

Chapter Five

Results and Discussion of LCEM

5.1 Results

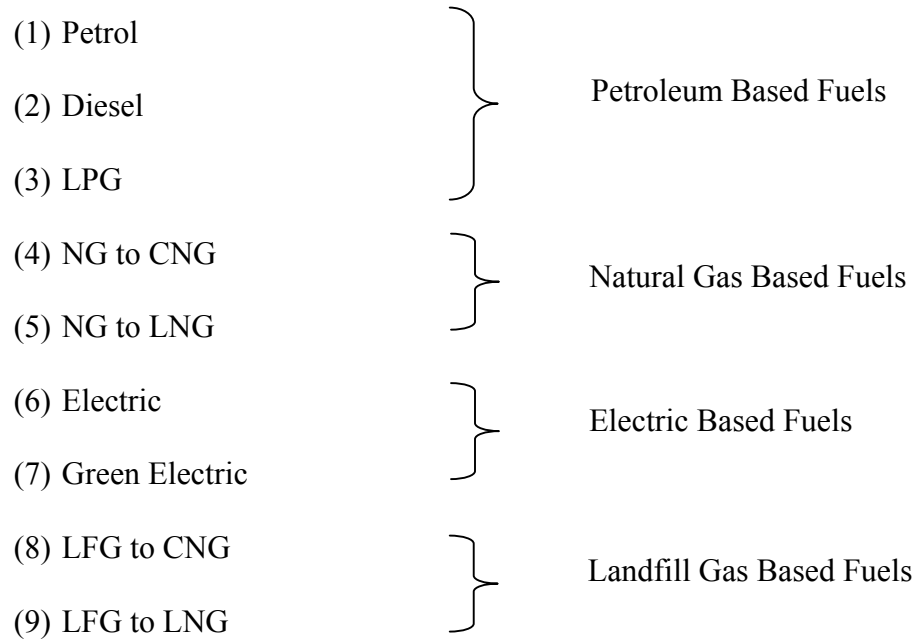
Having dealt with the formulation of the LCEM, this chapter discusses the results of the LCEM, focusing upon the comparisons between each individual fuel and vehicle cycle and other studies.

The results are presented as contribution based percentage graphs, with the detailed absolute values in Appendices K and M. These graphs enable the user to quickly identify the relative impact, each compound under investigation, has on the overall results. Fuel cycle, vehicle cycle and life cycle results are presented, for each of the nine fuel cycles and three vehicle cycles. Throughout each cycle a detailed dissemination and cross-comparison with other studies are documented, providing justification for each of the results obtained.

The Chapter closes with the emissions for the complete life cycles of each vehicle and fuel under investigation in a form suitable for subsequent normalisation and weighting in Chapter 6.

5.2 Fuel Cycle Results

Nine fuel cycles are considered; see Figure 2.4 (duplicated below), which represent the range of commercially available fuels in the year 2000.



A range of fuels has been selected for each Public Service Vehicle (PSV) based on technical feasibility and data availability.

Euro 4 Large Van: Petrol, Diesel, LPG, NG-CNG, NG-LNG, Electric, Green Electric, LFG-CNG and LFG-CNG.

Euro 4 HGV: Diesel, NG-CNG and LFG-CNG

Euro 4 Bus: Diesel, LPG, NG-CNG, LFG-CNG

The reader may wonder why an electric bus combination has not been considered. The electric bus is inhibited by: cost, energy density, power density, cycle life and the ability to be recharged rapidly. To fulfil all of these requirements simultaneously is still a major challenge. The renaissance in EV began in the 1970s with the ‘oil crisis’ and development was given a further impetus twenty years later with the increasing

concerns, especially in California, over atmospheric pollution. Greatly improved battery performance is now available, but the key commercialisation consideration of cost has not yet been resolved, and this is likely to be the factor limiting widescale introduction, as discussed by Vincent (1999). However, electric trolleybuses have been in operation since the first demonstration project in 1882, but their limit to use on specific routes causes many problems. From its introduction to the UK from Germany in 1911, the trolleybus quickly developed into a sophisticated, non-polluting, silent, fast and popular means of urban transport, achieving in its heyday a total count of over 4000 vehicles in 35 of our towns and cities. Economics turned against the trolleybus, leading to its demise in the 1960s, and final total abandonment in 1972, Bunton (1999). Recent attempts to revive interest in the mode in the UK have all failed. However, the electric bus may one day become a commercially viable option with the introduction of fuel cells. Fuel cells generate electricity without combustion by harnessing the energy created when hydrogen and oxygen are chemically combined. Fuel cell technology was first used on the Gemini V Spacecraft in 1965 and Ford alone has spent £300 million developing the technology. It has the advantage of driving a clean electric motor without the need for bulky batteries and constant recharging, Massey (1999). Furthermore this hydrogen could be produced via the reformation of the hydrocarbon Natural gas (NG) and Landfill Gas (LFG).

A new approach to hybrid bus design was unveiled by the Wright Group at the start of 2002: the Electrocitiy. This bus uses a small turbine and an electric drive system and can run on a variety of fuels. There are currently two prototypes, one on a Dart chassis, the other on a DAF BUS SB120, Brown (2003). This combination of electric and conventional fuels may see the commercialisation of hybrid electric buses in the future. At the time of the present study, it was decided not to include the issues of trolley buses or indeed trains, limited to rail routes – important as these options may be to inner urban integrated transport schemes.

A description of each fuel cycle follows.

5.2.1 Euro 4 Van Fuel Cycle

Considering the fuel cycles for the Euro 4 Large Van (Figures 5.1-7), they represent the total contribution of each compound due to the extraction, transfer, refinement, distribution and end-use of one tonne of feedstock/fuel. The end-use values (F6) contribute the highest percentage of output and represent the emissions as a result of fuel combustion within Internal Combustion Engines (ICE). Singh *et al* (1998a, 1998b), Tyson (1993) and Wang (1999) also concluded that vehicle operations contribute the most to total fuel-cycle results.

Emissions of CO₂ are calculated in kg/t of fuel delivered and used in the F6 stage, all other compounds are represented by g/t. Figure 5.1 illustrates the relative impacts for comparison by the reader. Actual values for all other fuel, vehicle and life cycle results are presented in Appendices K and M, a sample output is given in Table 5.1. The total percentage contribution graphs provide a simplistic view of the relative contribution made by each compound to the total of each fuel cycle.

Figure 5.1 – Euro 4 Petrol Powered Van

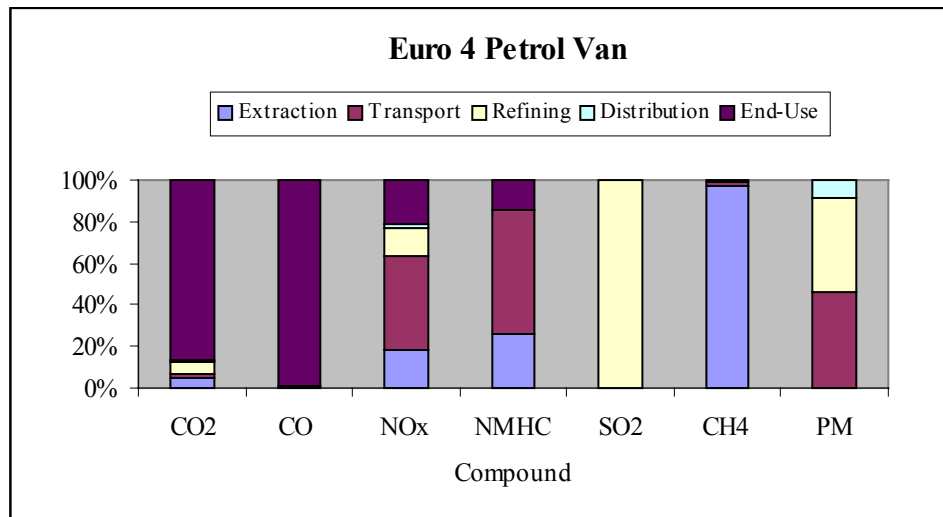


Table 5.1: Typical Emission Summary

PETROL	Euro IV Large Van						
	CO ₂ (g/t)	CO (g/t)	NO _x (g/t)	NMHC (g/t)	SO ₂ (g/t)	CH ₄ (g/t)	PM (g/t)
Extraction	122,000	53.0	343.0	393.0	0.0	529.0	0.0
Transport (oil tanker only) Pipeline inc	11,700	15.1	238.5	1,364.1	0.0	2.6	5.3
Refining	172,133	53.0	286.5	0.0	792.0	6.8	21.8
Distribution	3,663	16.7	56.2	1.7	1.3	0.0	4.7
End-Use	3,384,701	19,620	637	353	0	0	131
Overall	3,694,197	19,758.1	1,561.3	2,112.2	793.3	535.8	162.7

As can be seen in Figure 5.1, CO₂ and CO have the highest contribution to the fuel cycle of petrol during end-use (combustion), values of 3384701g and 19620g of CO₂ and CO are emitted for every tonne of petrol combusted in a Euro 4 specification large van in the UK. The recent work of Findsen and Radoff (2002) has shown that for every tonne of petrol used within the average vehicle in the USA, approximately 2,600,000g of CO₂ are released. Wang (1999) found that CO₂ and CO emissions for vehicle operation account for 80-85% and 95-98% respectively of the total inventory. In comparison, Tyson (1993) noted that CO emissions in vehicle operation account for 98% of total fuel cycle emissions. Kuhn and Bilitewski (1999) and Toyota (1998) found that the utilisation (F6 equivalent) of an automobile consumes 80% of the total primary energy consumption of the life cycle of a European car. This percentage is directly linked to emissions by Kuhn and Bilitewski who show that 79% of Greenhouse Gas (GHG) emissions, principally CO₂, are derived from utilisation, 10% from fuel production, 7% from material production, 4% from manufacturing and 0.2% from recycling. This study gives similar results to those presented in Figure 5.1 and to the work of Tyson (1993) and Wang (1999).

NO_x and NMHC releases are at their highest during the transportation of feedstock to the refinery via ocean tankers. These tankers have an assumed mass of 250000 tonnes, travelling from the Middle East (ME) to the UK, consuming 4000t of bunker diesel fuel per tanker, see Appendix D. The NO_x emissions associated with the transport of crude required to produce a 1 tonne of petrol used in the F6 stage, are higher than the emissions as a result of the combustion that 1 tonne of petrol in a van. NMHC emissions in the F2 stage are the result of evaporative losses of crude oil during loading/unloading and

transit due to, in particular, tanker ballasting with water at the dock which releases vapour laden air to the atmosphere, Passant (1993).

