Contents

Volume 4 - Analytical Framework & Model Descriptions: Part E

Part E Road Map

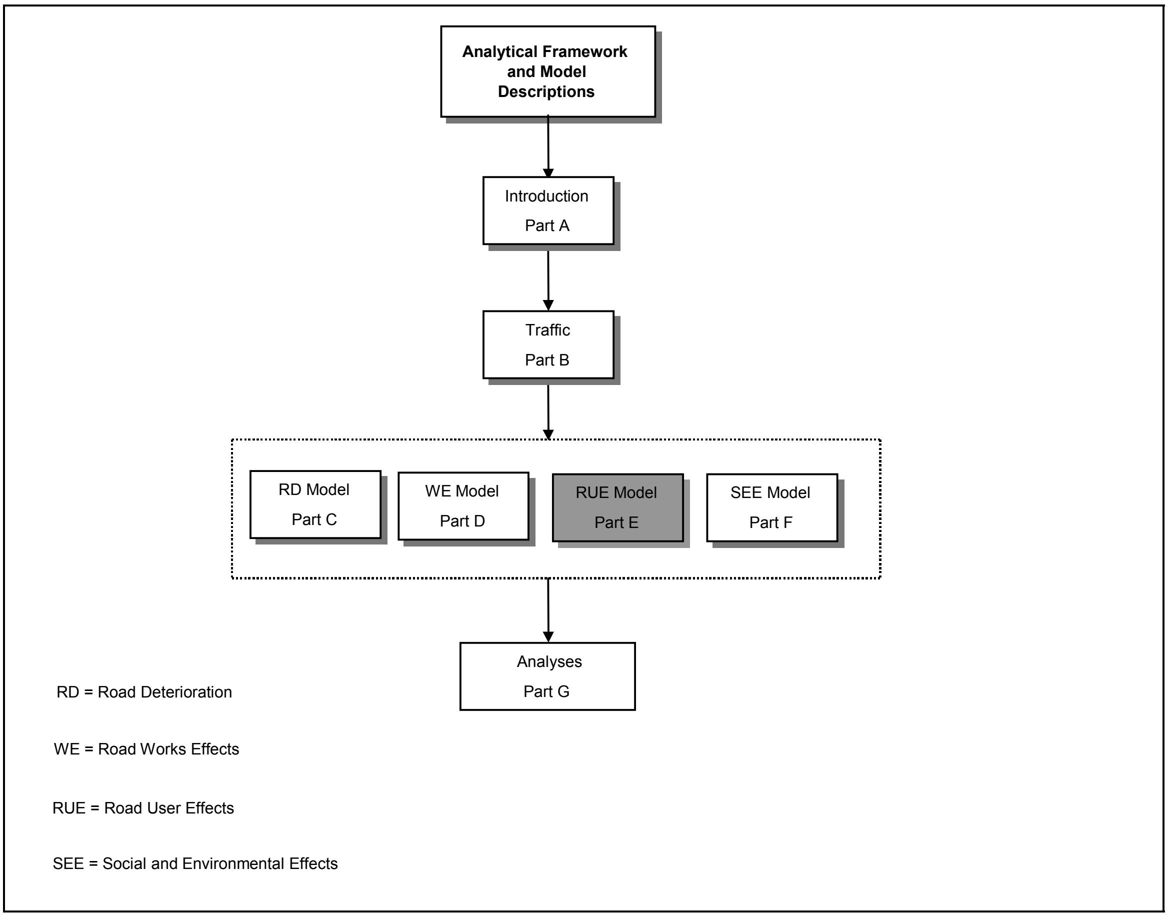


Figure E Analytical Framework and Model Descriptions Road Map

E1 Overview

1 Introduction

The modelling of Road User Effects (RUE) in HDM-4 (see Figure E1.1) comprises analysis of the following:

- **Motorised vehicle (MT) speed, operating costs and travel time** (see Figure E1.2)
- **Non-motorised transport (NMT) speed and operating costs** (see Figure E1.3)
- **Road safety** (see Chapter E4)

This chapter gives an overview of the HDM-4 vehicle classification system; and describes the different RUE components considered in HDM-4.

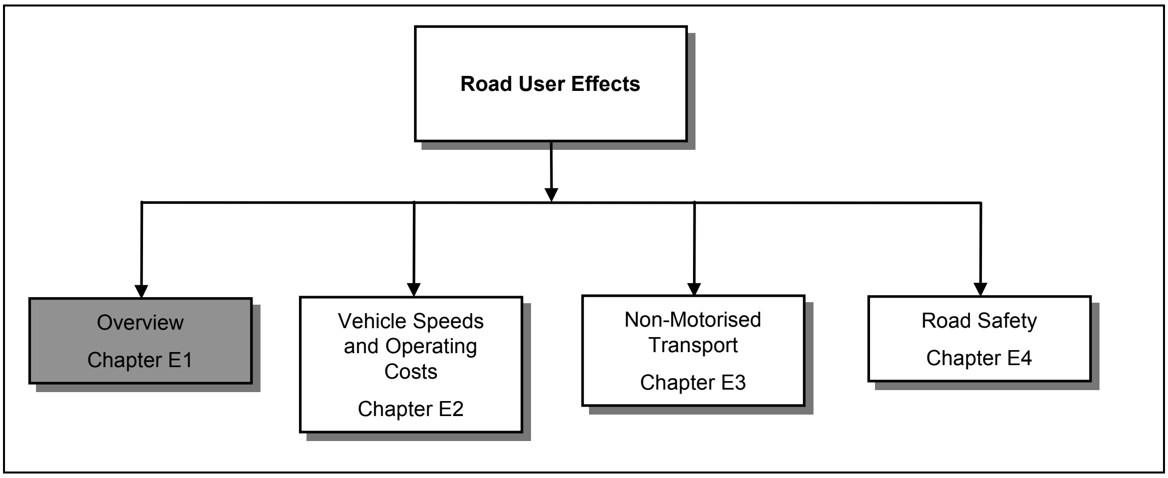


Figure E1.1 Road User Effects modules

2 Vehicle classification system

The vehicle classification system uses a flexible approach in which vehicles are divided into motorised and non-motorised categories, and each category is divided into vehicle classes (*Kerali et al., 1994*). A class comprises several vehicle types or representative vehicles, which can be user specified based on one of several standard vehicle types. This approach suits the needs of many countries and satisfies all the analytical requirements in the system.

Thus, vehicles are defined by a three-level hierarchy:

1 **Categories**

Differentiates between motorised and non-motorised transport.

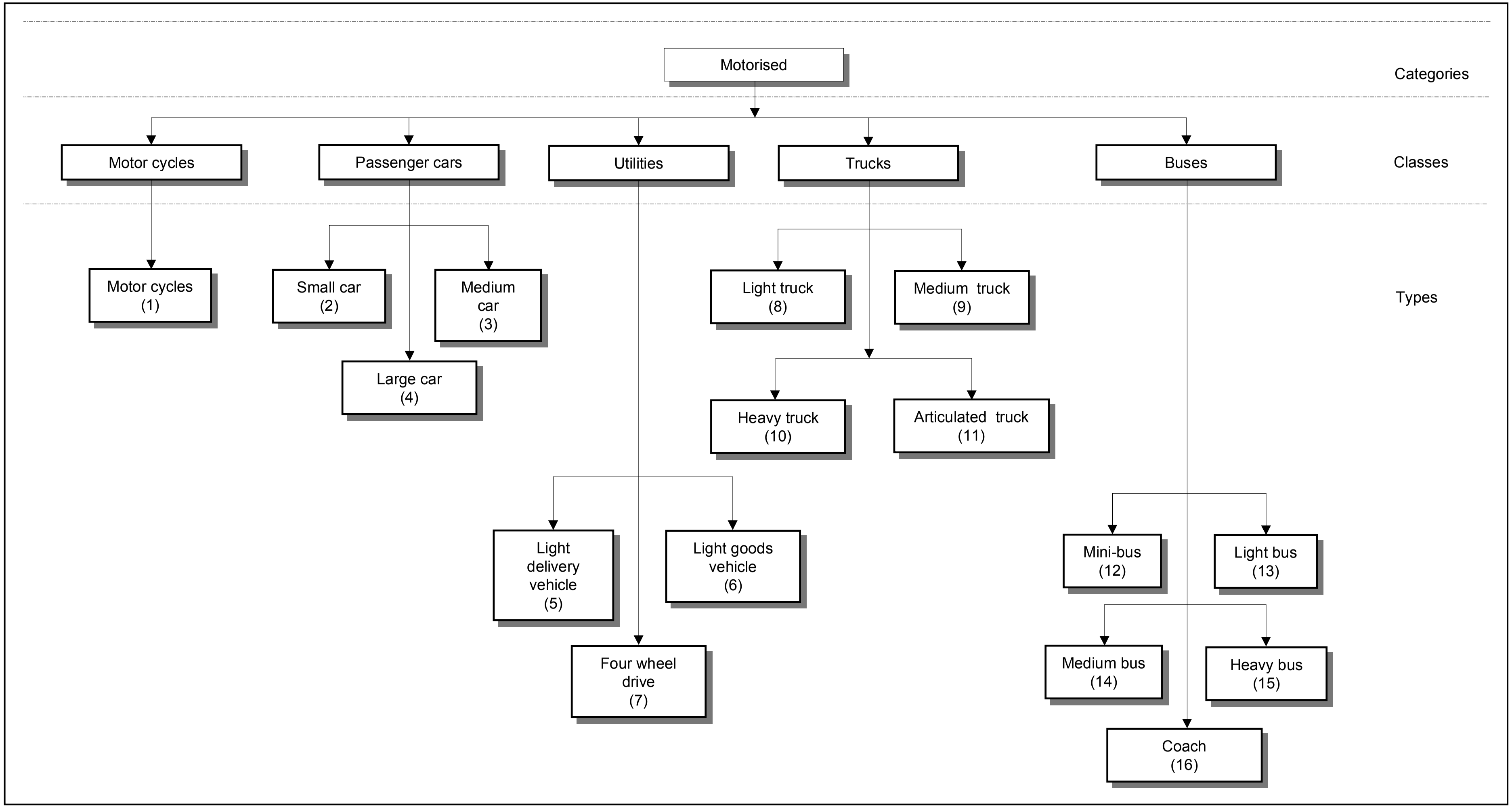
2 **Classes**

Groupings of similar vehicles, for example passenger cars, trucks.

3 **Types**

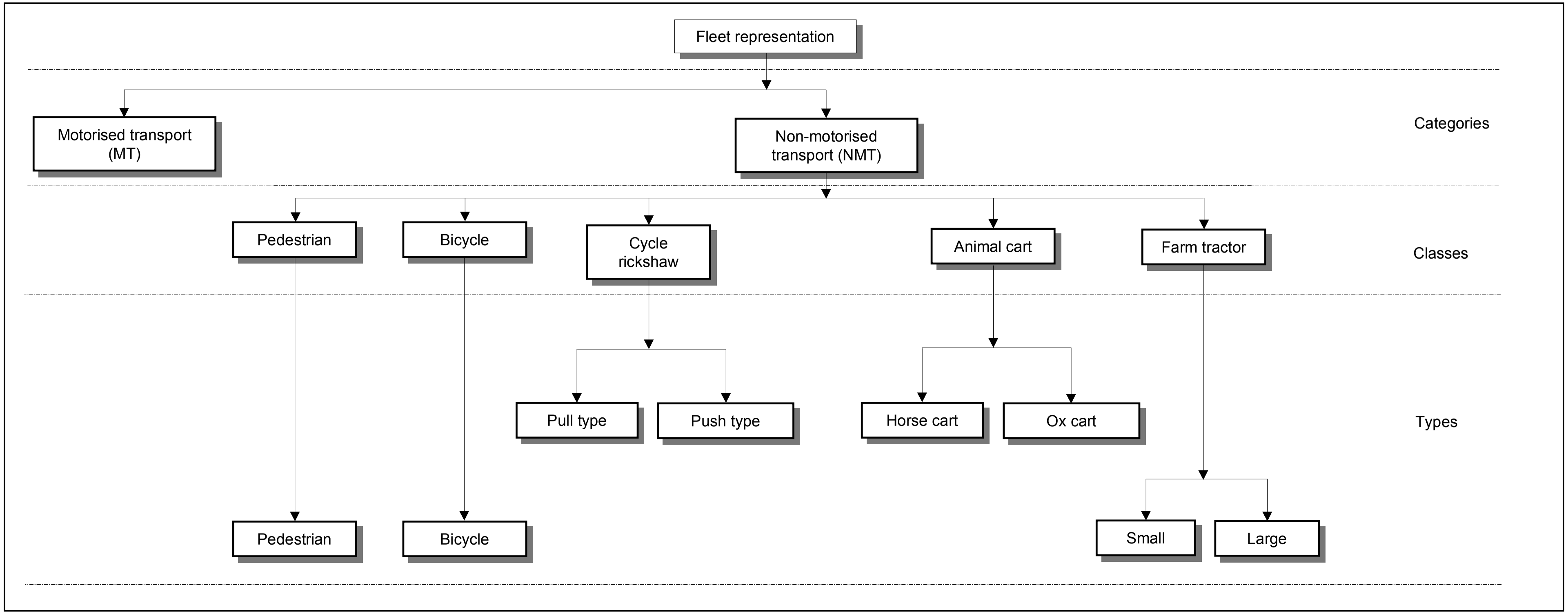
Individual representative vehicle types, for which a set of RUE relationships has been provided.

Figure E1.2 shows the hierarchical representation of motorised vehicles into categories, classes and types (*NDLI, 1995*). Figure E1.3 shows a similar hierarchical representation of non-motorised transport (*PADECO, 1996*).



Source: *NDLI (1995)*

Figure E1.2 Definition of motorised vehicle categories, classes and types



Source: *PADECO (1996)*

Figure E1.3 Definition of non-motorised vehicle categories, classes and types

3 Vehicle speeds and operating costs

Motorised vehicle speeds and operating resources are determined as functions of the characteristics of each type of vehicle and the geometry, surface type and current condition of the road, under both free flow and congested traffic conditions. The operating costs are obtained by multiplying the various resource quantities by the unit costs or prices, which are specified by the user in financial or economic terms.

Financial costs represent the actual costs incurred by transport operators in owning and operating vehicles over the road. Economic costs represent the real costs to the economy of that ownership and operation, where adjustments are made to allow for market price distortions such as taxes, subsidies, foreign exchange restrictions, labour wage laws, etc., (*Watanatada et al., 1987*).

The following components of vehicle operating cost (VOC) are considered (see Chapter E2):

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

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

4 Non-motorised transport

Non-motorised transport (NMT) modes such as bicycles, cycle rickshaws, animal carts, and pedestrians play a major role in moving passengers and freight in many countries (see Chapter E3). The use of NMT is increasing in some regions mainly because of their affordability, flexibility and cost-effectiveness in providing low cost transportation. Furthermore, the increasing focus on efficiency in energy use, and the environmental impacts arising from the ever-increasing use of motorised transport (MT), has highlighted the need for better provision of NMT facilities. This has led to the recognition that the full range of transport needs in many countries would not be catered for adequately by MT alone. Therefore, investment policies in the road transport sector should include NMT issues.

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

5 Road safety

The HDM-4 system allows users to define a series of **Accident Classes** for accident rates. These define the expected accident rates for a user-defined road description. The Accident Class defined by the user should take into account the road and traffic attributes (for example, road type, traffic level and flow pattern, presence of NMT, and geometry class). Each Accident Class defines the accident rate for each severity (that is, fatal, injury or damage only) in terms of the numbers of accidents per 100 million vehicle-kilometres. This tabular approach to implementing road safety analysis was recommended (*ISOHDM, 1995*) following a detailed review of various road safety studies, modelling and analysis methods.

For each section a users is required to specify the Accident Class. When a road is improved (for example, providing separate NMT lanes, and widening of road shoulders) a new Accident Class can be specified based on data observed for roads with similar traffic flow and geometric characteristics. Thus, it is possible to analyse the change in total numbers of accidents and the costs resulting from the improvement.

6 Total road user costs

The total road user cost comprises:

- **Motorised transport (MT) vehicle operating cost**
- **MT travel time cost**
- **Non-motorised transport (NMT) time and operating cost**
- **Accident cost**

The annual road user cost for each investment option is given by:

$$RUC_j = VOC_j + TTC_j + NMTOC_j + AC_j \qquad ...(6.1)$$

where:

RUC_j	road user cost under investment option *j* (*currency*)
VOC_j	MT vehicle operating cost under investment option *j* (*currency*)
TTC_j	MT travel time cost under investment option *j* (*currency*)
$NMTOC_j$	NMT time and operating cost under investment option *j* (*currency*)
AC_j	annual accident cost under investment option *j* (*currency*)

7 References

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E2 Motorised Vehicle Speeds and Operating Costs

1 Introduction

This chapter describes the implementation of Road User Effects (RUE) models for calculating motorised vehicle speeds, operating costs and travel time (see Figure E2.1). It provides an overview of the modelling concepts and logic, and a description of the relationships and default parameter values for each of the RUE components and HDM-4 standard representative vehicles. For further details and background to the equations refer to *NDLI (1995)* and *Watanatada et al. (1987a)*.

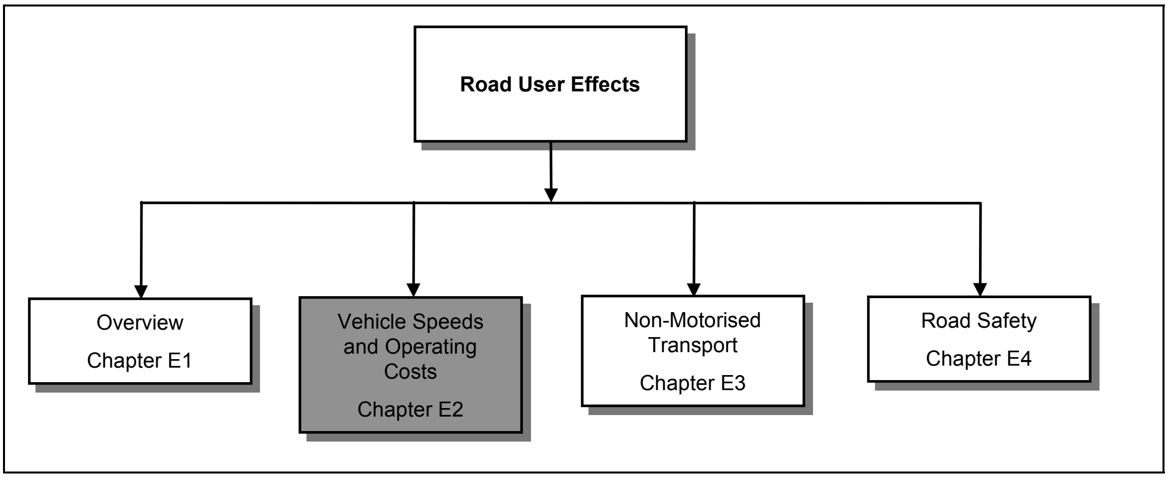

Figure E2.1 Road User Effects module

After describing the modelling concepts and logic the chapter is divided into four modules as follows:

- **Module A** (Sections 3 and 4)

  Describes the methods of calculating the different vehicle speed components.

- **Module B** (Sections 5 - 13)

  Describes models of the vehicle operating resources.

- **Module C** (Sections 14 - 16)

  Discusses travel time and unsealed road impassability.

- **Module D** (Section 17)

  Costs vehicle resources.

A list of research documents referenced from this chapter is given in Section 18.

2 Modelling concepts and logic

2.1 Representative vehicles

HDM-III allowed up to 10 representative vehicles in a single analysis (*Watanatada et al., 1987a*). HDM-4 is more flexible with respect to the number of representative vehicles that can be used in the analysis. The user may define any number of vehicles based on 16 motorised representative vehicle types. This enables the user to model, for example, several heavy trucks, each having different loading patterns. The HDM-4 standard representative vehicles are given in Table E2.1.

For modelling RUE, it is necessary to assign certain key characteristics to the representative vehicles. These include:

- **Vehicle physical attributes**

  For example, number of axles, number of wheels, etc.

- **Performance characteristics such as driving power and braking power**
- **Vehicle utilisation and service life**

The basic data for each of the 16 representative vehicle types are also given in Table E2.1. These values were estimated from a variety of sources, as reported in *NDLI (1995)*.

2.2 Primary modelling parameters

The primary data which are required together with the key vehicle characteristics for modelling RUE, may be grouped as follows:

- **Road geometry**

  Includes the road alignment data, speed limit, roadside friction factor, section length, width and the number of lanes.

- **Speed-flow relationship**

  Includes road capacity and the parameters that determine the vehicle operating speeds and flow characteristics at different traffic flow levels.

- **Traffic flow pattern**

  Includes parameters that describe the road use in terms of the hourly traffic flow distribution, and are used to determine the traffic flow in passenger car space equivalents per hour (PCSE/h) for each traffic flow period.

- **Road condition**

  Comprises data on the annual average surface roughness and texture depth for the road section. These are obtained from the output data of the Road Deterioration module.

- **Traffic**

  Comprise traffic volumes specified in terms of AADT (annual average daily traffic), traffic composition and growth for each road section. These data should be obtained from the traffic models.

- **Unit costs**

Includes costs of vehicle resources, (for example, fuel cost per litre, crew wages, new vehicle price, tyre cost, etc.) and value of time. The vehicle resource and value of time data should be defined in economic terms.

2.3 Computational procedure

The overall computational procedure for modelling motorised vehicle speeds, operating costs and travel time for each section alternative, for each vehicle type in a given analysis year can be summarised by the following steps:

1 **Calculate vehicle speeds**

The following speed components are calculated for a given road section:

(a) Free speed of each vehicle type

(b) Congested speeds by vehicle type - these are the operating speeds at different traffic flow levels

(c) Annual average operating speed of each vehicle type

(d) Annual average traffic speed – this is the weighted average speed of all the vehicles in a traffic stream.

