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Volume 4 - Analytical Framework & Model Descriptions: Part F

Part F Road Map

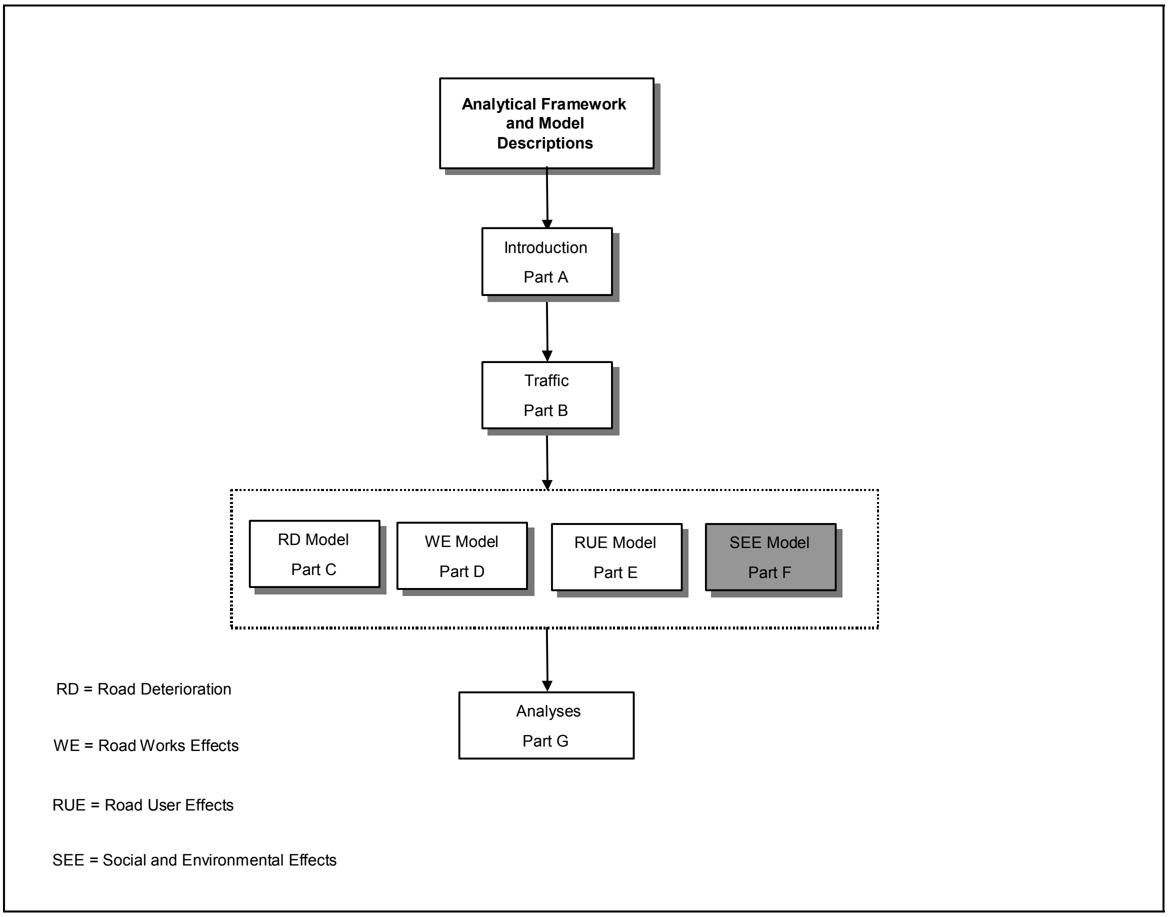

Figure F Analytical Framework and Model Descriptions Road Map

F1 Overview

1 Introduction

The Social and Environmental Effects (SEE) models (see Figure F1.1) are for the analysis of:

- **Energy balance** (see Section 2)
- **Vehicle emissions** (see Section 3)

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

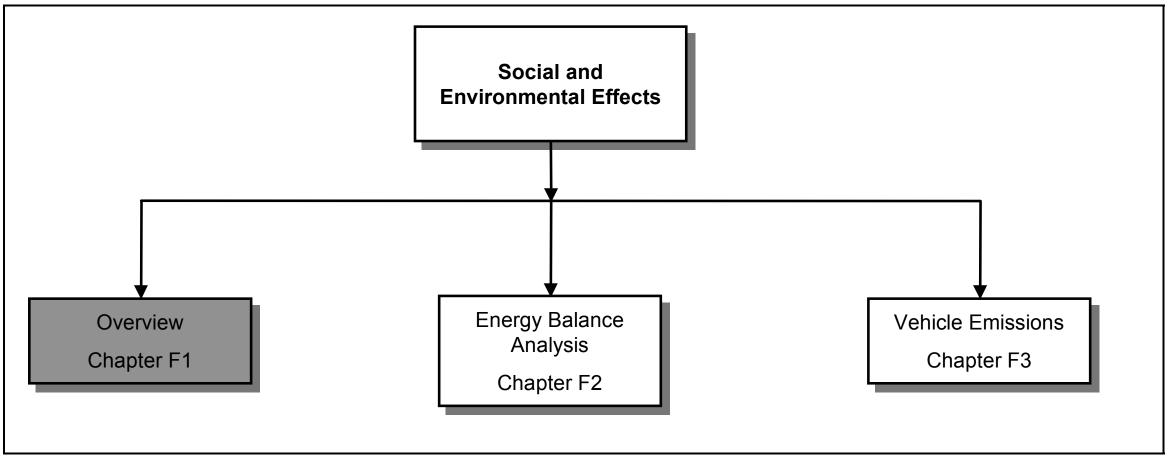

Figure F1.1 Social and Environmental Effects module

The assessment of alternative investment policies and projects requires that the various impact measures be translated or reduced into common policy-sensitive units, which can be considered under a framework of multi-criteria analysis. It is expected that the evaluation of other aspects of environmental impacts that arise from road transport (for example, noise pollution, damage to crops and buildings, etc.) will be included in a later release.

2 Energy balance

The energy used in the road transport sector forms a significant share of the total energy consumption in most countries. The impact of road investment strategies and projects, and of road transport policies on energy use has become an important aspect of the appraisal process.

The appraisal of road transport projects is based primarily on the assessment of economic benefits which are estimated by comparing the total discounted costs calculated for a base case against that for the project case. This is essentially an **economic balance** analysis. A similar analytical framework is implemented for comparing the total energy used by different modes of road transport for the base case and project case. The proposed **Energy Balance** framework is used to calculate:

- **Life-cycle energy consumption**

  Total life-cycle energy consumption at both project and network level analyses of road investment policies.

- **Differences in consumption**

  Differences in the consumption of renewable and non-renewable fuels by non-motorised (NMT) and motorised transport (MT) modes.

- **Total national and global energy use**

This permits comparisons to be made between different modes of road transport and thereby influence policy on long term investment in the road sector (*Kerali et al., 1998*).

The analytical framework, for assessing the energy implications of road investment projects and strategies, considers a number of parameters. These have been classified into three energy use categories:

- **Energy used by motorised vehicles**

  The energy consumption associated with the use of motor vehicles can be split into two broad categories:

  - energy used to produce and deliver both the fuel and vehicle
  - energy used to power and operate the vehicle

  Together, the energy used in each of these categories constitutes the full life-cycle energy consumption. The energy consumed by motorised vehicles depends on a wide range of factors, related to:

  - vehicle size
  - weight
  - design
  - age
  - road characteristics and condition
  - traffic characteristics

  The energy used by motorised vehicles is generally from non-renewable sources. The following resource components, used in vehicle operation are included in the energy balance analysis:

- fuel consumption
- lubricating oil consumption
- tyre wear
- vehicle parts consumption

- **Energy used by non-motorised vehicles**

  Non-motorised modes of transport (NMT) account for the vast majority of the movement of people and goods in many countries. For this reason the inclusion of NMT in the appraisal of transport projects and policies in developing countries is essential. For example the presence of NMT can influence the speed of motorised transport, thereby affecting the operating costs of motorised vehicles. In addition, policies such as road improvements influence the costs and benefits to both motorised and non-motorised road users. The energy used by NMT is calculated separately for animal-drawn carts, cycle-rickshaws, bicycles and pedestrians.

- **Energy used during the construction and maintenance of road networks**

  This is a significant aspect of the complete energy balance picture for road transport investments. Thus, when comparing the energy implications of alternative policy or project alternatives, it is important that this type of energy use is considered.

- **Energy used by vehicles at Work Zones** (not included in this version of HDM-4)

  Work zone effects are defined as those areas affected by road works and typically cause delays, additional vehicle resource fuel consumption and accidents. The effects of works are not restricted to the length of road where the work activities are being performed but extend to the area of approach to and departure from the work zone. The result on the change in speed-flow cycle in a work zone creates additional energy consumption.

