fairness in providing road access, promotion of political stability, strategic importance of roads, etc. A representative value is externally user-defined for each alternative.

Note that by using the ranking indices and road agency costs the MCA analysis could be taken a step forward to prioritise investment alternatives under budget constraints. Road agency cost (RAC) is therefore not included in the set of criteria available for MCA analysis in order to avoid the problem of double counting. (This feature will be implemented in a later version).

3.2.3 Weightings (Relative importance)

The user (on behalf of the stakeholders) must assign a weighting for each of the criteria selected. These weights are numerical values, between 1 and 9, which represent the importance of one criterion relative to the other based on the scale given in Table G5.2. The user has to choose a base criterion to be used as the basis for comparing all the other selected criteria. The relative weight of the base criterion will always be unity (one). The default value is ‘equally preferred’ denoted by a numerical value of 1.

A criteria hierarchy matrix can be established by carrying out a number of pair-wise comparisons, in which each criterion is compared to all the other criteria, according to their performance in achieving the pre-established objective. This involves assignment of weights or numerical judgments ranging between 1 and 9 to represent the importance of one criterion relative to the other. Assign a value of 1 if both criteria are equally important, and a value of 9 if the criterion to be compared is clearly more important than the other. Intermediate values are assigned according to their relative importance.

Table G5.2: Relative Weightings for the Criteria

Intensity of importance	Definition
1	Equally preferred
2	Equal to moderately preferred
3	Moderately preferred
4	Moderately to strongly preferred
5	Strongly preferred
6	Strongly to very strongly preferred
7	Very strongly preferred
8	Very strongly to extremely preferred
9	Extremely preferred

3.2.4 Parameters for calculating performance indices

HDM-4 includes models for predicting impacts that can be used as input to the multiple criteria analysis framework (e.g. economic benefits, environmental effects, etc.). Other factors that are not internally calculated by HDM-4 could be estimated externally and input to the multicriteria analysis framework.

The calculation of performance indices for environmental, social and political criteria require the user to input additional data. These data requirements are discussed in detail in Section 3.4.

3.3 Hierarchy matrix of criteria

3.3.1 Establishing a hierarchy matrix of criteria

A hierarchy matrix of criteria **HM** should be established before carrying out a multicriteria analysis *(Cafiso et al., 2002)*. The **HM** is built using the relative weights defined by the user for the selected criteria as shown in Table G5.3. The base criterion in this example is Criterion 1. The value of the matrix cell denoted as RW_{ij} is the relative weight of criterion i with respect to criterion j. hence the values of RW_{i1} will be derived directly from the relative weights defined. Note that i = row; j= column.

Table G5.3: Hierarchy Matrix (HM)

	Criteria					
Criteria	**1**	**2**	**3**	**4**	**5**	**N**
1	1.00	RW_{12}	RW_{13}	RW_{14}	RW_{15}	RW_{1N}
2	RW_{21}	1.00	RW_{23}	RW_{24}	RW_{25}	RW_{2N}
3	RW_{31}	RW_{32}	1.00	RW_{34}	RW_{35}	RW_{3N}
4	RW_{41}	RW_{42}	RW_{43}	1.00	RW_{45}	RW_{4N}
5	RW_{51}	RW_{52}	RW_{53}	RW_{54}	1.00	RW_{5N}
N	RW_{N1}	RW_{N2}	RW_{N3}	RW_{N4}	RW_{N5}	1.00

For the rest of the matrix cells, the value of RW_{ij} for i = m and j=n are calculated from the following expression:

$$RW_{mn} = \frac{RW_{m1}}{RW_{n1}} \quad . . . (3.1)$$

where:

RW_{mn} the value of matrix cell described by row m, column n

RW_{m1} the value of matrix cell described by row m,column 1

RW_{n1} the value of matrix cell described by row n, column 1

3.3.2 Normalized hierarchy matrix

The second step is to define the normalized hierarchy matrix **NHM** based on **HM**. This is obtained by dividing the elements of each column by the sum of that column. The resulting matrix is of the format shown in Table G5.4.