2 **Compute quantities of vehicle operating resources**
in the following order:

(a) Fuel

(b) Lubricating oil

(c) Tyre

(d) Spare parts

(e) Maintenance labour hours

(e) Capital costs (comprises depreciation and interest)

(f) Crew hours

(g) Overhead

3 **Calculate travel time**
in terms of passenger-hours during working and non-working time, and cargo holding hours

4 **Cost vehicle resources and travel time**
by applying unit costs to the predicted quantities of the resources consumed

5 **Calculate increased operating cost**
due to reduced passability on seriously damaged unsealed roads

6 **Summarise and store data**
for use in subsequent analysis and for reporting

Table E2.1 Default representative vehicle classes and basic characteristics

Vehicle Number	Type	Description	Abbre-viation	Fuel type	Number of axles	Number of wheels	Aero-dynamic drag Coeff.	Projected frontal area (m^2)	Tare weight (t)	Operating weight (t)
1	Motorcycle	Motorcycle or scooter	MC	P	2	2	0.70	0.8	0.1	0.2
2	Small car	Small passenger cars	PC-S	P	2	4	0.40	1.8	0.8	1.0
3	Medium car	Medium passenger cars	PC-M	P	2	4	0.42	1.9	1.0	1.2
4	Large car	Large passenger cars	PC-L	P	2	4	0.45	2.0	1.2	1.4
5	Light delivery vehicle	Panel van, utility or pickup truck	LDV	P	2	4	0.50	2.0	1.3	1.5
6	Light goods vehicle	Very light truck for carrying goods (4 tyres)	LGV	P	2	4	0.50	2.8	0.9	1.5
7	Four wheel drive	Landrover/Jeep type vehicle	4WD	P	2	4	0.50	2.8	1.5	1.8
8	Light truck	Small two-axle rigid truck (approx. < 3.5 t)	LT	D	2	4	0.55	4.0	1.8	2.0
9	Medium truck	Medium two-axle rigid truck (> 3.5 t)	MT	D	2	6	0.60	5.0	4.5	7.5
10	Heavy truck	Multi-axle rigid truck	HT	D	3	10	0.70	8.5	9.0	13.0
11	Articulated truck	Articulated truck or truck with drawbar trailer	AT	D	5	18	0.80	9.0	11.0	28.0
12	Mini-bus	Small bus based on panel van chassis (usually 4 tyres)	MNB	P	2	4	0.50	2.9	1.1	1.5
13	Light bus	Light bus (approx. < 3.5 t)	LB	D	2	4	0.50	4.0	1.75	2.5
14	Medium bus	Medium bus (3.5 - 8.0 t)	MB	D	2	6	0.55	5.0	4.5	6.0
15	Heavy bus	Multi-axle or large two-axle bus	HB	D	3	10	0.65	6.5	8.0	10.0
16	Coach	Large bus designed for long distance travel	COACH	D	3	10	0.65	6.5	10.0	15.0

Source: *NDLI (1995)*

Notes:

1 Fuel type P=Petrol, D=Diesel

2 Classification of vehicle types are shown in Chapter E1

Module A: Vehicle Speeds

The average speed of each vehicle type is required for calculating vehicle operating costs, travel time, energy use and emissions. The speeds of MT vehicles are influenced by a number of factors, which include:

- Vehicle characteristics
- Road severity characteristics, for example, road alignment, pavement condition, etc.
- The presence of non-motorised transport (NMT) (see Section 3.2.5)
- Roadside friction, for example, bus stops, roadside stalls, access points to roadside development, etc. (see Section 3.2.5)
- Total MT traffic volume (see Section 4)

The methods of calculating the different vehicle speed components are described below:

- **Free speed** (see Section 3)
- **Average operating speeds at different traffic flow levels** (see Section 4)

3 Free speeds

This is defined as the speed of each vehicle travelling on uncongested sections of road in the environment under investigation. Free speeds are required for determining the operating speeds of each vehicle type on a given road section under different flow characteristics.

The modelling of free speed described in this section is focused on the individual representative vehicle types.

3.1 Free speed model

The free speeds are calculated using a mechanistic/behavioural model predicting that the steady-state speed for each vehicle type *k* is a probabilistic minimum of five constraining speeds based on driving power, braking capacity, road curvature, surface roughness and the desired speed. The expression steady-state implies that the effects of speed variations or speed change cycles along the road section are not considered. The speed constraints, generated by the interaction of road severity factors and the relevant characteristics of the vehicle, are described in Section 3.2. A more detailed representation of the methodology and its validation is given in *Watanatada et al. (1987*).

Free speed analysis over a road section is carried out separately for each of the possible two traffic-flow directions, known as the uphill segment and the downhill segment, and the results averaged for a round trip. Both idealised homogeneous segments have the same characteristics, except that the uphill is of positive grade and the downhill is of negative grade.

The modelling of the uphill speed, the downhill speed and the average round trip speed is described in sections 3.1.1, 3.1.2 and 3.1.3, respectively.

3.1.1 Uphill segment speed

The free speed for the uphill segment is given by the expression:

$$VS_{ku} = \frac{\exp\left[\frac{\sigma^2}{2}\right]}{\left[\left(\frac{1}{VDRIVEu}\right)^{\frac{1}{\beta}} + \left(\frac{1}{VBRAKEu}\right)^{\frac{1}{\beta}} + \left(\frac{1}{VCURVE}\right)^{\frac{1}{\beta}} + \left(\frac{1}{VROUGH}\right)^{\frac{1}{\beta}} + \left(\frac{1}{VDESIR}\right)^{\frac{1}{\beta}}\right]^{\beta}} \quad ...(3.1)$$

where:

VS_{ku}	the predicted steady-state speed for the uphill segment (m/s)
VDRIVEu	the speed limited by gradient and used driving power for the uphill segment (m/s) (see Section 3.2.1)
VBRAKEu	the speed limited by gradient and used braking power for the uphill segment (m/s) (see Section 3.2.2)

VCURVE the speed limited by curvature (m/s) (see Section 3.2.3)

VROUGH the speed limited by roughness (m/s) (see Section 3.2.4)

VDESIR the desired speed under ideal conditions (m/s) (see Section 3.2.5)

σ SPEED_SIG Weibull model parameter (see Table E2.2)

β SPEED_BETA Weibull model parameter (see Table E2.2)

The model parameter β determines the shape of the assumed Weibull distribution of the constraining speeds. When β approaches zero, the mean speed would be equal to the minimum of the five constraining speeds. The greater the value of β the further away the predicted mean speed will be from the constraining speed.

As described in *Watanatada et al. (1987*), the model parameter σ is an estimate of the standard error of residuals in the estimation, which involves a logarithmic transformation. The numerator of Equation 3.1 above gives the value of the bias correction factor.

3.1.2 Downhill segment speed

The free speed for the downhill segment is given by the expression:

$$VS_{kd} = \frac{\exp\left[\frac{\sigma^2}{2}\right]}{\left[\left(\frac{1}{VDRIVEd}\right)^{\frac{1}{\beta}} + \left(\frac{1}{VBRAKEd}\right)^{\frac{1}{\beta}} + \left(\frac{1}{VCURVE}\right)^{\frac{1}{\beta}} + \left(\frac{1}{VROUGH}\right)^{\frac{1}{\beta}} + \left(\frac{1}{VDESIR}\right)^{\frac{1}{\beta}}\right]^{\beta}} \qquad ...(3.2)$$

where:

VS_{kd} the predicted steady-state speed for the downhill segment (m/s)

VDRIVEd the speed limited by gradient and used driving power for the downhill segment (m/s)

VBRAKEd the speed limited by gradient and used braking power for the downhill segment (m/s)

All other parameters are as defined above in Section 3.1.1.

Table E2.2 Default steady-state speed model parameters

Vehicle Number	Model Parameters		VDRIVE	VBRAKE			
	SPEED_ SIGMA σ	SPEED_ BETA β	PDRIVE (kW)	PBRAKE (kW)	CGR_a0	CGR_a1	CGR_a2
1	0	0.151	12	5	94.9	0.85	2.80
2	0	0.151	26	20	94.9	0.85	2.80
3	0	0.151	33	20	94.9	0.85	2.80
4	0	0.151	36	20	94.9	0.85	2.80
5	0	0.151	40	25	94.9	0.85	2.80
6	0	0.151	40	20	94.9	0.85	2.80
7	0	0.151	45	25	94.9	0.85	2.80
8	0	0.191	50	45	94.9	0.85	2.80
9	0	0.164	87	70	94.9	0.85	2.80
10	0	0.110	227	255	94.9	0.85	2.80
11	0	0.110	227	255	94.9	0.85	2.80
12	0	0.151	40	26	94.9	0.85	2.80
13	0	0.191	50	45	94.9	0.85	2.80
14	0	0.191	65	70	94.9	0.85	2.80
15	0	0.110	120	120	94.9	0.85	2.80
16	0	0.110	180	180	94.9	0.85	2.80

Source: *Bennett and Greenwood (1996)*

3.1.3 Round trip speed

The average speed for a round trip is computed to correspond to the space-mean speed over the two segments, that is, the round trip distance divided by the round trip time. This is given by the harmonic mean of the uphill and downhill speeds as follows:

$$S_k = \frac{7.2}{\left[\left(\frac{1}{VS_{ku}}\right)+\left(\frac{1}{VS_{kd}}\right)\right]} \qquad ...(3.3)$$

where:

S_k the average steady-state free speed (km/h) for vehicle type *k*

All other parameters are as defined previously.

3.2 The constraining speeds

The following sub-sections describe how the constraining (or limiting) speeds are calculated.

3.2.1 Limiting speed based on road gradient and engine power (VDRIVE)

The limiting speed due to driving power is related to the used driving power and the road gradient through the balance of forces in the absence of acceleration. It is calculated by solving the following cubic equation, which is based on the hypothesis that the vehicle is driven at steady-state speed on a smooth, straight road:

$$1000 * PDRIVE = z0 * VDRIVE^3 + z1 * VDRIVE \quad ...(3.4)$$

where:

PDRIVE used driving power (kW)

z0 and z1 are functions of the forces opposing motion (see below)

The used driving power is generally less than the rated power of the engine. The forces opposing motion, under the hypothesis given above, are the aerodynamic resistance, gradient resistance and rolling resistance (see Section 5.2).

The parameters z0 and z1 are calculated as follows:

$$z0 = 0.5 * RHO * CDmult * CD * AF + b13 * CR1 * CR2 * FCLIM$$

$$z1 = \left[\begin{array}{l} b11 * CR2 * FCLIM * NUM\_WHEELS \\ + b12 * CR1 * CR2 * FCLIM * WGT\_OPER + WGT\_OPER * g * GR \end{array} \right]$$

where:

RHO	mass density of air (kg/m^3) (default value = 1.20)
Cdmult	CD multiplier
CD	aerodynamic drag coefficient
AF	projected frontal area of the vehicle (m^2)
CR1	tyre type dependent coefficient of rolling resistance
CR2	pavement dependent coefficient of rolling resistance
FCLIM	climatic adjustment factor
NUM_WHEELS	number of wheels per vehicle
WGT_OPER	vehicle operating weight (kg)
g	acceleration due to gravity taken as equal to 9.81 m/s^2
GR	average gradient of the road section (as a fraction)
b11, b12 and b13	rolling resistance parameters

The mass density of air is required for computing the aerodynamic resistance, and is given by *St. John et al. (1978)* as:

$$RHO = 1.225 * \left(1 - 2.26 * ALT * 10^{-5}\right)^{4.255} \quad ...(3.5)$$

where:

ALT road altitude, defined as the elevation of the road section above the mean sea level (m)

Rolling resistance is calculated as a function of tyre and pavement characteristics, and climatic factors.

The tyre factor CR1 depends upon the tyre type as follows:

$CR1 = 1.0$ if TYRE_TYPE = Radial

$CR1 = 1.3$ if TYRE_TYPE = Bias-ply

The pavement dependent coefficient of rolling resistance CR2 is calculated as:

$$CR2 = Kcr2 * \left(CR\_CR2\_a0 + CR\_CR2\_a1 * TD_{av} + CR\_CR2\_a2 * RI_{av}\right) \quad ...(3.6)$$

where:

Kcr2 rolling resistance factor

TD_{av} average sand patch texture depth (mm) (TD is set to zero for concrete and unsealed roads)

RI_{av} average roughness (IRI m/km)

Table E2.3 gives the default values for the various rolling resistance model parameters.

Table E2.3 Rolling resistance model parameters

		WGT_OPER < = 2500 kg				WGT_OPER > 2500 kg			
Surface class	**Surface type**	**CR_ CR2_ a0**	**CR_ CR2_ a1**	**CR_ CR2_ a2**	**Kcr2**	**CR_ CR2_ a0**	**CR_ CR2_ a1**	**CR_ CR2_ a2**	**Kcr2**
Bituminous	AM or ST	0.90	0.022	0.022	1	0.84	0.03	0.03	1
Concrete	JP, JR or CR	0.90	0.022	0.022	1	0.64	0.03	0.03	1
Unsealed	GR	1.00	0.00	0.075	1	1.00	0.00	0.075	1
Unsealed	EA	0.80	0.00	0.10	1	0.80	0.00	0.10	1
Unsealed	SA	7.50	0.00	0.00	1	7.50	0.00	0.00	1
Block	CB, BR or SS	2.00	0.00	0.00	1	2.00	0.00	0.00	1

Source: *NDLI (1995)*

Notes: The following abbreviations are used:

AM = Asphalt Mix,

ST = Surface Treatment,

JP = Jointed Plain,

JR = Jointed Reinforced,

CR = Continuously Reinforced,

CB = Concrete Block,

BR = Brick,

SS = Set Stone.

For the definition of surface types see Chapter C1.

The diameter and number of wheels influence rolling resistance as follows:

$$b11 = CR\_B\_a0 * WHEEL\_DIA$$

$$b12 = \frac{CR\_B\_a1}{WHEEL\_DIA}$$

$$b13 = \frac{CR\_B\_a2 * NUM\_WHEELS}{(WHEEL\_DIA)^2}$$

where:

WHEEL_DIA	wheel diameter (m)
NUM_WHEELS	number of wheels per vehicle
CR_B_a0 to	model coefficients

CR_B_a2

The default values for tyre parameters CR_B_a0 to CR_B_a2 are given in Table E2.4.

The rolling resistance depends upon the percentage of time travelled on snow covered (PCTDS) and water covered (PCTDW) roads:

$$FCLIM = 1 + 0.003 * PCTDS + 0.002 * PCTDW$$

The average road section gradient GR is estimated from the following expression taken from *Watanatada et al. (1987a)*:

$$GR \pm \frac{RF}{1000} \qquad ...(3.7)$$

where:

RF average road **rise** plus **fall** (m/km)

Thus, solving the cubic equation with GR = + [RF/1000] would yield the value for VDRIVEu, and solving it with GR = - [RF/1000] would yield the value for VDRIVEd.

The solution of the cubic equation is through *Descartes'* rule of signs:

$$z2 = \frac{z1}{(3 * z0)}$$

$$z3 = \frac{1000 * PDRIVE}{(2 * z0)}$$

$$DT = z2^3 + z3^2$$

if $DT > 0$:

$$VDRIVE = \sqrt[3]{\sqrt{DT} + z3} - \sqrt[3]{\sqrt{DT} - z3}$$

if $(\sqrt{DT} - z3) < 0$, set $(\sqrt{DT} - z3) = 0$

if $(\sqrt{DT} + z3) < 0$, set $(\sqrt{DT} + z3) = 0$

if $DT \leq 0$:

$$VDRIVE = MAX\left[r * \cos(z), r * \cos\left(z + \frac{2\pi}{3}\right), r * \cos\left(z + \frac{4\pi}{3}\right)\right]$$

where:

$$z = \frac{1}{3}\arccos\left(\frac{-2 * z3}{z2 * r}\right)$$

$$r = 2 * \sqrt{-z2}$$

The default values for the VDRIVE model parameters are given in Table E2.2.

Table E2.4 Parameters for calculating aerodynamic, rolling and inertial resistance

Vehicle number	Aerodynamic resistance parameters			Rolling resistance parameters						Inertial Resistance Parameters		
	CD multiplier	Aero. Drag Coeff.	Projected frontal Area (m^2)	Number of wheels	Wheel diameter (m)	Type of tyre	Tyre parameters					
	CDMULT	CD	AF	NUM_ WHEELS	WHEEL_ DIA	TYRE_ TYPE	CR_B_a0	CR_B_a1	CR_B_a2	EMRAT_a0	EMRAT_a1	EMRAT_a2
1	1.10	0.70	0.8	2	0.55	Bias	37	0.064	0.012	1.10	0	0
2	1.10	0.40	1.8	4	0.60	Radial	37	0.064	0.012	1.14	1.010	399.0
3	1.10	0.42	1.9	4	0.60	Radial	37	0.064	0.012	1.05	0.213	1260.7
4	1.10	0.45	2.0	4	0.66	Radial	37	0.064	0.012	1.05	0.213	1260.7
5	1.11	0.50	2.8	4	0.70	Radial	37	0.064	0.012	1.10	0.891	244.2
6	1.11	0.50	2.8	4	0.70	Bias	37	0.064	0.012	1.10	0.891	244.2
7	1.11	0.50	2.8	4	0.70	Bias	37	0.064	0.012	1.10	0.891	244.2
8	1.13	0.55	4.0	4	0.80	Bias	37	0.064	0.012	1.04	0.830	12.4
9	1.13	0.60	5.0	6	1.05	Bias	37	0.064	0.012	1.04	0.830	12.4
10	1.14	0.70	8.5	10	1.05	Bias	37	0.064	0.012	1.07	1.910	10.1
11	1.22	0.80	9.0	18	1.05	Bias	37	0.064	0.012	1.07	1.910	10.1
12	1.11	0.50	2.9	4	0.70	Radial	37	0.064	0.012	1.10	0.891	244.2
13	1.13	0.50	4.0	4	0.80	Bias	37	0.064	0.012	1.10	0.891	244.2
14	1.14	0.55	5.0	6	1.05	Bias	37	0.064	0.012	1.04	0.830	12.4
15	1.14	0.65	6.5	10	1.05	Bias	37	0.064	0.012	1.04	0.830	12.4
16	1.14	0.65	6.5	10	1.05	Bias	37	0.064	0.012	1.04	0.830	12.4

Source: *Bennett and Greenwood (1996)*

3.2.2 Limiting speed based on road gradient and braking capacity (VBRAKE)

For uphill segments, the value of VBRAKE is infinite, (that is, the speed on upgrades is not limited by the braking power).

$$VBRAKEu = \infty \quad ...(3.8)$$

The speed on downgrades is dependent upon the length of gradient. Once the gradient length (GL) exceeds a critical value, the brakes are used to reduce the speed. Below this critical gradient there is no effect of downgrade on speed.

The critical gradient length CGL is calculated as follows:

$$CGL = CGR\_a0 * \exp(CGR\_a1 * GR) + CGR\_a2 \quad ...(3.9)$$

where:

CGL	critical gradient length (km)
GR	average gradient of the road section (absolute value as a fraction)
a0 to a2	regression coefficients

Thus, the following two conditions need to be analysed for the downhill segment:

If GL < CGL

$$VBRAKEd = \infty \quad ...(3.10)$$

If GL > CGL,

VBRAKEd is obtained by solving the following cubic equation, which is formulated using the mechanistic principle of balancing forces:

$$-1000 * PBRAKE = z0 * VBRAKEd^3 + z1 * VBRAKEd \quad ...(3.11)$$

where:

PBRAKE used braking power of the vehicle (kW)

$$z0 = 0.5 * RHO * Cdmult * CD * AF + b13 * CR1 * CR2 * FCLIM$$

$$z1 = \begin{bmatrix} b11 * CR2 * FCLIM * NUM\_WHEELS \\ + b12 * CR1 * CR2 * FCLIM * WGT\_OPER + WGT\_OPER * g * GR \end{bmatrix}$$

All other parameters are as defined above in Section 3.2.1.

The average road gradient length, GL, (km) is estimated from the expression given below:

$$GL = \frac{1}{NUM\_RF} \quad ...(3.12)$$

where:

NUM_RF average number of road **rise** and **fall** per kilometre (minimum value = 0.1)

The solution of the above cubic equation is through *Descartes'* rule of signs:

$$z2 = \frac{z1}{3 * z0}$$

$$z3 = \frac{-1000 * PBRAKE}{2 * z0}$$

$$DT = z2^3 + z3^2$$

if DT ≥ 0

$$VBRAKEd = \infty$$

else if DT < 0

$$z = \frac{1}{3} \arccos\left(\frac{-2 * z3}{z2 * r}\right)$$

$$r = 2 * \sqrt{-z2}$$

$$VBRAKEd = r * \cos\left(z + \frac{4\pi}{3}\right)$$

The default values for the VBRAKE model parameters are given in Table E2.2 (see Section 3.1.2).

3.2.3 Limiting speed determined by road curvature (VCURVE)

The limiting curve speed is calculated as a function of the radius of curvature. It is based on the postulate that drivers select their curve speed such that the side friction generated would not cause the wheels to skid. The limiting curve speed, based on the work carried out by *McLean (1991)*, is given as:

$$VCURVE = VCURVE\_a0 * R^{VCURVE\_a1} \qquad ...(3.13)$$

where:

R average radius of road curvature (m)

VCURVE_a0 and VCURVE_a1 regression parameters

The average radius of road curvature, R, is estimated from the following expression taken from *Watanatada et al. (1987a)*:

$$R = \frac{180{,}000}{\pi * MAX\left(18/\pi, C\right)} \qquad ...(3.14)$$

where:

C average horizontal curvature of the road (deg/km)

The default values for the limiting curve speed parameters are given in Table E2.5.

