

Chapter Three

Review of work on Alternative Fuels

3.1 Databases

The majority of LCAs use databases and spreadsheets as a means of comparing and contrasting alternatives in a holistic manner. Data can be arranged in a specific style unique to the user with features such as: linked worksheets, macros and descriptive analysis. The major transport related LCAs of today use all of these features and more and commonly use Microsoft Excel. Excel enables the user to manipulate data in many different ways and allows complex calculations to take place with a user-friendly interface.

3.2 Sources of Data

An inventory is required in order to build an LCA. This will normally consist of vast amounts of data drawn from many different sources. Difficulties lie in normalisation of the data to a common reference. American, Australian and European data sets are included within this thesis with large variations in the samples dependent upon the source of reference. In general, agencies and government bodies tend towards supplying data in mass units whereas conference and journal papers normally provide data in mass/distance travelled or mass/energy unit. A large amount of scaling and averaging together with several assumptions are required in order to derive a common reference value. Further difficulties arise from the loose definitions of some data and in being confident that one knows what has been measured and reported and where the boundaries lie between statistics of a similar and possibly overlapping nature.

In order to collate the data, a holistic and robust LCA is required. The user must be able to change data sets and values with ease, specific to a certain country and/or application. The user must also be vigilant when incorporating new data and, where possible, look for consistency checks by reference to other sources etc.

The principal organisations and agencies that provided data for building LCA models are as follows.

3.2.1 American Governments and Agencies (US EPA/NREL)

One of the largest Environmental Protection Agencies in the world exists in the US, the United States Environmental Protection Agency (USEPA). It provides leadership and works closely with Federal Agencies, State and Local Governments and enforces regulations under existing environmental laws. Within the USEPA, a Technology Transfer Web was developed (*TTNWeb*) within which an Inventories and Emissions Factors Database has been established. The Clearinghouse for Inventories and Emissions Factors (CHIEF) Group developed the Compilation of Air Pollutant Emission Factors (AP-42), Volume I: Stationary Point and Area Sources and Volume 2: Mobile Sources *fifth edition*, see www.epa.gov/otaq/ap42.htm

Within the AP-42 documents, EPA (1985, 1995) there is a vast amount of atmospheric emissions data from: combustion, evaporation, waste disposal, chemical and petroleum processes, minerals and metallurgy of stationary sources in Volume 1 through to: vehicle standards, fleet information, gasoline and diesel vehicles, guidelines and emission factors in Volume 2. All of the data is gathered from established, reliable emissions models. The AP-42 series is the key text used by legislative bodies and Offices of Transportation throughout the US. The information however is specific to the US and cross comparisons with European work can prove difficult. For example the US electricity mix differs from the UK and European mixes, with electricity generated via different process, dependent upon the region of production. The AP-42 documents are also becoming outdated, with current studies referencing emissions data from some 18 and 8 years from the current year respectively. Furthermore, the size and complexity of the

AP-42 documents (over 1000 pages) inhibit a quick and simple analysis of emissions profiles to be made from the various processes.

The National Renewable Energy Laboratory (NREL) is the US Department of Energy's premier laboratory for renewable energy research and development. The Environmental Programs Division, see www.nrel.gov/environment implements environmental programmes in close collaboration with partners in the U.S. Federal, State and Local Agencies, developing countries, the business community, international organizations, environmental organizations, and other technical institutions. NREL uses LCA to develop and commercialise various research projects being supported by the Department of Energy (DOE). This has led to the formation of the NREL Energy Analysis Division, see www.nrel.gov/analysis/life_cycle.html. The Energy Analysis Division produced LCAs of alternative fuels; see Tyson (1993) and Sheenan *et al* (1998).

3.2.2 Australian Government (Australian Greenhouse Office)

The Australian Greenhouse Office established one of the world's major scientific research institutions, see www.greenhouse.gov.au.

The Commonwealth Scientific and Industrial research Organisation (CSIRO) of Australia, see www.csiro.au, is one of the world's largest scientific research institutions. Within CSIRO, Atmospheric Research is a group specialising on LCA of Alternative Fuels. This group is led by Professor Beer, who has produced numerous LCA studies for the Australian Greenhouse Office, the details of which are discussed below. The CSIRO has produced the largest percentage of Alternative Fuels LCA work in Australia.

3.2.3 UK Governments and Agencies (DETR/DTLR/EA/ETSU/NETCEN)

The original Department of the Environment, Transport and the Regions (DETR) was in 2001 split into the Department of the Environment (DoE), the Department for Transport (DfT) (former Department of Transport and Local Government Regions (DTLR)) and the regions section integrated into the Office of the Deputy Prime Minister. The DTLR,

see www.dtlr.gov.uk in 2001 became the Department for Transport (DfT), see www.dft.gov.uk in order to focus specifically on transport issues. Through the Department, a number of services are available, from aviation through to shipping. Statistical information on transport in the UK and overseas is available and used within the current discussion.

The Department for Environment, Food and Rural Affairs, (DEFRA), see www.defra.gov.uk focuses upon many environmental issues ranging from health and welfare through to conservation and sustainable development.

Department of Trade and Industry (DTI), see www.dti.gov.uk provides detailed information pertaining to science, technology and industry. In particular the Energy Policy Directorate, see www.dti.gov.uk/epa produces the following detailed annual energy statistics: Energy Report, Digest of UK Energy Statistics (DUKES), Development of the Oil and Gas resources in the UK, UK Energy Sector Indicators, UK Energy in Brief, Energy Trends and Energy Prices. Of these publications, the DUKES report has been of the most use in the current work. Information within DUKES includes all statistics for energy, petroleum, gas, electricity, combined heat and power, renewable sources of energy and foreign trade. The information produced with DUKES must be treated with caution, as numerous values within can be misleading to the user. The information within is received annually from the oil and gas industry and the author has had regular communicated with Corrie (2002), Evans (2002), Janes (2002), Purkis (2002), Vitalis (2002), Williamson (2002) from the DTI. The data presented in mass and energy units for solid and gaseous fuels respectively, stretching across a five-year span. The majority of values are rounded up to their whole numbers, Khanbhai (2002) and therefore may have implications on any mass balance studies. Input and output values are presented through the fuel cycles (petrol, diesel, LPG, NG and electricity) from their first derivatives (ground) to their consumption by the UK for that chosen year. Energy supply, demand and use values are also presented, Purkis (2002) within the earlier chapters and measured in tonnes of oil equivalent (toe). The most reliable sources of UK energy and fuel statistics are presented within DUKES and the work is the product of the

DTI's foremost statisticians, energy and policy advisors, oil and petroleum experts and sustainability experts.

