Camden

Life Cycle Assessment of Vehicle Fuels and Technologies

Clear Zones
For Liveable Cities

Final Report
London Borough of Camden
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Accompanying document:

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1 Acknowledgements

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2 Background

In September 2005, the London Borough of Camden commissioned Ecolane Limited to conduct a desk-based research project to assess the life cycle environmental impacts of road vehicle fuels and technologies. The evidence review was to be based on existing reference data and was to include: petrol, diesel, bioethanol, biodiesel, natural gas, liquefied petroleum gas, battery electric, and hybrid electric vehicles. The study was to focus on passenger cars and light-duty vans, including car-derived vans.

The environmental impacts of these options to be considered on a life cycle basis were to include impacts associated with: fuel production (primary production, extraction, transportation, refining, and storage of vehicle fuels); vehicle operation; vehicle manufacture (materials production and assembly) and shipping; and disposal and separation of components (including battery) or recycling. The environmental impacts to be considered by the evidence review were to include emissions of greenhouse gases and regulated vehicle pollutants with particular focus on carbon dioxide (CO_2), nitrogen oxides (NOx), particulates (PM_{10}) and sulphur dioxide (SO_2) emissions.

The outputs of the research were to be used to compare the life cycle environmental performance of cleaner vehicles with each other and against conventional vehicle fuels/technologies to inform future transport policy developments within the London Borough of Camden. The results were also intended to be shared with other local authorities in the course of Camden's coordinated support for cleaner fuelled road transport.

3 Executive summary

A large number of cleaner vehicle fuels and technologies are now commercially available. However, the complexity of comparing the emissions profiles of each of the options makes it difficult for the consumer, fleet manager or policy maker to decide the most appropriate vehicle fuel or technology for a particular application. Even at the policy maker level there may be a degree of uncertainty regarding the relative benefits of each cleaner option and the relative impacts of fuel and vehicle cycles. For these reasons, this report aims to assess the life cycle environmental impacts of road vehicle fuels and technologies to enable the comparison of cleaner options with each other and against conventional vehicle fuels/technologies – and to inform future transport policy developments within the London Borough of Camden.

The evidence presented is based on existing reference data and includes: petrol, diesel, bioethanol, biodiesel, natural gas, liquefied petroleum gas, battery electric, and hybrid electric vehicles. The study focuses on passenger cars and light-duty vans. As previous comparative studies have done, the analysis includes an assessment of the environmental impacts associated with the *fuel cycle* (primary production, transportation, refining, and vehicle operation). Unlike other UK studies, the analysis also assesses the impacts associated with the *vehicle cycle* (materials production, vehicle manufacture and disposal).

Although the environmental impacts of the fuel and vehicle life cycles include a wide range of resource, pollutant and land-use issues, this LCA study focuses exclusively on quantifying the extent and impacts of life cycle air-borne emissions arising from the fuel and vehicle cycles. The reason for this focus is due in part to the importance of air emissions in the context of road transport, and also due to the time and resource limitations of the study. The air emissions assessed include the three main greenhouse gases: carbon dioxide, nitrous oxide and methane. In addition, the regulated emissions associated with road transport are assessed (carbon monoxide, oxides of nitrogen, hydrocarbons and particulates). Sulphur dioxide and nitrous oxide data are sourced where available.

In addition to making emissions comparisons for each of the vehicle types considered, the LCA study also goes beyond an *inventory* phase and includes an *impact assessment* as part of the life cycle emission methodology. This is achieved by the use of the Environmental Rating Tool developed by the European Cleaner Drive Programme. This rating system uses recognised ‘external costs’ to establish the relative weight to attach to different emissions – the external costs are values expressed in monetary terms that reflect the overall damage to the environment and to human health caused by emissions. Using the Cleaner Drive system, the level of environmental impact is expressed as a score between 0-100 (for greenhouse gases, regulated pollutants and total impact); the lower the score, the less the environmental impact.[1]

One of the key findings of the LCA study is that vehicle size is as important a determinator of emission impact as fuel/technology type – the results show that vehicle size is strongly correlated to overall environmental impact as quantified by the Cleaner Drive rating system. Moving down one FISITA passenger car category typically reduces the Total Cleaner Drive rating by 6-8 points – for a medium sized passenger car, this equates to a reduction in the total life cycle environmental impact of around 12%-16%. The importance of vehicle size is due to the effect of fuel economy on vehicle emissions, and also to the fact that higher fuel use requires an increase in fuel production energy which in turn leads to increased emissions. In addition, the vehicle cycle also contributes to this correlation – larger vehicles (that tend to have higher fuel use) require more materials and assembly energy during manufacture.

Focusing on the impact of cleaner fuels/technologies, the LCA analysis shows that all the alternative options analysed offer some degree of reduction in life cycle environmental impact. Using conventional petrol as a baseline, for most vehicle classes, mineral diesel is equivalent within confidence limits. Compressed natural and liquefied petroleum gas cases are rated (for life cycle environmental impact) at approximately 18%-19% below the baseline, and biodiesel is rated 11%-24% lower than petrol (depending on vehicle class). Bioethanol, battery electric using average mix electricity and petrol-hybrids are the next cleanest cases at around 23%-26% lower. As expected, the renewable battery electric case is the cleanest according to the Cleaner Drive rating system and scores over 70% less than the petrol baseline.

[1] Note that for this report, a reverse rating is used based on the Cleaner Drive score – this is simply the original Cleaner Drive score subtracted from 100 (ie New Cleaner Drive score = 100 – Original Cleaner Drive score).

The findings of the LCA analysis of specific vehicle models show that, in those vehicle classes where available, the use of battery-electrics consistently result in the least overall environmental impact. Although in some cases this is true for battery electrics using average electricity mix, it is always the case if renewable energy is used for recharging. In the best case, as compared to a petrol baseline, the overall environmental impact is reduced by over 70%. Although currently, there are very few battery electric models available, two models of note are the Reva GWIZ in the Citycar category and the Citroen Berlingo Electrique (Small Family car and Car-derived van categories).

The findings also demonstrate the benefits of hybridisation. In particular, in those vehicle classes where they are commercially available, petrol hybrids (such as the Toyota Prius and the Lexus RX400h) provide significant reductions in overall environmental impact. Given that the Cleaner Drive rating system is weighted in favour of greenhouse gas emissions, and given the improvement in fuel economy of around a quarter offered by hybrids, the overall impact is reduced by around 26%. The Cleaner Drive analysis also shows that, in the event of diesel hybrids becoming available, they would also provide a significant reduction in overall environmental impact – with a possibly greater life cycle emission benefit than is the case for currently available petrol hybrid cars.

The two pure biofuels analysed by the LCA also offer consistently reduced overall environmental impacts. Across all vehicle classes, switching from mineral diesel (ULSD) to biodiesel reduces overall impacts by around 13% and changing from petrol (ULSP) to bioethanol reduces environmental impacts by 23%. However, it should be remembered that these benefits are estimated for 100% biofuels (ie E100 and B100). In practice, biofuel blends (eg E5, B5) are more likely to be available in the short-term. In addition, the use of pure biofuels may require some engine modification and invalidate a vehicle's warranty. Furthermore, there remains some uncertainty regarding the emissions data associated with biofuel production. For these reasons, the quantified biofuel benefits should be treated with caution.

The results of the specific LCA analysis show that, liquefied petroleum gas (LPG) and natural gas (CNG) vehicles still offer greenhouse gas and air quality benefits. As compared to a petrol baseline, the data analysed show (for passenger cars) an 18%-19% reduction in the overall environmental impact for the two road fuel gases.

Regarding the source of the emissions, the results of the LCA analysis shows that, in most cases, the vehicle and fuel production stages account for around 20% of total lifetime greenhouse gas emissions – the emissions associated with fuel and vehicle production are roughly equal in magnitude. This is the case for conventional petrol and mineral diesel, the two road fuel gases and also for petrol-hybrids. However, this proportion does not hold true for biofuels, the emissions associated with fuel production being significantly increased. For battery electrics, vehicle manufacture and fuel production emissions account for all life cycle emissions, the vehicles being zero-emission in operation.

Considering the regulated emissions, apart from battery electrics, the vast majority of life cycle hydrocarbon emissions originate during fuel production. In contrast, (excluding battery electrics and bioethanol) a significant proportion of life cycle carbon monoxide emissions are generated during vehicle use. The picture for particulates and NOx is more complex. For non-diesel fuels, the majority of these two emissions are produced during fuel and vehicle production – for the two battery electric cases, fuel and vehicle manufacture emissions account for all life cycle impacts. For diesel fuels, a significant proportion of these two emissions are produced during vehicle operation.

The location of regulated emissions sources has implications for the environmental impact of the emitted pollutants – and one that is accounted for by the Cleaner Drive rating system. From the perspective of the life cycle analysis, with the exception of carbon monoxide, and particulates and NOx from vehicles using diesel fuels, the majority of regulated pollutants are emitted away from most major urban areas (unless a refinery, fuel processing or vehicle manufacturing plant lies within a populated region).

4 Introduction

Road transport is responsible for the consumption of significant quantities of energy and raw materials and the production of air emissions, water emissions and solid wastes. Emissions to the air include greenhouse gases that are responsible for climate change, chlorofluorocarbons that lead to stratospheric ozone depletion, and local and regional air-pollutants that can lead to acidification and photochemical 'smog'. The extraction of raw materials for vehicle manufacture and roads, the construction of roads and the disposal of end-of-life vehicles not only lead to further emissions, but also have significant impacts on land use and terrestrial ecotoxicity (Schexnayder *et al.* 2001).

The principal greenhouse gas emissions associated with the *fuel cycle* – fuel production and vehicle operation – are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Road transport is the third largest source of UK greenhouse gases accounting for around 25% of total emissions and is the fastest growing source of greenhouse gases (DEFRA 2005). Of the total greenhouse gas emissions from transport, over 85% are due to CO_2 emissions from road vehicles. In the UK, conventional road transport also remains the predominant source of many local emissions including benzene, 1,3-butadiene, nitrogen oxides (NOx) and particulates (PMs). Within urban areas, the percentage contributions due to road transport are particularly high. For example, although road transport is responsible for around a quarter of particulates on a national level, in London road transport contributes almost 60% of known primary emissions (DEFRA 2005).

Significant environmental impacts are also produced during the *vehicle cycle* – the production, recycling and disposal of materials used for vehicle manufacture. Although the materials and their impacts vary greatly according to the type of vehicle, for conventional vehicles around 75% of the energy use impacts associated with the vehicle cycle arise due to the production of the raw materials required (Funazaki *et al.* 2003). These include iron and steel, non-ferrous metals (particularly aluminium), plastics, composites, glass, rubber and fluids. The disposal of these and other substances also contribute to the production of solid wastes that are either recycled, incinerated or land-filled, each option leading to a complex set of environmental issues and concerns – and now subject to EU waste legislation under the Directive 2000/53/EC on end-of-life vehicles (TRL 2003).

There is a growing body of evidence to link vehicle generated pollutants directly to human ill health including the incidence of respiratory and cardio-pulmonary disease and lung cancer. In 1998 the Committee on the Medical Effects of Air Pollutants estimated that 12,000-24,000 people die prematurely each year in the UK as a direct result of air pollution. Between 14,000 and 24,000 hospital admissions may also be the result of poor air quality (Holgate 1998). Similar findings are emerging from international research. According to the World Health Organisation, up to 13,000 deaths per year among children (aged 0-4 years) across greater Europe are directly attributable to outdoor pollution – most notably due to high levels of particulates (WHO 2004). The organisation estimates that if pollution levels were returned to within EU limits, more than 5,000 or these lives could be saved each year.

In order to reduce vehicle emissions (from vehicle operation), regulations have been introduced that set mandatory limits for what are known as the *regulated* pollutants. These include carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC) and particulate matter less than 10 microns in size (PM_{10}) (DTI 2000). First introduced in 1992, these form a set of rolling regulations designed to become more stringent year on year (see Table 4.1). As of January 2006, all cars and light-duty vans have to conform to Euro IV. In contrast to the legislation for regulated pollutants, there is no current EU law which limits the amount of carbon dioxide produced by vehicles. However, the European Commission reached a voluntary agreement with the motor manufacturers to reduce the average CO_2 emissions from its current average of around 160g/km to 140g/km by 2008 for all new cars sold in the EU with a possible second target of 120g/km by 2012 (ACEA 2003). Although this appears to be on-track as of 2005, there is already some evidence that manufacturers will find it difficult to achieve the targets set (LowCVP 2005a).

The effect of tighter Euro standards on vehicle emissions has been to accelerate the introduction of cleaner vehicle technologies. For petrol cars, this has been achieved in part through the use of the three-way catalytic converter and the move to fuel injection systems. For diesels, NOx and particulate emissions have been reduced through the development of direct injection engines and diesel particulate traps (DPFs).

These technological advances, together with the cleaner fuels that make these developments possible (such as sulphur-free petrol and diesel), have led to a dramatic reduction in regulated pollutants; so much so, that a car manufactured today produces two orders of magnitude fewer regulated emissions than one made in the early 1990s (DfT 2005b). Car manufacturers are well aware that future cars will have to conform to yet tighter regulations such as those that are expected to come into force in 2008.

Table 4.1 European emissions limits for cars (<2500kg) and Class I goods vehicles (<1305kg)

Maximum vehicle emissions limits	Petrol (gms/km)				Diesel (gms/km)			
	CO	HC	NOx	PM_{10}	CO	NOx	HC+NOx	PM_{10}
Euro III (2001)	2.30	0.20	0.15	N/A	0.64	0.50	0.56	0.050
Euro IV (2006)*	1.00	0.10	0.08	N/A	0.50	0.25	0.30	0.025
*Euro IV limits also come into force for Class II (1305<1760kg) & Class III (>1760kg) goods vehicles from 01/01/07								
Sources: DTI 2000; DfT 2005a								

Despite the achievement of manufacturers to significantly reduce conventional car emissions through technological improvements, some air quality issues still remain. Of the four regulated car emissions, NOx and PMs are the most difficult to control and are closely associated with poor air quality. Although significant reductions in NOx and PM_{10} from UK road transport have occurred, legislated Air Quality Strategy standards for NOx and particulates are failing to be achieved in many urban areas – including parts of the London Borough of Camden (Camden 2005). Furthermore, within a decade, these emissions are forecast to increase by a small margin as engine and fuel improvements are offset by continuing traffic growth.

To further reduce the regulated emissions and achieve the 2012 CO_2 target will require the increased uptake of cleaner vehicles and/or the restriction of the use of conventional vehicles. This is likely to involve the further development of conventional engine design (such as the introduction of Gasoline Direct Injection). However, if conventional technologies are unable to deliver the emissions reductions required, then fuels and technologies other than petrol, diesel and the internal combustion engine will have to be used to a much greater degree than they are at present.

Cleaner vehicle fuels and technologies

Fortunately, there have already been some successes in introducing cleaner fuels and vehicles into the UK market. To date, over 100,000 cars have already been converted or manufactured to run on liquefied petroleum gas (EST 2004). Electric vehicles have found niche applications, either as small city cars, as service utility vehicles (eg forklift trucks) or as milk-floats (which comprises the largest battery electric vehicle fleet in Europe). More recently, several models of petrol hybrid-electrics cars have become available in the UK with annual sales already exceeding those for battery-electric vehicles. Biofuels are also in the ascendancy. Supported by new EU legislation, biodiesel and bioethanol sales are increasing significantly and are likely to comprise around 6% of fuel sales (as blends) by 2010 (DfT 2004a).

The sales of cleaner vehicle fuels and technologies are being driven by a growing awareness concerning the environmental costs of motoring, ever tightening regulated emission standards and by an increasing number of cleaner car models on the market. The government is supporting this transition and, although cleaner vehicles currently represent less than 0.1% of all sales,[2] has set the target that cleaner cars (defined as ‘low carbon’; ≤ 100g/km CO_2) should represent 10% of all car sales by 2012 (DfT 2002).[3]

Broadly speaking, the development of alternative options encompasses one of two approaches – these provide a useful way to categorise the options available. The first involves the development of cleaner fuels that can be used with conventional engines. The second approach has been to develop partial or complete alternatives to the internal combustion engine. Therefore, we can classify cleaner car options in one of two ways: according to the fuel and according to the technology. The main options are therefore as follows:

[2] According to the SMMT, fewer than 500 cars sold in 2004 were classified as ‘low carbon’ (<100 gmsCO2/km) equating to the new ‘A’ VED band (SMMT 2005).
[3] This equates to the order of 200,000 vehicle sales per year.

Cleaner vehicle fuels:

- Biofuels – Fuels produced from plant or animal oils including: biodiesel and bioethanol;
- Gaseous Fuels – Fuels usually produced from fossil-fuel sources including: natural gas and liquefied petroleum gas (LPG);
- Electricity – Electricity can be generated using primary fossil fuels, fission or fusion of nuclear fuels, or from renewable sources;
- Hydrogen – Like electricity, hydrogen is a secondary form of energy, which can be derived from renewable and non-renewable sources.

Cleaner vehicle technologies:

- Battery-Electric – Electricity can be used to charge a battery of electrochemical cells on-board a battery-electric vehicle. When required, electrical energy is drawn from the cells and converted to motive power by the use of an electric motor;
- Hybrid-Electric – A conventional engine is used to generate electricity on-board the vehicle. Motive power is provided to the wheels via a mechanical drive-train and/or using electric motors via an electric drive;
- Fuel Cell-Electric – If hydrogen and oxygen (from the air) are fed into a fuel cell, a voltage difference is produced which can be used to drive an electric current, which in turn can operate an electric motor. This can be used to power a fuel cell car.

Each of the cleaner vehicle fuel/technologies listed above provide a different set of vehicle emission benefits. In general the road fuel gases significantly reduce regulated pollutants with a marginal improvement in greenhouse gas emissions. Use of biofuels can greatly reduce greenhouse gas emissions on a life cycle basis, but may lead to increased regulated emissions. Those options that employ an electric-drive train are in some cases able to significantly reduce both greenhouse gas and regulated emissions. In some cases, there are also emissions penalties – for example, the use of non-renewable electricity for recharging is associated with an increase in sulphur dioxide.

The large number of commercially proven cleaner fuel and technology options highlights the opportunities for reducing emissions associated with road transport. However, the complexity of comparing the emissions profiles of each option with existing fuels and vehicles, and with each other, often makes it difficult for the consumer, fleet manager or policy maker to decide the most appropriate vehicle fuel or technology for a particular application – a choice made more complex when economic factors are taken into account. In addition, in some market segments, there is evidence that misconceptions concerning alternative fuels and technologies are prevalent and include: *"LPG is dangerous", "hybrid electric cars have limited range need a special recharge point",* and *"no positive tax incentives for biodiesel as yet"* (LowCVP 2005b). Even at the policy maker level there may be a degree of uncertainty regarding the relative benefits of each cleaner option and the relative impacts of fuel and vehicle cycles.

For these reasons, this report aims to assess the life cycle environmental impacts of road vehicle fuels and technologies and present the information in a clear and concise format appropriate for input to the decision making process – in particular, to enable the comparison of cleaner vehicles with each other and against conventional vehicle fuels/technologies to inform future transport policy developments within the London Borough of Camden. The results are also intended for use by other local authorities in the course of Camden's coordinated support for cleaner fuelled road transport.

The evidence presented is based on existing reference data and includes: petrol, diesel, bioethanol, biodiesel, natural gas, liquefied petroleum gas, battery electric, and hybrid electric vehicles. The study focuses on passenger cars and light-duty vans, including car-derived vans. As previous studies have done (ETSU 1996, DTI 2000), the analysis includes an assessment of the environmental impacts associated with the fuel life cycle (primary production, extraction, transportation, refining, and vehicle operation). Unlike other UK studies, the analysis also assesses the impacts associated with the vehicle cycle (materials production, vehicle manufacture/assembly and disposal).

5 Report scope and structure

In line with previous UK studies, this study focuses on those vehicle fuel and technology options that are either currently commercially available (within the UK) or are considered by most analysts to be commercially viable within the near-term. These include the conventional fuels: ultra low sulphur petrol and diesel;[4] biofuels: biodiesel, bioethanol; the road fuel gases: natural gas and liquefied petroleum gas; and those vehicle technologies that employ electric drive trains: battery-electric and hybrid-electric vehicles.

Vehicle fuels excluded from the analysis are methanol (due to its toxicity) and hydrogen, Gas-to-Liquids fuels and Dimethyl Ester (DME) (due to their non-commercial status in the UK). Vehicle technologies excluded include fuel cell electric vehicles (due to the fact that they remain at the pre-commercial stage) and compressed air engines (such as the AirCar) that have not been sufficiently independently tested. Also, technologies such as the new 'Plug in Hybrid' that are conversions of existing vehicles (in this case the Toyota Prius petrol-hybrid) that have yet to be independently tested regarding their emission benefits are excluded from the detailed analysis, but are referred to in the text where relevant.

Also in line with previous studies, vehicle fuels and technology options are compared for several vehicle types. However, unlike the other studies mentioned, the approach adopted by this LCA study is based on the FISITA vehicle categories to provide the basis for generic comparisons and the context for particular models. These categories are as follows: for passenger cars: City-car, Supermini, Small family car/small MPV, Large family car/large MPV, SUV 4x4. For light-duty vans, non-FISITA categories are used: car-derived van,[5] and panel van.

In addition to the generic vehicle categories, models of particular interest and low relative environmental impact are included in the analysis. Mainly Euro 4 vehicle are selected.[6] These include:

- City-car – Reva GWIZ (electric), Toyota Aygo/Peugeot 107/Citroen C1 (petrol/bioethanol/diesel), Smart ForTwo (petrol/bioethanol);
- Supermini – Corsa (petrol/bioethanol), Citroen C3 (diesel/biodiesel); Citroen C3 Stop & Start (petrol), Toyota Yaris (petrol), Hyundai Getz (diesel);
- Small family car - Honda Civic IMA (petrol hybrid), Vauxhall Astra (petrol/diesel/LPG/bioethanol/ biodiesel), Audi A3 (petrol GDI), Citroen Berlingo (electric);
- Large family car – Toyota Prius (petrol hybrid), Toyota Avensis (diesel/biodiesel), Vauxhall Vectra (petrol/LPG), Peugeot 407 FAP (diesel with particulate filter), Volvo S60 (petrol/CNG);
- SUV 4x4 – BMW X3 (petrol/diesel/bioethanol/biodiesel), Lexus RX400h (petrol hybrid), Lexus RX300 (diesel); Suzuki Grand Vitara (diesel);
- Car-derived van – Citroen C2 (diesel/biodiesel), Citroen Berlingo (diesel/electric); Vauxhall Astravan (diesel/petrol/LPG);
- Panel van – Ford Transit (diesel/LPG), Volkswagen LT35 (diesel/electric/diesel-hybrid/biodiesel).

Although the environmental impacts of fuel and vehicle life cycles include a wide range of resource, pollutant and land-use issues, this LCA study focuses exclusively on quantifying the extent and impacts of life cycle air-borne emissions arising from the fuel and vehicle cycles. The reason for this focus is due in part to the importance of air emissions in the context of road transport and also due to the time and resource limitations of the study. While effort is required to source high quality data, in general, vehicle and fuel generated emissions data is more readily available than other environmental impact parameters. However, this report recognises the importance of non-airborne pollutant loadings and refers the reader to the discussion in Section 7.1.

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[4] These are in the process of being replaced by 'sulphur-free' fuels in the UK and across the EU.

[5] Most car-derived vans are from the Supermini, Small Family and Small /MPV categories.

[6] European directives set mandatory limits for what are known as the *regulated emissions*. These include carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC) and particulate matter less than 10 microns in size (PM_{10}). These form a set of rolling regulations designed to become more stringent year on year. Currently limits for new cars and light-duty vans must conform to 'Euro IV' standards.

The air emissions assessed include the regulated emissions (carbon monoxide, oxides of nitrogen, hydrocarbons and particulates). Sulphur dioxide and nitrous oxide data are sourced where available. In addition, the three main greenhouse gases associated with road transport are assessed: carbon dioxide, nitrous oxide and methane. These greenhouse gas emissions are combined to provide a single measure of greenhouse gas impacts by using accepted global warming potentials (GWP) for each of the gases – these provide a weighting for each gas, which is a measure of their effect on atmospheric warming over a determined time period.

The outputs of the study include emissions comparisons for each of the vehicle types assessed. However, as will be discussed in Section 7, most vehicle fuel/technology LCA studies do not attempt to quantify the environmental impact of the pollutants generated. To address this issue, the methodology includes an impact analysis stage within the life cycle emission methodology. This is achieved by the use of the Car Environmental Rating Tool developed by the European Cleaner Drive Programme.[7] The rating system uses recognised 'external costs' to establish the relative weight to attach to different emissions. External costs of emissions are values expressed in monetary terms that reflect the overall damage to the environment and to human health caused by emissions.

From this point forward, the structure of the report is as follows:

- Section 6 provides an overview of the key vehicle fuel and technologies considered by the LCA study;
- Section 7 provides a detailed account of the methodology used for the life cycle assessment;
- Section 8 compares the key vehicle fuel and technology options according to the life cycle emissions of greenhouse gases, life cycle emissions of the regulated pollutants and using the Cleaner Drive environmental impact rating system – a detailed description of Cleaner Drive is given in Appendix 3;
- Section 9 compares key vehicle models from a range of fuel and technology types according using the Cleaner Drive environmental impact rating system;
- Section 10 provides a discussion of the results of the LCA study and outlines the future developments of cleaner vehicle fuels and technologies;
- Section 11 provides a summary of the main findings of the report.

[7] For more information, see Appendix 3 and/or visit the Cleaner Drive website at: www.cleaner-drive.com.

6 Vehicle fuel and technology options[8]

6.1 Petrol and Diesel

The vast majority of vehicles on UK roads use petrol or diesel. Historically, petrol has been favoured over diesel for passenger cars, and diesel the fuel of preference for commercial vehicles, though the popularity of diesel cars has increased markedly over the last decade, due to cheaper fuel, diesel cars' higher fuel economy (compared to petrol), perceived lower maintenance costs and an improved product range. This 'dieselisation' has seen an increase in the proportion of diesel cars in Europe to almost 40% and in the UK to over 30% of new cars (SMMT 2004).

Spark-ignition (petrol) engines utilise the four-stroke cycle, comprising the induction, compression, power, and exhaust strokes. In conventional units, during the induction stroke a small amount of fuel and air are drawn into the cylinder. The petrol-air mixture is then compressed into a small volume (a compression ratio of 9:1 indicates reduction to a ninth of the volume). The mixture, now under high pressure, is ignited by an electrical spark from the spark plug. The explosion causes the gases to expand (power stroke) forcing the piston and turning the crankshaft. The burned gases are then expelled from the cylinder (exhaust stroke) via the exhaust valve.

Although diesel engines are also four-stroke, only air is compressed in the cylinder instead of an air-fuel mixture, and at the end of the compression stroke the fuel is directly injected into the combustion chamber by a fuel injection pump. Typical compression ratios of 20:1 are used, which is sufficient to raise the air temperature to over 400ºC. Once the diesel fuel is injected into the cylinder it immediately vaporises and spontaneously ignites. This combustion process produces a mixture of hot gases that then drive the piston. Diesel combustion is more explosive than petrol combustion. This explains why diesel engines are generally noisier and vibrate more than their petrol counterparts.

Modern petrol engines incorporate four or six cylinders with four valves per cylinder. Whereas older designs used a carburettor to mix the fuel and air before combustion, newer engines employ electronically controlled fuel injectors to provide the correct amount of petrol. In order to comply with EU legislation, three-way catalysts are fitted most new petrol vehicles. These use a mixture of precious metals (applied to a high surface area support structure within the exhaust pipe) to catalytically reduce the amount of CO, NOx and unburned hydrocarbons from the exhaust. As the metals are poisoned by lead and sulphur, the introduction of catalysts has been dependent on the availability of lead-free and ultra low sulphur fuels.

In order to comply with future emissions standards, new petrol engine technologies have been developed and are beginning to appear in production cars. One of the most important is Gasoline Direct Injection (GDI) (also known by its German acronym FSI) which reduces fuel use and vehicle CO_2 emissions by up to 15% (Europa 2005). In a GDI engine petrol is sprayed directly into the combustion cylinder (there is no pre-mixing stage as in a conventional petrol unit). This results in a cleaner burn and an increase in power. The fuel is injected from what is known as a 'common rail', a high-pressure fuel reservoir that is more generally associated with diesel engines (see below). GDI units are often used in conjunction with advanced exhaust emission control systems to cope with increased NOx; these units include a NOx accumulator catalyst and a NOx sensor, the data being used to optimise engine combustion. The main obstacle to this technology has been the sulphur content of petrol, which can damage the NOx control units. However, the advent of sulphur-free fuels has opened the way for widespread GDI introduction.

As with petrol-powered units, modern diesels use direct injection fuel delivery and computerised engine management systems. These replace indirect injection engines in which the fuel is injected into a pre-chamber before entering the cylinder. Diesel technologies are also continuing to develop and improve – new diesel technologies include common rail injection and advanced diesel turbochargers. In common rail systems, the injection pressure is independent from engine speed and load. This enables the injection parameters to be freely controlled leading to reductions in engine noise and NOx emissions. Diesel after-treatment systems are also being developed in order to comply with new Euro standards. These include the use of diesel particulate filters (DPFs), which are fitted to an increasing number of production cars.

[8] The text of Section 6 is based on extracts taken from The Green Car Buyer's Guide (Ecolane 2005).

The fuel efficiency of diesel engines is higher than for spark-ignition units due to their higher combustion temperature and lower rate of heat loss. Diesel also has a slightly higher energy content than petrol per unit volume. However, after frictional losses are taken into account, only around a quarter of diesel fuel's energy, and a fifth of petrol's energy ends up being used to move the car – the precise value depending upon the vehicle type and driving conditions. Although these figures could already be considered low, if the car's mass is taken into account only around 1%–2% of the fuel's energy is actually used to move the driver and passenger.

Despite advances in engine technology, between the mid 1980s and the late 1990s the fuel economy of cars in the UK improved by less than 5%. This was because most of the improvements in engine efficiency were offset by tighter emission and safety standards and by the increasing demand for energy-consuming features such as power steering and air conditioning. According to the annual National Travel Survey (which annually surveys real-world driving) the average fuel economy for UK cars of all ages currently stands at around 9.3 litres/100 km (30 mpg) for petrol cars and 7.2 litres/100 km (40 mpg) for diesel cars – for new cars the figures are 32 mpg and 41 mpg respectively (NTS 2005).

However, since 1998 the fuel economy of new cars sold in Europe has improved by almost 10% driven by a voluntary agreement between the European Commission and ACEA (the association of European car manufacturers) to reduce vehicle carbon dioxide emissions (see Section 4). According to the ACEA, new petrol and diesel cars in Europe have an average fuel economy of 7.1 litres/100 km (40 mpg) and 5.5 litres/100 km (51 mpg) respectively. (Note that this data is measured over a standard test-cycle rather than real-world driving conditions – unlike the figures quoted by the National Travel Survey quoted above). The fuel economy of conventional cars is projected to improve by at least a further 10% by 2008 under the ACEA agreement.

