

Chapter Four

Formulation of LCEM

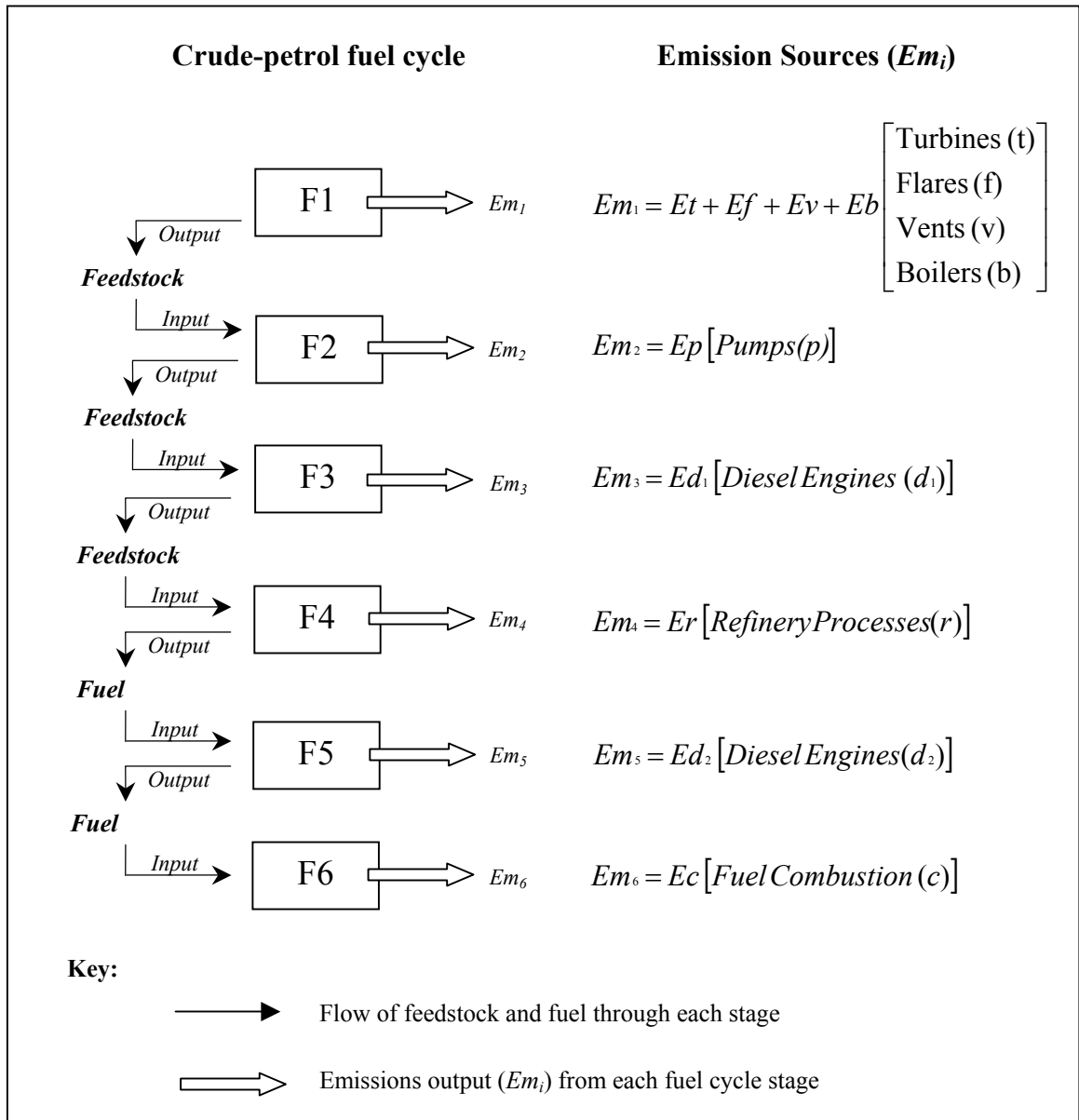
4.1 Life Cycle Emissions Model (LCEM)

As described in Chapter 2 the LCA model consists of a fuel and vehicle cycle which, when combined, produce the total life cycle model. The total emissions resulting from the use of a particular fuel and vehicle are then assessed in relation to their competitors.

The calculations of emissions released through each stage of the LCA are representative of the associated auxiliary processes that occur through each stage. If one examines the fuel cycle of crude to petrol, the emissions associated with the extraction of crude oil in the F1 stage are derived from the turbines, flares, vents and boilers. The F2 stage emissions are derived from pumping operations and so on, per tonne of fuel used in the final F6 stage, see Figure 4.1. These final F6 stage emissions are the result of the combustion of a tonne of fuel (e.g. petrol). Figure 4.1 is only applicable to the crude to petrol fuel cycle. Other fuel and vehicle cycles will differ in detail.

The vehicle cycle auxiliary emissions (V1 to V4) are generated in much the same way. However, the V1 emissions represent the amount of compounds released in the processes of extracting the weight of material required to build a vehicle. The V2 emissions are associated with the amount of compounds released to assemble a vehicle, with the V3 and V4 emissions representative of the emissions that result from vehicle use (minus fuel) and disposal, respectively.

Figure 4.1 – Emissions sources through the fuel cycle of crude-petrol only



In the crude to petrol cycle, the crude oil is termed feedstock between F1 output and F4 input. On transformation in the refinery, the feedstock becomes the fuel petrol from the F4 output to the F6 input. In other cycles the feedstock and fuel terminology will differ.

The total emissions sources are a combination of each Emission output (Em) from each fuel cycle stage as in 4.1:

$$TEm = \sum_{i=1}^6 Em_i = (Et + Ef + Ev + Eb) + (Ep) + (Ed_1) + (Er) + (Ed_2) + (Ec) \quad 4.1$$

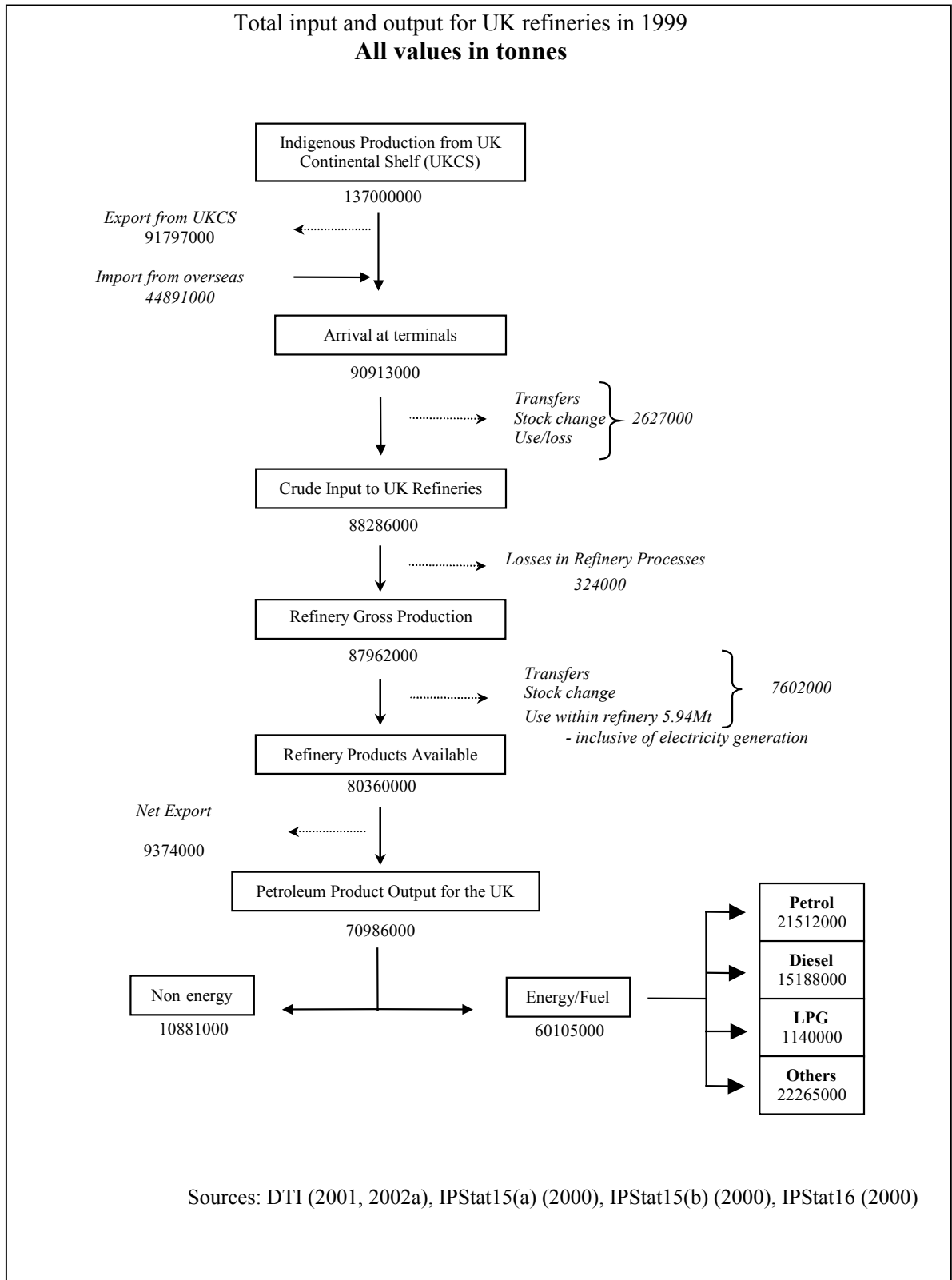
where:

- TEm - Total emission from F1-F6 (g/t)
- Em_i - Emission Source (i ≡ 1...6)
- Em₁ - F1 stage emissions generated through turbines, flares, vents and boilers
- Em₂ - F2 stage emissions generated through pumping operations in pipelines
- Em₃ - F3 stage emissions generated through bunker fuel powered oil tankers
- Em₄ - F4 stage emissions generated through fuel refining processes
- Em₅ - F5 stage emissions generated via fuel transfer in diesel powered road tankers
- Em₆ - F6 stage emissions generated through fuel combustion in an IC engine.
- Et - Turbine emissions on offshore platforms
- Ef - Flare emissions (gas flares) on offshore platforms
- Ev - Venting gas emissions on offshore platforms
- Eb - Boiler use on offshore platforms
- Ep - Pumping emissions in North Sea pipelines
- Ed₁ - Emissions due to bunker fuel powered oil tankers importing feedstock
- Er - Refining emissions associated with the production of fuel
- Ed₂ - Emissions due to Diesel powered road tankers delivering fuel to filling stations
- Ec - End-use fuel combustion emissions in an IC engine.

