Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles

Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles

Stage 1

by

Tom Beer[1,2], Tim Grant[3], Richard Brown[1] , Jim Edwards[4], Peter Nelson[4], Harry Watson[5] & David Williams[4]

[1]CSIRO Atmospheric Research, Aspendale, Vic.
[2]CSIRO Environmental Risk Network, Aspendale, Vic
[3]RMIT Centre for Design, Melbourne, Vic.
[4]CSIRO Energy Technology, North Ryde, NSW
[5]University of Melbourne, Dept. of Mechanical and Manufacturing Engineering, Parkville, Vic.

CSIRO Atmospheric Research Report C/0411/1.1/F2
to the Australian Greenhouse Office
March 2000

Contact
Professor Tom Beer
Co-ordinator CSIRO Environmental Risk Network
Private Bag 1
Aspendale
Vic. 3195

Phone: (03) 9239 4546
Fax: (03) 9239 4444
e-mail: Tom.Beer@dar.csiro.au

Table of Contents

Table of Figures and Tables

Acronyms[1]

3C	Threeway catalytic converter
ABARE	Australian Bureau of Agricultural and Resource Economics
ACTION	Australian Capital Territory Internal Omnibus Network
ADR	Australian Design Rule
AFCP	Alternative Fuel Conversion Program
AGA	Australian Gas Association
AGO	Australian Greenhouse Office
AIP	Australian Institute of Petroleum
ALPGA	Australian Liquefied Petroleum Gas Association
AQIRP	Air Quality Improvement Research Program
BD	Biodiesel
BD100	100% Biodiesel
BD20	20% Biodiesel
BRS	Bureau of Resource Science
BTCE	Bureau of Transport and Communications Economics
CAD	California Diesel
CBD	Central Business District
CFC	Chlorofluorocarbons
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CRPT	Continuous Regenerating Particulate Trap
CUEDC	Composite Urban Emissions Drive Cycle
DAFGS	Diesel and Alternative Fuels Grants Scheme
E100	Ethanol
E93	93% Ethanol
E95	95% Ethanol
ELR	European Load Response
EPA	Environmental Protection Agency (US) Environment Protection Authority (NSW & VIC)
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
ERDC	Energy Research and Development Corporation
ESC	European Stationary Cycle
ETC	European Transient Cycle
ETSU	Energy Technology Support Unit
FFC	Full Fuel-Cycle

[1] A glossary is given in Appendix 1

GCV	Gross Calorific Value
GJ	Gigajoule; unit of energy; 1 GJ = 1 x 10^9 J
GHG	Greenhouse Gases
GVM	Gross Vehicle Mass
GWP	Global Warming Potential
HC	Hydrocarbons
HDV	Heavy-duty Vehicle
HGV	Heavy Goods Vehicle
IANGV	International Association for Natural Gas Vehicles
IEA	International Energy Agency
IEA/AFIS	International Energy Agency/Alternative Fuels Information System
LCA	Life-cycle Analysis
LCV	Light Commercial Vehicle
LDV	Light Duty Vehicle
LEV	Low Emission Vehicle
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSD	Low Sulfur Diesel
MJ	Megajoule; unit of energy; 1 MJ = 1 x10^6 J
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NG	Natural Gas
NGGIC	National Greenhouse Gas Inventory Committee
NGV	Natural Gas Vehicle
NMHC	Non-methanic Hydrocarbon
NMVOC	Non-methanic Volatile Organic Compound
N_2O	Nitrous Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
NREL	National Renewable Energy Laboratory
NSW	New South Wales
OXC	Oxidation Catalyst
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate matter
PM10	Particulate matter below 10 µm diameter
RME	Rapeseed Methyl Ester
RMIT	Royal Melbourne Institute of Technology
RTA	Roads and Traffic Authority (NSW)

SAE	Society of Automotive Engineers
SO_2	Sulfur Dioxide
SO_x	Oxides of Sulfur
SULEV	Super Ultra-Low Emission Vehicle
THC	Total Hydrocarbons
TSP	Total Suspended Particles
TTVS	Trans Tasman Vehicle Standards
ULS	Ultra-Low Sulfur Diesel
US	United States of America
VOC	Volatile Organic Compounds
WVU	West Virginia University
W5	5% Waste Oil

Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles

Executive Summary

Abstract

This report examines available information on low and ultra-low sulfur diesel and alternative fuels for heavy vehicles in terms of their emissions of greenhouse gases and air pollutants. Most of this information is from overseas, and has been used to estimate emissions for heavy vehicles using such fuels in Australia. This is done within a life-cycle framework that considers both the pre-combustion emissions and the tailpipe emissions during combustion. This approach is sometimes called the full fuel-cycle or the "well-to-wheel" emissions (even though the raw materials for biofuels do not come from wells) and considers the chain of feedstock production, feedstock transportation, fuel production, fuel distribution and, finally, vehicle use.

It is difficult to compare and rank "like-with-like" when examining the emissions (in grams emitted per kilometre travelled) from different fuels. In the case of LPG, few heavy vehicles use it so that data concerning its emissions are scarce. In the case of other fuels it is rare for individual studies to have examined similar engines using similar pollution control equipment. This means that there is extreme variability in the available emissions data, and it is possible to produce misleading comparisons where the best result from one fuel is compared to the worst result from another fuel. Accordingly, wherever possible, this study is based on results that comprise sufficient samples to enable statistics to be used to estimate and quantify the uncertainty in the data. The rankings that are produced are based on rank-score statistics incorporating the uncertainty.