Table E2.5 Default model parameters for VCURVE and VROUGH

Vehicle Number	VCURVE		VROUGH	
	VCURVE_a0	VCURVE_a1	ARVMAX (mm/s)	VROUGH_a0
1	3.9	0.34	203	1.15
2	3.9	0.34	203	1.15
3	3.9	0.34	203	1.15
4	3.9	0.34	203	1.15
5	3.9	0.34	203	1.15
6	3.9	0.34	200	1.15
7	3.9	0.34	200	1.15
8	4.8	0.29	200	1.15
9	4.8	0.29	200	1.15
10	4.6	0.28	180	1.15
11	4.2	0.27	160	1.15
12	3.9	0.34	203	1.15
13	4.8	0.29	200	1.15
14	4.8	0.29	200	1.15
15	4.6	0.28	180	1.15
16	4.6	0.28	180	1.15

Source: *Bennett and Greenwood (1996)*

3.2.4 Limiting speed based on road roughness (VROUGH)

This is the constraining speed corresponding to the maximum allowable suspension motion of the vehicle, which governs ride severity. The ride suspension motion is measured by the rate of absolute displacements of the vehicle rear axle relative to the body, which is termed the **average rectified slope** (ARS). ARS is usually expressed in units of m/km or mm/m. The ride suspension motion is related to vehicle speed and road roughness as follows:

$$ARV = V * ARS \qquad ...(3.15)$$

where:

ARV	the average rectified velocity of suspension motion of the standard Opala-Maysmeter vehicle in response to roughness (mm/s)
V	the vehicle speed (m/s)
ARS	the average rectified slope (mm/m)

The limiting speed due to the effect of road roughness is calculated as:

$$VROUGH = \frac{ARVMAX}{VROUGH\,a0 * RI_{av}} \quad ...(3.16)$$

where:

ARVMAX	the maximum allowable average rectified velocity of suspension motion of the standard Opala-Maysmeter vehicle in response to roughness (mm/s)
VROUGH_a0	regression parameter
RI_{av}	average roughness of the road (m/km)

The default values for the roughness effects parameters are given in Table E2.5 (see Section 3.2.3).

3.2.5 Desired speed (VDESIR)

This is the speed at which a vehicle is assumed to be operated in the absence of the constraints based on the vertical grade, curvature, ride severity, and traffic congestion, that is, the desired speed on a flat, straight, smooth, uncongested road section. The desired speed is influenced by driver's behaviour in response to psychological, safety, cultural, and economic considerations in addition to factors such as:

- **Road width**
- **Roadside friction**
- **The presence of non-motorised transport**
- **Speed limits and enforcement**

The desired speed in the absence of posted speed limits is calculated as:

$$VDESIR0 = VDES * XFRI * XNMT * VDESMUL \quad ...(3.17)$$

where:

VDESIR0	desired speed in the absence of posted speed limits (m/s)
VDES	desired speed adjusted for carriageway width effects (m/s)
XFRI	speed reduction factor due to roadside friction for the section

	(dimensionless, in the range 0.4 - 1; default = 1.0)
XNMT	speed reduction factor due to non-motorised transport for the section (dimensionless, in the range 0.6 - 1; default = 1.0)
VDESMUL	desired speed multiplication factor (dimensionless, in the range 0.85 - 1.3; default = 1.0). The basic model is for two lane roads. This factor is used to adapt the model for single lane roads and multi-lane highways

Since desired speeds are affected by road widths, the speed values (VDES) need to be adjusted for these effects. The adjustment is based on the work carried out by *Hoban et al. (1994)*, which assumes that there is critical width (CW1) below which speeds will be unaffected by carriageway width. Between this minimum speed (VDESMIN) and the desired speed on two-lane roads (VDES2), there is a linear increase in the speed. On roads wider than two-lanes, *Yuli (1996)* showed that there is a continued increase in speed, but at a much lower rate.

The values of VDES are adjusted as follows:

$$\text{if} \quad CW \le CW1 \qquad VDES = VDESMIN$$

$$\text{if} \quad CW1 < CW \le CW2 \qquad VDES = VDESMIN + VDES\_a3 * (CW - CW1)$$

$$\text{if} \quad CW > CW2 \qquad VDES = VDES2 + VDES\_a1 * (CW - CW2)$$

where:

CW	carriageway width (m)
CW1	critical carriageway width for a single lane road (m)
VDESMIN	the minimum desired speed on a very narrow (single lane) straight road (m/s)
CW2	minimum width for a two lane road (m)
VDES2	desired speed on a two lane road (m/s)
VDES_a3	the rate of increase in desired speed for a single to two lane road (m/s per m road width)
VDES_a1	the rate of increase in desired speed for a two or more lane road (m/s per m road width) (see Table E2.6)

The speed/width slope between CW1 and CW2 is calculated from the expression:

$$VDES\_a3 = \frac{(VDES2 - VDESMIN)}{(CW2 - CW1)}$$

The relationship between the minimum desired speed and the desired speed on two-lane roads is given as:

$$VDESMIN = VDES\_a2 * VDES2$$

where:

VDES_a2 the ratio of the desired speed on a single lane road to the desired speed on a two lane road

The default values for the desired speed model parameters are given in Table E2.6.

Table E2.6 Default model parameters for VDESIR

Vehicle Number	Desired speed (Bituminous surface roads)					
	VDES2 (m/s)	VDES_a0	VDES_a1	VDES_a2	CW1	CW2
1	40.0	0.0020	2.9	0.75	4	6.8
2	40.1	0.0020	2.9	0.75	4	6.8
3	34.8	0.0020	2.9	0.75	4	6.8
4	34.4	0.0020	2.9	0.75	4	6.8
5	42.0	0.0020	2.9	0.75	4	6.8
6	40.0	0.0020	2.9	0.75	4	6.8
7	39.2	0.0020	2.9	0.75	4	6.8
8	35.6	0.0028	0.7	0.75	4	6.8
9	29.3	0.0028	0.7	0.75	4	6.8
10	24.6	0.0033	0.7	0.75	4	6.8
11	29.1	0.0039	0.7	0.75	4	6.8
12	46.1	0.0020	0.6	0.75	4	6.8
13	34.4	0.0028	0.6	0.75	4	6.8
14	39.4	0.0028	0.6	0.75	4	6.8
15	24.8	0.0033	0.6	0.75	4	6.8
16	24.5	0.0033	0.6	0.75	4	6.8

Source: *Bennett and Greenwood (1996)*

A complete set of desired speed parameters is required for each of the four road surface classes: bituminous, block, concrete, and unsealed.

The actual desired speed is the minimum of the desired speed and the enforced speed limit:

$$VDESIR = MIN\left[VDESIR0, \frac{PLIMIT * ENFAC}{3.6}\right] \quad ...(3.18)$$

where:

PLIMIT posted speed limit (km/h)

ENFAC speed enforcement factor (default = 1.10)

3.3 One-way traffic sections

For the analysis of one-way traffic sections, the user has to define whether the direction of flow is generally uphill or downhill.

For uphill sections, the steady-state speed VS_{ku} is calculated as explained in Section 5.1.1. The average steady-state free speed (km/h) is given as:

$$S_k = 3.6 * VS_{ku} \qquad ...(3.19)$$

For downhill sections, the steady-state speed VS_{kd} is calculated as explained in Section 5.1.2. The average steady-state free speed (km/h) is given as:

$$S_k = 3.6 * VS_{kd} \qquad ...(3.20)$$

4 Traffic congestion modelling

4.1 Modelling framework

The speed-flow model adopted for motorised transport (MT) is the **three-zone** model proposed by *Hoban et al. (1994)*. This model is illustrated in Figure E2.2.

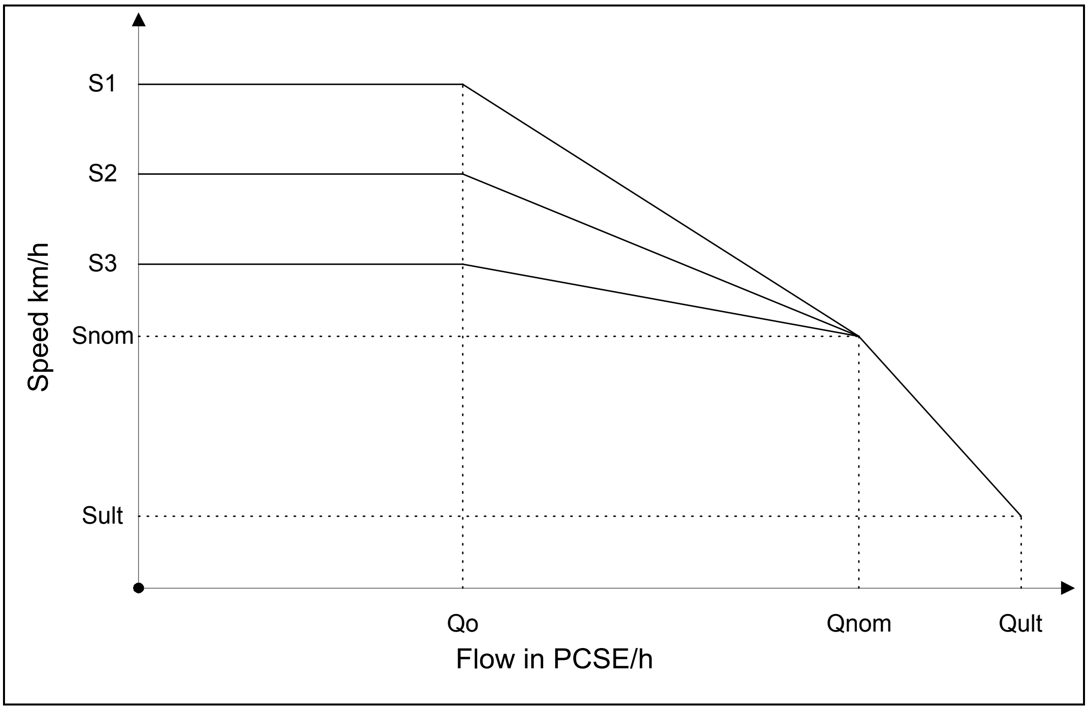

Figure E2.2 Speed-flow model

The following notation applies to Figure E2.2:

Qo	the flow level below which traffic interactions are negligible in PCSE/h
Qnom	nominal capacity of the road (PCSE/h)
Qult	the ultimate capacity of the road for stable flow (PCSE/h)
Sult	speed at the ultimate capacity, also referred to as jam speed (km/h)
Snom	speed at the nominal capacity (km/h)
S1 to S3	free flow speeds of different vehicle types (km/h)
PCSE	passenger car space equivalents (see Part B)

The model predicts that below a certain volume there are no traffic interactions and all vehicles travel at their free speeds. Once traffic interactions commence, the speeds of the individual vehicles decrease until the nominal capacity where all vehicles will be travelling at the same speed, which is estimated as 85% of the free speed of the slowest vehicle type. The speeds can then further decrease towards the ultimate capacity beyond which unstable flow will arise.

The values of the key parameters that define the speed-flow relationship vary depending upon the road type and width (see Part B), and are specified by the user. The free speeds of different vehicle types (S1, S2, etc.) and the speed at nominal capacity (Snom) are computed internally as described in Section 3 and Section 4.2, respectively.

For a given road section and for each analysis year, the modelling of traffic congestion is carried out for each traffic flow period. This is done separately for the uphill segment and the downhill segment, and the results are combined to give an average for a round trip over the road section. Further aggregation of the results is performed to obtain annual average values for each vehicle type and for all the vehicles using the road section.

The computational procedure can be summarised as follows:

1 **Adjust the speed-flow relationship**
by determining the speed at nominal capacity and using the free speeds calculated, for:

(a) Uphill segment

(b) Downhill segment

2 **For each vehicle type *k* and for each traffic flow period *p* calculate:**

(a) Steady-state congested speed for the uphill segment, the downhill segment, and for a round trip (see Section 4.2)

(b) Steady-state operating speed (see Section 4.3)

(c) Acceleration noise - a measure of the severity of speed changes (see Section 4.6)

3 **For each vehicle type *k* calculate the annual average operating speed**
(see Section 4.4)

4 **Calculate the annual average traffic speed**
(see Section 4.5)

(a) For all vehicles

(b) For heavy commercial vehicles only

4.2 Congested speeds

As traffic flows increase vehicle interactions also increase, and this leads to a reduction in speed. The resulting reduced speed is modelled as the steady-state congested speed, since it does not consider the effects of speed variations along the road section. The steady-state congested speed is modelled by traffic flow period (for the uphill and the downhill segments) and the values are used for calculating fuel consumption (see Section 5) and tyre consumption (see Section 7).

4.2.1 Uphill segment speed

The speed at nominal capacity is equal to 85% of the free speed of the slowest vehicle type:

$$VSnomu = 0.85 * MIN(VS_{ku}) \qquad ...(4.1)$$

where:

VSnomu speed at nominal capacity for the uphill segment (m/s)

VS_{ku} free speed of vehicle type *k* for the uphill segment (m/s)

The uphill segment speed, VU, at each traffic flow period *p* and flow Q_p is calculated as follows:

- **for Q_p < Qo**

$$VU_{kp} = VS_{ku} \qquad \text{...(4.2)}$$

- **for Qo ≤ Q_p ≤ Qnom**

$$VU_{kp} = VS_{ku} - \left[\frac{(VS_{ku} - VSnomu) * (Q_p - Qo)}{(Qnom - Qo)}\right] \qquad \text{...(4.3)}$$

- **for Qnom < Q_p ≤ Qult**

$$VU_{kp} = VSnomu - \left[\frac{(VSnomu - VSult) * (Q_p - Qnom)}{(Qult - Qnom)}\right] \qquad \text{...(4.4)}$$

The steady-state speed at each traffic flow period is adjusted as follows:

$$VU_{kp} = MAX\left(VU_{kp} * CALBFAC, VSult\right) \qquad \text{...(4.5)}$$

where:

VU_{kp} steady-state congested speed of vehicle type *k* during period *p* for the uphill segment (m/s)

Q_p traffic flow during period *p* (PCSE/h)

CALBFAC speed calibration factor (default = 1.0, range 0.1 to 10). This is a road type dependent **translation** factor for the speed-flow model

Here, the speeds Sult (km/h) are converted into VSult (m/s) by dividing them by 3.6.

The computed uphill segment speeds (VU_{kp}) are used in the calculation of fuel consumption (see Section 5).

4.2.2 Downhill segment speed

The speed at nominal capacity is calculated as:

$$VSnomd = 0.85 * MIN(VS_{kd}) \qquad \text{...(4.6)}$$

where:

VSnomd speed at nominal capacity for the downhill segment (m/s)

VS_{kd} free speed of vehicle type *k* for the downhill segment (m/s)

The downhill segment speed, VD, (m/s) at each traffic flow period *p* and flow Q_p (PCSE/h) is calculated as follows:

- **for Q_p < Qo**

$$VD_{kp} = VD_{kd} \qquad \text{...(4.7)}$$

- **for Qo ≤ Q_p ≤ Qnom**

$$VD_{kp} = VS_{kd} - \left[\frac{(VS_{kd} - VSnomd) * (Q_p - Qo)}{(Qnom - Qo)}\right] \qquad \text{...(4.8)}$$

- **for Qnom < Q_p ≤ Qult**

$$VD_{kp} = VSnomd - \left[\frac{(VSnomd - VSult) * (Q_p - Qnom)}{(Qult - Qnom)}\right] \qquad \text{...(4.9)}$$

These speeds (VD_{kp}) are used in the calculation of fuel consumption (see Section 5).

The steady-state speed at each traffic flow period is adjusted as follows:

$$VD_{kp} = MAX(VD_{kp} * CALBFAC, VSult) \qquad \text{...(4.10)}$$

where:

VD_{kp}	steady-state congested speed of vehicle type *k* during period *p* for the downhill segment (m/s)
Q_p	traffic flow during period *p* (PCSE/h)
CALBFAC	speed calibration factor (default = 1.0, range 0.1 to 10)

4.2.3 Round-trip congested speed

The average steady-state congested speed for a round trip (km/h) at each traffic flow period *p* and flow Q_p is calculated as follows:

$$S_{kp} = \left\{\frac{7.2}{\left[\left[\left(\frac{1}{VU_{kp}}\right) + \left(\frac{1}{VD_{kp}}\right)\right]\right]}\right\} \qquad \text{...(4.11)}$$

where:

S_{kp}	average steady-state congested speed (km/h) for vehicle type *k* for traffic flow period *p*

4.3 Vehicle operating speed

To account for the bias introduced to the analysis through the use of the **time mean speed** instead of the individual **space mean speed**, the individual congested speeds calculated above in Section 4.1 are adjusted by multiplying them with a speed-bias factor. Spot speeds are speeds measured as vehicles pass a point. Time mean speed is the arithmetic average speed of all vehicles passing a point on the road over a specified time period. Space mean speed (also called journey speed) is the average speed of all vehicles occupying a given section of road over a specified time period.

Thus, the adjusted speed, herein called **steady-state vehicle-operating speed**, is calculated as follows:

$$SS_{kp} = S_{kp} * SPEEDBIAS \qquad ...(4.12)$$

where:

SS_{kp}	vehicle operating speed (km/h) in traffic flow period *p*
S_{kp}	steady-state congested speed (km/h) for traffic flow period *p*
SPEEDBIAS	speed adjustment factor to account for the bias introduced through the use of the time mean speed instead of the space mean speed

The speed adjustment factor SPEEDBIAS is given by the expression:

$$SPEEDBIAS = 1.0000 + 0.0122 * COV - 0.8736 * COV^2 \qquad ...(4.13)$$

where:

COV	coefficient of speed variation within the traffic stream (default = 0.15)

These speed values (SS_{kp}) are used for the calculation of vehicle utilisation, crew hours, passenger travel time, and cargo transit time and for reporting purposes.

4.4 Annual average vehicle operating speed

The annual average vehicle operating speed is calculated as follows:

$$SS_{kav} = \left[\frac{\sum_{p=1}^{n} HRYR_p * HV_p * SS_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \right] \qquad ...(4.14)$$

where:

SS_{kav}	annual average operating speed of vehicle type *k* (km/h)
SS_{kp}	Operating speed of vehicle type *k* during traffic flow period *p* (km/h)

$HRYR_p$	the number of hours in traffic flow period *p*
HV_p	the hourly traffic flow in period *p* expressed as a proportion of AADT

These speeds (SS_{kav}) are used for reporting purposes.

4.5 Annual average traffic speed

The annual average traffic speed for a road section option is required for the modelling of pavement deterioration: edge-break, skid resistance and rutting due to wear by studded tyres, and are calculated as follows:

$$S = \frac{\sum_{k=1}^{K} SS_{kav}}{K} \qquad \text{...(4.15)}$$

where:

S	annual average traffic speed (km/h)
SS_{kav}	annual average operating speed of vehicle type *k* (for k = 1, 2, ..., K) (km/h)

The annual average speed of **heavy** vehicles is required for the modelling of pavement rutting due to plastic deformation, and is calculated as follows:

$$Sh = \frac{\sum_{kH=1}^{KH} SS_{kav}}{KH} \qquad \text{...(4.16)}$$

where:

Sh	annual average speed of heavy vehicles (km/h)
kH	heavy vehicles (WGT_OPER > 3500 kg) (for kH = 1, 2, ..., KH)

4.6 Acceleration effects

4.6.1 Concepts

The speed-flow model presented in Figure E2.2 shows that as flows increase, there is an increase in vehicle interactions and a decrease in speeds. The interactions are accompanied by an increase in the frequency and magnitude of vehicle accelerations and decelerations. Under ideal conditions drivers would maintain a steady-state speed without any decelerations and accelerations. However, this is not possible in reality since drivers are forced to adjust their speeds in response to traffic congestion, road alignment, pavement surface condition, the presence of NMT and other roadside activities.

The standard deviation of accelerations, referred to as the **acceleration noise**, gives an indication of the severity of speed changes. Low values of acceleration noise indicate that there are minor speed changes, large values indicate major speed changes. For each road section, it is considered that the additional vehicle operating costs due to speed change cycles is proportional to the magnitude of acceleration noise.