In Figure 4.1, the EM₁ emissions are derived from the use of turbines, flares, vents and boilers onboard offshore platforms in the UKCS. As with all Em_i emissions, the fuel weight to provide the power to use these specific appliances in the F1 stage are in addition to the weight of feedstock extracted.

In order to calculate TEm, an understanding of mass transfer through the UK crude to petrol cycle is required. Figure 4.2 details the total input and output of crude and petroleum products for the UK during 1999, the equivalent F1 to F5 output stages.

Figure 4.2 – UK Refinery Processes in 1999



In 1999 137Mt of crude oil were extracted from the United Kingdom Continental Shelf (UKCS), of which 88.286Mt was put through the UK refineries. Of the total petroleum products (70.986Mt), 60.105Mt were utilised for Energy/Fuels and 10.0881Mt for Non-energy fuels in the UK market. Of the Energy/Fuel mix the transport fuels were estimated as shown, DTI (2001, 2002a), IPStat15(a) (2000), IPStat15(b) (2000), IPStat16 (2000).

Figure 4.2 illustrates the F1 (crude input) to F5 output stage (fuels available in the UK) for the petrol fuel cycle. Should refining operations change and the market demand for petrol, diesel or LPG increases or decreases the resultant ratios would change and it is important to note that these ratios only apply to operations performed in 1999.

It should also be noted that 41% of LPG bypasses the refining stage and is transferred directly into storage prior to distribution through the UK network.

Example (crude oil to petrol)

If one considers crude oil which is to be converted to petrol. The total input of crude oil to UK refineries in 1999, see Figure 4.2, was 88.286Mt and in that year 21.512Mt of petrol (24.37%), 15.188Mt of diesel (17.2%), 1.14Mt of LPG (1.29%) and 22.265Mt (25.22%) of other commodities were produced. The remaining 31.92% of output is attributed to losses, stock change, use and net export. As a percentage of total crude input into UK refineries in 1999, 24.37% was converted into petrol for use in the UK.

Individual refineries will generate different ratios of product dependent upon the type of crude, costs and the individual system in place at each refinery. However under normal (1999) refinery circumstances, these values represent the totals produced. The resultant ratios of crude to petrol, diesel, LPG and others are therefore 4.1:1, 5.8:1, 77:1 and 3.97:1 respectively i.e. for every 1t of crude oil input into UK refineries in 1999, given the current output specification, 243kg of petrol, 172kg of diesel, 12.9kg of LPG and 252kg of other products would be produced for use as fuels in the UK. In order to produce 1t of petrol, the refinery requires 4.1t of crude, see Figure 4.3.

Using the Environment Agencies Pollution Inventory (PI), one can calculate the total amount of pollution from the generation of petroleum products from all UK refineries. The emissions (per tonne) in the refining stage are simply attributed to the percentage of output e.g. from all UK refineries in 1999 21.512Mt of petrol (24.37% of total output) was produced. The emissions per tonne of petrol produced and used in the F6 stage can be calculated.

UK refinery total CO₂ release in 1999 (PI) = 15.194Mt

Total attributed to Petrol production = 24.37% of 15.194Mt = 3.7Mt

Total attributed to a tonne of petrol produced = 3.7Mt/21.512Mt = 0.172 = 172kg/t

These values will then represent the emissions associated with a tonne of petrol equivalent.

Figure 4.3 – Crude input to product output in 1999

Input to Output Ratios		
(Fuels only)		
Crude – Petrol	88286000 / 21512000	4.1:1
Crude – Diesel	88286000 / 15188000	5.8:1
Crude – LPG	88286000 / 1140000	77:1
Crude – Others	88286000 / 22226000	3.9:1

In calculating these ratios and analysing total emissions throughout the fuel cycles of petrol, diesel, LPG and others a Numerical Checklist for each emission under investigation was developed, see Appendix C. This list calculates the total and g/t emissions throughout each stage within the life cycle of crude oil to each of the petroleum products. For example, initially 137Mt of crude oil is extracted from the UKCS, releasing 147.6kg of CO₂ per tonne of crude extracted, Gover *et al* (1996), see section F1 Primary Production/Extraction, in contrast 172kg/t of CO₂ are released due to the extraction of a tonne of petrol. In extracting 137Mt of crude, 2.022*10¹⁰kg of CO₂ are released into the atmosphere. One can then track the flow of CO₂ throughout the UK

refining network as illustrated in Figure 4.2, from the extraction to the end-use phase. Through a series of equations one can then calculate the amount of CO₂ released in order to produce 1t of petrol, diesel, LPG and other products. The Numerical Checklist enables cross comparisons to be made at a later stage, see section 4.2.4.

The fuel cycle consists of 6 stages (F1-F6), the emissions associated with each stage represent the extraction, transfer, refinement, distribution and end-use of a tonne of fuel derived and used in the final F6 stage. For example, if one considers the crude-petrol cycle, the emissions due to the extraction of one tonne of crude oil from the United Kingdom Continental Shelf (UKCS) are not expressed per tonne of crude extracted. They are in fact representative of the emissions (g) per tonne of petrol derived and used in the F6 stage. Once crude is refined into petrol in the F4 stage, the emissions calculated from then on are representative of a tonne of petrol.

A description of the CO₂ emissions from the crude-petrol cycle follows.

In total, see Figure 4.2, 137Mt of crude oil were produced in 1999 from the UKCS. A study by Gover *et al* (1996) suggests that for every tonne of crude oil extracted and delivered to the UK terminals, 147.6kg of CO₂ were released into the atmosphere. Therefore in order to generate 137Mt of crude oil 2.02×10^{10} kg of CO₂ were released. Of the total crude produced (137Mt), 91.79Mt was exported overseas to leave 45.2Mt (domestic UKCS production). An additional 44.89Mt of crude was imported into the UK from the Middle East (ME). The quality and market value of the crude determines the import to export ratio. In 1999 it may have been more cost effective to export 91.79Mt and import 44.89Mt, rather than use all of our own domestically produced 137Mt of crude for UK consumption. After UKCS (domestic production) 45.2Mt, export 91.79Mt and import 44.89Mt, a total of 90.09Mt of crude arrived at the UK terminals. After stock changes, loss and use, 88.286Mt was fed into the UK refineries.

In theory 2.02×10^{10} kg of CO₂ was released due to the extraction of 137Mt of crude, however the UK did not use all of this crude within its refineries and 91.79Mt of crude was exported. This export via oil tankers is not considered to have an impact on the UK,

although the emissions from the tankers will contribute to emission levels elsewhere. Moreover any crude that is imported into the UK will have an impact on the total UK emissions budget. In addition to the emissions generated from the oil tankers imported crude, one must also take into account the emissions associated with the extraction of crude in the Middle East. These values are unfortunately more uncertain, however some assumptions can be made. A higher percentage of crude oil extraction platforms in the Middle East are land based, in comparison to the offshore platforms in the UKCS. These land based platforms use less energy per tonne of crude extracted, therefore the resultant emissions would be lower. Moreover, the annual temperature in the ME is higher than the UK, resulting in less heat loss in operation, again resulting in fewer emissions per tonne of crude oil extracted. Therefore as a first approximation, to extract a tonne of crude oil in the Middle East would release 2/3 (66.6%) of the emissions per tonne of crude oil extracted in the UKCS. Gover *et al* (1996) assumed that the extraction emissions in the ME are similar to those from the UKCS. They noted that this is a rough approximation.

The emissions associated with the export of 91.79Mt of crude are removed from the emissions associated with the extraction of 137Mt of crude. The emissions associated with the import of 44.89Mt are combined with the emissions associated with the extraction of crude in the ME and added to the UK budget.

The export of 91.79Mt of crude accounts for 67%, by mass, of the total UKCS crude production, 137Mt. Assuming that a loss of 67%, by mass, is equal to a loss of 67% by emission, one can subtract 67% from the total emissions due to the extraction of 137Mt of crude ($2.02 \times 10^{10} / 100 \times 67 = 1.35 \times 10^{10}$ kg). This leaves a value (6.66×10^9 kg), which in theory represents the emission of CO₂ released into the UK due to the production of 45.2Mt of crude, the mass that remains in the UK after export. The emissions at this stage are therefore representative of the crude produced for use in UK refineries, not for total production (6.66×10^9 kg).

Import of crude oil in 1999 was 44.89Mt, all of which arrived into the UK from the Middle East. Each 250000t tanker travelled a distance of 7700miles. The emissions associated with the combustion of bunker fuel used to power the tankers is calculated, with the average tanker releasing 49.6kg of CO₂ per tonne of crude transported to the UK from the ME, see Appendix D. Therefore, in order to import 44.89Mt of crude, 2.23×10^9 kg of CO₂ were released.

In order to extract 44.89Mt of crude from the Middle East, 98.4kg of CO₂ were released per tonne (66.6% of 147.6kg/t) of crude extracted. Therefore 4.4×10^9 kg of CO₂ were released in order to extract 44.89Mt of crude from the ME.