The fuels examined are low sulfur diesel (LSD), ultra-low sulfur diesel (ULS), compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), ethanol, diesohol, canola oil, biodiesel, and waste oil.

Greenhouse gas emissions

Biodiesel has the lowest greenhouse gas emissions on a life-cycle basis. In fact, biodiesel emits larger quantities of CO_2 than conventional fuels, but as most of this is from renewable carbon stocks, that fraction is not counted towards the greenhouse gas emissions from the fuel. Ethanol comes next and then the gaseous fuels (LPG, CNG, LNG). The life-cycle emissions of greenhouse gases from diesel are reduced if waste oil is used as a diesel extender, but the processing energy required to generate LSD and ULS in Australia increase their greenhouse gas emissions compared to diesel fuel. The extra energy required to liquefy and cool LNG means that it has the highest life-cycle greenhouse gas emissions of all the fuels that were considered.

Air pollutant emissions

We used a risk-weighted scoring system, based on estimates of human health risk, to rank the fuels. On a life-cycle basis, the gaseous fuels (LPG, CNG) give the lowest contribution to air pollution on this criterion. In the case of urban buses, LSD and ULS come next (though these results are based on only one UK test), then ethanol. The use of waste oil as a diesel extender increases air pollution. Biodiesel scores poorly in relation to air quality because its production and use generates considerable amounts of particulate matter.

Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles

Recommendations

1. Biodiesel fuels are the lowest greenhouse gas emitters. We recommend that the information that has been collected on biodiesel be documented in a separate report that incorporates a quantitative uncertainty analysis.
2. We recommend that emission testing on imported biodiesel used in Australian vehicles be conducted. In particular, whether its use in Australian vehicles is accompanied by the large particulate emissions observed during its use elsewhere.
3. LPG has not been a serious contender for use with heavy vehicles, but it looks very good on greenhouse gas and air pollution criteria. There appears to be a lack of data on emissions from LPG trucks under highway conditions. We recommend that this data gap be addressed.
4. There are considerable uncertainties associated with the emissions of methane and non-methanic hydrocarbons from CNG and from LNG. In addition, there is a lack of data on actual methane and nitrous oxide from heavy vehicles. Because there are numerous CNG buses in operation in Australian cities, we recommend that a program of testing be undertaken to determine the factors responsible for the emission of methane, nitrous oxide and non-methanic hydrocarbons from CNG buses. During such testing the effect of exhaust catalysts needs to be determined as these increase some unregulated emissions.
5. The apparent decrease in CO_2 emissions quoted by the Western Australian Expert Reference Group when low sulfur diesel (LSD) or ultra low sulfur (ULS) diesel is used does not appear to agree with US results. As CO_2 emissions are related to fuel economy we recommend that three identical vehicles, one using diesel, one using LSD and one using ULS be tested over an identical route and their relative fuel economies and CO_2 emission determined.
6. It is of concern that top-down estimates of heavy-duty vehicle emissions, such as those of Apelbaum (1997) and Linzen (1999) do not agree with bottom-up estimates. Identifying the cause of this discrepancy is important and we recommend that this be done through the award of a post-doctoral fellowship.
7. We recommend that this study be repeated after 3 years. There are rapid technological developments taking place in heavy vehicle emission controls and in heavy vehicle fuel specifications and we expect that the emission characteristics of vehicles in 3 years' time will differ substantially from those of the current fleet.
8. A separate study be commissioned to examine heavy-vehicle emission-control technologies on individual fuels.
9. The use of waste oil blended into diesel offers a slight reduction in greenhouse gases, but leads to increased air pollution. The most favorable use of waste oil is as recycled lubricating oil.

Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles

Key Findings

The fuels examined in this report are low sulfur diesel (LSD), ultra-low sulfur diesel (ULS), compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), ethanol, diesohol, canola oil, biodiesel (BD), and waste oil.

The work for this report consisted of a detailed search for available literature and available data on the emissions of greenhouse gases and air pollutants arising from the use of alternative fuels. In particular, a life-cycle approach was adopted, in which the pre-combustion emissions of greenhouse gases and air pollutants are considered as well as the tailpipe emissions during combustion. We were unable to locate emissions data for vehicles using canola oil.

Because most of these fuels are rarely used in Australian heavy vehicles, the method that was adopted to quantify the pre-combustion emissions was based on typical industrial scenarios for the extraction, production, delivery, processing conversion and distribution of each of these fuels within Australia. There were insufficient Australian emission data to use to estimate tailpipe emissions. Furthermore, the available data exhibit a great degree of variability. We therefore sought emissions data that had been collected on statistically sufficient vehicles. The data set for alternative fuel buses, and other heavy vehicles, from the US Alternative Fuels Data Center, was used. Buses were taken as representative of urban heavy vehicles, whereas the other heavy-duty vehicles were taken as representative of the non-urban situation.