The Environment Agency (EA), see www.environment-agency.gov.uk, has produced an online database of environmental discharges from landfill sites, factories and offices across the UK. The information can be gathered by viewing either data maps or tables and by subsequently downloading the relevant sets of information. The user may search for a particular process and/or location for any given year and dataset. For example, with the known location of a particular factory, a complete set of substances released to air/water can be found, together with the total release over a particular route for a given year. This Pollution Inventory (PI) was formed in 1997 after changes were made to the original Chemical Releases Inventory (CRI) of 1990. The PI has been developed to provide information on annual mass releases of specified substances to air and water which may arise from any large industrial sites (i.e. those authorised by the Environment Agency under Integrated Pollution Control (IPC)). Under IPC a company must provide information from non-point (e.g. chimneys), point and fugitive emissions sources (e.g. leaks or spillages).

The PI results are presented under the titles of: Operator name, authorisation number, site address and process type for many different emissions. The values are rounded off to their nearest whole number and as previously mentioned may cause problems in mass balance analysis. One major stumbling block with the PI data is the recording of emissions below certain minimum levels. For example the PI will record an emission as being less than a certain value, without knowing what that value is. Take the emission of sulphur dioxide to the air in the year 2000 from the Shell oil refinery in Stanford-le-Hope, Essex. The emission is recorded as <10(t), this value could be anywhere in a ten tonne range and may cause problems if used at a later stage. Moreover, the impact of substances that have a very large Global Warming Potential (GWP) contribution, independent of size, may significantly alter any subsequent GWP calculations. Careful consideration must be given to the values used by the PI, however in most cases the significance of the amount of compound released to air is minimal and the majority of

compounds are recorded to the nearest tonne or kg. The majority of refinery emissions data available within the PI has not been updated since 1999.

The PI has been used extensively within this thesis in order to obtain the emissions data for the LCA model, so that comparisons of the different fuel cycles and vehicle cycles can be made.

The Energy and Technology Support Unit (ETSU), see www.etsu.com is now incorporated into Future Energy Solutions, part of the Atomic Energy Authority (AEA Technology). In 1996 Gover *et al* (1996a, 1996b) produced the first LCA of alternative fuels, see the ETSU Model in Section 3.3.6.

The National Environmental Technology Centre (NETCEN) was formed in 1993 through a merger of the Warren Spring Laboratories (WSL) with AEA Technology. The Environment section of AEA Technology was formed two years later in 1998. NETCEN is responsible for producing the UK Air Quality Information Archive, see www.airquality.co.uk and the UK's National Atmospheric Emissions Inventory and Greenhouse Gas Inventory (NAEI), see www.naei.org.uk. Within the archives and inventory the pollutant concentrations are expressed in mass output and g/km travelled (in the case of transport emissions). The results represent the emissions per mass/person/vehicle/area, as appropriate, based upon the total emissions in that region. Supplementary information is sparse with no clear explanation of the calculation of the results provided. The Air Quality Information Archive and the NAEI are the most widely used databases in the UK by local authorities, government agencies and industry. They provide a quick and simple estimation of the pollution generated by the various industrial, chemical and transport related industries. An assessment of Local and National air quality can also be found, providing information to the public, who may have concerns over the quality of the air they breathe.

3.3 Alternative Fuels LCAs

3.3.1 Argonne National Laboratory (ANL)

The ANL is a US Department of Energy (DOE) Laboratory operated by the University of Chicago, see www.anl.gov. Within ANL, a Transportation Technology Research and Development Centre exists, see www.transportation.anl.gov. Through this Center, see www.transportation.anl.gov/ttrdc/modeling/index.html, a LCA transport model has been developed entitled GREET (Greenhouse Gases, Regulate Emissions, and Energy Use in Transportation), see www.transportation.anl.gov/ttrdc/greet/index.html.

A variety of other LCA models have also been produced by and for the ANL, the majority of which commonly use data from the GREET model combined with other site specific data or studies.

3.3.2 GREET Model

The GREET model was developed as a multidimensional spreadsheet model in Microsoft Excel by Wang (1999a, 1999b) at the ANL in the US. The first model (GREET v.1.5) was released in 1996 and since then there have been regular updated versions. A test version (GREET v.1.6) was made available on 14th August 2001. In addition there is a heavy vehicle module, known as GREET 3 that is designed to estimate fuel-cycle energy and emissions of heavy-duty trucks and buses. This model is only available to ANL users.

The GREET v.1.5 model evaluates the energy and emissions impact of numerous light vehicle types. The US Department of Energy Office of Transportation Technologies sponsors the research. For a given vehicle and fuel system (in the US only) the GREET v.1.5 model will calculate the consumption of total energy through the life cycle, the emissions of the Greenhouse Gases (GHG) CO₂, CH₄ and N₂O and the emissions of five pollutants: VOCs, CO, NO_x, PM₁₀ and SO_x for light vehicles. These emissions were chosen because of their effect on the global and local environment respectively. See

Pollutants (preceding Chapter 1) for an explanation of the environmental impact of each emission.

The GREET model has been developed to calculate per-mile energy use and emission rates of various combinations of vehicle technologies and fuels for both fuel and energy cycles. The model includes more than 30 fuel cycles, involving 13 types of fuel feedstock (petroleum, NG, flared gas, coal, soybean, uranium, corn, woody biomass, herbaceous biomass, landfill gases, hydropower, solar energy and wind) and 14 fuels (conventional gasoline (petrol) (CG), reformulated gasoline (petrol) (RFG), conventional diesel (CD), reformulated diesel (RFD), LPG, CNG, LNG, methanol, dimethyl ether (DME), ethanol, hydrogen, Fischer-Tropsch diesel (FTD), biodiesel and electricity). These fuels were chosen because researchers are interested in them and because data regarding fuel production are available; unlike the present author's LCA analysis, which has chosen fuels commercially available in the year 2000 limited by data available in the UK. In terms of vehicles, the GREET model analysed the following; electric vehicles (EV), hybrid electric vehicles (HEV); fuel cell vehicles (FCV) fuelled with hydrogen, methanol, gasoline ethanol, or CNG; spark-ignition internal combustion engine vehicles (ICEVs) fuelled with CG, RFG, CNG, LNG, LPG, or ethanol; and compression-ignition ICEVs fuelled with CD, RFD, DME, FTD, or biodiesel.

To estimate fuel-cycle energy and emissions, units of British thermal units (Btu) and grams per million Btu ($\text{g}/10^6 \text{ Btu}$) of fuel throughput respectively were chosen. The energy and emissions values are aggregated (through a calculation of fuel throughput using emission factors and mass balances) to estimate total values for each fuel and vehicle cycle. For a given stage, energy input per unit of energy product is calculated by using the energy efficiency of the stage; unlike the author's LCA analysis, which calculates the emissions generated via the throughput of 1 tonne of feedstock/fuel regardless of stage efficiency.