F1 extraction *plus* F2 transport CO₂ emissions from Middle East

$$4.4 \times 10^9 \text{kg} + 2.23 \times 10^9 \text{kg} = 6.63 \times 10^9 \text{kg}$$

6.63×10^9 kg of CO₂ were released in order to import 44.89Mt of crude oil from the ME to the UK terminals.

At this point the UK has 45.2Mt from domestic production and has now received 44.89Mt from import. In total the UK terminals receive 90.09Mt of crude. The total release of CO₂ in 1999 in order for this amount of crude oil to arrive at the UK terminals is calculated.

$$\begin{aligned} \text{CO}_2 \text{ from } 137\text{Mt of crude produced} &= 2.02 \times 10^{10} \text{kg} \\ \text{minus } 67\% \text{ due to export} &= 1.3534 \times 10^{10} \text{kg} \\ \text{Total CO}_2 \text{ that remains after export} &= 6.66 \times 10^9 \text{kg} \\ \text{plus } 6.63 \times 10^9 \text{kg from import} &= \mathbf{1.33 \times 10^{10} \text{kg}} \end{aligned}$$

Therefore in order to produce 1t of petrol in the UK in 1999, of which the refineries produced 21.5Mt. In total 619kg of CO₂ were released in by the end of the F3 stage.

In the F1 stage the extraction of 44.9Mt of crude in the ME at a rate of 98.4kg/t releases 4.4×10^9 kg of CO₂. In addition the UK domestically produced 45.2Mt at a release rate of

147.6kg of CO₂ per tonne extracted, releasing 6.66*10⁹kg of CO₂. Therefore the addition of the F1 extraction emissions in the ME and the UK extraction emissions from the UKCS provides the total F1 emissions due to the generation of fuels in the F6 stage.

$$4.4*10^9\text{kg} + 6.66*10^9\text{kg} = 11.06*10^9\text{kg}$$

This total 11.06*10⁹kg multiplied by the ratio of fuels produced by UK refineries (t) and crude arrival at UK terminals (t) provides the total amount of emission (kg) per tonne of fuel produced in the F6 stage. This total must then be divided by the amount of fuel produced in order to calculate an emission rate of kg/t.

$$\text{F1 Emission (kg)} * \left(\frac{\text{Total petrol produced (t)}}{\text{Total Crude into Terminals (t)}} \right)$$

$$11.06*10^9 * \left(\frac{21.5*10^6}{90.9*10^6} \right) = \text{Total (kg)}$$

$$\frac{\text{Total (kg)}}{\text{Mass of Petrol Produced}} = \text{kg/t}$$

$$\frac{2.6*10^9}{21.5*10^6} = 120.9$$

Therefore 120.9kg of CO₂ released (in the F1 stage) per tonne of petrol produced in the F6 stage.

In the F2 stage of the crude-petrol cycle 90.9t of crude produces 21.5t of petrol. For every tonne of crude transported from the ME 49.6kg of CO₂ were released, therefore:

1t of petrol is responsible for (21.5/90.9*49.6 = 11.7) 11.7kg.

1t of diesel is responsible for (15.2/90.9*49.6 = 8.29) 8.29kg.

1t of LPG is responsible for (1.15/90.9*49.6 = 0.627) 0.627kg.

It now becomes possible to compare like-with-like in the summation of the F1 to F6 stages as each value represents the emission per tonne of fuel in the F6 stage. Similar calculations are made for the emissions of CO, NO_x, NMHC, CH₄ and PM for petrol, diesel and LPG, see Numerical Checklist, Appendix C.

In order to formulate the emission model effectively a unit of (g/t) of fuel¹ was used.

This unit of measure was chosen in order to combine the fuel and vehicle cycles and to calculate the lifetime operation emissions of the vehicles under examination. Other units such as (g/mile), (g/kWh) or (g/GJ) would not have been easily adapted to the complete life cycle results. In order to normalise and weight the results using the Environmental Design of Industrial Products (EDIP) method, masses of compounds are required. Initially the masses are multiplied by a factor to normalise them to a common basis (i.e. Global Warming). This normalisation could not occur with results measured on a per mile, kWh or GJ basis. Moreover, these units are not compatible with the emissions from the vehicle cycle, which are expressed per vehicle constructed, used and disposed of (g/vehicle). Without compatibility the life cycle emissions, which are a summation of the fuel and vehicle cycles, could not be estimated.

Throughout each of the fuel and vehicle cycle stages the unit of (g/t and g/vehicle) is used to represent the Emission Sources (Em_i) in (g) for the extraction, transformation, transfer or use of one tonne of fuel (F1-F6 stage) and the emissions per vehicle manufactured and disposed. Major changes to particular processes will require a recalibration of the numerical values of outputs. Some of the stage emissions will remain similar per tonne or vehicle produced, however some stages will be subject to a considerable amount of change. If one once again considers the crude to petrol cycle,

¹ The feedstock (crude) becomes a fuel only when converted in the F4 refining stage. However, since the feedstock values in the crude to petrol cycle are multiplied by 4.1, to represent a tonne of petrol, the term “fuel” refers to the feedstock and fuel through the F1-F6 stage. The term “fuel” from hereon refers to the extraction, transfer, transformation, distribution and end-use of a tonne equivalent of the feedstock/fuel in question.

the emissions associated with the import of crude oil may be subject to change, as the UK becomes more dependent on external sources of oil as home stocks are depleted. With increased imports come higher Ed_1 emissions in the F3 stage.

A main source of crude oil is the Middle East which has a politically volatile structure and future “oil shocks” could change the assumptions upon which the LCA is based i.e. the percentage split between import and export. However, these issues are beyond the scope of the present study.

The key stage within the LCA (F6 end-use) may also change over time, with the introduction of more stringent pollution control measures (EURO specifications) and improvements in vehicle efficiency. This represents a common problem with decision-making in the presence of technological change. Pragmatically decisions must be taken on the basis of the available data and scenario considered.

Within each cycle the following compounds were investigated, Carbon Dioxide (CO₂), Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Non-Methane Hydrocarbons (NMHC), Sulphur Dioxide (SO₂), Methane (CH₄) and Particulate Matter (PM). These were chosen in order to allow an assessment of regional and global impacts to be made.

For example, Global Warming Potential (GWP) is calculated by combining the effect (direct and indirect) that the compounds CO₂, CO and CH₄ have on the environment.

A Life Cycle Emissions Model (LCEM) is the result of the combination of the fuel and vehicle cycles.

A complete Environmental Impact Assessment (EIA) combines the impacts of gaseous, solid and liquid emissions. However in the present study the impact of solid and liquid emissions become second order due to their small contribution to the total life cycle results. The F6 stage contributes the most to the total life cycle results and primarily consists of gaseous emissions, see Chapters 5 and 6. Liquid or

solid materials are primarily unburnt hydrocarbons, which have little impact on the total life cycle results. As a result the author has decided to focus solely upon the gaseous emissions throughout each fuel and vehicle cycle.

4.2 The Fuel Cycle

The fuel cycle consists of six stages (F1-F6). Hydrocarbon fuels (petrol, diesel and gas) and electricity are compared from the initial extraction through to final combustion/use within an engine. Emissions are calculated in (g/t) of fuel; with slight differences for modelling electric vehicles to cover the remotely generated emissions as the vehicles, in use, produce almost zero emissions, see section 5.4.

The remainder of this Chapter discusses the methodology, analysis and interpretation of the assessment.

4.2.1 F1 Primary Production/Extraction

Hydrocarbon fuels used within the United Kingdom (UK) are derived from the oil and gas fields operating on the United Kingdom Continental Shelf (UKCS) in the North Sea together with imported products from around the world. On average, based upon DTI estimates DTI (1997b, 1998, 2001), 75% of the crude oil consumed in the United Kingdom is from domestic production sites (UKCS and onshore) and 25% is imported from the Middle East, with large variations possible. The EC Methodologies for Estimating Air Pollutant Emissions from Transport (MEET) project assumed percentages in 1996 of 60% and 40% respectively, Lewis (1997). The relative production percentages can be calculated from the data presented in DUKES 2001, Chart 3.8. From 1996 to 1999 the UK increased its domestic production of crude oil and less was imported. With this information, the MEET project assumptions seem reasonable.

The total amounts of extracted and imported products for specific use in the UK are compared against numerous publications for authenticity, DTI (1995, 1997a, 1997b, 1998, 2000a, 2000b), Gover *et al* (1996).

Domestic hydrocarbons are produced through a series of stages. Initially seismic surveys and drilling operations are carried out to locate and assess a hydrocarbon bearing sedimentary basin beneath the sea floor. Platforms of various types and designs are then positioned in different locations across a field. Small fields may only require a single platform to carry out the initial production, treatment and export phases, while larger fields tend to use separate production platforms, or sub-sea facilities, spread across field with a central treatment and export facility. With the exception of some of the more recently deployed Floating Production Systems (FPS), most products are exported by fixed pipeline, rather than shuttle tanker. Developments in the North Sea include fields which are predominantly gas or oil or both. In general any fluid extracted from a sedimentary basin is a complex mixture of liquid hydrocarbons, gases, water and some other impurities. Depending upon the fluid mixture extracted, the amount of treatment will vary and oil and gas quality is dependent upon the particular field characteristics.

At this F1 stage the total emissions are calculated as a result of the extraction of a tonne of hydrocarbons from the UKCS. The method used is that adopted by Gover *et al* (1996).

There are variations in emissions from individual platforms but taking the gross crude oil production from the UKCS and summing over emissions from all UKCS platforms provides the averaged grammes of emissions per tonne of crude extracted. The data for these values can be found within the LCA model and were calculated by Gover *et al* (1996), who expanded the earlier work of EPA (1985) and Williams (1994). Generating these results was not as straight forward as initially envisaged. Data from the DTI's annual statistics is vast and the numerous emission values are expressed in different units. Natural gas emissions are measured in joules (J), requiring conversion to mass values.