As a result of the differences in fuel composition and engine conditions, petrol and diesel cars differ in their relative emissions performance – petrol vehicles generally emit fewer NOx and particulates, and diesel vehicles produce 15%-20% fewer carbon dioxide emissions per kilometre. To some extent, there is a trade-off between reductions in local and global emissions – diesel's relatively high NOx and low CO_2 emissions are both the result of the engine's high combustion temperature.

Fuel production and supply

Petrol and diesel are mixtures of liquid hydrocarbons refined from crude petroleum. The production of these fuels involves extraction, separation of crude oil from other fluids, transport to refineries, processing (fractional distillation), transport to regional storage locations and distribution to retail or fleet refuelling stations. Each fuel must be carefully blended, either to control petrol's volatility and anti-knock performance (octane number) or diesel's ignition quality (cetane number).

Petrol and diesel specification standards have tightened over the past decade and will to continue to do so over the next. EU Directives now prohibit the general sale of leaded petrol and impose fuel standards across Europe. For petrol and diesel, the maximum sulphur limit is 50 parts per million and the maximum permissible benzene content (for petrol) is 1% (as from 2005) – the EU has voted for the mandatory introduction of 'sulphur-free' petrol and diesel (which in practice means a maximum of 10 ppm) by 2009.

The main motivation for reducing the sulphur content of fuels is to improve the performance of after-treatment systems (such as catalytic converters) and to support the introduction of new technologies such as Gasoline Direct Injection (GDI). There is already evidence that the introduction of 'ultra low' sulphur petrol (max. 50 ppm from 150 ppm) has reduced carbon monoxide (CO), nitrogen oxides (NOx) and hydrocarbon (HC) vehicle emissions by 6%-14%. Diesel with low sulphur content also inhibits the formation of particulates, so reducing vehicle emissions.

The UK's fuel sulphur standards have consistently been more stringent than the EU standards – with the introduction Ultra Low Sulphur Petrol (ULSP) and Diesel (ULSD) being promoted through the use of lower fuel duty (typically 1p-2p per litre below other blends) to compensate for slightly higher fuel production costs. A further 0.5p per litre differential is intended to promote the switch to 'sulphur-free' fuels, well ahead of the EU 2009 deadline.

6.2 Biodiesel

Biodiesels include straight vegetable oils (SVOs), modified waste vegetable oils (WVOs) and oils produced by the esterification of energy crops such as oil seed rape, sunflower oil, palm oil and soybeans.

Image courtesy of Greenergy Fuels

Figure 6.1 Taxi refuelling with biodiesel

The interest in biodiesel has greatly increased over the past decade for a number of reasons which include: the increase in popularity of diesel cars, the increase in price of mineral diesel and the realisation that biodiesel blends can be used in place of mineral diesel without any engine modification in modern diesel powered vehicles (a 'B5' blend is 5% biodiesel mixed with 95% mineral diesel). Indeed, with the correct fuel specification, many diesel engines run more smoothly on biodiesel fuels, which have good lubricating properties. Some diesel cars will also run on pure vegetable oils.

However, several practical issues concerning the use of biodiesel fuels have emerged. As straight and modified waste vegetable oils are more viscous than mineral diesel, these fuels can clog fuel lines and fuel filters. An emulsion can also form in the return fuel line from the fuel injectors to the tank. These problems are more likely to occur during cold weather when starting may also be difficult. Solutions include the use of a heated fuel filter (which is standard in some cars) or by the use of a heated fuel tank.

Pure rape methyl ester (RME) made from oil seed rape is also more viscous than mineral diesel. A cold filter plugging point additive is often used to alleviate starting problems. A more serious drawback is an increase in the corrosion of rubber products. Engine parts and equipment with rubber seals and piping are usually therefore replaced with non-rubber alternatives. One way around this is to only use biodiesel blends and is the reason that most car warranties are only valid for up to a B5 blend. To reduce these problems, national and EU standards have been developed – users of biodiesel should therefore ensure the fuel's compliance with standard EN14214 as well as with the standard for conventional diesel EN590.

Fuel production and supply

Biodiesel is commercially produced by the esterification of energy crops such as oil seed rape (producing RME) or from waste vegetable and animal oils (sourced from the food industry). The oils are filtered and pre-processed to remove water and contaminants and are then mixed with methanol and a catalyst. This breaks up the oil molecules that are first reformed into fatty acid methyl esters and glycerol and then separated from each other and purified. The industrial production of biodiesel has two valuable by-products: glycerine, used in the manufacture of pharmaceuticals; and cattle-cake made from the remaining plant material.

Biodiesel is widely produced in Germany, France, Italy, and Austria from rape seed and waste oil sources. Although domestic biodiesel production could reduce oil imports and improve energy security, there is as yet no large-scale UK production of biodiesel. However, this is set to change as Argent Energy are currently building the UK's first large-scale biodiesel plant in Scotland which will use waste oils to produce over 50 million litres per year. This marks the increasing importance of biofuels in the UK – whereas biofuels only accounted for 0.05% of fuel sales in 2004, this is set to increase by a factor of six by the end of 2005, and is well on the way to meeting the government's proposed biofuel target of 5% of all road fuels by 2010.

Fuel and vehicle availability

Commercially produced biodiesel is becoming increasingly available in the UK. Over 140 fuel stations now supply biodiesel with most regions having at least one retail outlet. Given the warranty issue already discussed, most of these stations supply B5 as these can be used by the majority of diesel cars with no engine modification being required. However, it is likely that as the fuel's popularity increases, so will the number of suppliers of B100. For bioethanol and methanol fuels, no national network of retail outlets currently exists.

For fleet and bulk fuel buyers, several companies are now supplying blended and pure biodiesel to order. One of the largest is Greenergy whose main product is GlobalDiesel, a B5 blend. The company are also able to supply any ratio of biodiesel/diesel blends (a popular order is for B20), bioethanol/petrol blends and pure RME as part of a 'Field to Forecourt' scheme (in which the carbon balance is independently audited). Greenergy also process cooking oil into a form of biodiesel branded as Used Cooking Methyl Ester.

Environmental emissions overview

The great promise of biofuels is their potential to be 'carbon-neutral' on a life cycle basis; all the carbon dioxide emitted during processing and use of the fuel being balanced by the absorption from the atmosphere during the fuel crop's growth. In practice the process of growing the crops requires the input of fossil fuels for fertilisers, harvesting, processing and fuel distribution. The actual extent of total life cycle greenhouse gas emissions is therefore strongly dependent on the crop grown and the fuel processing employed. Taking into account life cycle emissions of carbon dioxide and nitrous oxide (associated with agriculture), for RME, studies show that life cycle greenhouse gas emissions (per km) can be reduced by between 40%-57% (Concawe 2004; DfT 2004a). Proportionately, this means that a 5% RME blend would result in a carbon reduction of around 2.5%. Although independent test data is not readily available for WVOs, it is likely that, even after processing has been taken into account, carbon reductions of over 50% can easily be achieved.

For regulated vehicle emissions, the situation is more complex. In general, estimates based on a number of comparative tests suggest that RME particulate emissions are lower by 4%-55% than for mineral diesel (the reduction depending on the blend used) (DfT 2004b, E4Tech 2003, NREL 2003). Carbon monoxide is also reduced by up to 40%. RME's zero sulphur content also increases the efficiency of exhaust emission control systems, so assisting the reduction of carbon monoxide and hydrocarbons. However, without an emission control system, NOx emissions can be slightly increased for RME biodiesel as compared to mineral diesel fuel by as much as 13% (NREL 2003). However, in tests using straight vegetable oil, the picture is very different – with the exception of NOx emissions, SVO's can have negative air quality impacts "including a 100% increase in PM_{10} and a 420% increase in CO" in the worst performing vehicle (DfT 2004b).

Two further considerations make the full environmental impact of biofuels difficult to assess. On the one hand biofuels have the advantage over mineral oils in that, if spilled, they biodegrade more quickly leaving virtually no toxic residue. On the other hand their production usually involves synthetic fertilizer, pesticide and herbicide use (organic production is possible but rare). Despite these uncertainties, it is clear that some significant emission reductions can be achieved, especially for carbon. However, the precise emission benefits depend wholly on the composition and source of the fuel in question.

Economic considerations

Fixed costs are unaffected by switching from conventional to 5% biofuel blends as no engine modifications are required. However, the use of pure biodiesel may require the replacement of rubber components costing several hundreds of pounds. A further consideration is the assurance offered by car warranties, which may be rendered invalid by the use of more than 5% biofuel blends. In a worse case scenario, this could result in significant repair costs that would have to be paid by owner of the vehicle.

Due to economies of scale, commercially produced biofuels tend to have higher production costs. These are partly offset by tax benefits as the UK government has reduced fuel duty on biodiesel for the next three years by 20p/litre (to stimulate production). Despite this, the *retail* fuel price of biodiesel is often higher than mineral diesel, with forecourt prices starting from around 100p/litre – the price depending on whether the biodiesel is a pure or blended formulation. Note that as biofuels have lower energy content than conventional fuels, slightly more fuel is required – a car running on pure biodiesel uses almost 10% more fuel per mile (by volume) than it would using mineral diesel.

6.3 Bioethanol

Ethanol (also known as ethyl or grain alcohol) is a clear, colourless liquid and is the essential ingredient of all alcoholic drinks. It can be produced from virtually any fermentable source of sugar. Ethanol made from cellulosic biomass is called bioethanol.

Being a liquid at room temperature ethanol can be handled in a similar way to conventional fuels. The alcohol has a high octane rating (enabling a high engine compression ratio which increases engine efficiency). They can be used in spark-ignition engines with little or no modification as alcohol-petrol blends (‘E10’ is 10% ethanol; also known as ‘gasohol’) or as pure alcohol fuels in modified vehicles. The suitability of alcohol as vehicle fuel is demonstrated by its use as high performance motor-racing fuel.

The principal difficulty with alcohol fuels is their relatively low energy density. This means that vehicles running on pure alcohol require a fuel tank double the volume of an equivalent petrol tank. Also, as these fuels are difficult to vaporise at low temperatures, pure alcohol cars can be difficult to start in cold weather. For this reason, alcohol fuels are usually blended with a small amount of petrol to improve ignition. However, vehicles modified to use pure bioalcohol fuels have improved performance, as the compression ratio is often increased to take advantage of their high octane ratings.

Fuel production and supply

The production of ethanol first uses enzyme amylases to convert a feedstock into fermentable sugars. Yeast is then added to the mash to ferment the sugars to alcohol and carbon dioxide, the liquid fraction being distilled to produce ethanol. Globally, ethanol is one of the most widely used alternative vehicle fuels due to its popularity in Brazil and the USA. Over 50 production plants in North America are in operation providing fuel ethanol production from starch crops such as corn. Most European ethanol is commercially produced using sugarbeet.

Bioethanol is widely used as a vehicle fuel – particularly in Brazil where the ethanol from sugar cane comprises over 20% of all vehicle fuels. However, there is as yet no large-scale UK production of bioethanol. However, the Somerset Biofuels Project, a partnership including the local council, Wessex Grain and Ford motors is set to produce bioethanol specifically for a fleet of biofuel vehicles (see below) – the aim is to stimulate transport demand for bioethanol in the UK. This marks the increasing importance of biofuels in the UK – whereas biofuels only accounted for 0.05% of fuel sales in 2004, the government’s proposed biofuel target of 5% of all road fuels by 2010.

Fuel and vehicle availability

Commercially produced bioethanol is not widely available in the UK, and as of 2005, no national network of retail outlets currently exists. However, this is likely to change over the next few years as the demand for bioethanol grows to match the demand for biodiesel. Given the warranty issue already discussed, most future stations are most likely to initially supply low percentage blends (such as E10) as these can be used by the majority of petrol vehicles with no engine modification being required. For bulk fuel buyers, several companies are now supplying blended and pure bioethanol to order. One of the largest is Greenergy who supply any ratio of bioethanol/petrol blends.

One of the most significant developments has been the European development of vehicles that are able to operate on conventional petrol or any percentage petrol-alcohol blend – the so called ‘Flexi-Fuel Vehicles’ or (FFVs). These can operate on any petrol-biofuel blend of up to 85% bioethanol – the engine management system automatically detects which fuel is being used and adjusts the timing accordingly making the vehicles fuel-flexible.

Ford, Volvo and Saab are to produce Flexi-Fuel Vehicles (FFVs). Over 15,000 flexi-fuel versions of the Ford Focus have already been sold in Sweden, where there are nearly 200 filling stations selling bio-ethanol fuel. Ford plans to make the car available in the UK by 2006. Saab and Volvo are also launching bio-ethanol cars into the European market. The first FFVs in the UK will be used by the Somerset Bio-fuel

Project – Ford are to provide 40 Focus FFV cars for use on the fleets of Somerset County Council, Wessex Water, Avon and Somerset Constabulary, and Wessex Grain.

Environmental impacts overview

As is the case for biodiesel, the bioethanol has the potential to be 'carbon-neutral' on a life cycle basis; all the carbon dioxide emitted during processing and use of the fuel being balanced by the absorption from the atmosphere during the fuel crop's growth. However, in practice the process of growing the crops requires the input of fossil fuels for fertilisers, harvesting, processing and fuel distribution. The actual extent of total life cycle greenhouse gas emissions is therefore strongly dependent on the crop grown and the fuel processing employed.

For ethanol, estimates of life cycle carbon emissions vary widely. For example, in Brazil where sugar cane is used as the feedstock for ethanol production, large amounts of bagasse (the woody fibres remaining after the juice is extracted from the cane) are used to provide the process heat energy. As a result, the average energy-ratio of ethanol output to fossil fuel input is of the order of six – which means that carbon emissions are significantly reduced (Johansson *et al.* 1993). This contrasts with the energy ratio for US corn-derived ethanol, which in some cases can be less than one; ie the fossil fuel energy required to produce the ethanol is greater than the energy value of the final product. For EU production, it is estimated that life cycle greenhouse gas emissions can be reduced by over 50% (Concawe 2004; LowCVP 2004).

For E85 and pure-alcohol fuels, the consensus is that carbon monoxide and particulate emissions are significantly reduced (CO by up to 25%) (DfT 2004b, E4Tech 2003). Also, any unburned alcohols present in the exhaust gases of an alcohol-fuelled engine contribute less to tropospheric-ozone formation than do the volatile organic compounds present in petrol exhaust emissions. Although alcohol fuelled vehicles can emit less nitrogen oxides (as alcohol fuels burn at a lower temperature than petrol), in practice the compression ratio is often increased to improve engine efficiency. This raises the combustion temperature and offsets any NOx emission benefit – or can even lead to an increase in some cases.

As is the case with biodiesel, two further considerations make the full environmental impact of bioethanol difficult to assess. On the one hand biofuels have the advantage over mineral oils in that, if spilled, they biodegrade more quickly leaving virtually no toxic residue. On the other hand their production usually involves synthetic fertilizer, pesticide and herbicide use (organic production is possible but rare). Despite these uncertainties, it is clear that some significant emission reductions can be achieved, especially for carbon. However, the precise emission benefits depend wholly on the composition and source of the fuel in question.

Economic considerations

Fixed costs are unaffected by switching from conventional to biofuel blends as no engine modifications are required. However, additional costs may be incurred if pure biofuels are used. The use of pure alcohol fuels may require engine recalibration costing several hundreds of pounds. A further consideration is the assurance offered by car warranties, which may be rendered invalid by the use of more than 5% biofuel blends. In a worse case scenario, this could result in significant repair costs that would have to be paid by owner of the car.

Due to economies of scale, commercially produced biofuels tend to have higher production costs. These are partly offset by tax benefits as the UK government has reduced fuel duty on bioethanol for the next three years by almost 20p/litre (to stimulate production). Currently the tax on biodiesel stands at 27.1p/litre compared to 47.1p/litre for ULSP. Despite this, where the fuel is available, the price of bioethanol is often higher than petrol, the price depending on whether the biodiesel is a pure or blended formulation.

6.4 Natural gas

Figure 6.2 The Volvo Bi-Fuel V70

Image courtesy of Volvo Cars

Natural gas is a naturally occurring mixture of gaseous hydrocarbons consisting of at least 80% methane with lesser amounts of propane, ethane and butane.

Natural gas can be used within a modified internal combustion engine to provide motive power. The gas makes an ideal fuel for spark-ignition engines due to its high octane rating, low levels of volatile organic compounds and to the fact that it mixes easily with air prior to combustion. This offers lower idling speeds, better performance, easier cold starting and a more complete combustion, all of which help to reduce exhaust emissions. Due to the low number of refuelling stations most natural gas cars are bi-fuel conversions. These are able to operate on gas or petrol, the fuel being selected at the flick of a switch. Natural gas buses and trucks tend to use dedicated (gas only) or dual-fuel (gas-diesel mix) engines.

Over two million natural gas vehicles (NGVs) are in use worldwide. Excluding Italy, Europe has over 8500 NGVs, including cars, buses and trucks, serviced by 175 filling stations. There are around 850 NGVs on British roads, most of which are larger vehicles operated by company and local authority fleets.

In most respects current bi-fuel and dedicated gas engines have a performance similar to conventional power units. There are, however, several advantages of using natural gas. These include reduced engine noise (important for delivery vehicles that require late night and early morning access) and an extended engine life due to the fuel's clean burn characteristics which reduces engine stress. Conventional (petrol) three-way catalytic converters continue to be used by most natural gas bi-fuel cars, whereas dedicated gas vehicles use catalysts that are optimised for methane, further reducing vehicle emissions. Compared to petrol operation, drivers of bi-fuel cars may notice a small loss of power (and acceleration) at full throttle when in natural gas mode. Under most driving conditions, however, the difference is hardly discernable.

The most significant difference between natural gas and conventional cars is the method of fuel storage. Given that natural gas is gaseous at room temperature and pressure, it is stored on-board either as compressed natural gas (CNG) or as liquefied natural gas (LNG), the latter cooled to -190^{o}C. CNG is the most common option for cars, the gas being stored in pressurised cylinders (at 200 times atmospheric pressure), which are located within the boot space. Cars are typically fitted with a single steel cylinder of around 90 litres capacity that can hold 16 kg gas, equivalent to 23 litres of petrol. Being pressurised these are heavier than conventional fuel tanks and increase a car's total weight by around 60 kg. Although they occupy a similar volume to those designed for petrol, this can be a problem for bi-fuelled vehicles where two tanks have to be accommodated. The result is that the extra cylinder reduces the amount of luggage that can be carried and can preclude the ability to carry a spare wheel.

Fuel production and supply

Globally, natural gas is the second most abundant fossil fuel. With new interconnectors to European and Russian gas fields, demand for natural gas in the UK will be satisfied well into the foreseeable future. Users of natural gas cars who drive outside the UK should note that there are significant differences in the quality of gas across Europe and the rest of the world, with the methane content varying from 80% to 99% of the total (UK North Sea natural gas contains around 86% methane and requires little processing before use). In some situations (outside the UK) this high variability can adversely affect engine performance, as engine management systems cannot cope with large changes in gas composition.

Natural gas re-fuelling systems are of two types: fast-fill units use high pressure compressed natural gas to refuel vehicles in a matter of minutes; slow-fill compressor units 'trickle charge' one or two vehicles over 5-6 hours. To refuel, a flexible hose is connected between the dispenser and the car and is locked into place creating a sealed system. For fast-fill systems, the amount of gas required is then pre-selected before being automatically dispensed. Slow-fill units continue to operate until the tank is either full or the filling process is halted by the user.

The main barrier to the use of natural gas vehicles is the low number of gas refuelling stations. Although the UK has the advantage of having an extensive national gas grid, at present there are only around 35 CNG filling stations of which only 12 are fast-fill stations accessible by the general public (some of which require the setting up of an account). On a more positive note, slow-fill units are being developed for home refuelling – the only requirements being off-road parking (a garage or drive), a natural gas supply and a suitable location for the compressor.

Vehicle availability

The availability of natural gas cars has never really been an issue as the majority are either converted at the factory or are retrofitted after being sold as a new car. Although PowerShift grants are no longer available for natural gas cars, one of the central reasons for setting up the PowerShift programme was to ensure that the performance and build-quality of green cars met agreed minimum standards. Details of approved converters and OEMs who supply natural gas cars are available on the PowerShift Register and website. While it is possible, in principle, to convert most types of spark-ignition engine car, it is worth noting that there are only a small number of natural gas passenger cars currently on the PowerShift Register. At the time of going to press these include: the Vauxhall Zafira and Combo van, the Ford Focus, and three models in the Volvo range: the S60 and V70.

Environmental impacts overview

In principle, carbon emissions from natural gas cars are reduced due to the fuel's low carbon content and high octane number (which enables a high compression ratio to be used). However, in addition to carbon dioxide, methane (the main constituent of natural gas) is also an important greenhouse gas. Taking carbon dioxide and methane emissions into account, natural gas bi-fuel cars (and car-derived vans) currently show an improvement in life cycle greenhouse gas emissions (per km) of around 15%-20% as compared to those using petrol – this means that greenhouse gas emissions for natural gas cars are approximately the same as for light-duty diesel vehicles (Concawe 2004).

With the exception of methane, regulated vehicle emissions (per km) are reduced for natural gas cars – an OEM-supplied bi-fuel natural gas car will reduce NOx compared to petrol (which is itself much lower than diesel) (DTI 2000, VCA 2005). Sulphur oxides and particulates are also virtually eliminated. Furthermore, although hydrocarbon vehicle emissions are increased by 10%-15% (mainly methane), these contribute less to tropospheric-ozone formation than do the volatile organic compounds present in petrol exhaust emissions.

However, the relative environmental impact of NGVs is changing due to the development of dedicated gas engines that use optimised catalysts (which reduce methane emissions) and the parallel improvement in the fuel economy of conventional cars. Within a few years, the benefits of natural gas may be reduced or confined to the regulated emissions and noise reductions discussed above.

Economic considerations

Fixed costs for natural gas cars are higher than for their petrol equivalents due to the higher purchase price (if bought new from a manufacturer) or to the cost of conversion of an existing car. Typically, for car and car-derived vans, the additional capital or conversion costs are in the range £1500-£2500. Additional capital costs are incurred if a refuelling compressor unit is installed – the cost of units start at around £2000 for a slow-fill system.

However, fuels costs are significantly reduced for NGVs as a result of the fuel's low duty rate - natural gas retails at around 74p/kg. Taking account of the fuel economy of natural gas cars, this is equivalent to 55p/litre for petrol, significantly less than conventional fuel forecourt prices. The use of home refuelling units would result in even larger savings. Adding the average domestic cost of gas (around 25p/kg) to the fuel duty payable on natural gas used as a road fuel gives a total price of only 42p/kg (including VAT), which is equivalent to only 32p/litre for petrol. However, as the emissions benefits compared to petrol reduce over time, the UK government may reduce the fuel tax advantage for natural gas from 2007.

6.5 Liquefied petroleum gas

Liquefied petroleum gas (LPG) is a mixture of several hydrocarbons. The main constituent is propane with lesser amounts of ethane and butane.

Figure 6.3 Vauxhall Astra 'Dual-Fuel' LPG car-derived van refuelling

LPG can be used within a modified internal combustion engine. Most cars and car-derived vans that operate on LPG are conversions designed to run in bi-fuel mode, the engine being able to operate on gas or petrol. Whereas older bi-fuel conversions often had poor performance (the engine being optimised for petrol operation), recent conversions use electronically controlled gas-injection systems. The advantage of bi-fuel operation is that vehicles are less reliant on a fully developed LPG refuelling infrastructure and are able to be used in areas where the gas is unavailable. However, bi-fuel cars do not achieve the full emission benefits offered by LPG because a compromise in engine tuning is required for the two fuels.

Liquefied petroleum gas is a tried-and-tested vehicle fuel. There are currently over four million vehicles using LPG in Italy, Holland, the former Soviet Union, Japan, Australia, South Korea, the USA and Canada. In Europe, the LPG vehicle population numbers around two million vehicles. In the UK, there are over one 100,000 LPG vehicles in use. The majority of these are cars and light-duty vans, most which are bi-fuel conversions.

Used in conjunction with a spark-ignition engine, LPG is either added to the airflow or injected into the cylinder in gaseous or liquid form. The gas mixes readily with air, thus allowing a more complete combustion than is the case for conventional liquid fuels. In most respects, current bi-fuel and dedicated LPG vehicles have an engine performance similar to conventional cars. There are, however, several advantages of using LPG which include an extended engine life due to the fuel's clean burn characteristics and reduced engine stress. Conventional (petrol) catalytic converters are used by most bi-fuel cars, whereas dedicated LPG vehicles use catalysts optimised for the gas, further reducing vehicle emissions.

The most significant difference between gas and conventional cars is the method of fuel storage. As LPG is a gas at room temperature, a pressurised tank is required. Fortunately LPG liquefies under moderate pressure (one reason for its popularity over other gaseous fuels); the gas/liquid mixture is usually stored in cylinders at just over 10 atmospheres. For car conversions, LPG tanks are either cylindrical and located within the boot space or doughnut-shaped to fit into the recess normally occupied by the spare wheel. Being pressurised, these tanks are significantly heavier than conventional fuel tanks for the same range. Although they occupy a similar volume to petrol/diesel tanks, this can be a problem for bi-fuelled vehicles where two tanks have to be accommodated. The result is that the weight of the extra cylinder slightly increases the fuel consumption and marginally reduces the weight and size of luggage that can be carried.

Compared to petrol performance, drivers of bi-fuel cars may notice a small loss of power (and acceleration) at full throttle when in gas fuel mode. Under most driving conditions, however, the difference is hardly discernable.

Fuel production and supply

LPG is produced from two sources: directly during the extraction of natural gas and indirectly as a by-product of refining petroleum. The composition of the gas varies across Europe. Whereas UK gas typically contains more than 90% propane, in Italy this can be as low as 20%. With early conversions this affected the ability of LPG cars to travel throughout Europe. However, self-adjusting fuel management systems have overcome this problem and most new LPG engines are able to tolerate a wide variation in gas composition.

In the past the main barrier to the use of LPG in the UK has been the limited number of refuelling stations – fortunately, this is no longer the case. Although there were only around 200 LPG filling stations in 1999, the number has increased to around 1500. The situation is approaching the point where 10% of all refuelling stations offer LPG.

Vehicle availability

The availability of LPG cars has never really been an issue as the majority are essentially conversions of conventional petrol cars – these are either converted at the factory by the manufacturer or are retrofitted after being sold as a new car. In addition to providing capital grants for new LPG cars, one of the central reasons for setting up the PowerShift programme was to ensure that the performance and build-quality of green cars met agreed minimum standards. Details of approved converters and car manufacturers (OEMs) who supply natural gas cars are available on the PowerShift Register and website. Note also that the most favourable insurance quotes for LPG cars are likely to be available for models that appear on the Register.

At the time of writing, a large number of LPG passenger cars appear on the PowerShift Register. These include models from most of the major manufacturers including: Citröen, Ford, Mitsubishi, Nissan, Skoda, Rover and Peugeot. In particular, Vauxhall has embraced LPG technology and offer new factory-converted LPG cars. These include Vauxhall's Astra, Corsa, Omega, Vectra and Zafira 'dual-fuel' range

Environmental impacts overview

Compared to petrol, carbon emissions from LPG cars are reduced due to the gas' low carbon content – this more than balances the relatively high fuel consumption of LPG cars (litres per km), which is around 30% more than for petrol (DTI 2000, DfT 2002). Taking carbon dioxide emissions into account, real-world tests show around a 10%-15% reduction of life cycle greenhouse gas emissions (per km) for bi-fuel LPG cars as compared to petrol operation – placing the level of greenhouse emissions between those from petrol and diesel (VCA 2005).

Although it used to be the case that most regulated vehicle emissions (per km) are reduced for LPG cars as compared to conventional fuels, the relative environmental impact of LPG cars is changing due to the improvement in fuel economy of conventional cars. As a result, NOx and CO can be substantially increased compared to petrol – but are still much lower than for diesel (VCA 2005). Particulates are also virtually eliminated. LPG cars therefore also provide significantly lower regulated emissions than diesel.

Economic considerations

Some fixed costs for LPG cars are higher than for their petrol or diesel equivalents. This is principally due to their higher purchase price (if bought new from the manufacturer) or to the cost of conversion of an existing car. Typically, for new car and car-derived vans, the additional purchase price is in the range of £1500-£2000 (although some manufacturers have decided to absorb the extra cost). For conversions, the costs are in the range £1200-£1800.

The switch to LPG has been driven primarily by the potential for fuel cost savings rather than the fuel's environmental benefits. The low price of LPG used as a road fuel is a result of its low fuel duty rate (currently 4.5p/litre). At fuel station forecourts, LPG retails at around 40p/litre, around half of the price of petrol and diesel. (Note that the energy density of LPG is around a third less than for petrol, which means that a greater volume of fuel is required.) Taking into account LPG's energy content and the extra fuel required, the price of LPG effectively approximates to a petrol price of around 58p/litre (~30% below petrol).

Note: due to the fact that conventional cars are themselves becoming cleaner, the UK government has announced that it will reduce the fuel duty differential benefit of LPG by 1p/litre each year until 2007.

6.6 Hybrid-electric

Figure 6.4 Toyota Prius II Petrol Hybrid

Hybrid-electric vehicles (HEVs) are part battery-electric and part conventional vehicles. The underlying principle of all hybrid-electric vehicles is the use of a temporary energy storage device (usually a battery or capacitor) that enables the main engine to be operated at close to its maximum efficiency.

Two types of hybrid-electric drive have been developed. A *series* hybrid uses a combustion engine to generate electricity, which powers an electric motor so providing motive power. In a *parallel* hybrid the wheels can be either directly powered by the engine or from a battery-powered electric drive-train. In both types, when the engine loading is low, the excess energy is stored for later use. When a large amount of energy is required (eg during acceleration), the main power unit and the energy storage device work together to deliver the required power. In this way, hybrids provide significantly improved fuel economy and reduced emissions.

Hybrids are classed either as mild or strong to reflect the degree of battery power incorporated into the design, strong hybrids being able to spend more time in electric-only mode. Most hybrids operate in electric/zero-emission mode at low speeds (typically less than 15 mph), which makes them ideal for urban driving. Although on-board batteries add to vehicle weight, hybrids require high power batteries with a smaller energy capacity than are required by battery-electrics – currently, most commercial hybrids currently use nickel-metal hydride cells. Battery storage also enables the use of regenerative braking which tops up the battery when the brakes are applied, further reducing overall fuel consumption by around 20%.