Table G5.4: Normalized Hierarchy Matrix (NHM)

	Criteria					
Criteria	**1**	**2**	**3**	**4**	**5**	**N**
1	NM_{11}	NM_{12}	NM_{13}	NM_{14}	NM_{15}	NM_{1N}
2	NM_{21}	NM_{22}	NM_{23}	NM_{24}	NM_{25}	NM_{2N}
3	NM_{31}	NM_{32}	NM_{33}	NM_{34}	NM_{35}	NM_{3N}
4	NM_{41}	NM_{42}	NM_{43}	NM_{44}	NM_{45}	NM_{4N}
5	NM_{51}	NM_{52}	NM_{53}	NM_{54}	NM_{55}	NM_{5N}
N	NM_{N1}	NM_{N2}	NM_{N3}	NM_{N4}	NM_{N5}	NM_{NN}

The process of determining each element NM_{ij} of the normalized hierarchy matrix (**NHM**) can be represented by the following equation:

$$NM_{ij} = \frac{RW_{ij}}{\sum_{i=1}^{N} RW_{ij}} \quad \ldots (3.2)$$

where:

NM_{ij}	the normalized value of matrix cell described by row *i*, column *j*
RW_{ij}	the value of hierarchy matrix cell described by row *i*,column *j*

3.3.3 Vector of priorities (**TPV**)

The vector of priorities **TPV** is the principal eigenvector obtained from the normalized hierarchy matrix **NHM**. To define an element of the **TPV**, the elements in a row of the normalized matrix are added and the sum divided by the number of elements of that row. The **TPV** is a column matrix, and the element W_i in each cell of the matrix is obtained from the following expression:

$$W_i = \frac{\sum_{j=1}^{N} NM_{ij}}{N} \quad \ldots (3.3)$$

where:

W_i	the value of the column matrix cell described by row *i*
NM_{ij}	The normalized value of matrix cell described by row *i*, column *j*
N	number of elements of each row of the normalized hierarchy matrix **NHM**, that is the number of criteria selected

The resulting vector of priorities is of the format shown in Table G5.5.

Table G5.5: Vector of Priorities for Criteria Hierarchy (TPV)

TPV	=	W_1
		W_2
		W_3
		W_4
		W_5
		W_N

3.3.4 Consistency check

A consistency check is performed to verify the *consistency* of the matrix. The process involves calculation of a number of parameters as described below.

Calculate vector X

A new vector **X** is defined by multiplying each row of the Hierarchy Matrix **HM** by the vector of priorities **TPV**. This is a column matrix that can be represented as follows:

$$\mathbf{X} = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_N \end{bmatrix}$$

where the value of the element of each cell is obtained using the following equation:

$$X_i = \sum_i^N \sum_j^N RW_{ij} * W_j \qquad \text{. . . (3.4)}$$

where:

X_i the value of matrix cell described by row *i*

and all other variables are as defined previously

Calculate vector Y

Another vector **Y** is defined by dividing each of the elements of vector **X** by the corresponding element of the **TPV** matrix. This process is illustrated below.

$$Y_i = \frac{X_i}{W_i} \qquad \text{. . . (3.5)}$$

where:

Y_i the value of matrix cell described by row *i*

and all other variables are as defined previously

Y is a column matrix that can be represented as follows:

$$\mathbf{Y} = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \\ Y_5 \\ Y_N \end{bmatrix}$$

The arithmetic mean of the elements of vector **Y** is defined as λ_{max} That is, the parameter λ_{max} is calculated from this equation:

$$\lambda_{max} = \frac{\sum_i Y_i}{N} \qquad \text{. . . (3.6)}$$

where:

λ_{max} the arithmetic mean of the elements of vector **Y**

and all other variables are as defined previously

Consistency index

The consistency index (CI) is calculated using the following equation:

$$CI = \frac{(\lambda_{max} - N)}{N - 1} \qquad \text{. . . (3.7)}$$

where:

W_i the value of matrix cell described by row *m*, column *n*

NM_{ij} the value of matrix cell described by row *m*,column 1

N number of criteria selected

Random index

The random index parameter (RI) is obtained from Table G5.6. The RI values are defined according to the number of criteria used.