Greenhouse gas emissions

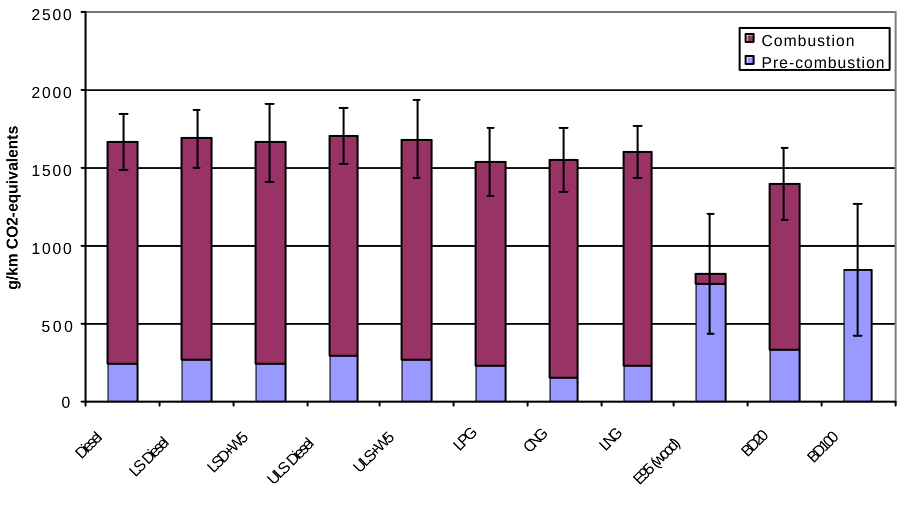


Figure 1

Total fossil-fuel greenhouse gas emissions (CO_2 - equivalents) in g/km for buses

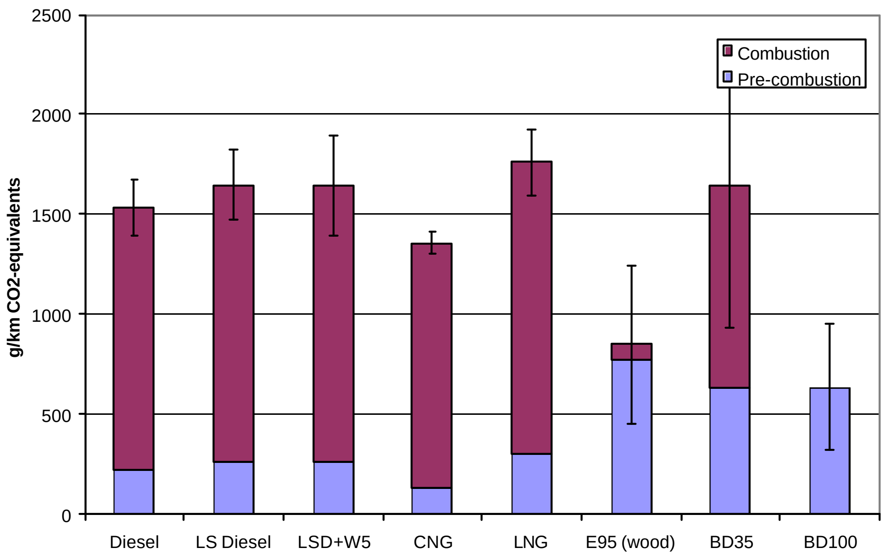
Figure 1 depicts the greenhouse gas emissions estimated for buses using the various alternative fuels. The results for diesel, low sulfur diesel, ultra-low sulfur diesel, and LPG are based on only one set of measurements made on a London transport bus. The results for the other fuels are based on the average of a number of different measurements. The lowest number of measurements was eight (in the case of 20% biodiesel, BD20), whereas 90 measurements were used in the case of CNG buses.

Biodiesel[2] has the lowest greenhouse gas emissions on a life-cycle basis. In fact, biodiesel emits larger quantities of CO_2 than conventional fuels, but as most of this is from renewable carbon stocks that fraction is not counted towards the greenhouse gas emissions from the fuel. Ethanol comes next and then the gaseous fuels (LPG, CNG, LNG). The life-cycle emissions of greenhouse gases from diesel are reduced if waste oil is used as a diesel extender, but the processing energy required to generate LSD and ULS in Australia increase their greenhouse gas emissions compared to diesel fuel.

Heavy vehicles other than buses

We have estimated emissions from heavy vehicles other than buses by using similar data to those used for buses, except that there is better fuel economy due to operation over a highway type cycle more pertinent to long-distance freight operations, which will change the relative proportions of pre-combustion and combustion emissions. We were unable to obtain representative data for ULS diesel or for LPG. The results are shown in Figure 2.

Figure 2



Total greenhouse gas emissions (CO_2-equivalents) in g/km for non-bus heavy vehicles

[2] The results are based on biodiesel derived from soy beans

Air pollutant emissions

We used a risk-weighted scoring system, based on estimates of human health risk, to rank the fuels. On a life-cycle basis, the gaseous fuels (LPG, CNG, LNG) give the lowest contribution to air pollution on this criterion. In the case of urban buses, LSD and ULS come next (though these results are based on only one UK test), then ethanol. The use of waste oil as a diesel extender increases air pollution. Biodiesel scores poorly in relation to air quality because its production and use generates considerable amounts of particulate matter. The results for particulate matter are shown in Figure 3.