The energy balance framework implemented provides an efficient and neutral mechanism for assessing the benefits of road transport investments. This avoids the possible distortion in economic balance methods that may be influenced by fuel prices. Whilst some of the parameters have had to be estimated from a desk study, the concept of energy balance framework can be applied to road investment appraisal using a similar method to that used in economic analyses.

3 Vehicle emissions

The objective of modelling vehicle emissions is to assess the effects (*Hammerstrom, 1995*), in terms of pollutant quantities and changes in the following:

- **Road characteristics**
- **Traffic congestion**
- **Vehicle technology**

The model predicts the different components of vehicle exhaust emissions as a function of fuel consumption. Fuel consumption is a function of vehicle speed, which in turn depends on road characteristics and the characteristics of the vehicle itself. Thus, it is possible to analyse the change in emissions effects as a result of implementing different road maintenance and improvement options, or the implications of major changes to the vehicle fleet (for example, due to improved vehicle technology). The different components of emissions modelled are:

- **Hydrocarbon**
- **Carbon monoxide**
- **Nitrous oxide**
- **Sulphur dioxide**
- **Carbon dioxide**
- **Particulates**
- **Lead**

In this release, the effects of exhaust emissions are not costed for inclusion in economic analysis of road investments, only the net differences in the quantities of pollutants are assessed for each pair of investment options. It is intended that the scope of vehicle emissions modelling will be extended (*Collings and Watkiss, 1998*) to include impacts on:

- **Air quality**
- **Health**
- **Damage costs**
- **Global warming**

4 Applications scope

The analysis of energy balance and environmental impacts has two levels of application:

1 Project level analysis

Allows users to compare the life-cycle energy and emissions implications of a range of project alternatives with the base line, **do-minimum,** alternative. The results of these comparisons will assist in deciding which road investment alternatives should be implemented.

2 Network level analysis

Enables decision makers to understand the energy and emissions implications of broader transport policy objectives which have an impact on specific road networks (for example, urban roads) as well as at the national level (for example, rural roads).

5 References

Collings S.A., and Watkiss P.R., (1998)

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Final project report for the Department for International Development, UK

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ISOHDM Supplementary Technical Relationships Study Draft Report
Swedish National Road Administration, Road and Traffic Management Division, Borlange, Sweden

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Energy Balance Framework for Road Transport Analysis
Transportation Research Board, Paper no. 980819, Washington D.C., USA

F2 Energy Balance Analysis

1 Introduction

1.1 Background to Energy Balance Analysis

The energy used in the road transport sector forms a significant share of the total energy consumption in most countries. The impact of road investment strategies and projects, and of road transport policies on energy use has become an important aspect of the appraisal process (see Figure F2.1). By adopting projects and policies that minimise total life-cycle energy use, related benefits such as reduced operating costs, reduced pollution, reduced dependency on imports of energy and reductions in balance of payments deficits can be maximised. For this reason it is important for planners and decision-makers to be able to understand the energy implications of alternative transport projects and policies.

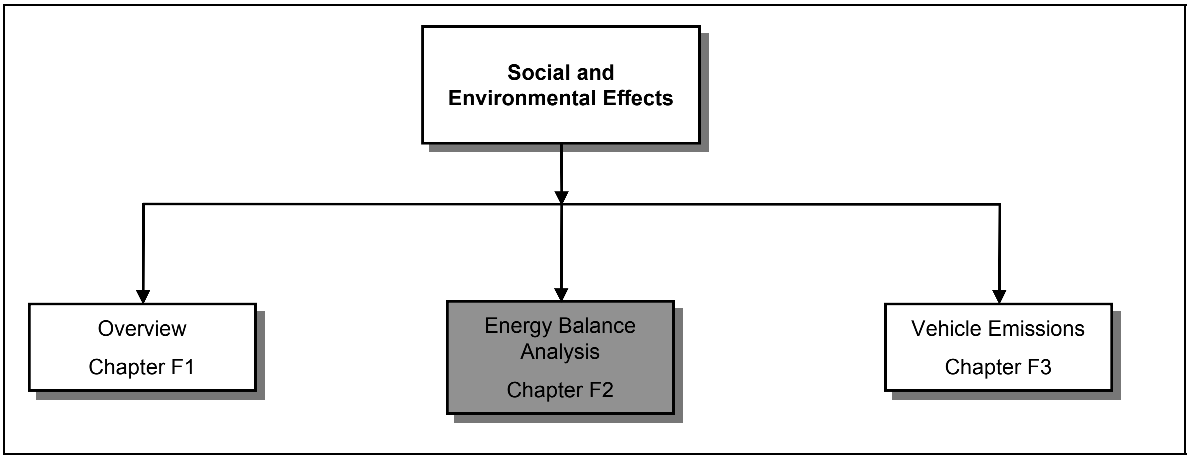


Figure F2.1 Social and Environmental Effects module

The HDM-4 system can be used for assessing technical, economic, social and environmental impacts of road investment. The assessment of alternative investment policies and projects requires that the various impact measures be translated or reduced into common policy-sensitive units. Examples of policy-sensitive units include monetary value, amount of time, safety level, quantity of pollutant, and energy used.

Economic analyses use monetary values of resources in order to derive economic indicators that serve in decision making on different alternatives for road investments. However, the results of economic analyses depend to some extent on the relative monetary values placed on the different components of vehicle resources. For example, a project whose justification is primarily dependent on savings in petroleum consumption shows relatively less economic benefits in an oil rich country than it would in a country which imports its fuel at a high cost. Viewing the benefits of such projects in terms of their efficiency in energy use would place them on an equal footing, and this yields more useful information to planners and decision-makers.

This chapter describes a methodology for assessing the energy implications of different road transport projects and policies within the context of the HDM-4 model. The assessment technique is referred to here as Energy Balance analysis.

1.2 Objectives of the energy balance analysis

The principal objective of the energy balance analysis is to be able to compare total life-cycle energy consumption as a result of different transport policies. A related objective is to determine the relative efficiency of the different modes of transport, both motorised and non-motorised. This efficiency should be measured with respect to the productivity of each mode of transport, that is, the energy used to move a certain number of people or tonnage of goods.

In addition to an overall total energy balance calculation, it is also important to distinguish between different sources of energy. Firstly, energy from renewable and non-renewable sources should be distinguished since the environmental and socio-economic implications of these are different. Secondly, energy expended outside of the country being studied (energy use in the manufacture of imported vehicles, for example) is unlikely to be of concern to the national policy maker, but is significant in terms of global sustainability.

The HDM-4 system offers tools in separate modules for project analysis, programme analysis and network strategy analysis. The energy balance analysis has two levels of application:

1 **Project appraisal level**

2 **Network strategic analysis level**

The project analysis allows users to compare the life-cycle energy implications of a range of project alternatives with the base line, **do-nothing** alternative. The results of these comparisons assist in the decision of which investment project alternatives to implement. For example; the decision over which maintenance techniques to use for a particular stretch of road is influenced by the trade off between:

- **Energy benefits**

  The energy benefits gained from lower vehicle fuel consumption, oil use and tyre wear, due to the improved flow characteristics of the road, and

- **Energy requirements**

  The actual energy requirements of carrying out the maintenance.

The strategic level analysis should enable decision-makers to understand the energy implications of broader transport policy objectives, which impact both specific road networks (for example, a particular urban area), as well as at a national level. For example, at a network level, the energy impacts of various regional public transport investment strategies may be investigated, or similarly, at a national level, the energy implications of fiscal policies to promote alternative fuel types may be a concern.

2 Analytical requirements

Vehicles have been categorised as Motorised Transport (MT) and Non-Motorised Transport (NMT). The development of a model framework for assessing the energy implications of road investment projects and strategies requires the consideration of a number of parameters. These have been broadly classified into three energy use categories:

1 **Energy used by motorised vehicles** (see Section 2.1)

2 **Energy used by non-motorised vehicles** (see Section 2.2)

3 **Energy used during road construction and maintenance** (see Section 2.3)

Sections 2.1, 2.2 and 2.3 describe the parameters that need to be considered for each category of energy use.

2.1 Energy used by motorised vehicles

The energy consumption associated with the use of motor vehicles can be separated into two broad categories; that used to:

1 **Power and operate the vehicle**

2 **Produce and deliver the fuel and vehicle**

Together, the energy used in each of these categories encompasses the full life-cycle energy consumption. Table F2.1 shows the various life-cycle stages that could be considered in determining the full life-cycle energy use.