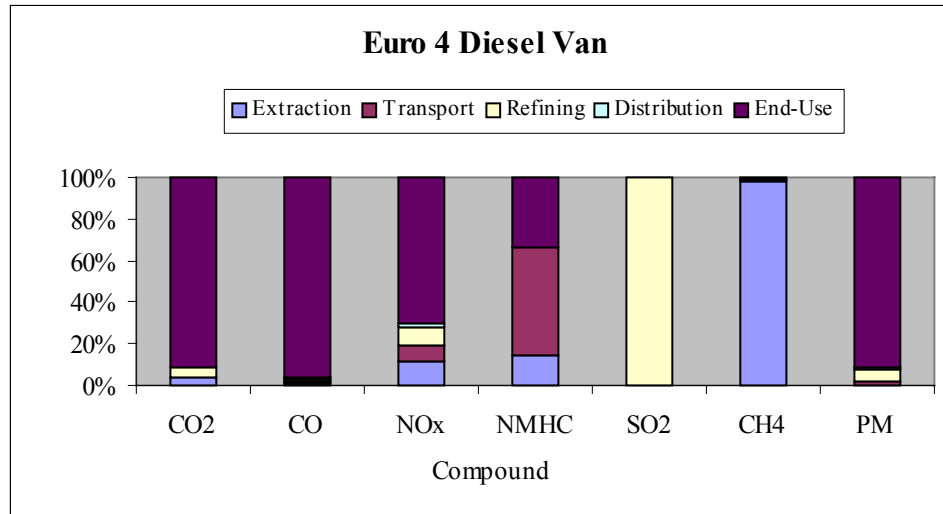
These results show that the majority of SO₂ is released during the refining of petrol with near to zero emissions occurring elsewhere, in agreement with the findings of Wang (1999). In the end-use (F6 stage) SO₂ emissions are effectively zero, as they depend upon the sulphur content of the fuel itself and with the introduction of Ultra-Low Sulphur Petrol (ULSP) and Diesel (ULSD) the amount of sulphur, in comparison to unleaded petrol and DERV, has been reduced by a factor of 3 and 7 respectively, see Chapter 4, F4 Fuel Production/Refining.

Methane (CH₄) emissions are dominated by the extraction phase, due to the release and flaring of gas onboard United Kingdom Continental Shelf (UKCS) hydrocarbon production platforms. Moreover, crude recovery in oil fields produced a large amount of CH₄ emissions, in agreement with the findings of Wang (1999). Boulter (2003) noted that CH₄ emissions in the F6 stage from ULSP and ULSD fuelled vehicles are effectively zero and measured outputs, since 1996 (Euro 1), are so low that no monitoring is necessary. Findsen and Radoff (2002) state that the amount of CH₄ emitted from gasoline vehicles in the US is effectively zero.

A diesel-powered van (Figure 5.2) exhibits essentially the same emissions characteristics. However, PM releases due to the combustion of diesel significantly change the PM fuel cycle. Wang (1999) draws a similar conclusion. Particulates from diesel fuel are a common problem and are generated as a result of diesel combustion.

Since SO₂ limits are considered to be zero in the F6 stage there is little change between the petrol and diesel fuel cycle results.

Figure 5.2 – Euro 4 Diesel Powered Van



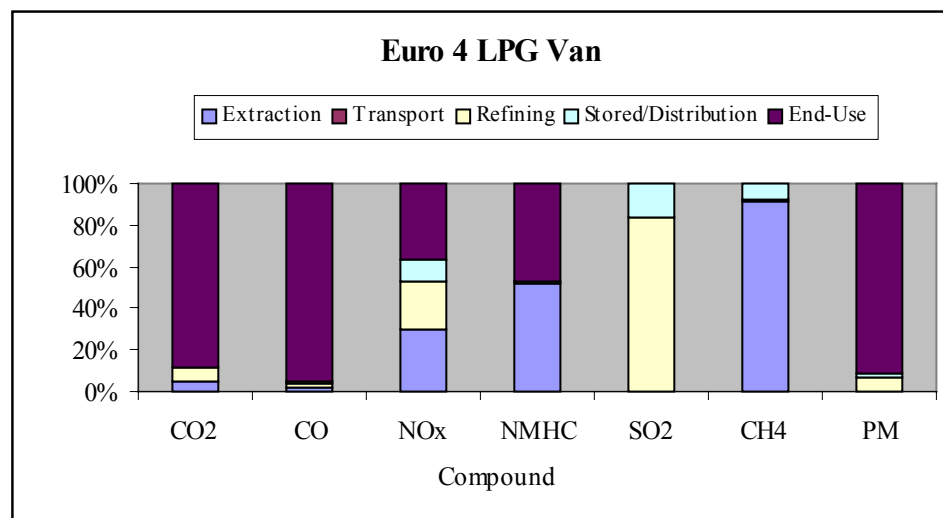
The results from Figure 5.2 show that diesel powered vans produce, relatively speaking, higher levels of CO₂ (11% in the F6 stage), NO_x, NMHC and PM per tonne of feedstock/fuel used in the F6 stage, see Appendix K, in comparison to Figure 5.1. All other emissions are slightly reduced, also in agreement with diesel vehicles modelled by Wang (1999), who found that the pattern of emissions from these vehicles is similar to petrol-fuelled vehicles apart from increases in NO_x and PM emissions. Tyson (1993) showed similar percentage contributions to each stage in the fuel cycle for CO, NO_x and PM emissions.

The equivalent Euro 4 van fuelled by LPG (Figure 5.3) expels less CO₂, CO, NO_x, NMHC and PM than its petrol and diesel alternatives, principally due to the percentage reductions in end-use (F6) per tonne of fuel, the lower carbon content of LPG and more specifically, the NMHC releases are reduced because there is less tanker ballasting associated with the loading/unloading of the LPG generated via crude oil refining (Refinery LPG), which accounts for 59% of the total. The remaining 41% is from Direct LPG transfer.

On an energy basis, LPG has a lower carbon content than petrol or diesel, however LPG is mostly propane (C_3H_8), which is similar in many respects to the main components of gasoline (e.g. Octane, C_8H_{18}), Delucchi and Lipman (1997). Hence the general emissions profiles are not too dissimilar. Hutcheson (1995) recorded that, as a result, less non- CO_2 greenhouse gases are released during combustion and production (F1-F6 equivalent) in passenger and Light Goods Vehicles (LGVs). DETR (1999) stated that LPG fuelled LGVs release lower levels of NO_x (>75% reduction against a comparative Euro 4 petrol vehicle) and PM (>60% reduction against a comparative Euro 4 diesel vehicle), which is also in agreement with Ebtekar (1995) and IEA (1999) respectively.

Larger percentages of SO_2 and CH_4 are released following the refining stage as a result of the storage and distribution of LPG to filling stations. In particular CH_4 emissions are derived from gas leakage and gas compression at service stations, IEA (1999). In the F6 stage, the absolute CH_4 emissions are considered to be zero, the IEA (1999) record a 43-71% reduction in hydrocarbon emissions for a LPG LGV in comparison to a petrol equivalent. Since the CH_4 emissions in the petrol and diesel cycles are effectively zero, any CH_4 emissions associated with a LPG vehicle will also be zero.

Figure 5.3 – Euro 4 LPG Powered Van



Wang (1999) showed that, for LPG vehicles modelled in the USA, upstream activities (F1-F5 equivalent) contribute to all of the SO₂ emissions. Wang also documented that crude recovery and processing of LPG contributed most to the total CH₄ emissions. This is similar to the results presented in Figure 5.3.

Gas powered vehicles and in particular NG-CNG (Figure 5.4) again show that the largest percentage of CO₂ and CO is derived from the combustion of fuel within an engine. Although levels of CO₂ are much lower than for the liquid fuels, actual values from the author estimate that the reduction is in the region of 20-30%. Schafer (2000) stated that the use of CNG reduces life-cycle emissions of CO₂ by some 25% over an equivalent gasoline-fuelled vehicle. Also, Yusaf *et al* (1999) quote the same percentage reduction when comparing CNG to diesel. CO, NMHC and CH₄ emissions are higher, on a relative basis, than for the liquid fuels, principally due to system losses in transportation and the incomplete combustion of gas in an ICE. The CO emissions for the CNG powered van are greater than the LPG equivalent and less than the petrol and diesel equivalent. This reduction in CO emissions, in comparison to a diesel-fuelled vehicle, was also noted by Cardenas *et al* (1996), Ebtekar (1995), Yang and Kraft-Oliver (1997) and Yusaf *et al* (1999).

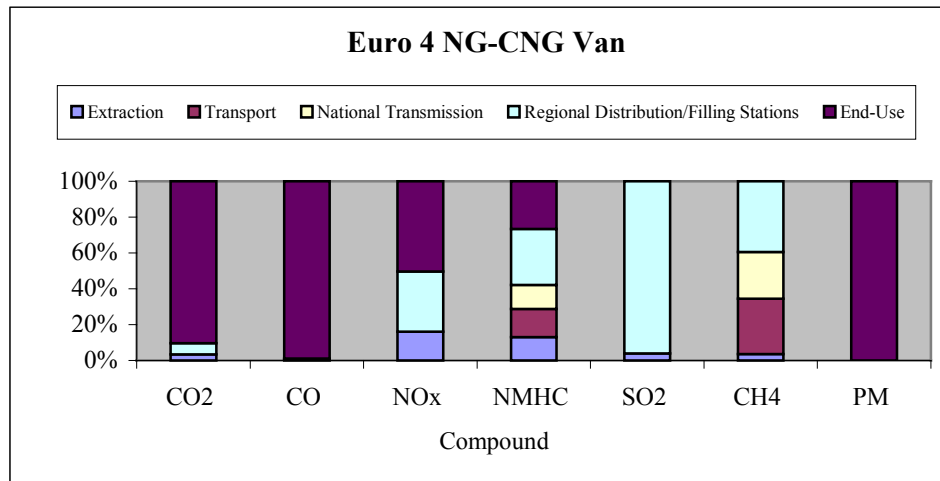
A HC (CH₄ and NMHC) increase occurs in CNG vehicles due to gas losses through the National Transmission System (NTS), and the Local Distribution Zones (LDZs) and unburnt HC fuel exiting the exhaust pipes of the vehicles. The monitoring of CH₄ emissions from gas vehicles is subject to a large degree of uncertainty and is not calculated by TRL within the UK Road Emissions Database, which only calculates HC emissions collectively (CH₄ and NMHC). Compared to gasoline and diesel, NG puts high levels of CH₄ into the exhaust gases, which are difficult to oxidise in an exhaust catalyst because the molecules are chemically stable. Many studies therefore tend to avoid commenting upon the release of CH₄ from gas vehicles, because the levels can be large in comparison to petrol and diesel vehicles. Findsen and Radoff (2002) noted that in spite of the significant contribution of CH₄ released by NG vehicles, studies of transportation-related emissions often exclude CH₄ due to the higher degree of

uncertainty and associated research, particularly for HGVs. The work of EST (2003), IEA (1999), Lane (2002) and Wang (1999a, 1999b) do however compare gas vehicles to conventional petrol and diesel vehicles. LGVs tested by IEA (French study), Lane (UK study) and Wang (US study) showed a large variation in the vehicles tested. Lane showed that a NG vehicle, compared to a Euro 3 diesel, released 15% more CH₄ per km travelled, whereas IEA noted that a NG LGV, compared to a Euro 2 diesel, released 131-226% more CH₄ per km travelled. It should be noted that each of the tests was performed in different countries with different vehicles and engines under separate conditions. The author therefore decided that a value of 96% would reasonably represent the increase in CH₄ emissions from a LGV in the UK in comparison to a diesel equivalent. This value was derived from the average increase in CH₄ emissions between the IEA study (178%) and the Lane study (15%), see Appendices C and K, to best represent an equivalent UK vehicle. The consequence of choosing this value has little impact on the total life cycle results; see Example 5.1.