The occurrence of oil spills, platform fires and leakages are excluded due to their relative rarity. All other liquid and solid waste as a result of oil and gas extraction in the UKCS are deemed insignificant with respect to the LCA emissions considered in this study. If

the study were extended to ecotoxicity assessments then liquid and solid wastes could be incorporated within the general framework, see further discussion in Chapter 6.

This final value (F1) is therefore representative of the total amount of emissions due to the extraction of one tonne of hydrocarbon supplied to the UK. Assumptions are made that all of the 75% domestically produced crude oil is piped ashore with no losses/leakage and therefore zero emissions. The emissions associated with crude oil exported directly from the UKCS via ocean tankers are excluded because only UK consumption (domestic and import) is considered. However, the Numerical Checklist developed by the author, see Appendix C, accounts for these emissions which are taken into consideration through the resultant stages, see section 4.1.

Natural Gas (NG) emissions in the F1 stage are a result of gas compression, flaring, venting and sweetening. As with crude oil, they represent the average contribution per tonne (equivalent) extracted, determined by the total emissions split between the resultant products in the ratio of their production quantities. NG, when extracted, contains a complex mixture of hydrocarbons, water, sulphur, hydrogen sulphide and other Natural Gas Liquids (NGLs). These percentage splits represents the total NG supply per tonne equivalent of NG delivered to the UK terminals. Once at the terminals any hydrogen sulphide is removed followed by a process of fractionation (removal of lower molecular weight NGLs), the gas is then ready to enter the National Transmission Grid (NTG).

Liquified Petroleum Gas (LPG) differs slightly in that it can be directly extracted or produced from crude oil within refineries. The emission values in the LPG F1 stage are attributed as follows: 59% emissions from LPG produced via crude oil refining (as with crude oil transfer) and 41% emissions from the direct piping of LPG to the mainland. The F1 stage emissions represent the combined emissions from the extraction of LPG directly (Direct LPG) plus the 1.29% of emissions attributed from the refinery produced LPG (Refinery LPG). The 1.29% is derived from the example and Figure 4.3 which

show that 77t of crude are required to produce 1t of LPG from UK refineries. The Direct LPG emissions are taken from Gover *et al* (1996).

For the Direct LPG transfer an assumption is made that any losses are hydrocarbon (CH₄ and NMHC) losses, as with the NG cycle. Assumptions made by Glover *et al* (1996) with cross-correlations made to the year 2000 through DTI (1997b, 1998, 2000) data.

At this F1 stage the Landfill Gas (LFG) and electric cycles differ from all the other cycles. The emissions included within the LFG cycle at this stage represent the extraction of 1 tonne of LFG from a typical landfill in the UK.

The Atomic Energy Authority (AEA) produced a report for the former DETR entitled: 'Emissions from UK Landfills', Brown *et al* (1999). The report details the methane emissions from 1990 to the year 2012. Future trends were predicted on the assumption that waste reduction and increased composting cause waste generation to stabilise at the 1995 level. The methane levels are a result of: (1) the amount of methane generated by decay and (2) the amount emitted following collection or methane oxidation. The amount of emission per tonne of waste landfilled can best be described by using the emission factors within the report for the year 2000. Attribution of the emissions factors takes place to produce an overall mass of methane produced per tonne of waste landfilled in the UK (2000) from Municipal Solid Waste (MSW) and industrial and commercial waste streams. This value is calculated within the LFG F1 stage. Further details pertaining to LFG production can be viewed within Manna *et al* (1999).

The electric cycles differ in that electricity cannot be represented as a mass unit value; instead an energy term is used (mass/GJ). Electricity in the UK is produced via the use of the following: Natural Gas (39.7%), Coal (32.4%), Nuclear (23%), Oil (1.5%) and Renewables/Hydro/Others make up the last (3.4%).

The UK Government has recently published the Energy White Paper, DTI (2003), which highlights the aim to cut CO₂ emissions by 60% of current levels (2003) by 2050. One

way of reducing these emissions is via an increased use of alternative energy providers. The renewables percentage is therefore set to increase, with a specific aim set of supplying 10% of electricity from many different energy forms in the UK, as the Government strives towards a low carbon economy.

The emissions from the fuel used to generate electricity (per GJ) are accumulated based upon their percentage contribution and summed to calculate a total emissions value per GJ of electricity supplied. Various publications contain the information required, with the main publication being the Digest of United Kingdom Energy Statistics (DUKES), published by the DTI (2001). A report published by Eyle and Michaelis (1991) provides data on coal and uranium extraction for the coal and nuclear contributions respectively. All other data could be found in DUKES. All of which required interpretation and conversion to the total emissions output (kg), see Appendix E.

The Green Electric (GE) cycle assumes that electricity is generated wholly from renewable sources. The majority of energy flow through this cycle is produced from wind power and small hydroelectric plants, together with a potential contribution from wave, tidal and solar power. Only electricity provided to the consumer by the Monkton Group plc under its brand name Unit(e) is considered, see www.unit-e.co.uk. Unit(e) currently sources its renewable energy from non-combustion technologies such as wind power and small hydro-power. All the Unit(e) generation is based in the UK and is not imported. The wind turbine generators are placed in North Cornwall (Delabole Wind Farm), South Cornwall (Goonhilly Downs) and Midlands (West Beacon Farm). The hydroelectric plants are located in North Devon (Glen Lyn Gorge) and Dunsford, Exeter (Sowton Mill). There are zero associated emissions in generating electricity via these means, see Unit(e) (2002), within the system boundaries set for this LCA i.e. the point of extraction to disposal.

The system boundaries for the LCA study only consider the emissions after construction of any extraction equipment. The hydrocarbon, electric and LFG cycle F1 emissions do not include the construction emissions associated with platforms, pipelines and buildings; therefore it is reasonable and equitable to assume zero emissions in the F1 stage of the GE Cycle.

4.2.2 F2 Separation/Filtration

Once the hydrocarbon fuel is transferred to the production platforms, a process of separation and filtration follows. Crude oil and gas are mixed with many other substances that need to be separated. An explanation of the processes can be seen in Glover *et al* (1996). The fuel will enter a separation plant that splits the fluids into gases, oil/condensate and water. Heating is used to assist the oil-water separation. The number of separation stages required is dependent upon the composition, temperature and pressure. These operations have associated emissions and it is these emissions that are included in the F2 stage.

If one considers crude oil, the emissions from the domestic production contribute 75% to the total with a further 25% from importation. It is assumed 250,000 Gross Registered Tonnes (GRT) tankers are used for a journey over a distance of 7,700 miles, the distance between Kuwait and the UK. The tankers used for the journey are not the same, by averaging the emissions from a cross section of studies an average value is sought. The Environmental Protection Agency (EPA) assessed vessels from the British Columbia Ferry Corporation, EPA (2000a) together with marine shipping activities within Canadian regions, EPA (2000b). Lloyd's Register (1993) examined a large number of vessels representing a cross section of marine vessels, tankers and tugs. Reynaulds (2001) was able to provide details pertaining to a cross section of tankers. Lewis (1997) calculated emissions factors for bulk marine petroleum transporters from Lloyds Register together with the International Maritime Organisation producing similar results to the other studies. From these publications, emissions values are calculated which, within this research, represent the emissions from the average tanker importing crude oil into the UK from the Middle East, see Appendix D for numerical values

The emissions associated with the domestic production of crude oil are incorporated within the F1 stage. This F2 stage considers the emissions associated with the combustion of diesel within oil tanker engines travelling from the Middle East, per tonne of crude oil transported onboard, plus the releases associated with loading/unloading and tanker ballasting when in dock.

The large percentage of direct LPG (98%) is piped ashore with approximately (2%) imported and deemed insignificant. The emissions associated with the direct LPG are included within the F1 LPG results. LPG produced, via crude oil refining, therefore produces the same emissions as F1 Petrol/Diesel and are included as a percentage of the total within F1 LPG. An assumption is made that the pipelines transferring the crude oil and LPG are completely sealed with zero spillages and zero emissions.

Following the natural gas extraction is a phase of compression, cooling and filtration where Natural Gas Liquids (NGLs) are removed in a separator. These NGLs (ethane, propane and butane) can be exported in a crude or gas export line. Data from DUKES 2001 was used to establish the emissions associated with the transport phase of NG to the UK shore. The upstream (gas from the production platform to the onshore terminals) pipeline losses and metering difference are recorded in volume and energy terms. An assumption is made that any losses will result in the release of CH₄ and NMHC. These gas losses are assumed to be metering differences. Zero losses are assumed for crude oil due to the lack of data. Ideally any pipeline losses should be included with the LCA analysis.

The metering difference is a measurement system used by British Gas (BG) at various points along the network to measure changes in gas quantity and hence any losses from point A to point B. With the assumption made by Gover *et al* (1996) that 93% of losses accounted for are methane and 7% are from NMHC, a conversion between energy value and mass can be made. The loss values are simply calculated with a mass balance equation. The total production minus the total supply is equal to the fugitive losses, which are then split into the respective hydrocarbon percentage loss assumptions.

Electricity generated in the F2 stage via coal, gas and nuclear sources are subject to the emissions as a result of coal transport via rail, gas losses (included in F1) and uranium transfer respectively. The percentage contribution emission from each fuel, to a total GJ energy value supplied, is summed within this stage. For nuclear fuel (uranium),

transportation emissions are assumed to be zero. Due to the fact that the emissions are calculated per GJ of electricity produced and that the mass of uranium required to generate a GJ of energy is very small. Therefore per GJ transported, assuming that a large amount of uranium would be transported at any one time, the emissions are very small.

Green electricity is generated from renewable sources and is immediately transmitted into the national electricity pool directly after generation. Zero emissions, of the compounds under investigation in this research, are assumed when utilising electricity produced by Unit(e).