Table G5.6: Random Index

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.16	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The values in Table G5.6 have been coded as defaults in HDM-4.

Consistency Ratio

The consistency ratio is calculated from the following expression:

$$CR = \frac{CI}{RI} \qquad \text{. . . (3.8)}$$

where:

CR	the consistency ratio
CI	the consistency index
RI	The random index

If CR ≤ 0.1, then the consistency of the hierarchy matrix **HM** has been verified.

If CR>0.1 the user should modify the relative weights of the criteria.

3.4 Performance indices

For each section alternative or project alternative, and for each criterion a performance index should be determined. The index indicates whether an alternative is better than another with respect to a particular criterion. The method of defining the performance indices for the criteria selected is described below.

3.4.1 Economic criteria

Road user cost (RUC)

The road user cost is obtained directly from the outputs of HDM-4 run, for each investment alternative (i.e. section alternative or project alternative). The performance index showing the achievement of the objective to minimise road user cost is calculated from the following equation:

$$RUCINDEX_j = \frac{MAX(RUC) - RUC_j}{MAX(RUC) - MIN(RUC)} \qquad \text{. . . (3.9)}$$

where:

$RUCINDEX_j$ the performance index of investment alternative *j* with respect to road user cost ($0 \leq RUCINDEX \leq 1$)

MAX(RUC) the highest total discounted road user cost over the analysis period from the set of investment alternatives being compared. The default value is that calculated within HDM-4. The user may specify a new value at the beginning of the analysis

RUC_j total discounted road user cost over the analysis period for investment alternative *j*, in currency

MIN(RUC) the lowest total discounted road user cost over the analysis period from the set of investment alternatives being compared. The default value is that calculated within HDM-4. The user may specify a new value at the beginning of the analysis

Notes:

If safety has been included as one of the criteria to be analysed together with that of minimization of road user cost, then the accident cost component of RUC is excluded.

If congestion delay has been included as one of the criteria to be analysed together with that of minimisation of road user cost, then the travel time cost component of RUC is excluded.

Net benefits to society (NPV)

The net present value is calculated in HDM-4 for each investment alternative. The performance index to show the achievement of an objective to maximise benefits to society is the NPV.

3.4.2 Safety criteria

The number of road accidents by severity is calculated internally within HDM-4, for each investment alternative (i.e. section alternative or project alternative).

For each section, the difference between the total number of accidents predicted for the base option and that predicted for alternative *j* is determined as follows:

$$varAN_j = AN_n - AN_j \qquad \text{. . . (3.10)}$$

where:

$varAN_j$ the difference in predicted total number of accidents per 100 million vehicle kilometres. A positive value means a reduction in the number of accidents. For the base option $varAN_j$ will be zero

AN_n total number of accidents per 100 million vehicle kilometres over the analysis period for the base option n.

AN_j total number of accidents per 100 million vehicle kilometres over the analysis period for investment alternative *j*

The performance index to show the achievement of the objective to reduce the number and severity of accidents is calculated from the following equation:

$$ANINDEX_j = \frac{varAN_j - MIN(varAN)}{MAX(varAN) - MIN(varAN)} \quad ...(3.11)$$

where:

$ANINDEX_j$	the performance index of investment alternative *j* with respect to accident numbers
MIN(varAN)	the lowest value of varAN from the set of investment alternatives being compared
MAX(varAN)	the highest value of varAN from the set of investment alternatives being compared

3.4.3 Functional service level criteria

Comfort (RN)

The comfort attribute is the ride number (RN) calculated from the following equation *(Janoff, 1988)*:

$$RN_j = \frac{\sum_{y=1}^{Y}(5 - 2.63 \cdot \log \frac{IRI_{jy}}{0.343})}{Y} \quad ...(3.12)$$

where:

RN_j	the ride number for investment alternative *j* with respect to comfort
y	analysis year (*y* =1,2,3,…..,Y), Y is the duration of analysis period, in years
IRI_{jy}	annual average roughness for investment alternative *j*, in IRI m/km.