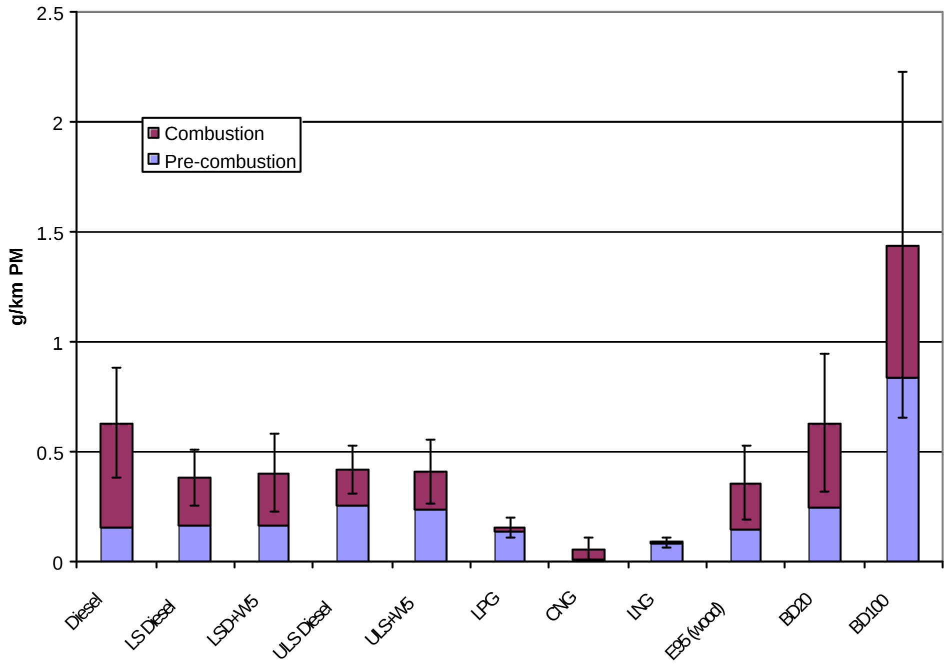


Figure 3

Particulate matter emissions (g/km) for urban buses

Ranking (including uncertainty)

The output of this study is to be a ranking of the fuels in terms of their greenhouse gas and air quality aspects, for both city driving, and highway driving conditions. We believe that any ranking method that is used must take into account the uncertainties associated with the data. Accordingly we have devised a ranking scheme that incorporates uncertainty, which is described in the following paragraph.

We rank the emissions according to their average characteristics in terms of global warming and pollution impact, and assign each gas as a score its rank value. We then rank the gases for one standard deviation above and below their average emissions and again score them. The three scores are summed, and the final ranking is based on this sum.

We have used the bus data as representative of city driving, and the truck data as representative of highway driving. For existing and known technology, such as that of diesel fuels, we have assigned 10% uncertainty. For gaseous fuels we have assigned 25% uncertainties, and for renewable fuels we have assigned 50% uncertainties.

This method is straightforward when calculating the rankings on the basis of greenhouse gases (expressed in CO_2-equivalents) and produces the results in Table 1.

Table 1

Fuel ranking in relation to greenhouse gases.
The lowest value denotes the lowest greenhouse gas emissions

Fuel	CityGHG Score	CityGHG Rank	HwyGHG Score	HwyGHG Rank
Diesel	24	**8**	13	**4**
LSD	28	**10**	20	**7**
LSD+W5	23	**7**	17	**6**
ULS	31	**11**		
ULS+W5	27	**9**		
LPG	12	**4**		
CNG	15	**5**	10	**3**
LNG	20	**6**	23	**8**
E95	4	**1**	6	**2**
BD20/35	9	**3**	16	**5**
BD100	5	**2**	3	**1**

+W5 denotes the use of 5% waste oil   Blanks indicate no data

In relation to air quality, it was thus decided to weight the air pollutants on the basis of their health risk. The main health risk for Australians arises from particulate matter and from hydrocarbons. Given the considerable uncertainties associated with these estimates of mortality, and the costs of morbidity, we have developed health risk weighted air quality rankings as follows:

The summed score for particulate matter was multiplied by 2, the summed score for hydrocarbons was multiplied by 1, the summed score for NOx was multiplied by 0, and the summed score for carbon monoxide was multiplied by 0, and the totals added together to produce a final air quality score. The results are given in Table 2.

Table 2

Fuel scores and final ranking in relation to air quality.
The lowest value denotes the lowest emissions

Fuel	CityPM	CityHC	CityNOx	CityAQ	CityAQ	HwyPM	HwyHC	HwyNOx	HwyAQ	HwyAQ
	weight=2	weight=1	weight=0	Score	**Rank**	weight=2	weight=1	weight=0	Score	**Rank**
Diesel	28	25	24	81	**10**	14	17	17	45	**5**
LSD	15	15	20	45	**4**	16	10	15	42	**4**
LSD+W5	21	10	19	52	**5**	20	11	24	51	**7**
ULS	18	19	14	55	**7**					
ULS+W5	21	14	13	56	**8**					
LPG	9	4	4	22	**1**					
CNG	3	18	7	24	**2**	7	3	7	17	**1**
LNG	6	32	33	44	**3**	3	18	3	24	**2**
E95	15	24	7	54	**6**	8	24	8	40	**3**
BD20/35	29	17	30	75	**9**	16	14	20	46	**6**
BD100	33	20	27	86	**11**	24	11	14	59	**8**

Overall Ranking

On the basis of greenhouse gas considerations, the renewable fuels: ethanol and biodiesel – either in the form of canola, or as an esterified biofuel - are the lowest emitters because they combust non-fossil fuels. This is true for both city and highway driving. Of the fossil fuels, LPG was the lowest greenhouse gas emitter for the city cycle, whereas for the highway cycle (for which LPG data were not found), CNG was the lowest emitter.

With respect to air quality considerations, the gaseous fuels – LPG, CNG and LNG – are the lowest emittors, primarily because their particle emissions are low. We were unable to obtain sufficient data on LPG to determine whether this is true for both city and highway driving. However, LPG was the lowest emitter under a city drive cycle, and CNG was the second lowest. Under highway conditions, for which we lacked LPG information, CNG was the lowest emitter. It is also worth noting that because of its large particle emissions, biodiesel is the worst fuel in relation to air quality for both city and highway driving.