Emission factors in the GREET model for different combustion technologies fuelled by different process fuels are included, derived from the EPA AP-42 documents, EPA

(1995). Information of this type, in the UK, is difficult to obtain due to the commercial sensitivity of petroleum processes and emissions in particular. The emissions information available, within this study, is that provided by the Environment Agency and is a simply summation of the various processes within a particular region. For example, the emissions associated with petroleum refining within Stanlow Oil Refinery are presented as the total released per year across the entire site. No data is available for point specific emissions from particular processes and/or machinery.

The overall energy and emission results are split into feedstock, fuel, vehicle operation and total for each fuel and vehicle type. The percentage contributions to each stage are included and illustrated within Wang (1999a, 1999b).

The GREET model is an expansion of the earlier LCA models of Acurex (1999), Bentley (1992), Brogan and Venkateswaran (1992), Darrow (1994a, 1994b), Delucchi (1991, 1993, 1997), Ecotrafic, AB (1992), National Renewable Energy Laboratory *et al* (1991, 1992), Sheehan *et al* (1998), Singh *et al* (1998a, 1998b) and Wang and Santini (1993).

3.3.2.1 Conclusions on the GREET model (v1.5)

GREET showed that, of the vehicles and fuels under investigation in 1999, there is no single fuel and vehicle combination that solves energy, GHG emissions and local air quality pollution problems, if indeed one exists. One technology may have positive energy and GHG emissions but adverse local air pollution impacts. In conclusion, it may be necessary to pursue multiple technology pathways specific for individual transport modes in order to achieve an overall GHG emissions and local air pollution benefit.

GREET is a model based on conventional and alternative fuels, as new fuel and vehicle technologies are introduced the results within the model may change and affect the overall life cycle results i.e. a change in crude oil refining or the introduction of hydrogen may lead to a decrease (or more unlikely - an increase) in localised and total emissions output.

The database size, coupled with the iterative calculations within the GREET model make it difficult to track through the various pathways and to identify each numerical value. However, with an understanding of the general processes and pathways, the model can be used to compare and contrast all of the fuels and vehicles under examination. A more friendly, Graphical User Interface (GUI), with detailed explanations of the results would prove beneficial. Indeed, the latest version of GREET v.1.6 uses a GUI.

Changes in fuel and vehicle technology could change the use of existing technologies and alter the balance of transport that currently exists. The effects of market change are beyond the modelling capability of GREET.

The results presented in GREET (v1.5) are subject to uncertainties, which will affect the outcomes of the life cycle results. Due to lack of resources, the ANL was unable to expand the work and conduct a sensitivity analysis and the results. This has been addressed, to some degree, in v1.6, see later discussion of the GM well-to-wheels study.

More than 100 organizations are using GREET (v1.5 and 1.6), including Government Agencies, the auto industry, the energy industry, research institutes, Universities, and public interest groups. GREET users are spread in North America, Europe, and Asia. The ANL has used GREET to evaluate various engine and fuel systems for the US DOE, other government agencies, and industry. An example of which is the detailed analysis of energy and emission impacts of ethanol fuel study for the Illinois Department of Commerce and Community Affairs.

3.3.3 The contribution from Gaines *et al* (1998)

A Life Cycle Analysis for Heavy Vehicles was undertaken by Gaines *et al* (1998) for the ANL. In concurrence with other LCA studies, a complete review of heavy-duty trucks from material extraction through to disposal and recycling was completed, specific to the US. Heavy duty trucks within this analysis are tractor-semitrailer combinations (articulated HGVs equivalents in the UK).

The purpose of the paper was to evaluate the potential for reductions in energy use and atmospheric emissions over the life cycle of American heavy trucks. The work was designed to evaluate the potential for reductions in energy use (petroleum use in particular) and atmospheric emissions over the life cycle of heavy trucks. A spreadsheet model (GREET) is used with energy use and GHG emissions evaluated over the entire life cycle, inclusive of vehicle production and recycling, maintenance, operation, fuel production, transportation and use. The emissions under examination are the same as those considered in the GREET study. Principally, the GREET model was run using the data for heavy trucks (> 11.7t GVW¹).

Total fuel cycle energy and emissions from diesel fuel made from NG via the Fischer Tropsch (F-T) process and NG, stored as LNG, were compared against conventional petroleum diesel, low-sulphur diesel (LSD). Biodiesel, di-methyl ether (DME), alcohols (methanol, ethanol) and CNG were not considered by Gaines *et al* (1998), due to the relative shortcomings in comparison to conventional diesel. The information upon which this judgement was made was taken from GREET.

The estimations of life cycle impacts within this study are taken from GREET and AP-42, with on-road emissions from EPA's Mobile5a model. The following compounds were under investigation, VOC, CO₂, CO, NO_x, PM₁₀, SO_x, CH₄, N₂O. Once again as chosen by GREET, see previous explanation.

3.3.3.1 Conclusions on the Gaines Model

The Gaines model uses the GREET model in the evaluation of life cycle emissions and as a result, similar conclusions are made. Gaines states that there are tradeoffs among impacts, the lowest fossil energy use does not necessarily result in lowest total energy use. Lower tailpipe (F6 equivalent) emissions may not necessarily result in lower life cycle emissions of all pollutants under investigation e.g. Gaines noted that the

¹ GVW refers to Gross Vehicle Weight. This is the maximum recommended weight for a vehicle, including: the weight of the vehicle itself, fuel and other fluids, passengers and all cargo.

substitution of aluminium for steel in HGVs increases energy use for production of the vehicle but decreases CO emissions from blast furnaces. This small increase in energy use would allow the HGV to haul extra weight over its life time, this would decrease total fuel consumption and the resultant emissions in the end-use (F6) stage.

Gaines states that the use of natural gas based alternative fuels in trucks (HGV equivalent) does not save energy or minimise GHG emissions. The greatest reduction in GHG emissions could be seen by improving engine and drive train efficiency, improving aerodynamics and by reducing vehicle weight. Natural gas would appear more attractive if a more efficient engine were developed. This conclusion has particular relevance to the present study and in particular the analysis of Landfill Gas (LFG) as a viable alternative fuel.

The output from the Gaines model is presented in a similar format to the GREET model. Emissions results are calculated (grams per mile) and a breakdown of the percentage contribution made to each stage is illustrated. Details pertaining to the calculations made are not clearly documented, however the model does present, compare and contrast the relative merits of alternative fuels against conventional fuels. The emissions reductions/additions with the various fuel options are clearly identified in a more transparent format than the GREET model.

The availability of reliable data was a problem for Gaines *et al* and as a result, speculative statements were made based upon the authors' judgement and knowledge. Moreover the variation in engine design, operating conditions and test procedures made it difficult to accurately predict tailpipe (F6 equivalent) emissions. A literature review found that the majority of tests, performed by the USEPA, were from pre-1996 vehicles on urban driving cycles. Given the uncertainty among tests on urban, rural and motorway tests plus variation in the emissions from the same engine, Gaines concluded that the test data used in his study would suffice to arrive at reasonable first estimates of life cycle emissions.