The NG-CNG and NG-LNG fuel cycles show similarities, in terms of the percentage contributions to each stage in the fuel cycles, to the work of Wang (1999), who has shown that for a CNG vehicle in the USA, natural gas compression results in a large output of SO₂; with the NG recovery and processing stages producing large amounts of CH₄.

Wang found that NO_x emissions in the F6 (end-use) stage account for approximately half of the total emissions and in comparison to petrol vehicles, levels of NO_x in this stage are reduced by a significant fraction. In support of these findings, Cardenas *et al* (1996), DETR (1999), Yang and Kraft-Oliver (1997) and Yusaf *et al* (1999) came to the same conclusion.

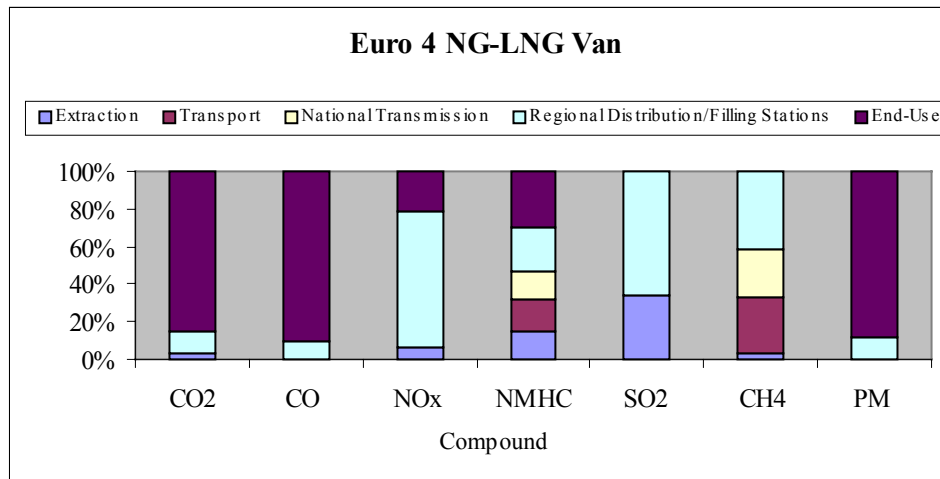
Figure 5.4 – Euro 4 NG-CNG Powered Van



Note: the (F1-F6) stage names within the gas vehicle fuel cycle graphs differ from the liquid fuel cycles to reflect more realistically the pathways of gas through the UK network.

A NG-LNG powered vehicle (Figure 5.5) has very similar fuel characteristics to the NG-CNG vehicle. Liquefaction of NG is required and the emissions associated with this process increases the emissions of CO₂, CO, NO_x, CH₄ and PM, see Appendix K, and decrease the emissions of NMHC and SO₂ when compared to the NG-CNG cycle.

Figure 5.5 – Euro 4 NG-LNG Van



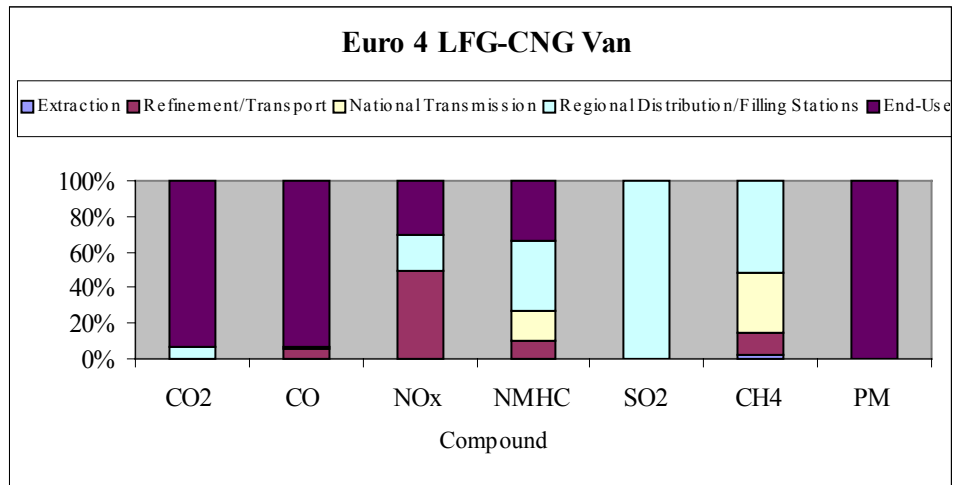
Gas powered vehicles fuelled by the fossil fuel natural gas are unsustainable. Replacing the NG portion of the gas cycles with a non-fossil fuel source i.e. Landfill Gas (LFG), promotes sustainability and results in fewer emissions. LFG is produced from landfill sites and can successfully be utilised within a CNG or LNG vehicle. Once the LFG has been filtered and cleaned to the standards of NG, the gas enters the British Gas (BG) National Transmission System (NTS) and Local Distribution Zones (LDZs). As a comparison, NG collected in the United Kingdom Continental Shelf (UKCS) network, is derived from a mixture of gas fields in the North Sea, each with variable compositions and quality. All the gas is cleaned to the same specification; therefore the origin of the gas is technically but not economically inconsequential.

It should be remembered that severe reductions in biodegradable material going to landfill are planned over the current and next decade. Sustainable sources of CH₄ (the main component of LFG) are in principle, available via digestion of these wastes, sewage sludge etc and biogas crops.

There are subtle differences between the LFG-CNG fuel cycle (Figure 5.6) and the NG cycles. Data availability for the F1 stage generated problems and the only release recorded from UK landfill sites was CH₄, which in theory is the most influential and common release. The CH₄ emissions associated with the F1 LFG cycles are approximately half that, in absolute terms, of the NG cycles per tonne of gas extracted from the UKCS.

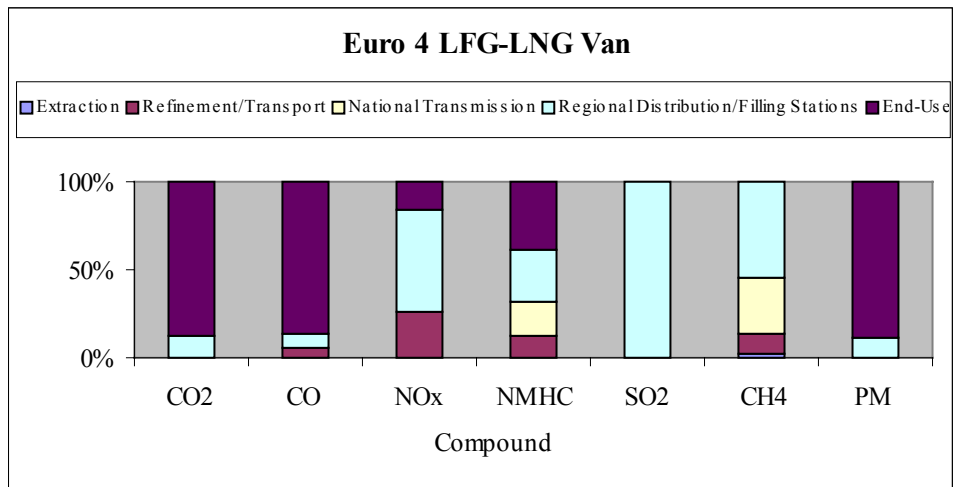
There are reduced levels of CH₄ and increased levels of all other compounds, in the refining and transport of LFG in the NTS, when compared to NG. From this point forward (when the LFG has entered the NTS), the emissions per tonne of gas are identical to the NG cycles above.

Figure 5.6 – Euro 4 LFG-CNG Van



The LFG-LNG fuel cycle (Figure 5.7) has the same characteristics as the first two stages (F1–F2), of the LFG-CNG fuel cycle and the same characteristics as the last three stages of the NG-LNG fuel cycle (F3-F6). Combining these stages produces the LFG-LNG cycle.

Figure 5.7 – Euro 4 LFG-LNG Van



The results presented above (Figures 5.1-5.7) represent the total percentage contributions, of each compound under investigation, for each of the fuel cycles modelled for a Euro 4 specification van. Two other fuel cycles exist, namely electric and green electric. However since the emissions represented within these cycles are

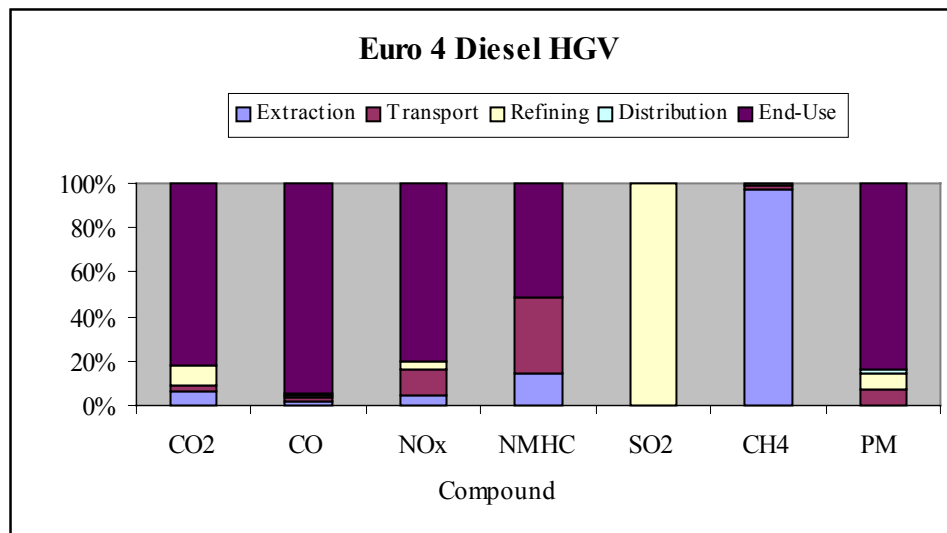
calculated in energy units a direct comparison with emissions per mass of fuel, at this stage, cannot be made, however a full account of the life cycle emissions comparisons is made at a later stage, see section 5.4.

5.2.2 HGV Fuel Cycle

This cycle is representative of a rigid HGV (of Euro 4 specification), used within an urban environment, transporting goods in and around major city centres. For this cycle only diesel and CNG fuels are compared on a like-with-like basis.

The following Figures 5.8-5.10 characterise the total emissions due to the production, transfer, refining, distribution and end-use of diesel, CNG and their feedstocks. The results for the (F1-F5) stage are similar for the diesel and CNG fuels, however the F6 results differ for each fuel type. Since the F6 stage is the most influential in the total fuel cycle, an analysis of each compound becomes necessary.