Table F2.1 Energy use stages associated with vehicle production and use

Major sections	Sub-sections
Fuel production	■ Raw material extraction ■ Feed stock transportation ■ Processing ■ Fuel distribution
Vehicle manufacture	■ Raw material extraction ■ Processing ■ Component manufacture ■ Component transportation ■ Assembly ■ Vehicle distribution
Vehicle use	■ Fuel consumption ■ Oil consumption ■ Tyre wearing
Vehicle maintenance and support	■ Component manufacture ■ Distribution

Source: *ETSU, RYCA 18825001 (1997)*

2.1.1 Energy use due to vehicle operation

The energy consumed by motorised vehicles is dependent upon a wide range of factors relating to the:

- **Vehicle size, weight, design and age**
- **Road characteristics and condition**
- **Traffic characteristics**

The energy used by motorised vehicles is from non-renewable sources.

The following resource components used in vehicle operation are considered in energy balance analysis:

- **Fuel consumption**
- **Lubricating oil consumption**
- **Tyre wear**
- **Vehicle parts consumption**

The prediction of a MT vehicle's energy consumption under specific driving conditions can be considered in two ways; either by using:

1 **A mechanistic approach based on physical and mechanical first principles**, or

2 **Actual measured data to give energy use factors for a range of vehicles operating under different conditions**

The former mechanistic approach provides a greater degree of accuracy but has far greater data requirements, whereas the energy use factor approach can be applied relatively easily.

Fuel consumption

The fuel consumption model follows a purely mechanistic approach that allows:

- **The flexibility to model individual vehicle and road characteristics**
- **The ability to alter the model as new technologies are introduced**

The mechanistic approach has been well researched, providing a theoretical and experimental justification for all of the numerical assumptions that are made for each of the parameters. The standard default vehicles are based on those using petrol and diesel fuel.

Suitable models for other vehicle technologies using different fuel types (for example, electricity, LPG, CNG, etc.) are still being developed. For analyses involving comparison with these vehicles, the energy consumption of alternative fuelled vehicles can be estimated by applying scale factors which relate the calculated energy consumption of petrol or diesel vehicles to the energy consumption of various alternative fuelled vehicles.

The fuel consumption model does not include the treatment of cold starts on fuel consumption. In order to provide the needed mixture strength for satisfactory combustion at the start of a journey, a large excess of fuel must be delivered to compensate for the condensing losses due to the cold engine. This is more of a problem for petrol vehicles than for diesel.

For the majority of road project appraisals the cold start issue is not considered to be important, with the assumption being made that all journeys are run under hot engine conditions. However, the influence of cold starting on fuel consumption may be of particular significance in relation to some transport policies, particularly in urban areas where there are a great number of shorter trips.

To overcome the problem of cold starts, scale factors relating the calculated fuel consumption under normal **hot** conditions to fuel consumption under **cold** conditions can be used. The proportion of the journey, which is run under cold conditions, can be estimated using the **CORINAIR** methodology (*Eggleston et al., 1993*) which takes into account the average trip length of the vehicle journeys and the average ambient temperature.

The average fuel use per vehicle kilometre for a full trip is calculated from the sum of the **cold start** fuel use and **hot conditions** fuel use, weighted by the proportion of journey run cold and hot, respectively.

Different transport fuels have different calorific values. Thus in order to compare like with like the average fuel use per vehicle kilometre should be converted to energy factors per vehicle kilometre using the energy content values given in Table F2.2.

Table F2.2 Energy content of transport fuels

Fuel	Energy content (MJ/litre)
Petrol	34.7
Diesel	38.7
LPG[1]	25.5
CNG[2]	40
Ethanol	23.9
Methanol	18.1
Biodiesel	32.8

Source: *ETSU (1996)*

Notes:

1 Assumes 90% propane, 10% butane

2 Units are MJ/m^3

Lubricating oil consumption

Oil consumption is calculated in terms of litres per 1000 vehicle kilometres as a function of fuel consumption. During the procedure for energy balance analysis, the amount of lubricating oil consumed is converted to an energy value using a conversion factor of 47.7 MJ per litre.

Tyre wear

The tyre consumption of a vehicle is proportional to the energy requirements (see *Watanatada et al., 1987*). It is calculated using a model based on slip energy theory.

Tyre consumption, in terms of number of tyres per 1000 vehicle kilometres, is calculated for light and heavy vehicles. These figures can be converted to an energy value using a conversion factor of 32 GJ/tonne of tyres (*Department of Trade and Industry, 1996*). The weight of tyres can be estimated using the factors given in Table F2.3.

Table F2.3 Tyre weights by vehicle type

Vehicle number	Vehicle type	Tyre weights (kg)
1	Motorcycle	2.0
2	Small car	3.0
3	Medium car	3.5
4	Large car	4.0
5	Light delivery vehicle	4.0
6	Light goods vehicle	4.0
7	Four wheel drive	5.0
8	Light truck	7.0
9	Medium truck	12.4
10	Heavy truck	12.4
11	Articulated truck	13.7
12	Mini-bus	4.0
13	Light bus	7.0
14	Medium bus	9.8
15	Heavy bus	11.2
16	Coach	11.2

Source: *ETSU (1996)*

Vehicle repair and parts consumption

Maintenance and support services are very difficult to consider given the fragmented nature of the vehicle repair and spares businesses. Their contribution to overall energy use is very small in comparison with the other life-cycle stages. For example, one study, based on transport in Switzerland, estimated maintenance and support services energy use to be approximately 4% of total life-cycle energy use (*Maibach et al., 1995*). However, in developing countries, where vehicle maintenance assumes a lower priority than it would in Switzerland, this proportion is likely to be much lower. For this reason the energy use associated with maintenance and support services is not considered to be a significant aspect of the overall energy balance.

Nevertheless, the RUE (Road User Effects) model does calculate vehicle parts consumption. This is measured in terms of the fraction of the new vehicle price per 1000 km. The energy use associated with this vehicle parts consumption can be estimated by multiplying the energy used to produce the vehicle (see Table F2.4) by the fraction of the parts price to the new vehicle price. To calculate vehicle parts energy consumption per vehicle kilometre, the energy used to produce the vehicle parts should be divided by the vehicle cumulative kilometreage, at the time the parts are replaced. The typical energy used during a year can be divided by annual average vehicle kilometres, to give vehicle maintenance energy use per vehicle kilometre.

Table F2.4 Energy use for vehicle production

Vehicle number	Vehicle type	Vehicle mass (kg)	Vehicle production energy (GJ)
1	Motorcycle	200	20
2	Small car	800	80
3	Medium car	1000	100
4	Large car	1200	120
5	Light delivery vehicle	1400	140
6	Light goods vehicle	1600	160
7	Four wheel drive	1800	180
8	Light truck	4000	400
9	Medium truck	6000	600
10	Heavy truck	10000	1000
11	Articulated truck	15000	1500
12	Mini-bus	3000	300
13	Light bus	5000	500
14	Medium bus	7000	700
15	Heavy bus	10000	1000
16	Coach	7000	700

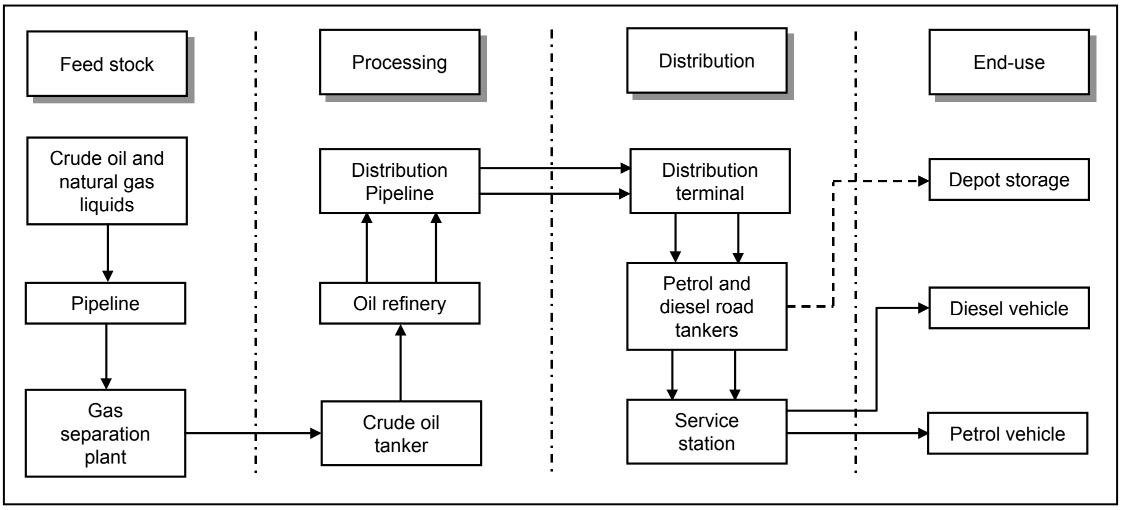
Source: *ETSU, RYCA/18825001 (1997)*

2.1.2 Fuel production and vehicle manufacture energy use

An accounting framework is needed to estimate the **cradle to grave** energy use for the various life-cycle stages. Under this category, the energy balance analysis framework considers energy use associated with **fuel production** and **vehicle manufacture** as described below:

Fuel production

Figure F2.2 illustrates the stages that must be considered for petrol and diesel fuel production. The energy use values from each stage of the fuel cycle are calculated on an-energy delivered basis, and then aggregated to give the total energy use per unit of energy delivered for the full fuel-cycle. In this way energy use for fuel production can be calculated per vehicle kilometre.