A technical breakthrough in hybrid car technology occurred in the 1990s, which saw several car manufacturers develop a hybrid-electric to prototype stage. However, only a few pioneering manufacturers have taken hybrids through to production. These include Toyota (with the Prius) and Honda (with the Insight and Civic IMA hybrids). Although several fuel/engine/drive-train combinations are possible, the hybrids that have been first to reach the marketplace use a petrol-fuelled spark-ignition engine. That said, hybrids are still at an early stage of development and, as yet, no single system design has emerged.

As most hybrids on the market use conventional petrol, fuel is dispensed from fuel pumps in exactly the same way as for conventional cars. Indeed, the great advantage of petrol- and diesel-fuelled hybrid-electric cars is that they require no change in fuel and can use any of the 17,000 conventional fuel stations in the UK. As the range and fuel-performance of hybrids is better than their conventional counterparts there are no restrictions on the applications for which they can be used. With no technical barriers to their use, hybrid vehicles therefore possess great potential to become the new standard automotive technology of the next decade.

Vehicle availability

At least four hybrid-electric cars are commercially available in the UK. One of the first to reach the salesroom, and probably still the most important production hybrid, is the Toyota Prius that has been available in Europe since 2000. Hybrids are also available from Honda, who currently offer two models, the two-seater Insight (launched in 2000) and the Civic Hybrid IMA (2003), and Lexus who launched a top-of-the-range hybrid, the RX400h in 2005. Honda aims to add the Accord Hybrid to its range in 2005/06. Undoubtedly, other manufacturers will follow suit within the next few years – hybrid models being prepared for production include the Ford Escape and the Nissan Altima.

With at least four hybrids already on the market (some offering an extended model range), UK buyers are beginning to have a real choice of hybrids from which to choose, ranging from the conventionally styled five-seater Honda Civic, to the slightly more modern-looking Prius II, to the futuristic two-seater Honda Insight. Given that the first hybrids appeared in the UK in 2000, a few are even beginning to appear on the used car market (several used Priuses have appeared on the eBay website).

The commercial prospects for hybrid-electric look extremely promising. Already, in their first year of manufacture (1997), the global monthly production of petrol-hybrids exceeded the annual sales of all battery-electric cars. The market leader, the Prius, has seen a strong growth in sales from just over 300 in its first year (in Japan) to over 120,000 cumulative sales worldwide. In 2003, hybrid sales were around 40,000 vehicles, with around half of sales being of Priuses, the rest Insights and Civics. Several industry analysts predict that annual global sales will exceed 300,000 by 2008. This view is backed up by the fact that Toyota increased its 2004 annual production of the Prius from 90,000 to 120,000.

One intriguing recent development is the after market conversion (by Amerjac Projects) of a Toyota Prius. Known as a ‘Plug in Hybrid’, the vehicle is given an additional battery pack (in this case Lithium-Iron-Phosphate) that can be recharged from the mains like a battery electric vehicle, or is topped up by the engine along with the existing battery pack. This added flexibility allows longer electric-only driving range and, according to the conversion company, increases the fuel economy to 130 mpg (EAST 2005).

Environmental impacts overview

On European roads, the Honda Civic hybrid has carbon dioxide emissions of 116g/km and the Prius II achieves 104g/km – this represents an improvement in life cycle greenhouse gas emissions (per km) of 25%-30% compared to an equivalent petrol car (Lave and MacLean 2002; Concawe 2004). Significant as these figures are, the two-seater Euro 3 Honda Insight goes one better achieving CO_2 emissions of 80g/km – life cycle carbon emissions around half of those for the average conventional petrol car (VCA 2005).

All regulated vehicle emissions (per km) are significantly reduced for a petrol-hybrid passenger car as compared to a conventional petrol vehicle. These include reductions in carbon monoxide, hydrocarbons and NOx of up to 90% (Lave and MacLean 2002; E4Tech 2003). No data is available regarding particulate emissions, but a significant reduction is expected. The result is that all hybrid cars are already Euro IV compliant, legislation not due to be mandatory for all cars until 2006.

Unlike other green cars, the future of hybrids is not threatened by the improving fuel and emissions performance of conventional cars. This is because a hybridised engine will always outperform its non-hybrid equivalent. The second reason, and the most telling, is that all conventional engines may have to be hybridised if they are to conform to future emission standards. In other words, the future conventional and hybrid-electric car may be one and the same.

Economic considerations

Some fixed costs for hybrid-electric cars are higher than for their petrol and diesel equivalents, due principally to the higher purchase price. Typically, for new car, the additional purchase price is in the range of £1500-£3000 (on a £14,000 model), depending on whether it is a mild or strong hybrid design.

However, the higher capital costs are offset by lower fuel costs due to the high fuel economy of the vehicles themselves. (As the fuel is conventional petrol/diesel, the price paid per litre on fuel is unchanged.) As is the case with carbon emissions (see above), hybrids typically use around 15%-30% less fuel per mile, depending on driving conditions and whether a mild or strong hybrid design is used. For example, the Honda Civic IMA achieves 4.9 litres/100 km (57.7 mpg) and the Prius II 4.3 litres/100 km (65.7 mpg) on a combined cycle.

Due to their novelty and use of traction batteries, servicing, maintenance and repair costs remain somewhat unknown. Although there is good reason to think that these costs will remain similar to those for conventional cars, servicing may require going to a specialist centre. In order to reduce consumer uncertainty many hybrid car manufacturers provide high-mileage warranties that cover the additional hybrid-electric components (typically for 8-10 years or 100,000 miles).

6.7 Battery-electric

Image courtesy of GoinGreen

Figure 6.5 G-WIZ battery-electric car

A battery-electric vehicle (BEV) utilises an on-board rechargeable battery to store electrical energy. The battery is recharged by connecting it to an electricity supply (usually the mains). When required, energy is drawn from the electric-cells and converted to motive power by the use of an electric motor. Battery storage also enables the use of regenerative braking which tops up the battery when the brakes are applied.

Other than the 16,000 milk-floats (which comprise the largest number of UK registered electric vehicles) or commercial electric vehicles used in a number of specialist applications such as forklift trucks, airport and electric delivery vehicles, there are probably less than 400 electric cars in use on public UK roads.

Historically, the lead-acid cell has been the most widely used traction battery – in spite of having a relatively low energy density, it is possible to build cars with a range of around 45-60 miles (70-100 km). The latest generation of rechargeable traction batteries include nickel metal-hydride (Ni-MH) cells. These provide a significant improvement in performance and range (typically 95-125 miles). Despite their relatively high cost, these new battery types have proved to be well suited to automotive applications and are now preferred by most BEV manufacturers.

Most first generation BEVs used direct current motors that give high torque at low speeds and are easy to control using semi-conductor technology. However, their low specific power (around a third of the power of a petrol engine per kg) does not represent the best possible performance of available motor technology. An alternative is to convert the direct current from the battery to alternating current using an inverter, which then drives an induction motor. These have increased efficiency, double the specific power and require less maintenance. Alternating current power-trains are also more suited to fast-charging systems (see below). Disadvantages include higher costs and an increased complexity of the controller that needs to both act as an inverter and regulate the motor's speed.

While most battery-electric cars do not match the performance of conventional vehicles, current models have a range and performance that is adequate for many applications including: city driving, predictable drive cycles (such as delivery routes), short range trips (less than 60 miles per day) and where only zero or low emission vehicles are allowed access. As a result, BEVs are most suited for use in commercial fleets (for small loads), company car-pools and as 2^{nd}/3rd private cars for city use.

Fuel production and supply

Electricity can be generated using a large number of energy sources. UK electricity is currently generated from gas (37%), coal (35%) and nuclear (22%) with renewables (such as solar, wind and hydro-electric) accounting for almost 3%. The last decade has seen a 'dash for gas' driven by deregulation of the electricity market and the low cost of natural gas. This has fortuitously resulted in a decrease in power station emissions of carbon dioxide and other pollutants. The coming decade is likely to see an increase in renewable generation as part of the drive to further combat climate change and improve security of supply.

BEVs can be slow- or fast-charged. The most common method is an overnight charging cycle, which typically takes 6 to 8 hours. A typical slow-charging unit comprises a transformer to reduce voltage and a rectifier to charge the cells using direct current. Fast charging units usually require the use of alternating current – these can take as little as 10 minutes for a 50% charge. Given the almost total coverage of the national grid, it is relatively easy to install recharge points as compared with other green fuels. For slow charging, all that is required is access to a standard domestic 13-Amp socket. However, private users without access to a garage or private road face significant difficulties in getting electricity companies to install roadside recharging points.

Other than connecting up to a mains supply, a national network of fast-charging points has yet to be developed. Currently, only around a dozen car parks and parking spaces (operated by several London

Boroughs) provide free or reduced cost access to recharging units for top-up or opportunity refuelling. The level of coverage may improve in city centres in the next few years, but is unlikely ever to match the number of refuelling stations for some of the other green fuels. For the foreseeable future BEV users, therefore, will have to rely on home- or fleet-based charging systems.

Vehicle availability

As recently as 2002, several motor manufacturers were selling a range of battery-electric cars in the UK. These included the Peugeot 106E, the Toyota RAV4 Electric and the Ford 'Think!'. However, these did not sell well are no longer sold as new cars. As a result, with the exception of Peugeot-Citröen, there are very few major manufacturers currently marketing and supporting battery-electric cars within the EU – a situation that is unlikely to change in the next few years. Having said that, a few tried-and-tested models are available and include: the Citröen Berlingo (in van or car form), the Reva G-WIZ micro-car (imported from Bangalore) and the Bradshaw 600 mini-van.

Environmental impacts overview

The principle advantage of battery-electric cars is that they are the only commercially available zero-emission vehicles (ZEVs). However, emissions are produced during the generation of electricity, the amount depending on the method of generation used (see above). Therefore, the greenhouse gas and regulated emissions quoted in this section are quoted on a life cycle basis (regulated pollutants are usually quoted for vehicle emissions only).

Taking carbon dioxide and methane emissions into account, all BEVs charged from the mains (using an average UK fuel mix) show a significant reduction in life cycle greenhouse gas emissions (per km). Using a petrol baseline, the figures suggest a reduction of around 35%-40% (DTI 2000).[9] The benefits are mainly due to the fact that BEVs are significantly more energy efficient than ICE petrol vehicles – electric power-trains are well suited to stop-start, low-speed operation and use almost no energy when stationary. Also regenerative braking improves fuel efficiency by up to 20%. These emission reductions are predicted to further improve with the introduction of cleaner generating plant. Furthermore, if renewable electricity is used, life cycle greenhouse gas emissions are virtually zero – this is a true zero-emission car.

For life cycle regulated emissions (per km), assuming the average UK generating mix, carbon monoxide and hydrocarbons are significantly reduced for BEVs (DTI 2000). However, life cycle emissions of particulates, NOx and SO_2 are significantly increased. Having said that, these are emitted from power stations that are well away from urban areas. As is the case with greenhouse gas emissions, if renewable electricity is used, then life cycle regulated emissions are also reduced by almost 100%.

Economic considerations

The capital costs of battery-electric cars are significantly higher than their petrol or diesel equivalents. Typically for new car (and small van) the price is increased by 50%-80%. Due to the high cost of the batteries, these are often not included within the purchase price. Instead they are usually leased for £60-£70 a month. If the battery is purchased outright, further capital is required after around five years for battery replacement. Other investment is required for new infrastructure. Costs per standard charge point are of the order of £500-£2000, depending on the difficulty of installation. Fully installed fast-chargers cost between £10,000-£30,000 (depending on whether an on-board or off-board charging system is used).

However, the high capital costs are offset by very low fuel costs, due to the competitive price of electricity (fuel duty is zero-rated) and to the high efficiency of the vehicles themselves. Taking into account the fuel economy of battery-electric cars, the fuel costs can be as low as 1.6p/mile (1p/km). For a typical annual mileage of around 10,000 miles (16,000 km) per year, a saving of around £800 per year could be achieved. But, and it is a big but, if the battery lease is considered as an operating cost, then the saving on fuel is cancelled out by the battery leasing costs.

[9] Updated data using methodology from The Report of the Alternative Fuels Group of the Cleaner vehicle task Force Report (DTI 2000).

7 Life cycle assessment methodology

A Life Cycle Assessment (LCA)[10] is an attempt to quantify the environmental impacts over the life cycle associated with a material, product or process. The methods employed by an LCA involve the systematic assessment of each stage of the life cycle, which are then summed to provide an overall estimate of the environmental impacts. The four stages that comprise a full LCA approach are:

(1) Scoping – defines the purpose of the analysis, the boundary parameters within which the analysis occurs, the product/material/process of study, and lists the information sources and assumptions used in the analysis;
(2) Inventory analysis – accounts for all the energy, raw materials and emissions used and/or generated throughout the life cycle of the product/material/process under assessment;
(3) Impact analysis – identifies and quantifies the impacts on the environment (eg eco-systems, human health, natural resources) as defined in the scope of the assessment;
(4) Improvement analysis – a qualitative and quantitative comparison of the options assessed to identify opportunities for a reduction in the environmental impacts within the scope of the assessment.

LCAs are most commonly used to assess and compare the overall environmental burdens from a range of competing technologies. The strength of the approach is that, as the analyses is made on a life cycle basis, materials, products or processes with different resource use and emission pathways can be compared. As noted by MacLean and Lave (2002):

> *"The most important contribution of these methods and studies is getting decision-makers to focus on the important attributes and to avoid looking and only one aspect of the fuel cycle or propulsion system or at only one media for environmental burdens"*.

In the case of road transport, the product/process cycles include the fuel and vehicle life cycles – covering the environmental impacts occur during the vehicle and fuel manufacture/production, use, recycling and disposal. Transport product/process LCAs can also include an assessment of the impacts associated with the extraction of raw materials, infrastructure requirements, and the end-of-life phases of the vehicle – these may include: solid, liquid and gaseous emissions; impacts on land use; resource depletion; and waste disposal issues. A comprehensive study of the range of approaches employed is provided by MacLean and Lave (2002).

While all LCAs include a scoping stage, most road transport life cycle assessments have tended to focus on the inventory analysis rather than the impact analysis stage. The inclusion of the improvement analysis is dependent on the options assessed and varies widely from one study to another. MacLean and Lave note the difficulties encountered in conducting a fuel/vehicle LCA and the controversies that can occur due to differences in boundary selection. For example, most LCAs applied to vehicle fuels and technologies in the UK have tended to focus solely on the fuel cycle and have not included the impacts associated with materials production, vehicle manufacture/assembly, transport and disposal.

Another important issue for a LCA of vehicle fuel and technology options is the comparability of vehicle types. Comparability in this context means that the vehicles compared should have similar performance characteristics such as engine power, physical size, range, etc. In this way the fuel/technology employed is the sole determinant of the environmental impact comparison. Conversely vehicles that use the same fuel/engine/drive-train of different size can be compared. One way the former comparison can be achieved is to use the same vehicle model for the evaluation – for example, a Vauxhall Astra using petrol and/or LPG. However, in many cases no corresponding model variant exists using two fuels or technologies. In this case, a vehicle type with specified performance characteristics must be defined, one that includes the two fuels/technologies to be compared.

For these reasons, this study therefore includes both the fuel and vehicle life cycles and assesses the cumulative impacts for a large range of vehicle types, vehicle fuels and vehicle technologies.[11] This builds on and combines the approach taken by previous life cycle studies such as the *Alternative Fuels Group of the Cleaner Vehicle Task Force Report* (DTI 2000) and the *Well-To-Wheels Analysis Of Future*

[10] Also known as a Life Cycle Analysis.
[11] Note that the impacts associated with infrastructure construction and use are not assessed.

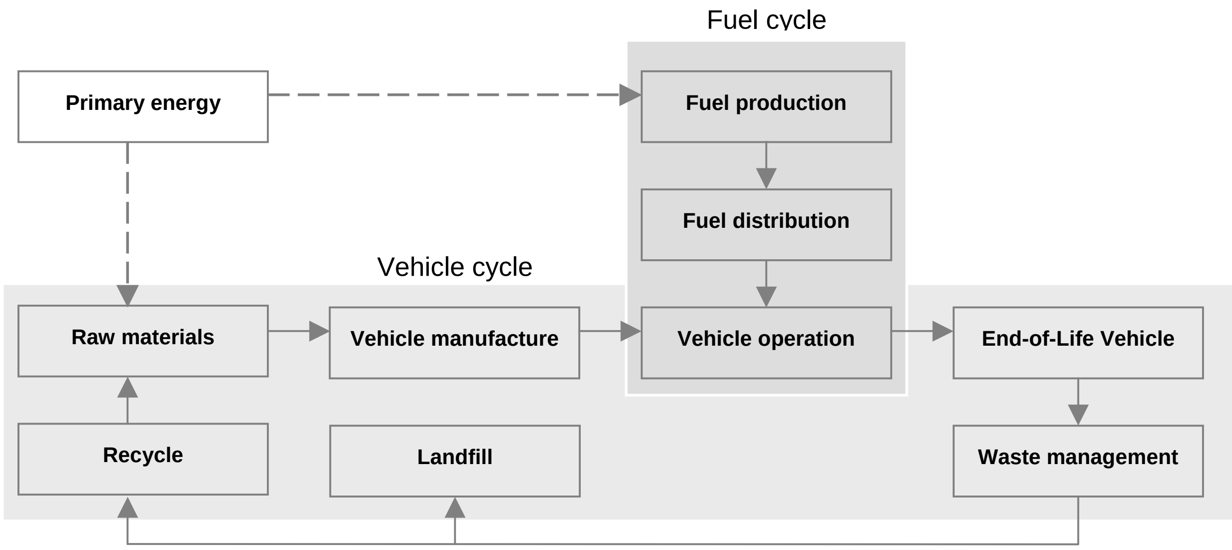
Automotive Fuels And Powertrains (Concawe 2004). As the methods employed by these studies focus exclusively on the fuel life cycle, they have been extended to include an assessment of the vehicle life cycle. The methodologies employed to account for the vehicle cycle impacts are taken from existing studies that include the *Life Cycle Inventory for the Golf A4* (Schweimer and Levin 2000), the *Environmental Evaluation of New Generation Vehicles and Vehicle Components* (Schexnayder *et al.* 2001), *Automobile Life Cycle Assessment Issues At End-Of-Life And Recycling* (Funazaki *et al.* 2003) and *Life Cycle Analysis Of Vehicles Powered By A Fuel Cell And By Internal Combustion Engine For Canada* (Zamel and Li 2005).

The next section begins by outlining the processes associated with the fuel and vehicle life cycles noting the key issues involved, before presenting a detailed description of the life cycle methodology used for this particular LCA study.

7.1 Fuel and vehicle life cycles

The environmental impacts of vehicles can be divided into two categories: those impacts associated with the production, processing and use of the fuel; and those impacts that arise during the manufacture, maintenance and disposal of the vehicle. Respectively, these are termed the *fuel cycle* and the *vehicle cycle*. If these cycles are taken to include all the product processes from cradle-to-grave, the terms used are *fuel life cycle* and *vehicle life cycle*. Figure 7.1 shows a diagrammatic representation of the intersecting fuel and vehicle life cycles.

Figure 7.1 Intersecting fuel and vehicle life cycles for road vehicle LCA



In the case of fossil fuels and biofuels, the ***fuel life cycle*** includes the following processes during which energy is consumed and emissions are generated:

- Feedstock production – production of the raw materials in order to obtain the fuel needed;
- Feedstock transport – the raw material has to be transported to the refineries or processing plants;
- Fuel production – refining/processing of the raw materials into standard fuel;
- Fuel distribution – distribution of the fuels to fuel stations;
- Fuel use – consumption of fuel during *vehicle operation* (sometimes assessed as part of vehicle cycle).

For petrol, diesel and some liquefied petroleum gas, the feedstock production and distribution stages involve the extraction and separation of crude oil or gas, gas flaring and venting, and the use of gas turbines to provide on-site power where required. After transport by tanker or pipeline to the refinery, the crude oil undergoes simple distillation with the possible addition of fluid catalytic cracking or hydrocracking processes to maximise the yield of useful distillation products (Concawe 2004). In most cases these are then distributed by pipeline to a terminal and then by road tanker to fuel stations for use.

Natural gas (and liquefied petroleum gas) may be extracted directly from a gas field or as part of a mixture from an oil and gas field. As for oil, energy is consumed during the extraction, gas flaring and venting. Usually, energy is supplied by gas turbine generators. The processing of natural gas (which is minimal) is carried out at terminals prior to the long distance transmission pipeline network. All that is required is removal of hydrogen sulphide and drying - sulphur dioxide is the main emission. During distribution by pipeline, some gas is lost via leakage so contributing to the overall emission impacts. Energy and emission are also generated during the compression required for high pressure refuelling systems.

For biofuels (biodiesel, bioethanol), the feedstock production involves either the growing of energy crops (oil seed rape, sunflower oil, palm oil and soybeans for biodiesel; and maize, wheat or sugar beet for ethanol) or the use of waste vegetable and animal oils (sourced from the food industry) (Concawe 2004). After harvesting the feedstock is transported to a processing plant for conversion to useful fuel. In the case of biodiesel, the crop is first crushed to extract the oils, which are then filtered and pre-processed to remove water and contaminants. The oils then undergo *esterification* (oil seed rape produces rape methyl ester or RME) whereby they are mixed with methanol and a catalyst. This breaks up the oil molecules that are first reformed into fatty acid methyl esters and glycerol and then separated from each other and purified. The production of ethanol first uses enzyme amylases to convert a feedstock into fermentable sugars. Yeast is then added to the mash to ferment the sugars to alcohol and carbon dioxide, the liquid fraction being distilled to produce ethanol. Biofuels of all types are finally distributed to fuel stations ready for use.

Electricity can be generated using a large number of energy sources. UK electricity is currently generated from gas (37%), coal (35%) and nuclear (22%) with renewables accounting for almost 3% (DTI 2004). In the case of the generation of electricity using fossil fuels, energy and emissions are generated during the extraction, transport and processing of the fuel feedstock (as mentioned above). These fuels are then used in either coal-fired (Conventional Steam Cycle, Pressurised Fluidised Bed Combustion, Or Integrated Gasification Combined Cycle) of gas-fired (mainly Combined Cycle) generating stations. For nuclear electricity, uranium must first be mined, then enriched and processed into a form suitable for the reactor type (Magnox, Gas Cooled, Advanced Gas Cooled or Pressurised Water Reactor). Excluding the construction and infrastructure environmental impacts, renewably generated electricity (from solar, wind and hydro-electric sources) produces virtually no emissions during the generation stage. Whichever sources are used to generate electricity, further energy losses occur during transmission to point of use.

For fossil fuels, biofuels and the two road fuel gases, the fuel use stage (vehicle operation)[12] involves the fuel's combustion either in an Otto (spark-ignition) or a Diesel (compression-ignition) engine. This converts the stored chemical energy into useful kinetic energy. Depending on the fuel used and the engine conditions, the combustion process leads to the formation of emissions that include: carbon dioxide and carbon monoxide. Nitrogen from the air is also oxidised to nitrogen oxides. Partially burnt and unburned fuel is present in the exhaust gases forming a complex cocktail of hydrocarbons such as methane and other volatile organic compounds including benzene and 1,3-butadiene. Particulate matter (PM) is also produced and is especially prevalent in diesel exhaust. Some pollutants are also produced away from the vehicle – for example, ground-level (tropospheric) ozone is formed by the chemical action of sunlight on emitted organic compounds.

The ***vehicle life cycle*** includes the following processes during which energy is consumed and emissions and waste are generated:

- Material production – the materials used include steel, plastics, non-ferrous metals such as aluminium, glass, rubber and composites such as glass fibre;
- Vehicle assembly – energy is required to assemble components and operate manufacturing plant;
- Vehicle distribution – transport of a vehicle from the assembly line to the dealerships;
- Vehicle maintenance – maintenance and repair over the lifetime of the vehicle;
- Vehicle disposal – end-of-life vehicles (ELVs) are shredded and a proportion of some materials are recycled for further use.

[12] Some LCAs include this stage as part of the vehicle cycle – but here the focus is on the fuel use and its combustion/transformation to provide energy, a process that (with the exception of pure electric vehicles) involves the production of vehicle emissions.

For conventional vehicles, approximately two-thirds of the weight of the average car is metal, most of which is comprised of sheet- and rolled-steel. Plastics (of many types) also comprise a large proportion of a vehicle mass (around 15% for a conventional car). For a complete breakdown (by mass) of a popular European model, the VW Golf, and of the most popular petrol-hybrid car, the Toyota Prius, see Table 7.1 (Schweimer *et al.* 2000; Daniels *et al.* 2004).

Table 7.1 Breakdown of the materials for VW Golf (2000) and Toyota Prius (2004)

Source: Schweimer 2000	Golf A4 1.4 petrol			Source: Schweimer 2000	Golf A4 1.9 diesel			Source: Daniels 2004	2004 Toyota Prius	
	kg				kg				kg	
Ferrous	634.4	59.9%		Ferrous	721.8	61.1%		Ferrous	776.9	59.8%
Aluminium	51.8	4.9%		Aluminium	49.9	4.2%		Aluminium	167.3	12.9%
Other non-ferrous metals	19.4	1.8%		Other non-ferrous metals	27.0	2.3%		Other non-ferrous metals	77.4	6.0%
Synthetics	167.5	15.8%		Synthetics	182.3	15.4%		Plastics	154.9	11.9%
Fluids	64.0	6.0%		Fluids	71.5	6.1%		Fluids+Organics	35.5	2.7%
Tyres and rubber	44.1	4.2%		Tyres and rubber	50.5	4.3%		Elastomers	39.7	3.1%
Glass	30.1	2.8%		Glass	30.1	2.5%		Inorganic mat	34.7	2.7%
Electronics	24.9	2.4%		Electronics	25.2	2.1%				
Insulation	16.3	1.5%		Insulation	16.4	1.4%				
Paints	4.2	0.4%		Paints	4.2	0.4%				
Others	2.1	0.2%		Others	1.9	0.2%		Others	13.6	1.0%
Total	**1058.8**	**100.0%**		**Total**	**1180.8**	**100.0%**		**Total**	**1300.0**	**100.0%**

For most conventional vehicles, the overall metal content of cars has declined during the past 20 years accompanied by an increase in the proportion of non-ferrous metals (in particular aluminium) and plastics used in their manufacture.[13] As can be seen from Table 7.1, for innovative vehicle types (especially those that employ electric drive trains) the range of materials used for vehicle construction differs from those that are based on a conventional mechanical drive unit with more non-ferrous metals used for lightweight body panels and for electric components (eg copper, zinc, nickel, lead). This is true to a greatest extent for battery-electric vehicles, especially if lightweight composites are used to form the body shell in place of steel or aluminium.

For all vehicle types, significant environmental impacts are associated with the use of process energy consumed during the production of raw materials for vehicle construction and assembly. The gaseous emissions produced by these processes include greenhouse gases (predominantly carbon dioxide) and other pollutants such carbon monoxide, oxides of nitrogen, hydrocarbons such as methane and other volatile organic compounds, and particulate matter. As is the case for the fuel cycle, these air emissions contribute to global warming, poor air quality, acidification and ozone depletion. Importantly, the vast majority of the energy use and carbon emissions (>99%) associated with the vehicle life cycle are due to the material production and assembly stages (Funazaki *et al.* 2003; Zamel and Li 2005). Although some environmental impacts specifically occur during vehicle distribution, maintenance, and disposal (see below), the energy use and carbon emissions associated with these stages can therefore be considered as not significant.[14]

When a car reaches the end of its useful life it is usually first dismantled to remove environmentally polluting materials such as operating fluids and batteries and those parts that can be sold for reuse. The remaining vehicle is then 'shredded' – this material comprises around 70% steel, 25% 'fluff' and the remainder, so-called, heavy media (Wasteonline 2004). Ferrous metals are then removed by magnetic separation and non-ferrous metals are sorted both mechanically and by hand. Even though the proportion of end-of-life vehicles currently recycled is much greater than any other UK consumer product, over

[13] There are a small number of car models that have body shells constructed entirely from aluminium – such as those in the Audi range.

[14] Although the energy use and carbon emissions associated with vehicle disposal are not significant (compared to the vehicle manufacture and assembly stages), some emissions do significantly contribute to global warming and stratospheric ozone depletion. For example, nearly three-quarters of the impact of ozone depletion is due to release of CFCs during the disposal stage (Funazaki *et al.* 2003).

400,000 tonnes of remaining material is still sent to landfill sites each year. This material is mainly made up of plastics, rubber, glass, dirt, carpet fibres and seat foam.

Currently about 98% of the (ferrous and non-ferrous) metals sourced from ELVs are recycled (Wasteonline 2004; ACCORD 2001). These metals are subsequently utilised by the steel industry and re-smelting plants. For other materials such as plastics and glass, the proportion of ELV materials recycled is low due, in part, (for plastics) to the wide variety of polymer types used and to the high cost of sorting and removal. Engine oil is also increasingly being recovered – where this occurs, the fluids are either processed (by removing excess water and filtering out particulates) and used as a fuel by heavy industry and power stations or used as a base lubricant.

EC Directive 91/157/EEC requires the separate collection of batteries containing more than 0.4% lead by weight, which includes vehicle starter batteries. Given the well-established system for the recovery of lead-acid car batteries (through local authorities and garage collection points), the recycling rate for car batteries is estimated to exceed 90%. Tyres, which account for around 3.5% of the mass of an ELV, are treated as a controlled waste under the Environmental Protection Act 1990. According to the Used Tyre Working Group's 2001 survey 22% were recycled, 8.3% went to energy recovery, 9.9% were retreaded, 16% were reused and 3.3% were used in landfill engineering (ACCORD 2001). The remainder (approximately 40%) will have been land-filled, stockpiled or disposed of illegally.

To control the disposal of waste and to increase the proportion of materials reused, recycled, the procedures and systems for the disposal of vehicles have been increasingly regulated. Since April 2002, all Member States within the EU have had to comply with the End-of-Life Vehicles Directive (2000/53/EC). This requires EU Member States to:

- Ensure that all ELVs are only treated by authorised dismantlers;
- 'De-pollute' vehicles before being recycled;
- Provide free take-back of all ELVs for new vehicles put on the market after 2002 – and for all vehicles including those put on market before 2002 from 2007;
- Restrict the use of heavy metals in vehicles from July 2003;
- Ensure that a minimum of 85% of vehicles are reused or recovered (including energy recovery) – at least 80% must be reused or recycled from 2006, increasing to a 95% reused or recovered (including energy recovery) and 85% reused or recycled by 2015.

7.2 Life cycle emissions methodology

As discussed in Section 4, this LCA study focuses on those vehicle fuel and technology options that are either currently commercially available (within the UK) or are considered by most analysts to be commercially viable within the near-term. These include the conventional fuels: ultra low sulphur petrol and diesel; biofuels: biodiesel, bioethanol; the road fuel gases: natural gas and liquefied petroleum gas; and those vehicle technologies that employ electric drive trains: battery-electric and hybrid-electric vehicles.