Figure 5.8 – Euro 4 Diesel HGV



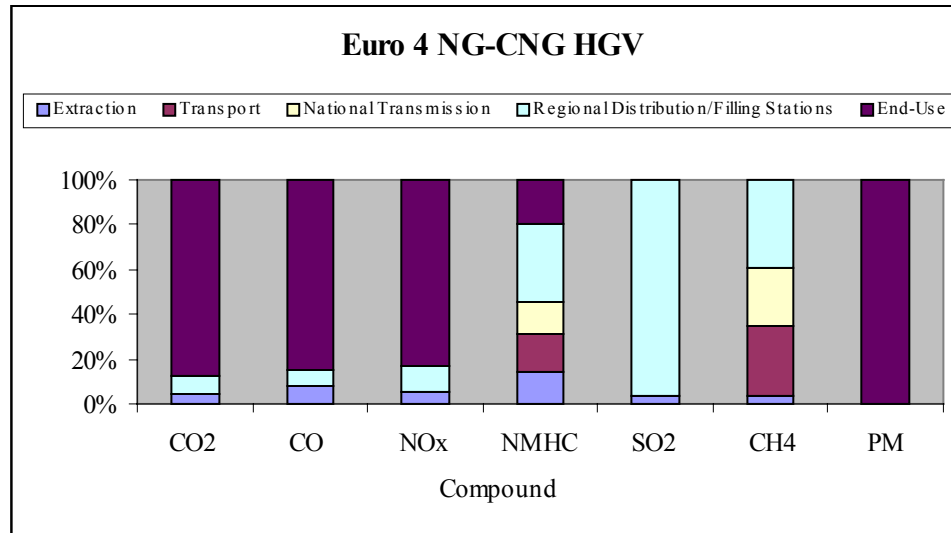
At this point the author has decided to remind the reader of the calculations made in order to generate the result presented in Figure 5.8. All values can be found in Appendix K. In order to produce 1 tonne of petrol in the F6 stage, 122kg of CO₂ are released into the atmosphere at the F1 stage, which accounts for 5.27% of the total CO₂ released in the complete fuel cycle (F1-F6). In refining this mass of crude oil in order to generate one tonne of diesel in the F6 stage 172.1kg of CO₂ (7.24% of the total) are released in the F4 stage. Finally, in order to combust one tonne of diesel within a Euro 4 specification

HGV weighing 25 tonnes GVW (16t UVW), 3047kg of CO₂ are released (90.79% of the total). The total CO₂ released for every tonne of diesel consumed within this HGV is 3356kg (with the assumed specific operational characteristics, see Appendix G and K).

The amount of CO₂ released, per tonne of fuel consumed, in a diesel powered HGV (3356kg) differs from that of a diesel van (3495kg), principally due to the F6 contribution, which for the HGV is, in absolute terms, almost 96% lower. The actual emissions, per km travelled, for a diesel HGV (478g/km) compared to a diesel van (249g/km) are higher. With the assumed operational characteristics, see Appendix G, the van on a suburban delivery round releases 4% more CO₂, per tonne of diesel used, than the HGV. Even with a lower emission rate per km travelled, the van will travel further on a tonne of diesel than the HGV and therefore release a greater volume of emissions. Also, the vans have a lower assumed average speed 20kph vans (48kph HGVs); a greater distance to travel 80 miles per day van and 62 miles per day for the HGV and the mpg of the diesel vans (30.6) is higher than that of the diesel HGVs (15.2). These different operational characteristics alter the rate of fuel consumption, which alters the F6 fuel consumption, which subsequently changes the total amount of compound released.

The NG-CNG fuelled HGV (Figure 5.9) illustrates once again the same (F1-F5) results as the van cycles, with changes in the total contributions evident due to the differences in end-use (F6).

Figure 5.9 – Euro 4 NG-CNG HGV



The relative values of output for this figure have been included in Table 5.2 below, as another example of processes. All data can be viewed in Appendix K. The reader may note some differences between Figures 5.4 and 5.9 and may query why the graphs differ even though the Van and HGV are using the same fuel. The results differ because the contributions to the F6 stage differ. This then changes the relative percentage contributions to the total fuel cycle results. The absolute impacts cannot be seen on these graphs and the reader must refer to Appendix K.

Table 5.2 – NG-CNG HGV Absolute Values

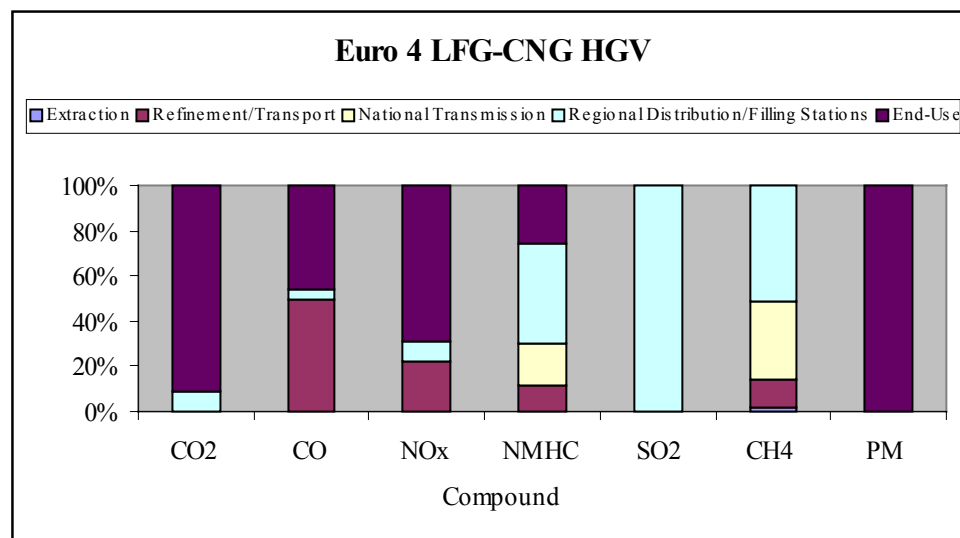
NG to CNG		Euro IV HGV (RIGID)						
		CO ₂ (g/t)	CO (g/t)	NO _x (g/t)	NMHC (g/t)	SO ₂ (g/t)	CH ₄ (g/t)	PM (g/t)
F1	Extraction	89,500	55	226	612	60	1,111	0
	Transport	0	0	0	749	0	9,373	0
	National Transmission	0	0	0	632	0	7,909	0
	Regional Distribution/Filling Stations	169,700	48	478	1,474	1,439	12,010	0
F6	End-Use	2,955,780	1,137	3,749	804	0	442	63
	Overall	3,214,980	1,239.7	4,452.9	4,269.7	1,499.0	21,030.2	62.7

The NG-CNG HGV fuel cycle shows that CO₂, CO, NO_x and PM emissions are dominated by the end-use stage, with similar levels of CO₂ and much smaller levels in CO, NO_x and PM (also noted by EIA (1999) and Gaines *et al* 1998), in comparison to the diesel fuelled HGV. Hutcheson (1995) noted a reduction in CO, HC and NO_x for a

typical HGV powered by NG, due to the lower emissions levels of gas powered vehicles, per km travelled, and absence of a refinery stage (F4). On the other hand, HC releases in transport of NG to the filling stations increases the overall NMHC and CH₄ levels by a 52% and 98% percentage respectively. The emissions of CH₄ from the exhaust of NG powered vehicles has been calculated separately, as the TRL UK Road Emissions Database does not separate HC into CH₄ and NMHC. HGV tests, to European and US standards, were conducted and the results were presented in EST (2003), IEA (1999) and Lane (2002). These studies show that the average NG powered HGV, in the UK and France, released 442% more CH₄ than a diesel equivalent. This average value, see Appendix I, was calculated as the average from each of the Euro 2 and Euro 3 HGVs under examination. The author suggests that this value is a reasonable average, however specific vehicles operating under specific conditions may alter this value. The impact of this choice has little effect on the life cycle calculations, See Example - life cycle emissions, p 5.22.

The HGVs using a fuel derived from LFG (Figure 5.10) exhibit the same emissions characteristics as HGVs powered from NG. Levels of each compound are reduced across the board, with the exception of slightly higher NO_x levels due to the compression of LFG into the NTS. The F6 emissions are identical to the NG-CNG cycle.

Figure 5.10 – Euro 4 LFG-CNG HGV

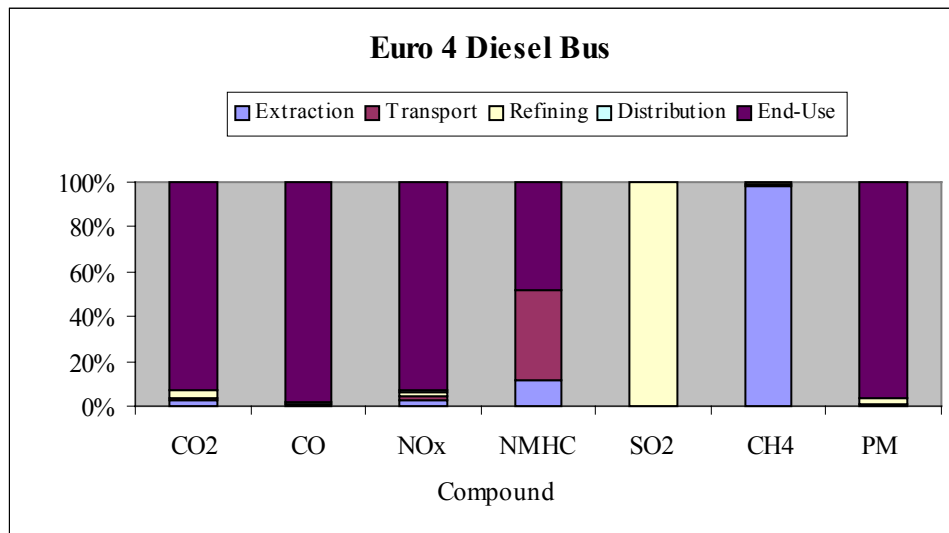


5.2.3 Bus Fuel Cycle

There are numerous types of buses operating in the UK, from inner city and outer city routes, across long and short distances, through congested inner city roads and motorways. For the analysis of a bus within this research, a bus transporting people on the inner city centre was chosen of 10 tonnes UVW. It is not the purpose of this research to extensively model vehicles based upon particular routes across city centres. The research is to be used as a cross comparison of an individual vehicle, fuelled by alternative and conventional fuels (petrol/diesel) over their life cycles.

The diesel fuelled bus results below (Figure 5.11), illustrate that the largest contribution of CO₂, CO, NO_x and PM occur during combustion of diesel in the F6 stage. The largest releases of NMHC occur during tanker ballasting in the F2 stage.