3.3.4 The Hackney Model

The Hackney model compares emissions, energy efficiency and cost for different fuel and vehicle technologies. A multiple-page Excel spreadsheet is again used for the LCA. The model is based upon a fuel chain model developed by Arthur D. Little, ADL (1996) for the Ford Motor Company. Hackney and de Neufville (2001) expanded the original work by adding a cost model, several new fuel and vehicle cycles. In total 27 fuel cycles and 17 vehicle cycles were analysed specific to passenger cars in the US.

The model consists of a fuel chain consisting of 5 stages: resource extraction, transportation, refining into fuel, transport of fuel to a retailer and final delivery as fuel. The emissions, energy efficiency and cost performance of different fuel and vehicle technologies, over an identical life cycle are compared. The program is a multiple page Excel spreadsheet with table formatted inputs, iterative calculations and graphical output. Emissions and costs results are expressed per gigajoule (GJ) of energy contained in the resulting fuel. The vehicle models calculate the amount of energy, in the form of the fuel used by each vehicle over its lifetime, and multiplies this value by the corresponding cost or emission per unit energy of fuel from its production chain. Adding the cost and emissions of using the vehicle to this former result from the fuel chain gives the life cycle output, Hackney and Neufville (2001).

The data for the model is taken from the International Energy Agency (IEA), US National Renewable Energy Laboratory (NREL), US Department of Energy (DOE), US Office of Domestic and International Energy Policy (ODIEP), Argonne National Laboratory (ANL), US Government Accounting Office, US National Research Council (NRC), Delucchi (1991, 1993) plus others.

The emissions are modelled for impacts at a regional level, with some modelling of global impact (GHG emissions), however a higher heating value is used for a comparison of the greenhouse gases as opposed to the now more conventional method of

global warming potential (GWP). The results are presented once again in units of mass per distance travelled, with graphical outputs an option.

3.3.4.1 Conclusions on the Hackney Model

Hackney and Neufville state that in the longer term, electric drive vehicles using liquid hydrocarbons in fuel cells may offer large emissions and energy savings at a competitive cost. Natural gas and battery electric vehicles may prove to be feasible at reducing emissions in niche areas within the inner city.

Alternative fuels have potential advantages over petroleum vehicles in reducing the emissions from the fuel cycle and the tailpipe (F6 equivalent) and they have less reliance on crude oil, which has further implications on National Security and stabilisation of any economy. Of these alternatives, electric vehicles were found to release an equivalent amount of Particulate Matter (PM) from stationary sources as conventional petroleum vehicles do from the tailpipe, but other life cycle emissions are lower.

Given the present US situation, Hackney suggested that vehicles based on petroleum fuels using some form of Internal Combustion Engine (ICE) are likely to dominate the automotive fleet for the conceivable future. However, introducing a number of future alternatives, along with coordinated research offers less risk and an increased probability for an optimal solution. A similar conclusion is made by GREET.

The model can be more easily interpreted in comparison to GREET and the user can more easily modify the spreadsheets to ones own specification. The current version (2001) uses parameters based on the best available data, but can be modified to suit. Users can amend the input to exploit more recent data and explore any scenario they might desire.

However, uncertainty in the output can produce errors and the trade and government publications used in this study only provide reasonable forecasts of emissions. As a result Hackney noted that estimates for developing technologies and market scenarios

are uncertain. A sensitivity analysis was performed in this study by changing different components and identifying the parameters that most strongly influence the life cycle outcomes. In view of the life cycle as a whole, even some large uncertainties within the model do not change the overall conclusion. The cost, emissions and energy for most vehicle and fuel combinations are unchanged, however for some values, which are nearly equal, even small changes in the models can affect the outcome e.g. Gaines noted that the relative efficiency and tailpipe emissions of an ICE affects the total life cycle emissions. The formation of hydrogen from natural gas or coal has an affect on the CO₂ and PM output together with implications for cost. Following identification of the sensitive parameters, simulation occurred.

3.3.5 Australian Models (CSIRO)

3.3.5.1 Beer *et al* (2000, 2001)

CSIRO has developed a Life Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles, Beer *et al* (2000, 2001). The earlier version (Stage 1) of the assessment presents the abstract, key findings, contents and tables. Stage 2 presents the LCA background information, methodology and results.

The report examines diesel and alternative fuels in terms of their emissions of greenhouse gases and air pollutants. This is done within the LCA framework of a fuel cycle only using a “cradle-to-grave” analysis. The emissions are compared relative to the distance travelled by the vehicle for the following fuel types: low sulphur diesel (LSD), ultra-low sulphur diesel (ULSD), compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), ethanol, diesohol, canola oil, biodiesel and waste oil.

A later publication Beer *et al* (2002) examines the pre-combustion and combustion emissions of GHGs from Australian heavy vehicles, similar to the work of Wang. This later study provides a succinct account of the LCA methodology used within the Beer *et al* (2000) study and concludes with a discussion of the results and sensitivity analysis.

3.3.5.1.1 Conclusions on the Beer HGV Models

Of the fuels under examination, Biodiesel had the lowest GHG emissions on a life cycle basis. However, biodiesel emits larger quantities of CO₂ than conventional diesel and petrol vehicles but the source is from renewable carbon stocks. Ethanol and then the gaseous fuels (LPG, CNG, LNG) are next in succession. The extra processing energy required to produce LSD and ULSD in Australia increase their GHG emissions compared to conventional diesel. The extra energy required to liquefy and cool LNG also leads to a higher GHG emissions output, moreover the life cycle GHG emissions for LNG are the highest for heavy vehicles compared to all other fuels examined.

Only the fuel cycles are considered in the Beer model and the system boundaries exclude the analysis of a vehicle, together with oil, gas and petrochemical production and exploration infrastructure. However there is an input from fuel delivery to filling stations, vehicle manufacture and maintenance and end of life management of vehicle fleets.

Beer noted that it is rare for individual studies to have examined similar engines using similar pollution control measures for heavy vehicles. As a result the emissions data varies and it is possible to produce misleading comparisons. Where possible the data used by Beer is collected from a number of sources and statistics are used to quantify uncertainty. Estimates are made where data sources are unavailable.

Beer used the work of GREET to cross check the results he produced from the use of the SimaPro database, which is an extensive Australian database of manufacturing energy input and emissions. The advantage of SimaPro is its ability to produce a process tree of each component within the LCA. This tree is similar to the Emissions Checklist developed by the present author, see Appendix C. This checklist uses a simply mass flow technique to calculate theoretical emissions outputs through various stages in the fuel cycle.