The total acceleration noise for a vehicle type *k* operating on a road section during traffic flow period *p* is considered in two components:

1 **Natural acceleration noise**

2 **Traffic induced acceleration noise**

These are combined to give the total acceleration noise as:

$$\sigma a_{kp} = \sqrt{\left(\sigma an_k^{\ 2} + \sigma at_{kp}^{\ 2}\right)} \qquad ...(4.17)$$

where:

σa_{kp} total acceleration noise (m/s^2) for vehicle type *k* in flow period *p*

σan_k natural acceleration noise for vehicle type *k* (m/s^2)

σat_{kp} traffic induced acceleration noise for vehicle type *k* in flow period *p* (m/s^2)

4.6.2 Natural acceleration noise

The total natural acceleration noise arises due to the following:

1 **Driver's natural behaviour** (on uncongested, straight, smooth road section without NMT and other roadside activities)

2 **Road alignment**

3 **Roadside friction**

4 **Non-motorised transport**

5 **Road surface roughness**

The total natural acceleration noise (σan_k) for each vehicle type *k* is given by the following expression:

$$\sigma an_k = MAX\left[0.1, \sqrt{MAX\left(\sigma\, adral_k^{\ 2}, \sigma\, asf_k^{\ 2}, \sigma anmt_k^{\ 2}, \sigma\, airi_k^{\ 2}\right)}\right] \qquad ...(4.18)$$

where:

$\sigma adral_k$ natural acceleration noise due to driver behaviour and road alignment (m/s^2) (default value = 0.1)

σasf_k acceleration noise due to roadside friction

$\sigma anmt_k$ acceleration noise due to non-motorised transport

$\sigma airi_k$ acceleration noise due to road roughness

The driver behaviour acceleration noise (σadr) and the road alignment acceleration noise (σaal) are combined into a single value (σdral) as it is difficult to differentiate between these two components. The other three components of natural noise are modelled as linear functions. This is done using the following relationships:

$$\sigma asf_k = 2.5 * (1.0 - XFRI) * FRIAMAX_k \qquad ...(4.19)$$

$$\sigma anmt_k = 2.5 * (1.0 - XNMT) * NMTAMAX_k \qquad ...(4.20)$$

$$\sigma airi_k = MIN\left[RIAMAX_k, \left(RI_{av} * \frac{RIAMAX_k}{AMAXRI_k}\right)\right] \qquad ...(4.21)$$

where:

XFRI	Speed reduction factor due to road side friction for the road section (0.6 to 1)
$FRIAMAX_k$	maximum acceleration noise due to side friction (default value = 0.20 m/s^2 for all vehicle types)
XNMT	Speed reduction factor due to non-motorised transport for the road section (0.6 to 1)
$NMTAMAX_k$	maximum acceleration noise due to non-motorised transport (default value = 0.40 m/s^2 for all vehicle types)
$RIAMAX_k$	maximum acceleration noise due to roughness (default value = 0.30 m/s^2 for all vehicle types)
RI_{av}	average roughness for a road section (IRI m/km)
$AMAXRI_k$	roughness at which maximum acceleration noise $RIAMAX_k$ occurs (default value = 20 for all vehicle types) (IRI m/km)

4.6.3 Traffic acceleration noise

The acceleration noise due to traffic interactions is modelled as a sigmoidal function depending upon the volume-to-capacity ratio (VCR) and the flow level (Qo) at which traffic interactions start on the speed-flow model illustrated in Figure E2.2. Thus, when traffic flow at any flow period (Q_p) is less than Qo, there is only natural acceleration noise; and when Q_p exceeds Qo there is a combination of natural and traffic acceleration noise.

The traffic induced acceleration noise for vehicle type *k* during traffic flow period *p* is calculated as:

$$\sigma at_{kp} = \sigma atmax_k \left[\frac{1.04}{1 + \exp(a0 + a1 * VCR_p)}\right] \qquad ...(4.22)$$

where:

$\sigma atmax_k$	maximum traffic acceleration noise (m/s^2) for vehicle type *k*

VCR_p volume to capacity ratio (or, relative flow) in period *p*

a0 and a1 regression coefficients

The relative flow in traffic flow period *p* is given by the expression:

$$VCR_p = \frac{Q_p}{Q_{ult}} \qquad ...(4.23)$$

The regression coefficients a0 and a1 are quantified as follows:

$$a0 = 4.2 + 23.5 * XQ1^2 \qquad ...(4.24)$$

$$a1 = -7.3 - 24.1 * XQ1^2 \qquad ...(4.25)$$

where:

XQ1 the ratio of Qo to Qult

The maximum traffic acceleration noise for each vehicle type can be determined by taking measurements of total acceleration noise under severely congested conditions. This gives the maximum total acceleration noise on the road section, which includes both natural acceleration noise and the maximum traffic induced acceleration noise. The maximum traffic acceleration noise for each vehicle type *k* is then calculated as:

$$\sigma atmax_k = \sqrt{\left(\sigma amax_k^{\;2} - \sigma an_k^{\;2} \right)} \qquad ...(4.26)$$

where:

$\sigma amax_k$ maximum total acceleration noise for vehicle type *k* (m/s^2)

σan_k natural acceleration noise for vehicle type *k* (m/s^2)

The maximum total acceleration noise is given by the expression:

$$\sigma amax_k = MAX[0.1, MIN(0.75, \sigma amaxv_k, \sigma amaxgr)] \qquad ...(4.27)$$

where:

$\sigma amaxv_k$ maximum acceleration noise for a vehicle type *k*, input by the user in Vehicle Fleet (default = 0.75 m/s^2 for all vehicle types, with a range 0.1 - 0.75)

σamaxgr the gradient adjusted maximum acceleration noise for a road section (m/s^2)

To account for the changes in driver behaviour due to gradients effect, the maximum acceleration noise for a road type (σamaxr) is adjusted using the following expression:

$$\sigma amaxgr = \sigma amaxr\{1 - 0.05 * ABS[MIN(GRAN, 10)]\} \quad ...(4.28)$$

where:

GRAN	if GR ≤ 0.02 GRAN=0
	if GR > 0.02 GRAN=100*GR
σamaxr	maximum acceleration noise for a road type (m/s^2) (range from 0.1 to 0.75, see Part B)
GR	average gradient of road section (as a fraction)

Section 5.4 describes the application of acceleration noise within the RUE models.

Module B: Vehicle Operating Resources

Savings in vehicle operating cost are the main benefits that justify road improvements. Road users perceive these benefits in terms of lower expenditures.

Vehicle operating costs depend on the following:

- **Types of vehicles using the road**
- **Traffic volume on the road section**
- **Road geometry** (particularly, the curvature, gradient and road width)
- **Road surface condition** (primarily roughness and texture depth)
- **Driver behaviour**

Changes in any of these parameters as a result of a project will result in a change in vehicle operating costs.

For a given road section and for each analysis year, vehicle resource consumption is modelled by considering the operation of each vehicle type under the conditions of each traffic flow period, and the results are aggregated into annual totals. The prediction of vehicle resource consumption is done for each vehicle type in the following order:

1 **Fuel consumption** (see Section 5)

2 **Oil consumption** (see Section 6)

3 **Tyre consumption** (see Section 7)

4 **Vehicle utilisation** (see Section 8)

5 **Parts consumption** (see Section 9)

6 **Labour hours** (see Section 10)

7 **Capital costs** (see Section 11)

8 **Crew hours** (see Section 12)

9 **Overhead** (see Section 13)

5 Fuel consumption

5.1 Modelling approach

Fuel consumption contributes significantly to the total vehicle operating cost. The HDM-4 fuel consumption model is based on the ARFCOM mechanistic fuel model *(Biggs, 1988)*. The mechanistic model predicts that fuel consumption is proportional to the total power requirements of the engine. These are made up of three components:

- **Tractive power** – this is the power required to overcome forces opposing motion
- **Engine drag** – this is the power required to overcome internal engine drag (or friction)
- **Accessory power** – this is the power required to run the vehicle accessories such as the cooling fan, power steering, air conditioner, alternator, etc.)

For each vehicle type, fuel consumption is calculated for each traffic flow period separately for the uphill segment and for the downhill segment, the results are then averaged for a round-trip over the road section.

The computational procedure can be summarised as follows:

1 **For each vehicle type *k* and for each traffic flow period *p* calculate:**

(a) Total power requirements of the engine for the uphill segment and the downhill segment (see Section 5.2)

(b) Fuel-to-power efficiency factor for the uphill segment and the downhill segment (see Section 5.3)

(c) Instantaneous fuel consumption for the uphill segment and the downhill segment. This combines the steady-state fuel consumption with the additional fuel consumption due to speed change cycles (see Section 5.4).

(d) Specific fuel consumption for a round trip over the road section (see Section 5.5)

2 **For each vehicle type *k* calculate the annual average fuel consumption** (see Section 5.6)

5.1.1 Uphill segment instantaneous fuel consumption

For the uphill segment, the instantaneous fuel consumption for each vehicle type *k* during traffic flow period *p* is given by:

$$IFC_{kpu} = MAX[IDLE\_FUEL_k,\ ZETA_{kpu} * PTOT_{kpu} * (1 + dFUEL_{kpu})] \quad ...(5.1)$$

where:

IFC_{kpu} instantaneous fuel consumption of vehicle type *k* during traffic flow period *p* (ml/s)

$IDLE\_FUEL_k$ idle rate of fuel consumption of vehicle type *k* (ml/s)

$ZETA_{kpu}$ uphill fuel-to-power efficiency factor of vehicle type *k* (ml/kW/s)

$PTOT_{kpu}$	uphill total power requirement for steady-state motion (kW)
$dFUEL_{kpu}$	additional fuel consumption factor due to vehicle speed-change cycles (that is, accelerations and decelerations) discussed in Section 5.4

The expression **steady-state** implies that speed-change cycles are not considered. Thus, the steady-state instantaneous fuel consumption for the uphill segment is calculated using Equation 5.1 above with the value of dFUEL set to zero.

5.1.2 Downhill segment instantaneous fuel consumption

For the downhill segment, the instantaneous fuel consumption for each vehicle type *k* during traffic flow period *p* is given by:

$$IFC_{kpd} = MAX\left[IDLE\_FUEL_k,\ ZETA_{kpd} * PTOT_{kpd} * \left(1 + dFUEL_{kpd}\right)\right] \quad ...(5.2)$$

where:

IFC_{kpd}	instantaneous fuel consumption of vehicle type *k* during traffic flow period *p* (ml/s)
$IDLE\_FUEL_k$	idle rate of fuel consumption of vehicle type *k* (ml/s)
$ZETA_{kpd}$	downhill fuel-to-power efficiency factor of vehicle type *k* (ml/kW/s)
$PTOT_{kpd}$	downhill total power requirement for steady-state motion (kW)
$dFUEL_{kpd}$	additional fuel consumption factor due to vehicle speed-change cycles

The steady-state instantaneous fuel consumption for the downhill segment is calculated using Equation 5.2 above with the value of dFUEL set to zero.

5.1.3 One-way traffic flow

For the analysis of one-way traffic flow, the instantaneous fuel consumption is calculated as follows:

- **For uphill segments**
  IFC_{kpu} is calculated using Equation 5.1 above
- **For downhill segments**
  IFC_{kpd} is calculated using Equation 5.2 above

5.2 Power requirements

The total power requirements of the engine comprise the tractive power needed to overcome forces opposing motion and the power to overcome engine drag and run vehicle accessories. These are calculated separately for the uphill segment and the downhill segment.

5.2.1 Tractive power

At any instant of vehicle movement along a road section, the tractive power may be positive, negative or zero depending upon the road and vehicle characteristics. The tractive power required for each vehicle type *k* during traffic flow period *p* (PTR) is given by the expression:

$$PTR_{kp} = \left[\frac{(FTR_{kp} * V_{kp})}{1000}\right] \quad ...(5.3)$$

where:

PTR_{kp} tractive power for vehicle type *k* during traffic flow period *p* (kW)

FTR_{kp} total resistance to steady-state motion experienced by vehicle type *k* during traffic flow period *p* (N)

V_{kp} Speed of vehicle type *k* during traffic flow period *p* (m/s)

- **For calculating the tractive power (PTR_{kpu}) for the uphill segment**

  Use $V_{kp} = VU_{kp}$, and FTR_{kpu} is given by Equation 5.4 below.

- **For calculating the tractive power (PTR_{kpd}) for the downhill segment**

  Use $V_{kp} = VD_{kp}$, and FTR_{kpd} is given by Equation 5.5 below.

The total resistance to **steady-state** motion comprises aerodynamic resistance, gradient resistance, rolling resistance, and curvature resistance. Inertial resistance is considered only under the regime of speed change cycles. The total resistance to steady state motion is calculated as follows:

- For the uphill segment

$$FTR_{kpu} = FA_u + FG_u + FR_u + FCV_u \quad ...(5.4)$$

- For the downhill segment

$$FTR_{kpd} = FA_d + FG_d + FR_d + FCV_d \quad ...(5.5)$$

where:

FA aerodynamic resistance to motion (N)

FG gradient resistance to motion (N)

FR rolling resistance to motion (N)

FCV curvature resistance to motion (N)

The subscripts *u* and *d* denote the uphill and downhill segments, respectively.

The components of total resistance to steady state motion are calculated as given below:

- **Aerodynamic resistance**

  The aerodynamic resistance to motion is calculated as:

$$FA = 0.5 * RHO * CDmult * CD * AF * V_{kp}^{2} \quad ...(5.6)$$

All the parameters are as defined previously.

The default parameter values to calculate aerodynamic resistance for each vehicle type are given in Table E2.4.

- **Gradient resistance**

The gradient resistance to motion is calculated separately for the uphill and downhill segments using the following expression:

$$FG = WGT\_OPER * g * GR \qquad ...(5.7)$$

where:

All the parameters are as previously defined.

For the uphill segment FG_u use the positive value of GR, and for the downhill segment FG_d use the negative value of GR.

- **Rolling resistance**

The rolling resistance to motion is calculated as:

$$FR = FCLIM * CR2 * \left(b11 * NUM\_WHEELS + CR1 * b12 * WGT\_OPER + CR1 * b13 * V_{kp}^{2}\right) \qquad ...(5.8)$$

All the parameters are as defined previously.

The default parameter values to calculate rolling resistance for each vehicle type are given in Table E2.4.

- **Curvature resistance**

The curvature resistance to motion is calculated as follows:

$$FCV = \left\{ \frac{\left(MAX\left[0, \left(\frac{WGT\_OPER * V_{kp}^{2}}{R} - WGT\_OPER * g * e\right)\right]^{2}\right)}{\left[(NUM\_WHEELS * CS) / 1000\right]} \right\} \qquad ...(5.9)$$

where:

e	superelevation of the road (as a fraction)
CS	cornering stiffness of the tyres

The cornering stiffness is calculated as:

$$CS = Kcs * \left[CS\_a0 + \frac{CS\_a1 * WGT\_OPER}{NUM\_WHEELS} + CS\_a2 * \left(\frac{WGT\_OPER}{NUM\_WHEELS}\right)^{2} \right] \qquad ...(5.10)$$

where:

Kcs	tyre stiffness factor
CS_a0 to CS_a2	model parameters

All the other parameters are as previously defined.

Table E2.7 gives the parameter values for the cornering stiffness model.

Table E2.7 Cornering stiffness model parameters

Coefficient	WGT_OPER < =2500 kg		WGT_OPER > 2500 kg	
	Bias	Radial	Bias	Radial
CS_a0	30	43	8.8	0
CS_a1	0	0	0.088	0.0913
CS_a2	0	0	-0.0000225	-0.0000114
Kcs	1	1	1	1

Source: *NDLI (1995)*

- **Inertial resistance**

The inertial resistance is not included in the total tractive power for steady-state motion. It is considered in the modelling of speed-change cycle effects described in Section 5.4. The inertial resistance is calculated as follows:

$$FI = WGT\_OPER * EMRAT * ACC \quad ...(5.11)$$

The parameter EMRAT is calculated as:

$$EMRAT = EMRAT\_a0 + EMRAT\_a1 * atan\left(\frac{EMRAT\_a2}{V_{kp}^3}\right) \quad ...(5.12)$$

where:

EMRAT_a0 to EMRAT_a2	inertial resistance parameters
ACC	vehicle acceleration in m/s^2

Note that the inertial resistance to motion is considered to be zero under steady-state conditions.

The default parameter values to calculate inertial resistance for each vehicle type are given in Table E2.4.

5.2.2 Engine and accessories power

The total power required for overcoming engine drag and running vehicle accessories (PENGACCS) by each vehicle type is calculated as a function of the engine speed and vehicle speed:

$$PENGACCS_{kp} = Kpea * PRAT_k * \left[PACCS\_a1 + \frac{(PACCS\_a0 - PACCS\_a1) * (RPM_{kp} - RPM\_IDLE)}{(RPM100 - RPM\_IDLE)} \right] \quad ...(5.13)$$

where:

$PENGACCS_{kp}$	total engine and accessories power of vehicle type *k* during traffic flow period *p* (kW)
Kpea	calibration factor for total engine and accessories power (default 1.0)
$PRAT_k$	the maximum rated engine power of vehicle type *k* (kW)
RPM_{kp}	engine speed (rev/min)
RPM_IDLE	idle engine speed (rev/min)
RPM100	the engine speed calculated at 100 km/h (rev/min)
PACCS_a0	the ratio of engine and accessory drag to rated engine power when travelling at 100 km/h
PACCS_a1	a model parameter

The parameter PACCS_a1 is related to the idle fuel consumption rate. It is calculated from the user-supplied value for IDLE_FUEL as follows:

$$a = ZETAB * EHP * Kpea^2 * PRAT * \frac{(100 - PCTPENG)}{100}$$

$$b = ZETAB * Kpea * PRAT$$

$$c = - IDLE\_FUEL$$

$$PACCS\_a1 = \frac{\left(- b + \sqrt{b^2 - 4ac}\right)}{2a} \quad ...(5.14)$$

where:

ZETAB	base fuel-to-power efficiency factor (ml/kW/s) (see Table E2.8)
EHP	decrease in engine efficiency when producing higher power
PCTPENG	percentage of the total engine and accessories power produced from the engine (default = 80)

The engine speed (RPM) depends upon the vehicle speed, and it is calculated using Equations 5.15 below to 5.16 **Error! Reference source not found.** with $V_{kp} = VU_{kp}$ for the uphill segment and $V_{kp} = VD_{kp}$ for the downhill segment:

$$RPM_{kp} = RPM\_a0 + RPM\_a1 * SP_{kp} + RPM\_a2 * SP_{kp}^{2} + RPM\_a3 * SP_{kp}^{3} \quad ...(5.15)$$

where

$$SP_{kp} = \max(20, 3.6 * V_{kp}) \quad ...(5.16)$$

The engine speed RPM100 at 100 km/h is calculated as follows:

$$RPM100 = RPM\_a0 + RPM\_a1 * 100 + RPM\_a2 * 100^{2} + RPM\_a3 * 100^{3} \quad ...(5.17)$$

The values for the above model are given in Table E2.8.

5.2.3 Total power requirement

The total power requirement of the engine (PTOT) is calculated depending on whether or not the total tractive power is negative as follows:

If $PTR_{kp} \geq 0$

$$PTOT_{kp} = \left(\frac{PTR_{kp}}{EDT} + PENGACCS_{kp}\right) \quad ...(5.20)$$

else

$$PTOT_{kp} = (PTR_{kp} * EDT + PENGACCS_{kp}) \quad ...(5.21)$$

where:

$PTOT_{kp}$	total power requirement for steady-state motion by vehicle type *k* during traffic flow period *p* (kW)
PTR_{kp}	total tractive power of vehicle type *k* during traffic flow period *p* (kW)
EDT	drivetrain efficiency
$PENGACCS_{kp}$	total engine and accessories drag power (kW)

Table E2.8 Default fuel model parameters

Vehicle number	Engine speed model parameters				Idle engine speed	Idle fuel rate	Base fuel efficiency	Decrease in efficiency	Rated engine power	Efficiency of the drivetrain	Engine and Accessories Power	
	RPM_a0	RPM_a1	RPM_a2	RPM_a3	RPM_IDLE	IDLE_FUEL	ZETAB	EHP	PRAT	EDT	PACCS_a0	PCTPENG
	RPM	RPM/(km/h)	RPM/(km/h)²	RPM/(km/h)³	RPM	ml/s	ml/kW/s		kW			
1	-162	298.86	-4.6723	-0.0026	800	0.12	0.067	0.25	15	0.95	0.20	80
2	1910	-12.311	0.2228	-0.0003	800	0.25	0.067	0.25	60	0.90	0.20	80
3	1910	-12.311	0.2228	-0.0003	800	0.36	0.067	0.25	70	0.90	0.20	80
4	1910	-12.311	0.2228	-0.0003	800	0.48	0.067	0.25	90	0.90	0.20	80
5	1910	-12.311	0.2228	-0.0003	800	0.48	0.067	0.25	60	0.90	0.20	80
6	2035	-20.036	0.3560	-0.0009	800	0.37	0.067	0.25	55	0.90	0.20	80
7	2035	-20.036	0.3560	-0.0009	800	0.48	0.057	0.10	60	0.90	0.20	80
8	2035	-20.036	0.3560	-0.0009	500	0.37	0.057	0.10	75	0.86	0.20	80
9	1926	-32.352	0.7403	-0.0027	500	0.37	0.057	0.10	100	0.86	0.20	80
10	1905	-12.988	0.2494	-0.0004	500	1.12	0.056	0.10	280	0.86	0.20	80
11	1900	-10.178	0.1521	0.00004	500	1.12	0.055	0.10	300	0.86	0.20	80
12	1910	-12.311	0.2228	-0.0003	800	0.48	0.067	0.25	60	0.90	0.20	80
13	2035	-20.036	0.3560	-0.0009	500	0.37	0.057	0.10	75	0.86	0.20	80
14	1926	-32.352	0.7403	-0.0027	500	0.37	0.057	0.10	100	0.86	0.20	80
15	1926	-32.352	0.7403	-0.0027	500	1.12	0.057	0.10	130	0.86	0.20	80
16	1926	-32.352	0.7403	-0.0027	500	1.12	0.057	0.10	150	0.86	0.20	80

Source: *Bennett and Greenwood (1996)*

5.3 Efficiency factor

The fuel-to-power efficiency factor ZETA relates instantaneous fuel consumption to the total power requirement of the engine as expressed by Equations 5.1 above and 5.2 above. For each vehicle type and for each traffic flow period ZETA is calculated separately for the uphill segment and the downhill segment as given below.

5.3.1 Uphill segment efficiency factor

$$ZETA_{kpu} = ZETAB * \left\{ 1 + EHP * \left[\frac{PTOT_{kpu} - PCTPENG * PENGACCS_{kpu} / 100}{PRAT_k} \right] \right\}$$

...(5.22)

5.3.2 Downhill segment efficiency factor

$$ZETA_{kpd} = ZETAB * \left\{ 1 + EHP * \left[\frac{PTOT_{kpd} - PCTPENG * PENGACCS_{kpd} / 100}{PRAT_k} \right] \right\}$$

...(5.23)

All the other parameters are as previously defined.

The values for the above model are given in Table E2.8.