The emissions relating to the filtration of one tonne equivalent of LFG into a NG equivalent are reported in the F2 LFG cycle. The compression of LFG into CLG, pressurised to the 75 bar necessary for injection into the national natural gas network, is assumed herein, with the resultant emissions, CAT (2002a, 2020b), Chinnery (2002). The compressor in question is a Caterpillar G3508 Gas Driven Engine operating at 75% load. Waste CO₂ from the filtration system is liquefied and sold to industry. Energy values are converted into masses of LFG compressed via the use of simple conversion factors. At this stage there are only filtration emissions, transport related emissions are zero because the gas is 'reticulated'. This is a term used in industry to describe the process of gas injection into the national network. See Appendix F, for details of the Membrane Separation (MEMBRASEP) system used to reticulate LFG, plus photographs of the Sustainable Bus (SUSBUS) filtration plant in operation at Coxhoe landfill site, Durham.

4.2.3 F3 Transportation and Storage

Once ashore and processed through terminals, the feedstock is either transported to a refinery, transferred into a national pipeline, used directly by a consumer, exported or stored.

The majority of emissions associated with the F3 stage are included within F2 for the hydrocarbon fuel cycles, generally because, at present, the distance between the terminals, refineries, storage depots and national pipelines is minimal and insignificant when compared to the North Sea pipelines. NG is processed ashore and directly transferred into the national pipelines, then on to the regional pipelines to the consumers. A user could incorporate a degree of uncertainty into the model and predict the emissions based upon pipeline leakage and more importantly change in infrastructure. The introduction of new pipelines (for example with the increased use of hydrogen for fuel cell vehicles) would increase the importance of the F3 stage. This stage therefore exists in order to assist the user in updating the research should information become available, or should circumstances change in the future.

4.2.4 F4 Fuel Production/Refining

The second most significant stage in the fuel cycle is F4. At this stage the hydrocarbons are transformed into a product that can be used within an Internal Combustion Engine (ICE). The various DTI, DETR and DUKES publications are able to provide detailed annual statistical information on the quantities and quality of all products in the UK together with an overall understanding of the numerous and complex refining processes. Due to the nature of the material, a prior knowledge of the processes and conditions under which refining occurs is essential. The data presented can be overwhelming.

With prior knowledge of the fuel quantities, an emissions model was initially sought in order to calculate the pollution generated in transforming the hydrocarbon fuels that require refining (petrol, diesel and LPG). Initially a Gaussian Plume Model was developed to attempt to calculate the emissions from the average UK refinery, see Masters (1998). The point, area and line source modelling techniques produced tolerably realistic results; however, they presented values in (mass/m³) units. These units could then be compared against the Environment Agency's (EA) Environmental Assessment Level (EAL) exposure limits. These EALs have been developed from the Health and Safety Executive (HSE) EH40/95 operational exposure limits. These limits or so-called "benchmarks" were used by the EA in the assessment of relative harm/harmlessness of a

release from any processes. Provisional EALs for various environmental media (air, water, soil) have been developed from a variety of UK and international sources. Both short and long term EALs are provided for the user to assess short and long-term exposure limits respectively, EA (1998a, 1998b). With knowledge of a process contribution and the EAL for that process an Environmental Quotient (EQ) is calculated. These quotients are then summed for each medium under investigation to calculate an Integrated Environmental Index (IEI). These indices are then considered for each process in order to determine the Best Practicable Environmental Option (BPEO).

A comparison with the UK National Air Quality Standards (NAQS), www.airquality.co.uk and specific industrial activities through the National Atmospheric Emissions Inventory (NAEI), www.naei.org.uk was also sought. These NAQS are a measure of air pollution concentrations over a given time period that are considered to be acceptable in the light of what is known about the effects of each pollutant on health and on the environment. They can also be used as a “benchmark” to see if air pollution is getting better or worse. Standards exist for Human Health and Vegetation and Ecosystems for eight hour, twenty-four hour and annual means. Further details can be seen in CVTF (1999).

As the LCA developed, it became clear that the EALs, IEI and NAQS were not appropriate for successful integration with the remainder of the fuel and vehicle cycle information, due to the units of measure ($\mu\text{g}/\text{m}^3$). The fuel and vehicle cycles were naturally cast in terms of mass of fuel and emissions related to distance travelled and emissions per vehicle manufactured respectively. Thus it was apparent that scenarios specifying the fuel-vehicle combinations were required to enable the emissions from each major cycle to be combined. Each cycle can be seen in Appendix G.

The outcome of further searches revealed that a Pollution Inventory (PI) developed by the EA www.environment-agency.gov.uk would be much more compatible with the aims of the current study.

The EA website provides the following background information pertaining to the history and use of the PI. In 1990 the Chemical Release Inventory (CRI) was created to provide a compilation of reports of releases from industrial sites. As the CRI developed, significant limitations were identified in its use. In November 1997, the Environment Agency launched an extensive consultation exercise with Government, industry and other interested organisations on proposals to improve the consistency of reporting in the CRI. Following the consultation exercise, the Agency has reviewed its proposals and is implementing the changes to the CRI under the new name of the Pollution Inventory (the name 'Inventory of Sources and Releases (ISR)' was originally used in the collection of information). The Pollution Inventory has been developed to provide information on annual mass releases of specified substances to air, water and land or produced as waste that arises from any large industrial sites (i.e. those authorised by the Environment Agency under Integrated Pollution Control (IPC) regulations). This includes, point sources (e.g. chimneys), non-point sources and fugitive emissions (e.g. leaks or spillages). Within the PI, a series of datasets are available, i.e. databases of emissions by: location, year, process type and/or substance released.

The present author selected a database of emissions by every refinery in the UK in 1999. The total emissions from each (major and minor) refinery were summed. Data from DUKES could then be combined with the EA data to produce a value representative of the average emissions from a UK refinery as a result of the production of one tonne of fuel (petrol, diesel or LPG).

At this point the author referred to the Numerical Checklist in order to cross compare the EA PI data. The PI recorded the total emissions of CO₂ from UK refineries in 1999 as 1.5194×10^{10} kg. In that year 24.37% of refinery output was petrol, therefore an equivalent mass of CO₂ released per tonne of petrol produced can be calculated (172kg). The Numerical Checklist (E_7) calculated the emission of CO₂ from UK refineries in 1999 as 1.3633×10^{10} kg, see Appendix C. Using the Numerical Checklist (E_{16}), one can calculate the amount of CO₂ released per tonne of petrol produced (177.288kg). Given the similarity between the two values, 172.33kg and 177.288kg, the author decided to

use the PI data within this study, with the knowledge that the value has been independently verified. The differences of about 3% are not unexpected when the uncertainties in record keeping and assumptions embedded in the estimating procedures are recognised.

NOTE: The PI data for some UK refineries has not been updated since 1999. However all petrol and diesel sold in the UK today, is either Ultra Low Sulphur Petrol (ULSP) or Diesel (ULSD). Any change in operations may increase emissions e.g removal of sulphur from 150ppm to 50ppm in the transition of unleaded petrol to ULSP and 350ppm to 50ppm from Diesel-Engine Road Vehicle (DERV) fuel to ULSD, BABFO (2001), DTI (2000). Any increased emissions are noted to be marginal, Lane (2002) and will have little effect on the total life cycle emissions. Therefore the emissions in the F4 stage due to the production of petrol and diesel in 1999 are assumed to be similar to the current emission levels as a result of the production of ULSP and ULSD.

Other fuels (gas and electric) do not require transformation and therefore bypass the F4 stage.

4.2.5 F5 Transportation Storage and Distribution

On refining crude oil into ULSP, ULSD and LPG, the fuels are either stored or taken to filling stations. An assumption is made that all refined fuels are transported in road tankers with estimated mileage and fuel consumption estimates per tanker journey in the UK. The emissions as a result of the transportation of one tonne of product are included in this stage.

LPG is stored prior to distribution and the loading of the fuel into tankers releases emissions into the atmosphere. These emissions are combined with the tanker distribution emissions.

Personal consultation with British Petroleum (BP), Hull (2002), revealed that the distribution of LPG is a complex issue. For a simple analysis, a number of assumptions are made as follows: 50% of LPG is transported via HGVs (>17 tonne GVW) direct to filling stations from onshore terminals. The remaining 50% requires a journey of equal distance as the first half, not to the filling station but to a distribution terminal where the LPG is transferred to smaller HGVs of <17 tonne GVW. It is then assumed that these smaller tankers will have half the engine size of the larger tankers and will transport half the load to filling stations across the UK. This assumption should be treated with caution, however, in view of the complete LPG fuel and life cycle emissions, the consequences are negligible. Therefore, in view of these percentage contributions, this first approximation of engine size and mass transported is used.

It is then assumed that, for every tonne of LPG used in an LPG powered vehicle (UK), half was derived from direct transportation and half from the transfer process. The emissions in the distribution phase are attributed to the direct and transfer LPG pathways. The results in LPG F5 represent the emissions via distribution of LPG from 50% of method 1 (direct) transport of LPG from terminals to suppliers and 50% of method 2 (direct) transport to a distribution terminal and subsequent transfer to smaller HGVs of approximately half the size. Therefore method 2 is further broken down into 25% direct (>17 tonne HGVs) and 25% transfer (<17 tonne HGVs). The average tanker emissions per tonne of fuel transported through each method are included in LPG F5 and combined with the storage emissions.

NG in the National Transmission System (NTS) transfers gas at pressures of up to 75 bar to the Local Distribution Zones (LDZs) operating at pressures up to 38 bar. The distribution system itself is a network of mains operating in three pressure tiers: intermediate (2 to 7 bar), medium (75 mbar to 2 bar) and low (below 75 mbar), TRANSCO (2001). The gas losses in the NTS are recorded in the same manner as within the NG F2 cycles. The BP measurement system is again used to calculate the emissions within this stage for the downstream (gas from the onshore terminals to the consumer) pipeline losses. Losses in the LDZs are cross-compared with other UK,

Mitchell *et al* (1990) and worldwide studies, Delucchi and Lipman (1997). For details of these values see Appendix H.