3.3.5.2 Beer (2000)

A LCA of GHG Emissions from road transport has been developed by Beer (2000), for the CSIRO. Unlike the Beer *et al* studies, this study examined passenger vehicles and diesel, LSD, ultra-low sulphur diesel (ULSD), CNG, NLG, LPG and Biodiesel fuels on a life-cycle basis. The fuels are compared on a “like-with-like” basis based upon the mass of emissions per kilometre of distance travelled per vehicle.

The study relates the life-cycle of infrastructure and road construction to the vehicles themselves. The GHG emissions associated with maintenance and administration of the New South Wales Road and Traffic Authority was under scrutiny.

3.3.5.2.1 Conclusions on the Beer (2000) Model

Beer examined GHG emissions and energy consumption in the life cycle of passenger vehicles. He found that 80% of the energy consumption is in the actual driving of the vehicle (F6 equivalent). This total energy refers to the energy involved in production, utilisation and disposal of the vehicle itself. This percentage reduces if a vehicle is more fuel efficient, or if the associated manufacturing and fuel processing is less efficient.

Beer noted that it is difficult to compare like-with-like in the examination of conventional and alternative fuels. Data availability on alternative fuels also caused a problem within the evaluation stage of the study. As a result there is extreme variability in the available emissions data, and as noted again in his later studies, Beer *et al* (2000, 2001), it is possible to produce misleading information. Uncertainty has been built into the Beer (2000) study in the form of error bars to represent one standard deviation from the average value.

3.3.6 Gover *et al* (1996) - The ETSU Model

The Energy Technology and Support Unit (ETSU) was established in 1974, undertaking technical, economic and environmental analysis of energy technologies for the former DTI, the European Commission (EC) plus others. ETSU is a Division of AEA Technology.

The first LCA of alternative fuels was produced by ETSU and co-funded by the DTI and Department of Transport. The Alternative Road Transport Fuels Life-cycle Study, Vol. 1 and 2 Gover, M. *et al* (1996) was the first of its kind in the UK and was an expansion to an earlier impact model developed at AEA Technology, Eyre and Michaelis (1991). Liquid, gaseous, electric and renewable fuels were compared on a fuel life-cycle basis only. The study reviewed energy use, emissions and economics from production of fuel through to final consumption. A LCA of the vehicles using the fuel was beyond the scope of the ETSU study that had a focus upon the operational aspects of the production and end-use of the various fuels.

As with all LCAs, the energy use and emissions from each stage of the fuel cycle are calculated, and then aggregated to estimate the life-cycle emissions for fuel production, supply and end-use.

The following fuels were considered: petrol, diesel, LPG, CNG, electric, biomethanol, bioethanol, biodiesel and Rape Methyl Ester (RME); to be used within passenger cars, Light Goods Vehicles (LGVs), Heavy Goods Vehicles (HGVs) and buses² in the UK. Unlike other LCA studies, Gover *et al* extended the fuel generation and tailpipe emissions to include the total emissions as a result of lifetime use for each of the vehicle types under examination. For the Internal Combustion Engine (ICE) vehicles, annual mileage estimates were calculated as 16000km over an operational lifetime of 12 years. Electric vehicles have a lower assumed annual mileage of 10000km, with the same estimated 12-year use. The author makes similar calculations and assumptions, see Chapters 5 and 7.

3.3.6.1 Conclusions on the Gover Model

Volume 1 of the Gover *et al* study details the individual emissions reductions and additions for each of the fuels under investigation. For example, diesel LGVs offer CO,

² ETSU vehicle weight assumptions are as follows: cars are (1400-2000cc), LGVs (<3.5t), HGVs (>17t), buses (new and old large)

HC and CO₂ savings on a life cycle basis in comparison to a petrol equivalent with the forfeit of higher levels of NO_x and PM.

In terms of urban pollution, LPG, natural gas, electric and alcohol fuels show the greatest reduction levels, with GHG emissions of natural gas and LPG LGVs similar to petrol. Alcohol fuels also show large reductions in GHG emissions in the Beer *et al* (2000, 2001) studies.

Early introduction of various alternative fuels into niche markets will have the greatest long term influence, nevertheless, Gover *et al* noted that petrol and diesel vehicles will dominate for the foreseeable future.

The work of Gover *et al* is subject to a large variety of assumptions and simplifications. A change in any of the assumptions made would change the overall life cycle results. A sensitivity analysis was not performed and as a result all data must be viewed sceptically.

In data collection Gover *et al* noticed that some information is scarce, with some companies unwilling to divulge information. Moreover some information has only been available from a single source, for instance where only one company could be found that was prepared to help. Thus there are numerous uncertainties in the data, however at the time of publication (1996) the values present in the study represented the most up-to-date and complete information available in the UK to ETSU.

3.3.7 General Motors (GM-North America) Study

The General Motors Corporation (2001) in collaboration with the Argonne National Laboratory, BP, ExxonMobil and Shell developed a Well-to-Wheel (WTW) Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems. The study was split into three volumes, the first being an Executive Summary Report, the second a three-part study and the third a complete Well-to-Tank (WTT) report plus data. The study utilised the GREET energy model and estimated total energy, fossil energy, petroleum use and

GHG emissions (CO₂, CH₄, N₂O). It analysed 75 fuel pathways for application to Hybrid Electric Vehicles (HEVs) and Fuel Cell Vehicles (FCVs).

A series of fuels were considered in the analysis. Gasoline, diesel and naphtha were considered for the petroleum-based fuels. Natural Gas cycles included: CNG, methanol (MeOH), Fischer-Tropsch diesel³ (FTD), Fischer-Tropsch naphtha, gaseous hydrogen (GH₂), liquid hydrogen (LH₂) and flared gas (FG). Finally electricity and ethanol production pathways were included.

A number of probability distribution functions for key stages in the study were included to determine uncertainty statistically. For most parameters a normal probability distribution was assumed. If a normal distribution could not describe the parameter correctly a triangular distribution was assumed. The previous studies, with the exception of the Beer 2000 sensitivity analysis, have been deterministic in the sense that, in most cases, one single value is taken for each variable in the calculation and as a result, single valued output variables form the data for assessment. In the GM study an attempt was made to recognise the uncertainties in the variable values by adopting probability distributions for those variables likely to show significant variability. Sampling via Monte Carlo simulation gives an indication of the variability in the output variables. This is the basis upon which Chapter 7 is built.

Like many other LCAs, the GM study combines information from many different sources and integrates the information to produce an overall impact assessment. The General Motors approach is to review two cycles, the first is the WTT cycle developed using GREET and the second is a Tank-to-Wheel (TTW) cycle vehicle simulation model developed by GM. These two models combine to form a Well-to-Wheels (WTW) Integration Model comprised of 12 fuel pathways and 15 propulsion systems. The development of a rating system for uncertainty followed to identify the parameters with the greatest and least uncertainty through each WTT cycle.