5.4 Additional fuel consumption

5.4.1 Fuel-acceleration simulation model

The additional fuel consumption due to vehicle speed-change cycle effects is estimated using a simulation model called ACCFUEL. This model is described in detail by *Bennett (1996c)*. The model computes the additional fuel consumption factor dFUEL as a function of the total acceleration noise and the vehicle mean speed. These factors are then used in the calculation of fuel consumption, tyre consumption and spare parts consumption as described in this document. High magnitudes of total acceleration noise lead to high consumption of fuel, tyres and spare parts.

The method is as follows:

1 The user runs a calibration routine external to HDM-4 (that is, ACCFUEL) which generates a matrix of values for dFUEL as a function of mean speed and acceleration noise, for each vehicle type.

2 These matrices are read in HDM-4. A default set of matrices for the standard vehicle types is contained within HDM-4. Values of dFUEL are linearly interpolated for intermediate speeds and acceleration noise, and applied in the analyses.

5.4.2 Mean speeds and acceleration noise

The mean speeds (km/h) that are used for determining the corresponding values of dFUEL for the uphill and downhill segments are given as follows:

- **For uphill segments**

  The mean speed for each vehicle type *k* and traffic flow period *p* is given by:

$$SU_{kp} = 3.6 * VU_{kp} \quad \text{...(5.24)}$$

- **For downhill segments**

  The mean speed for each vehicle type *k* and traffic flow period *p* is given by:

$$SD_{kp} = 3.6 * VD_{kp} \quad \text{...(5.25)}$$

The total acceleration noise (σa_{kp}) for each vehicle type *k* and for each traffic flow period *p* used for determining dFUEL is calculated as described in Section 4.6.

5.5 Fuel consumption per 1000 vehicle-km

The specific fuel consumption (ml) per vehicle-kilometre on the road section is calculated from the expression:

$$SFC_{kp} = 500\left[\frac{IFC_{kpu}}{VU_{kp}} + \frac{IFC_{kpd}}{VD_{kp}}\right] \quad \text{...(5.26)}$$

where:

SFC_{kp}	specific fuel consumption (ml/km)
IFC_{kpu}	instantaneous fuel consumption for uphill travel (ml/s)
VU_{kp}	uphill speed (m/s) of vehicle type *k* in traffic flow period *p*
IFC_{kpd}	instantaneous fuel consumption for downhill travel (ml/s)
VD_{kp}	downhill speed (m/s) of vehicle type *k* in flow period *p*

For one-way traffic, the specific fuel consumption is calculated as follows:

- **For uphill segments**

$$SFC_{kp} = \frac{1000 * IFC_{kpu}}{VU_{kp}} \quad \text{...(5.27)}$$

- **For downhill segments**

$$SFC_{kp} = \frac{1000 * IFC_{kpd}}{VD_{kp}} \quad \text{...(5.28)}$$

The fuel consumption (litres per 1000 vehicle-kilometres) is thus given by the expression:

$$FC_{kp} = SFC_{kp} * FUELBIAS \qquad ...(5.29)$$

where:

FC_{kp} fuel consumption of vehicle *k* in traffic flow period *p* (l/1000 veh-km)

FUELBIAS fuel adjustment factor to account for the bias introduced through the use of the time mean speed instead of the space mean speed

The traffic stream is comprised of vehicles travelling at different speeds and, thus, different fuel consumption rates. Since fuel consumption is non-linear with speed, the mean fuel consumption does not correspond to the fuel consumption at the mean speed. The fuel adjustment factor (FUELBIAS) is therefore applied to correct the bias introduced to the analysis through the use of the mean speed instead of individual vehicle speeds. It is given by the following expression:

$$FUELBIAS = MAX(dFUEL, 1.0000 - 0.0182 * COV + 0.7319 * COV^2) \qquad ...(5.30)$$

5.6 Annual average fuel consumption

The annual average fuel consumption in litres per 1000 vehicle-kilometres of each vehicle type is required for reporting purposes, and it is calculated as follows:

$$FC_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * FC_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad ...(5.31)$$

where:

FC_{kav} annual average fuel consumption of vehicle type *k* (km/h)

$HRYR_p$ the number of hours in traffic flow period *p*

HV_p the hourly traffic flow in period *p* expressed as a proportion of AADT

FC_{kp} fuel consumption of vehicle type *k* during traffic flow period *p*

6 Lubricating oil consumption

The model used for predicting lubricating oil consumption is based on that developed by *Pienaar (1984)*, reported in English by *du Plessis, editor (1989)*. This models lubricating oil consumption in two components: oil loss due to contamination and that due to operation. Oil loss due to contamination is a function of distance between oil changes. Oil loss due to operation is calculated as a function of fuel consumption.

Thus, the oil consumption for each vehicle type *k*, for each traffic flow period *p* is calculated from the expression:

$$OIL_{kp} = OILCONT + OILOPER * FC_{kp} \qquad ...(6.1)$$

where:

OIL_{kp}	oil consumption (l/1000 km)
OILCONT	oil loss due to contamination (l/1000 km)
OILOPER	oil loss due to operation (litre/litre)
FC_{kp}	fuel consumption (l/1000 km) in traffic flow period *p*

The loss due to contamination is determined as follows:

$$OILCONT = \frac{OILCAP}{DISTCHNG} \qquad ...(6.2)$$

where:

OILCAP	engine oil capacity (litres)
DISTCHNG	distance between oil changes (1000s kilometres)

The values in Table E2.9 are the defaults for oil consumption model values.

Table E2.9 Default oil consumption model values

Vehicle type	Distance between oil changes (km)	Engine oil capacity (l)	Oil loss due to operation OILOPER
Motorcycle	5000	2.0	0.0014
Passenger car	10000	4.0	0.0028
Light goods and delivery vehicle, mini-bus, 4WD	7500	5.0	0.0028
Light and medium truck	9000	14.0	0.0021
Heavy and articulated truck	10000	31.0	0.0021
Light and medium bus	8000	14.0	0.0021
Heavy bus and coach	8000	20.0	0.0021

Source: *Bennett and Greenwood (1996)*

The annual average oil consumption (litres per 1000 vehicle-kilometres) is given by:

$$OIL_{kav} = OILCONT + OILOPER * FC_{kav} \quad ...(6.3)$$

where:

OIL_{kav} oil consumption (l/1000 km)

OILCONT oil loss due to contamination (l/1000 km)

OILOPER oil loss due to operation (litre/litre)

FC_{kav} annual average fuel consumption (l/1000 km)

7 Tyre consumption

7.1 Modelling approach

The tyre consumption model is based on slip energy theory used in the HDM-III model. As described by *Watanatada et al. (1987a)*, the tyre consumption of a vehicle is proportional to the energy requirements. The energy requirements are calculated as a function of the circumferential, lateral and normal forces acting on each wheel.

The rate of tyre consumption is expressed in terms of the number of equivalent new tyres consumed per 1000 vehicle-kilometres for each vehicle wheel. This is calculated separately for the uphill and the downhill segments. The results are then the averaged to represent the tyre consumption for a round trip over the road section.

The computational procedure can be summarised as follows:

1 **For each vehicle type *k* and for each traffic flow period *p* calculate:**

(a) The circumferential, lateral and normal forces acting on a tyre for the idealised uphill and downhill segments (see Section 7.2.2)

(b) The tyre energy for the uphill segment and the downhill segment (see Section 7.2.1)

(c) Tyre consumption per 1000 vehicle-kilometres for a round trip over the road section (see Section 7.3)

2 **For each vehicle type *k* calculate the annual average tyre consumption** (see Section 7.5)

7.1.1 Uphill segment tyre consumption

The number of equivalent new tyres consumed per 1000 vehicle-kilometres for each wheel of vehicle type *k* during traffic flow period *p* is calculated as follows:

$$EQNT_{kpu} = \frac{1 + 0.01 * RREC_k * NR_k}{DISTOT_{kpu}} + 0.0027 \quad ...(7.1)$$

where:

$EQNT_{kpu}$ number of equivalent new tyres consumed per 1000 veh-km for each wheel during traffic flow period *p*

$RREC_k$ retread cost as a percentage of new tyre cost (default = 15 for all vehicle types)

NR_k the number of retreads per tyre carcass

$DISTOT_{kpu}$ total distance travelled in the uphill direction by the tyre (1000s of kilometres) during traffic flow period *p*

The number of retreads per tyre carcass is given by the expression:

$$NR_k = MAX[0, NR0_k * \exp(-0.03224 * RI_{mod}) - 1] \quad ...(7.2)$$

where:

$NR0_k$	base number of recaps specified by the user (default = 1.30 for all vehicle types)
RI_{mod}	modified value of the average road roughness (m/km), see Section 7.4

The total distance travelled by a tyre carcass during traffic flow period *p* is given by:

$$DISTOT_{kpu} = (1 + NR_k)\frac{VOL_k}{TWT_{kpu}} \quad ...(7.3)$$

where:

TWT_{kpu}	the rate of tread wear (dm^3/1000 veh-km) during traffic flow period *p*
VOL_k	volume of wearable rubber (dm^3), see Table E2.10

7.1.2 Downhill segment tyre consumption

The number of equivalent new tyres consumed per 1000 vehicle-kilometres for each wheel of vehicle type *k* during traffic flow period *p* is calculated as follows:

$$EQNT_{kpd} = \frac{1 + 0.01 * RREC_k * NR_k}{DISTOT_{kpd}} + 0.0027 \quad ...(7.4)$$

where:

$EQNT_{kpd}$	number of equivalent new tyres consumed per 1000 veh-km for each wheel during traffic flow period *p*
$DISTOT_{kpd}$	total distance travelled in the downhill direction by the tyre (1000s of kilometres) during traffic flow period *p*

The total distance travelled by a tyre carcass during traffic flow period *p* is given by:

$$DISTOT_{kpd} = (1 + NR_k)\frac{VOL_k}{TWT_{kpd}} \quad ...(7.5)$$

7.2 Rate of tread wear

The rate of tread wear during each traffic flow period is calculated as a function of tangential energy. This is done separately for the uphill and downhill segments, as follows:

$$TWT_{kp} = C0tc + Ctcte * TE_{kp} \quad ...(7.6)$$

where:

TE_{kp} the tangential energy of each tyre (J-m)

C0tc constant term of the tyre tread wear model (dm^3).

Ctcte the wear coefficient of the tyre tread wear model, (dm^3/J-m)

The default values for C0tc and Ctcte are given in Table E2.10.

Table E2.10 Default tyre consumption model values

Vehicle Number	Vehicle type	NR0	C0tc	Ctcte	VOL (dm^3)
1	Motorcycle	1.30	0.00639	0.00050	0.35
2	Small car	1.30	0.02616	0.00204	1.40
3	Medium car	1.30	0.02616	0.00204	1.40
4	Large car	1.30	0.02616	0.00204	1.40
5	Light delivery vehicle	1.30	0.02400	0.00187	1.60
6	Light goods vehicle	1.30	0.02400	0.00187	1.60
7	Four wheel drive	1.30	0.02400	0.00187	1.60
8	Light truck	1.30	0.02400	0.00187	1.60
9	Medium truck	1.30	0.02585	0.00201	6.00
10	Heavy truck	1.30	0.03529	0.00275	8.00
11	Articulated truck	1.30	0.03988	0.00311	8.00
12	Mini-bus	1.30	0.02400	0.00187	1.60
13	Light bus	1.30	0.02173	0.00169	1.60
14	Medium bus	1.30	0.02663	0.00207	6.00
15	Heavy bus	1.30	0.03088	0.00241	8.00
16	Coach	1.30	0.03088	0.00241	8.00

Source: *Bennett (1996)*

7.2.1 Tangential energy

The tangential energy of each tyre is calculated as a function of the forces acting upon the tyre. This is executed separately for the uphill segment and the downhill segment, using the general expression:

$$TE_{kp} = \frac{\left(CFT_{kp}^{2} + LFT_{kp}^{2}\right)}{NFT} \qquad ...(7.7)$$

where:

CFT_{kp}	the circumferential force acting on a tyre (N)
LFT_{kp}	the lateral force acting on a tyre (N)
NFT	the normal force per tyre (N)

7.2.2 Forces acting on a tyre

There are three components of forces acting upon a tyre: circumferential, lateral and normal. These are calculated for each of the idealised road segments (that is, uphill and downhill).

- **Circumferential force**

The circumferential force CFT_{kp} is quantified as follows:

$$CFT_{kp} = \frac{(1 + CTCON_k * dFUEL_{kp})(FA_{kp} + FG_{kp} + FR_{kp})}{NUM\_WHEELS} \quad ...(7.8)$$

where:

$CTCON_k$	the incremental change of tyre consumption related to additional fuel, dFUEL, (default = 0.1)
$dFUEL_{kp}$	additional fuel consumption factor due to speed change cycle effects (see Section 5.4)
FA_{kp}	aerodynamic resistance to motion (N) (see Section 5.2.1)
FG_{kp}	gradient resistance to motion (N) (see Section 5.2.1)
FR_{kp}	rolling resistance to motion (N) (see Section 5.2.1)

All the other parameters are as defined previously.

Since the acceleration effects will result in additional longitudinal wear on the tyres, the circumferential component is increased based on the additional fuel factor (dFUEL).

- **Lateral force**

The lateral force LFT_{kp} is quantified as follows:

$$LFT_{kp} = \frac{FCV_{kp}}{NUM\_WHEELS} \quad ...(7.9)$$

where:

FCV_{kp}	curvature resistance to motion (N) (see section 5.2.1)
NUM_WHEELS_k	number of wheels per vehicle type *k*

- **Normal force**

The normal force per wheel NFT is given by the expression:

$$NFT = \frac{WGT\_OPER * g}{NUM\_WHEELS} \quad ...(7.10)$$

where:

WGT_OPER	vehicle operating weight (kg)
g	acceleration due to gravity taken as equal to 9.81 m/s^2

7.3 Tyre consumption per 1000 vehicle-km

7.3.1 Two-way traffic sections

The total tyre consumption expressed in terms of equivalent number of new tyres per 1000 vehicle-kilometres for each vehicle type *k*, for each traffic flow period *p*, is calculated from the expression:

$$TC_{kp} = \frac{[0.5 * (EQNT_{kpu} + EQNT_{kpd}) * NUM\_WHEELS]}{MODFAC_{kp}} \quad ...(7.11)$$

$$MODFAC_{kp} = VEHFAC_k * TYPEFAC * CONGFAC_{kp} \quad ...(7.12)$$

where:

TC_{kp}	number of tyres consumed per 1000 veh-km by vehicle type *k* during traffic flow period *p*
$MODFAC_{kp}$	tyre life modification factor for vehicle type *k* during traffic flow period *p*
$VEHFAC_k$	vehicle type modification factor (see Table E2.11)
TYPEFAC	tyre type modification factor (see Table E2.12)
$CONGFAC_{kp}$	Congestion effects modification factor for vehicle type *k* during traffic flow period *p*

The default values of these modification factors are supplied in Section 7.4.

The life of a single tyre of vehicle type *k* operating in traffic flow period *p*, TLIFE, (1000s kilometres) is given as:

$$TLIFE_{kp} = \frac{1000}{0.5 * (EQNT_{kpu} + EQNT_{kpd})} \quad ...(7.13)$$

7.3.2 One-way traffic sections

For uphill segments, the total tyre consumption expressed in terms of equivalent number of new tyres per 1000 vehicle-kilometres for each vehicle type *k*, for each traffic flow period *p*, is calculated from the expression:

$$TC_{kp} = \frac{[EQNT_{kpu} * NUM\_WHEELS]}{MODFAC_{kp}} \quad ...(7.14)$$

For downhill sections, the total tyre consumption expressed in terms of equivalent number of new tyres per 1000 vehicle-kilometres for each vehicle type k, for each traffic flow period p, is calculated from the expression:

$$TC_{kp} = \frac{[EQNT_{kpd} * NUM\_WHEELS]}{MODFAC_{kp}} \quad ...(7.15)$$

Tyre life ($TLIFE_{kp}$) is calculated using Equation 7.13 above with the denominator replaced with $EQNT_{kpu}$ for the uphill segment and $EQNT_{kpd}$ for the downhill segment.

7.4 Modification to the tyre consumption model

Harrison and Aziz (1998) recommended the following adjustments to the tyre consumption model:

- **Road roughness effects**

  The values of adjusted average roughness (RI_{mod}) used in Equation 7.2 above, and of VEHFAC used in Equation 7.12 above are given in Table E2.11.

Table E2.11 Roughness effects and vehicle type modification factor

Vehicle number	Adjusted roughness (RI_{mod})	VEHFAC
1, 2, 3, 4, 5, 6, 7, 8, 12, 13	$= RI_{av}$	2.0
10, 11, 15, 16	$= \min[7, RI_{av}]$	1.0
9, 14	= 7	1.0

Source: *Harrison and Aziz (1998)*

Note: A vehicle number is related to a vehicle type as given in Table E2.10

- **Tyre type effects**

  The values of tyre type modification factor, TYREFAC, used in Equation 7.12 above is given in Table E2.12.

Table E2.12 Tyre type modification factor (TYREFAC)

Tyre type	Paved roads	Unpaved roads	
		IRI ≤ 6 m/km	IRI > 6 m/km
Bias	1.00	1.00	1.00
Radial	1.25	1.20	1.00

Source: *Harrison and Aziz (1998)*

- **Traffic congestion (or acceleration) effects**

  The values of congestion effects factor ($CONGFAC_{kp}$) used in Equation 7.2 above are obtained as follows:

  - **for Qp < Qo**

    $$CONGFAC_{kp} = 1 \qquad ...(7.16)$$

  - **for Qo ≤ Qp ≤ Qnom**

    $$CONGFAC_{kp} = 1 - \left[\frac{0.3 * (Qp - Qo)}{(Qnom - Qo)}\right] \qquad ...(7.17)$$

  - **for Qnom < Qp ≤ Qult**

    $$CONGFAC_{kp} = 0.7 - \left[\frac{0.2 * (Qp - Qnom)}{(Qult - Qnom)}\right] \qquad ...(7.18)$$

7.5 Annual average tyre consumption

The annual average number of tyres consumed per 1000 vehicle kilometres for each vehicle type *k* is calculated from the formula:

$$TC_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * TC_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad ...(7.19)$$

where:

TC_{kav}	annual average number of tyres consumed per 1000 veh-km by vehicle type *k*
$HRYR_p$	the number of hours in traffic flow period *p*
HV_p	the hourly traffic flow in period *p* expressed as a proportion of AADT
TC_{kp}	number of tyres consumed per 1000 veh-km by vehicle type *k* during traffic flow period *p*

8 Vehicle utilisation and service life

Vehicle utilisation and service life are required for calculating parts consumption, capital costs, and overhead costs.

8.1 Utilisation

Vehicle utilisation is expressed in terms of the annual kilometreage driven during the annual working time. Working time as defined by *Hine (1996)* is the time spent undertaking the essential tasks of making a complete round trip, in normal circumstances. This excludes time spent idle, when the driver is eating, sleeping or otherwise resting, but includes time spent driving, loading, unloading and refuelling. In certain circumstances it may be appropriate to include the time that the vehicle must spend waiting to move forward in a queue.

8.1.1 Annual number of kilometres driven

Road investment may affect vehicle annual kilometreage through changes in journey times and trip distances. The utilisation of commercial vehicles can be quite sensitive to these changes. Although passenger car utilisation is not absolutely fixed in most situations the assumption of constant utilisation is probably appropriate.

The baseline average annual utilisation (AKM0) is either entered as a constant value by the user or calculated if the user specifies an age distribution along with the percentage of vehicles at each age:

$$AKM0 = \sum_{i=1}^{n} AKMVi * PCTVi \Big/ 100 \qquad ...(8.1)$$

where:

AKM0 baseline average number of kilometres driven per year , input by the user (km/year)

AKMVi average number of kilometres driven per vehicle of age *i* per year, input by the user (km/year)

PCTVi percentage of vehicles of age *i* in the fleet (for *i* = 1, 2, ..., *n*)

8.1.2 Annual number of working hours

The baseline average annual working time (HRWK0) is either input as a constant value by the user or calculated if the user specifies an age distribution along with the percentage of vehicles at each age:

$$HRWK0 = \sum_{i=1}^{n} HRWKVi * PCTVi \Big/ 100 \qquad ...(8.2)$$

where:

HRWK0 baseline average number of vehicle working hours per year, input by the user (hrs/year)

HRWKVi number of working hours per vehicle of age i per year

PCTVi percentage of vehicles of age i in the fleet (for i = 1, 2, ..., n)

8.2 Service life

The following two methods of calculating vehicle service life are provided:

- **Constant vehicle life method** (see Section 8.2.1)
- **Optimal vehicle life method** (see Section 8.2.2)

The user chooses which of the two methods should be used for calculating vehicle parts consumption and for modelling capital costs.

8.2.1 Constant vehicle life method

This method uses straight-line depreciation, in which the vehicle service life, LIFE, is assumed to be constant irrespective of vehicle speed and equal to the user-specified value. For details, refer to *Watanatada et al. (1987a)*.

8.2.2 Optimal vehicle life method

This is the expected service life defined as the distance at which it becomes appropriate to scrap the vehicle (see *Bennett, 1996b*). The optimal life of a vehicle under the condition of different road roughness values is determined as follows:

$$LIFEKM = \frac{LIFEKM0 * LIFEKMPCT}{100} \quad ...(8.3)$$

where:

LIFEKM the predicted optimal lifetime vehicle utilisation in kilometres

LIFEKM0 baseline average vehicle service life in kilometres

LIFEKMPCT optimal lifetime kilometreage as a percentage of baseline vehicle service life

The baseline average vehicle service life is calculated from the expression:

$$LIFEKM0 = AKM0 * LIFE0 \quad ...(8.4)$$

where:

AKM0 baseline average number of kilometres driven per vehicle per year, input by the user (km/year)

LIFE0 baseline average vehicle service life in years, input by the user

The optimal life as a percentage of the user defined baseline vehicle service life is given by:

$$LIFEKMPCT = \left[\frac{100}{1 + \exp\left(a0 * RI_{adj}^{\ a1}\right)} \right] \qquad ...(8.5)$$

where:

RI_{adj} the adjusted road roughness (IRI m/km), see Section 9.2

a0, a1 regression coefficients. The default values (for all vehicle types) are as follows:

a0 = -65.8553
a1 = -1.9194

The default values for vehicle utilisation parameters are shown in Table E2.13.