Figure 5.11 – Euro 4 Diesel Bus



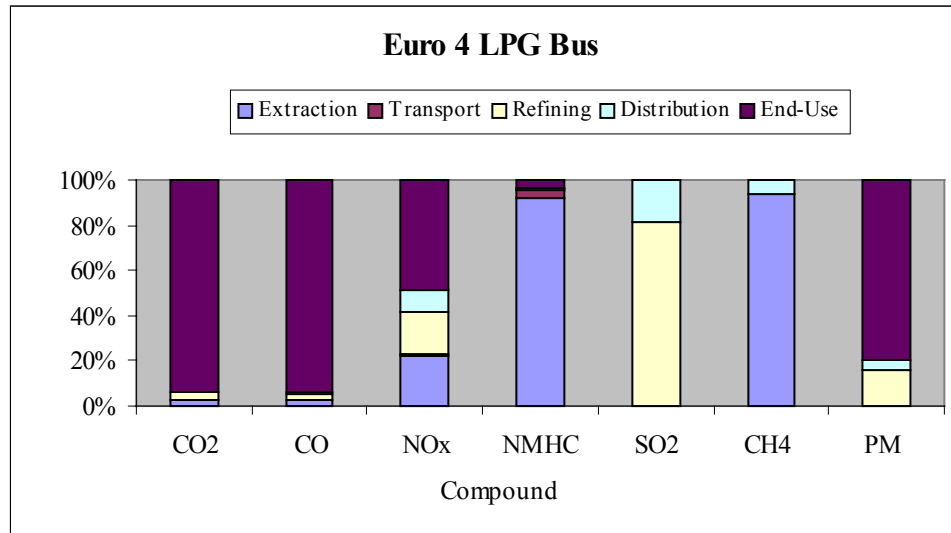
A European Community (EC) project, Rabl (2002) compared the emissions, per energy unit, for a diesel EURO 2 and CNG powered bus, on an equivalent life cycle basis (without any data on recycling and disposal). Results from the production and distribution stages of diesel only (the equivalent of F1-F5), indicate that 95% of CO₂,

93% of CO, 99% of CH₄, 97% of NO_x, 99% of SO₂ and 90% of PM emissions are associated with the production of the fuel itself with the remaining percentages assigned to distribution. Figure 5.11 shows similar results. The relative contributions however differ, the relevance of which can be seen when reviewed the CO₂ fuel cycle. The F1-F5 stage emissions contribute approximately 8% to the total life cycle emissions, so even if the production and distribution percentage contributions alter, they would still have little impact to the total. It should also be noted that a percentage change in the CO₂ cycle would have a much larger impact, on say Global Warming Potential (GWP), than the other fuel cycles. This is because the CO₂ cycle is measured in kg, whereas all other fuel cycles are measured in grammes. Any percentage change to this cycle would contribute to a greater extent, to say GWP, than a percentage change in either of the CO, NO_x, NMHC, SO₂, CH₄ or PM cycles.

Buses powered by LPG show different characteristics (Figure 5.12). Levels of CO₂, SO₂ and CH₄ are marginally increased; see Appendix K, with all other compounds showing decreased levels of output.

The largest changes occur in CO, NO_x, NMHC and PM, principally due to the reduction in tailpipe emissions of LPG in the F6 stage, together with the altered production pathway in comparison to diesel production, see Appendix K. In comparison the National Society for Clean Air (NSCA) suggested that the use of LPG in buses can result in 61% lower emissions of PM than the same vehicle would produce using conventional diesel (Euro 2), as well as 79% less NO_x, 33% less CO and 44% less NMHC, NSCA (1998). In comparison, the present study recorded reductions in PM, NO_x, CO and NMHC of 85%, 95%, 79% and 99% respectively, see Appendix K, for a LPG vehicle compared to a ULSD Euro 3 Bus. The bus make, model and design together with operational characteristics data were unavailable from the NSCA.

Figure 5.12 – Euro 4 LPG Bus



In general the F1-F5 fuel production values in the LPG fuel cycle tend to contribute more to the total emissions than those in the diesel fuel cycle, per tonne of feedstock/fuel. This is generally due to the advances in engine efficiency and the ‘cleaning up’ of fuel for use within transport (EURO specifications).

Gas powered buses are more frequently used today than anytime in the past. The emissions of all compounds in the F6 stage of NG-CNG are reduced when compared to diesel buses (Figure 5.11). In support of these findings, Meretei *et al* (1998) analysed urban air quality improvements, by using a CNG powered city bus. The results show that a reduction of NO_x, NMHC and PM occurs in the end-use stage (F6 equivalent), although levels of CH₄ are increased by an assumed average of 355%, see Appendix K. Analysis of bus emissions performance by Lawson (2003) has shown that NG powered buses are inherently cleaner than diesel buses (Euro 3) under all test conditions. With diesel buses producing almost four times the NO₂ emissions, in absolute terms, of an equivalent CNG powered bus. In contrast, see Appendix K, the results presented by the author for the fuel cycle of a Euro 4 Bus, suggests that the emissions of all oxides of nitrogen (NO_x) for a diesel powered bus (13111g/t) are approximately three times that of a CNG powered equivalent in the F6 stage (5104g/t).

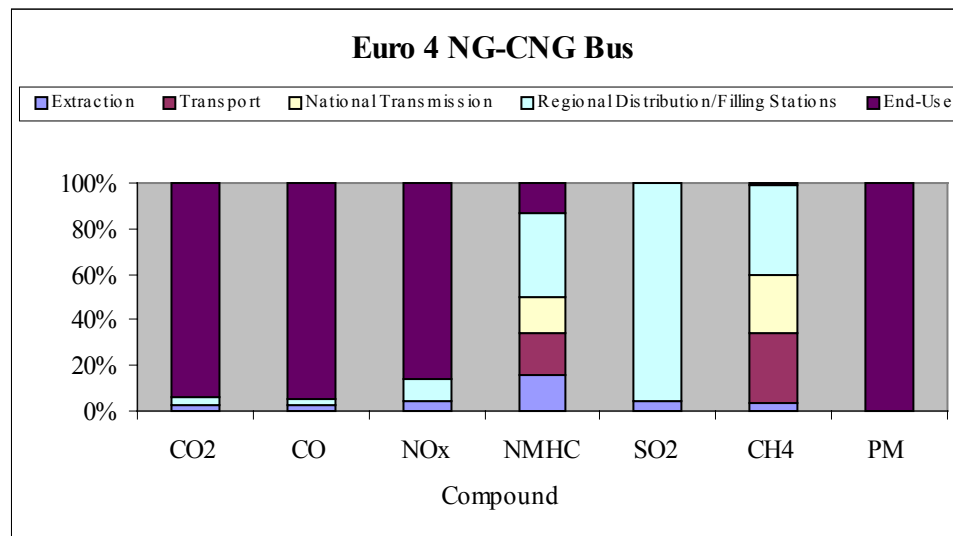
A recent study by Pelkmans and Lenaers (2001) has shown that levels of CO for a NG bus can be some 4 to 5 times lower than a diesel equivalent. In the present study, 1373g of CO are released during the lifetime use of a diesel bus; in comparison an equivalent NG-CNG bus releases 512kg of CO, approximately 3 times lower.

The emissions of NMHC and CH₄ in the F1-F5 stages are increased due to the leakage of NG in the NTS and LDZs, the associated emissions due to compression of NG into CNG and the assumed average increase of CH₄ from a NG Bus, see example 5.1.

Example – life cycle emissions

An assumption is made that 355% more CH₄ is released, in end-use F6, from the average UK NG Bus, in comparison to a diesel equivalent. This assumption has little effect on the total CH₄ life cycle results. If the assumed value were to be increased to 1000%, the total fuelcycle Bus emissions, over the operational life of the vehicle, would change from 3003t, see Appendix K, to 3101t. This additional mass would have very little effect on the subsequent calculations of GWP in Chapter 6.

Figure 5.13 – Euro 4 NG-CNG Bus

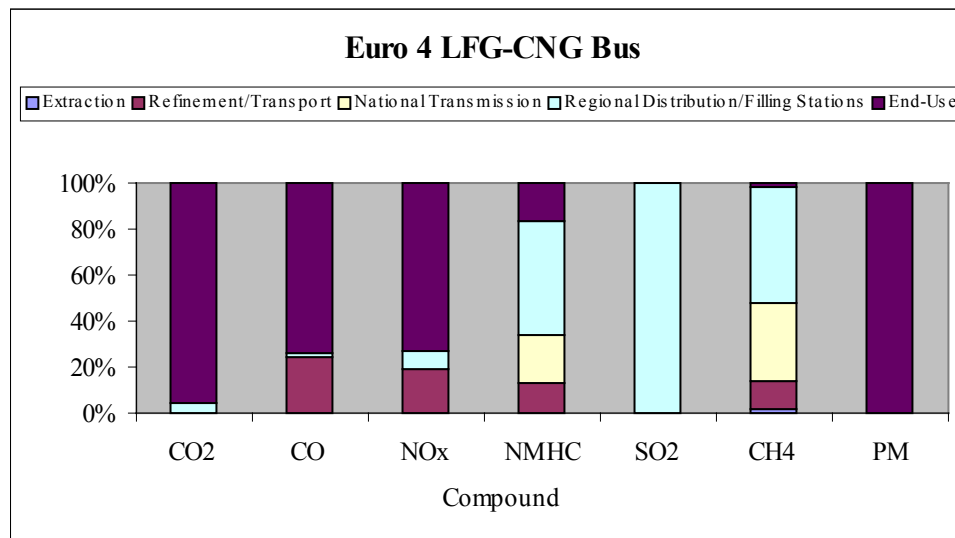


As can be seen in Figure 5.13 the end-use emissions contribute the highest amount of CO₂, CO, NO_x, and PM to the NG-CNG cycle per tonne of NG.

Replacing the NG cycle with the LFG cycle, see Figure 5.14, leads to further reductions in CO₂ and NMHC and slight increases in NO_x and CH₄ in the F1 and F2 stage. For the remainder of the life cycles the LFG and NG cycles are similar.

By collecting and using the waste CO₂ from landfill gas filtration, a reduction in the total emission is possible. The LFG filtration plant is capable of collecting the waste CO₂ product and producing a liquefied product. The CO₂ is initially compressed, where it is either fed through the membrane separation system and liquefied or liquefied directly. The liquid product is then used in commercial applications, such as fire extinguishers. The ability to separate and utilise CO₂, gives LFG a distinct advantage over the other conventional and alternative fuels. Wide-scale use of LFG in vehicles could see large reductions in CO₂ and subsequently GWP levels when compared to petrol and diesel use. See Appendix F for further details of the membrane separation (MEMBASEP) process.

Figure 5.14 – Euro 4 LFG-CNG Bus



The results presented above for the Euro 4 bus can be compared to the work of Beer (2000), who examined conventional and alternative fuels for buses on a CO₂ life cycle

basis. Beer examined pre-combustion (F1-F5 equivalent) and combustion (F6 equivalent) emissions. His results show that approximately 5-10% of the total fuel cycle CO₂ emissions of diesel, LPG, CNG and LNG are derived from pre-combustion.

5.3 Vehicle Cycle Results

The vehicle cycle can be used to compare and contrast any vehicle type. The present study chose to investigate three types of vehicle, a Euro 4 Van, HGV and Bus. They are compared on a full life cycle basis, from extraction of materials through to disposal. At each stage, emissions are attributed to: (V1) the material recovery and manufacture, (V2) vehicle assembly, (V3) vehicle operation and (V4) disposal, separation and re-use, per vehicle under examination, in contrast to the fuel cycles, which calculate the emissions released per tonne of fuel generated and used plus the lifetime use of the fuel. The total vehicle cycle emissions, account for the life cycle emissions associated with the operation of a vehicle.

There are four vehicle cycles under investigation; a 3.5t van, a 25t HGV, a 14t bus and a 4.2t electric van (All Gross Vehicle Weights¹). Unladen Vehicle Weights (UVW) of 1.8t van, 16t HGV, 10t bus and 2.5t electric van are used in the V1 manufacturing and V4 recycling stages. Each represents the average PSV in operation for the year 2000.

As with the fuel cycle, the following figures illustrate the percentage contribution to the full emissions cycle, from each of the vehicle stages (V1-V4). Absolute values can be viewed in Appendix K.