NG to be used within a NG vehicle must be either compressed (CNG) or liquefied (LNG). For CNG, a compressor station is required which is connected to the NTS, the gas requires compression to ~250 bar for use within a vehicle. Emissions data for the compression of NG is not readily available however Gover *et al* (1996) and Wang (1999) provided some data. Wang collated the emissions derived from a compressor using electricity (USA mix 1990) and gas power, whereas Gover *et al* collected emissions data for an electric driven compressor unit using the UK electric power mix of 1995. The Gover *et al* data set was used due to its similarity with the present study. The gas losses in the LDZs and the compressor emissions are combined and included within the NG-CNG F5 stage.

Liquefaction data was unavailable for the UK with BP and others unable to provide any robust values. Personal communication with BP, Phillips (2002) however revealed that TRANSCO has plans to build two LNG terminals in 2004/2005 and at present operates five peak shaving sites, these are plants connected to the NTS where, in the summer, NG is taken, liquefied and stored until winter. If the LNG is not used it is re-gasified and injected (reticulated) back into the NTS.

Only one BP site (Glenmavis, Scotland) is being used for transport operations. For this analysis an assumption is made that liquefaction of NG can take place with a mobile unit gasometer. BG can connect LNG gasometers to the NTS. Once liquefied the LNG is placed into containers. Woking Borough Council has a small trailer attached to a van that collects bottled LNG and delivers it once a week to nearby consumers (transport emissions are therefore negligible), Hull (2002). Wang (1999) has produced emissions values for small liquefaction plants (gasometers). The values are converted into mass units and included with CNG-LNG F5. As a cross comparison, personal consultation with an LNG expert Haynes (2002) revealed that the numbers presented in the GREET model are typical of the equivalent UK liquefaction emissions, which are held in

commercial confidence by BG. Further details pertaining to LNG processes can be found within Midgett *et al* (1996)

Electricity is distributed throughout a series of step-up and step-down transformers, typically from 22,000 to 275,000 or 400,000 volts. The national grid uses these values. The electricity is transferred through sub-stations and sent through transmission lines to area electricity boards for sale to consumers. Any losses through the system are heat losses, however consultation with the Electricity Association www.electricity.org.uk/memb_fr.html, Bags (2002) and Mills (2002) have mentioned that sulphur hexafluoride (SF₆) is used within transformers, the switch gear or circuit breakers within the National Grid (National network of electricity transfer), see www.nationalgrid.com/uk (electric magnetic fields - environment). The significance of SF₆ to global warming is very large, with a GWP of 23900 (CO₂ and CH₄ have GWP of 1 and 21 respectively), EA (1998a). However, SF₆ emissions are not included in this study due to the system boundaries and choice of pollutants under investigation. If one incorporates these emissions, a review of each and every life cycle would be necessary to include all emissions that may contribute to GWP. Given the scope of the investigation this is not feasible. However, any future user of the LCEM may wish to consider SF₆ when analysing electricity related emissions through the electric and Green Electric (GE) fuel cycles.

LFG is reticulated into the NTS at any location throughout the country. The LFG is simply cleaned and compressed to the standards of NG on location at the landfill, the anaerobic digestion site (AD) and/or sewage plant through a membrane separation and compression process, see Coetzer (1997) and Wheless *et al* (1996) for a complete explanation. Here it is noted that LFG resources may decline but other sources of waste-derived methane may be substituted, see Butt *et al* (1998), Coetzer (1997), Collins (1985), Fiscon *et al* (1996, 1997). Once reticulated, LFG effectively becomes NG and is subject to the same emission losses as the CNG and LNG cycles. Details of which can be found in Huang and Crookes (1998).

4.2.6 F6 Vehicle Operation

The most significant stage in the LCA is that of the combustion of fuel in an IC engine. At this stage the largest amounts of pollution are released into the atmosphere.

Throughout the F1-F5 stages the emissions per tonne of fuel extracted, transported, refined and delivered have been reported. Within the F6 stage the emissions per tonne of fuel used (combusted) are calculated. Once found, estimations are made of the operational life of the vehicles and total mass of fuel used. There are numerous emissions models and vehicle test cycle data sets that can be used to calculate the total life cycle emissions. The models differ dramatically and it becomes no straightforward task to estimate the emissions from the 'average' vehicle. However the most common European emissions test for numerous vehicle types is the European Driving Cycles (EDC) that consists of the Urban Driving Cycles (UDC or ECE15) and the Extra Urban Driving Cycles (EUDC). These are more commonly referred to as the EURO specifications, Ntziachristos and Samaras (2001). These emissions standards were introduced in 1993, together with future standards now agreed on as a result of the European Commission's (EC) Auto-Oil programme, DETR (1999). Further recommendations from the Auto-Oil programme formed the basis of decisions made by the European Council of Ministers and Parliament in 1998. These set tighter limits for cars and light-goods vans (LGVs) (<3.5t GVW), from the initial Euro 1 and 2 limits too, on the 1st of January 2000, Euro 3 limits with further, more stringent limits (Euro 4) coming into force in 2005. New limits have also been set for heavy-duty engines from 2001 (Euro 3), with more stringent limits being introduced in 2006/8 (Euro 4), CVTF (2000)

It should be noted that the LCEM is comparative at the first level and becomes less accurate as an absolute model. The model is based upon the use of EURO 4 vehicles, any other modelling with lower specification engine emissions standards would require additional information.

If one considers a bus operating through the suburbs, the speed, mass, fuel consumption, distance travelled and air temperature become so variable with each round that the resultant emissions profiles significantly differ. The study's UK vehicle and its drive cycle has to be represented in terms of average characteristics, however if a study of conventional and Alternative Fuels (AF) is being made based upon the replacement of fuel within the same vehicle, operating under the same conditions, a comparison can be made. Since extensive and time consuming field trials are beyond the scope of this study an emissions database for vans, buses and HGVs was sought.

The UK Road Transport Emissions Database developed by the Transport Research Laboratory (TRL), see www.trl.co.uk/1024/mainpage.asp?page=759, provided the answer. The database consists of emission functions, recorded over real world drive cycles² and expressed in terms of average vehicle speeds. They are incorporated into Volume 11 of the Design Manual for Roads and Bridges (DMRB), and the National Atmospheric Emissions Inventory (NAEI), for further details see the website www.archive.official-documents.co.uk/document/ha/dmr/index.htm. Each Excel spreadsheet provides coefficients for equations expressing pollutant emission rates as a function of average vehicle speed. The equations follow the standard form:

$$E = k + av + bv^2 + cv^3 + d/v + e/v^2 + f/v^3 \quad 4.2$$

Where,

- v - is the Average speed (km/h)
- E - is the Emission rate (g/km)
- k, a–f - are Coefficients

² The term 'real-world driving cycle' refers to a driving cycle that has been developed from vehicle-based measurements in traffic conditions, which are representative of the real world. For research purposes, almost all cycles now used are 'real-world'. The term originally came about to distinguish such cycles from the ones used in legislation, which tend to be artificially structured (e.g. EDC), Boulter (2003)

Five vehicles classes were examined by TRL: passenger cars, LGVs, heavy goods vehicles (HGVs), buses and motorcycles under each of the emission control standard, Euro 1 to Euro 4 for vehicles on unclassified urban roads in 1998, 2000, with theoretical limits set for 2005. The Department for Transport (DfT) and the DMRB provided this information to TRL. Other simple methods are available such as the EPA Mobile 5a model for estimating on-road vehicle emissions, Wang and Santini (1995), which unfortunately considers only passenger vehicles prior to Euro 3 for a small number of compounds.

Within this study, public service vehicles are under examination, therefore the Euro 4 specification (tightest emissions standards) for LGVs, rigid HGVs and buses (all powered by ULSP and ULSD) were chosen and the following emissions were calculated: CO₂, CO, HC, NO_x and PM. The emissions of CH₄ and SO₂ from tailpipes are assumed to be zero. Consultation with Boulter (2003), the principal designer of the TRL database, has revealed that after the EURO 1 specification, emissions of CH₄ from petrol and diesel combustion are effectively zero. Any SO₂ emissions are only estimates of the original fuel sulphur content. Since ULSP and ULSD are assumed in this study and have very low levels of sulphur, any resultant oxidised sulphur (SO₂) will also be very small. TRL, therefore assumes zero SO₂ emissions from the combustion of ULSP and ULSD. Moreover specific emissions factors do not exist. TRL do have some values for the trace outputs of CH₄ and SO₂ from petrol and diesel vehicles, however these are currently not in the public domain. Unfortunately, at the time of writing, TRL has no plans to incorporate AF vehicles or analyse additional compounds due to lack of personnel. On completion of the emissions calculations a value of g/km is obtained for ULSP and ULSD powered vehicles. In developing countries the availability of ULSP and ULSD is limited and a large amount of vehicles still use conventional petrol and diesel. Should the LCEM be used to model these conventional fuels, with inherently higher levels of sulphur, the user must amend the emission rates accordingly.

TransportEnergy PowerShift is an Energy Saving Trust (EST) programme to help establish a sustainable market for alternative, clean fuel vehicles in the UK. It aims to

create the conditions for clean fuel vehicles to be practically and economically viable, see www.powershift.org.uk. It produced a Powershift Register, which is a buyer's guide to clean fuel vehicles. It is the only comprehensive source of impartial information available in the UK. It allows vehicle buyers to make informed choices about the merits of the different clean fuel vehicles on offer and provides the basis on which PowerShift grants are offered. Through this register, an advanced search option is available where it is possible to search for a vehicle by: type, registration year, fuel type, funding band and/or new/converted vehicles. From this database, a Ford Transit 2.3L <3500kg vehicle (powered by CNG, LPG and Electricity) model year 2002 was selected, together with a Dennis Eagle Elite C8.3G CNG powered HGV, model year 2001, a Dennis Super Dart B5.9G dedicated CNG bus and a DAF SB220 dedicated LPG bus³, both model year 2000. Each of these vehicles was tested, at Millbrook Test Track in the UK, by the USEPA and by TNO Wegtransportmiddeln (Germany). These vehicles were chosen as typical vehicles of their type in the UK and therefore represent a range of PSVs. The emissions reduction/addition for their comparable Ultra-Low Sulphur Petrol and Diesel (ULSP and ULSD) counterparts are included within the fuel cycle F6 stage for each vehicle.