Vehicle fuels and technology options are compared for several vehicle types. However, unlike previous studies, the approach adopted by this LCA study uses the FISITA vehicle categories to provide the basis for generic comparisons and the context for particular models. These categories are as follows: for passenger cars: Citycar, Supermini, Small family car/small MPV, Large family car/large MPV, SUV 4x4. For light-duty vans, non-FISITA categories are used: Car-derived van,[15] Panel van. In addition to the normal vehicle class definitions, kerb mass parameters are also set for each category. For petrol vehicles, these are: Citycar (<900 kg), Supermini (900-1200 kg), Small family/MPV (1100-1350 kg), Large family/MPV(1300-1700 kg), SUV 4x4(>1600 kg), Car-derived van (900-1200 kg), Panel van (1750-2150 kg). Vehicles outside of these mass ranges are moved to another class or excluded from the analysis.

Particular models are also assessed. These are chosen to be representative (where possible) of the cleanest cars/vans for each FISITA segment and for each vehicle fuel/technology analysed. These vehicles include:

[15] Most car-derived vans are from the Supermini, Small Family and Small /MPV categories.

- City-car – Reva GWIZ (electric), Toyota Aygo/Peugeot 107/Citroen C1 (petrol/bioethanol/diesel), Smart ForTwo (petrol/bioethanol);
- Supermini – Corsa (petrol/bioethanol), Citroen C3 (diesel/biodiesel); Citroen C3 Stop & Start, Toyota Yaris (petrol), Hyundai Getz (diesel);
- Small family car - Honda Civic IMA (petrol hybrid), Vauxhall Astra (petrol/diesel/LPG/biethanol/ biodiesel), Audi A3 (petrol GDI), Citroen Berlingo (electric);
- Large family car – Toyota Prius (petrol hybrid), Toyota Avensis (diesel/biodiesel), Vauxhall Vectra (petrol/LPG), Peugeot 407 FAP (diesel with particulate filter), Volvo S60 (petrol/CNG);
- SUV 4x4 – BMW X3 (petrol/diesel/bioethanol/biodiesel), Lexus RX400h (petrol hybrid), Lexus RX300 (diesel); Suzuki Grand Vitara (diesel);
- Car-derived van – Citroen C2 (diesel/biodiesel), Citroen Berlingo (diesel/electric); Vauxhall Astravan (diesel/petrol/LPG);
- Panel van – Ford Transit (diesel/LPG), Volkswagen LT35 (diesel/electric/diesel-hybrid/biodiesel).

Due to the importance of air emissions in the context of road transport and also due to the time and resource limitations of the study, this LCA study focuses exclusively on quantifying the extent and impacts of life cycle *air emissions* arising from the fuel and vehicle cycles. However, this report recognises the importance of non-air pollutant loadings and refers the reader to the discussion in the previous section – for detailed inventories and assessments of emissions/impacts other than air emissions, see Sullivan (1998), Schweimer and Levin (2000), Schexnayder *et al.* (2001).

The emissions analysed include the regulated emissions (carbon monoxide, oxides of nitrogen, hydrocarbons and particulates). Sulphur dioxide (SO_2) and nitrous oxide (N_2O) data are sourced where available. In addition, the three main greenhouse gases associated with road transport are assessed: carbon dioxide, nitrous oxide and methane. These greenhouse gas emissions are combined to provide a single measure of greenhouse gas impacts by using accepted global warming potentials (GWP) for each of the gases – these provide a weighting for each gas, which is a measure of their effect on atmospheric warming over a determined time period. (The GWP for carbon dioxide is taken as unity; the GWP for methane is equal to 21 for a 100-year time horizon. Where nitrous oxide is assessed, a GWP value of 310 is used.)

The outputs of the study include an emissions comparison for each of the vehicle types assessed. However, as discussed previously in Section 7, most vehicle fuel/technology LCA studies do not attempt to quantify the environment impact of the pollutants generated. To address this issue, the methodology also includes a (partial) impact analysis stage within the life cycle emission methodology. This is achieved by the use of the Car Environmental Rating Tool developed by the European Cleaner Drive Programme.[16] The rating system uses recognised 'external costs' to establish the relative weight to attach to different emissions. External costs of emissions are values expressed in monetary terms that reflect the overall damage to the environment and to human health caused by emissions.

Table 7.2 summarises the scope and emissions assessed for the separate and combined analysis of greenhouse gas and regulated emissions, over the vehicle and fuel life cycles.

Table 7.2 Scope and outputs of life cycle assessment

	Scope of environmental impact analysis	Life cycle emissions comparison	Life cycle emissions rating
Fuel cycle	Fuel production	Greenhouse gas and regulated emissions comparison for cars and light-duty vans	Greenhouse gas and regulated emissions comparison for light-duty vehicles – using single score rating system (based on Cleaner Drive Environmental Rating Tool)
	Vehicle operation		
Vehicle cycle	Materials manufacture		
	Vehicle assembly		

[16] For more information, see Appendix 3 and/or visit the Cleaner Drive website at: www.cleaner-drive.com.

Fuel life cycle emissions methodology

As described in detail by MEET (1997), Concawe (2004) and LowCVP (2004), the following outlined energy pathways are assumed for the purposes of the LCA analysis:

- **Petrol/diesel**: Crude oil extraction → production and conditioning → shipping → refining → mixed transport to depot → 150 km road transport to fuel stations;
- **Natural gas** (EU mix): extraction → production and conditioning → transport by pipeline within EU → national NG grid → on-site compression ready for use;
- **Liquefied petroleum gas**: Either as a by-product from petrol/diesel energy pathway or during extraction of natural gas;
- **Biodiesel**: Rape seed cultivation (with glycerine as animal feed export) → drying → 50 km transport to processing plant → 150 km road transport to fuel stations;
- **Bioethanol**: Wheat cultivation → transport to processing plant → fermentation, distillation, dehydration (combined heat + power unit using natural gas turbine) with animal feed export;
- **Average UK Electricity**: Mix of coal, gas, nuclear and renewable pathways → power station → high voltage distribution via national grid to point of use;
- **Renewable UK Electricity**: Mix of hydro and wind pathways → high voltage distribution via national grid to point of use.

Fuel production emissions are calculated using published data quoted on an energy delivered basis (grams per GJ) for the following emissions (where available): CO, HCs, NOx, PMs, SO2, CO_2, CH_4, and N_2O. Data is used from the following sources: Concawe (2004), LowCVP (2004), Wang (2001), Hart *et al.* (2000), the Cleaner vehicle task Force Report (DTI 2000) and MEET (1997). This figure is then multiplied by the vehicle energy use (MJ/km) (sourced from the VCA database – see below) to give the production emission in grams per kilometre. (Note that secondary energy and environmental effects are not quantified – eg impacts associated with the construction of energy generating, refinery, and process plants are not included.)

For vehicles that are powered by petrol, diesel or the two road fuel gases, estimates for fuel economy and vehicle emissions generated during vehicle operation are sourced from the Vehicle Certification Agency (VCA) that provides fuel economy and CO_2, NOx, HC, PM, CO and noise emission data for all new cars available in the UK.[17] The data is specified in grams per kilometre and is taken from measurements made over a test cycle as described in Directive 93/116/EC. With the use of an additional parameter, the VCA sourced data set is categorised according to FISITA vehicle categories to provide the basis for generic comparisons. These categories are as follows: for passenger cars: Citycar, Supermini, Small Family car/ MPV, Large family car/MPV, SUV 4x4; for light-duty vans: Car-derived van, Panel van.

Although the test cycle used is not fully representative of real world driving conditions, it does attempt to model these conditions and includes cold start conditions.[18] The test consists of two parts: an urban and an extra-urban cycle. The urban test cycle is carried out on a rolling road and consists of a series of accelerations, steady speeds, decelerations and idling – maximum speed 31 mph, average speed 12 mph and the distance covered is 2.5 miles. The extra-urban cycle is conducted immediately following the urban cycle and consists of roughly half steady-speed driving and the remainder accelerations, decelerations, and some idling – maximum speed is 75 mph, average speed is 39 mph and the distance covered is 4.3 miles. The combined figures for the urban and extra-urban cycle together, are weighted by the distances covered in each part.

For vehicles fuelled by liquefied petroleum gas and natural gas, estimates of fuel economy and vehicle emissions are made from comparative tests data sourced from the Energy Saving Trust and the Vehicle Certification Agency – using this data direct comparisons of emissions using road fuel gases can be made

[17] Vehicle Certification Agency. VCA website URL: http://www.vca.gov.uk/.

[18] There is some evidence that the difference between test cycle data and actual on-road fuel economy is of the order of 20% (Fleet News 2005). However, the advantage of using this test cycle is that it makes comparison of the options possible by having a standardised test.

with petrol using a bi-fuel conversion. For vehicles powered by biofuels, estimates of fuel use emissions are made from comparative studies of biofuel and fossil fuel operation. These reports include: DfT 2004a; DfT 2004b; LowCVP 2004; E4Tech 2003; NREL 2003; and Concawe 2004. For hybrids vehicle emissions are compared with petrol operation based on theoretical and empirical data (Lave and MacLean 2002; E4Tech 2003; Concawe 2004) (see Table 7.3). For battery-electric vehicles, all fuel use emissions are assumed to be zero – data for fuel economy are based on scaling a Peugeot Berlingo Electric (fuel economy 22 kWh/km) according to vehicle mass.

Table 7.3 Relative vehicle emissions used in model

Fuel/ Technology	PM	HC	CO	NOx	CH_4	CO_2	Fuel economy	Baseline
	g/km	g/km	g/km	g/km	g/km	g/km	lit/100km	
Biodiesel[1] (RME)	▼15%	▼20%	▼20%	▲7.5%	N/A	▲3.6%	▲9.6%	ULSD-ICE
Bioethanol[2]	N/A	►same	▼20%	▲5%	N/A	▼4.1%	▲51%	ULSP-ICE
LPG[3]	N/A	▼4%	▲2%	▼33%	N/A	▼9%	▲34%	ULSP-ICE
CNG[4]	N/A	▲12%	▼6%	▼58%	▲82%	▼23%	N/A	ULSP-ICE
Petrol-HEV[5]	N/A	▼75%	▼75%	▼75%	N/A	▼30%	▼30%	ULSP-ICE

Sources: [1] DfT 2004a; DfT 2004b; E4Tech 2003; NREL 2003; Concawe 2004
[2] DfT 2004b; E4Tech 2003; LowCVP 2004; Concawe 2004 [3] EST 2006; VCA 2005
[4] DTI 2000; VCA 2005; Concawe 2004 [5] Lave and MacLean 2002; E4Tech 2003; Concawe 2004

Vehicle life cycle emissions methodology

Standardised emission data associated with the vehicle cycle is not as widely available as it is for the fuel cycle (ie fuel production and vehicle emission stages). Therefore, for the vehicle life cycle emissions, a method has been developed based on existing research by Zamel and Li (2005). This method enables an estimate to be made for the emissions associated with the vehicle cycle on a per vehicle basis. Combined with assumptions about lifetime mileages, a value for emissions per kilometre can be calculated.

The method used by Zamel and Li considers the energy use and emissions associated with the production of the vehicle materials, its assembly, distribution and disposal. From an *energy and emissions perspective*, the research finds that:

> *"The material production step is very much dependent upon the average weight of each material being used in the vehicle… The analysis shows that the material production step is responsible for almost 75% of the energy consumption and emissions during the vehicle life cycle" (Zamel and Li 2005*).

Furthermore, most of the remaining energy use and emissions is associated with vehicle assembly with less than 1% being associated with distribution and disposal. Therefore, for the method employed by this LCA analysis, only material production and vehicle assembly stages are analysed for the vehicle cycle. This simplification of the methodological approach enables a workable method to be used, one that required only limited input data, but that gives a robust indication of vehicle cycle emission impact.

The data required by the model to estimate the emissions associated with the vehicle cycle are: the mass of the vehicle (kg), the distribution of the material used in the vehicle by mass (kg) using a system of 12 material category types, the emissions associated with the production of each material category (grams/kg) and the total energy required for vehicle assembly (MJ). The production emissions for each of the material categories analysed are shown in Table 7.4.

Note that given the largest proportion of a conventional vehicle's mass is composed of Iron and Steel and given the high energy requirement of aluminium production, emission data for these particular materials has been sourced from International agencies in detail: IPAI (2000), IISI (2002), IAI (2003). Due to time/resource constraints in compiling equivalent data for all other categories, generic data has been used for material types (Rydh and Sun 2005). Errors introduced by these assumptions are minimal due to the low content of these materials within a vehicle (see Table 7.5). Note that not all emissions data is available – however, as an *indicator* of emission extent rather than a full emission inventory, it is believed that the data represents the quantity of emission associated with each vehicle type (see Section 7.4)

Table 7.4 Material production emissions per unit mass

gms/kg	PMs	NOx	CO	HCs	SO2	CO2	CH4	N20	Reference
Ferrous	1.85	3.33	29.02	1.40	3.77	2352	1.23	0.12	IISI 2002
Composites		36.00		12.00	23.00	12000	12.00		Rydh and Sun 2005
Aluminium	8.25	12.00	1.65	15.45	33.15	6049 (i)			IPAI 2000; IAI 2003
Copper		10.00		1.40	658.00	20000	1.40		Rydh and Sun 2005
Zinc		20.00		9.70	65.00	10000	9.70		Rydh and Sun 2005
Lead		2.60	0.34	0.16	7.40	1680	0.06		DeLucci 2004
Magnesium		20.00		9.70	65.00	10000	9.70		Rydh and Sun 2005
Nickel		10.00		1.40	658.00	20000	1.40		Rydh and Sun 2005
Plastics		20.70		19.00	26.70	3800	19.00		Rydh and Sun 2005
Rubber		10.00		5.00	15.00	1700	5.00		Rydh and Sun 2005
Glass		2.30		0.79	2.30	760	0.79		Rydh and Sun 2005
	Note: no entry denotes that no data is available - the model therefore assumes no emissions of this type. (i) CO2 equivalent (inlcudes all greenhouse gas emissions).								

Six vehicle types are assumed to represent all the vehicles analysed – using the 12 material categories mentioned above, these are characterised by their material composition and are normalised to a total mass of 1000 kg – see Table 7.5. For each of these vehicle types, the mass of each of the constituent materials is multiplied by the respective emissions per unit mass associated with the material's production (Table 7.4). This provides an estimate of the manufacture emissions profile associated with that particular vehicle type.

Added to this figure is an estimate of the emissions produced during vehicle production and assembly – this is estimated as a linear function of vehicle mass and is assumed the same for all vehicle types irrespective of technology used (due to the complex supply chain in the automobile industry). The assembly emissions used are sourced from VW production plant data (Schweimer and Levin 2000). This total figure is then divided by the total vehicle mass and lifetime vehicle mileage to provide an estimate of the emissions associated with that particular vehicle type per kg-km. Finally, multiplying by a vehicle's mass – or the average mass for each FISITA segment considered – provides the emissions associated with a vehicle's production.

Table 7.5 Material composition of six normalised vehicle types
(Sources: Schweimer and Levin 2000; Daniels *et al.* 2004; Reva 2005)

Normalised composition	ICE Petrol		ICE Diesel		HEV Petrol-NiMH		ICE bi-fuel		Conversion BEV Pb-Ad		Dedicated BEV Pb-Ad	
	kg		kg		kg		kg		kg			
Ferrous	*599.2*	59.9%	*611.3*	61.1%	*597.7*	59.8%	*620.0*	62.0%	*475.6*	47.6%	340.01	34.0%
Composites	*0.0*	0.0%	*0.0*	0.0%	*0.0*	0.0%	*0.0*	0.0%	*0.0*	0.0%	18.337	1.8%
Aluminium	*48.9*	4.9%	*42.3*	4.2%	*128.7*	12.9%	*46.4*	4.6%	*12.4*	1.2%	33.619	3.4%
Copper	*3.2*	0.3%	*4.1*	0.4%	*31.6*	3.2%	*3.1*	0.3%	*9.9*	1.0%	55.471	5.5%
Zinc	*3.2*	0.3%	*4.1*	0.4%	*3.0*	0.3%	*3.1*	0.3%	*5.8*	0.6%	0	0.0%
Lead	*8.6*	0.9%	*10.7*	1.1%	*5.0*	0.5%	*8.1*	0.8%	*154.3*	15.4%	283.47	28.3%
Magnesium	*3.2*	0.3%	*4.1*	0.4%	*8.5*	0.9%	*3.1*	0.3%	*5.8*	0.6%	0	0.0%
Nickel	*0.0*	0.0%	*0.0*	0.0%	*9.2*	0.9%	*0.0*	0.0%	*0.0*	0.0%	0	0.0%
Plastics	*158.2*	15.8%	*154.4*	15.4%	*119.2*	11.9%	*150.0*	15.0%	*140.4*	14.0%	108.19	10.8%
Fluids	*60.4*	6.0%	*60.6*	6.1%	*27.3*	2.7%	*57.3*	5.7%	*26.8*	2.7%	89.089	8.9%
Rubber	*41.7*	4.2%	*42.8*	4.3%	*30.5*	3.1%	*39.5*	3.9%	*37.0*	3.7%	30.562	3.1%
Glass	*28.4*	2.8%	*25.5*	2.5%	*26.7*	2.7%	*27.0*	2.7%	*25.2*	2.5%	30.562	3.1%
Others	*44.9*	4.5%	*40.4*	4.0%	*12.5*	1.2%	*42.5*	4.3%	*106.9*	10.7%	10.697	1.1%
Total	**1000**	**100.0%**	**1000**	**100.0%**	**1000**	**100.0%**	**1000**	**100.0%**	**1000**	**100.0%**	**1000**	**100.0%**

Life cycle environmental impact rating

To assess environmental *impact*, the LCA study makes use of the Car Environmental Rating Tool developed by the European Cleaner Drive Programme.[19] The rating system uses recognised 'external costs' to establish the relative weight to attach to different emissions. External costs of emissions are values expressed in monetary terms that reflect the overall damage to the environment and to human health caused by emissions – see Appendix 3.

The Cleaner Drive rating methodology uses a weighted index of carbon dioxide, methane, nitrous oxide, oxides of nitrogen, hydrocarbons, carbon monoxide, particulate matter and sulphur dioxide emissions associated with fuel use and production to produces a single score out of 100 – the higher the score, the lower the environmental impact (see Box below). The cleaner Drive rating system can also provide separate scores for greenhouse gas and air quality impacts. In order to include the vehicle life cycle emissions, this methodology has been extended to include emissions associated with vehicle manufacture – materials production and vehicle assembly (see last Section). As far as the author is aware, this is the first time this method has been extended to include vehicle life cycle impacts.

Note that for consistency of presentation of charts, a reverse rating is used based on the Cleaner Drive score – this is simply the score subtracted from 100 (ie New Cleaner Drive score = 100 – Original Cleaner Drive score). This results in cleaner vehicles with *lower* emissions having a *lower* environmental rating.

Note also that, for vehicles with very high life cycle emissions, the New Cleaner Drive score can occasionally be greater than 100. This mainly occurs in cases where total life cycle CO_2 emissions are greater than 300 grams/km. This anomaly is due to that fact, as the original methodology excluded vehicle life cycle emissions, 300 grams/km was rarely exceeded. However, cases with scores greater than 100 are still rare, and are referred to in the text where appropriate.

The integration of fuel and vehicle life cycle emission using the Cleaner Drive rating system has the advantage of simplifying the interpretation of results. This is because the comparison of options is made complex due to the fact that each fuel/technology type offers different global and local emission benefits, as well as a different range of vehicle manufacture and ELV issues – for example, hybrid-electric, natural gas and liquefied petroleum gas vehicles provide reductions (to different degrees) in life cycle greenhouse gas and NOx emissions. For other options, such as biodiesel and battery-electric cars, a reduction in one emission may be accompanied by an increase in another pollutant. This makes balancing the environmental pros and cons of each option a difficult task and highlights an important question – is a reduction in greenhouse gases more or less important than a reduction in local pollutants? Given that there is no definitive method of balancing the global environmental impacts with those that are local, using Cleaner Drive to combine emissions of all types (from all cycles) goes someway to integrating the climate change and air quality impacts.

It should be noted that other impact assessment methodologies (such as Ecoscore) could have been used. Both vehicle rating systems have been developed for the assessment of vehicles with alternative types of fuels as well as different types of drive train, such as electric, hybrid and fuel cell vehicles. However, Mierlo *et al.* (2004) has compared the Cleaner Drive methodology with Ecoscore, using a well-to-wheel approach to compare the methodologies regarding several types of pollution including: acid rain, photochemical air pollution, noise pollution and global warming; and their impact on ecosystems, buildings and human beings (cancer, respiratory diseases, etc.). Although Ecoscore shows higher sensitivity to changes in input variables, the parameters used are specifically designed for the Brussels region. Cleaner Drive is therefore more transferable to all areas within the EU. It also gives higher weighting to greenhouse gas emissions than Ecoscore and is therefore better suited to the UK transport policy context.

[19] For more information, see Appendix 3 and/or visit the Cleaner Drive website at: www.cleaner-drive.com.

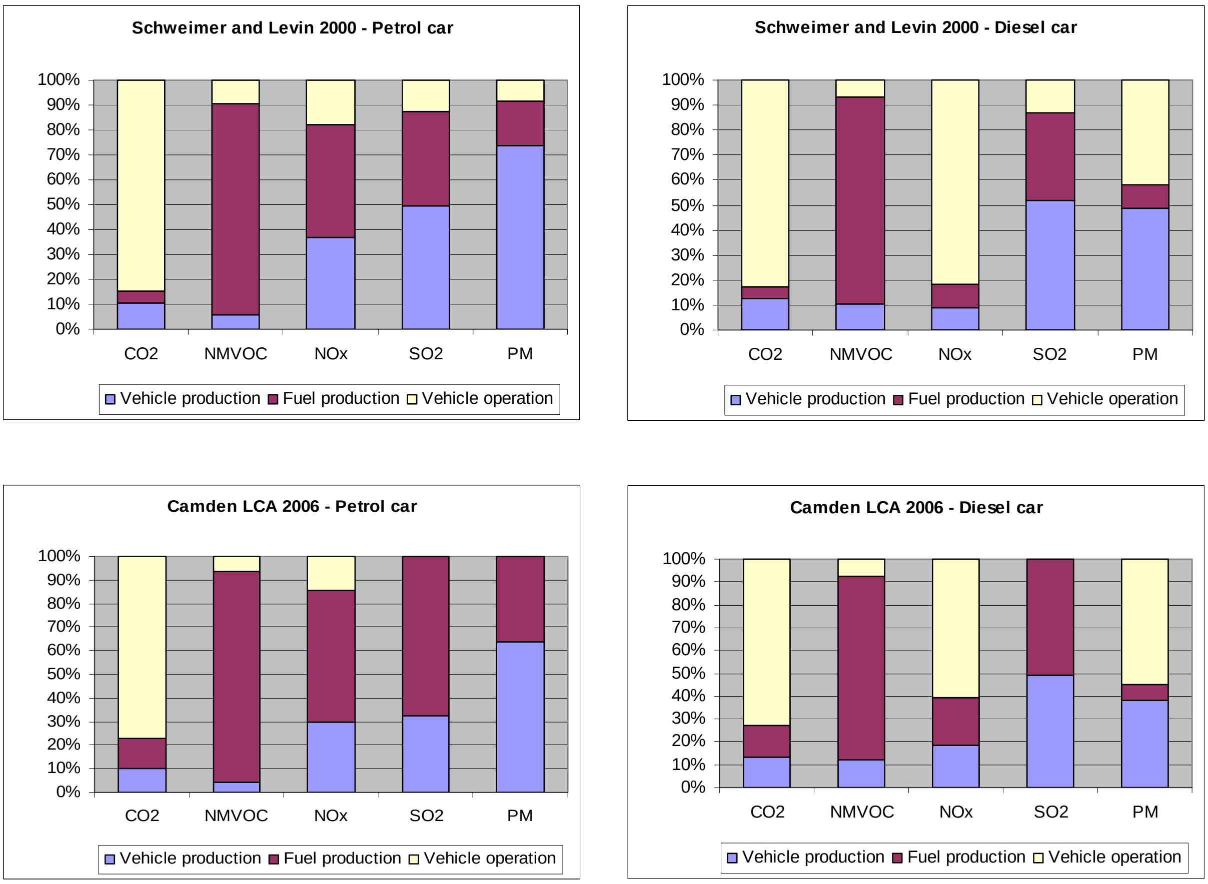
7.3 Methodology consistency checks

As a check of the LCA methodology used by this study, the estimated proportion of emissions arising from the vehicle and fuel life cycles have been compared with the figures from other research reports. Comparison of the results from this study with Schweimer and Levin (2000) and Sullivan *et al.* (1998) show very close agreement. After total lifetime mileages have been equalised, all three studies show that, for a medium sized petrol car, the vehicle production stage accounts for approximately 10% of total life cycle CO_2 emissions, the remaining 90% arising during fuel production and vehicle operation – the figures are equivalent to within 0.8%. Although Funazaki *et al.* (2003) reports a larger proportion (19%), it is unclear from the paper cited what type of vehicle has been analysed (petrol or diesel), or what lifetime mileage has been assumed.

A more detailed comparison can be made with Schweimer and Levin (2000) as this report provides a breakdown of the emissions generated during vehicle production, fuel production and vehicle operation for five emissions (CO_2, non-methane HCs, NOx, SO_2 and PM). Data are given for both petrol and diesel cars. After total lifetime mileages have been adjusted, the data show close agreement – as can be seen in Figures 7.2 to 7.5.

The main differences are due to (i) slightly lower vehicle operation NOx emissions for this LCA study – possibly a reflection of tighter EU vehicle emission regulations; (ii) slightly lower vehicle operation CO_2 emissions for this LCA study – possibly a reflection of the ACEA voluntary agreement on fuel economy; (iii) increased SO_2 and PM emission associated with petrol fuel production stage; (iv) the omission of vehicle operation SO_2 emissions from this LCA study (the data-set assumes zero vehicle SO_2 emissions); and (v) the omission of vehicle operation PM emissions from this LCA study for petrol cars (the data-set assumes zero vehicle particulate emissions);

Figures 7.2 – 7.5 Comparison of Camden LCA data with Schweimer and Levin (2000)



8 Life cycle emissions results – generic

This section uses the methodology developed to estimate the life cycle emissions for generic vehicle types based on five FISITA car and two light-duty van classes. As described in Section 7, life cycle comparisons are made for greenhouse gases (CO_2, CH_4, N_2O) and four regulated emissions (PM_{10}, NOx, CO, HCs). The Cleaner Drive rating system is also used to assess and compare the overall life cycle impacts for different vehicle fuels/technologies using the amended Cleaner Drive score[20] (see Appendix 3).

The results of the LCA analysis are shown in Figures 8.1-8.18. Note the key used on the charts: petrol (ULSP), diesel (ULSD), bioethanol (BioE), biodiesel (BioD), liquefied petroleum gas (LPG), compressed natural gas (CNG), battery electric using average mix electricity (AvBEV), battery electric using renewable electricity (ReBEV) and petrol-hybrid (HEV).

When using the charts, it is important to remember the restricted definitions of the fuel/technology options considered. Petrol and diesel are ULSP and ULSD as defined by the existing sulphur content specifications (see Section 6.1). Biofuels values are for 100% biofuels (ie E100 and B100). Although in practice biofuel blends (eg E5, B5) are more likely to be available in the short- to medium-term (due to vehicle manufacture warranty issues – see Sections 6.2 and 6.3), the charts are intended to shown the full potential of biofuels. To a first approximation, life cycle impacts for biofuel blends can be interpolated from the values shown. The two road fuel gases (CNG and LPG) cases shown are for bi-fuel vehicles – dedicated vehicles may offer larger environmental benefits than shown (see Sections 6.4 and 6.5). Hybrid cars are assumed to be 'strong' petrol-hybrids (see Section 6.6). The two battery-electric cases shown are for average UK electricity mix (including non-renewable sources) and 100% renewable electricity (see Section 6.7).

The following sections refer primarily to passenger cars – however, the comparisons for car-derived and panel vans are broadly the same (for fuel/technologies analysed).

8.1 Carbon dioxide (CO_2) and other Greenhouse Gases (GHGs)

The first observation is that, in most cases, the vehicle manufacture and fuel production stages account for around 20% of total lifetime CO_2 emissions – the emissions associated with fuel and vehicle production are roughly equal in magnitude. This is the case for conventional petrol and mineral diesel, the two road fuel gases and also for petrol-hybrids. This proportion does not hold true for biofuels, the emissions associated with fuel production being significantly increased – note that the charts only show the emissions associated with vehicle and fuel production as the vehicle operation emissions are assumed to balance the carbon capture during biomass growth). For battery electrics, vehicle and fuel production emissions account for all life cycle emissions, the vehicle being zero-emission in operation.

Across the vehicle categories, petrol has the highest CO_2 emissions on a life cycle basis. In comparison, liquefied petroleum gas shows a 13% reduction (lying almost midway between petrol and diesel), mineral diesel 16%, and compressed natural gas show a 25% reduction, bioethanol a 37% reduction, and biodiesel >70% reduction. For those vehicles using an electric drive train, petrol-hybrids show a 27% reduction, battery electric cars using average mix electricity a 43% reduction, and for those using renewables for propulsion the reduction is at least 80%. Note that the CO_2 reductions for battery electrics are not as great as might be expected, as vehicle production emissions are higher than for conventional cars.

In all cases other than the two battery electric cases, total life cycle CO_2 emissions are dominated by vehicle emissions (during operation) – again note that for biofuels, although the vehicle still emit CO_2, vehicle emissions do not appear on the charts as these are balanced by carbon uptake during growth of energy crop. For biofuels (after the carbon-balance is accounted for) and the two BEV cases, life cycle emissions are dominated by fuel production emissions.

[20] This is simply the score subtracted from 100 (ie New score = 100 – Cleaner Drive score). This results in cleaner vehicles with *lower* emissions having a *lower* environmental rating**.**

Life cycle Greenhouse Gas (GHG) emissions are very similar to those of CO_2, the only differences being where lifetime methane (CH_4) and nitrous oxide (N_2O) emissions are significant. The two cases where these gases have a significant impact are: biodiesel – the amount of N_2O released during crop production reduces the CO_2 benefit of >70% to a GHG reduction of around 43% (as compared to petrol); and natural gas – life cycle methane emissions reduce the 25% CO_2 benefit to a GHG benefit of 19%.

As expected, the results show that vehicle size (according to the FISITA classes analysed) is strongly correlated to life cycle emissions of greenhouse gases. This is due to the effect of fuel economy on vehicle emissions (for every fuel considered) and also to the fact higher fuel use requires an increase in fuel production energy which in turn leads to increased emissions. In addition, the vehicle cycle also contributes to this correlation – larger vehicles (that tend to have higher fuel use) require more materials and assembly energy during manufacture.