Due to data unavailability, some data in the V1 and V2 stage have not been included. The addition of which would have little impact on the total life cycle emissions. The V2 stage emissions are generated due to the assembly of the vehicle. The largest power sources used are boilers, of which the CO₂ releases are accounted for. Any other releases of CO, NO_x, HC, SO₂ and PM from this main power source

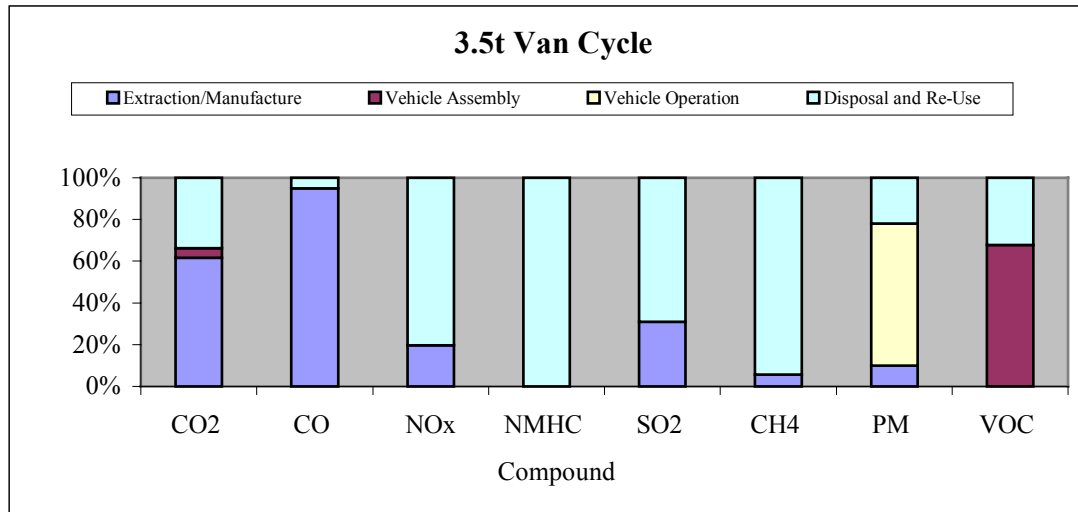
¹ GVW is the maximum recommended weight for that vehicle, including: the weight of the vehicle itself, fuel and other fluids, passengers and all cargo. MMS (2002) and Ford (2003)

will have little effect on the total emissions. It should also be noted that, the V1 emissions only include steel/iron, aluminium and glass, these components make up, by weight, 75% of the average van, 90% of the average HGV and Bus, and are by far the most significant contributors to the total vehicle cycle emissions.

It should also be noted that in the calculations of GWP and HT in Chapter 6, the fuel cycle emissions dominate and the vehicle cycle emissions are deemed second order.

The 3.5t van cycle (Figure 5.15), as with all vehicle cycles, is split into four stages. Results show that the largest percentage contributions occur during the V1 extraction and manufacture stage and the V4 disposal and re-use stage, see Appendix K.

Figure 5.15 – 3.5t Van Cycle

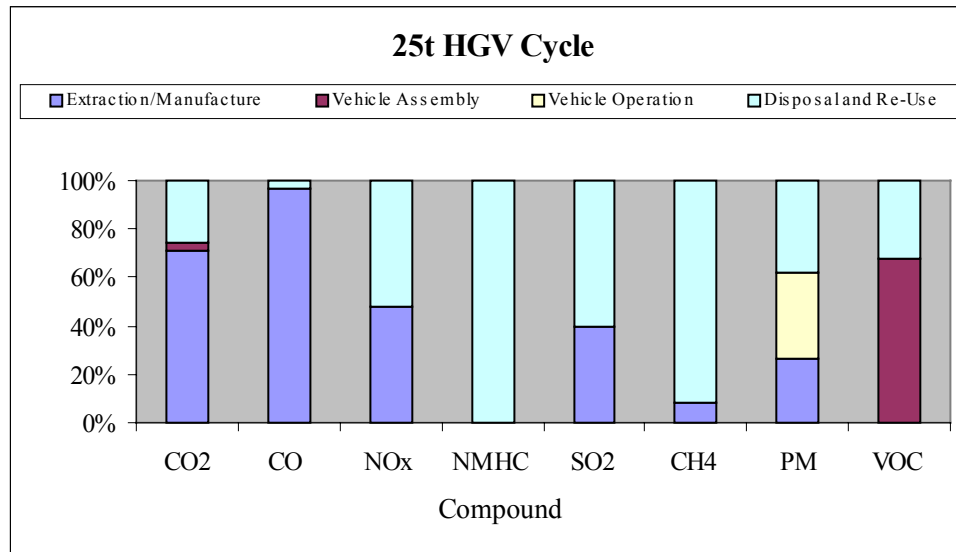


The emissions associated with the V2 stage of the 1.8t UVW van cycle are assumed from an analysis of HGV vehicle assembly emissions. It is noted that the production of aluminium is less energy and emissions intensive than steel production. As a result replacing steel with aluminium results in a decrease in the majority of the compounds under investigation. This decrease in emissions, in particular CO, was also noted by Gaines *et al* (1998). In the future vans and other vehicles are likely to become more

aluminium intensive. A LCA of the potential energy saving from Aluminium-Intensive Vehicles (AIV) was completed by Stodolsky *et al* (1995). High performance composite plastics may also play a part in the alteration of existing vehicles.

The second vehicle cycle under consideration is the 16t UVW HGV vehicle (Figure 5.14). Again the most significant stages are V1 and V4. These two stages contribute the highest levels of emissions and in the case of CO and SO₂, the emissions are shared more or less equally. As with the 1.8t UVW van cycle, the same set of data is excluded here, however any additions would not significantly increase total output in V2, this is due to the nature of the vehicle assembly plant operations. There is little involvement in direct combustion processes but of course production line welding together with emissions from plating, glueing and painting, metal cutting and stamping will occur.

Figure 5.16 – 25t HGV Cycle

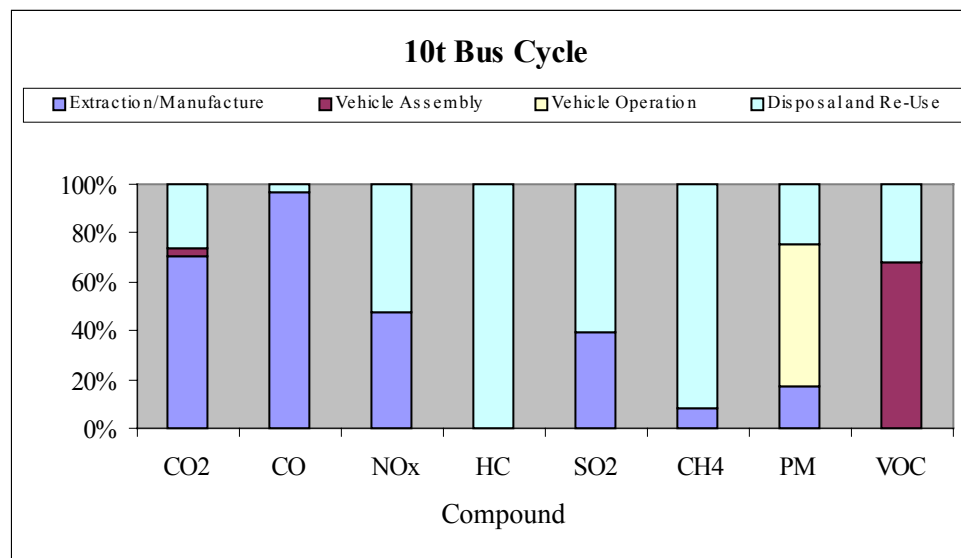


The actual amounts of compound released are of significance in this HGV cycle. Levels of CO₂, CO, NO_x, SO₂ and CH₄ per vehicle are approximately 10 times greater, in absolute terms, than that of the 1.8t van cycle, see Appendix K.

Overall the percentage contributions within the 16t HGV cycles are similar to the 1.8t van cycles, principally due to the similarities in the V1 and V4 stages.

A 10t bus once again displays very similar contribution characteristics as the previous two vehicle cycles. Figure 5.17, illustrates these similarities with the only significant change occurring with the seemingly increased levels of PM emissions during the operation of the vehicle. In fact the V3 PM emissions (tyre and brake wear) are the same as the 16t HGV, however less materials are required to construct a bus and as a result the V1 emissions are decreased, thereby increasing the percentage contribution of V3. The V3 PM emissions are calculated with the use of the EPA (1995a) program for calculating particulate emissions and the MOBILE6 particulate emissions factor model, EPA (2002). Both studies are used to calculate PM emissions based upon the number of wheels the vehicle has, the vehicle type and the total distance travelled, see Appendix L. The total F6/V3 emissions are a combination of the PM emissions as a result of fuel combustion; together with the brake and tyre wear micro-particles that are released during the vehicle use.

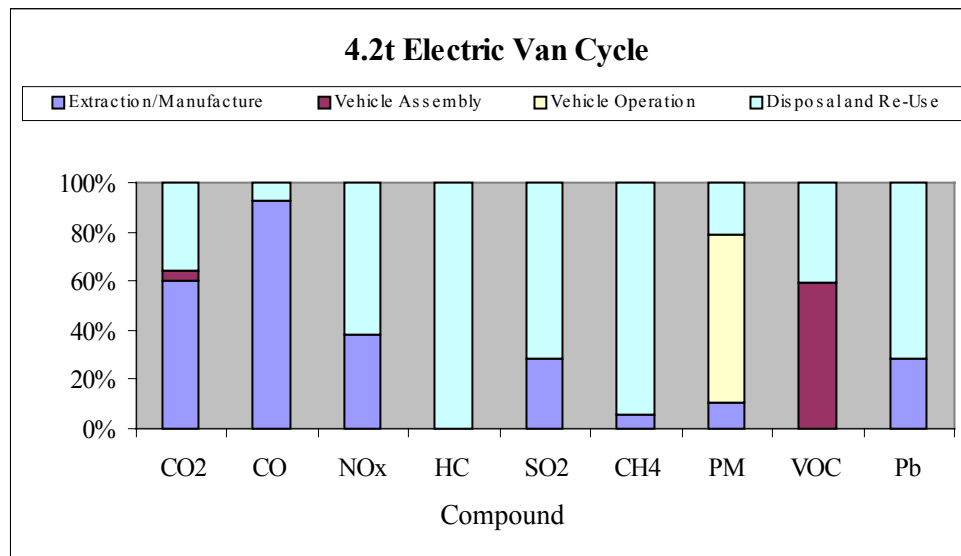
Figure 5.17 – 10t Bus Cycle



On a relative scale, the 10t bus contributes approximately half of the total vehicle cycle emissions in comparison to the 16t HGV vehicle cycle emissions.

The final vehicle cycle under investigation is the 2.5t UVW electric van (Figure 5.18), which displays similar results to the previous cycles. In comparison to the 1.8t van, the weight of the electric van is increased, due to the additional weight of batteries. Data provided courtesy of Baker (2002). The inclusion of these batteries and removal of the ICE block leads to a slight increase in CO₂, NO_x and VOCs with the obvious addition of Lead (Pb). All additional emissions, whether increased or decreased, within this 2.5t electric van cycle arise due to the manufacture and disposal of lead-acid batteries. These must be added to the emissions associated with the production, operation and disposal of the vehicle itself (gearing, chassis, body, and auxiliaries).