³ The Fischer-Tropsch process converts coal gas into liquid fuels and was first used in the UK in 1915 during the First World War, to assist in the transformation of coal to oil fired Royal Naval battleships.

3.3.7.1 Conclusions on the GM Study

In the analysis section, GM found that many pathways to produce a given fuel were similar. In the US, petroleum based fuels offered the lowest total energy use for each unit of energy delivered to the vehicles. Natural gas based fuels (except CNG) generally use a large amount of energy.

Petroleum based fuels and NG produced in North America (NA) are associated with low 'well-to-tank' (F1-F5 equivalent) GHG emissions, due to their high production efficiency. CNG from NA NG sources has relatively high GHG emissions because of CH₄ leakage during transportation.

Individual results are presented for the equivalent fuel and vehicle cycles within GM (2001). The main conclusions reached on the complete life cycle analysis are presented in Volume 3 of the study. The standard diesel and petrol fuel and vehicle pathways show larger life cycle GHG emissions (a factor of 1.5-2) in comparison to the Hybrid Electric Vehicles (HEV).

The GM study uses the GREET model within the analysis section and it is subject to a similar critical review.

Where this study differs from the previous studies is in the sensitivity analysis. A series of probability distribution functions are assumed for the input parameters of the model. These functions are estimates of the efficiencies from each stage. The efficiency of petroleum recovery onboard North Sea oil platforms is assumed to be 97%, with a min and max efficiency of 96% and 98% respectively. Should these or any other assumptions be incorrect the LCA model results would differ. In an ideal world each of the LCA studies considered in this chapter would be subject to a sensitivity analysis of this type. Enabling a user to simulate change within the system. It is the intention of the present author to report a sensitivity analysis on the results obtained, see Chapter 7.

3.3.8 Michaelis (1998) – The RCEP study

The Royal Commission Environmental Pollution (RCEP) produced a LCA of Energy Systems, Michaelis (1998). The report assessed the environmental impacts of four different types of energy systems, heat, transportation, electricity and combined heat and electricity. These impacts are considered under: resource depletion, greenhouse gas emissions, acidification and eutrophication. Only two transport fuels were considered, unleaded petrol and diesel, on a fuel life cycle basis. No consideration was given to the type of vehicles using the fuel.

A conventional LCA framework was selected for this study with the impact categories above selected due to the author's judgement of their relevance to energy systems. Once again a spreadsheet model is used for the data collection and manipulation, with the production of numerous graphical outputs to illustrate the relevance of each impact.

3.3.8.1 Conclusions on the Michaelis Study

In this limited study, results revealed that the main difference between the two fuels was in the refining stage where catalytic cracking was used to make the unleaded petrol from heavier fuel fractions in the refinery. Apart from refining, Michaelis noted that the two fuel cycles are very similar. These results are similar to the petrol and diesel fuel cycle results presented in section 4.2.

Unlike the other LCA studies, the results were presented per GJ of resource, material and emission for petrol and diesel used within road, rail and ship transport. No details were provided on the specific type of vehicles within each category. A detailed Life Cycle Inventory (LCI) for each of the four energy systems was presented in appendices. These provide an indication of the relative impact from each system and are useful for a simple cross-reference of information.

Michaelis used a study, produced by Frischknecht and Suter (1996), which detailed the flows of materials and energy in the life cycle of European energy systems. UK systems were excluded from this study, however many of the systems are similar to those found

in this country. Michaelis noted that if greater accuracy were to be required for particular UK systems a new set of data would be required. He also commented upon the use of LCA packages and the flexibility they have in modern day applications.

3.3.9 National Renewable Energy Laboratory (NREL)

3.3.9.1 Tyson (1993)

A Fuel Cycle Evaluation of Biomass-Ethanol and Reformulated Gasoline study has been developed by the NREL, Tyson (1993). The US DOE used the Total Fuel Cycle Analysis (TFCA) model to evaluate energy choices. The TFCA is a tool used to describe and quantify the environmental, social and economic costs and benefits associated with energy alternatives. The study is limited to three fuels:

- (1) Reformulated Gasoline (RFG), to the standards of the Clean Air Act Amendments 1990 (CAAA).
- (2) Gasohol (E₁₀), which is a mixture of 10% ethanol from municipal solid waste (MSW) and 90% gasoline.
- (3) E₉₅, a mixture of 5% gasoline and 95% ethanol.

Estimations are made of inputs/outputs for each fuel cycle, similar to a mass balance study. Each of these fuel cycles is further represented by a flow chart of activities, where inputs (electricity, chemicals, materials) and outputs (fuel, emissions, wastes) are illustrated graphically. The cycles are split into, feedstock production, transportation, fuel production, fuel distribution and end-use. Results are expressed in g/mile as with many other LCA studies. Fuel cycle scenarios are set using the three fuels in question across various states in the US. Site-specific environmental impacts are evident.

Crude oil import/export, transportation, refining and distribution was examined and simulated for varying time periods and locations, with a final complete LCA of each fuel under each regime.

Atmospheric emissions of CO₂, CO, NO_x, SO₂, PM, VOC, waste-water and solid waste were examined for each fuel, with an LCI appendix following.

3.3.9.1.1 Conclusions on the Tyson Study

The work of Tyson combines the data presentation techniques in GREET with the LCI inventory of Michaelis (1998) and produces a series of flow charts to illustrate graphically the various fuel pathways through their life cycles. The results showed that the most gaseous emissions occurred in the end-use stage (F6 equivalent) and by replacing conventional fuels (petrol and diesel) with Ethanol fuels can reduce global CO₂ emissions. Results were presented in g/mile

Tyson stated that the results of his LCA work could be used to rank the various fuels on an emissions basis however the relative impacts could not be assessed. Some form of normalisation and weighting was required. He suggested that any full LCA requires some form of impact assessment to fully evaluate the life cycle results. The methods adopted in his study can be used as a tool for ranking technological options for the US DOE even with the use of experimental data.

The study relies heavily on the expert opinion of researchers in the fields and on technological changes. This is not the best form of data acquisition but the only one that Tyson could use.

He developed a highly generalised version of the US industry structure for the fuel pathways and as a result of this generalisation a degree of technical accuracy was lost. However this loss did not affect the major conclusion and life cycle results of the study.

If data is unavailable for a specific part of the LCA, a best estimate was used from similar operations in the US. Tyson used trend analysis, where values could be inferred either through interpolation or extrapolation. The data used within his study presented a 'snapshot' of emissions through each cycle and no levels of uncertainty were specified.

A number of research teams in the US DOE reviewed the datasets and results with some researchers seeking technical advice from external agencies and corporations.

3.3.9.2 Sheenan *et al* (1998)

A US Department of Agriculture and US Department of Energy study by Sheenan *et al* (1998) investigated biodiesel and petroleum diesel use within an urban bus. Biodiesel is made by chemically combining any natural oil or fat with an alcohol such as methanol or ethanol.