8.2 Particulates (PM_{10})

Of the cases compared, battery electric vehicles using average mix electricity (AvBEV) and bioethanol have the largest particulate emissions by far on a life cycle basis. This is due to high levels of particulates emitted during electricity generation and biofuel production respectively. Diesel and biodiesel life cycle emissions are also greater in particulates than for other cases due to significant particulate emissions generated during vehicle operation. That said, all other cases are remarkably similar in life cycle particulates – this is due primarily to the fact that (for most cases) the majority of life cycle particulate emissions are associated with vehicle manufacture. Although difficult to distinguish within confidence limits, the vehicle types associated with the lowest levels of life cycle particulates are those using the two road fuel gases, petrol-hybrids and battery electrics using renewable electricity.

For diesel vehicle operation (including biodiesel), up to half of life cycle particulates are emitted during vehicle use. However, for all other cases, all particulate emissions are generated away from most major urban areas – the exception being where a refinery, fuel processing or vehicle manufacturing plant lies within a populated region.

For mineral and biofuel diesels, the correlation of life cycle particulate emissions with vehicle class is far less strong that is the case for greenhouse gases – indeed, particulate emissions associated with all diesel vehicle classes are equivalent within the confidence limits shown. For other cases, as the level of PM emissions is dependent on fuel economy (the emissions being associated with fuel and vehicle production), the correlation still applies.

8.3 Nitrogen Oxides (NOx)

The biofuels bioethanol and biodiesel have the largest life cycle NOx emissions due to emissions generated during fuel production, and (for biodiesel) to the additional emissions generated during vehicle operation. The next highest NOx emissions are associated with battery electrics using average electricity mix due to power station emissions (as is the case for particulates). This is in contrast to vehicles using mineral diesel whose NOx emissions are dominated by vehicle operation emissions. Indeed, for both diesel cases, vehicle operation contributes significantly to life cycle emissions of NOx. Life cycle NOx for petrol is around 60% of the level for conventional diesel. The lowest life cycle NOx is associated with petrol-hybrids, natural gas and renewable powered battery-electrics, all of which are equivalent within confidence limits.

For diesel vehicle operation (including biodiesel), around 25%-75% of life cycle NOx emissions are emitted during vehicle use. However, for all other cases, all NOx emissions are generated away from most major urban areas – the exception being where a refinery, fuel processing or vehicle manufacturing plant lies within a populated region.

For mineral and biofuel diesels, the correlation of life cycle NOx emissions with vehicle class is far less strong than is the case for greenhouse gases – indeed, NOx emissions associated with all mineral diesel vehicle classes are broadly equivalent within the confidence limits shown. For other cases, as the level of

NOx emissions is dependent on fuel economy (the emissions being associated with fuel and vehicle production), the correlation still applies.

8.4 Carbon Monoxide (CO)

In general, for options using mechanical drive trains, the chart shows that vehicle (and life cycle) emissions of CO are highest for conventional spark-ignition engines and less for compression engines. Overall, bioethanol is associated with the highest life cycle CO emissions due to high levels of CO generated during fuel production. The lowest life cycle CO is associated with vehicles that use electric drive trains including battery electrics and petrol-hybrids – the hybrid's vehicle (and therefore life cycle) CO emissions being significantly lower than for a conventional petrol equivalent.

Note that, for conventional fuels and the two road fuel gases, most CO emissions are generated at the point of use. However, CO is generally considered one of the least harmful pollutants (with respect to air quality) and Air Quality Targets are usually satisfied with regard to this pollutant.

With the exception of battery electric vehicles and bioethanol (where fuel production emissions dominate), there is no apparent correlation of life cycle CO emissions with vehicle class – CO emissions associated with all vehicle classes are broadly equivalent within the confidence limits shown. For the two battery electric cases and bioethanol, as the level of CO emissions is dependent on fuel economy (the emissions being associated with fuel and/or vehicle production), the correlation still applies.

8.5 Hydrocarbons (HCs)

In contrast to the situation for carbon monoxide, the vast majority of life cycle HC emissions (including methane) occur during fuel production – the only exception being where renewables are used for propulsion energy. Natural gas vehicle generate the largest level of life cycle hydrocarbons due primarily to methane emissions associated with the extraction and distribution of natural gas (which also has implications for global warming as methane is a potent greenhouse gas). Conventional petrol fuelled vehicles have significantly larger hydrocarbon emissions as compared to their conventional diesel equivalents due to higher processing/manufacturing plant emissions. However, the difference is almost reversed for their biofuel equivalents (ie bioethanol versus biodiesel). Overall life cycle HC emissions are low for mineral diesel, bioethanol, liquefied petroleum gas and battery electric using average mix electricity, and lowest for renewably charged battery electric vehicles.

Note that for all cases, the vast majority of life cycle hydrocarbon emissions are generated away from most major urban areas – the exception being where a refinery, fuel processing or vehicle manufacturing plant lies within a populated region.

As is the case for greenhouse gas emissions, the results show that vehicle size (according the FISITA classes analysed) is strongly correlated to life cycle emissions of HCs. This is due to the fact that higher fuel use requires an increase in fuel production energy, which in turn leads to increased emissions. In addition, the vehicle cycle also contributes to this correlation – larger vehicles (that tend to have higher fuel use) require more materials and assembly energy during manufacture.

8.6 Cleaner Drive Rating[21]

Focusing on the Cleaner Drive rating for greenhouse gases (Figure 8.7), and using petrol as a baseline, as expected from the emission data already discussed, the rating for mineral diesel is lower by 15%. The two road fuel gases (LPG and CNG) are rated at 12% and 19% below the petrol baseline respectively (again as expected from CO_2 and CH_4 methane comparisons). The ratings for petrol-hybrids are around 27% lower than for petrol reflecting the fuel efficiency improvements offered by hybridisation. Bioethanol and biodiesel fare particularly well on a greenhouse gas rating, lying respectively around 37% and 43% below

[21] This report subtracts the original Cleaner Drive score (which is out of 100) from 100 to give a rating from 0 to 100 – the lower the rating, the lower the environmental impact.

the petrol baseline. The cleanest scoring case (as rated by the Cleaner Drive) is the renewable battery-electric case with a reduction of over 80%.

Within each vehicle fuel/technology type, the Cleaner Drive GHG rating is highly dependent on vehicle size – for the four smallest FISITA classes, moving down one category typically reduces the Cleaner Drive GHG Rating by 7-10 points (with the exception of renewable BEV case which is scored consistently low). For all fuels/technologies, the difference between the rating of the smallest (Citycar) and largest (SUV) categories is around a factor of 2.5 – ie according to the Cleaner Drive GHG rating, Citycars have less than half the environmental impact than SUVs (irrespective of fuel/technology type used).

Focusing on the Cleaner Drive rating for air quality (Figure 8.8)[22], the picture is slightly more complex than the greenhouse gas comparison. Using petrol as a baseline, again as expected from the emission data already discussed, the rating for mineral diesel is higher by up to 67% (depending on vehicle class) indicating a greater environmental impact. The two biofuels (bioethanol/biodiesel) show an increase of around 24%/28% as compared to their petrol ULSP/diesel ULSD counterparts. The two cleanest scoring cases (as rated by the Cleaner Drive air quality system) are LPG and the renewable battery-electric case– with a reduction of around 37%.

Within each vehicle fuel/technology type, the Cleaner Drive air quality rating is broadly dependent on vehicle size, but less so than is the case for GHGs – for the four smallest FISITA classes, moving down one category typically reduces the Cleaner Drive GHG Rating by 3-6 points for spark-ignition technologies (ULSP, BioE, LPG, CNG). Based on the data sourced from VCA, the differences between adjacent FISITA categories is less marked for compression engine vehicles – a reflection of the fact that weaker correlation between engine size and regulated emissions. Although less marked, for all fuels/technologies, the difference between the rating of the smallest (Citycar) and largest (SUV) categories is still around factor of 2.0 – ie according to the Cleaner Drive Air Quality rating, Citycar's have around half the environmental impact than SUVs.

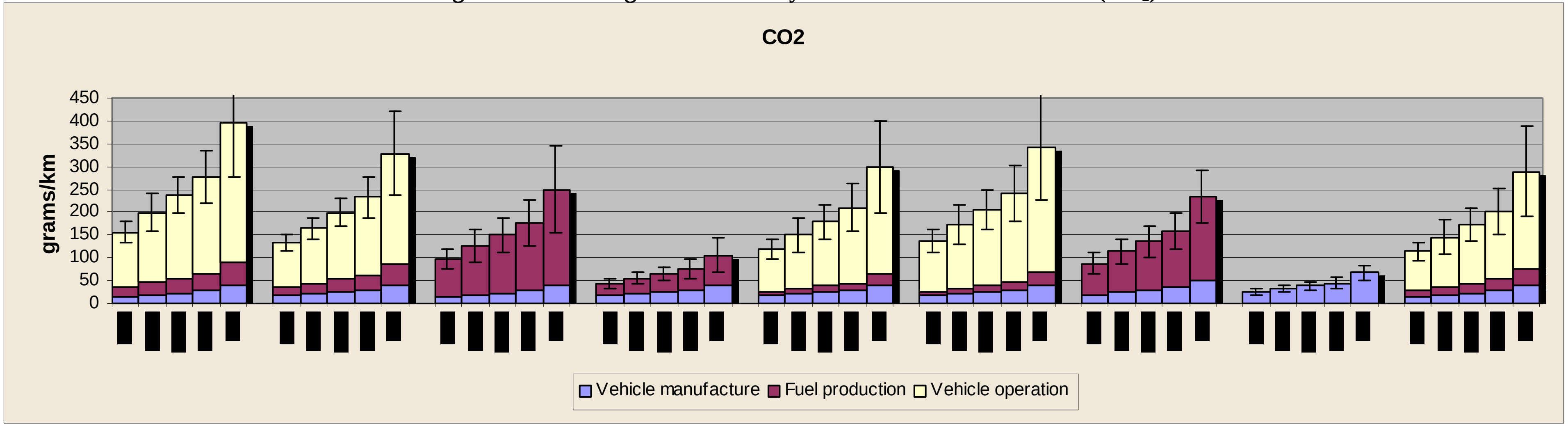
The Total Cleaner Drive rating accounts for both the air quality and greenhouse gas life cycle impacts (see Figure 8.9). The first observation is that the total Cleaner Drive ratings for many cases are surprisingly similar (obscuring the complexity of the air quality and greenhouse gas rating as already described). Excluding renewably charged battery electrics, average scores vary only by up to 20 points between fuels/technologies. That said, discernable differences are apparent and are consistent with the greenhouse gas and regulated emission comparisons already described.

Using conventional petrol as a baseline, mineral diesel is rated lower by 0%-13% (depending on vehicle class) and is, importantly, equivalent within confidence limits. This is followed by compressed natural and liquefied petroleum gas cases that are rated at approximately 18%-19% below the baseline. Biodiesel is rated 11%-24% lower than petrol (depending on vehicle class). Bioethanol, battery electric using average mix electricity and petrol-hybrids are the next cleanest cases at around 23%-26% lower. As expected the renewable battery electric case is the cleanest according to the Cleaner Drive rating system and scores over 70% less than the petrol baseline.

As is the case for the greenhouse gas scores, within each vehicle fuel/technology type, the Total Cleaner Drive rating is correlated with vehicle size – for the four smallest FISITA classes, moving down one category typically reduces the Total Cleaner Drive rating by 6-8 points (with the exception of renewable BEV case which is scored consistently low). For all fuels/technologies, the difference between the rating of the smallest (Citycar) and largest (SUV) categories is around a factor of 2.5 – ie according to the Total Cleaner Drive rating, Citycar's have less than half the environmental impact than SUVs (irrespective of fuel/technology type used).

[22] Based on the four life cycle regulated emissions PMs, NOx, CO, HCs

Figure 8.1 - Passenger cars – Life cycle carbon dioxide emissions (CO_2)



PET DSL BioE BioD CNG LPG AvBEV ReBEV HEV

Figure 8.2 - Passenger cars – Life cycle greenhouse gas emissions (GHG)

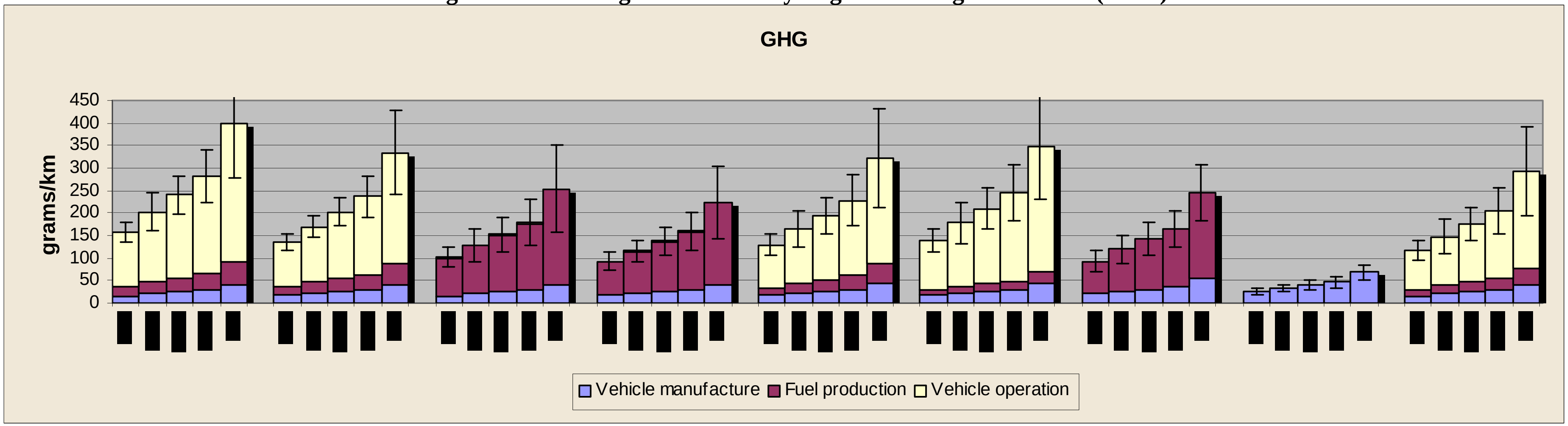


Figure 8.3 - Passenger cars – Life cycle particulate emissions (PM_{10})

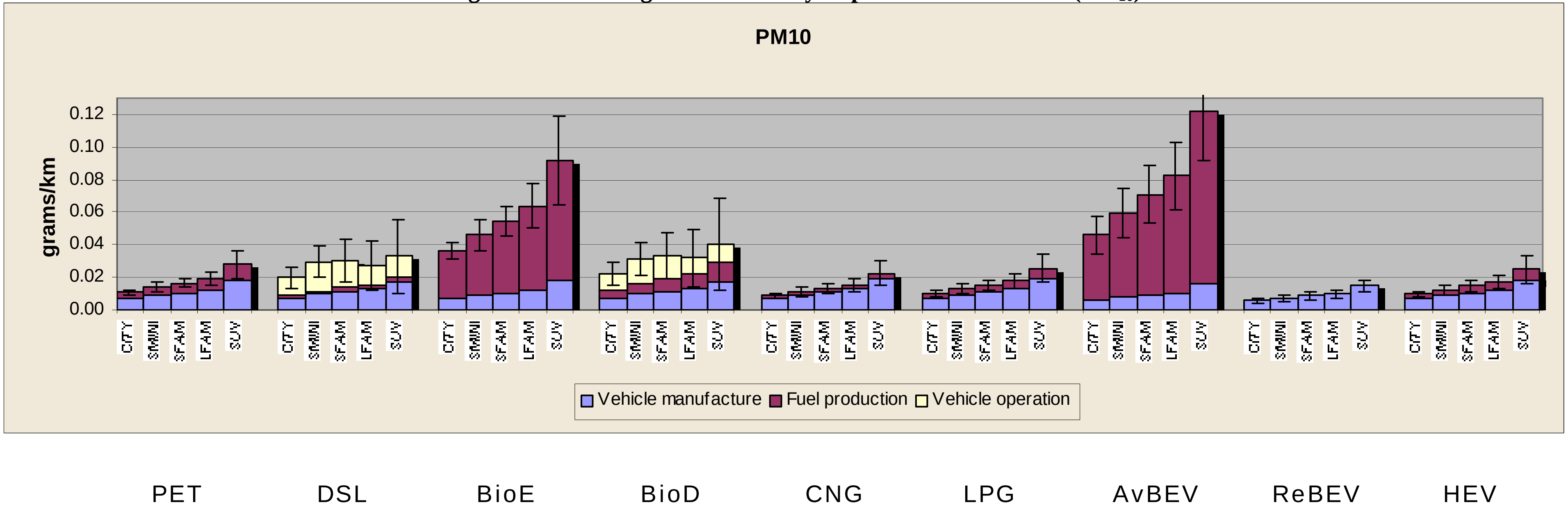


Figure 8.4 - Passenger cars – Life cycle nitrogen oxides emissions (NOx)

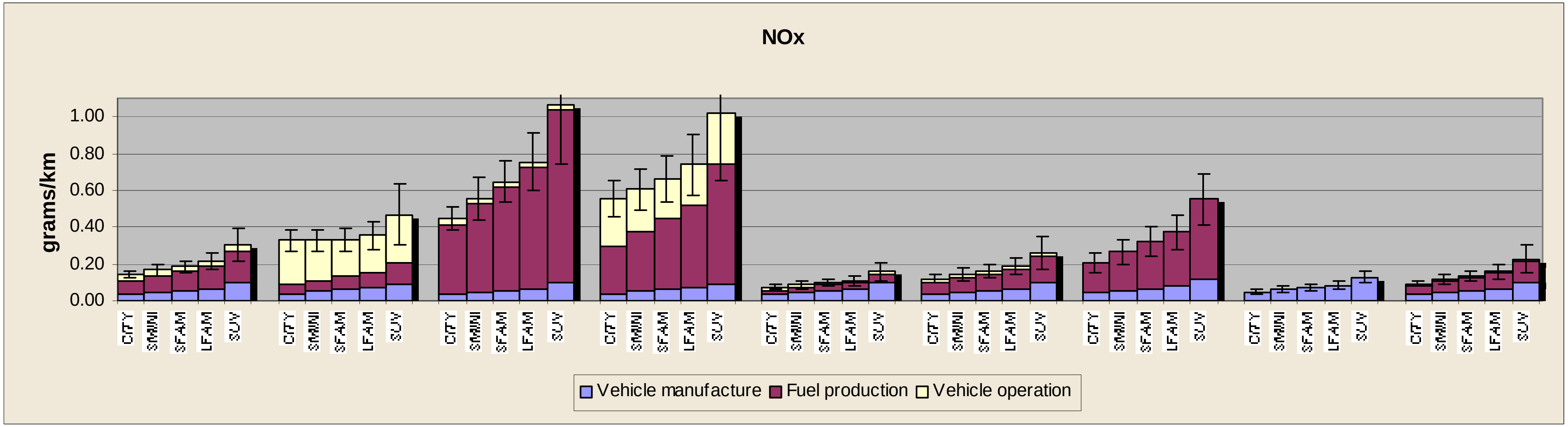
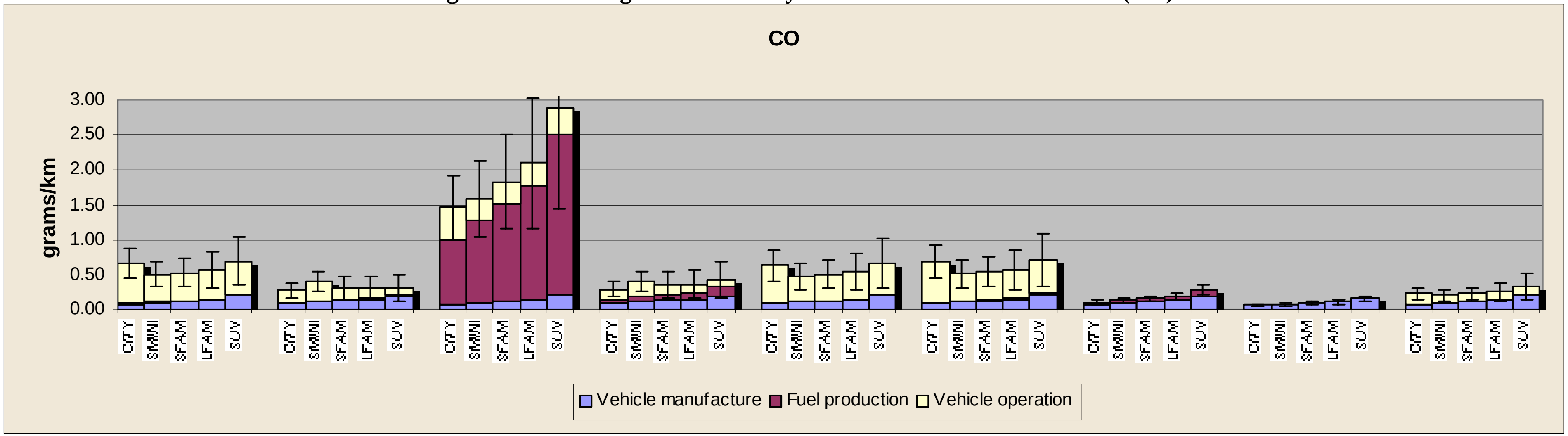


Figure 8.5 - Passenger cars – Life cycle carbon monoxide emissions (CO)



PET DSL BioE BioD CNG LPG AvBEV ReBEV HEV

Figure 8.6 - Passenger cars – Life cycle hydrocarbon emissions (HC)

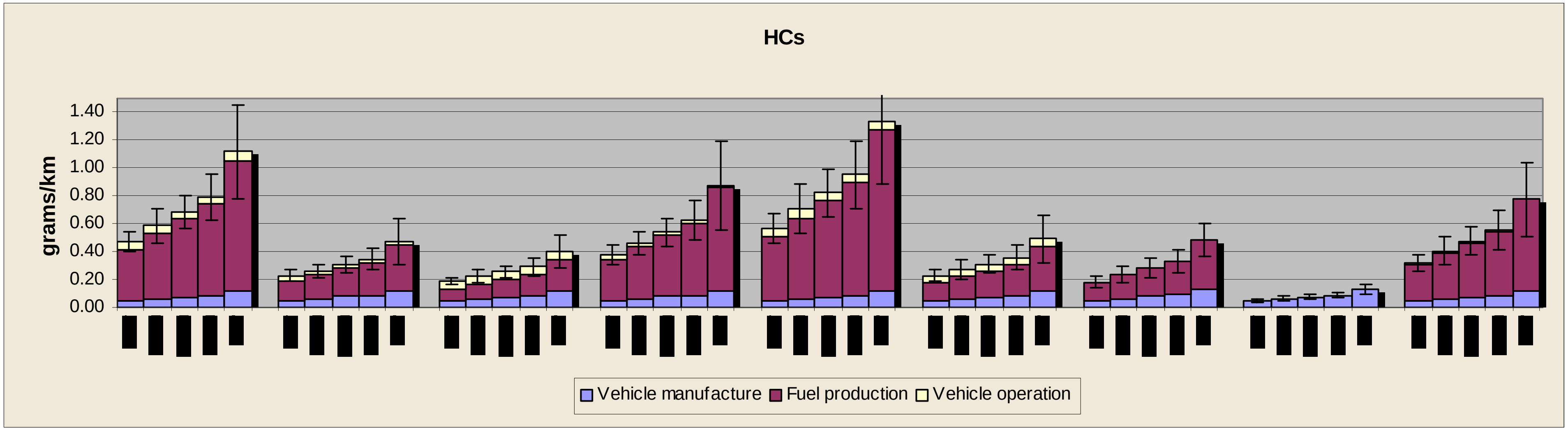
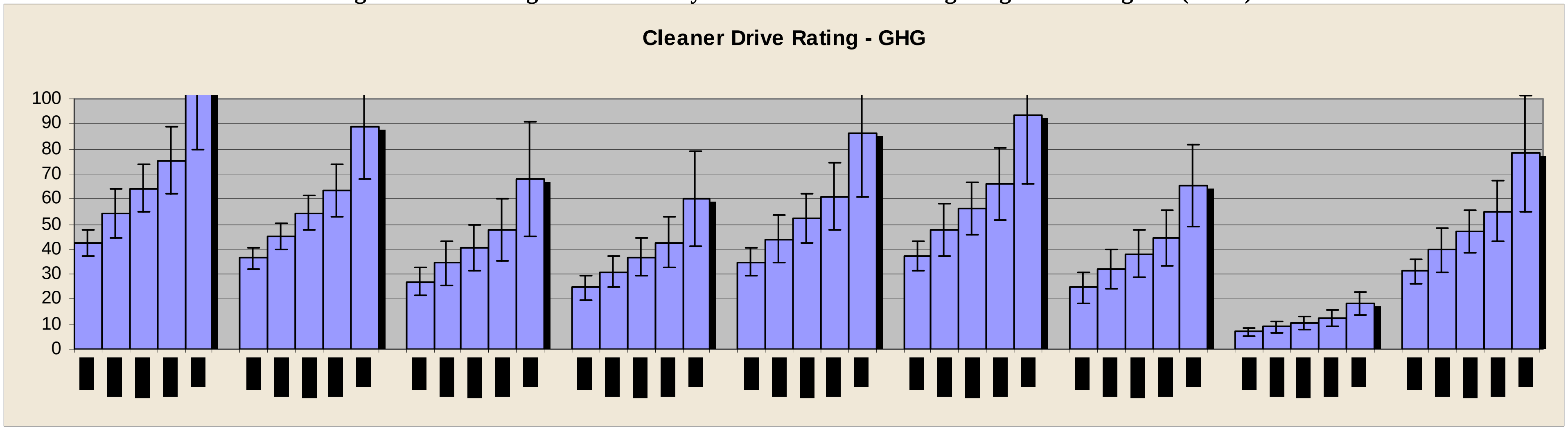


Figure 8.7 - Passenger cars – Life cycle Cleaner Drive Rating for greenhouse gases (GHG)



PET DSL BioE BioD CNG LPG AvBEV ReBEV HEV

Figure 8.8 - Passenger cars – Life cycle Cleaner Drive Rating for regulated pollutants (AQ)

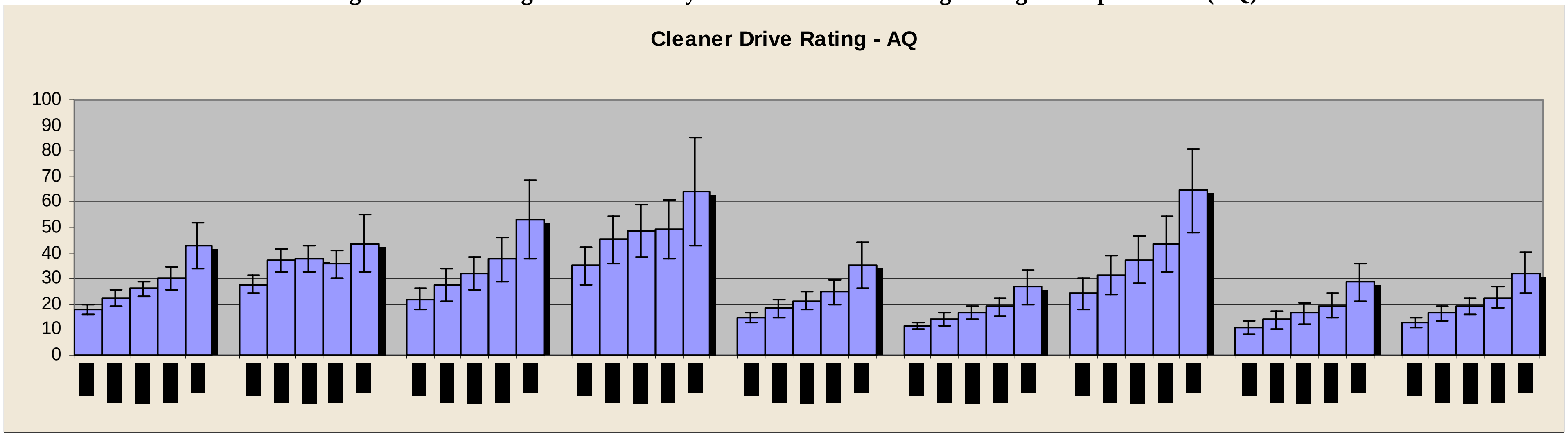


Figure 8.9 - Passenger cars – Life cycle Total Cleaner Drive Rating (TOTAL)

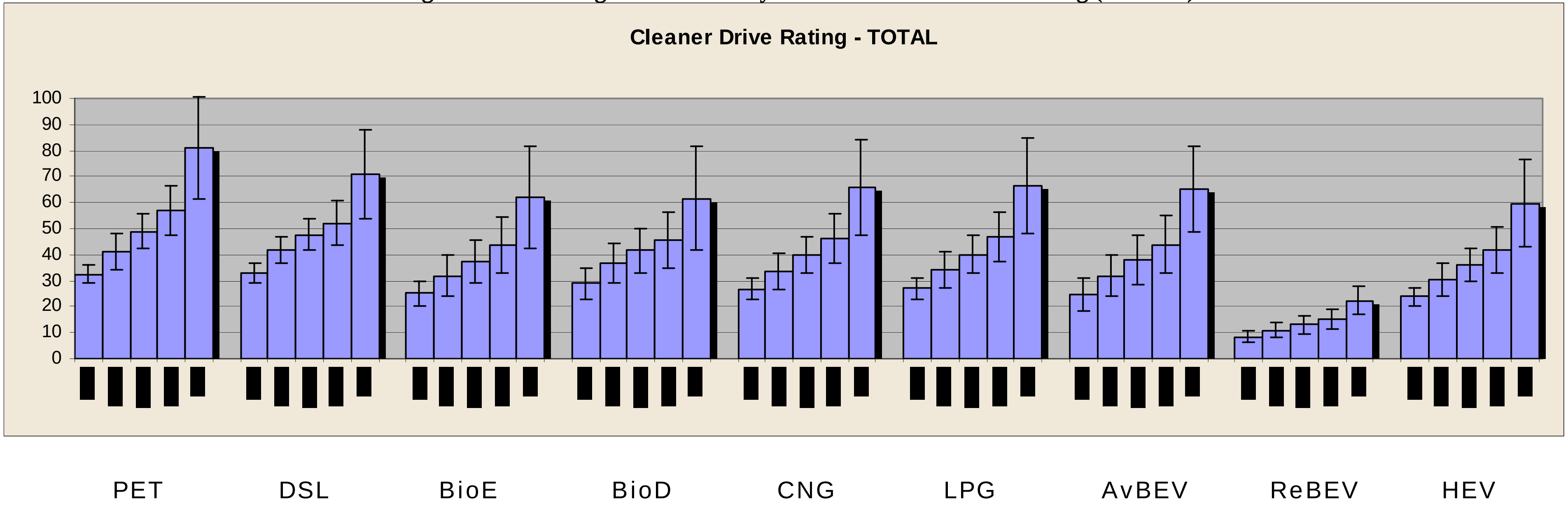
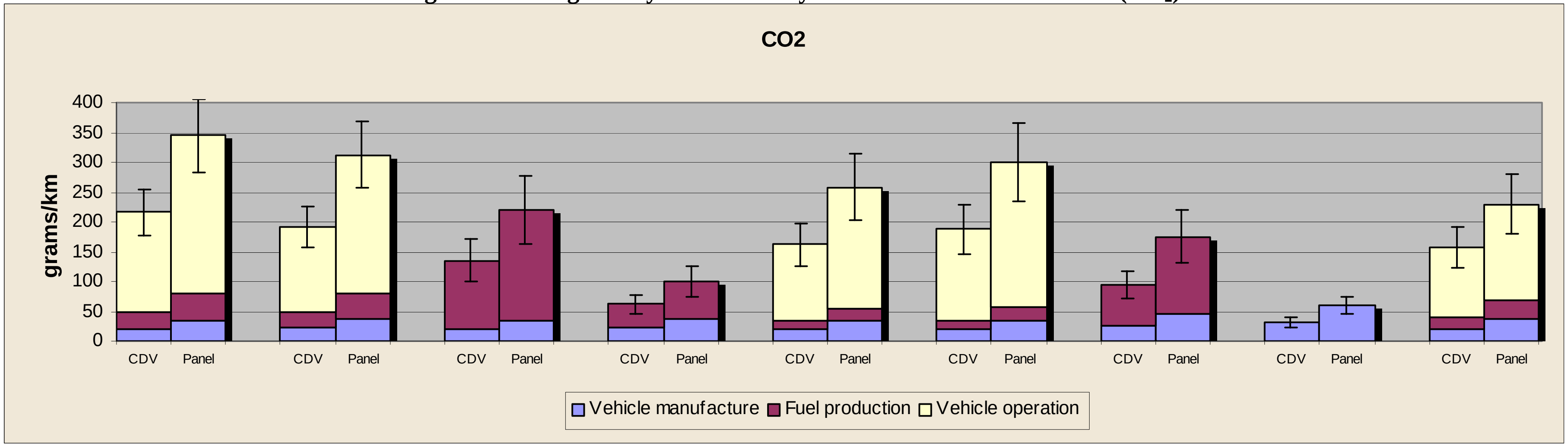