The g/km emissions for each vehicle and fuel type under examination were calculated, based upon the average speeds of each vehicle (speed data estimates from the DTLR (2001a) publication). An account of the total emissions over the operation life of the vehicles was then required.

A LGV will generally be used for delivery purposes and a series of assumptions is made as follows, see Appendix G: average miles per gallon (mpg) values following consultation with the DfT (2002), Parkin (2003) and DTLR (2001b), distances travelled with reference to DTLR (2001b) and DVLA (2001) plus daily and annual estimations of operational use.

³ It should be noted that the information for the Dennis Super Dart bus has now (May 2003) been removed from the Powershift Register. Powershift informed the author that the bus information has been removed from the register as that they are currently re-testing the vehicles.

Rigid HGVs used within outer city delivery routes, see Appendix G. Average mpg, speed and distances are assumed from the above references plus DTLR (2001c, 2001d).

A correlation between mpg and speed has been produced for each of the vehicle types, see the end of Appendix G. In the appendix the reader may note the overlap between petrol and diesel at approximately 28kph. Below this speed the diesel van has higher fuel consumption than the equivalent petrol van and above 28kph a reversal occurs. This may seem odd given that on average a diesel van would travel further than a petrol van, given that diesel is more dense than petrol. However, if one plots the change in CO₂ emissions against speed using the TRL formula in equation 4.2, the same trend can be seen.

Buses operating within the inner city are modelled with average speeds and distances travelled assumed, as before see Appendix G. The same references as above are used with the addition of Chan (2002) in order to estimate operational characteristics. Inner city busses are very difficult to accurately model due to their interchangeable speed and loading and accurate information is difficult to obtain. The results represent the average vehicle and would require amendments for particular bus routes.

With the assumed average speeds, for each of the vehicles under examination, together with appropriate conversion factors, the TRL formula, see equation 4.2, will calculate a value which represents the total emissions due to the combustion of 1 tonne of fuel, see Appendix G. These values are placed in the petrol and diesel cycle (F6 stage). Percentage reductions/additions of the AF to these conventional fuels are calculated and placed within their respective data cells e.g. A CNG van produces 23% less CO₂ per km travelled in comparison to its diesel equivalent, when tested during the EU standard urban, extra urban and combined test cycles at Milbrook (plus others) test tracks, see Appendix I. This appendix also provides details of the percentage reductions for each fuel and vehicle combination, taken from the VCA (2001) and www.powershift.org.uk. An assumption is made that if the vehicles tested under EU standards, on the test track, produced the reductions in emissions shown, then the vehicles operating in the suburbs

of a city will show similar percentage reduction in emissions to their petrol and diesel equivalents. A reduction in the emissions per km travelled will reduce the total emissions per tonne of fuel consumed.

This is the basis upon which the alternative fuels have been compared to the conventional fuels (petrol and diesel), in the F6 stage, for each of the fuels under examination.

At this point in the fuel cycle (F6) a clear comparison can be made with electric vehicles. The EA Technology Wavedriver van is modelled against its diesel equivalent for the purpose of this research. With a number of conversions and steps, see Appendix J, an energy rate per km travelled is used to calculate the time taken to consume a tonne equivalent of fuel. From the fuel cycle F1-F5 calculations a total emission per GJ of electricity was calculated, therefore multiplying this value by the total theoretical time taken to consume a tonne equivalent of fuel and the distance travelled provides a value representing the total life cycle emissions via the use of the Electric Van (EV).

Results are presented in Chapter 5 for the fuel and vehicle cycle emissions of the following combinations: A large van powered by petrol, diesel, NG-CNG, NG-LNG, Electricity, Green Electricity, LFG-CNG, LFG-LNG; a HGV powered by diesel, NG-CNG, LFG-CNG and a bus powered by diesel, LPG, NG-CNG, LFG-CNG. Having dealt with the fuel cycle issues, a similar discussion on the vehicle cycle follows below.

4.3 The Vehicle Cycle

There are four stages to consider in the review of the vehicle cycle (V1-V4). They are used to clarify the calculation and accumulation of a set of characteristic emissions arising from the generation, use and disposal of a public service vehicle. Modifications can be made and any other vehicle could be modelled, provided the database is available. The combination of the fuel and vehicle cycles produces the Life Cycle Emissions Model (LCEM), see Chapter 5.

4.3.1 V1 Material Recovery and Manufacture

The first stage to consider is V1, dealing with the emissions attributed to the manufacture of the materials required to construct the vehicle under examination.

A large car, average weight ~1030 kg GVW consists of: 66% Steel, 10% Plastics, 6% Aluminium, 4% Tyres and 14% Others (3% Paint, 3% Glass, 3% Other, 2% Textiles, 2% Zinc, Copper, Lead and 1% Fluids) by mass, ACCORD (2001). If one assumes the same composition for a large van and simply multiplies by a factor of three to get approximate composition values (assuming that a van weights 3.5 tonne GVW and 1.8t Unladen Vehicle Weight (ULV)⁴), mass values are then calculated from the percentages for each of the component parts. Only steel (66%), aluminium (6%) and glass (3%) are included due to data accessibility and limited emissions information applicable specific to vehicle manufacture. However, since the vehicle cycle emissions only contribute a very small percentage to the overall life cycle emissions, see Chapter 5, the additional components not modelled are deemed insignificant at the present time. As a first approximation this is true, however a more detailed inventory could be developed, given the necessary data. Moreover, these impacts could be important in an absolute sense, as vehicle parts and improvements occur in the future. Subsequently, movements in car design to light weight specialised plastics and other man-made composites will need to be kept under review.

⁴ ULV refers to the weight of the vehicle as built in the factory with full fuel, engine (generator) oil and coolants. It does not include cargo, water, occupants or accessories. As defined by the Recreation Vehicle Safety Education foundation, see <http://rvsafety.org/terms.htm>

The average rigid HGV in the UK weighs 25 tonnes (GVW), DfT (2002a). A typical Dennis Eagle HGV is 15-17 tonnes ULV, Dennis Eagle (2003). The average GVW value is calculated from the total number of vehicles and the number of classes of HGV, of which there are 11, ranging from 3.7 tonne to 38 tonne in operation in the year 2000. These HGVs (in general) comprise the following: 67% Steel, 23% Cast Iron, 10% Others, Scania (1999). The same composition is assumed for the average UK bus (also assumed Scania) weighting 10 tonnes (UVW). Weight estimate taken from by Chan (2002) and Croft (2003).

The largest percentage of steel and iron consumed in the UK is produced in the EU by the CORUS Group. One can therefore attribute the emissions from their production plants in order to find the emissions associated with the vehicle production. Another assumption is made in that EU steel and iron manufacture plants are similar to UK plants, with resultant similar emissions profiles since most steel and iron is imported, Funnel (2002), Hunt (2002), Parker (2002), Taylor (2002). Steel in the EU is manufactured from 60% raw materials and 40% recycled steel - scrap. Within stage V1 the author has assumed that emissions are zero from the 60% raw material extraction phase with the 40% recycled steel (extraction phase) emissions included in the V4 disposal and re-use stage. The V1 raw material extraction phase emissions are assumed to be zero because of the system boundaries set in this study and because the emissions are common across all of the vehicle cycles under examination and are therefore unnecessary additions. The 40% recycled steel emissions account for the ferrous metal taken to the smelter from the dismantler in a diesel-powered HGV (plus all other associated processing emissions). Further details, pertaining to iron and steel manufacture, can be found within the energy cycle assessment of electric and conventional vehicles by Singh *et al* (1998a, 1998b).

Data from the EA (as with F4) is combined with the CORUS Group data, see www.corusgroup.com and the Iron and Steel Statistics Bureau www.issb.co.uk, in order

to attribute the emissions due to the generation of steel and iron. These emissions do not take into account the emissions due to the extraction of limestone, iron ore and coal.

Aluminium may be used more extensively in the construction of vehicles in the future; therefore an estimation of emissions is produced. Audi announced in 2001 www.audiworld.com/news/01/071201/content.shtml that they have built more than 150000 vehicles with aluminium bodies, since production started in 1994. The European Aluminium Association (EAA) have forecast that the amount of aluminium used in each car is set to increase from about 100 kg in 2000 to 150 kg in the year 2005, www.eaa.net/transportation/passenger.asp. The Aluminium Federation (ALFED), www.alfed.org.uk provide information and data pertaining to aluminium casting (sheet and extrusion) for use within vehicles, Askew (2002). Rolled aluminium sheets, extruded aluminium and re-melted process scraps are all used within vehicles. A description of processes and information on the structure of the UK industry can be found at www.alfed.org.uk/recycling.htm and www.alupro.org.uk/frame9.htm. The emissions due to the manufacture of one kg of aluminium, obtained from ALFED, Askew (2002) are multiplied by the weight of aluminium required and included within V1. An assumption based upon a personal communication with Davenport (2002) is that 55% of sheet and 45% of block aluminium is required in the construction of a large van. The emissions associated with the manufacture of sheet and block aluminium are collated and included.

Glass manufactured for vehicles is derived through a complex mix of processes. During the melting process a range of compounds are emitted through chimneys. The emissions data for a typical UK furnace have been obtained from Slade (2002) and included within V1. Calculations are made based upon the weight of glass required. Comparative data is available within Singh *et al* (1998a, 1998b).