A biodiesel and petroleum diesel (LSD) energy and emissions LCA model was developed by the NREL. A flow chart documented the life-cycle of LSD through: extraction; transport; refining, transport to a filling station and end-use plus biodiesel through: production of soybeans; transport; recovery of oil from crusher; transport to manufacturer; conversion of soybean to biodiesel, transport to a filling station and end-use. All values within were based upon US national averages.

Several types of energy flow through each fuel cycle were considered.

- (1) Total Primary Energy – raw material energy value
- (2) Feedstock Energy – raw material energy that is contained within the final product
- (3) Process Energy – energy inputs exclusive of energy in the feedstock
- (4) Fossil Energy – coal, oil, NG (fossil or non-fossil energy)
- (5) Fuel Product Energy – energy within the fuel

Within each energy flow the following compounds were under inspection CO₂, CO, NO_x, THC, PM, water and solid waste, water consumption. The amounts of compound released to air within each stage of each cycle were accumulated with a mass allocation procedure.

The LSD and biodiesel cycles were modelled using different methodologies. The LSD cycle initially set geographic boundaries within the US, then reviewed crude oil

(extraction, material use, energy, import and export), proceeded to examine crude and NG refining and concluded with a review of transport through pipeline, tankers and road vehicles. The transport modelling was carried out with the use of a Data for Environmental Analysis and Management (DEAM) model, with all other air emissions data taken from the Compilation of Air Pollutant Emissions Factors (AP-42). The DEAM model is a database of materials and processes and is one of the most extensive LCI databases on environmental impacts available today. The model was developed by Ecobilian, see www.ecobilian.com and is based upon the data presented in AP-42.

The modelling of biodiesel began with gathering information from the National Agricultural Statistical Service (NASS) combined with the use of a Tool for Environmental Analysis and Management (TEAM) model to assess soybean agriculture. The TEAM model contains information modules that allow a LCA to be streamlined. Several processes can be gathered into a simplified single system. The model is generally used to organise very large blocks of information. The majority of other modelling was similar to the LSD cycle. Both cycles were then compared on a combustion and energy content for an urban bus.

3.3.9.2.1 Conclusions on the Sheenan Study

Life cycle emissions and energy consumption for biodiesel were calculated and compared in comparison to the conventional LSD bus. Life cycles of fuels, materials and resources were considered for the substitution of biodiesel for conventional diesel. Results highlighted the effects of change in fuel type and life cycle consumption of petroleum. The net emissions of CO₂ for biodiesel were reduced by 79% in comparison to diesel. Sheenan *et al* noted that approximately 86.5% of the total life cycle CO₂ emissions were released in the end-use stage, combustion of the fuel in a bus engine (F6 equivalent), similar to the findings of Beer (2000). Further details of all the emissions percentage reductions can be found within Sheenan *et al* (1998). An Appendix of emission factors closed the study, similar to the work of Michaelis and Wang.

A sensitivity analysis was performed which reviewed buses in operation in 1998. A series of limitations and assumptions were made based upon buses operating that year. Sheenan *et al* noted that this limits the study to be specific to certain fuels and vehicles.

The data quality was tested against US predictions made by Government Agencies and external bodies. Some data was derived from modern day operations, with other information some 10 years old. However a certain degree of consistency was maintained with some interpretation and analysis required. Where possible, real data was used over modelled data.

3.4 The Future of Vehicle Fuels

3.4.1 Conventional Fossil Fuels

The transport sector, including aviation, produces about one quarter of the UK's total carbon emissions. Road transport contributes 85% of this, with passenger cars accounting for around half of all carbon emitted by the transport sector, DTI (2003). Despite this conventional fossil fuels dominate the vehicle market and will continue to do so for many years to come. The world's transportation and power infrastructure is principally based on the recovery of hydrocarbons. A sudden switch to global use of alternative fuels will not occur overnight; however a step-by-step introduction into a multi-modal system of transport use may kick-start the alternative fuels market. The massive investment seen by the US, UK and others into new oil fields in Russia and China's Bohai Sea demonstrates that conventional fuels are the number one priority. Royal/Dutch Shell have recently announced that it would invest \$400 million to develop two offshore blocks in China's Bohai Sea, www.eia.doe.gov/emeu/perfpro and in the largest foreign direct investment in Russian history, an expected \$13 billion is starting to pour into two gas and oil projects to supply Japan with oil and gas within a decade, www.webprowire.com/summaries/260259.html. These are two examples from many that highlight the dependency on hydrocarbons of today's economy.

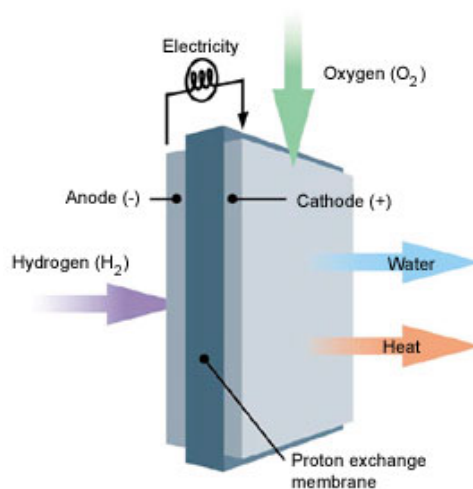
3.4.2 Alternative Fuels

Although vehicle technologies seem capable of becoming twice as fuel-efficient as today's vehicles, deeper carbon reductions will need low-carbon fuels, such as hydrogen (H₂), which can be generated from non-fossil sources or biomass-based liquid fuels. The auto industry expects hydrogen powered fuel cell cars to move towards mass production around 2020. In the longer term, hydrogen use in transport has major potential for reducing carbon emissions, if current technological and cost barriers can be overcome, DTI (2003).

Creating a future hydrogen economy is seen as the "holy grail" for energy and transport policy, promising a solution to energy security and climate change. In February 2003 President Bush asked the US Congress to spend \$1.2 billion over the next five years on a programme "to take hydrogen FC vehicles from the laboratory to the showroom" - adding \$700 million to the present allocation. Bush's enthusiasm for hydrogen stems from US concerns over oil supplies in the Middle East. Prime Minister Tony Blair has made similar noises - in a speech to the Royal Society in 2002, he mentioned "hydrogen technologies offer the potential of zero-pollution transport", ENDS (2003). However hydrogen itself could become a significant contributor to global warming if produced from the reformation of natural gas and not from the splitting of water. In effect, worries over oil security and availability in the Middle East could be replaced by over-reliance on imported natural gas. One solution may be to produce hydrogen from LFG or any other waste derived gas (WDG). Another approach would be to split water, resulting in the producing of H₂ and oxygen, which however requires electricity. There is growing interest from the US and UK into alternative fuels, however they are still investing massive amounts of money into the continued supply of hydrocarbons. Should the hydrocarbon supplies begin to run short in the future, both countries would like to be in a position to switch to hydrogen or other alternatives. National security also plays an important role in the supply and demand for fuels; a country which has less reliance on imported fuels has greater stability.