Sensitivity Analysis

During the course of this study it was noted that the final results were particularly sensitive to some of the assumptions made. In particular:

- We have assumed CNG and LNG are compressed using gas. If it is assumed that electricity is used then the life-cycle emissions of greenhouse gases from CNG and LNG exceed those of diesel.
- We have assumed that LNG is shipped in sea-going vessels using gas, whereas CNG is piped. If diesel powered ships are used then substantial particulate matter is emitted, and the life-cycle air quality aspects of LNG are substantially reduced.
- Fugitive emissions from filling and servicing of CNG and LNG have been incorporated into the analysis. However, no allowance was made for possible fugitive emissions as a result of leakage from reticulated gas supplies.

PART 1

METHODS AND INTERPRETATION

Chapter 1

Background

1.1 Introduction

This report responds to a brief from the Australian Greenhouse Office (AGO) to undertake a life-cycle analysis of alternative fuels. It incorporates a desk study and literature review of existing Australian and overseas data concerning the emissions characteristics of alternative and conventional fuels that are or may be suitable for use in road vehicles weighing 4.5 tonnes gross vehicle mass (GVM) or more. This review is a consequence of the Prime Minister's, *Taxation Reform* Statement of May 1999, which announced two alternative fuels programs. These programs are intended to contribute significantly to the reduction of greenhouse gas emissions, and other emissions impacting on air quality, that are generated by heavier commercial vehicles and public transport vehicles. The programs relevant to this report are:

- Alternative Fuel Conversion Program (AFCP)
- Diesel and Alternative Fuels Grants Scheme (DAFGS).

The Australian Greenhouse Office (AGO) wishes to:

- Assess the relative performance of a range of alternative fuels in relation to their greenhouse gas emissions and other air pollutants
- Obtain findings of the emission characteristics of alternative fuels that will assist the Chief Executive of the AGO in the determination of additional alternative fuels as eligible under the DAFGS.

The objectives of this report are to:

- Provide an objective assessment of the emissions characteristics of the alternative and conventional fuels that are addressed in the study, covering a representative range of vehicle types and technology
- Provide an assessment of the commercial performance of alternative and conventional fuels
- Identify any gaps in available data that preclude such an assessment of emission characteristics, and provide recommendations on the primary data collection and analysis methodology required to make such an assessment, including any fuels-testing requirements.

The AFCP provides financial assistance for the conversion of heavier commercial road vehicles and buses to either Compressed Natural Gas (CNG) or Liquefied Petroleum Gas (LPG) fuels. The DAFGS is designed to maintain existing price relativities between diesel and alternative fuels after the reduction in the diesel fuel excise rate in July 2000. The DAFGS will apply to commercial vehicles, weighing 4.5 tonnes GVM or more, and operating in a number of regional areas and throughout Tasmania. It will also apply to commercial vehicles weighing 20 tonnes or more operating in metropolitan areas throughout Australia.

The fuels assessed, in terms of their full fuel life-cycle, were decided after consultation with the Sustainable Transport Section of the AGO. They are:

- Compressed Natural Gas (CNG)
- Liquefied Petroleum Gas (LPG)
- Liquefied Natural Gas (LNG)
- Recycled waste oil
- Canola oil
- Ethanol

- Biodiesel
- Diesohol
- Conventional low sulfur diesel (LSD)
- Conventional ultra-low sulfur diesel (ULS).

1.1.1 Approach

This study consists of a literature review and a desk analysis of existing Australian and overseas studies that assess the emissions characteristics of the fuels listed above. Two classes of emissions are considered:

- Greenhouse gases, which comprise carbon dioxide, nitrous oxide, hydrofluorocarbons, methane, sulfur hexafluoride, and perfluorocarbons
- Air pollutants, which comprise carbon monoxide, oxides of nitrogen, sulfur dioxide, non-methanic volatile organic compounds, visible smoke and particles.

This study was completed over six-weeks during the traditional summer vacation period. Given the large number of fuels, and large number of emissions involved, the time-frame allowed for the study was very tight. In particular, there was insufficient time to procure, and properly study, all of the literature pertinent to the topic so that in some cases the literature cited has not been sighted. In such cases, secondary sources have been used to deduce the content of the particular item. Literature that has been sighted is marked with an asterisk in the reference list.

1.2 National Environment Protection Measures

With the establishment of the National Environment Protection Council, as a result of the May 1992 Intergovernmental Agreement on the Environment, Australia decided to declare National Environment Protection Measures (NEPMs) so as to enact uniform environmental standards. Information on NEPMs may be found at the National Environment Protection Council website at www.nepc.gov.au.

NEPMs are broad framework-setting statutory instruments defined in NEPC legislation. They outline agreed national objectives for protecting particular aspects of the environment.

NEPMs may consist of any combination of goals, standards, protocols, and guidelines. Typically a NEPM will contain:

- A goal
- One or more standards
- One or more monitoring and reporting protocols
- May also contain guidelines.

The NEPMs that relate, either directly or indirectly, to motor vehicles and their emissions are the NEPM for Ambient Air Quality, the National Pollutant Inventory (NPI), and the proposed Diesel NEPM. The NEPM for Ambient Air Quality sets air quality standards for the ambient environment and does not deal with emissions, as such. Emission controls on vehicles are achieved through Australian Design Rules (ADR), and the proposed Diesel NEPM. The NPI requires industry to report on emissions.

1.2.1 Ambient Air Quality

The first NEPM to be undertaken was the NEPM for Ambient Air Quality (National Environment Protection Council, 1998). This produced air quality standards for six pollutants, namely:

nitrogen dioxide, sulfur dioxide, carbon monoxide, ozone, particulate matter, and lead.