The performance index to show the achievement of the objective to maximise comfort is calculated from the following equation:

$$RNINDEX_j = \frac{RN_j - MIN(RN)}{MAX(RN) - MIN(RN)} \quad ...(3.13)$$

where:

$RNINDEX_j$	the performance index of investment alternative *j* with respect to comfort
MIN(RN)	the lowest value of RN computed from the set of investment alternatives being compared
MAX(varAN)	the highest value of RN from the set of investment alternatives being

compared

Road congestion

This criterion is defined by the volume-capacity ratio, VCR, which is calculated internally within HDM-4 for each investment alternative.

The performance index to show the achievement of the objective to reduce road congestion is calculated as follows:

If $VCR_j \leq XQ1$, then:

$$VCRINDEX_j = 1 \qquad \text{. . . (3.14)}$$

If $XQ1 < VCR_j < XQ2$, then:

$$VCRINDEX_j = 1 - \left[\frac{VCR_j - XQ1}{XQ2 - XQ1} \right] \qquad \text{. . . (3.15)}$$

If $VCR_j \geq XQ2$, then:

$$VCRINDEX_j = 0 \qquad \text{. . . (3.16)}$$

where:

$VCRINDEX_j$	the performance index of investment alternative *j* with respect to road congestion
VCR_j	the average volume capacity ratio over the analysis period for investment alternative *j*
XQ1	the ratio of free flow capacity to ultimate capacity
XQ2	the ratio of nominal capacity to ultimate capacity

3.4.4 Environmental Criteria

Quantities of different types of pollutants (vehicle emissions) are calculated internally within HDM-4 for each investment alternative.

The environmental impact in terms of air quality index for each investment alternative is calculated from the following equation.

$$AQI_j = \frac{\sum_y \sum_i EYR_{iyj} \frac{1}{S_i}}{\sum_i \frac{1}{S_i}} \qquad \text{. . . (3.17)}$$

where:

AQI_j the average air quality index over the analysis period for investment alternative *j*

EYR_{iyj} quantity of emissions type *i* in year *y* for investment alternative *j*, in tonnes

S_i the concentration limit of emission type *i*, see Table G5.7 for default values

The performance index to indicate the achievement of the objective to reduce air pollution is based on the air quality index (AQI), and it is calculated from the following equation:

$$AQINDEX_j = \frac{MAX(AQI) - AQI_j}{MAX(AQI) - MIN(AQI)} \quad \text{. . . (3.18)}$$

where:

$AQINDEX_j$ the performance index of investment alternative *j* with respect to air pollution

MAX(AQI) the highest value of AQI from the set of investment alternatives being compared

MIN(AQI) the lowest value of AQI from the set of investment alternatives being compared

Table G5.7: Threshold values for Concentration of Pollutants

Pollutants, i	**Threshold value, S**
Hydrocarbon	99
Carbon monoxide	99
Nitrous oxide	40
Carbon dioxide	99
Sulphur dioxide	125
Particulates	40
Lead	0.5

Notes: *These defaults provided are based on the *European Council Directive values (1999)*.

3.4.5 Energy efficiency

The amount of energy consumption is obtained directly from the outputs of HDM –4 run, for each investment alternative. The performance index to show the achievement of an objective to maximise efficiency in energy use is calculated from the following equation:

$$ENGYINDEX_j = \frac{MAX(GLOENGY) - GLOENGY_j}{MAX(GLOENGY) - MIN(GLOENGY)} \quad ...(3.19)$$

where:

$ENGYINDEX_j$	the performance index of investment alternative *j* with respect to road agency cost
MAX(GLOENGY)	the highest value of GLOENGY from the set of investment alternatives being compared
$GLOENGY_j$	total global energy use over the analysis period for investment alternative *j*, in MJ
MIN(GLOENGY)	the lowest value of GLOENGY from the set of investment alternatives being compared