Source: *ETSU, RYCA/18825001 (1997)*

Key: - - - - - means optional (storage)

Figure F2.2 Petrol and diesel fuel production cycle

The energy use associated with each of the fuel production stages (shown in Figure F2.2 for petrol and diesel) varies considerably from country to country. However, if no local data exists and neither do the resources to carry out a fuel-cycle analysis, then default data such as that shown in Table F2.5 could be used to estimate the energy use associated with fuel production. Fuel production energy use on a vehicle kilometre basis is derived from the energy consumption during vehicle use.

Table F2.5 Fuel-cycle energy use factors

Fuel	Energy use (MJ/MJ of fuel delivered)
Petrol	0.169
Diesel	0.122
LPG[1]	0.122
CNG	0.061
Electric[2]	2.857
Biomethanol	0.514
Bioethanol	0.510
Biodiesel	0.655

Source: *ETSU (1996)*

Notes:

1 Assumes 40% of LPG comes from refineries and 60% is directly extracted

2 Assumes a higher calorific value (HCV) average generating efficiency of 35%

Vehicle manufacture

Data concerning the energy used to manufacture and deliver a motor vehicle is very difficult to obtain due to the commercial sensitivities of the motor manufacturing industry. A recent survey of what data is available revealed a typical value of 100 GJ per medium-sized car with a weight of 1 tonne (*ETSU, 1995*). This represents approximately 15% of total life-cycle energy use and is therefore a significant part of the overall energy balance.

To estimate the energy used to manufacture other vehicle types, a first order approximation can be obtained by scaling 100 GJ by the ratio between the weight of a medium sized car and the weight of the other vehicle. Based on this approach Table F2.4 shows some estimates of energy use for vehicle production for each of the 16 standard vehicle types. In addition, it shows estimates of total life-time vehicle kilometres which can be used to calculate default values for vehicle production energy use on a per vehicle kilometre basis. The user can input their estimates of vehicle service life in the Vehicle Fleet folder.

The energy used in the production process of each vehicle can simply be divided by the average total lifetime vehicle kilometres to give vehicle production energy use per vehicle kilometre.

2.2 Energy used by non-motorised vehicles

Non-motorised modes of transport (NMT) account for the vast majority of the movement of people and goods in developing countries. For this reason the inclusion of NMT in the appraisal of developing country transport projects and policies is essential. For example, 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 improvement influence the costs and benefits of not only motorised road users, but also non-motorised road users.

With animal-drawn transport, the energy used can be justifiably included on the grounds that possibly the only reason that the animals are kept, and fed, is so that they can provide transport services to their owners. Thus the feed used can be looked upon as an energy loss equal to the opportunity cost of forfeiting its energy input for another purpose. However, with human powered transport such as cycling and walking, it is very difficult to say that the energy consumed would not have been consumed if the trip had not taken place. It is unlikely that people consciously **fill-up** by consuming say 10% more calories when they know they are going to be making a trip.

Nevertheless, walking and cycling expend energy, and it could be argued where food is a particularly scarce resource that this energy should be included as a cost to society. In addition, where individuals are using their energy for powering their business (for example, cycle-rickshaws) and are therefore very active for most of the day, they probably need to consume several times the calories of a sedentary person.

Sections 2.2.1, 2.2.2 and 2.2.3 describe the principles behind calculating energy use for various types of NMT.

2.2.1 Animal-drawn vehicles

The energy required for animal-drawn carts can be split into two parts:

1 **Energy required for the animal to walk the required distance**

2 **Energy required to move the load** (if a load is being pulled)

Data on energy use by animals is sparse. As a broad assumption, a relationship derived for human walking activity may be used:

1.8 kJ/km/kg (*Replogle, 1992*)

The two main loads that have to be overcome in pulling a laden cart are rolling resistance and hill climbing. Thus the energy required to pull a laden cart can be estimated from the following equation:

$$\text{Power} = C_R M g \nu + M g \nu \sin\theta \qquad \ldots(2.1)$$

where:

C_R	coefficient of rolling resistance
M	cart mass including the load
g	acceleration due to gravity
ν	Speed
θ	slope gradient

Table F2.6 shows a range of energy use factors derived using this formula. The animal and load weights have been chosen to reflect those typically seen in certain parts of the world. For example the weight of a laden cart pulled by two oxen (common in more humid zones of West Africa (*Starkey, 1993*) is estimated to be 1000kg (*Dennis, 1995*). An ox could be assumed to weigh 400kg. For comparison a donkey pulling a 100 kg laden cart, common in the drier zones of West Africa, weighs around 150 kg (*Starkey, 1993*). A pack animal, commonly used in hilly areas, would tend to carry loads in the region of 30-70 kg.

The values in Table F2.6 have assumed a rolling resistance for carts of 0.04 (*Dennis, 1995*), an average speed of 6.4 km/h and a zero gradient.

Table F2.6 Typical energy use factors for animal transport (kJ/km)

Animal weight (kg)	**Cart weight, including load (kg)**			
(including any load)	**No cart**	**100**	**500**	**1000**
200	360	399	556	752
400	720	759	916	1110
600	1080	1119	1276	1470
800	1440	1479	1636	1830

2.2.2 Cycling

There is over 800 million bicycles worldwide (*United Nations, 1993*). Of these, approximately 400 million are in Asia, with 300 million in China (*Replogle, 1992*).

Published figures regarding the energy used in cycling vary widely. Naturally, the specific energy use depends upon the weight of the rider and bicycle, the friction due to the cycle and the speed of motion. Table F2.7 shows a range of cycling energy use factors quoted by *Lewis (1995)*.

Table F2.7 Energy use factors for cycling (kJ/km)

Weight (kg)	Speed (km/h)			
	19.2	**24**	**27.2**	**30.4**
50	64.12	70.73	78.63	91.50
59	73.97	82.11	91.45	106.84
68	83.82	93.49	104.28	122.05
77	93.45	104.87	117.09	137.25
86	103.30	116.25	129.92	152.60
91	108.33	122.03	136.41	160.20

2.2.3 Walking

Replogle (1992) estimates the energy used in walking as:

1.8 kJ/km/kg

This is equivalent to 144 kJ/km for an 80-kg person (see Chapter E3).

2.3 Energy used during road construction and maintenance

Energy use during the construction and maintenance of road networks is a significant aspect of the complete energy balance picture for road transport investments. Thus when comparing the energy implications of alternative policy or project options it is important that this type of energy use is considered.

Data on energy use during road construction and maintenance is sparse and, as yet, none has been obtained. The energy used in performing the various road works activities can be broadly considered under the following:

- **Production of materials** - (for example, bitumen, cement, lime, stone-aggregates, etc.)
- **Delivery of materials to work sites**
- **Operation of equipment**

However, for the purpose of energy balance analysis, such a detailed treatment is not appropriate. Instead, a framework is implemented using aggregate level data for the energy used in performing each of the different types of road works modelled. For example, an average representative value of energy used per cubic metre of overlay can be specified. This value is then multiplied by the total quantity of overlay performed on the road section to give the total energy used. It is also necessary to distinguish between labour intensive works and mainly mechanised works.

3 Energy balance framework

Based on the approach described in Section 2, the following sections specify the calculations required to compare the energy consumption implications of alternative transport policy options. The outputs that are required from an energy balance analysis are:

- **Total energy consumption**
- **Total consumption of renewable and non-renewable energy**

  (This is essentially a distinction between Non-Motorised Transport (NMT) energy use and all other energy use, except if biofuels are used).
- **Total consumption of energy used nationally and energy used globally**
- **Specific energy consumption**

These can be reported by vehicle types or aggregated by vehicle class.