Figure 8.10 - Light-duty vans – Life cycle carbon dioxide emissions (CO_2)



PET DSL BioE BioD CNG LPG AvBEV ReBEV HEV

Figure 8.11 - Light-duty vans – Life cycle greenhouse gas emissions (GHG)

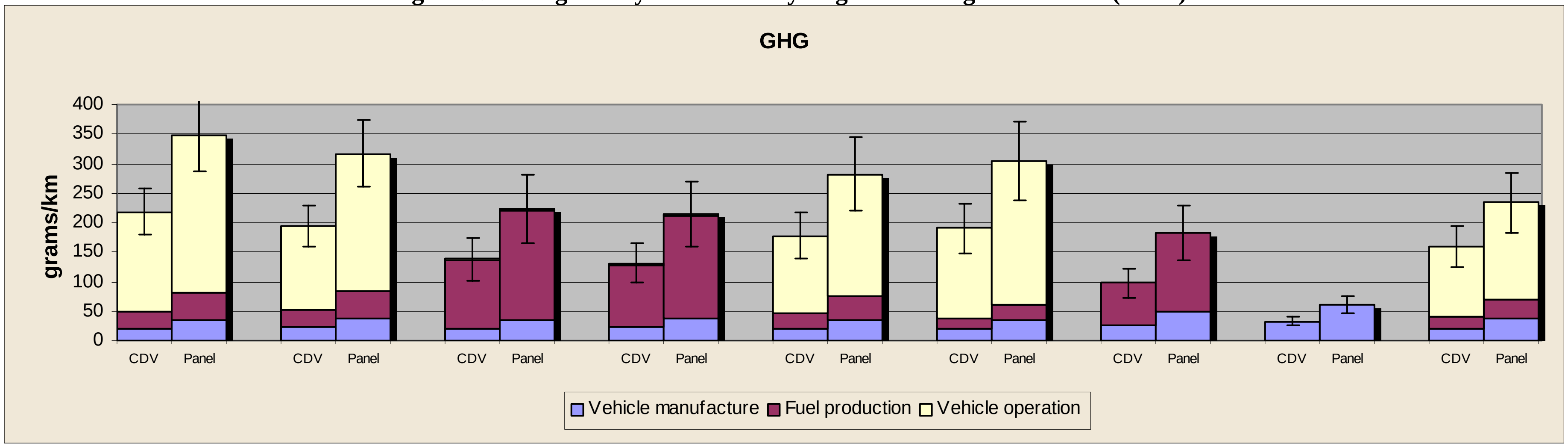
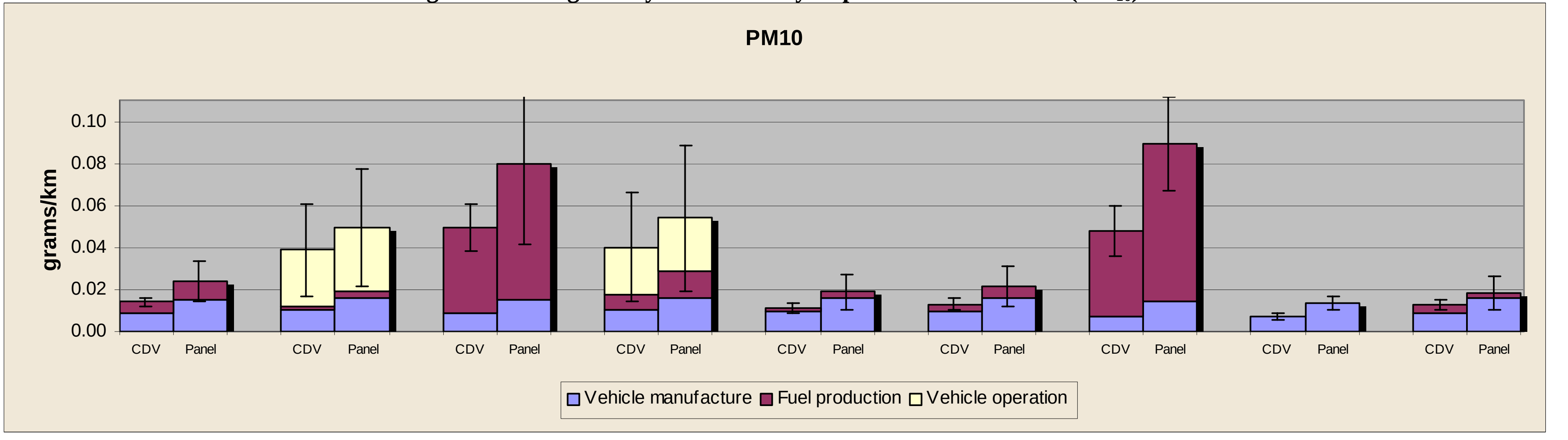


Figure 8.12 - Light-duty vans – Life cycle particulate emissions (PM_{10})



PET DSL BioE BioD CNG LPG AvBEV ReBEV HEV

Figure 8.13 - Light-duty vans – Life cycle nitrogen oxides emissions (NOx)

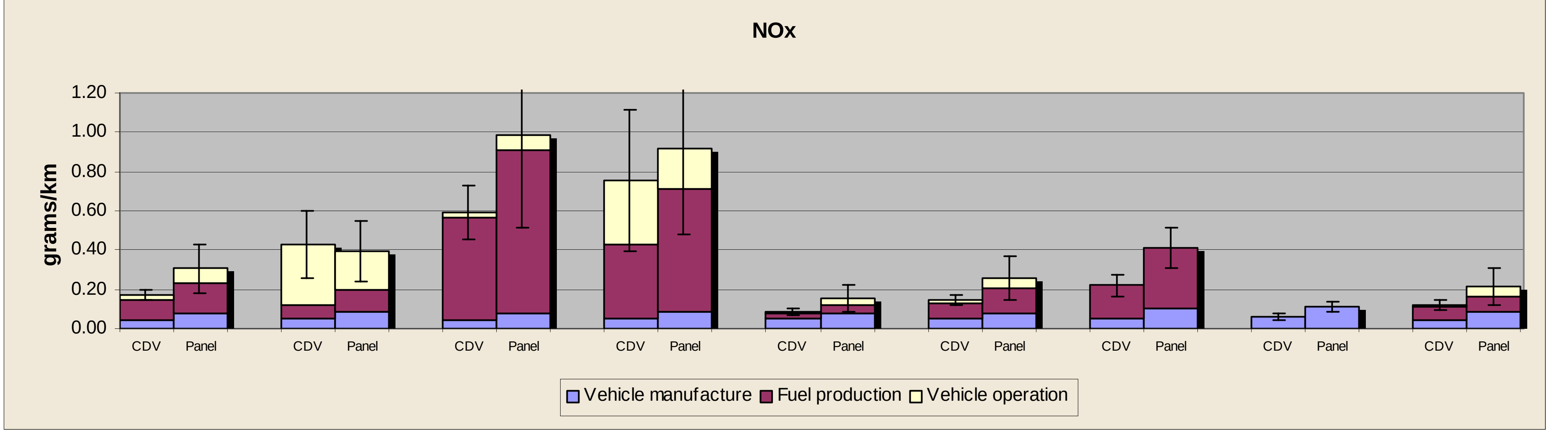
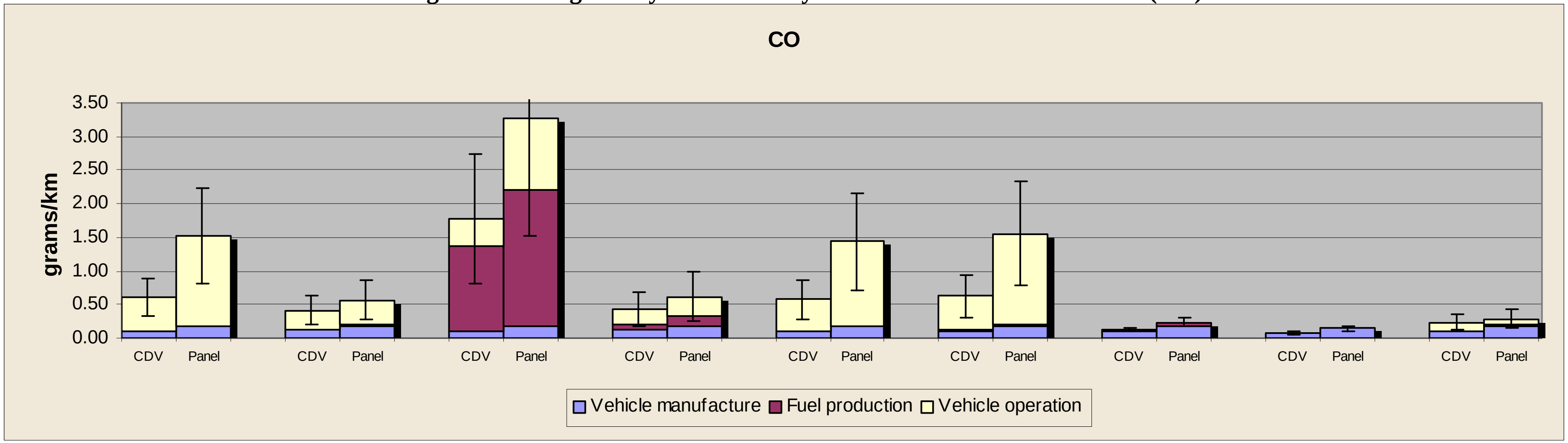


Figure 8.14 - Light-duty vans – Life cycle carbon monoxide emissions (CO)



PET DSL BioE BioD CNG LPG AvBEV ReBEV HEV

Figure 8.15 - Light-duty vans – Life cycle hydrocarbon emissions (HC)

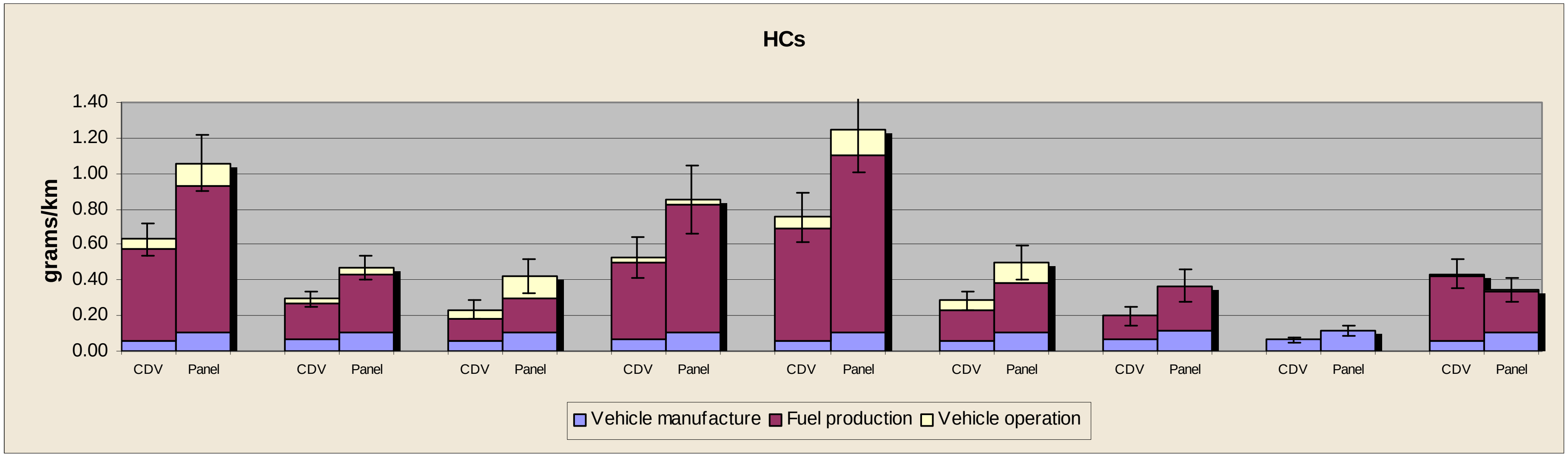


Figure 8.16 - Light-duty vans – Life cycle Cleaner Drive Rating for greenhouse gases (GHG)

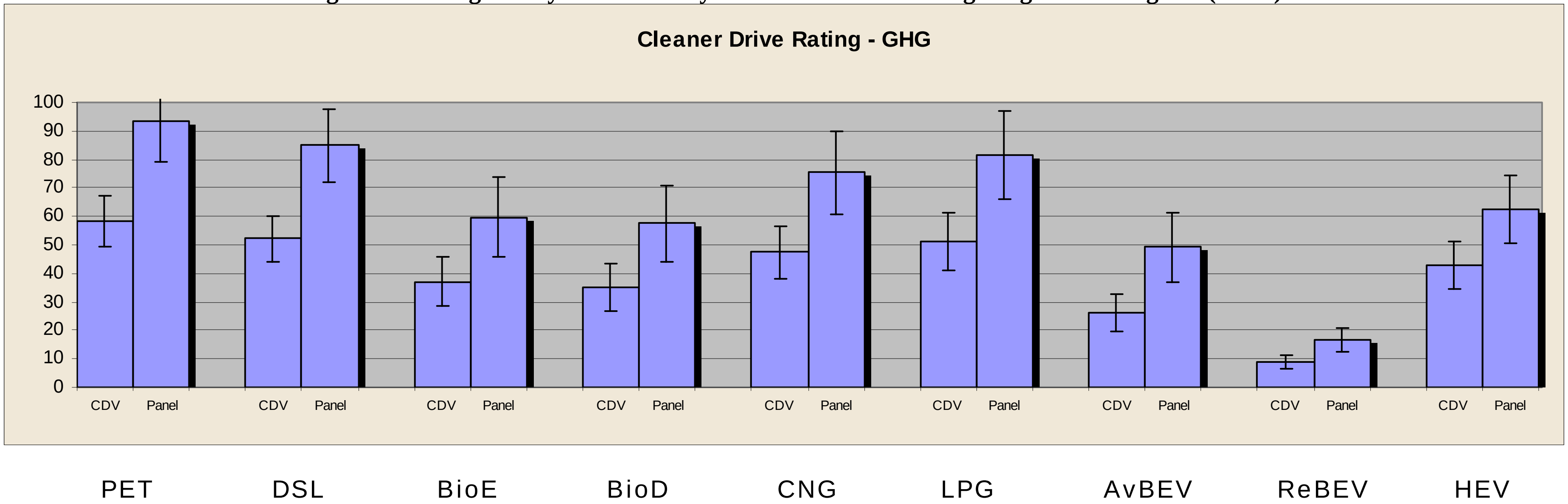


Figure 8.17 - Light-duty vans – Life cycle Cleaner Drive Rating for regulated pollutants (AQ)

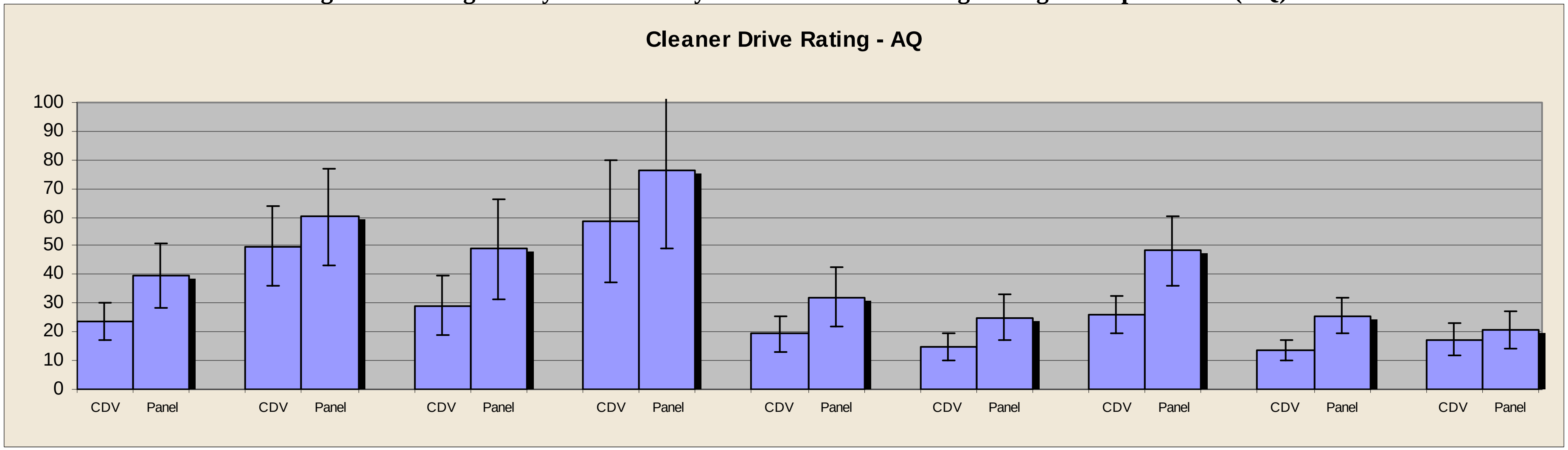
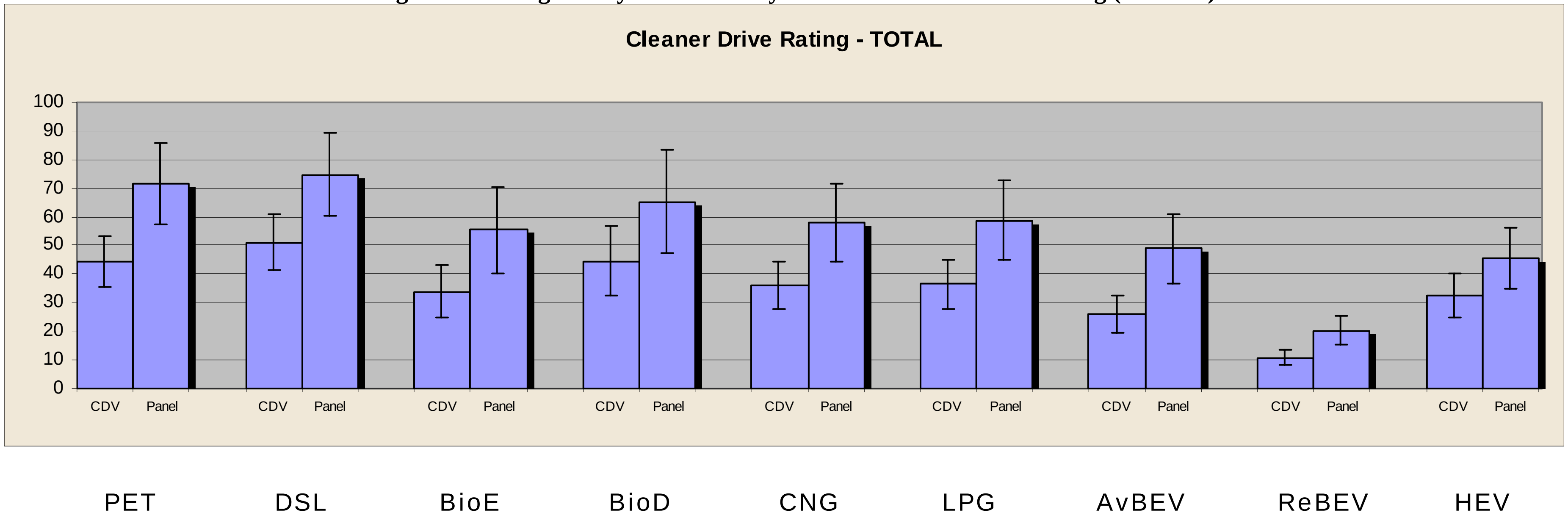


Figure 8.18 - Light-duty vans – Life cycle Total Cleaner Drive Rating (TOTAL)



9 Life cycle emissions results – specific

This section uses the methodology developed to estimate the life cycle emissions for specific vehicle models from five FISITA car and two light-duty van classes. As described in Section 7, life cycle comparisons are made using the Cleaner Drive rating system for greenhouse gases (GHGs), air quality (AQ) and total life cycle impact (Total) (see Appendix 3).

Greenhouse Gas, Air Quality and Total Cleaner Drive ratings are plotted for selected vehicles from each class. In general, the models selected are those with vehicle carbon dioxide emissions below the average for that vehicle class (as vehicle CO_2 emissions correlate strongly with total Cleaner Drive ratings for each fuel/technology type). Some models are also selected as comparator vehicles. Therefore, for each fuel/technology analysed, although the vehicles shown are among the cleanest in their class, they should not all necessarily be taken to be the vehicles with the lowest environmental impact.

The results for passenger cars are shown in Figures 9.1-9.5 and for light-duty vans in Figures 9.6-9.7.

Within the charts, each fuel technology is denoted by a unique symbol (see key for details). The charts' scales have been kept constant to enable comparison of vehicles across vehicle categories (ie from one chart to another). Note also that the average values shown link back to the charts shown in Section 8 (Figures 8.1-8.18).

When using the charts, it is important to remember the restricted definitions of the fuel/technology options considered. Petrol and diesel are ULSP and ULSD as defined by the existing sulphur content specifications (see Section 6.1). Biofuels values are for 100% biofuels (ie E100 and B100). Although in practice biofuel blends (eg E5, B5) are more likely to be available in the short- to medium-term (due to vehicle manufacture warranty issues – see Sections 6.2 and 6.3), the charts are intended to shown the full potential of biofuels. To a first approximation, life cycle impacts for biofuel blends can be interpolated from the values shown. The two road fuel gases (CNG and LPG) cases shown are for bi-fuel vehicles – dedicated vehicles may offer larger environmental benefits than shown (see Sections 6.4 and 6.5). Hybrid cars are assumed to be 'strong' petrol-hybrids (see Section 6.6). The two battery-electric cases shown are for average UK electricity mix (including non-renewable sources) and 100% renewable electricity (see Section 6.7).

9.1 Passenger cars

Citycar

In the Citycar class (which is dominated by spark-ignition engine vehicles), among the cleanest vehicles analysed are: the Citroen C1 1.0 (petrol, diesel, bioethanol and biodiesel),[23] the Toyota Aygo 1.0 (petrol), the Peugeot 107 1.0 (petrol), Smart ForTwo (petrol) and the Reva GWIZ (electric). The results are shown in Figure 9.1. The C1, the Aygo and 107 are essentially the same engine and chassis manufactured under three different badges – given that the emission profiles are virtually identical, only the Citroen C1 is shown on the chart.

Comparing average petrol and diesel cars in this class, diesel scores 7 points better than petrol on the Cleaner Drive rating for greenhouse gases, but petrol scores 10 points better than diesel on air quality. Taken overall, the Cleaner Drive system rates petrol and diesel is equivalent. The two biofuels cases presented show a significant greenhouse gas advantage over their conventional counterparts with a worsening of life cycle regulated pollutants – overall, bioethanol is rated at 7 points below petrol and biodiesel 5 points cleaner than diesel.

[23] The C1 also has a diesel version – although this uses a 1.4 litre engine, the body shape and overall vehicle weight are still in the Citycar class.

The cleanest vehicle in this class is the zero-emission electric powered Reva GWIZ.[24] The environmental impact, however, is strongly dependent on the source of the fuel used as is shown by the large difference between vehicles recharged using either average mix or renewable electricity. Although the average electricity mix case is still one of the cleanest cars on the chart (being approximately equivalent to the cleanest spark-ignition case – the Citroen C1 using bioethanol), the cleanest car in this class is the GWIZ using renewable supply at only 7 points (around a fifth of the overall impact of the average conventional vehicles).

Supermini

In the Supermini class (which is dominated by spark-ignition engine vehicles), among the cleanest vehicles analysed are: the Toyota Yaris 1.0 VVT-I (petrol), the Vauxhall Corsa 1.0i (petrol and bioethanol), the Hyundai Getz 1.5 CRTD (diesel), and the Citroen C3 1.4 HDi SensoDrive (diesel and biodiesel). The results are shown in Figure 9.2.

Comparing average petrol and diesel cars in this class, diesel scores 9 points better than petrol on the Cleaner Drive rating for greenhouse gases, but petrol scores 15 points better than diesel on air quality. Taken overall, the Cleaner Drive system rates petrol and diesel equally. The two biofuel cases presented show a significant greenhouse gas advantage over their conventional counterparts with a worsening of life cycle regulated pollutants – overall, bioethanol is rated at 7 points below petrol and biodiesel 4 points cleaner than diesel.

The cleanest vehicle shown in this class is Vauxhall Corsa 1.0i fuelled by 100% bioethanol – this is rated by the Cleaner Drive system at 25 points. This represents around 60% of the environmental impact of the average petrol car in this vehicle category. However, it should be pointed out that this case is based on a comparison estimate (as described in Section 7) as is not based on an actual emission test (it is also unlikely that E100 will be widely available at retail outlets throughout the UK – see Section 6.3). However, the results identify bioethanol as potentially on of the cleanest vehicle options in this class.

Small Family/MPV

In the Small Family/MPV class, among the cleanest vehicles analysed are: the Vauxhall Astra 1.4i (petrol, bioethanol and LPG), the Skoda Fabia 1.2 (petrol), the Vauxhall Astra 1.7 CTDi (diesel and biodiesel), the Honda Civic IMA petrol-hybrid (petrol) and the Citroen Berlingo (electric). The results are shown in Figure 9.3.

Comparing average petrol and diesel cars in this class, diesel scores 10 points better than petrol on the Cleaner Drive rating for greenhouse gases, but petrol scores 12 points better than diesel on air quality. Taken overall, the Cleaner Drive system rates petrol and diesel as equivalent. The two biofuel cases presented show a significant greenhouse advantage over their conventional counterparts with a worsening of life cycle regulated pollutants – overall, bioethanol is rated at 9 points below petrol and biodiesel 6 points cleaner than diesel.

Although the benefits of liquefied petroleum gas compared to petrol have decreased as petrol engines have improved, the chart shows that LPG still reduces life cycle emissions. In the case shown, LPG reduces overall environmental impact (as quantified by Cleaner Drive) by around 8 points (petrol baseline) – this benefit comprises a moderate reduction in both greenhouse gas and regulated emissions.

The cleanest vehicle shown in this class is the zero-emission Citroen Berlingo electric. The environmental impact, however, is strongly dependent on the source of the fuel used as is shown by the large difference between cars recharged using either average mix or renewable electricity. Although the average electricity mix case is still one of the cleanest cars on the chart, the cleanest car by far in this class is the Berlingo using renewable supply at only 13 points (around a quarter of the overall impact of the average conventional petrol/diesel vehicles).

[24] Note that the GWIZ is actually classed as a quadracycle, it is usually purchased to perform the role of a Citycar (often to replace a 2nd or 3rd household vehicle).

Large Family/MPV

In the Large Family/MPV class, among the cleanest vehicles analysed include: the Mercedes B-Class (petrol), the Vauxhall Vectra 1.8i (petrol, bioethanol and LPG), the Toyota Avensis 2.0 D4-D (diesel and biodiesel), the Peugeot 407 1.6 HDi FAP (diesel with particulate filter), the Toyota Prius petrol-hybrid (petrol) and the Volvo S60 Bi-fuel (petrol and CNG). The results are shown in Figure 9.4.

Comparing average petrol and diesel cars in this class, diesel scores 12 points better than petrol on the Cleaner Drive rating for greenhouse gases, but petrol scores 6 points better than diesel on air quality. Taken overall, the Cleaner Drive system rates diesel with a 5-point improvement over petrol – and is, therefore, equivalent within confidence limits. The two biofuels cases presented show a significant greenhouse gas advantage over their conventional counterparts with a worsening of life cycle regulated pollutants (particularly for biodiesel) – overall, bioethanol is rated at 11 points below petrol and biodiesel 6 points cleaner than diesel.

With the exception of battery electric vehicles (none of which are identified in this category), the cleanest vehicle analysed in this class is the Toyota Prius petrol-hybrid, which is rated by the Cleaner Drive system at 31 points – this is around half of the overall impact of average petrol cars in this class and 22 points lower than the Avensis 2.0 litre diesel, one of the vehicles in the Toyota range considered a 'consumer-equivalent' to the Prius. These comparisons reflect the significant improvements in fuel economy and regulated emissions offered by hybridisation.

For completeness, a compressed natural gas case has been included in this vehicle class to represent one of several Volvo CNG bi-fuel models. Using the Cleaner Drive rating system to compare the Volvo S60 bi-fuel operating on petrol and CNG shows a 10-point advantage for the CNG operation – mainly attributable to the lower life cycle greenhouse gases associated with the CNG case. However, it should be noted that Volvo manufacture a range of OEM supplied CNG vehicles as part of their normal range – the advantage shown by the data used may therefore represent the best case (after-sale conversions may not offer as large a greenhouse gas benefit).

SUV 4x4

In the Large Family/MPV class, among the cleanest vehicles analysed are: the BMW X3 2.0i (petrol and bioethanol), the BMW X3 2.0d (diesel and biodiesel), the Suzuki Grand Vitara 1.9D (diesel), the Lexus RX400h petrol-hybrid (petrol), and for comparison, the Lexus RX300 (petrol). The results are shown in Figure 9.5.