Table E2.13 Default vehicle utilisation model values

Vehicle Number	Vehicle type	AKM0 (km/year)	LIFE0 (years)	HRWK0 (h/year)
1	Motorcycle	10000	10	400
2	Small car	23000	10	550
3	Medium car	23000	10	550
4	Large car	23000	10	550
5	Light delivery vehicle	30000	8	1300
6	Light goods vehicle	30000	8	1300
7	Four wheel drive	30000	8	1300
8	Light truck	30000	8	1300
9	Medium truck	40000	12	1200
10	Heavy truck	86000	14	2050
11	Articulated truck	86000	14	2050
12	Mini-bus	30000	8	750
13	Light bus	34000	8	850
14	Medium bus	70000	7	1750
15	Heavy bus	70000	12	1750
16	Coach	70000	12	1750

9 Parts consumption

9.1 Modelling approach

Spare parts costs constitute a significant component of vehicle operating costs. The requirements for spare parts depend on vehicle age in kilometres and road surface roughness. Speed-change cycles (or acceleration and deceleration) due to traffic congestion, road alignment, the presence of NMT, roadside friction and driver behaviour also affect the rate of wear and tear of vehicle and components. The parts consumption model therefore considers the effect of vehicle age, roughness and speed-change cycles.

Parts consumption cost is expressed as a fraction of the replacement vehicle price. For each vehicle type, parts consumption is predicted for the particular operating conditions of each traffic flow period.

The computational procedure can be summarised as follows:

1 **For each vehicle type *k* calculate:**

   (a) The adjusted road roughness to be used in the model (see Section 9.2)

   (b) The age in terms of cumulative number of kilometres driven (see Section 9.3)

2 **For each vehicle type *k* and for each traffic flow period *p* calculate:**

   (a) The incremental change in parts consumption due to speed change cycles (see Section 9.4)

   (b) The parts consumption per 1000 vehicle-kilometres as a fraction of replacement vehicle price

3 **For each vehicle type *k* calculate the annual average parts consumption** (see Section 9.5)

The parts consumption for each vehicle type *k*, and for each traffic flow period *p*, is calculated as follows:

$$PC_{kp} = K0pc * \left[CKM^{KP} * \left(a0 + a1 * RI_{adj}\right) + K1pc\right]\left[1 + CPCON_k * dFUELavg_{kp}\right] \quad ...(9.1)$$

where:

PC_{kp}	parts consumption per 1000 veh-km, expressed as a fraction of the average new (or replacement) vehicle price, NVP_k,
CKM	average cumulative number of kilometres driven per vehicle type (km)
KP	the age exponent in parts consumption model
RI_{adj}	the adjusted road roughness (IRI m/km)
$CPCON_k$	incremental change factor in parts consumption due to vehicle speed change cycles effects (default value = 0.10)

$dFUELavg_{kp}$ is the average additional fuel consumption due to congestion for all speeds at a given acceleration noise as a decimal (that is, accelerations and decelerations)

a0 the constant term model parameter

a1 roughness dependent model parameter

K0pc parts consumption rotational calibration factor (default value = 1.0)

K1pc parts consumption translational calibration factor (default value = 0)

The default values for the model parameters are shown in Table E2.14, and are based on the default CKM values shown.

Table E2.14 Proposed default parts consumption model values

Vehicle Number	Vehicle type	CKM	KP	a0 $\times 10^{-6}$	a1 $\times 10^{-6}$
1	Motorcycle	50,000	0.308	9.23	6.20
2	Small car	115,000	0.308	36.94	6.20
3	Medium car	115,000	0.308	36.94	6.20
4	Large car	115,000	0.308	36.94	6.20
5	Light delivery vehicle	120,000	0.308	36.94	6.20
6	Light goods vehicle	120,000	0.308	36.94	6.20
7	Four wheel drive	120,000	0.371	7.29	2.96
8	Light truck	120,000	0.371	7.29	2.96
9	Medium truck	240,000	0.371	11.58	2.96
10	Heavy truck	602,000	0.371	11.58	2.96
11	Articulated truck	602,000	0.371	13.58	2.96
12	Mini-bus	120,000	0.308	36.76	6.20
13	Light bus	136,000	0.371	10.14	1.97
14	Medium bus	245,000	0.483	0.57	0.49
15	Heavy bus	420,000	0.483	0.65	0.46
16	Coach	420,000	0.483	0.64	0.46

Source: *Bennett (1998)*

9.2 Roughness effects

Roughness does not significantly influence the parts consumption below a certain level. The parts consumption model needs to be adjusted to reflect this by limiting the roughness using the following equation:

$$RI_{adj} = MAX\left[RI_{av}, MIN\left(RI0, RIMIN + a2 * RI^{a3}\right)\right] \quad ...(9.2)$$

where:

RI_{av}	the average roughness of the road (IRI m/km)
RIMIN	represents the minimum roughness to be used in the model . It has a default value of 3.0
RI_SHAPE	shape factor; it has a default of 0.25

Thus, the calculations are as follows:

$$RI0 = RIMIN + RI\_SHAPE \qquad ...(9.3)$$

$$a2 = \frac{RI\_SHAPE}{RI0^{\frac{RI0}{RI\_SHAPE}}} \qquad ...(9.4)$$

$$a3 = \frac{RI0}{RI\_SHAPE} \qquad ...(9.5)$$

where:

a2 and a3	model shape parameters

9.3 Vehicle age effects

Vehicle age is given in terms of the cumulative number of kilometres driven CKM. This is calculated using one of the following three methods:

1 **For the constant vehicle life method**

$$CKM_k = 0.5 * AKM0_k * LIFE0_k \qquad ...(9.6)$$

where:

CKM_k	average cumulative number of kilometres driven per vehicle type *k* (km)
$AKM0_k$	baseline average number of kilometres driven per vehicle type *k* per year , input by the user (km/year)
$LIFE0_k$	baseline average service life of vehicle type *k* in years, input by the user

2 **For the optimal vehicle life method**

$$CKM_k = 0.5 * LIFEKM_k \qquad ...(9.7)$$

where:

$LIFEKM_k$	the predicted optimal vehicle service life in kilometres

3 **User specifies the age spectrum distribution and the percentage of vehicles**

If the user specifies the age spectrum distribution along with the percentage of vehicles at each age *i*, then the value of CKM_k is calculated from the following expression:

$$CKM_k = \sum_{i=1}^{n} \frac{AKMV_i * VEHAGE_i * PCTV_i}{100} \quad ...(9.8)$$

where:

CKM_k	cumulative number of kilometres driven, for vehicle type *k* (km)
$AKMV_i$	average number of kilometres driven per vehicle of age *i* per year, input by the user (km/year)
VEHAGEi	vehicle age *i* in years (for *i* = 1, 2, …., n)
$PCTV_i$	percentage of vehicles of age *i* in the fleet

The CKM_k value is used in Equation 9.1 above to calculate parts consumption PC_{kp} per 1000 vehicle-km during each traffic flow period *p*. Note that the value of CKM_k is the same for all the traffic flow periods.

Note that at present HDM-4 treats used cars in the same way as new cars. This may be revised at a future date.

9.4 Acceleration effects

The effect of speed fluctuations on increasing parts consumption is modelled using the additional fuel factor dFUEL, which is calculated as a function of acceleration noise and vehicle speed (see Section 5.4). It is assumed that the fractional change in parts consumption due to vehicle accelerations and decelerations (dPARTS) is related to the fractional change in fuel consumption due to the same effect (dFUEL). Thus, the fractional change in parts consumption is expressed as:

$$dPARTS_{kp} = CPCON * dFUEL_{kp} \quad ...(9.9)$$

where:

$dPARTS_{kp}$	fractional change in parts consumption per 1000 veh-km (PC)

All the other parameters are as defined previously.

The expression given in Equation 9.9 above forms the last part of Equation 9.1 above. Using the default value of CPCON = 0.1 implies that for every 10% increase in fuel consumption there will be a 1% increase in the parts consumption.

9.5 Annual average parts consumption

The annual average parts consumption as a fraction of the new vehicle price per 1000 veh-km is calculated as follows:

$$PC_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * PC_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad ...(9.10)$$

where:

PC_{kav}	annual average parts consumption per 1000 veh-km, expressed as a fraction of the average new vehicle price
$HRYR_p$	the number of hours in traffic flow period *p*
HV_p	hourly traffic flow in period *p* expressed as a proportion of AADT
PC_{kp}	parts consumption per 1000 veh-km by vehicle type *k* during traffic flow period *p*, expressed as a fraction of the average new vehicle price

10 Labour hours

10.1 The model

Maintenance labour hours are predicted to determine the labour component of fitting spare parts and repairing vehicles. Labour wage rates (input by the user) are applied to the predicted number of labour hours to obtain maintenance labour costs. Maintenance labour hours are calculated as a function of the parts consumption.

The computational procedure can be summarised as follows:

1 **For each vehicle type *k* and for each traffic flow period *p* calculate maintenance labour hours per 1000 vehicle-kilometres**

2 **For each vehicle type *k* calculate the annual average labour hours**

The number of labour hours per 1000 vehicle-kilometres is calculated for each vehicle type *k*, and for each traffic-flow period *p* as follows:

$$LH_{kp} = K0lh * \left(a0 * PC_{kp}^{a1}\right) + K1lh \qquad ...(10.1)$$

where:

LH_{kp}	number of labour hours per 1000 veh-km of vehicle type *k* in traffic flow period *p*
PC_{kp}	parts consumption per 1000 veh-km of vehicle type *k* during traffic flow period *p*, expressed as a fraction of average new vehicle price
a0	constant term of the maintenance labour model
a1	parts exponent of the maintenance labour model
K0lh	rotational calibration factor (default value = 1.0)
K1lh	translational calibration factor (default value = 0)

The default values for the labour hours model parameters are shown in Table E2.15, and are based on the default CKM values given in Table E2.14.

Table E2.15 Proposed default labour hours model parameter values

Vehicle Number	Vehicle type	a0	a1
1	Motorcycle	77.14	0.547
2	Small car	77.14	0.547
3	Medium car	77.14	0.547
4	Large car	77.14	0.547
5	Light delivery vehicle	77.14	0.547
6	Light goods vehicle	77.14	0.547
7	Four wheel drive	77.14	0.547
8	Light truck	242.03	0.519
9	Medium truck	242.03	0.519
10	Heavy truck	301.46	0.519
11	Articulated truck	301.46	0.519
12	Mini-bus	77.14	0.547
13	Light bus	242.03	0.519
14	Medium bus	293.44	0.517
15	Heavy bus	293.44	0.517
16	Coach	293.44	0.517

Source: *Bennett (1998)*

10.2 Annual average labour hours

The annual average number of labour hours per 1000 veh-km are calculated as follows:

$$LH_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * LH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \quad ...(10.2)$$

where:

LH_{kav} annual average number of labour hours per 1000 veh-km of vehicle type *k*

$HRYR_p$ number of hours in traffic flow period *p*

HV_p the hourly traffic flow in period *p* expressed as a proportion of AADT

LH_{kp} number of labour hours per 1000 veh-km for vehicle type *k* during traffic flow period *p*

11 Capital costs

11.1 Modelling approach

Capital costs comprise of depreciation and interest costs. These constitute a significant component of the total vehicle operating cost. Capital costs, and their allocation, are sensitive to both the utilisation of a vehicle and its service life, which in turn depends on vehicle speed and road condition. The modelling of capital costs is therefore performed for each particular set of operating conditions pertaining to a traffic flow period.

For each analysis year, the capital cost per 1000 vehicle-kilometres for each vehicle type *k*, and for each traffic flow period *p*, is calculated using the formula:

$$CAPCST_{kp} = DEPCST_{kp} + INTCST_{kp} \qquad ...(11.1)$$

where:

$CAPCST_{kp}$	capital cost per 1000 veh-km incurred during traffic flow period *p*
$DEPCST_{kp}$	depreciation cost per 1000 veh-km incurred during traffic flow period *p*
$INTCST_{kp}$	annual interest cost per 1000 veh-km incurred during traffic flow period *p*

The depreciation and interest costs are computed separately as described below.

- **Depreciation cost** is given as:

$$DEPCST_{kp} = DEP_{kp} * NVPLT_{k} \qquad ...(11.2)$$

where:

DEP_{kp}	depreciation cost factor per 1000 veh-km for traffic flow period *p*
$NVPLT_{k}$	average new (or replacement) vehicle price less tyres

For each vehicle type *k*, the average new vehicle price less tyres (to avoid double counting) is calculated from the expression:

$$NVPLT_{k} = NVP_{k} - NUM\_WHEELS_{k} * NTP_{k} \qquad ...(11.3)$$

where:

NVP_{k}	average new (or replacement) vehicle price
NUM_WHEELS_{k}	number of wheels of vehicle type *k*
NTP_{k}	average new tyre price

- **Interest cost** is given as:

$$INTCST_{kp} = INT_{kp} * NVP_k \qquad ...(11.4)$$

where:

INT_{kp}	annual interest cost factor per 1000 veh-km for traffic flow period *p*
NVP_k	average new (or replacement) vehicle price less tyres

11.2 Depreciation

Vehicle depreciation arises mainly due to use, time/ageing and technical obsolescence. There are two methods of calculating depreciation costs based on vehicle service life:

1 **Constant life method** (see Section 11.2.2)

2 **Optimal life method** (see Section 11.2.3)

Both methods calculate depreciation cost over the service life of a vehicle using a straight-line method. The residual value at the end of the vehicle's service life is deducted from the vehicle price before calculating depreciation.

11.2.1 Residual vehicle value

The residual value at the end of a vehicle's life is a function of road roughness, with user-definable parameters. Vehicles operated on rougher roads will have a lower residual value since they will have suffered more wear and tear. Residual vehicle value is calculated from the following expression:

$$RVPLTPCT = MAX[a2, a3 - MAX(0, (RI_{av} - a4))] \qquad ...(11.5)$$

where:

RVPLTPCT	residual vehicle price less tyres at the end of its service life (%)
RI_{av}	average road roughness (IRI m/km)
a2	minimum residual value of the vehicle (%) (default = 2)
a3	maximum residual value of the vehicle (%) (default value = 15)
a4	average roughness, IRI, below which the maximum value arises (default value = 5)

11.2.2 Constant life depreciation method

The depreciation cost factor per 1000 vehicle-kilometres, DEP_{kp}, for each traffic flow period is calculated as follows:

$$DEP_{kp} = \frac{1000 * (1 - 0.01 * RVPLTPCT_k)}{AKM0_k * LIFE0_k} \qquad ...(11.6)$$

where:

$RVPLTPCT_k$	residual vehicle price less tyres of vehicle type *k* (%)
SS_{kp}	vehicle operating speed (km/h) during traffic flow period *p*
$AKM0_k$	baseline average number of kilometres driven per year , input by the user (km/year)
$LIFE0_k$	baseline average service life of vehicle type *k* in years, input by the user (years)

11.2.3 Optimal life depreciation method

The depreciation cost factor per 1000 vehicle-kilometres for each traffic flow period is calculated as follows:

$$DEP_{kp} = \frac{1000 * (1 - 0.01 * RVPLTPCT_k)}{LIFEKM_k} \qquad ...(11.7)$$

where:

$RVPLTPCT_k$	residual vehicle price less tyres of vehicle type *k* (%)
$LIFEKM_k$	predicted optimal service life of vehicle type *k* (km)

Note that the value of DEP_k is the same for all the traffic flow periods.

11.3 Interest

Interest costs are the opportunity cost of vehicle ownership. These consist of the income that would have been received had the capital invested in the vehicle been invested elsewhere.

The interest cost factor per 1000 vehicle-kilometres INT_{kp} for each traffic flow period is calculated as follows:

$$INT_{kp} = \frac{1000 * AINV_k}{2 * SS_{kp} * HRWK0_k * 100} \qquad ...(11.8)$$

where:

$AINV_k$	annual interest charge on the purchase cost of the average new vehicle type *k* (%)

All other parameters are as defined previously.

11.4 Annual average capital cost

The annual average capital cost per 1000 vehicle-kilometres is calculated as follows:

$$CAPCST_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * CAPCST_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad ...(11.9)$$

where:

$CAPCST_{kav}$	average capital cost per 1000 veh-km for vehicle type *k*
$HRYR_p$	number of hours in traffic flow period *p*
HV_p	hourly traffic flow in period *p* expressed as a proportion of AADT
$CAPCST_{kp}$	capital cost per 1000 veh-km for vehicle type *k* during flow period *p*

12 Crew hours

12.1 The model

Crew cost is included as a vehicle operating cost rather than as a time cost. It is obtained from the product of the number of crew hours and the crew wage rate. In HDM-4, the cost of crew labour is considered to be a variable cost rather than a fixed cost. This means that the time the crew spends on non-driving activities such as loading, unloading and layovers is not charged against this cost category. Thus, the number of crew hours required per 1000 vehicle-kilometres (or distance-dependent annual vehicle hours) for each vehicle type *k*, during each traffic flow period *p* is calculated as a function of the vehicle operating speed, as follows:

$$CH_{kp} = \frac{1000 * (100 - PP_k)}{100 * SS_{kp}} \qquad ...(12.1)$$

where:

CH_{kp}	number of hours per crew member per 1000 veh-km for traffic flow period *p*
PP_k	percentage of vehicle use on private trips (%)
SS_{kp}	vehicle operating speed (km/h) during traffic flow period *p*

12.2 Annual average number of crew hours

The annual average number of hours for each crew member per 1000 vehicle-kilometres is calculated as follows:

$$CH_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * CH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad ...(12.2)$$

where:

CH_{kav}	average number of hours per crew member per 1000 veh-km for vehicle type *k*
$HRYR_p$	the number of hours in traffic flow period *p*
HV_p	the hourly traffic flow in period *p* expressed as a proportion of AADT
CH_{kp}	number of hours per crew member per 1000 veh-km for vehicle type *k* during traffic flow period *p*

13 Overhead costs

13.1 The model

This covers all other cost elements including administration, insurance, parking/garaging, and any overheads associated with the crew (for example, training, uniform, etc.). Overhead costs are calculated as a function of the annual vehicle utilisation and average operating speed.

For each analysis year, and for each vehicle type *k*, the overhead cost per 1000 vehicle-kilometres incurred during traffic flow period *p*, is calculated using the formula:

$$OC_{kp} = \frac{1000 * OA_k * (100 - PP_k)}{100 * SS_{kp} * HRWK0_k} \quad ...(13.1)$$

where:

OC_{kp}	overhead cost per 1000 veh-km for vehicle type *k* incurred during traffic flow period *p*
OA_k	overhead cost per year, for vehicle type *k*, input by the user
PP_k	percentage of vehicle use on private trips
SS_{kp}	vehicle operating speed (km/h) during traffic flow period *p*

13.2 Annual average overhead costs

The annual average overhead costs per 1000 vehicle-kilometres is calculated as follows:

$$OC_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * OC_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \quad ...(13.2)$$

where:

OC_{kav}	annual average overhead costs per 1000 veh-km for vehicle type *k*
$HRYR_p$	the number of hours in traffic flow period *p*
HV_p	the hourly traffic flow in period *p* expressed as a proportion of AADT
OC_{kp}	overhead costs per 1000 veh-km for vehicle type *k* during traffic flow period *p*

Module C: Travel Time

14 Passenger travel time

The number of passenger-hours is calculated as a function of the vehicle operating speed.

The number of passenger-hours spent in travelling for each vehicle type *k*, during each traffic flow period *p* is calculated separately for travel during working hours and for travel during non-working hours. This makes it possible to assess the delays associated with the particular operating conditions of each traffic flow period.

14.1 Working passenger-hours

The number of passenger-hours per 1000 vehicle-kilometres spent travelling during working time is given as:

$$PWH_{kp} = \frac{1000 * PAX_k * W_k}{100 * SS_{kp}} \quad ...(14.1)$$

where:

PWH_{kp} number of working passenger-hours per 1000 veh-km, for vehicle type *k* during traffic flow period *p*

PAX_k number of passengers (non-crew occupants) in vehicle type *k*

W_k percentage of passengers on work-purpose journey (%)

SS_{kp} vehicle operating speed (km/h) during traffic flow period *p*

14.2 Non-working passenger-hours

The number of passenger-hours per 1000 vehicle-kilometres spent in travelling during non-working time is given by the following expression:

$$PNH_{kp} = \frac{1000 * PAX_k * (100 - W_k)}{100 * SS_{kp}} \quad ...(14.2)$$

where:

PNH_{kp} number of non-working passenger-hours per 1000 veh-km for vehicle type *k* during traffic flow period *p*

PAX_k number of passengers (non-crew occupants) in vehicle type *k*

W_k percentage of passengers on work-purpose journey (%)

SS_{kp} vehicle operating speed (km/h) during traffic flow period *p*

14.3 Annual average number of passenger-hours

The annual average number of working and non-working passenger-hours is calculated as shown in Sections 14.3.1 and 14.3.2.