The following indicators usually measure the specific energy consumption:

- **Average energy use, per kilometre, by mode**
- **Energy use, per passenger kilometre, for passenger transport modes**
- **Energy use, per tonne kilometre, for freight transport modes**

3.1 Outline of the energy balance framework

The proposed methodology for assessing the energy implications of transport policies splits into four main elements:

1. **Generation of the energy use characteristics** - for each vehicle type (both motorised and non-motorised)
2. **Incorporation of life-cycle effects**
3. **Calculation of total energy use**
4. **Generation of indicator results**

The average energy use factors are combined with the estimated total annual vehicle-kilometres operated by each mode to give total annual energy use for the policy or measure being considered. These totals are then used to give a range of indicator results for comparative analysis.

3.2 Energy use factors for a motorised vehicle

3.2.1 Fuel

Vehicle fuel use factors are split into factors for hot and cold operation. The fuel use per vehicle kilometre under **hot** conditions comes as output from the RUE (Road User Effects) model.

The cold start fuel use is related to the basic hot fuel use, the ambient temperature and the average vehicle trip length. The level of cold start fuel use is related to the hot fuel use by factor CRAT, which is a function of the ambient temperature. This is expressed as follows:

$$FCOLD_k = CRAT_k * FHOT_k \qquad \ldots(3.1)$$

where:

$FCOLD_k$	cold start fuel use for vehicle type *k* (litres per km)
$CRAT_k$	cold start ratio at a given ambient temperature
$FHOT_k$	hot fuel use for vehicle type *k* (litres per km)

The hot fuel use is obtained from the following equation:

$$FHOT_k = FC_{kav} * 10^{-3} \qquad \ldots(3.2)$$

where:

FC_{kav}	annual average fuel consumption for vehicle type *k* (litres per 1000 vehicle-km)

The cold start ratios (CRAT) are for passenger cars of petrol and diesel technologies, but are also applicable to two-wheelers and vans. These ratios can be estimated from the following **CORINAIR** relationships (*Eggleston, 1993*):

- **Petrol engine cars**

$$CRAT = 1.47 - 0.009 * TEMP \qquad \ldots(3.3)$$

- **Diesel engine cars**

$$CRAT = 1.34 - 0.008 * TEMP \qquad \ldots(3.4)$$

where:

TEMP	the average day temperature (degrees Celsius)

Buses and trucks are usually considered to operate permanently under hot conditions, to a good approximation, since their average trip lengths are very high.

This fuel use under cold conditions only occurs in the initial stages of a journey. The proportion of any journey run cold is calculated as follows:

$$CRUN_k = MAX\{0, [0.698 - 0.051 * L_k - (0.01051 - 0.000770 * L_k) * TEMP]\} \qquad \ldots(3.5)$$

where:

$CRUN_k$	the proportion of the journey run under cold conditions
L_k	average trip length for vehicle type *k* (km) (default=15)

Taking into account the proportion of the journey run cold, the average vehicle fuel use per kilometre for the full trip can be calculated as follows:

$$FAVE_k = CRUN_k * FCOLD_k + (1 - CRUN_k) * FHOT_k \qquad \text{...(3.6)}$$

where:

$FAVE_k$ average fuel use for vehicle type *k* (litres per kilometre)

The average vehicle fuel use, FAVE, is converted to energy use factor per kilometre by applying the energy content of fuel given in Table F2.2. Thus,

$$ENFUEL_k = FAVE_k * FEC_{fk} \qquad \text{...(3.7)}$$

where:

$ENFUEL_k$ annual average fuel energy consumption of vehicle type *k* (MJ/km)

FEC_{fk} energy content of fuel type *f* used in vehicle type *k* (MJ/litre). Defaults are given in Table F2.2

3.2.2 Lubricating oil

The annual average oil consumption, in litres per 1000 vehicle-kilometres, output from the RUE (Road User Effects) model is converted to energy use factor using the energy conversion factor given in Section 2.1.1 as follows:

$$ENOIL_k = OIL_{kav} * OEC * 10^{-3} \qquad \text{...(3.8)}$$

where:

$ENOIL_k$ annual average oil energy consumption of vehicle type *k* (MJ/km)

OIL_{kav} annual average oil consumption of vehicle type *k* (litres per 1000 vehicle-km)

OEC energy content of lubricating oil (MJ/litre), default = 47.7

3.2.3 Tyre

The annual average number of equivalent new tyres consumed per 1000 vehicle-kilometres output from the RUE (Road User Effects) model is converted to energy use factor using the energy conversion factor given in Section 2.1.1 as follows:

$$ENTYRE_k = TC_{kav} * TEC * TWGT_k * 10^{-3} \qquad \text{...(3.9)}$$

where:

$ENTYRE_k$ annual average tyre energy consumption of vehicle type *k* (MJ/km)

TC_{kav} annual average number of equivalent new tyres consumed per 1000 veh-km

TEC energy content of tyre (MJ), default = 32 MJ/Kg

$TWGT_k$ tyre weight of vehicle type *k* (kg per tyre) (see Table F2.3)

3.2.4 Vehicle repair and parts

The annual average parts consumption per 1000 vehicle kilometres expressed as a proportion of the new vehicle price output from the RUE (Road User Effects) model is converted to an energy use factor using the energy conversion factor given in Section 2.1.1 as follows:

$$ENPART_k = PC_{kav} * ENVP_k * 10^{-3} \qquad \ldots(3.10)$$

where:

$ENPART_k$	annual average parts energy consumption of vehicle type *k* (MJ/km)
PC_{kav}	annual average parts consumption per 1000 veh-km as a proportion of the new vehicle price
$ENVP_k$	vehicle production energy use (MJ per km)

and:

$$ENVP_k = \frac{ENVPROD_k}{LIFEKM_k} \qquad \ldots(3.11)$$

where:

$ENVPROD_k$	total energy used in the production of vehicle type *k* (MJ) (see Table F2.4)
$LIFEKM_k$	the predicted vehicle service life (km)

3.2.5 Global life-cycle energy use factors

To incorporate certain life-cycle aspects into the energy use factors, as discussed in Sections 3.1 and 3.3, the following relationships should be used:

$$EGLICY_k = ENFUEL_k + ENOIL_k + ENTYRE_k + ENPART_k + ENVP_k + (ENFUEL_k * FP_f) \qquad \ldots(3.12)$$

where:

$EGLICY_k$	annual average life cycle energy use factor for vehicle type *k* (MJ/km)
FP_f	fuel production factor of fuel type *f* (MJ per MJ of fuel used), defaults are shown in Table F2.5

The annual average global energy use per passenger-kilometre is calculated as:

$$EGPAXKM_k = \frac{EGLICY_k}{PAX_k} \qquad \ldots(3.13)$$

where:

$EGPAXKM_k$ annual average global energy use per passenger-kilometre for vehicle type *k* (MJ/passenger-km)

PAX_k average number of passengers per vehicle type *k*

The annual average global energy per tonne-km is calculated as:

$$EGGDSKM_k = \frac{EGLICY_k}{PAYLD_k} \quad \ldots(3.14)$$

where:

$EGGDSKM_k$ annual average global energy use per tonne-km for vehicle type *k* (MJ/tonne-km)

$PAYLD_k$ average payload per vehicle type *k* (tonnes)

The average payload for each vehicle type *k* is calculated from the difference between the average operating weight and the tare weight as follows:

$$PAYLD = MAX[0, (WGT\_OPER - WGT\_TARE)] \quad \ldots(3.15)$$

3.2.6 National life-cycle energy use factors

To incorporate certain life-cycle aspects into the energy use factors, as discussed in Sections 2.1 and 2.3, the following relationships should be used:

$$EGLICY_k = \begin{bmatrix} ENFUEL_k + ENOIL_k + ENTYRE_k + (PNP_k * ENPART_k) \\ + (PNV_k * ENVP_k) + (PNF_f * ENFUEL_k * FP_f) \end{bmatrix} \quad \ldots(3.16)$$

where:

$ENLICY_k$ annual average national life cycle energy use factor for vehicle type *k* (MJ/km)

PNP_k proportion of parts for vehicle type *k* produced within the country (as a fraction)

PNV_k proportion of vehicle type *k* produced within the country (as a fraction)

PNF_f proportion of fuel type *f* produced within the country (as a fraction)

The annual average national energy use per passenger-kilometre is calculated as:

$$ENPAXKM_k = \frac{ENLICY_k}{PAX_k} \quad \ldots(3.17)$$

where:

$ENPAXKM_k$ annual average national energy use per passenger-km for vehicle *k* (MJ/passenger-km)

PAX_k average number of passengers per vehicle type *k*

The annual average national energy per tonne-km is calculated as:

$$ENGDSKM_k = \frac{ENLICY_k}{PAYLD_k} \quad \text{...(3.18)}$$

where:

$ENGDSKM_k$ annual average national energy use per tonne-km for vehicle type *k* (MJ/tonne-km)

$PAYLD_k$ average payload per vehicle type *k* (tonnes)