Comparing average petrol and diesel cars in this class, diesel scores 18 points better than petrol on the Cleaner Drive rating for greenhouse gases, but petrol scores 1 point better than diesel on air quality.[25] Taken overall, the Cleaner Drive system rates diesel with a 10-point improvement over petrol – although there is a significant overall of confidence limits. The two biofuels cases presented show a significant greenhouse gas advantage over their conventional counterparts with a worsening of life cycle regulated pollutants – overall, bioethanol is rated at 14 points below petrol and biodiesel 10 points cleaner than diesel.

Of particular note in this category, however, is the Lexus RX400h petrol-hybrid, which is rated by the Cleaner Drive system at 55 points. Although this level of impact is comparable to the BMW X3 and Suzuki Grand Vitara, the Lexus has by far the most powerful 3.3 litre engine and is therefore a cleaner technology than conventional petrol or diesel engine SUVs. For comparative purposes, the Lexus RX300 (which uses a 3.0 litre engine) is rated by the Cleaner Drive system at 76, almost a third more than the RX400h. This comparison reflects the significant improvements in fuel economy, performance and regulated emissions offered by hybridisation.

[25] The average petrol case is not shown on the chart as it scores >100 points for life cycle greenhouse gases (due to Cleaner Drive baseline data used).

Among the cleanest vehicles analysed in this class are SUVs powered by 100% biofuels – the Cleaner Drive system rated the BMW X3 using bioethanol/biodiesel at 47 and 46 points respectively. This represents around 60% of the environmental impact of the average petrol car in this vehicle category. However, it should be pointed out that this case is based on a comparison estimate (as described in Section 7) as is not based on an actual emission test (it is also unlikely that E100 and B100 will be widely available at retail outlets throughout the UK – see Section 6.3). However, the results identify biofuels as potentially the cleanest vehicle options currently in this class.

9.2 Light-duty vans

Car derived vans

In the car-derived van class, among the cleanest vehicles analysed are: the Vauxhall Astravan 1.6i (petrol, LPG and CNG), the Vauxhall Astravan 1.7 CTDi (diesel and biodiesel), the Citroen C2 1.4HDi (diesel) Citroen Berlingo (petrol, diesel, electric). The results are shown in Figure 9.6.

The Citroen C2 1.4 HDi van is shown by the chart to be one of the cleanest conventional Euro IV diesels currently available. Its low environmental impact is primarily due to its small size (vehicle weight) and illustrates the important influence of vehicle size on life cycle emissions impact.

Comparing average petrol and diesel vans in this class, diesel scores 6 points better than petrol on the Cleaner Drive rating for greenhouse gases, but petrol scores 26 points better than diesel on air quality. Taken overall, the Cleaner Drive system rates petrol with a 7-point improvement over diesel. The biodiesel Astravan case presented shows a significant greenhouse gas advantage over its mineral diesel counterpart with a worsening of life cycle regulated pollutants – overall biodiesel shows a 5-point improvement over diesel.

Two road fuel gases (LPG and CNG) are also included in the analysis for this vehicle category. Using the Cleaner Drive rating system to estimate ratings for a Vauxhall bi-fuel Astravan results in an 8-point advantage for LPG/CNG operation (as compared to petrol operation) – this is attributable to both greenhouse gas and air quality benefits associated with the gaseous operation.

The cleanest vehicle shown in this class is the zero-emission electric powered Citroen Berlingo. The environmental impact, however, is strongly dependent on the source of the fuel used as is shown by the large difference between cars recharged using either average mix or renewable electricity. Although the average electricity mix case is still one of the cleanest cars on the chart, the cleanest car by far in this class is the Berlingo using renewable supply at only 13 points (around a quarter of the overall impact of the average conventional petrol/diesel vehicles).

Panel Vans

Note: As the EC type approval regulations are not effective for this vehicle class until 01/01/07, emission data are not publicly available (as is the case for passenger cars). Therefore, data have been sourced from the Energy Saving Trust (EST 2006) and WhatVan? online databases. The EST data provide a full greenhouse gas and regulated emission data-set for a selection of spark-ignition engine panel vans. WhatVan? provide fuel economy data for a selection of road-tested diesel vans – as this information does not include regulated emissions, it is assumed that regulated emissions correspond to 0.5 of the relevant Euro 4 emission limits.

In the panel van category, the vehicles analysed are: the Ford Transit 2.3 (diesel/LPG), the Volkswagen LT35 2.8TDI (diesel and biodiesel). To show the potential for electric drive-train technologies, estimates are also made for hypothetical vehicles including a VW LT35 diesel-hybrid and a VW LT35 battery electric van. The results are shown in Figure 9.7.

Comparing average petrol and diesel vans in this class, diesel scores 8 points better than petrol on the Cleaner Drive rating for greenhouse gases, but petrol scores 20 points better than diesel on air quality.

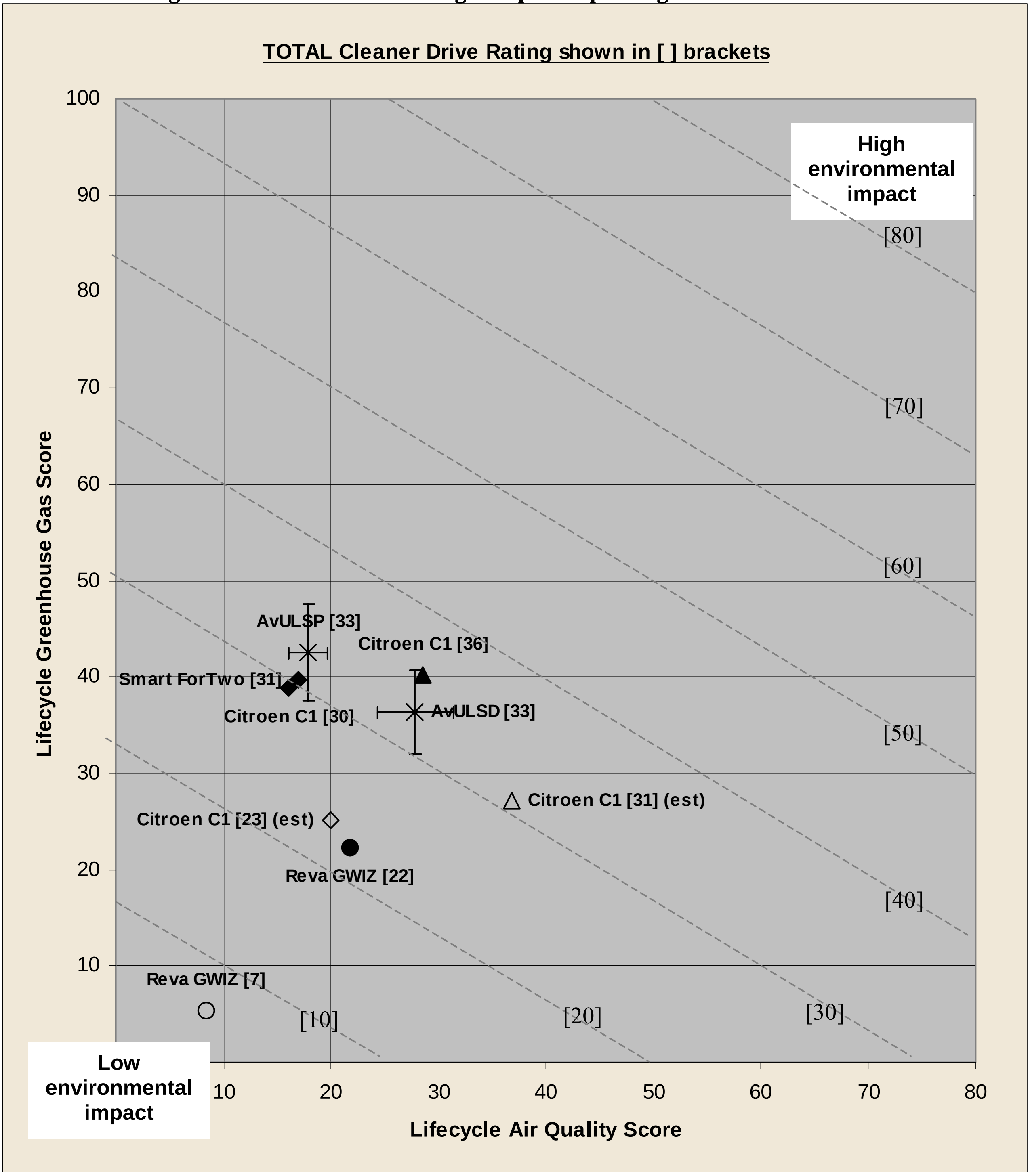
Taken overall, the Cleaner Drive system rates petrol with a 3-point improvement over diesel – and is, therefore, equivalent within confidence limits.

Regarding cleaner fuels, the LPG panel van case compares well with its petrol counterpart – and is rated at 17 points below the petrol baseline due to life cycle greenhouse gas and regulated emissions benefits. The biodiesel VW LT35 case presented also shows a significant greenhouse gas advantage over its mineral diesel counterpart – with an 8-point improvement over diesel. However, the greenhouse gas benefits are accompanied by a worsening of life cycle regulated pollutants.

Of particular note in this category, however, is the potential offered by a hypothetical diesel hybrid panel van. The comparison is based on the assumption of a 25% improvement in fuel economy and a 50% reduction in vehicle regulated pollutants (a smaller reduction than occurs for existing petrol hybrids). The diesel hybrid case is rated by the Cleaner Drive system at 48 points, 20 points lower than its non-hybridised counterpart. Although diesel hybrids have yet to be offered commercially, this comparison reflects the potential reduction in environmental impact that could be offered by diesel hybridisation.

The cleanest vehicle shown in this van category is the (theoretical) zero-emission electric powered VW LT35. The environmental impact, however, is strongly dependent on the source of the fuel used as is shown by the large difference between vans recharged using either average mix or renewable electricity. Although the average electricity mix case is still one of the cleanest vehicles on the chart, the cleanest van by far in this class is the VW LT35 electric using renewable supply at only 20 points (around a quarter of the overall impact of the average conventional diesel case).

Figure 9.1 Cleaner Drive rating for specific passenger cars – CITYCAR



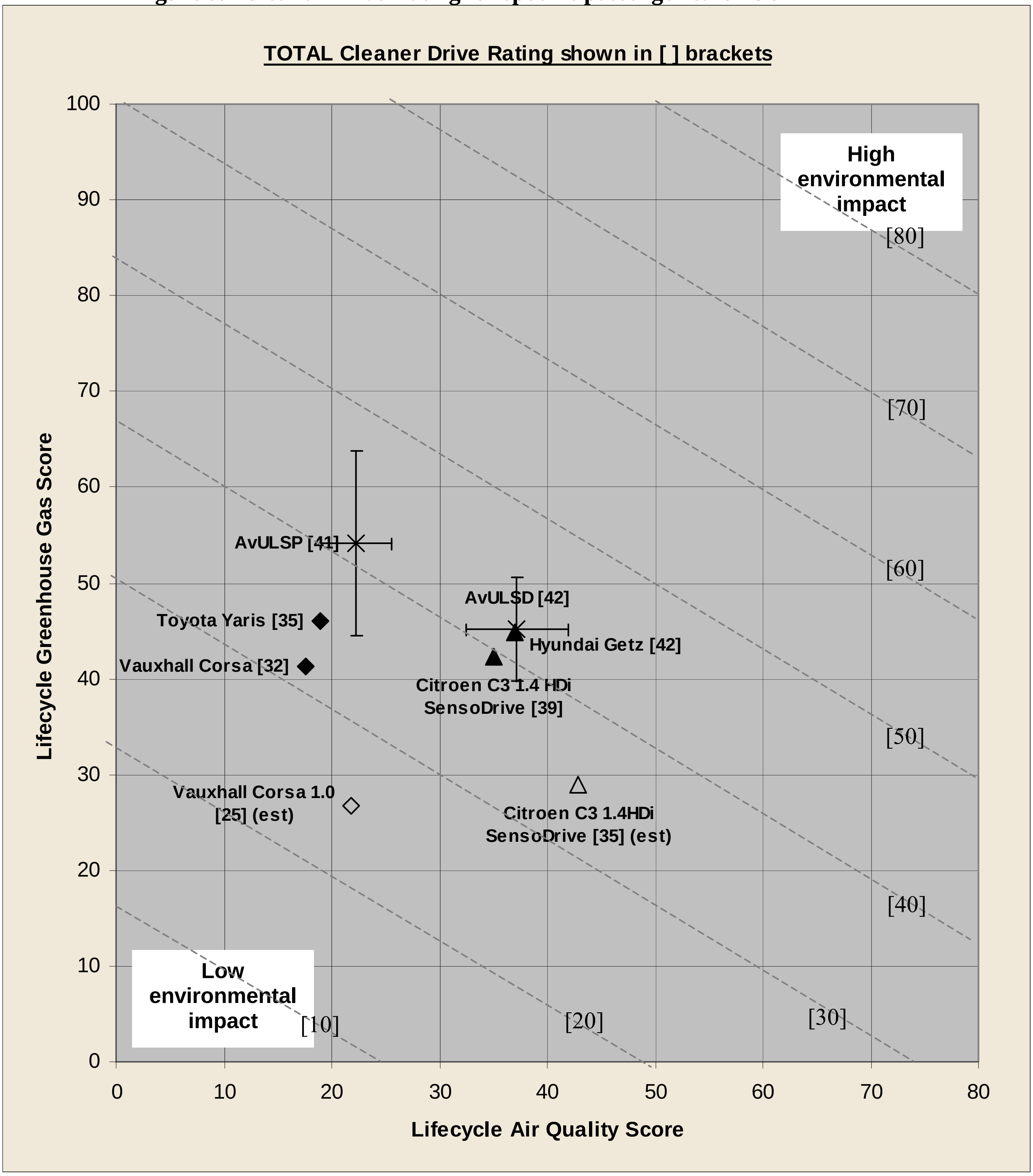
KEY TO SYMBOLS

× Av. ULSP / ULSD
◆ ULSP Petrol
◇ E100 Bioethanol
▲ ULSD Diesel
△ B100 Biodiesel
■ Bi-fuel LPG
□ Bi-fuel CNG
● Average mix BEV
○ Renewable BEV

Notes

Chart uses Cleaner Drive Rating methodology as described in Section 7 of report. For vehicles using ULSP, ULSD, LPG, CNG fuels, the chart shows Cleaner Drive scores based on emission data sourced from the Vehicle Certification Agency (VCA 2005). For vehicles using biofuels, ratings are based on comparison of ULSP/bioethanol or ULSD/biodiesel as described in Section 7 of report. For battery-electric vehicles, Cleaner Drive scores are based on fuel economy data as published by manufacturers.

Figure 9.2 Cleaner Drive Rating for specific passenger cars - SUPERMINI



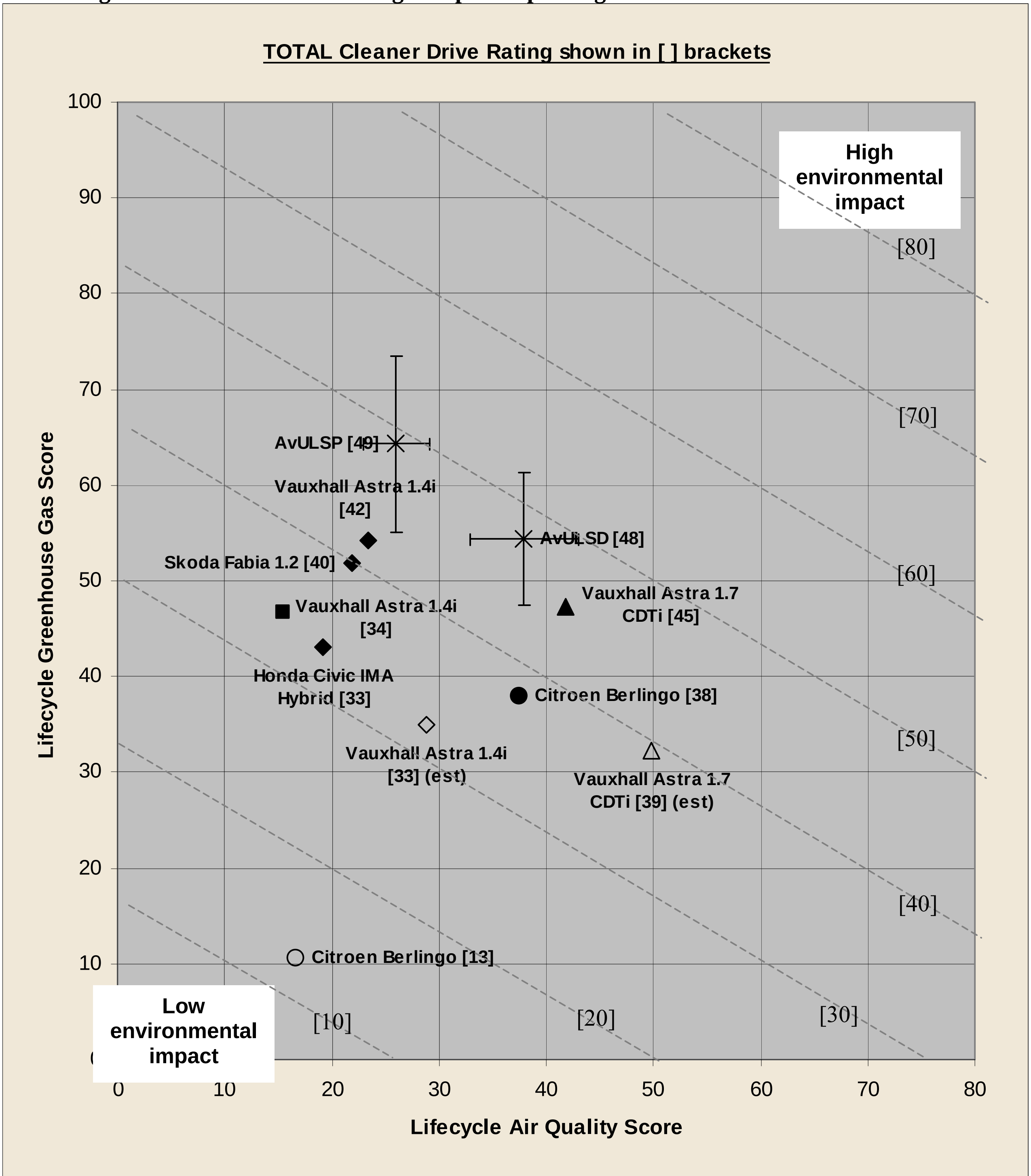
KEY TO SYMBOLS

- × Av. ULSP / ULSD
- ◆ ULSP Petrol
- ◇ E100 Bioethanol
- ▲ ULSD Diesel
- △ B100 Biodiesel
- ■ Bi-fuel LPG
- □ Bi-fuel CNG
- ● Average mix BEV
- ○ Renewable BEV

Notes

Chart uses Cleaner Drive Rating methodology as described in Section 7 of report. For vehicles using ULSP, ULSD, LPG, CNG fuels, the chart shows Cleaner Drive scores based on emission data sourced from the Vehicle Certification Agency (VCA 2005). For vehicles using biofuels, ratings are based on comparison of ULSP/bioethanol or ULSD/biodiesel as described in Section 7 of report. For battery-electric vehicles, Cleaner Drive scores are based on fuel economy data as published by manufacturers.

Figure 9.3 Cleaner Drive Rating for specific passenger cars – SMALL FAMILY CAR



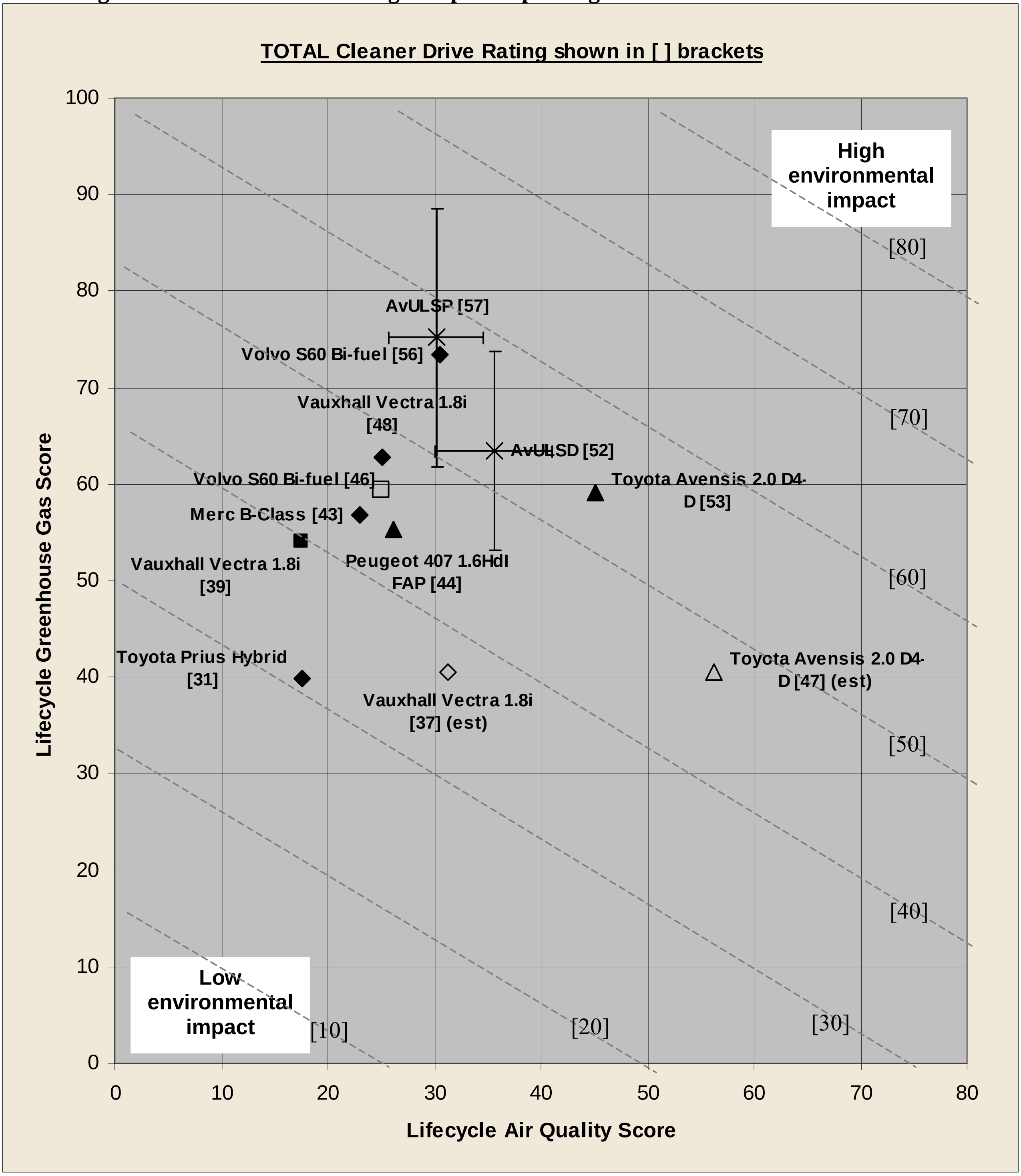
KEY TO SYMBOLS

- × Av. ULSP / ULSD
- ◆ ULSP Petrol
- ◇ E100 Bioethanol
- ▲ ULSD Diesel
- △ B100 Biodiesel
- ■ Bi-fuel LPG
- □ Bi-fuel CNG
- ● Average mix BEV
- ○ Renewable BEV

Notes

Chart uses Cleaner Drive Rating methodology as described in Section 7 of report. For vehicles using ULSP, ULSD, LPG, CNG fuels, the chart shows Cleaner Drive scores based on emission data sourced from the Vehicle Certification Agency (VCA 2005). For vehicles using biofuels, ratings are based on comparison of ULSP/bioethanol or ULSD/biodiesel as described in Section 7 of report. For battery-electric vehicles, Cleaner Drive scores are based on fuel economy data as published by manufacturers.

Figure 9.4 Cleaner Drive Rating for specific passenger cars – LARGE FAMILY CAR



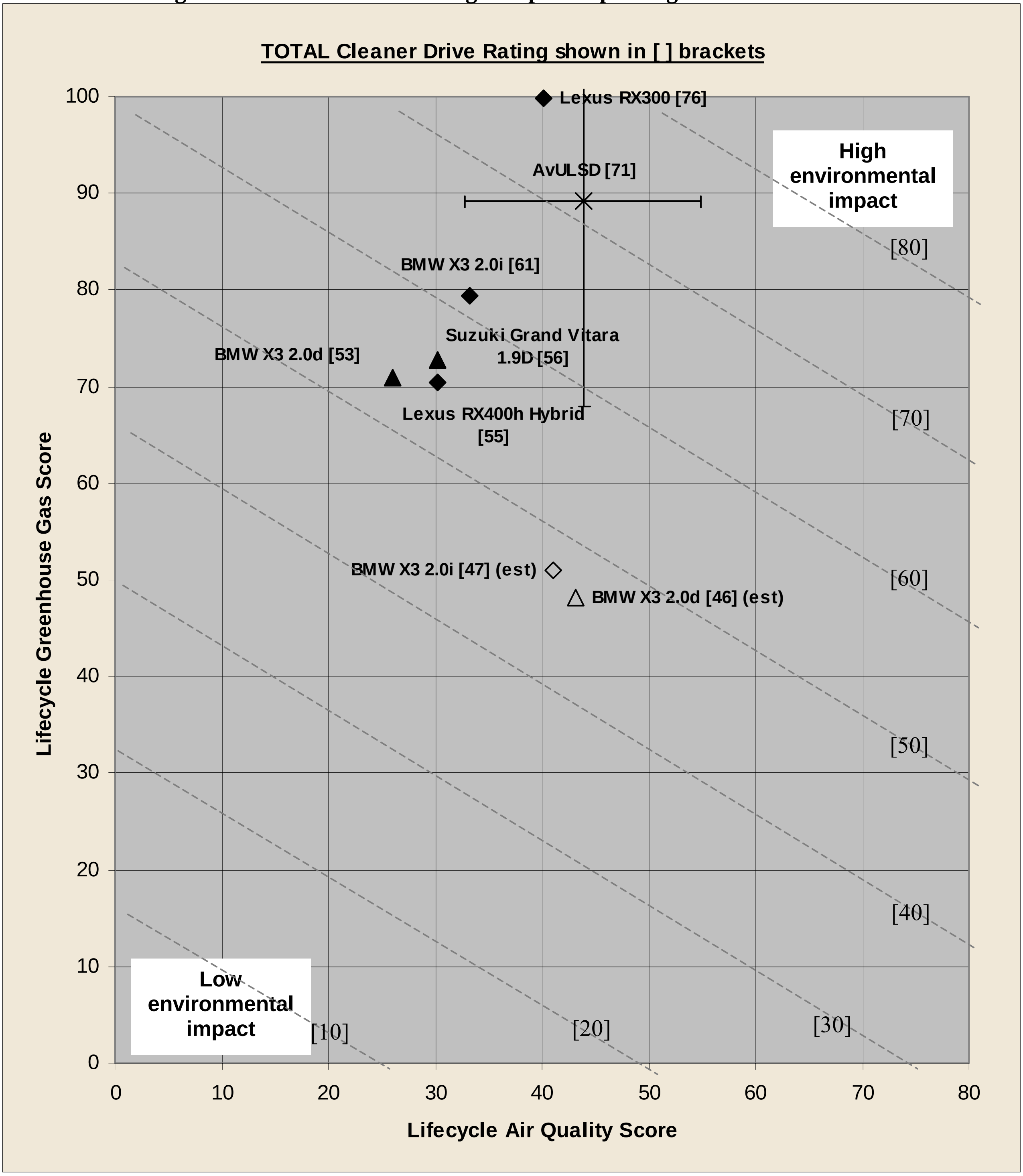
KEY TO SYMBOLS

- × Av. ULSP / ULSD
- ◆ ULSP Petrol
- ◇ E100 Bioethanol
- ▲ ULSD Diesel
- △ B100 Biodiesel
- ■ Bi-fuel LPG
- □ Bi-fuel CNG
- ● Average mix BEV
- ○ Renewable BEV

Notes

Chart uses Cleaner Drive Rating methodology as described in Section 7 of report. For vehicles using ULSP, ULSD, LPG, CNG fuels, the chart shows Cleaner Drive scores based on emission data sourced from the Vehicle Certification Agency (VCA 2005). For vehicles using biofuels, ratings are based on comparison of ULSP/bioethanol or ULSD/biodiesel as described in Section 7 of report. For battery-electric vehicles, Cleaner Drive scores are based on fuel economy data as published by manufacturers.