Figure 5.18 – 4.2t Electric Van Cycle



Results indicate that the lowest levels of CO, HC, SO₂, CH₄ and PM arise from the use of the electric van, when compared to the other vehicle cycles, see Appendix K. However levels of CO₂ and NO_x are slightly higher than the diesel engine equivalent, due to the increase in energy use to re-use of or dispose the batteries and the associated extraction/manufacture of materials respectively.

The total emissions from each of the vehicle cycles account for a small percentage of the overall life cycle emissions. This becomes evident when comparing the total amount of fuel used over the operational lifetime of the vehicle. Therefore, the small data losses in the vehicle cycle (noted earlier) become insignificant when a full life cycle is made. Vehicle cycle emissions do contrast the relative merits within each stage and provide the user with an appreciation of the relative impacts.

The following section on life cycle results combines the fuel and vehicle cycles in order to represent an evaluation of the emissions associated with the generation, use and disposal of the fuel and vehicle under examination. Only when the two cycles are combined can a full inventory of emissions be obtained.

5.4 Life Cycle Results

Life cycles exist for each of the vehicles under examination, with numerous fuel cycles investigated. These life cycles are inclusive of the vast majority of emissions associated with the operational use of a PSV.

By far the largest contributor to the fuel and life cycles is that of F6 end-use, which is the amount of fuel combusted (per tonne) and (per vehicle) over the vehicles operational life respectively.

In order to demonstrate the relative volumes of emissions, a petrol fuelled Euro 4 van in the year 2000, expels approximately 3.215 tonnes of CO₂ over the manufacture, assembly, use (not including fuel use) and disposal (V1-V4) of the vehicle, over an operational life of 15 years, see Appendix M. In comparison approximately 3.694 tonnes of CO₂ are released into the atmosphere per tonne of petrol generated, transport, refined, distributed and used (F1-F6), of which approximately 91% is derived from the F6 stage, see Appendix M. By multiplying the total amount of fuel (tonnes) used over the 15-year cycle an estimation of the full life cycle emissions is made. This method has been used to derive the results in Figure 5.19-5.21.

Results in Figure 5.19 represent the total emissions of each of the compounds under investigation, over the operational life of a Euro 4 van. All values are in grammes with the exception of CO₂ (kg). The barchart combines the fuel and vehicle cycle emissions with the resultant totals, plotted against the various fuel types. These totals can be further split to represent the contributions to the fuel and vehicle cycles, these splits can be viewed in Appendix M.

Generally the CO₂ component of the vehicle cycles contribute approximately 5% to the total CO₂ life cycle emissions, with other compounds demonstrating similar or even much lower percentages. The work of Gover *et al* (1996) suggests that CO₂ component of the life cycles for LGVs (per km travelled), consists of a 5% contribution from fuel production and a 95% contribution from the vehicles operation. CO fuel production

contributes approximately 1-2% towards the total life cycles for petrol, diesel, LPG and CNG. Conversely HC and NO_x levels for fuel production are much higher than calculated in this thesis (the analysis of HC in Gover includes additional CH₄ emissions from gas flaring, accounting for the higher fuel production HC levels). However, as noted in Gover, diesel has higher emissions of NO_x, with differences becoming smaller as tighter emissions standards are introduced in future years. Since these results are from 1996, the Euro 4 vehicles examined in the present study, with much tighter emissions standards, are in agreement with Gover’s predictions.

Stodolsky *et al* (1999) compared the fuel and vehicle cycles of hybrid electric vehicles and also found that the vehicle cycle impacts (including recycling) were small relative to the fuel cycle for a passenger vehicle, which is defined as a car or light truck.

Figure 5.19 – Life Cycle Euro 4 Van

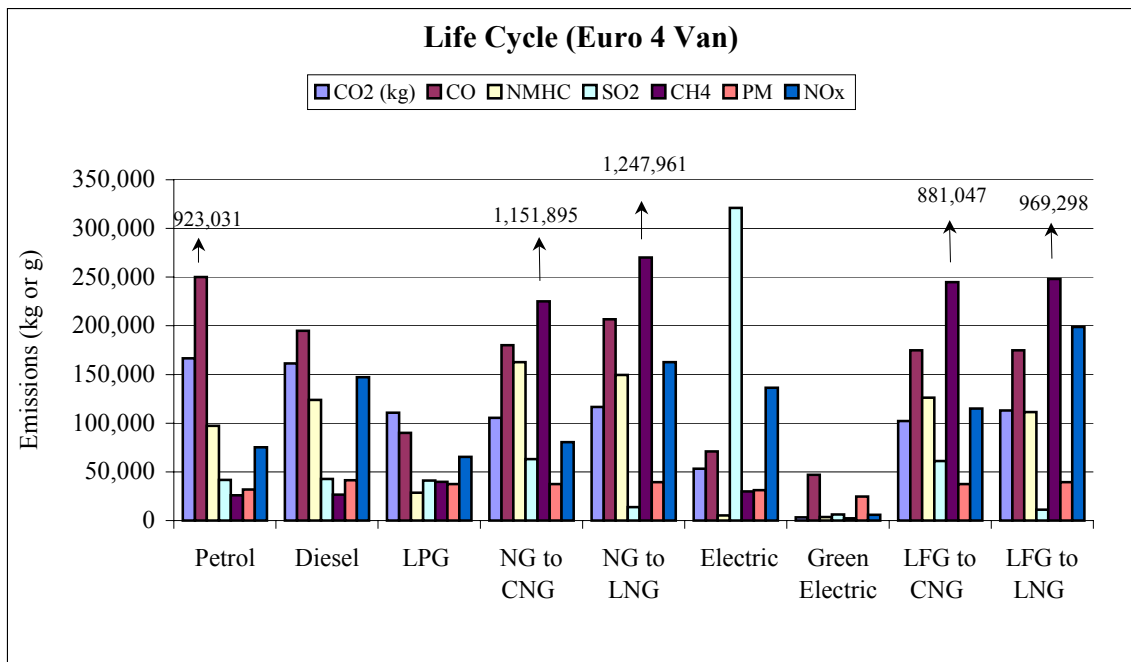


Figure 5.19 shows that the contributions from the electric and green electric cycles are small in comparison to all other vehicle cycles. This may seem strange given that the electric vehicles must generate emissions through the production of electricity. However, if the reader refers to Appendix J, a full explanation of the calculations is

given. The total CO₂ emissions of the electric van equal 53,136 kg. Approximately three and a half electric vans release the same amount of CO₂ as one petrol van. The life cycle emissions of, for example, the petrol van are much larger than those from the electric or green electric equivalent.

The reader may note a peak in SO₂ emissions from the electric vehicle cycle, this was noted in many other studies, see page 5.33. These are derived from the production of electricity from coal and Combined Cycle Gas Turbines (CCGT) in the F4 stage, which emit SO₂ at a much higher rate than the SO₂ released in the conversion of crude oil to liquid road fuels and natural gas compression or liquefaction.

The results in Figure 5.19 reveal that the highest contribution from all compounds is that of CO₂ (166,678kg), from a petrol fuelled Euro 4 3.5t GVW van, with the smallest contribution of 2.3kg from the CH₄ from the green electric van. In comparison, 800000 automobiles daily produced in Beijing an estimated 24000t of CO₂, Yang and Kraft-Oliver (1997), an average of 30kg per vehicle per day and 135t per lifetime (assumed use of 300 days per year for 15 years). A UK 3.5t petrol van operational for 300 days per year for 15 years emits 166t of CO₂. A study by the CVTF (2000) and Lane (2001) showed that the lifetime use of a petrol Ford Transit LGV (<3.5t), in operation for 22 years, released 80-130t of CO₂ and between 70-105t when fuelled by diesel. Variations in the modelling techniques and assumptions made have resulted in the differences in values presented here. The CVTF, now disbanded, and Lane studies take into consideration a reduced operational mileage per year, in comparison to the present study, and in the last 10 years of operation the annual mileage is heavily reduced, the studies do not incorporate a complete fuel and vehicle cycle and only consider the direct emissions from the exhaust pipes, nor do they comment upon specific operational characteristics such as average vehicle speed and mpg. These factors account for the differences in results. Nonetheless, the studies do quote a value of 234g of CO₂ released per km travelled by a petrol Ford Transit van, in comparison to the present study which uses the TRL Road Emissions Database and calculates a value of 201g of CO₂ per km travelled at 30mph. The assumed average speeds of the present study and the CVTF are therefore

similar. In light of these findings, the operational estimates made by the author, see Appendix G, seem reasonable.

Results show that the use of a petrol powered Euro 4 van emits 167t of CO₂ into the atmosphere over the 15 years of operation. This value includes fuel use and vehicle manufacture/disposal, combining (F1-F6) with (V1-V4). Once again the majority of this value is derived from the combustion of fuel in the F6 stage of the fuel cycle. All other fuel options for the van can now be compared on a life cycle basis. Absolute values can be seen in Appendix M.

It is only at this point in the LCA that it becomes possible to incorporate the use of electric vehicles. An explanation of this is given in Section 4.2.6. An EA Technology Wavedriver van is modelled through its theoretical operational life of 15 years. Since the two electric cycles consist of electricity generated through gas, coal and nuclear sources (electric cycle) and electricity generated through renewable sources (green electric cycle), the resultant emissions in electricity generation and renewable generation (assumed to be zero) are included in the fuel cycles.

At point of use, the F6 emissions are assumed to be zero, however the emissions due to the manufacture, use and disposal of the electric vans are included within the vehicle cycle. As can be seen in Figure 5.19, these cycles result in the lowest contributions towards the compounds under investigation, aside from the peak in SO₂ emissions as a result of electricity generation, [also noted by Wang and Santini (1993) and Singh *et al* (1998a, 1998b)], even with the additional payload of the batteries [noted by Gaines and Singh (1995) and Singh *et al* (1998a, 1998b)]. In addition, Delucchi and Lipman (2001), Gaines and Singh (1995), Lester and MacLean (2002), Singh *et al* (1998a, 1998b) and Wang and Santini (1993) concluded that, in general, the emissions associated with the use of electric vehicles are much lower than those from conventional vehicles. They also concluded that further reductions are evident from electric vehicles using electricity generated from renewable sources (green electric equivalent). Singh *et al* (1998a, 1998b) also noted that the production of electric vehicle batteries, to replace the

conventional diesel or petrol engines in light goods vehicles, generally leads to more pollutant emissions than the manufacture of the conventional vehicle itself. In conventional vehicle operation it was also noted that the most important contributors are CO₂, CO and NO_x, whereas vehicle manufacture is the most important contributor to SO₂ and Pb, with fuel production generating the largest contribution to CH₄. In concurrence with these findings the present study calculates that 27.5kg of CH₄ are released in the fuel cycle and 2281g in the vehicle cycle per 4.2t GVW electric van used for 15 years in the UK.