These six pollutants are known as criteria pollutants, because they are the air pollutants for which air quality criteria have been established.

Table 1.1

National Environment Protection Standards for Ambient Air Quality.

Pollutant	Averaging period	Maximum concentration	Goal: (10 years) Allowed exceedences (days per year)
Carbon monoxide	8 hours	9.0 ppm	1
Nitrogen dioxide	1 hour	0.125 ppm	1
	1 year	0.03 ppm	0
Photochemical oxidant	1 hour	0.10 ppm	1
(as Ozone)	4 hours	0.08 ppm	1
Sulfur dioxide	1 hour	0.20 ppm	1
	1 day	0.08 ppm	1
	1 year	0.02 ppm	0
Lead (as TSP)	1 year	0.5 $\mu g/m^3$	0
Particles (as PM_{10})	1 day	50 $\mu g/m^3$	5

Source: National Environment Protection Council (Australia) (1998). TSP = Total suspended particles

The final standards promulgated in the Ambient Air Quality NEPM are given in Table 1.1, along with the time period over which each pollutant should be averaged to examine compliance with the standard. These values, being ambient standards, do not specify controls on emissions.

1.2.2 Diesel Vehicle Emissions

Environmental impacts of diesel vehicle emissions

Emissions from motor vehicles constitute the most significant source of urban air pollution in Australia. Continued annual growth in freight tonne-kilometres travelled and fuel consumption by the diesel fleet highlights this as an area of growing concern from the air quality perspective. Apelbaum Consulting Group (1997) note that the 1994/95 road freight task of 114.4 billion tonne-kilometres is an increase of 30% compared with 1990/91 and the tonne-kilometre undertaken by road freight vehicles is expected to more than double between 1994/95 and 2014/15.

The emissions of most interest in relation to diesel vehicles are oxides of nitrogen (NOx) and fine particles (also known as fine particulates). NOx is a precursor to the formation of photochemical smog. There is also evidence that NOx reacts with other pollutants to form particles. Fine particles have been identified as a major health risk. The smaller the particle the greater the risk.

Motor vehicles, particularly those with diesel engines, are significantly disproportionate contributors of fine particle pollution and oxides of nitrogen. Since 1996 diesel vehicle emission standards in the Australian Design Rules (ADRs) (http://www.dot.gov.au/land/environment/envrev99.htm) have placed limits on the emission of particles for new vehicles. Prior to 1996 diesel vehicles sold in Australia were required to meet a smoke opacity standard. Australia is currently developing legislation to amend its Australian Design Rules for diesel vehicle emissions that will bring about the introduction of Euro2, Euro3 and Euro4 standards. These standards are described in more detail in section 1.3, below.

Analysis of the Australian diesel fleet, commissioned as part of the Diesel NEPM, shows that diesel vehicles are increasing as a proportion of the total fleet. In 1995 diesel vehicles comprised 8.3% of the fleet and this will increase to 15% by 2015. Over this time diesel vehicle travel in metropolitan areas is expected to increase by 146%. The age structure of the fleet shows that older vehicles up to 16 years of age continue to contribute significantly to the total distance travelled in metropolitan areas. This implies that vehicles built to older emission standards will continue to play a significant role in fleet emissions.

Action by NEPC

In June 1996 the National Environment Protection Council endorsed continued discussions between NEPC Committee and the National Road Transport Commission with the aim of integrating NEPM development processes and the Australian Design Rule processes.

In November 1996 NEPC agreed to establish a diesel emissions working group to develop a detailed proposal for the diesel NEPM taking into account the necessity to consider both heavy and light vehicles.

In June 1998, NEPC approved funding for preparatory projects to fill identified knowledge gaps in regard to emissions from diesel road vehicles.

In July 1999, NEPC resolved to direct the NEPC Committee to develop, to the extent possible, the scope, content, timelines and budget for the development of a proposed NEPM for diesel emissions, for consideration by Council at its December 1999 meeting. NEPC also approved further funding for additional preparatory projects to fill identified knowledge gaps in regard to emissions from diesel road vehicles.

The first of these preparatory projects examined the existing vehicle characteristics of the Australian diesel fleet, and examined the modelling of transport demand, vehicle populations and emissions (Cox and Apelbaum Consulting Group, 1999).

1.3 Diesel fuel and the Diesel engine

1.3.1 Introduction

Most heavy vehicles over 10 tonnes GVM use turbocharged four stroke compression ignition engines. Smaller vehicles use normally aspirated engines. All are commonly referred to as `diesel engines'. In the diesel engine, the diesel fuel is injected at over 1000 atmospheres pressure and is ignited as a result of the heat of compression, whereas in the petrol engine the fuel is ignited by a spark from a spark plug. The fuel in the spark ignition engine is injected into the air outside the cylinders in the manifold at 4 atmospheres pressure. In the diesel engine air is supplied to the cylinder at about the same point of the engine cycle as spark ignition occurs in the petrol engine.

1.3.2 Fuel Quality Review

The report by the Australian Academy of Technological Sciences and Engineering (1997) identified a number of specific links between fuel characteristics and vehicle emissions. The report of the Task Group on transport vehicles (Anyon, 1997) briefly reviewed emission from alternative fuels. A number of overseas studies have been undertaken on fuel specifications. The recent Auto/Oil Air Quality Improvement Research Program (AQIRP) in the US showed a clear relationship between fuel specifications and emissions in petrol fuelled vehicles. A similar study in Europe, identified the effect of changing specific fuel characteristics on emissions from diesel and petrol vehicles.