Figure 9.5 Cleaner Drive Rating for specific passenger cars – SUV 4x4



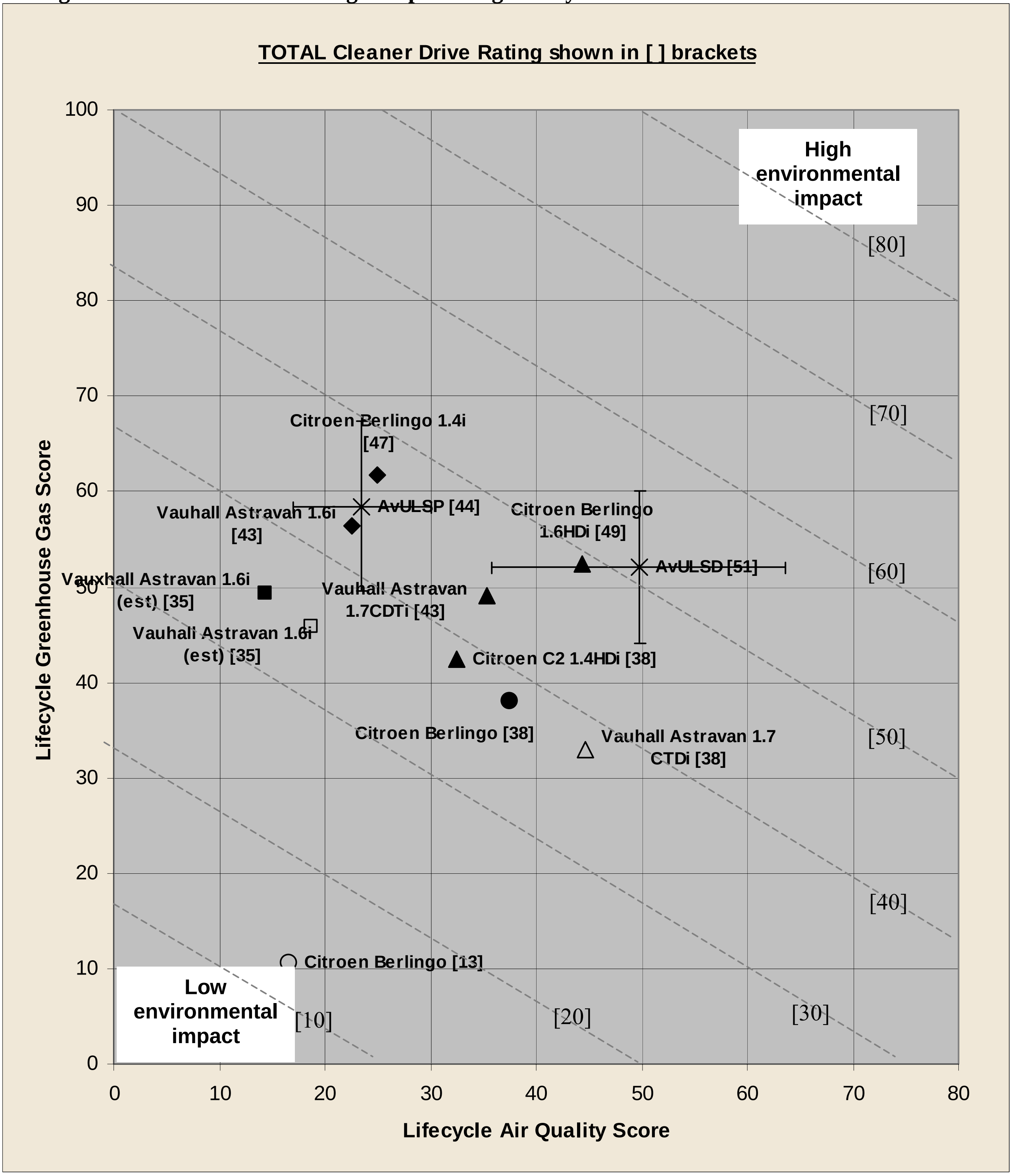
KEY TO SYMBOLS

- × Av. ULSP / ULSD
- ◆ ULSP Petrol
- ◇ E100 Bioethanol
- ▲ ULSD Diesel
- △ B100 Biodiesel
- ■ Bi-fuel LPG
- □ Bi-fuel CNG
- ● Average mix BEV
- ○ Renewable BEV

Notes

Chart uses Cleaner Drive Rating methodology as described in Section 7 of report. For vehicles using ULSP, ULSD, LPG, CNG fuels, the chart shows Cleaner Drive scores based on emission data sourced from the Vehicle Certification Agency (VCA 2005). For vehicles using biofuels, ratings are based on comparison of ULSP/bioethanol or ULSD/biodiesel as described in Section 7 of report. For battery-electric vehicles, Cleaner Drive scores are based on fuel economy data as published by manufacturers.

Figure 9.6 Cleaner Drive Rating for specific light-duty vehicles cars – CAR DERIVED VANS



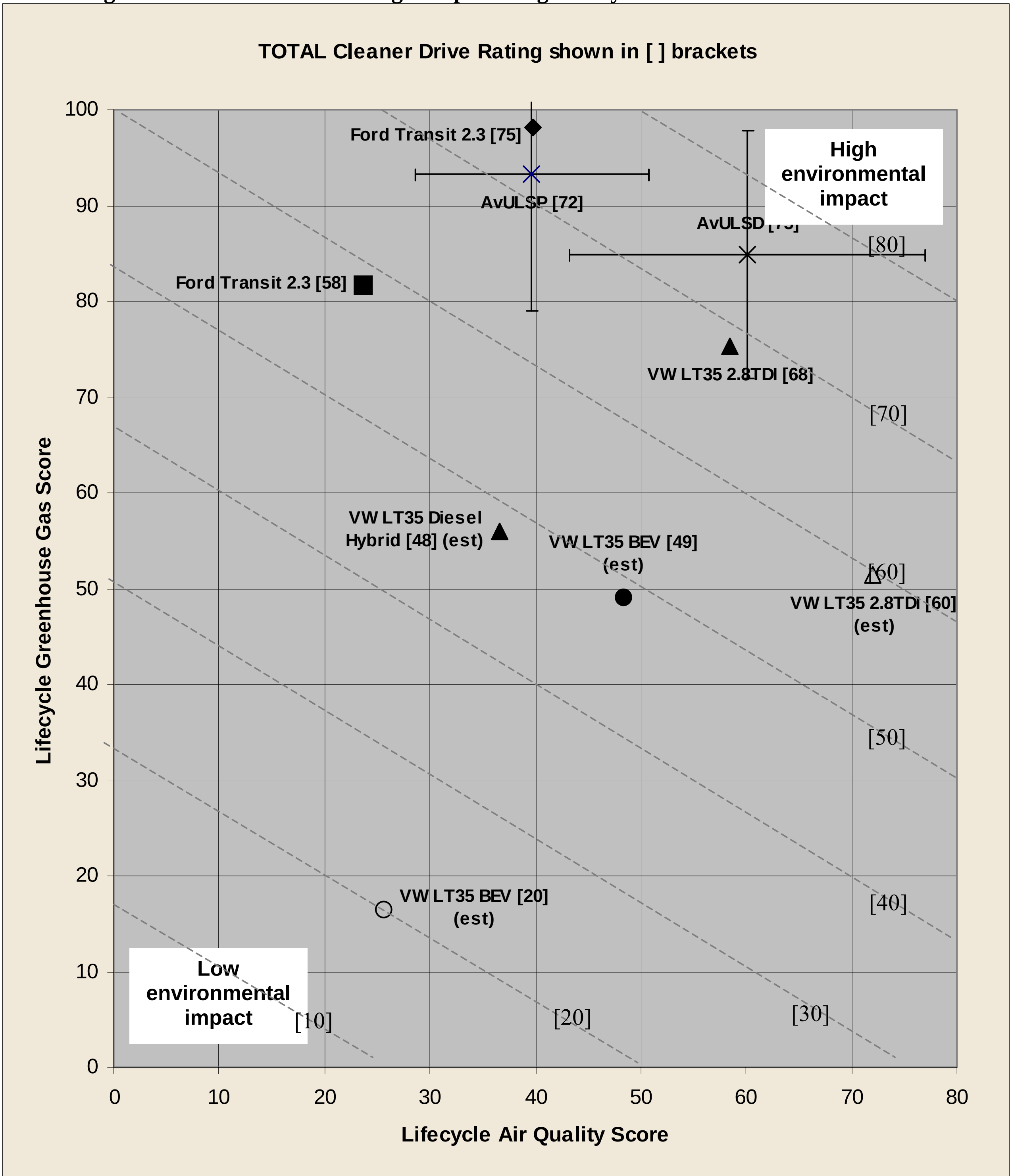
KEY TO SYMBOLS

- × Av. ULSP / ULSD
- ◆ ULSP Petrol
- ◇ E100 Bioethanol
- ▲ ULSD Diesel
- △ B100 Biodiesel
- ■ Bi-fuel LPG
- □ Bi-fuel CNG
- ● Average mix BEV
- ○ Renewable BEV

Notes

Chart uses Cleaner Drive Rating methodology as described in Section 7 of report. For vehicles using ULSP, ULSD, LPG, CNG fuels, the chart shows Cleaner Drive scores based on emission data sourced from the Vehicle Certification Agency (VCA 2005). For vehicles using biofuels, ratings are based on comparison of ULSP/bioethanol or ULSD/biodiesel as described in Section 7 of report. For battery-electric vehicles, Cleaner Drive scores are based on fuel economy data as published by manufacturers.

Figure 9.7 Cleaner Drive Rating for specific light-duty vehicles cars – PANEL VANS



KEY TO SYMBOLS

- × Av. ULSP / ULSD
- ◆ ULSP Petrol
- ◇ E100 Bioethanol
- ▲ ULSD Diesel
- △ B100 Biodiesel
- ■ Bi-fuel LPG
- □ Bi-fuel CNG
- ● Average mix BEV
- ○ Renewable BEV

Notes

Chart uses Cleaner Drive Rating methodology as described in Section 7 of report. For vehicles using ULSD fuel, the chart shows Cleaner Drive scores based on emission data sourced from the WhatVan website. For vehicles using biofuels, ratings are based on comparison of ULSP/bioethanol or ULSD/biodiesel as described in Section 7 of report. For battery-electric and diesel-hybrid vehicles, Cleaner Drive scores are based on modelling of hypothetical vehicles based on a VW LT35 platform.

10 Discussion of results

Given the large number of global and local air emissions considered by the LCA study, the picture of the environmental pros and cons of each fuel and technology analysed is a complex one. For this reason the Cleaner Drive rating system is used to weight emissions according to their environmental impact so providing three scores: an air quality impact score, a greenhouse gas score and a total rating that accounts for all emissions analysed (CO_2, CH_4, N_2O, PM_{10}, NOx, CO, HCs).

The following sections refer primarily to passenger cars – however, the comparisons for car-derived and panel vans are broadly the same (for fuel/technologies analysed).

One important finding from the study is that vehicle size is as important a determinator of emission impact as fuel/technology type – the results show that vehicle size is strongly correlated to overall environmental impact as quantified by the Cleaner Drive rating system (see Figure 10.1). Moving down one FISITA passenger car category typically reduces the Total Cleaner Drive rating by 6-8 points (with the exception of renewable battery electric vehicle case which is scored consistently low). For a medium sized passenger car, this equates to a reduction in the total life cycle environmental impact of around 12%-16%. For all fuels/technologies, the difference between the rating of the smallest (Citycar) and largest (SUV) car categories is around a factor of 2.5.

The importance of vehicle size is due to the effect of fuel economy on vehicle emissions and also to the fact that higher fuel use requires an increase in fuel production energy, which in turn leads to increased emissions. In addition, the vehicle cycle also contributes to this correlation – larger vehicles (that tend to have higher fuel use) require more materials and assembly energy during manufacture.

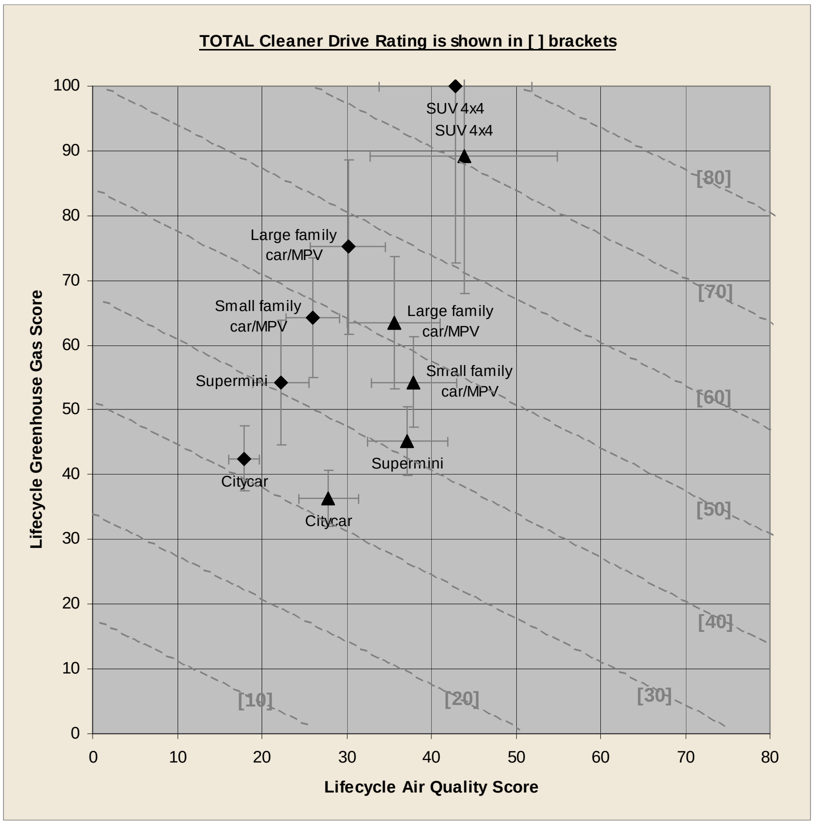
In assessing the relative impact of different vehicle fuels and technologies, the following comparisons can be made (as described in Section 8.6). Using conventional petrol as a baseline, for most vehicle classes, mineral diesel as equivalent within confidence limits. Compressed natural and liquefied petroleum gas cases are rated (for life cycle environmental impact) at approximately 18%-19% below the baseline, and biodiesel is rated 11%-24% lower than petrol (depending on vehicle class). Bioethanol, battery electric using average mix electricity and petrol-hybrids are the next cleanest cases at around 23%-26% lower. As expected the renewable battery electric case is the cleanest according to the Cleaner Drive rating system and scores over 70% less than the petrol baseline.

As mentioned in Section 8.6, the Total Cleaner Drive ratings for many cases are surprisingly similar – excluding renewably charged battery electrics, the average scores vary only by up to 20 points between the fuels/technologies analysed. This is because the Total Cleaner Drive score obscures much of the complexity of the relative air quality and greenhouse gas ratings. That said, discernable differences are more apparent if the Cleaner Drive ratings for greenhouse gases and air quality are considered separately. As was done in Section 9, plotting the greenhouse gas against the air quality ratings makes these differences very clear graphically (see Figure 10.2 for Small Family car/MPV case).

The findings of the LCA analysis of specific vehicle models show that, in those vehicle classes where available, the use of battery-electrics consistently result in the least overall environmental impact (as quantified by Cleaner Drive).[26] Although in some cases this is true for battery electrics using average electricity mix, it is always the case if renewable energy is used for recharging. In the best case, as compared to a petrol baseline, the overall environmental impact is reduced by over 70%. Although currently, there are very few battery electric models available, two models of note are the Reva GWIZ in the Citycar category and the Citroen Berlingo Electrique (Small family and Car-derived van categories).

[26] This is the case despite the increase in emissions associated with vehicle manufacture (due to the greater use of heavy battery metals and light-weight construction materials such as composites).

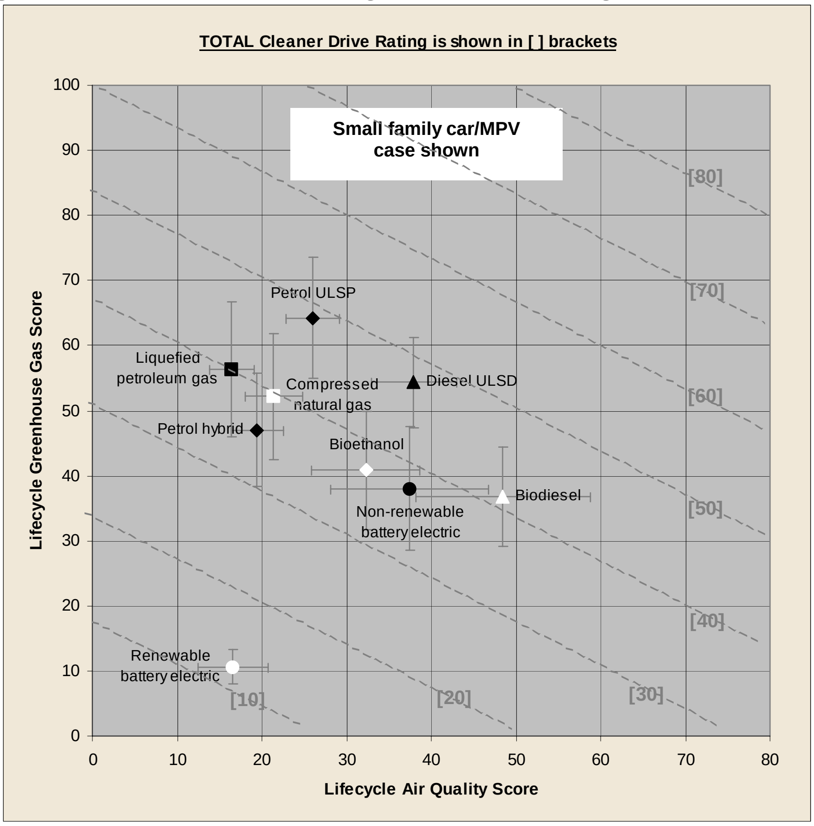
Figure 10.1 Cleaner Drive rating for cars according to vehicle size



KEY TO SYMBOLS

- ◆ ULSP Petrol
- ◇ E100 Bioethanol
- ▲ ULSD Diesel
- △ B100 Biodiesel
- ■ Bi-fuel LPG
- □ Bi-fuel CNG
- ● Average mix BEV
- ○ Renewable BEV

Figure 10.2 Cleaner Drive rating for cars according to fuel/technology



KEY TO SYMBOLS

- ◆ ULSP Petrol
- ◇ E100 Bioethanol
- ▲ ULSD Diesel
- △ B100 Biodiesel
- ■ Bi-fuel LPG
- □ Bi-fuel CNG
- ● Average mix BEV
- ○ Renewable BEV

The findings demonstrate the benefits of hybridisation. In particular, in those vehicle classes where they are commercially available, petrol hybrids (such as the Toyota Prius and the Lexus RX400h) provide significant reductions in overall environmental impact. Given that the Cleaner Drive rating system is weighted in favour of greenhouse gas emissions, and given the improvement in fuel economy of around a quarter offered by hybrids, the overall impact is reduced by around 26%. The Cleaner Drive analysis also shows that, in the event of diesel hybrids becoming available, they would provide a significant reduction in overall environmental impact – with a possibly greater life cycle emission benefit than is the case for currently available petrol hybrid cars.

The two pure biofuels analysed by the LCA also offer consistently reduced overall environmental impacts. Across all vehicle classes, switching from mineral to biodiesel reduces overall impacts by around 13% and changing from petrol (ULSP) to bioethanol reduces air pollution impacts by 23% (as quantified by Cleaner Drive). However, it should be remembered that these benefits are estimated for 100% biofuels (ie E100 and B100). In practice, biofuel blends (eg E5, B5) are more likely to be available in the short-term. In addition, the use of pure biofuels may require some engine modification and invalidate a vehicle's warranty – see Sections 6.2 and 6.3. Furthermore, there remains some uncertainty regarding the emissions data associated with biofuel production. For these reasons, the quantified biofuel benefits should be treated with caution. That said, the benefits suggest that biofuels (of a suitable specification) used appropriately are an important method of reducing the impact of road transport.

The results of the specific LCA analysis show that, liquefied petroleum gas (LPG) and natural gas (CNG) vehicles still offer greenhouse gas and air quality benefits. As compared to a petrol baseline, the data analysed show (for passenger cars) an 18%-19% reduction in overall environmental impacts for the road fuel gases (as quantified by Cleaner Drive). The main OEM proponents of these bi-fuelled vehicles are Vauxhall for LPG and Volvo for CNG (Volvo have recently discontinued their LPG bi-fuel range). However, as explained in Section 9, it should be noted that Volvo manufacture a range of OEM supplied CNG vehicles as part of their normal range – the advantage shown by the CNG data used may therefore represent the best case (after-sale conversion may not offer as large a greenhouse gas benefit).

Regarding the source of the emissions, the results of the LCA analysis shows that, in most cases, the vehicle and fuel production stages account for around 20% of total lifetime greenhouse gas emissions – the emissions associated with fuel and vehicle production are roughly equal in magnitude. This is the case for conventional petrol and mineral diesel, the two road fuel gases and also for petrol-hybrids. This finding is in line with an earlier study conducted by Volkswagen (Schweimer and Levin 2000). This proportion does not hold true for biofuels, the emissions associated with fuel production being significantly increased.[27] For battery electrics, vehicle manufacture and fuel production emissions account for all life cycle emissions, the vehicles being zero-emission in operation.

For the four regulated emissions, no similar brief summary can be made. However, apart from battery electrics, the vast majority of life cycle hydrocarbon emissions originate during fuel production. In contrast, (excluding battery electrics and bioethanol) a significant proportion of life cycle carbon monoxide emissions are generated during vehicle use. The picture for particulates and NOx is more complex. For non-diesel fuels, the majority of these two emissions are produced during fuel and vehicle production – for the two battery electric cases, fuel and vehicle manufacture emissions account for all life cycle impacts (the vehicles being zero-emission at point of use). For diesel fuels, a significant proportion of these two emissions are produced during vehicle operation.

The location of regulated emissions sources has implications for the environmental impact of the emitted pollutants – and one that is accounted for by the Cleaner Drive rating system. From the perspective of the life cycle analysis, with the exception of carbon monoxide, and particulates and NOx from vehicles using diesel fuels, the majority of regulated pollutants are emitted away from most major urban areas (unless a refinery, fuel processing or vehicle manufacturing plant lies within a populated region).

[27] Note that for biofuels, vehicle carbon emissions are not shown on the chart as they are assumed to exactly balance carbon uptake during fuel crop growth.

Future developments

It is worth noting that the two base technologies (spark-ignition and compression-ignition) are themselves evolving, driven to a large extent by tightening regulations and the ACEA Agreement (see Section 6.1). As a result new petrol and diesel engine technologies are now commercially available and are included in the VCA database analysed by the LCA study – however, as these models may not deliver the lowest environmental impact in their class, these advances are not immediately apparent from the data shown.

Figure 10.3 Cleaner Drive rating comparison for Gasoline Direct Injection (GDI or FSI)

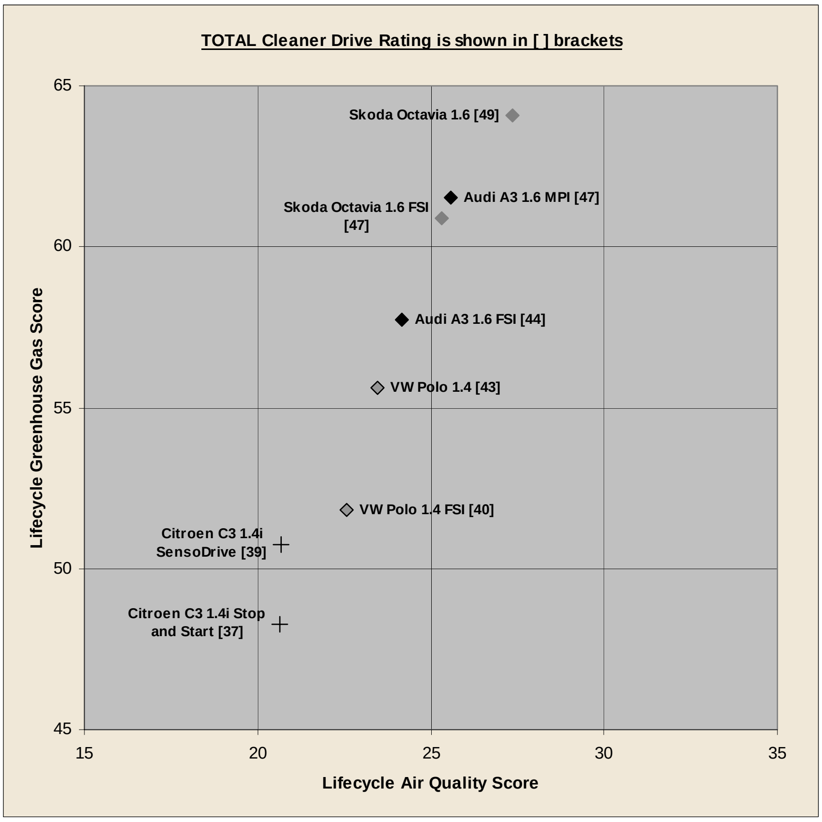


Chart uses Cleaner Drive rating methodology as described in Section 7 of report. The chart shows Cleaner Drive scores based on emission data sourced from the Vehicle Certification Agency (VCA 2005).

One new technology in particular is Gasoline Direct Injection (often known by its German acronym FSI) (see Section 6.1) that can provide a reduction in life cycle greenhouse gas emissions with vehicle CO_2 emissions reduced by up to 15% (Europa 2005). The main proponents of FSI technology are Mitsubishi (who first introduced a GDI passenger car on the market in 1995), Renault, Audi, VW and latterly Skoda. As can be see from the three GDI cases analysed in Figure 10.3, the use of FSI reduces the Total Cleaner Drive rating by 2-3 points. (In practice the cases compared have vehicle CO_2 reduced by around 8% as the power-output of FSI models is slightly increased to take advantage of reduced CO_2 emissions.)

A new commercial diesel technology also worthy of note is the increasing use of Diesel Particulate Filters (DPFs) on some modern diesels (particularly Peugeot and Renault models) – see Section 6.1. Although no VCA data is available to directly compare a vehicle with and without a filter, the Peugeot 407 1.6 HDi FAP shown on Figure 9.4 has a significantly lower (and therefore cleaner) Cleaner Drive rating for air quality than the average diesels in this class.

Also worth noting is the latest version of 'stop-and-start' technology which automatically switches the engine off during idling. This technology was offered by Volkswagen in the late 1990s and later withdrawn for lack of interest. With fuel prices once again increasing Citroen have reintroduced the concept in their Citroen Stop and Start (see Figure 10.3). In the cases compared, the vehicle CO_2 emissions are reduced by around 6% resulting in a lower Cleaner Drive rating by 2 points. (In real traffic

Carpages (2005) estimate a 15% improvement in fuel economy – this would indicate a 15% reduction in vehicle CO_2 emissions and imply a greater environmental benefit than suggested in the chart.)

In the future, petrol and diesel technologies are likely to continue to improve with respect to their level of emissions. Euro 5 regulations are in the process of being agreed as are likely to involve a 25% reduction in NOx and particulates for petrol engines, with a marginal improvement in NOx and an 80% reduction in particulates for diesels (VCA 2005). New particulate limits may also be set for petrol engines, although these are most likely to be first applied to direct injection models. The ACEA fuel-economy agreement is also ongoing, and although there is some uncertainty whether the targets will be achieved, is likely to continue to lead to lower vehicle carbon emissions (see Section 6.1).

The effect of the further tightening of emissions legislation is that conventional and 'alternative' vehicle fuels/technologies will be forced to improve. For petrol and diesel vehicles, this is likely to mean more models that utilise petrol injection (GDI) and diesel particulate filters (DPFs). Most importantly, it will lead to further hybridisation of conventional petrol vehicles and also to the introduction of diesel-hybrids in the light-duty commercial sector. Indeed, there are reports that Toyota have announced that they are aiming to hybridise all their currently available petrol models (Toyota 2005). DaimlerChrysler are also planning to launch a diesel hybrid version of the Mercedes-Benz Sprinter panel van in 2008 – this will have the capacity to the recharged directly from the mains in much the same way as the 'plug in' Prius hybrid (see Section 6.6) (WhatVan? 2005). Under pressure to improve fuel economy (and reduce carbon emissions) more novel engine types, such as the Citroen C3 Stop & Start are also likely to appear – the benefits of these technologies will need to be assessed on a case-by-case basis.

In the longer term fuel cell engines are predicted by many analysts to be the ultimate technological solution to providing high performance vehicles (in the passenger car and commercial sectors) with reduced life cycle greenhouse gas and regulated emissions. Although beyond the scope of this LCA study, previous studies have made estimates of the potential environmental benefits offered by fuel cell vehicles. Depending on the method of on-board fuel storage and fuel production, fuel cell vehicles are predicted to show a significant reduction in life cycle greenhouse gas emissions (per km) of up to 55% as compared to a petrol operation (Concawe 2004). For life cycle regulated emissions, estimates based on modelling show that regulated emissions from UK hydrogen fuel cell vehicles (using hydrogen produced from reformed natural gas) are likely to be significantly lower than petrol cars with NOx emissions being cut by over 70%.[28]

Demonstration fuel cell vehicles are already in use on UK roads and include three Citaro fuel cell buses in London – the buses are part of the 'CUTE' programme, which is demonstrating 30 fuel cell buses across Europe. Worldwide, small fleets of fuel cell cars are being used by companies and government agencies in trials – these include the Mercedes-Benz 'F-Cell' cars based on the A-Class car (in Berlin) and the Honda FCX (in San Francisco). Indeed, almost every car manufacturer has a fuel cell car development programme. The only question that remains is how long it will be before the first fuel cell vehicles become commercially available.

[28] Based on modelling conducted by the author.

11 Summary of findings

One key finding of the LCA study is that vehicle size is as important a determinator of emission impact as fuel/technology type – the results show that vehicle size is strongly correlated to overall environmental impact as quantified by the Cleaner Drive rating system. Moving down one FISITA passenger car category typically reduces the Total Cleaner Drive rating by 6-8 points (with the exception of renewable BEV case which is scored consistently low). For a medium sized passenger car, this equates to a reduction in the total life cycle environmental impact of around 12%-16%. For all fuels/technologies, the difference between the rating of the smallest (Citycar) and largest (SUV) car categories is around a factor of 2.5.

In assessing the relative impact of different vehicle fuels and technologies using the Cleaner Drive rating system, the following comparisons can be made:

- For most vehicle classes, mineral diesel and petrol are equivalent (within confidence limits) regarding total life cycle environmental impact;
- In those vehicle classes where available, the use of battery electric vehicles consistently result in the lowest overall environmental impact. Although in some cases this is true for battery electrics using average electricity mix, it is always the case if renewable energy is used for recharging. In the best case, as compared to a petrol baseline, the overall environmental impact is reduced by over 70%;
- In those vehicle classes where they are commercially available, petrol hybrids provide significant reductions in overall environmental impact (by around 26%). The analysis also shows that, in the event of diesel hybrids becoming available, they would also provide a significant reduction in overall environmental impact – with a possibly greater life cycle emission benefit than is the case for currently available petrol hybrid cars;
- Across all vehicle classes, switching from mineral diesel (ULSD) to pure biodiesel (RME) reduces the overall environmental impact by around 13%, and changing from petrol (ULSP) to pure bioethanol (sourced from wheat) reduces air pollution impacts by 23%. However, there remains some uncertainty regarding the emissions data associated with biofuel production. For these reasons, the quantified biofuel benefits should be treated with caution;
- Although conventional vehicles have markedly improved emissions performance, the analysis shows that, liquefied petroleum gas (LPG) and natural gas (CNG) vehicles still offer greenhouse gas and air quality benefits. As compared to a petrol baseline, the data analysed shows (for passenger cars) an 18%-19% reduction in the overall life cycle environmental impact for the two road fuel gases.

Regarding the source of the emissions, the results of the analysis shows that, in most cases, the vehicle and fuel production stages account for around 20% of total lifetime greenhouse gas emissions – the emissions associated with fuel and vehicle production are roughly equal in magnitude. This is the case for conventional petrol and mineral diesel, the two road fuel gases and also for petrol-hybrids. However, this proportion does not hold true for biofuels, the emissions associated with fuel production being significantly increased. For battery electrics, vehicle manufacture and fuel production emissions account for all life cycle emissions, the vehicles being zero-emission in operation.

Considering the regulated emissions, apart from battery electrics, the vast majority of life cycle hydrocarbon emissions originate during fuel production. In contrast, (excluding battery electrics and bioethanol) a significant proportion of life cycle carbon monoxide emissions are generated during vehicle use. The picture for particulates and NOx is more complex. For non-diesel fuels, the majority of these two emissions are produced during fuel and vehicle production – for the two battery electric cases, fuel and vehicle manufacture emissions account for all life cycle impacts (the vehicles being zero-emission at point of use). For diesel fuels, a significant proportion of these two emissions are produced during vehicle operation.

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