14.3.1 Working passenger-hours

The annual average number of working passenger-hours per 1000 vehicle-kilometres is given by the expression:

$$PWH_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * PWH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \quad ...(14.3)$$

where:

PWH_{kav} annual average number of working passenger-hours per 1000 veh-km, for vehicle type *k*

$HRYR_p$ the number of hours in traffic flow period *p*

HV_p the hourly traffic flow in period *p* expressed as a proportion of AADT

PWH_{kp} number of working passenger-hours per 1000 veh-km, for vehicle type *k* during traffic flow period *p*

14.3.2 Non-working passenger-hours

The annual average number of non-working passenger-hours per 1000 vehicle-kilometres is given by the expression:

$$PNH_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * PNH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \quad ...(14.4)$$

where:

PNH_{kav} annual average number of non-working passenger-hours per 1000 veh-km

$HRYR_p$ the number of hours in traffic flow period *p*

HV_p the hourly traffic flow in period *p* expressed as a proportion of AADT

PNH_{kp} number of non-working passenger-hours per 1000 veh-km, for vehicle type *k* during traffic flow period *p*

15 Cargo holding time

This refers to the number of vehicle-hours spent in transit, and it is calculated as a function of the vehicle operating speed.

The number of cargo holding hours per 1000 vehicle-kilometres for each vehicle type *k*, during each traffic flow period *p*, is calculated using the formula:

$$CARGOH_{kp} = \frac{1000}{SS_{kp}} \qquad ...(15.1)$$

where:

$CARGOH_{kp}$	annual number of cargo holding hours per 1000 veh-km, for vehicle type *k* during traffic flow period *p*
SS_{kp}	vehicle operating speed (km/h) during traffic flow period *p*

The annual average number of cargo holding hours per 1000 vehicle-kilometres is calculated as follows:

$$CARGOH_{kav} = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * CARGOH_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad ...(15.2)$$

where:

$CARGOH_{kav}$	annual average number of cargo holding hours per 1000 veh-km, for vehicle type *k*
$HRYR_p$	the number of hours in traffic flow period *p*
HV_p	the hourly traffic flow in period *p* expressed as a proportion of AADT
$CARGOH_{kp}$	number of cargo holding hours per 1000 veh-km, for vehicle type *k* during traffic flow period *p*

16 Road impassability costs

The cost due to impassability of a seriously damaged unsealed road is calculated as follows:

$$CPASS_k = VC_{kav} * (FPASS_k - 1) \quad ...(16.1)$$

$$FPASS_k = 1 + (FPLIM_k - 1) * MAX\left[0, \left(1 - \frac{GH}{GHMIN}\right)\right] \quad ...(16.2)$$

where:

$CPASS_k$	cost due to impassability of vehicle type *k*, in *currency* per 1000 km
VC_{kav}	unit annual average vehicle operating cost and travel time cost per 1000 veh-km of vehicle type *k*
$FPLIM_k$	user-specified vehicle-specific dimensionless maximum value of FPASS (default = 1.0)
GH	mean gravel thickness for the analysis year (mm)
GHMIN	minimum gravel thickness (mm), determined as:

GHMIN = MIN (100.0, MAX (40.0, 2*D95))

where:

D95 = maximum particle size (mm)

Note that the physical explanation for increasing FPASS for gravel thickness less than the minimum is that there is greater risk of weak spots and of increased vehicle costs, in this range than for roads with adequate gravel cover thickness.

The factor FPLIM ranges in value, from:

1 for subgrade materials with soaked CBR greater than 10% (that is, fully passable)

to

3 for heavy vehicles on soft soils

A default value of 1.0 is used which the user may override. By definition, CPASS is zero for paved roads, and GH is zero for earth roads.

Module D: Costing Vehicle Resources

17 Vehicle resource costs

17.1 Unit costs

In previous sections the analysis has dealt, wherever feasible, with physical quantities of resources used, so that fundamental physical relations would not be obscured by price variations. Once the physical quantities are determined, they are multiplied either by unit costs or prices. The user provides the unit costs or prices.

Physical concepts prove difficult to define and quantify for maintenance parts and for overhead costs, and are not relevant for depreciation and interest, which are financial in nature. For three of these elements, that is, all except overhead costs, it is convenient and valid to deal with the ratio of the element's cost to the price of a new vehicle, another cost factor to be supplied by the user. The Annual overhead cost is supplied by the user and treated as a lump sum per year.

Table E2.16 shows the units in which each element of resource consumption is measured and the dimensions of the price, unit cost, or other factor by which each has to be multiplied to obtain its value as a component of vehicle operating cost per 1000 vehicle-kilometres.

17.2 Vehicle-trip costs over the road section

For each section alternative *j*, for each vehicle type *k*, and for each year of the analysis period, the costs per vehicle-trip over the road section are obtained from the following expression:

$$TRIPCOST_{jk} = \frac{KCOST_{jk} * L_j}{1000} \qquad ...(17.1)$$

where:

$TRIPCOST_{jk}$	cost per vehicle-trip over the road section under investment alternative *j*
$KCOST_{jk}$	cost per 1000 vehicle-kilometres of vehicle type *k* under section alternative *j*
L_j	road section length under investment alternative *j* (km)

The annual average costs per vehicle trip are required as inputs for economic analysis and comparisons of different investment options. They are used for calculating the net benefits of each pair of section options to be compared (see Part G).

Table E2.16 Resource consumption and cost units

Resource component	Units of measurement	Unit cost or other multiplying factor
Fuel	Litres per 1000 vehicle-kilometres, FC	Cost per litre
Oil	Litres per 1000 vehicle-kilometres, OIL	Cost per litre
Tyres	Number of equivalent new tyres per 1000 vehicle-kilometres, TC	Cost per tyre
Parts	Proportion of new vehicle cost per 1000 vehicle-kilometres, PC	Cost of new vehicle
Labour	Labour-hours per 1000 vehicle-kilometres, LH	Wage cost per hour
Depreciation	Fraction of new vehicle cost less tyres per 1000 vehicle-kilometres, DEP	Cost of new vehicle minus cost of tyres
Interest	Fraction of new vehicle cost per 1000 vehicle-kilometres, INT	Cost of new vehicle
Crew	Hours per 1000 vehicle-kilometres, CH	Crew wages per hour
Overhead	Cost per 1000 vehicle-kilometres, OH	No factor needed
Passenger working time	Working passenger-hours per 1000 vehicle-kilometres, PWH	Value per hour of passenger working time
Passenger non-working time	Non-working passenger-hours per 1000 vehicle-kilometres, PNH	Value per hour of passenger non-working time
Cargo holding time	Vehicle-hours per 1000 vehicle-kilometres, CARGOH	Cargo holding cost per vehicle-hour
Unsealed road impassability	Fraction of above costs	Sum of costs above

17.3 Annual cost streams

The annual road user costs for each vehicle type are obtained by multiplying the cost per vehicle-trip by the annual traffic volume of the particular vehicle type. Summing these values over all the vehicle types used in the analysis yields the total vehicle operating cost and travel time cost. These annual total costs may also be computed by:

- **Traffic flow periods**
- **Vehicle resource component**
- **Traffic categories**
  (that is, normal and diverted, and generated)

17.4 Annual vehicle-kilometres

For each section alternative j, the annual vehicle-kilometres (VKM_{jk}) of vehicle type k is obtained by multiplying the annual traffic volume of vehicle type k (T_{jk}) by the section length (L_j).

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E3 Non-Motorised Transport

1 Introduction

This chapter describes the implementation of Road User Effects (RUE) models for calculating non-motorised vehicle speeds, operating costs and travel time (see Figure E3.1). It provides an overview of the modelling concepts and logic, a description of the relationships, and default parameter values for each of the RUE components and the HDM-4 representative Non-Motorised Transport (NMT) types.

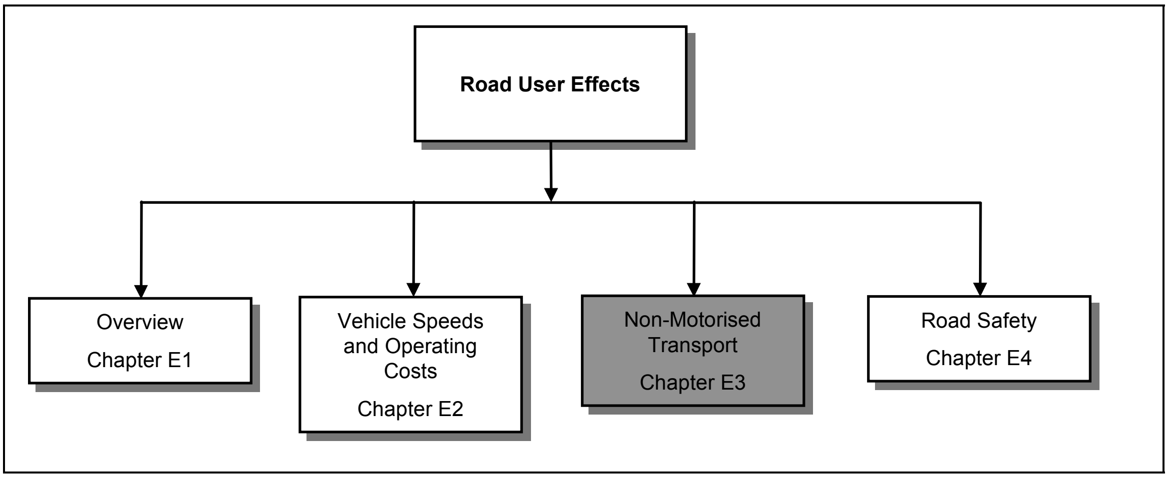

Figure E3.1 Road User Effects modules

2 Modelling concepts and logic

Non-motorised modes of transport account for the vast majority of the movement of people and goods in many developing countries. For this reason the inclusion of NMT in the appraisal of transport projects and policies in countries with significant volumes of NMT is essential. For example, the presence of NMT can influence the speed of motorised transport (MT), thereby affecting the operating costs of motorised vehicles. In addition, policies such as road improvements influence the costs and benefits to both motorised and non-motorised road users.

2.1 NMT vehicle types

Non-motorised transport is considered as separate vehicles used for moving passengers and goods in their own right, and not only as side-friction or nuisance to motorised vehicles. Hence, NMT effects can be included within the analytical framework for road projects, programmes and strategies. The NMT costs and benefits are calculated separately for different types of NMT **vehicles**.

The NMT category includes the following representative classes (see Chapter E1):

- **Pedestrian**
- **Bicycle**
- **Cycle rickshaw**
- **Animal cart**
- **Farm tractor** (not included in this release)

Users can define their own set of NMT vehicles within each class by calibrating the default NMT class. Table E3.1 gives the default values of the key NMT characteristics required for the analyses.

The calculation of NMT speeds utilises the performance and physical size of these NMT types. The operating costs are calculated separately according to the utilisation of the NMT vehicle (for example, private or commercial use, passenger or freight use).

Table E3.1 Default values of key NMT characteristics

Key parameters	Units	NMT type			
		Bicycle	Rickshaw	Animal cart (Bullock)	Pedestrian
Wheel type		Pneumatic	Pneumatic	Wood	
Number of wheels, NUM_WHEELS		2	3	2	
Wheel diameter, WHEEL_DIA	m	0.7	0.7	1.0	
Operating weight, WGT_OPER	kg	100	300	1200	80
Payload, PAYLD	kg	35	235	900	15
Average life, LIFE0	years	10	6	3	
Baseline annual number of kilometres travelled, AKM0	km	2500	7200	4000	
Baseline annual number of working hours, HRWK0	hours	150	500	1300	
Number of passengers, PAX		1	3	0	1

Source: *Odoki and Kerali (1999)*

2.2 Modelling issues

The types of road improvements that are directly relevant to NMT user costs and benefits include the following:

- **Addition of NMT lanes**
- **NMT designated shoulders**
- **Pavement widening**
- **Improvement of pavement surface condition**
- **Improvement of road geometry characteristics**

These improvements would affect the performance characteristics of NMT; thereby affecting NMT user costs and benefits in terms of the following:

- **Travel speed and time**
- **Wear and tear of NMT vehicles and components**
- **Fares/user charges**
- **Degree of conflicts with MT traffic**
- **Accident rates**

In modelling terms, the effects on NMT that need to be considered in the economic analysis of road investments can be quantified separately as follows *(PADECO, 1996)*:

1 **MT flow and speed**

2 **MT operating costs**

3 **NMT flow and speed**

4 **NMT operating costs**

5 **NMT energy consumption**

6 **MT and NMT safety-related costs**

7 **Road deterioration and maintenance**

8 **NMT travel demand**

The first six effects (1 to 6) are modelled in HDM-4, and are discussed further in the following sections. The NMT effects on road deterioration and maintenance, and NMT travel demand are currently not considered.

2.3 Data requirements

The data required for modelling NMT can be grouped as follows:

- **Physical characteristics of NMT**
  (for example, operating weight, type of wheels).
- **NMT utilisation**
  (for example, average service life, annual number of kilometres travelled, annual number of working hours).
- **Unit costs**
  (for example, purchase cost, interest rate, hourly crew wages, passenger and freight value of time, energy). It is recognised that energy costs may be difficult to obtain, therefore the default values given in Table E3.2 may be used.
- **Road characteristics**
  (for example, length, vertical alignment, surface condition).
- **Model calibration parameters**
- **NMT traffic data**
  (in terms of AADT, composition, and growth).

Table E3.2 Default energy unit costs in US dollars per MJoule

NMT type			
Bicycle	**Rickshaw**	**Animal cart**	**Pedestrian**
0.10	0.10	0.07	0.10

Source: *Odoki and Kerali (1999)*

2.4 Computational logic

For each road investment option, and for each analysis year, the NMT models are applied in the following sequence:

1 **Calculate average daily flow for each NMT type**

2 **Calculate the operating speed for each NMT type**

3 Calculate time costs and operating costs

4 Perform economic analysis, and energy balance analysis

3 Impact of NMT on motorised transport

3.1 Impact on MT speed

The impact of Non-Motorised Transport (NMT) on Motorised Transport (MT) speed is modelled through the **side-friction** or speed reduction approach (*Hoban, 1987*). In this approach, it is assumed that the reduction in the steady-state speed of MT vehicles is directly proportional to the degree of conflicts between MT and NMT. This is user defined through the MT speed reduction factor (XNMT) for each road section being analysed. The XNMT value is used in the relationship for calculating the **free speeds** of MT vehicles (see Chapter E2 Section 3.2.5). The XNMT value for a road section remains constant over the analysis period until a road improvement alters the characteristics or degree of conflicts between NMT and MT. The benefits to motorised traffic of improving the flow conditions for NMT traffic can therefore be quantified from the effects of changing the XNMT value before and after the road improvement.

3.2 Impact on MT operating costs

The impact of NMT on MT operating costs is estimated through speed change cycles or **acceleration effects** models. Under ideal conditions drivers would maintain a steady-state speed without any decelerations and accelerations. However, this is not possible in reality since drivers are forced to adjust their speeds in response to traffic congestion, road alignment, pavement surface condition, the presence of NMT and other roadside activities (*Greenwood and Bennett, 1996*; *Bennett, 1996; NDLI, 1995*).

The standard deviation of accelerations, referred to as the **acceleration noise**, gives an indication of the severity of speed changes. Low values of acceleration noise indicate that there are minor speed changes, large values indicate major speed changes. For each road section, it is considered that the additional MT operating costs due to speed change cycles arising from the presence of NMT is proportional to the magnitude of acceleration noise (see Chapter E2 Section 4.6). An appropriate intervention (for example, road improvement) to reduce the degree of conflicts between NMT and MT would lead to lower values of acceleration noise, and hence a benefit to motorised traffic in terms of savings in vehicle operating costs (VOC).

4 NMT speeds

4.1 Factors influencing NMT speeds

There are several factors that influence NMT speeds (*PADECO, 1997*):

- **MT traffic volume and speed**
- **NMT traffic volume**
- **Roadside activities**
- **Roadway grade**
- **Rolling resistance**
- **Road width (where NMT can travel safely) and/or number of lanes**
- **Method of separating NMT/MT traffic** (for example, markings, physical separation)
- **Roughness of road surface** (particularly shoulder roughness)
- **Inclement weather**

However, to capture the effects of all these factors would necessitate the formulation of a complex NMT speed model and calibration procedure. A simplified speed model has therefore been adopted, based on the minimum limiting velocity approach used in HDM-4 (*Watanatada et al., 1987b*). The steady-state speed of NMT vehicles is regarded as the minimum of potential speed constraints generated by the interaction of road severity factors with relevant characteristics of the vehicle. The limiting factors include road roughness, desired speed, and the road gradient. With the exception of NMT traffic volume, all of the factors given above have been considered either explicitly or implicitly in the speed model or in the calculation of forces opposing motion and their impact on energy use.

4.2 The speed model

The NMT speed over a road section is calculated separately for each direction of traffic flow, the uphill segment and the downhill segment, and the results are then averaged for a round trip.

The uphill and downhill speeds are calculated using Equations 4.1 below and 4.2 below respectively:

$$VS_{ku} = MAX[0.14, MIN(VDES_{ks}, VROUGH_k, VGRAD_{ku})] \quad \ldots(4.1)$$

$$VS_{kd} = MAX[0.14, MIN(VDES_{ks}, VROUGH_k, VGRAD_{kd})] \quad \ldots(4.2)$$

The average speed for a round trip is calculated as the harmonic mean of the uphill and downhill speeds from the expression:

$$S_k = \frac{7.2 * XMT}{\left[\left(\frac{1}{VS_{ku}}\right) + \left(\frac{1}{VS_{kd}}\right)\right]} \quad \ldots(4.3)$$

where:

S_k	the average speed for NMT type *k* (km/h)
VS_{ku}	the predicted speed of NMT type *k* for the uphill segment (m/s)
VS_{kd}	the predicted speed of NMT type *k* for the downhill segment (m/s)
$VDES_{ks}$	desired speed of NMT type *k* on a smooth, level road (*s* = paved or unpaved surface) (m/s) (see Table E3.3)
$VROUGH_k$	the speed limited by roughness (m/s) (see Section 4.2)
$VGRAD_k$	the speed limited by the roadway gradient (m/s), (the uphill and downhill directions are denoted by the subscripts *u* and *d* respectively) (see Section 4.3)
XMT	speed reduction factor due to motorised traffic and roadside activities, allowable range: MIN 0.4 to MAX 1.0 (default = 1.0)

For the analysis of one-way traffic, the average speed is calculated as follows:

- **For uphill segments**

$$S_k = 3.6 * VS_{ku} * XMT \qquad \text{...(4.4)}$$

- **For downhill segments**

$$S_k = 3.6 * VS_{kd} * XMT \qquad \text{...(4.5)}$$

The benefits to NMT users of improving traffic flow conditions, for example by separating NMT and MT traffic flows can be assessed by changing the value of the parameter XMT in Equations 4.3 above to 4.5 above.

4.3 VROUGH

The limiting speed due to road roughness and the associated ride severity on NMT is estimated from:

$$VROUGH_k = MAX[0.14, (VDES_{ks} + a\_rgh * RI_{av})] \qquad \text{...(4.6)}$$

where:

RI_{av}	average road roughness (IRI m/km)
a_rgh	roughness dependent model coefficient for NMT type *k*

Table E3.3 shows typical default parameter values for the NMT speed-roughness model. It is expected that a proportion of NMT traffic will use part of the carriageway and the shoulders (if provided). This will need to be specified, so that carriageway roughness is applied to the former and the shoulder roughness applied to the latter. The NMT benefits arising from improvement of road surface condition can be assessed in terms of increased operating speeds given by Equation 4.6 above.

Table E3.3 Default values of NMT speed model parameters

Key parameters	Units	NMT type			
		Bicycle	**Rickshaw**	**Animal cart** (Bullock)	**Pedestrian**
Desired speed on paved roads $VDES_p$)	km/h	21.26	18.60	3.83	5.11
Desired speed on unpaved roads ($VDES_u$)	km/h	18.00	15.40	3.20	4.60
Roughness dependent speed model coefficient (a_rgh)		-0.225	-0.197	-0.036	-0.048
Gradient dependent speed model coefficient (a_grd)		-28.00	-33.00	-6.00	-4.00
Critical gradient (CRGR)		-0.04	-0.04	-0.04	-0.04

Source: *Odoki and Kerali (1999)*

4.4 VGRAD

The effect of gradient on NMT speed is calculated separately for uphill and downhill travel. For the uphill direction, the limiting speed due to gradient effects is given by:

$$VGRAD_{ku} = MAX\left[0.14, \left(VDES_{ks} + a\_grd * GR\right)\right] \qquad ...(4.7)$$

where:

GR average road gradient (as a fraction)

a_grd gradient dependent model coefficient for NMT type *k*

For the downhill direction, the limiting speed depends on the critical gradient (CRGR). It is assumed that below the critical gradient, there is no effect of downgrade on NMT speed. The downhill speed is therefore calculated as follows:

if: $abs(GR) > abs(CRGR)$

$$VGRAD_{kd} = VDES_{ks} + a\_grd * ABS(GR - CRGR_k) \qquad ...(4.6)$$

otherwise:

$$VGRAD_{kd} = VDES_{ks} \qquad ...(4.9)$$

where:

$CRGR_k$ the critical gradient for NMT type *k* (default = -0.04 for all NMT types, range: -0.15 < CRGR < 0)

The average road section gradient (GR) is estimated from the following expression (*Watanatada et al., 1987a*):

$$GR = \pm \frac{RF}{1000} \qquad ...(4.10)$$

where:

GR	For uphill speed:	GR = + [RF/1000]
	For downhill speed:	GR = - [RF/1000]
RF	road **rise** plus **fall** (m/km)	

Table E3.3 includes typical default parameter values for the NMT speed-gradient model. The benefits to NMT of improving the vertical alignment of roadway, measured in terms of increased speeds, can be estimated using Equations 4.7 above and 4.8 above.