The recent review of Australian Design Rule (ADR) 70 on compression ignition (diesel) vehicles highlighted issues with respect to fuel characteristics. The level of sulfur in diesel is a critical factor in ensuring that diesel vehicles comply with Euro2 standards in service.

In addition, the Prime Minister's statement on climate change in November 1997 "*Safeguarding the future: Australia's response to climate change*" includes a commitment to improve the fuel economy of vehicles, encourage alternative fuels, move to internationally harmonised emission standards and phase out leaded petrol.

In 1999, Environment Australia commissioned a study to undertake a comprehensive review of possible new fuel specifications for Australia, designed to reduce emissions of greenhouse gases and air pollutants from Australian road transport. The project assessed the impact on Australian refineries, vehicle manufacturers, consumers and the economy-wide effects of changing fuel specifications for petrol and diesel. Impacts on air pollutants and greenhouse emissions were also analysed in terms of their full life-cycle.

The report of the fuel quality review is available at: http://www.environment.gov.au/epg/fuel/.

1.3.3 Australian Design Rules

The Commonwealth's Tax Package Agreement announced by the Prime Minister of Australia on 28 May 1999 included a section entitled *Measures for a Better Environment*. There are three main elements of this Package, which deal with new vehicle standards and transport fuel, viz:

- Staged introduction of Euro2 and Euro3 standards for petrol vehicles
- Staged introduction of Euro2, Euro3 and Euro4 standards for diesel fuel
- The introduction of a clean diesel policy to ensure that low sulfur diesel is available within the timeframe for the proposed new vehicle standards.

Five new ADRs, which are expected to be made as Trans Tasman Vehicle Standards (TTVS), will be required to implement the package of changes to emission standards. The New ADRs/TTVS that relate to heavy vehicles are:

- 80/00 Emission Control for Heavy Vehicles

This ADR/TTVS requires heavy vehicles to meet Euro3 standards by 2002/3.

- 80/01 Emission Control for Heavy Vehicles (Euro3 and 4)

This ADR/TTVS requires heavy vehicles to meet Euro4 standards by 2006/7.

- 30/01 Smoke Emission Control for Diesel Vehicles

The smoke standard will apply from 2002/3 and will adopt UN ECE R24/03 and allow the US 94 smoke standards as an alternative. This new ADR will replace ADR30/00.

Table 1.2

EU Emission Standards for Heavy-duty Diesel Engines, g/MJ [3]

Tier	Test Cycle	CO	NMHC	NOx	PM	CH_4
Euro 1	ECE R-49	1.25	0.306	2.22	0.1000	
Euro2	ECE R-49	1.11	0.306	1.94	0.0417	
Euro3	ESC/ELR	0.58	0.183	1.39	0.0278	
	ETC	1.51	0.217	1.39	0.0583	0.44
Euro4	ESC/ELR	0.42	0.013	0.97	0.0056	
	ETC	1.11	0.015	0.97	0.0083	0.31
Euro 5	ESC/ELR	0.42	0.013	0.56	0.0056	
	ETC	1.11	0.015	0.56	0.0083	0.31

Source: http://www.dieselnet.com/standards/eu/hd.html

Table 1.2 is a simplified description of the emission standards comprising the various tiers of the Euro standard. Changes in the engine test cycles were introduced in the Euro3 standard. The old

[3] The standards are given in g/kWh and have been converted using 3.6 g/kWh = 1g/MJ.

steady-state engine test cycle ECE R-49 was replaced by two cycles: a stationary cycle ESC (European Stationary Cycle) and a transient cycle ETC (European Transient Cycle). Smoke opacity is measured on the ELR (European Load Response) test. The methane emission standard applies to gas fuelled vehicles only.

1.3.4 Vehicle Emissions and Fuel Consumption

There are some generalisations concerning the emissions from diesel vehicles resulting from different fuels. These include: the less volatile and more aromatic the fuel, the higher the exhaust particle emissions; oxygenated fuels produce less particles due to more complete combustion providing other fuel-related qualities, e.g. cetane number, remain constant; significant evaporative emissions may result from use of volatile fuels such as LPG or ethanol. The presence of impurities such as sulfur will result in extra particles formation (in the form of sulphate). In regard to fuel consumption, provided the fuel is within the normal specification range, then for a given engine technology and transport task, fuel economy will be related to the energy content of the fuel.

However, it must be borne in mind that measurements of exhaust pollutants on chassis dynamometers show considerable variation between similar vehicles that can mask small changes that might result from using a different fuel. The reasons are that, for pollutants other than CO_2, we are dealing with trace amounts of unburnt fuel or combustion side reactions. These vary according to engine condition and maintenance and also, if non-steady state test cycles are used, the accuracy with which the cycles have been performed by the driver. Whilst six repeats of a transient drive cycle, performed recently on the same vehicle with the same driver, resulted in a variability in fuel consumption of only $\pm$ 2%, (even less if the variability in the applied power was factored in) the average deviation for CO and VOC was 21% and 15% respectively. NO_x emissions were more constant with 4.5% variability (D.J. Williams, *pers. comm.*).

Emissions are often expressed in terms of g/km. Obviously, on this basis, a heavy-duty vehicle will emit more than a much lighter one. The impact of vehicle size on emission rates can be overcome by normalising to power output or unit fuel consumption. In this report a 'standard bus' has been used. However, when evaluating Full Fuel-cycle emissions, the split between non-vehicle and vehicle emissions will vary according to vehicle classification.