3.3 Energy use factors for non-motorised transport

Energy use factors $EGLICY_k$, $ENLICY_k$ for each Non-Motorised Transport (NMT) mode *k* can be obtained as follows:

The calculation of energy used by NMT is shown in Chapter E3.

$$EGLICY_k = ENUSD_k * 10^6 \quad \text{...(3.19)}$$

$$ENLICY_k = EGLICY_k \quad \text{...(3.20)}$$

where:

$EGLICY_k$ annual average global life cycle energy use factor for NMT type *k* (MJ/km)

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

$ENLICY_k$ annual average national life cycle energy use factor for NMT type *k* (MJ/km)

3.4 Total energy use

3.4.1 Total global energy use

The annual global energy use for each vehicle type *k* is calculated by multiplying the average energy use factor $EGLICY_k$ by the total kilometres travelled by the vehicle. Thus:

$$EGLOB_k = EGLICY_k * VKM_k \quad \text{...(3.21)}$$

where:

$EGLOB_k$ annual global energy use for vehicle type *k* (MJ)

VKM_k annual vehicle kilometres operated by vehicle type *k* (km)

The annual total global energy use is then the sum of the energy use for each vehicle type *k* (of MT and NMT, for *k* = 1, 2, …, K) plus the energy used for road works performed on the particular section(s) in that analysis year:

$$EGTOT = \sum_{k=1}^{K} EGLOB_k + ENROAD \qquad \ldots(3.22)$$

where:

EGTOT annual total global energy use (MJ)

ENROAD energy used for road works performed in the given analysis year (MJ)

The energy used for road construction and maintenance in the given analysis year is calculated from the following equation:

$$ENROAD = \sum_{w=1}^{W} QTY_w * WEF_w \qquad \ldots(3.23)$$

where:

QTY_w amount of works type *w*

WEF_w energy used for a unit amount of works type *w* (MJ/unit). (Default data is not yet available)

The total global energy used over the analysis period for each investment option is given by the expression:

$$GLOENGY = \sum_{y=1}^{Y} EGTOT_y \qquad \ldots(3.24)$$

where:

GLOENGY total global energy use over the analysis period (MJ)

$EGTOT_y$ total global energy use in analysis years *y* (*y*= 1, 2, . . Y) (MJ)

3.4.2 Total national energy consumption

Energy use within a country is associated with vehicle use (both MT and NMT) together with the energy use associated with any fuel, oil, vehicle and parts production that occurs within the country.

The annual national energy use for each vehicle type *k* is calculated by multiplying the average energy use factor $ENLICY_k$ by the total kilometres travelled by the vehicle. Thus:

$$ENAT_k = EGLICY_k * VKM_k \qquad \ldots(3.25)$$

where:

$ENAT_k$ annual national energy use for vehicle type *k* (MJ)

VKM_k annual vehicle kilometres operated by vehicle type *k* (km)

The annual total national energy use is then the sum of the energy use for each vehicle type *k* (of both MT and NMT, for *k* = 1, 2, …, K) plus the energy used for road works on the section(s) involved in that analysis year:

$$ENTOT = \sum_{k=1}^{K} ENAT_k + ENROAD \qquad \ldots(3.26)$$

where:

ENTOT annual total national energy use (MJ)

ENROAD energy used for road works performed in the given analysis year (MJ)

The total national energy used over the analysis period for each investment option is given by the expression:

$$NATENGY = \sum_{y=1}^{Y} ENTOT_y \qquad \ldots(3.27)$$

where:

NATENGY total national energy use over the analysis period (MJ)

$ENTOT_y$ total national energy use in analysis years *y* (*y*= 1, 2, . . Y) (MJ)

3.4.3 Total renewable and non-renewable energy consumption

Assuming that renewable and non-renewable energy use can be split between energy use by Non-Motorised Transport and Motorised Transport respectively, then total renewable and non-renewable energy consumption is simply the total energy use for NMT modes and MT vehicles, respectively.

Thus, annual renewable energy is calculated as:

$$ERNWi = \sum_{k \in NMT} EYi_k \qquad \ldots(3.28)$$

where:

EYi_k annual energy use for NMT vehicle type *k* (MJ) (that is, $EGLOB_k$ or $ENAT_k$)

i global (g) or national (n)

The total renewable energy (RNWTEi) used over the analysis period for each investment option is obtained by summing ERNWi over the years.

The annual non-renewable energy is calculated as:

$$ENONRWi = \sum_{k \in MT} EYi_k \qquad \ldots(3.29)$$

where:

EYi_k annual energy use for MT vehicle type *k* (MJ)

i global (g) or national (n)

The total non-renewable energy (NORNTEi) used over the analysis period for each investment option is obtained by summing ENONRWi over the years.

3.5 Comparison of investment options

The true benefit of the assessment outlined above is in comparing results from before a transport measure or policy has been implemented (base case option *n*) with results after implementation (option *m*), so that the impact of the policy or measure can be seen.

The basic indicator of the performance of a measure is simply the difference between the base case results and the alternative case results:

$$\Delta ENERGYM_{(m-n)} = ENERGYM_n - ENERGYM_m \quad \ldots(3.30)$$

Indicators are computed and implemented in the reports for each comparison of investment options *m* and *n*. The indicators are changes in the:

- **Annual average global and national life-cycle energy use factors**

  $\Delta EGLICY_{k(m-n)}$ and $\Delta ENLICY_{k(m-n)}$, respectively, for vehicle type *k* (MJ/km).

- **Annual global and national energy use**

  $\Delta EGLOB_{k(m-n)}$ and $\Delta ENAT_{k(m-n)}$, respectively, for vehicle type *k* (MJ).

- **Annual average global and national energy use per passenger-km**

  $\Delta EGPAXKM_{k(m-n)}$ and $\Delta ENPAXKM_{k(m-n)}$, respectively, for vehicle type *k* (MJ/passenger-km).

- **Annual average global and national energy use per tonne-km**

  $\Delta EGGDSKM_{k(m-n)}$ and $\Delta ENGDSKM_{k(m-n)}$, respectively, for vehicle type *k* (MJ/tonne-km).

- **Annual total global and national energy use**

  $\Delta EGTOT_{(m-n)}$ and $\Delta ENTOT_{(m-n)}$, respectively (MJ).

- **Total global and national energy use over the analysis period**

  $\Delta GLOENGY_{(m-n)}$ and $\Delta NATENGY_{(m-n)}$, respectively (MJ).

- **Annual total global and national renewable energy use**

  $\Delta ERNWg_{(m-n)}$ and $\Delta ERNWn_{(m-n)}$, respectively (MJ).

- **Annual total global and national non-renewable energy use**

  $\Delta ENONRNWg_{(m-n)}$ and $\Delta ENONRNWn_{(m-n)}$, respectively (MJ).

- **Total global and national renewable energy use over the analysis period**

  $\Delta RNWTEg_{(m-n)}$ and $\Delta RNWTEn_{(m-n)}$, respectively (MJ).

- **Total global and national non-renewable energy use over the analysis period**

  $\Delta NORNTEg_{(m-n)}$ and $\Delta NORNTEn_{(m-n)}$, respectively (MJ).

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F3 Vehicle Emissions

1 Introduction

This chapter describes the implementation of Vehicle Emissions analysis in HDM-4 (see Figure F3.1). The objective of modelling vehicle emissions is to assess the effects, in terms of pollutant quantities, of changes in road characteristics, traffic congestion, and vehicle technology.

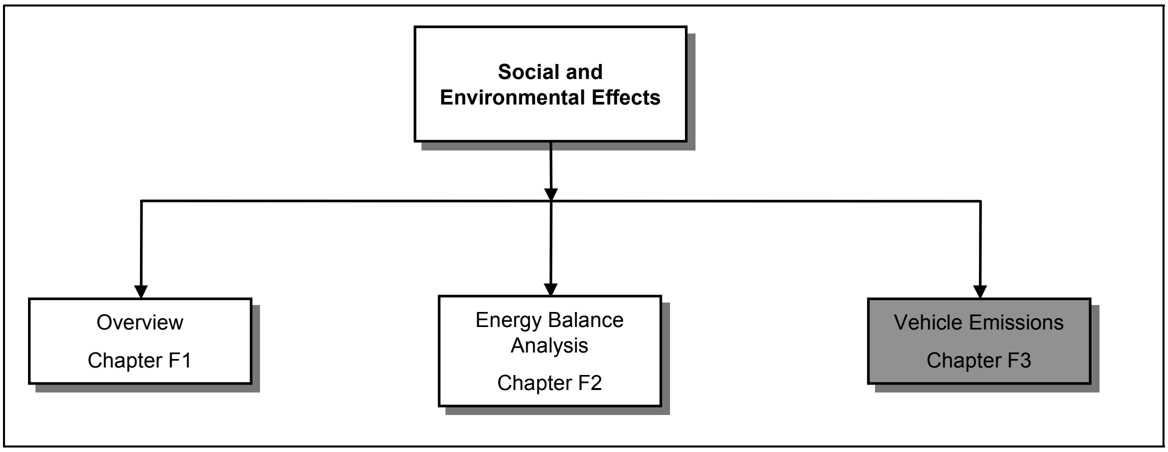

Figure F3.1 Social and Environmental Effects module

The HDM-4 modelling approach has been adapted from that proposed by An, *et al. (*1997). Originally a variety of units were used. The relationships and model coefficients have been adjusted so that all emissions predictions are in terms of grammes per vehicle-kilometre, *Bennett & Greenwood (2003)*.