4.5 Resistance to motion

Speeds of motorised vehicles include a component derived from the main forces opposing motion; that is, aerodynamic resistance, gradient resistance, and rolling resistance. These forces could be used to derive a limiting speed (VDRIVE) based on the driving power of NMT vehicles from mechanistic principles, and could then be used to substitute VGRAD in Equations 4.1 above and 4.2 above. However, this formulation would require the estimation of **used driving power** for each NMT type. Since this is difficult to determine, a simple form of the NMT speed model is used incorporating gradient effects only.

The effect of rolling resistance on NMT speed can be significant on unsealed roads, particularly on soft and sand surfaces. This together with gradient resistance has therefore been incorporated in the NMT energy cost model described in Section 5.6. The benefits to NMT in terms of savings in energy used would therefore result from the upgrading of pavement types, and improving road geometry characteristics. The gradient and rolling resistance forces are calculated as described below.

4.5.1 Gradient resistance

The gradient resistance is calculated separately for the uphill and downhill segments using the following expression:

$$FG = WGT\_OPER * g * GR \qquad ...(4.11)$$

where:

FG	gradient resistance (N)
WGT_ OPER	NMT operating weight (kg)
g	acceleration due to gravity, taken as equal to 9.81 (m/s^2)

For the uphill travel direction, FG_u is calculated using the positive value of GR, and for the downhill travel direction, FG_d is calculated using the negative value of GR. The subscripts **u** and **d** denote uphill and downhill, respectively.

4.5.2 Rolling resistance

Several studies including those by *Cenek (1994)*, *Bester (1981)*, and *CRRI (1985)*, has found that a relationship exists between motorised vehicle speeds and the rolling resistance characteristics of roads. This finding has been extended to apply to NMT. The rolling resistance to NMT (excluding pedestrians) is calculated using the model formulation by *Biggs (1988)*, as follows:

$$FR = FCLIM * CR2 * \left[b1 * NUM\_WHEELS + CR1 * \left(b2 * WGT\_OPER + b3 * v^2\right)\right] \quad ...(4.12)$$

where:

FR	rolling resistance to motion (N)
NUM_ WHEELS	number of wheels of NMT
v	NMT speed (m/s), taken as VS_{ku} or VS_{kd}
CR1	wheel dependent factor of rolling resistance
CR2	pavement dependent coefficient of rolling resistance
FCLIM	climatic/inclement weather factor
b1, b2, b3	model parameters

The wheel factor CR1 depends on the wheel type as follows:

- wheel type is steel or wood

  CR1 = 0.9

- wheel type is pneumatic

  CR1 = 1.0

The pavement dependent coefficient of rolling resistance CR2 is given by:

$$CR2 = Kcr2 * [CR2\_a0 + CR2\_a1 * TD_{av} + CR2\_a2 * RI_{av}] \quad ...(4.13)$$

where:

RI_{av}	average road roughness (IRI m/km)
TD_{av}	average sand patch texture depth (mm)
Kcr2	rolling resistance factor

Table E3.4 gives the default values for the various rolling resistance model parameters. The diameter and number of wheels influence the rolling resistance parameters as follows:

$$b1 = WD\_a0 * WHEEL\_DIA \qquad ...(4.14)$$

$$b2 = \frac{WD\_a1}{WHEEL\_DIA} \qquad ...(4.15)$$

$$b3 = \frac{WD\_a2 * NUM\_WHEELS}{WHEEL\_DIA^2} \qquad ...(4.16)$$

where:

WHEEL_DIA	wheel diameter (m)
WD_a0 WD_a1 WD_a2	model coefficients (defaults = 37, 0.064, and 0.012 respectively)

Table E3.4 Rolling resistance model parameters

Pavement		WGT_OPER < = 2500 kg				WGT_OPER > 2500 kg			
Surface class	**Surface type**	**CR2 _a0**	**CR2 _a1**	**CR2 _a2**	**Kcr2**	**CR2 _a0**	**CR2 _a1**	**CR2 _a2**	**Kcr2**
Bituminous	AM or ST	0.90	0.022	0.022	1	0.84	0.03	0.03	1
Concrete	JP, JR or CR	0.90	0.022	0.022	1	0.64	0.03	0.03	1
Unsealed	Gravel	1.00	0.00	0.075	1	1.00	0.00	0.075	1
Unsealed	Earth	0.80	0.00	0.10	1	0.80	0.00	0.10	1
Unsealed	Sand	7.50	0.00	0.00	1	7.50	0.00	0.00	1
Block	CB, BR or SS	2.00	0.00	0.00	1	2.00	0.00	0.00	1

Source: *NDLI (1995)*

Notes: (see Part C, Chapter C1 for the definitions of surface types)

The following abbreviations were used in Table E3.4:

AM = Asphalt Mix

ST = Surface Treatment

JP = Jointed Plain

JR = Jointed Reinforced

CR = Continuously Reinforced

CB = Concrete Block

BR = Brick

SS = Set Stone

The effect of inclement weather is incorporated in the rolling resistance model in a similar manner to that for motorised vehicles. The rolling resistance factor depends upon the percentage of time travelled on water covered roads (PCTDW), and if applicable, on snow covered roads (PCTDS) as follows:

$$FCLIM = 1 + 0.002 * PCTDW + 0.003 * PCTDS \quad ...(4.17)$$

5 NMT time and operating costs

The total time and operating costs of each NMT type are calculated separately then added:

$$TOC_k = TMC_k + VOC_k \qquad \text{...(5.1)}$$

where:

TOC_k	total time and operating cost of NMT type *k* per veh-km
TMC_k	travel time cost of NMT type *k* (*cost*/km)
VOC_k	operating cost of NMT type *k* (excluding pedestrians) (*cost*/km)

5.1 Travel time cost

The cost of travel time is directly related to average speeds. The time cost comprises passenger time value and cargo holding cost, and this is expressed as follows:

$$TMC_k = PAXC_k + CARGC_k \qquad \text{...(5.2)}$$

where:

$PAXC_k$	passenger time value for NMT type *k* per veh-km
$CARGC_k$	cargo holding cost for NMT type *k* (*cost*/km)

The value of passenger time is given by:

$$PAXC_k = \frac{PAXV_k}{S_k} \qquad \text{...(5.3)}$$

where:

$PAXV_k$	average hourly value of passenger time for NMT type *k* (*cost*/h), and is equal to the number of passengers per vehicle (PAX) multiplied by the value of passenger time (PTV)
S_k	annual average speed of NMT type *k* (km/h)

The cost of cargo holding is given by:

$$CARGC_k = \frac{CAGV_k}{S_k} \qquad \text{...(5.4)}$$

where:

$CAGV_k$	average hourly value of cargo holding time for NMT type *k* (*cost*/h)

5.2 Operating cost

The cost of operating each NMT type is obtained from the costs of capital depreciation, repair and maintenance, crew (if any), energy and overheads:

$$VOC_k = CAPC_k + RMC_k + CRWC_k + ENC_k + OVHD_k \qquad ...(5.5)$$

where:

VOC_k	total operating cost of NMT type *k* per veh-km
$CAPC_k$	capital cost of NMT type k per km (excluding pedestrians) (*cost*/km)
RMC_k	repair and maintenance cost of NMT type *k* (excluding pedestrians) (*cost*/km)
$CRWC_k$	crew cost of NMT type *k* (excluding pedestrians) (*cost*/km)
ENC_k	energy cost of NMT type *k* (*cost*/km)
$OVHD_k$	overhead cost of NMT type *k* (excluding pedestrians) (*cost*/km)

5.3 Capital cost

The capital cost is derived from the purchase cost depreciated over the average service life of each NMT vehicle, the frequency of utilisation, and the interest charge on the purchase cost. Hence, the capital cost per km, CAPC, is given by:

$$CAPC_k = DEPC_k + INTC_k \qquad ...(5.6)$$

where:

$DEPC_k$	depreciation cost of NMT type *k* per veh-km
$INTC_k$	interest cost of NMT type *k* (*cost*/km)

The depreciation cost per km, DEPC, is calculated using the expression:

$$DEPC_k = \frac{PCHC_k}{LIFE0_k * AKM_k} \qquad ...(5.7)$$

where:

$PCHC_k$	average purchase cost (price) of NMT type *k*
$LIFE0_k$	baseline average service life of NMT type *k* (years), input by the user
AKM_k	annual kilometres travelled by NMT type *k* (km/year)

Interest cost per km, INTC, is calculated from the following expression:

$$INTC_k = \frac{PCHC_k * AINV_k}{2 * 100 * AKM_k} \qquad ...(5.8)$$

where:

$AINV_k$	the annual interest charge on the purchase cost of NMT type *k* (%)

For each analysis year, the annual kilometres travelled, AKM, is calculated as follows:

$$AKM_k = S_k * HRWK0_k \quad ...(5.9)$$

where:

S_k	annual average speed of NMT type *k* (km/h)
$HRWK0_k$	baseline average number of NMT working hours per year, input by the user

5.4 Repair and maintenance cost

The repair and maintenance cost per km, RMC, includes costs of replacing tyres, braking devices and other components, lubricating oil and the cost of maintenance labour. This can be estimated using the model form in Equation 5.10 below comprising two components:

1 **Road roughness (RI)**

2 **NMT vehicle age** measured in terms of cumulative kilometres travelled (CKM).

$$RMC_k = (a\_rmc + b\_rmc * RI_{av}) * CKM_k * PCHC_k * 10^{-3} \quad ...(5.10)$$

$$CKM_k = 0.5 * AKM0_k * LIFE0_k \quad ...(5.11)$$

where:

CKM_k	average cumulative kilometres travelled by NMT type *k* (km)
$AKM0_k$	baseline average annual kilometres travelled by NMT type *k* (km/year), input by the user
a_rmc and b_rmc	model calibration coefficients

Table E3.5 gives the default values of the repair and maintenance cost model calibration coefficients.

Table E3.5 Default parameter values for NMT repair and maintenance cost model

NMT type	Model parameter	
	a_rmc ($x 10^{-6}$)	b_rmc ($x 10^{-6}$)
Bicycles	1.600	0.267
Rickshaws	0.712	0.178
Bullock carts	2.780	0.617
Pedestrians		

Source: *Odoki and Kerali (1999)*

5.5 Crew cost

The crew cost per km, CRWC, of each NMT vehicle type is calculated from the average crew wages per hour as follows:

$$CRWC_k = \frac{CRWV_k}{S_k} \quad ...(5.12)$$

where:

$CRWC_k$ average crew wages per hour for NMT type *k* (*cost*/hr)

S_k annual average speed of NMT type *k* (km/hr)

5.6 Energy cost

Methods for modelling energy used by motorised and non-motorised transport is described in *Kerali et al. (1997)* and in Part F of this document. Therefore only a summary of the quantitative methods used is given here:

Energy cost per km, ENC, is calculated as follows:

$$ENC_k = ENUSD_k * UCEN_k \quad ...(5.13)$$

where:

ENC_k energy cost per km for NMT type *k* (*cost*/km)

$ENUSD_k$ average energy consumption of NMT type *k* (Joules/km)

$UCEN_k$ unit cost of energy used by NMT type *k* (*cost*/Joule)

Energy consumption per NMT veh-km, ENUSD, is calculated for the uphill and downhill directions of traffic flow using Equations 5.14 below and 5.15 below, respectively:

$$ENUSD_{ku} = (FR_{ku} + FG_{ku}) * DIST \quad ...(5.14)$$

$$ENUSD_{kd} = (FR_{kd} + FG_{kd}) * DIST \quad ...(5.15)$$

The average energy consumption for a round trip is then calculated using Equation 5.16 below, which incorporates an energy factor to account for energy used to overcome other forces opposing motion:

$$ENUSD_{k} = 0.5 * Kef_{k} * (ENUSD_{ku} + ENUSD_{kd}) \quad ...(5.16)$$

where:

$ENUSD_k$	the average energy consumption (Joules/km) for NMT type *k*
FR_{ku}	uphill rolling resistance to NMT type *k* (N)
FG_{ku}	uphill gradient resistance to NMT type *k* (N)
DIST	unit distance travelled by NMT (m), taken as equal to 1000
FR_{kd}	downhill rolling resistance to NMT type *k* (N)
FG_{kd}	downhill gradient resistance to NMT type *k* (N)
Kef_k	energy efficiency factor for NMT type *k*, to account for energy used to overcome other forces opposing motion (default = 1.1 for all NMT types)

Walking

Replogle (1992) estimates the energy used in walking as 1.8 kJ/km/kg. This is equivalent to 144 kJ/km for an 80kg person. Thus, the average energy consumption used by walking is estimated from the following expression:

$$ENUSD_{k} = 1.8 * WGT\_OPER * 10^{3} \quad ...(5.17)$$

5.7 Overheads

This covers all other cost elements including; taxes, administration, insurance, parking/garaging, and any overheads associated with the crew (for example, training, uniforms, etc.). The overhead cost per NMT vehicle-km, OVHD, is calculated using the expression:

$$OVHD_{k} = \frac{OHC_{k}}{S_{k} * HRWK0_{k}} \quad ...(5.18)$$

where:

OHC_k	overhead cost per year for NMT type *k*

6 Estimation of economic benefits

For a given road section, the annual economic benefits in terms of savings in NMT user costs are calculated separately for normal traffic and diverted traffic, and for generated traffic. The economic analysis method is described in Part G - Section 5.2.2.

The key input parameter for the economic analysis is the annual average NMT time and operating cost per vehicle-trip over the road section. This is determined from the following expression:

$$UTOC_{jsk} = TOC_{jsk} * L_{js} \quad ...(6.1)$$

where:

$UTOC_{jsk}$	annual average NMT total time and operating cost per vehicle-trip over the road section *s* for vehicle type *k* under investment option *j*
TOC_{jsk}	total time and operating cost of NMT type *k* for section *s* under investment option *j* (cost/km)
L_{js}	road section length under investment option *j* (km)

The types of outputs for Non-Motorised Transport are similar to that for Motorised Transport. The outputs include the following:

- **NMT speeds**
- **NMT traffic flows**
- **Time and operating cost**

The amounts of energy consumption are considered as **renewable energy** in Energy Balance analysis within Social and Environmental Effects module (see Part F).

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E4 Road Safety

1 Introduction

This chapter describes the specification for Road Safety analysis in HDM-4 (see Figure E4.1). The HDM-4 system allows users to define a series of **look-up tables** for accident rates. These are basically broad, macro descriptions of the expected accident rates which can be defined in several different ways according to a particular set of road and traffic attributes (for example, road type, traffic level and flow pattern, presence of Non-Motorised Transport (NMT), and geometry class). This tabular approach to implementing road safety analysis in HDM-4 was recommended (*ISOHDM, 1995*), following a detailed review of various road safety studies, modelling and analysis methods.

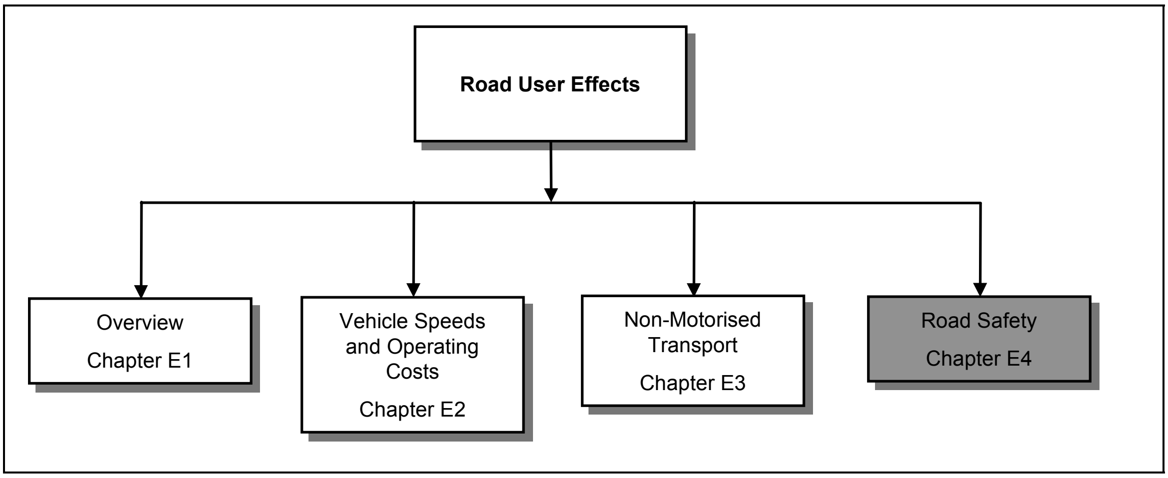

Figure E4.1 Road User Effects modules

2 Modelling logic

2.1 Accident types

An accident is an event involving one or more road vehicles, which results in death, personal injury and/or damage to property. In HDM-4, road safety effects are analysed according to the following accident severity/types:

- **Fatal**

  An accident is considered as fatal if death occurs within a fixed period (for example, 31 days) following the accident. The fixed period may vary from one country to another.

- **Injury**

  An accident causing injury but not resulting in fatalities.

- **Damage only**

  An accident in which no personal injuries occur is considered as a damage (to property) only accident.

2.2 Accident rates

The term **accident rate** is defined as the average number of reported accidents per year, measured over a period of time (for example, 5 calendar years), divided by the exposure. This is expressed as follows:

$$ACCRATE = \frac{ACCYR}{EXPOSURE} \quad ...(2.1)$$

where:

ACCRATE accident rate

ACCYR number of accidents per year

EXPOSURE annual exposure to accidents

The annual exposure to accidents is calculated as follows:

- **Road sections**

  The annual exposure is expressed in terms of one hundred million vehicle-kilometres as:

$$EXPOSSEC = \frac{365 * AADT * L}{10^8} \quad ...(2.2)$$

- **Road intersections**

  The annual exposure is expressed in terms of one hundred million vehicles as:

$$EXPOSINT = \frac{365 * AADT_{in}}{10^8} \quad ...(2.3)$$

where:

EXPOSSEC	annual accident exposure on a road section (100 million veh-km)
AADT	annual average daily traffic on the section (veh/day)
L	road section length (km)
EXPOSINT	annual accident exposure at an intersection (100 million veh-km)
$AADT_{in}$	annual average daily traffic entering the intersection (veh/day)

For each road type or intersection type, the user is required to enter the rate for each accident severity (that is, fatal, injury or damage only), in terms of the number of accidents per 100 million vehicle-kilometres or per 100 million vehicles. For analyses at the aggregate data level, the user has the option of entering a single rate for **All** accident types. This value is equal to the sum of the values of the rates for the three accident types. When a road is improved (that is, providing separate NMT lanes, widening of road shoulders) a change to the road type or intersection type occurs, and different accident rates need to be defined for the new road type. Thus, it is possible to analyse the change in accident rates and costs resulting from improving a road section or an intersection node.

Note: Modelling of intersection nodes is not included in this release.

2.3 Primary data

The following primary data are required for modelling accident effects:

- **Traffic volumes**

  The annual average daily traffic (AADT) on a road section, in vehicles per day, (or the total AADT entering an intersection) and the growth rates.

- **Length of road section**
- **Accident Classes**

  Different accident rates are defined in an Accident Class and may apply in different analysis years depending upon the changes in road type (or intersection type) resulting from the road works carried out over the analysis period.

- **Unit costs of accidents**

  The unit costs can be defined either by accident types, or a weighted mean value may be specified for **All** accident types.

2.4 Computational procedure

Road safety analysis is included within the Road User Effects (RUE) module. For each section (or investment) option, the computational procedure for each analysis year can be summarised as follows:

1. **Initialise input data**
2. **Calculate the annual exposure to accidents**
3. **Calculate the annual number of accidents** (by accident type)
4. **Calculate the annual accident costs** (if applicable)

5 **Store results for economic analysis, comparisons and the reporting phase**

2.5 Number of accidents

The annual number of accidents for each investment option is given by:

$$ACCYR_i = EXPOSSEC_j * ACCRATE_i \quad ...(2.4)$$

where:

$ACCYR_i$	the annual number of accidents of type *i*
$EXPOSURE_j$	the annual exposure to accidents under investment option *j*
$ACCRATE_i$	the accident rate of accident type *i*

2.6 Accident costs

The annual accident costs for each investment option are calculated from the following expression:

$$ACCOST_{ji} = ACCYR_{ji} * UNITCOST_i \quad ...(2.5)$$

where:

$ACCOST_{ji}$	the annual cost of accident type *i* under investment option *j*
$UNITCOST_i$	the unit cost of accident type *i* (*currency*)

The total annual accident cost is given as:

$$AC_j = \sum_i ACCOST_i \quad ...(2.6)$$

where:

AC_j	the annual accident cost under investment option *j*

3 Economic analysis and comparisons

3.1 Economic analysis

The user can specify whether or not to include accident costs together with vehicle operating costs, travel time costs, road agency costs, and exogenous benefits and costs in economic analysis. For each pair of investment options to be compared (that is, option *m* and the base case option *n*), the annual difference in accident costs is calculated as follows:

$$\Delta ACC_{(m-n)} = AC_n - AC_m \qquad ...(3.1)$$

where:

$\Delta ACC_{(m-n)}$ the annual difference in accident costs

For the details of economic analysis and comparisons, see Part G.

3.2 Net change in the number of accidents

For each pair of investment options, the user may choose to compare only the number of predicted accidents for one investment option against that predicted for the base case option. The annual net number of accidents (by accident type) is given by:

$$\Delta ACCYR_{(m-n)i} = ACCYR_{ni} - ACCYR_{mi} \qquad ...(3.2)$$

where:

$\Delta ACCYR_{(m-n)i}$ the annual difference in the number of accidents (for accident type *i*)

3.3 Outputs

The standard reports for safety analysis are supplied in the Applications Guide. These may be added to in the future to include:

1 **Annual number of accidents, by accident type, for each investment option**

2 **Annual accident costs, by accident type, for each investment option**

3 **Net annual streams of accident numbers for each pair of investment options**

4 References

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