The second life cycle under review is that of a 25t GVW HGV. In the present UK transport industry, the use of alternative fuels (AF) for HGVs is limited. A logistics company optimises its carrying capacity for every HGV they operate. The larger the load they can move the more profit it can make. The additional payload of fuel tanks and expensive conversions limits the development of AF, moreover the lack of infrastructure and fuelling points is a major inhibitor. As a result there are only two fuels considered for commercial use today, diesel and CNG, with little information available on the alternatives. Although LNG and hybrid vehicles are now being considered. Ideally a comparison with all fuel types would prove beneficial.

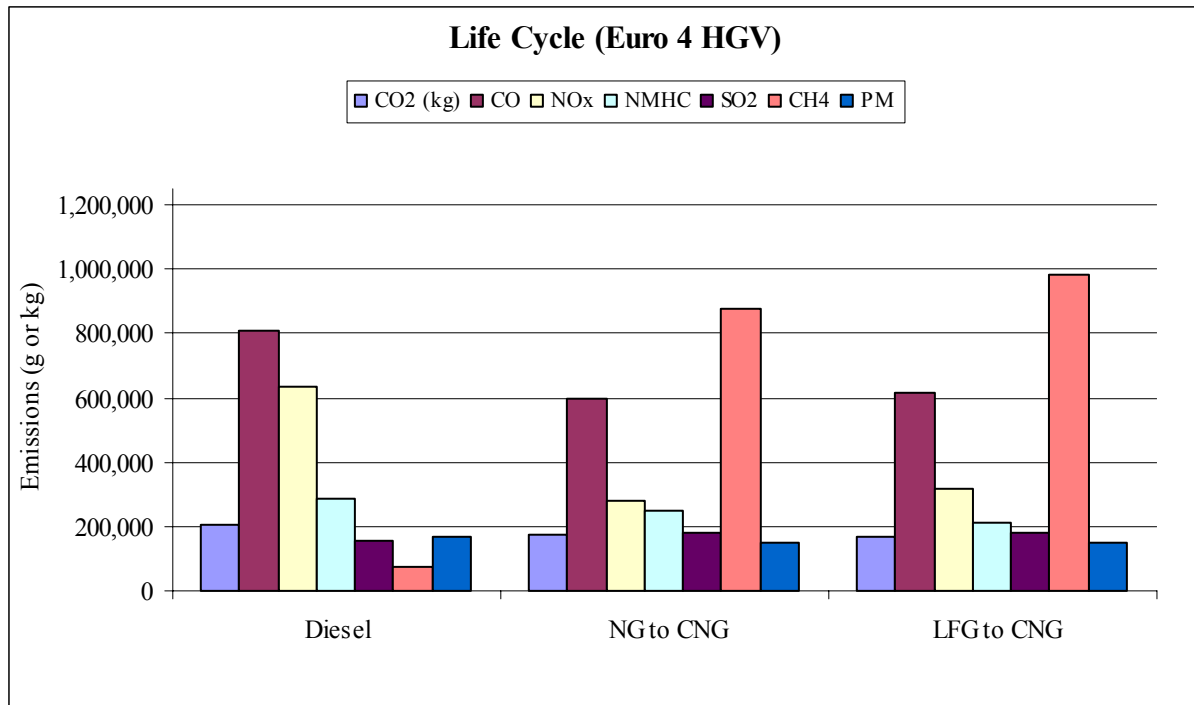
As can be seen in Figure 5.20, the largest and smallest contributions are made from the diesel life cycles, CO₂ (203254kg or ~203t) and CH₄ (76415g) from the diesel life cycle. The studies of the CVTF (2000) and Lane (2001) show that a diesel HGV of smaller GVW (17t) releases between 800-1500t of CO₂ over a 22-year lifespan. An operational life of 10 years is assumed in the present study. Without any knowledge of the vehicle types, assumed speeds, mpg, distances travelled per day etc. within the studies it becomes difficult to compare like-with-like. The author of the present study has decided to analysis HGVs operating under the conditions specified in Appendix G. Should another user decide upon a longer operational life or different average speed, a simple update of each fuel and vehicle cycle would be necessary, with a resultant increase or decrease in total life cycle emissions.

Example – average speed and emissions correlation

Should one estimate that a HGV has an average speed of 16kph (~10mph), as apposed to the assumed speed of 48kph (30mph) in the present study, the resultant CO₂ emissions per km travelled would increase from 479g/km to 850g/km. Furthermore the total emissions over the 10-year operational life of the HGV would increase from 170t of CO₂ released per year to 326t per year. As one can now see, if the lifetime use and/or speed changes the resultant emissions change by a significant proportion. If the operational lifetime is extended to 22 years, as in the CVTF and Lane studies, the resultant emissions, at an average speed of 48kph, of CO₂ increase from 203t to 359t, if one now changes the vehicle speed to 16kph from the assumed average of 48kph, the lifetime CO₂ released for a HGV in operation for 22 years increases to 664t. As one can see, changes in the average speed and lifetime use alter the total emissions profile. The assumptions made in the present study are justified, as they are constant for each vehicle under examination, and as a result it is possible to compare like-with-like.

In comparison to the HGV (203t of CO₂ released over its lifetime), a Euro 4 petrol van (15-year life span) releases 163t of CO₂, it becomes clear to see that the use of a HGV over a 10-year life span contributes (on average) towards similar releases of CO₂, even with a shorter operational life.

Figure 5.20 – Life Cycle Euro 4 HGV

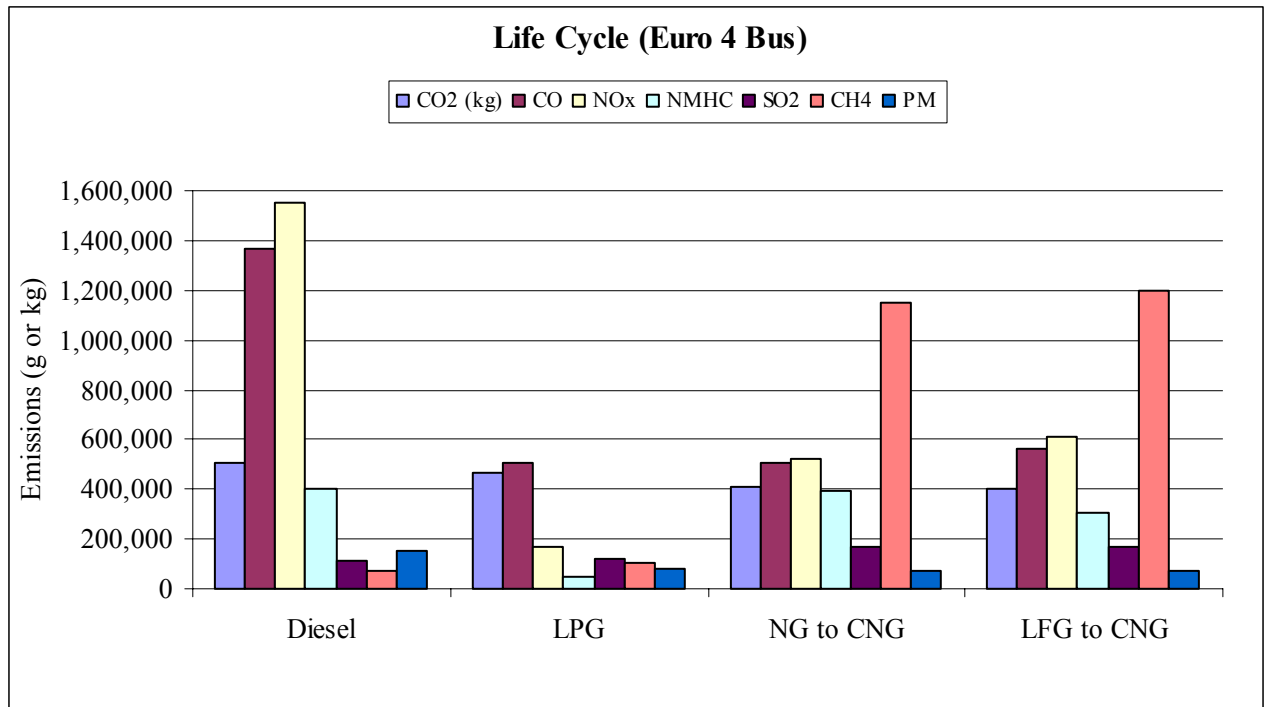


Levels of CO₂, CO and CH₄ dominate the life cycle emissions of the Euro 4 HGV, see Figure 5.20, due to the oxidation of the HC fuel during combustion in the F6 stage.

As with the van cycle the percentage splits between the fuel and vehicle cycles differ depending upon the compound in question. Appendix M provides details of the absolute values for each of the fuels listed in Figure 5.20. The HGV life cycle in general has higher percentage contribution from the vehicle cycles than the average 5% contribution noted in the life cycle analysis of a Euro 4 van.

The final life cycle under investigation is a Euro 4 Bus (Figure 5.21) powered by diesel, LPG, NG to CNG and LFG to CNG. The largest outputs of CO₂ (510202kg), NO_x (1566kg) and NMHC (416kg) from all cycles are derived from the use of a Euro 4 bus over a 10-year operational cycle. Due to varying operational characteristics and vehicle type, an average diesel fuelled 25t GVW HGV emits approximately 305t less CO₂, 919kg less NO_x and 120kg less NMHC over its operational life than a 10t Bus, given the assumed operational characteristics.

Figure 5.21 – Life Cycle Euro 4 Bus



As with previous cycles, the life cycle of a 10t bus consists of the accumulation of emissions from the fuel and vehicle cycle, see Appendix M. This accumulation is similar to the HGV life cycle, however the contributions from the vehicle cycles within this bus life cycle are almost half that of the HGV. Once again a comparison is made with the CVTF, which estimate that an inner city London diesel bus operating in the year 2000 contributes towards the following life cycle emissions. Releasing approximately 250-370 tonnes of CO₂ over its lifetime. A Euro 4 bus in the present study, on an inner city route, with different operational characteristics, suggests that lifetime CO₂ emissions for diesel account for 508 tonnes. Without any details of the operational characteristics of the buses examined by the CVTF it becomes difficult to compare the results.

5.5 Summary

The majority of results presented in this chapter are similar to the results made from other LCA studies, although some differences do occur. The relevance of any differences becomes less important when the values are normalised and weighted in

Chapter 6, furthermore the results are subject to a sensitivity analysis in Chapter 7. This chapter highlighted the significance of each variable within the model and informs the user of the relative importance each stage in the fuel and vehicle cycle has to the total life cycle emissions. This chapter has also highlighted the importance and significance of the user discretion and the assumptions made. Another user of the model may have a contrast of opinion and/or may want to specifically focus upon a certain fuel and vehicle combination. The holistic approach to this LCA enables a user to perform such a task. The results are highly dependent upon the choice of vehicle and its everyday use; this LCA only provides the building blocks on which assessments and decisions can be made.

The percentage contribution based graphs show the relative impacts from each fuel, vehicle and life cycle. Of particular interest are Figures 5.19, 5.20 and 5.21 that compare the fuels used in each of the vehicles under examination, vans, HGVs and buses. The relative impacts of each fuel can clearly be seen. The normalisation and weighting of these results enables the user to observe the true environmental impact made by each fuel and vehicle combination, see chapters 6 and 7.