It is assumed that lead-acid EXIDE batteries power the electric vehicles. These batteries would replace the internal combustion engine (ICE) plus auxiliary components (fuel, fuel tank, batteries etc.) and add extra weight to a conventional diesel powered van, Baker

(2002). Only electric powered vans have been modelled within this LCA, due to data availability at the F6 stage. The lack of an internal combustion engine reduces the V1 emissions due to the generation of the steel that would of been required for construction. The emissions from the production of the weight of EXIDE batteries required to replace the engine of the van are included in V1, provided by the EA Pollution Inventory (PI) and Beal (2001). With reference to the electric motor unit, It should be noted that copper emissions are not included in this study (not selected as a compound under investigation) and with the introduction of lead-acid batteries into the vehicles, any subsequent recycling of more copper than the conventional ICE vehicle would inevitably lead to an increase in emissions. The general emissions are specific to operations in the year 2000 at the EXIDE car battery production site in Gwent, Wales, which at the time was the largest supplier of lead-acid batteries in the UK. Today, all EXIDE batteries are imported and operations at Gwent have ceased but it is considered that the data is still relevant.

4.3.2 V2 Vehicle Assembly

Assembly plant emissions are difficult to collect, as the plants are not committed to document an inventory to the EA. However, based on personal communications, estimates can be made on the emissions per vehicle assembled.

Ford Transit vans are manufactured in a fabrication plant in Southampton. If one assumes that all Transits built in the year 2000 were derived from here one can attribute the emissions due to the generation of one van, with the knowledge that 51,225 vans were produced, see www.ford.co.uk. Following personal communication with Bray (2002) and Janes (2002), emissions data was received, dealing with solvents from paint, from the Southampton plant; however no data was available on the materials under investigation within this LCA. Scania (1999) however produced data on the average emissions per vehicle (Bus and HGV) assembled in Sweden, Europe and America. The total emissions have been divided by the number of vehicles produced and represent average values per vehicle. The emissions are from electricity, district heating and fossil fuel use from all Scania factories. The VOC and CFC emissions are a result of painting

and general solvent use. If one assumes that emissions from a UK van assembly plant are similar to a Swedish HGV assembly plant and that the basic processes may not differ dramatically between products, then one can assign the percentage of the Scania plant emissions to the van, based upon the weight of vehicle assembled. The Large Van (Ford Transit) V2 emissions and the Scania Bus V2 emissions are calculated as percentages of the Scania HGV V2 emissions and placed within their respective cells.

Gas vehicles (LPG, CNG, LNG), whether dedicated or dual fuel, will require a minor change in engine design plus a more substantial or additional fuel tank. These additions increase the weight of the vehicle by approximately 90kg for a passenger car and will decrease payload (unless mounted in the spare wheel compartment), James (2000). In terms of additional emissions contribution to a conventional vehicle, the tanks have very little impact to the overall emissions and are therefore deemed insignificant contributors or second order emissions. The same assumption applies to HGVs and buses, which require, in the case of a LPG and a CNG 12m single deck bus, tanks that weight approximately 250kg and 800kg respectively, EST (2003).

Electric vehicle emissions associated with the fitting of a series of lead-acid batteries are negligible in comparison to the overall fuel and vehicle cycle emissions. Moreover, the author suggests that the emissions associated with replacing an ICE during manufacture with a battery-powered engine to a standard Ford Transit van are also negligible.

4.3.3 V3 Vehicle Operation

The most significant addition to the emissions inventory from vehicle operation is that of PM due to tyre and brake wear. The US EPA produced two major studies into PM emissions, EPA (1995a) and EPA (2002) based upon petrol and diesel-fuelled vehicles fitted with and without catalysts. PM emission estimates are based upon the amount of material lost from brake and tyre wear plus the number of wheels the vehicle has.

The PM emissions are the only emissions included in V3. Other emissions are insignificant in relation to the compounds under investigation within this study. These

V3 emissions are added to the F6 emissions to calculate the total vehicle operation emissions, see Figure 2.2.

4.3.4 V4 Disposal/Recovery and Re-use

Nine million tonnes of waste material arise each year in Europe from motor vehicles that have come to the end of their useful lives. Around 1.8 million tonnes of this is in the UK. To cope with the environmental effects, the EU drew up the End-of-Life Vehicles (ELVs) Directive in September 2000. The ELVs Directive set recycling targets of 85% of all ELVs, by weight by January 2006 and 95% by January 2015. In the UK, the Department of Trade and Industry's (DTI) ELV Consultation Group, which includes: The British Metal Recyclers' Association (BMF), The Motor Vehicle Dismantlers Association (MVDA) of Great Britain, The British Vehicle Salvage Federation (BVSF) and The Society of Motor Manufacturers and Traders (SMMT), is currently (March 2003) considering how the UK will implement the EU Directive on ELVs, <http://www.letsrecycle.com/legislation/elv.htm>.

Data appertaining to the ELV processes is difficult to obtain from each of the above listed associations and organisation. However, the EA and DTI produced a key report, EA (2002) dealing with the disposal and processing of ELVs. The study was undertaken in 1997 and applied to vehicles in the year 2015, using a 'gate to grave' analysis of vehicles that undergo disposal and recycling. A generic ELV vehicle was chosen for the study, weighting 1043kg (the average UK car weight).

A Life Cycle Inventory (LCI) has been developed within the EA and DTI study from information provided by the following: The Automotive Consortium on Recycling and Disposal (ACORD), MVDA, BMF, SMMT, The Consortium of Automotive Recycling (CARE), British Plastics Federation (BPF), British Rubber Manufacturing Association (BRMA), British Secondary Metals Association, The Lead Development Association and ETSU.

Since the emissions values are representative of a generic ELV, the values used within Large Van V4 are multiplied by a factor of two to be representative of the disposal and re-use emissions for that vehicle type, making the basic assumption that it takes twice as much energy and therefore emissions to dispose of a 1800 kg UVW van as it does to a car weighing 1043 kg.

Data in V4 represents the emissions (total) to dismantle and recycle of a vehicle in the UK based upon the 1997 method of 75% reused/recycled and 25% landfill. Some modifications have been made to the datasets in order to make the model UK specific. In particular the study states that, of the ferrous metal scrap that is taken from the shredder to a smelter, approximately half is exported to Turkey only and the remaining half taken via road transport to UK smelters, see EA (2002). These export emissions are ignored and replaced with the transport emissions as an assumption is made that 100% of the ELV is disposed off and recycled in the UK. The export emissions data sets are replaced with the associated diesel truck emissions as a result of transporting scrap to the smelter.

The emissions associated with the transport (towing) of a dumped ELV to a smelter are assumed to be similar to the emissions from the transport of dismantled ferrous metal (proceeding dismantling) to the smelter.

The emissions are the total "gate-to-grave" emissions inclusive of the dismantling, transporting, shredding, materials used/required for the processes, feeder sites and fluff deposits to landfill (plastics, tyres and material).

The present study's rigid HGV weight is 25t (GVW) and between 15-17t (16t assumed) UVW and would expect to have 4.57 times the emissions associated with the dismantling, processing and re-use of the component parts of a van weighing 3500kg (UVW). Therefore the values in HGV V4 are simply multiplied by this factor.

The present study's bus weight is assumed to be 10000kg (UVW), therefore one would expect to have 2.86 times the emissions associated with the dismantling, processing and re-use of the component parts when compared to a van.

The use of an electric-powered van will require recycling and disposal of the lead-acid batteries plus the vehicle itself. Approximately 90% of lead-acid batteries in the UK are recycled, the same applies to the USA, Gaines and Singh (1995). The largest lead-acid recycler in the UK is H J Enthoven Limited, who recycles some 75,000 t of batteries per annum. They are a secondary lead recycler with 60% of their input from car batteries (traction and lead-acid⁵), with the remainder from lead (roofing and manufacturing scrap). The EA Pollution Inventory (PI), Slarke (2002) was used to estimate emissions per weight of battery recycled through the plant. The conventional disposal and re-use emissions of the equivalent diesel fuelled van are replaced by the battery emissions within the electric vehicle model. Within this LCA analysis it is assumed that EXIDE use these recycled parts in the manufacture of new batteries.

Other types of battery exist and are used commercially in many vehicles. Further details of battery recycling, sinter plant processes and smelting can be found in Cooney (2002), G & P Batteries (2002) and Gaines and Singh (2002).

4.4 Summary

The LCEM has been used to calculate the total life cycle emissions for each fuel and vehicle combination. The fuel cycle emissions, through the F1-F5 stages, are representative of a tonne of fuel delivery and used in the F6 stage. In this way all emissions, through each stage, can be represented by the units g/t of fuel. The vehicle

⁵ The traction battery is the "fuel tank" of the electric vehicle, that is where the energy needed for driving is stored. It is also the most critical component of the vehicle.

The principle of a battery is very simple: between two different materials (electrodes) immersed in an electrolyte solution a potential difference will occur. Numerous battery types have been developed, only a small number of these can be taken into consideration for traction purposes. Lead-acid batteries are the most common used for traction purposes

cycles are different in that they are representative of the emissions associated with the construction of one vehicle, see Chapters 5 and 6.

In general, the F6 stage emissions contribute the most to the total life cycle emissions for each fuel and vehicle combination, with the exception of electric vehicles. Moreover, the cumulative F1 to F5 emissions are smaller than the F6 emissions and the total vehicle cycle emissions contribution to the life cycle emissions are minimal. The F6 calculations were made with the use of the TRL UK Road Emissions Database. This is the only UK database to include vans, HGVs and buses, which are the vehicles chosen to represent public service vehicles. Depending upon the operational characteristics of each vehicle the F6 emissions can be highly variable. Equation 4.2 shows that the emissions are based upon average speed. Each vehicle, whether operating in the inner city or suburbs, will have interchangeable average speed. Therefore on review of the total emissions from each vehicle, the user must take caution in comparing results and not jump to conclusions concerning the impact of one vehicle to the next. This LCA study compares conventional and alternative fuels used within the same vehicle, not within each vehicle.