The model predicts the different components of vehicle exhaust and tailpipe emissions as a function of fuel consumption and speed. Fuel consumption is a function of vehicle speed, which in turn depends on road characteristics and the characteristics of the vehicle itself. Thus, it is possible to analyse the change in emissions effects as a result of implementing different road maintenance and improvement options, or when there are major changes to the vehicle fleet using the road network (for example, due to improved vehicle technology).

In this release, the effects of exhaust emissions are not costed for inclusion in economic analysis of road investments, only the net differences in the quantities of pollutants are assessed for each pair of investment options.

2 Emissions model

2.1 Types of pollutants

The following seven different components of exhaust emissions are considered:

1. **Hydrocarbon** (HC)
2. **Carbon monoxide** (CO)
3. **Nitrous oxide** (NO_X)
4. **Sulphur dioxide** (SO_2)
5. **Particulates** (Par)
6. **Lead** (Pb)
7. **Carbon dioxide** (CO_2)

2.2 Basic Model Form

The engine out emissions are estimated based on the fuel consumption rates, with CO_2 being calculated from Carbon balance assumptions. The engine out emissions are treated by the catalytic converter, if present, to yield the tailpipe emissions observed by the environment.

The basic model form is:

$$\mathrm{TPE}_i = \mathrm{EOE}_i \mathrm{CPF}_i \qquad \text{...(2.1)}$$

and

$$\mathrm{CPF}_i = \left[1 - \varepsilon_i \exp\left(-b_i \ \mathrm{IFC\,MassFuel}\right)\right] \min\left[(1 + \frac{r_i}{100} \mathrm{AGE}) \, , \mathrm{MDF}_i \right] \qquad \text{...(2.2)}$$

where

TPEi	Tailpipe Emissions in g/veh-km for emission i
EOEi	Engine Out Emissions in g/veh-km for emission i
CPFi	Catalyst Pass Fraction for emission i
Ri	deterioration factor for emission i in %/year
AGE	vehicle age in years
MDFi	maximum deterioration factor for emission i (default = 10)
εi	maximum catalyst efficiency for emissions
Bi	stoichiometric CPF coefficient
IFC	instantaneous fuel consumption (including congestion effects) in mL/s
MassFuel	mass of fuel in g/mL

Table F3.1: Default Emission Model Parameter Values for HDM-4 Representative Vehicle Classes

Vehicle No.	Fuel	HC			NOx			CO			SO_2			Pb			Particulates		
	Type	ε_i	b_i	r_i	ε_i	b_i	r_i	ε_i	b_i	r_i	ε_i	b_i	r_i	ε_i	b_i	r_i	ε_i	b_i	r_i
1	P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
3	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
4	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
5	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
6	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
7	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8
8	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8
9	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8
10	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8
11	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8
12	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
13	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8
14	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8
15	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8
16	D	0.900	0.00	20	0.250	0	11	0.900	0.00	4.8	0	0	0	0	0	0	0.5	0	4.8

Source: An, et al (1997), Clean Cat (2000), Discount Converters Ltd (2000), Greenwood (2000), Hammarstrom (1999), SNRA (1995)

The effectiveness of catalytic converters in reducing emissions is modelled through the term Catalyst Pass Fraction (CPF). The effectiveness of catalysts is dependent on the temperature of the catalytic converter, with significant variations often observed between hot-stabilised and cold-start conditions. For the model being developed for HDM-4, only the hot-stabilised portion is required.

2.3 The relationships

The quantities of the different emission components are predicted using the relationships, together with default parameter values (see Table F3, Table F3 and Table F3) for the 16 standard motorised vehicle types, given below:

1 **Hydrocarbon**

$$EOE_{HC} = a_{HC}\, FC + \frac{r_{HC}}{v} 1000 \qquad \text{…(2.3)}$$

and

$$FC = \frac{IFC \quad MassFuel \quad 1000}{v} \qquad \text{...(2.4)}$$

where:

EOE_{HC}	is the engine-out hydrocarbon emissions (g/veh-km)
a_{HC}	is the ratio of engine-out emissions per gram of fuel consumed for emission HC (g_{HC}/g_{fuel})
r_{HC}	is a constant to account for incomplete combustion in g/s
IFC	instantaneous fuel consumption (ml/s)
FC	is the fuel consumption (including congestion effects) in g/km
v	is the vehicle speed in m/s
MassFuel	is the mass of fuel in g/mL

The default values of the model parameters are given in Table F3.

The mass of fuel (MassFuel) may be taken as (Heywood, 1988):

- Petrol: MassFuel = 0.75 g/mL; and,
- Diesel: MassFuel = 0.86 g/mL.

Table F3 Model parameters for HC and CO emissions

Veh N°	Vehicle type	HC		CO
		a_{HC}	r_{HC}	a_{CO}
1	Motorcycle	0.060	0	0.20
2	Small car	0.012	0	0.10
3	Medium car	0.012	0	0.10
4	Large car	0.012	0	0.10
5	Light delivery vehicle	0.012	0	0.10
6	Light goods vehicle	0.012	0	0.10
7	Four wheel drive	0.040	0	0.08
8	Light truck	0.040	0	0.08
9	Medium truck	0.040	0	0.08
10	Heavy truck	0.040	0	0.08
11	Articulated truck	0.040	0	0.08
12	Mini-bus	0.012	0	0.10
13	Light bus	0.040	0	0.08
14	Medium bus	0.040	0	0.08
15	Heavy bus	0.040	0	0.08
16	Coach	0.040	0	0.08

Source: An, et al. (1997), ETSU (1997), SNRA (1995)

2 Carbon monoxide

$$EOE_{CO} = a_{CO}\, FC \qquad ..(2.5)$$

where:

EOE_{CO}	Engine-out carbon monoxide emissions (g/veh-km)
a_{CO}	ratio of engine-out emissions per gram of fuel consumed for emission CO (g_{CO}/g_{fuel})

All other variables are as defined previously.

The default values of the model parameters are given in Table F3.

3 Nitrous oxide

$$EOE_{NOx} = \max\left[a_{NOx}\left(FC - \frac{FR_{NOx}}{V}1000\right), 0\right] \qquad \ldots(2.6)$$

where:

EOE_{NOx}	Engine-out nitrous oxide emissions (g/veh-km)

a_{NOx} ratio of engine-out emissions per gram of fuel consumed for emission NOx (g_{NOx}/g_{fuel})

FR_{NOx} is a the fuel threshold below which NOx emissions are very low in g/s

All other variables are as defined previously.

The default values of the model parameters are given in Table F3.

Table F3 Model parameters for NO_X and SO_2 emissions

Veh N°	Vehicle type	NO_X		SO_2
		aNOx	FRNOx	aSO2
1	Motorcycle	0.020	0.00	0.0005
2	Small car	0.055	0.17	0.0005
3	Medium car	0.055	0.17	0.0005
4	Large car	0.055	0.17	0.0005
5	Light delivery vehicle	0.055	0.17	0.0005
6	Light goods vehicle	0.055	0.17	0.0005
7	Four wheel drive	0.027	0.00	0.005
8	Light truck	0.027	0.00	0.005
9	Medium truck	0.027	0.00	0.005
10	Heavy truck	0.027	0.00	0.005
11	Articulated truck	0.027	0.00	0.005
12	Mini-bus	0.055	0.17	0.0005
13	Light bus	0.027	0.00	0.005
14	Medium bus	0.027	0.00	0.005
15	Heavy bus	0.027	0.00	0.005
16	Coach	0.027	0.00	0.005

Source: *Hammerstrom (1995)*

4 Sulphur dioxide

$$EOE_{SO_2} = 2\, a_{SO_2}\, FC \qquad ...(2.7)$$

where:

EOE_{SO2} engine-out sulphur dioxide emissions (g/veh-km)

a_{SO2} ratio of engine-out emissions per gram of fuel consumed for emission SO_2 (g_{SO2}/g_{fuel})

All other variables are as defined previously.

The default values of the model parameters are given in Table F3.