3.4.6 Social concerns

The attributes required to calculate the performance index to show the achievement of an objective to maximise social benefits to society are not calculated within HDM-4. Therefore, the user has to define the performance index for each investment alternative, based on their own judgement, by choosing from the options given in Table G5.8:

Table G5.8: Performance Index for Social Concerns

Performance Index SOCINDEX	Definition
0	Major dissatisfaction
0.25	Minor dissatisfaction
0.50	Indifferent
0.75	Minor satisfaction
1	Major satisfaction

3.4.7 Political concerns

The attributes required to calculate the performance index to show the achievement of political objectives are not calculated within HDM-4. Therefore, the user has to define the performance index for each investment alternative, based on their own judgement, by choosing from the options given in Table G5.9.

Table G5. 9: Performance Index for Political Concerns

Performance Index POLINDEX	Definition
0	Major dissatisfaction
0.25	Minor dissatisfaction
0.50	Indifferent
0.75	Minor satisfaction
1	Major satisfaction

3.5 Matrix of comparisons

The matrix of comparisons (MC) is built from the performance vectors calculated for each criterion as described in Section 3.4. Table G5.10 shows the format of this matrix.

Table G5.10: Matrix of Comparisons (MC)

		Criteria					
Section	**Alternative**	**1**	**2**	**3**	**4**	**5**	**N**
1	**1**	V_{111}	V_{112}	V_{113}	V_{114}	V_{115}	V_{11N}
1	**2**	V_{121}	V_{122}	V_{123}	V_{124}	V_{125}	V_{12N}
1	**3**	V_{131}	V_{132}	V_{133}	V_{134}	V_{135}	V_{13N}
1	**4**	V_{141}	V_{142}	V_{143}	V_{144}	V_{145}	V_{14N}
2	**1**	V_{211}	V_{212}	V_{213}	V_{214}	V_{215}	V_{21N}
S	**A**	V_{MA1}	V_{MA2}	V_{MA3}	V_{MA4}	V_{MA5}	V_{MAN}

3.6 Determination of ranking vectors

The ranking vectors are the ratings used for ranking all the road investment alternatives included in the study. These are obtained by multiplying each row of MC matrix by the matrix of priorities TPV computed from the hierarchy matrix of criteria described given in Table G5.5. The ranking vectors can be presented as shown in Table G5.11.

Table G5.11: Determination of Ranking Vectors

Section-Alternatives	Ranking Vectors
11	R_{11}
12	R_{12}
13	R_{13}
14	R_{14}
21	R_{21}
SA	R_{SA}

Where the value of the elements for each cell is obtained from the following equation:

$$R_i = \sum_{i=1}^{N} \sum_{j=1}^{N} V_{ij} * W_j \qquad \text{. . . (3.20)}$$

where: i = row; j = column

3.7 Outputs

The MCA procedure described above will produce a matrix of "multiple criteria ranking numbers" or ratings for each alternative of each road section included in the study.

The alternative with the highest value is selected for each section. If ranking vector number is the same for two or more mutually exclusive alternatives then the minimum cost alternative should be selected.

4 References

Cafiso S., Di Graziano A., Kerali H.R. and Odoki J.B., (2002)

Multicriteria analysis method for pavement maintenance management
Transportation Research Record,
Journal of the Transportation Research Board No. 1816, pages 73 - 84
Transportation Research Board, Washington, DC

European Council Directive, (1999)

Limit values for pollutants in ambient air, 1999/30/EC and 1999/100/EC
The Council of the European Union, Brussels

Janoff, M.S., (1988)

NCHRP Report 308: Pavement roughness and rideability field evaluation.
Transport Research Board,
National Research Council, Washington, DC

Saaty, T.L., (1990)

The analytic hierarchy process: planning, priority setting, resource allocation
RWS Publications
Pittsburgh, Pa.