The successful supply of H_2 is the first of two stages; the second would be to provide a suitable vehicle. Fuel Cell Vehicles (FCV) are receiving a huge amount of interest. Some suggest that these types of vehicles could one day replace the ICE, Ford (1999), Wang (2002). FCVs require hydrogen (H_2) as the Fuel-Cell (FC) fuel. Inside the FC there are two electrodes, one positive and one negative. They allow the H_2 to react with oxygen from the air intake, creating electricity and water, through a Proton Exchange Membrane (PEM), see Figure 3.1. The electricity drives the engine; the water is piped away via the exhaust system. Advanced fuel cells also exist such as the Solid Polymer Fuel Cells (SPFCs), Hart *et al* (1999).

Figure 3.1 – The PEM Fuel Cell



Although H_2 is currently used in fertiliser manufacture, petroleum refining, and other chemical processes, it is not yet produced as a transportation fuel, and the infrastructure for mass production and distribution of H_2 for FCVs is not in place. A study by Hart *et al* (2000) comments upon the supply of H_2 for SPFC vehicles. BMW have developed a hydrogen car, the 750h, see www.bmw.com/bmwe/pulse/enterprise/. BMW state that hydrogen will replace petrol and the production of this dual fuel hydrogen/petrol vehicle will ease the transition to hydrogen.

Many believe that in the foreseeable future, hydrocarbon (HC) fuels may be stored on board FCVs for production of H₂ via fuel processes. Many HC fuels, such as methanol (commonly referred to as MeOH), petrol, diesel, ethanol (commonly referred to as EtOH) and naphtha (liquid hydrocarbon fuel) could serve as FC fuel, Wang (2002). Moreover MeOH and H₂ produced from biomass are promising carbon neutral fuels and are both well suited for use in FCVs, Namelinck and Faaij (2002). Hart and Hormandinger (1997) noted that FC powered buses carrying hydrogen are genuine zero-emission vehicles and are carbon neutral. This statement, which is incorrect, if one considers the life cycle of the bus. Hart comments upon the use of a steam (plus other) reformers, which converted MeOH to H₂ within a FC. This steam reformer consists of a reaction chamber heated by a catalytic burner, in which part of the fuel is burned, while the rest is used in feedstock. Although the process is carbon neutral, the CO₂ and CO are converted with hydrogen into methane, Hamelinck and Faaij (2002), a potent greenhouse gas.

Emissions comparison with conventional and FCVs have been made by Hart and Bauen (1998), Lane (2002) and Tan (2002). Similar conclusions are made in each study. Fuelling a vehicle with pure H₂, stored on board the vehicle, offers the chance for a truly zero emissions vehicle. The production, reformation and compression will inevitably lead to the release of some emissions. The relative impact of which would need to be compared.

The use of H₂ fuelled vehicles offers many benefits if the H₂ can be generated using local reformers at filling stations or from the splitting of water. Emissions from H₂ vehicles are lower when compared to conventional and electric vehicles (EV), with negligible CO, NMHC and PM levels. CO₂ is also reduced to the same levels as EV, when using the 1997 UK electricity generation mix, Hart and Bauen (1998). The use of the Green Electric mix would reduce the emissions further.

3.5 Summary

A review of work on alternative fuels is presented in this chapter. Data used within each country differ, however most LCAs have common aims and goals and tend to assess similar emissions on a life cycle basis. Some LCAs conclude at the distribution of fuel to the filling stations, some encompass combustion within a vehicle and some expand to include the fuel and vehicle. A small number of LCAs continue a step further to perform a sensitivity analysis to highlight the most important stages in the system. Table 3.1 highlights the emissions, fuels and vehicles considered by each of the studies reviewed in this chapter, plus the present study, Finnegan (2003).

Table 3.1 Summary of work on alternative fuels.

Study	Gaseous Emissions Considered	Fuel Cycles	Vehicle Cycles
Beer (2000)	CO ₂ , CO, CH ₄ , NO _x , N ₂ O, PM	12	1
Beer <i>et al</i> (2000)	CO ₂ , CO, CH ₄ , NO _x , N ₂ O, PM, NMHC	10	2
Beer <i>et al</i> (2001)	CO ₂ , CO, CH ₄ , NO _x , N ₂ O, PM, NMHC	10	2
Beer <i>et al</i> (2002)	CO ₂ , CO, CH ₄ , N ₂ O	8	2
Finnegan (2003)	CO₂, CO, CH₄, NO_x, PM, NMHC, SO₂	9	3
Gaines <i>et al</i> (1998)	CO ₂ , CO, CH ₄ , NO _x , N ₂ O, PM, SO _x , VOC	4	2
GMC (2001)	CO ₂ , CH ₄ , N ₂ O	12	15
Gover <i>et al</i> (1996)	CO ₂ , CO, CH ₄ , NO _x , HC, SO ₂	9	4
Hackney and Neufville (2001)	CO ₂ , CO, CH ₄ , NO _x , N ₂ O, PM	27	17
Michaelis (1998)	CO ₂ , CH ₄ , NO _x , SO _x , NMVOC	2	3
Sheenan <i>et al</i> (1998)	CO ₂ , CO, NO _x , THC, PM	3	1
Tyson (1993)	CO ₂ , CO, NO _x , PM, SO ₂ , VOC	3	1
Wang <i>et al</i> (1999a, 1999b)	CO ₂ , CO, CH ₄ , NO _x , N ₂ O, PM, SO _x , VOC	14	17

3.6 General Critical Review

A critical review of each study follows each of models under review in this chapter. In general the LCA studies encounter similar problems. The quality and availability of data seems to be an overriding factor within each model. The resulting uncertainties associated with this are a cause for concern. From the earlier work of Tyson (1993) to the more recent work of Beer *et al* (2002), each author has identified similar problems. Even with this nine-year gap, the quality of data has not improved and the present author has experienced similar problems.

Each LCA study has attempted to be holistic to some degree, however each author cannot avoid making certain assumptions and estimations. These limit the scope and scale of the study and in some cases the assumptions are so numerous that the study becomes limited to a small number of fuels and vehicles. Conversely, with more resources and finances any study can be extended to encompass much larger datasets e.g. the limited work of Michaelis, who analysed two fuels and three vehicles, to the more detailed work of Hackney and Neufville, who analysed twenty-seven fuels and seventeen vehicle cycles.

There is no universal agreement on the scope and methodology of the LCAs reviewed herein but they serve to highlight, through their own limited scopes, the need for sensitivity analysis and an expansion of the application of the results on emission to be assessed for impacts other than on GHG budgets.