Table F3 Model parameters for carbon dioxide, particulates and lead emissions

Veh N°	Vehicle type	CO_2	Particulates		Pb	
		a_{CO2}	a_{PM}	b_{PM}	Prop_Pb	a_{Pb}
1	Motorcycle	1.8	0.0001	0.0	0.75	0
2	Small car	1.8	0.0001	0.0	0.75	0
3	Medium car	1.8	0.0001	0.0	0.75	0
4	Large car	1.8	0.0001	0.0	0.75	0
5	Light delivery vehicle	1.8	0.0001	0.0	0.75	0
6	Light goods vehicle	1.8	0.0001	0.0	0.75	0
7	Four wheel drive	2.0	0.0032	0.0	0.75	0
8	Light truck	2.0	0.0032	0.0	0.75	0
9	Medium truck	2.0	0.0032	0.0	0.75	0
10	Heavy truck	2.0	0.0032	0.0	0.75	0
11	Articulated truck	2.0	0.0032	0.0	0.75	0
12	Mini-bus	1.8	0.0001	0.0	0.75	0
13	Light bus	2.0	0.0032	0.0	0.75	0
14	Medium bus	2.0	0.0032	0.0	0.75	0
15	Heavy bus	2.0	0.0032	0.0	0.75	0
16	Coach	2.0	0.0032	0.0	0.75	0

Source: An, et al. (1997), ETSU (1997), SNRA (1995)

5 **Particulates**

$$EOE_{PM} = a_{PM}\, FC + \frac{r_{PM}}{v} 1000 \qquad ...(2.8)$$

where:

EOE_{PM}	engine-out particulates emissions (g/veh-km)
a_{PM}	ratio of engine-out emissions per gram of fuel consumed for emission PM (g_{PM}/g_{fuel})

All other variables are as defined previously.

The default values of the model parameters are given in Table F3.

6 **Lead emission**

$$EOE_{Pb} = Prop\_Pb\; a_{Pb}\; FC \qquad ...(2.9)$$

where:

EOE_{PB}	engine-out lead emissions (g/veh-km)
a_{Pb}	ratio of engine-out emissions per gram of fuel consumed for emission Pb (g_{Pb}/g_{fuel})
Prop_Pb	is the proportion of lead emitted (default = 0.75)

All other variables are as defined previously.

The default values of the model parameters are given in Table F3. The parameter a0 in the E_PB equation is the percentage content, by weight, of lead in fuels and has the default value of 0.15 % for petrol.

7 Carbon dioxide

The equation for Carbon dioxide (CO_2) utilises the tailpipe emissions, as the catalytic converter increases the output of CO_2 by converting CO and HC and particulate matter into CO_2.

$$TPE_{CO_2} = 44.011\left(\frac{FC}{12.011 + 1.008\, a_{CO2}} - \frac{TPE_{CO}}{28.011} - \frac{TPE_{HC}}{13.018} - \frac{TPE_{PM}}{12.011}\right) \quad \text{...(2.10)}$$

where:

TPE_{CO2}	Tail pipe carbon dioxide emissions (g/veh-km)
a_{CO2}	fuel dependent model parameter representing the ratio of hydrogen to carbon atoms in the fuel

All other variables are as defined previously.

The default value of the model parameter is given in Table F3.

3 Modelling logic

For each section (investment) option and for each analysis year, the quantities of each component of exhaust emissions are computed separately for each vehicle type *k* and for each traffic flow period *p*. The annual total quantities of emissions (by component) are obtained by summing over all the vehicle types.

3.1 Primary data

The following primary data is required for modelling vehicle emissions:

- **Traffic volume on the road section**

  The annual traffic volume during each flow period (vehicles per year).

- **Length of road section**
- **Vehicle speeds**

  Calculated within the RUE module.

- **Fuel consumption**

  The instantaneous fuel consumption, for each vehicle type, in each traffic flow period is calculated within the RUE module.

- **Vehicle service life and model parameters**

  Defined with other Vehicle Fleet data.

3.2 Emissions quantities

For each section option, the quantities of emissions for each vehicle type *k* and for each traffic flow period *p* are calculated using the following expression:

$$EYRi_{kp} = T_{pk} * L_j * EMi_{kp} * 10^{-9} \qquad ...(3.1)$$

where:

$EYRi_{kp}$	the annual quantity of emission component *i* from vehicle type *k* in traffic flow period *p* (tonnes)
T_{pk}	the annual traffic volume of vehicle type *k* in traffic flow period *p* (vehicles per year)
L_j	length of road section under investment option *j* (km)
EMi_{kp}	the average quantity of emission component *i* (g/1000 veh-km), from vehicle type *k* during traffic flow period *p*

The value of the average quantity of emission (EMi_{kp}) is obtained from the following expression:

$$EMi_{kp} = 500\left(Ei_{kpu} + Ei_{kpd}\right) \qquad ...(3.2)$$

where:

Ei_{kpu} the quantity of tail pipe emission component *i* (g/veh-km) for the uphill trip on the section. It is calculated using the respective equations for each emission component given in Section 0 (see Equations 2.1 **Error! Reference source not found.** to 2.10 above), using the following parameters (also see Part E):

IFC taken as IFC_{kpu} - the instantaneous fuel consumption (ml/s) for the uphill road segment

SPEED taken as SU_{kp} (km/h)

Ei_{kpd} the quantity of tail pipe emission component *i* (g/veh-km) for the downhill trip on the section. It is calculated using the respective equations for each emission component given in Section 2.2 (see Equations 2.1 **Error! Reference source not found.** to 2.10 above), using the following parameters:

IFC taken as IFC_{kpd} - the instantaneous fuel consumption (ml/s) for the downhill road segment

SPEED taken as SD_{kp} (km/h)

For the analysis of one-way, the values of EMi_{kp} are obtained as follows:

- One-way uphill

$$EMi_{kp} = Ei_{kpu} * 10^3 \qquad ...(3.3)$$

- One-way downhill

$$EMi_{kp} = Ei_{kpd} * 10^3 \qquad ...(3.4)$$

The annual average quantities of vehicle emissions (by component *i*) per 1000 vehicle-kilometres is given by the following expression:

$$EAVi_k = \frac{\sum_{p=1}^{n} HRYR_p * HV_p * EMi_{kp}}{\sum_{p=1}^{n} HRYR_p * HV_p} \qquad ...(3.5)$$

where:

$EAVi_k$ annual average quantity of emission component *i* by vehicle type *k* (g/1000 veh-km)

$HRYR_p$ the number of hours in traffic flow period *p* (*p* = *1, . . ., n*)

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

The annual quantities of emissions (by component *i*) for each vehicle type *k* using the road section under investment option *j* is calculated from the following expression:

$$EYRi_{jk} = \sum_{p=1}^{n} EYRi_{kp} \qquad ...(3.6)$$

where:

$EYRi_{jk}$ the annual quantity of emissions of component *i* by vehicle type *k* for section option *j* (tonnes)

The total annual quantities of emissions (by component *i*) for all vehicles using the road section are calculated from the following expression:

$$EYRi_j = \sum_k \sum_{p=1}^{n} EYRi_{kp} \quad \text{...(3.7)}$$

where:

$EYRi_j$ the annual quantity of emissions of component *i* (tonnes), for section option *j*

4 Comparisons of investment options

In this release, the predicted quantities of exhaust emissions are not costed for inclusion in economic analysis. The comparison of each pair of investment options is based on the changes in the annual net difference in the predicted quantities of emissions (by component). Thus, for each pair of investment options *m* and the base case *n* the annual net difference in the predicted quantities of emissions of component *i* is calculated as follows:

$$\Delta EYRi_{(m-n)} = EYRi_n - EYRi_m \qquad ...(4.1)$$

where:

$\Delta EYRi_{(m-n)}$ the annual net difference in the quantity of emissions component *i*

The standard reports for emissions analysis include:

- **Quantities of vehicle emissions** (g/1000 veh-km)

  By component *i* and by vehicle type *k* for each traffic flow period *p* (EMi_{kp}). These quantities will be reported for each section option *j*.

- **Annual average quantities of vehicle emissions** (g/1000 veh-km)

  By component *i* and by vehicle type *k* ($EAVi_{jk}$). These quantities will be reported for each section option *j*.

- **Annual quantities of vehicle emissions** (tonnes)

  By component *i* and by vehicle type *k* ($EYRi_{jk}$). These quantities will be reported for each section option *j*.

- **Annual total quantities of vehicle emissions** (tonnes)

  By component *i* ($EYRi_j$) for each section option *j*.

- **Annual net quantities of vehicle emissions**

  By component *i* ($\Delta EYRi_{(m-n)}$) for each pair of investment options *m* and *n* being compared.

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