An example of this type of difficulty is to be found in the greenhouse gas emission factors for diesel fuel (National Greenhouse Gas Inventory Committee, 1998) viz:

CO_2 69.7 g/MJ, SO_2 0.116 g/MJ with a fuel energy density of 38.6 MJ/L.

whereas, for other emissions listed in Table 1.3, the default emission factors are expressed as g/km:

Table 1.3

Default Australian emission factors for automotive diesel fuel (g/km)

Vehicle	CH_4	N_2O	NO_x	CO	NMVOC
Light trucks	0.01	0.014	1.18	1.11	0.53
Medium trucks	0.02	0.017	3.1	1.82	0.99
Heavy trucks	0.07	0.025	15.29	7.86	3.78
Buses	0.03	0.025	4.9	2.88	1.56

Source: National Greenhouse Gas Inventory Committee. (1996)

Obviously, it is difficult to relate the two emission types without fuel consumption data for the various vehicle categories in Table 1.3.

Most of the vehicle emissions data relate to gasoline vehicles as they dominate the urban population. Much less data are available for in-use diesel vehicles (a large study is currently under way in Australia) and even less for alternative fuels. In view of the variability noted above, caution must be exercised in assessing exhaust emissions of CO, VOC and NO_x that arise from the different fuels. This is illustrated in Table 1.4, which summarises the results of emissions testing of 21 in-use heavy-duty vehicles, mostly four stroke, over four different drive cycles (Yanowitz et al. 1999). The data are summarised in terms of distance and energy for average, minima and maxima values.

Table 1.4

Emission test results for 21 in-use heavy diesel vehicles

	Fuel Economy (L/100km)	Emission units	Particles	NO_x	VOC	CO
Average	44.6	g/km	1.95	1.71	23.39	18.23
Min	98.3	g/km	0.30	0.14	4.15	2.09
Max	24.6	g/km	7.43	8.57	57.70	86.20
Average	44.6	g/MJ	0.05	0.04	0.58	0.47
Min	98.3	g/MJ	0.06	0.003	0.004	0.05
Max	24.6	g/MJ	0.31	0.35	2.18	2.76

Source: Yanowitz et al. (1999)

Vehicle test masses ranged from 9 to 25 tonne. In view of this picture of 'real-world' emissions, it is doubtful that small projected changes in emission rates of CO, VOC and NO_x due to other fuels from engine bench tests are that useful. Indeed similar variability was found by Motta et al, (1996) even when testing a more uniform group of vehicles namely transit buses as listed in Table 1.5.

A selection of emissions data for compression ignition engines burning a range of fuels is listed in Table 1.6 and expressed in terms of primary energy content. Emissions in terms of unit distance can be estimated from fuel consumption data for the transport task being considered.

1.3.5 Evaporative emissions

Due to the low volatility of traditional diesel fuel, there has been no need to take account of evaporative emissions or running losses. However, use of volatile liquids such as alcohols and LPG will, or could, raise the vapour pressure to the level where such losses need to be estimated or controlled. In the gasoline vehicle, carbon canisters are employed to pick up fuel tank vapours during protracted periods of congestion, which are then back flushed into the engine as part of the fuel. This is managed by monitoring the exhaust gas to maintain stoichiometric air fuel ratios. This option is not available to compression ignition engines as they are unthrottled devices and a more passive canister technology may be necessary as a replacement/service item.

Table 1.5

Average, maximum, and minimum values of the tailpipe emissions (g/km) recorded for buses undergoing an urban (CBD) drive cycle on a dynamometer

Fuel		PM	NOx	VOC	CO	CO_2
Diesel	**Average**	**0.79**	**21.26**	**1.30**	**7.72**	**1736.97**
	Max	1.77	36.75	1.75	28.94	2313.75
	Min	0.06	11.50	0.81	2.50	1436.88
Biodiesel	**Average**	**0.90**	**25.66**	**1.21**	**11.41**	**1948.35**
	Max	1.93	35.63	1.44	17.63	2120.00
	Min	0.45	9.75	0.94	6.50	1755.00
BD20	**Average**	**0.56**	**35.06**	**n.a.**	**6.38**	**1965.00**
	Max	0.88	49.25		11.50	2113.75
	Min	0.24	19.81		3.31	1883.13
CNG	**Average**	**0.02**	**12.17**	**6.90**	**5.33**	**1343.51**
	Max	0.11	43.19	43.88	28.81	1873.13
	Min	0.01	2.88	0.88	0.25	1156.25
E93	**Average**	**0.36**	**5.16**	**n.a.**	**9.84**	**2119.17**
	Max	0.46	6.63		13.88	2256.25
	Min	0.15	4.13		1.56	1986.88
E95	**Average**	**0.31**	**11.37**	**7.02**	**20.62**	**2154.10**
	Max	0.61	20.94	21.04	38.31	3611.88
	Min	0.04	5.00	0.69	0.69	1481.88
LNG	**Average**	**0.02**	**36.68**	**4.76**	**10.21**	**1496.68**
	Max	0.04	53.38	4.81	36.75	1706.25
	Min	0.01	19.38	3.09	0.06	1332.50

Source: Motta et al. (1996) as supplemented with data at www.afdc.doe.gov
BD-biodiesel; BD20 – 20% biodiesel, 80% diesel; E93 – 93% ethanol blend; n.a – not available

1.3.6 Change in heavy-duty diesel vehicle emissions with diesel fuel properties

The European Programme on Emissions, Fuels and Engine Technologies (EPEFE) has examined the effect of variations in European diesel fuel properties on emissions of light duty and heavy-duty diesel engines. The heavy-duty engines conformed to the Euro2 limits. The results are summarised in Faiz et al. (1996) and are reproduced in Table 1.7. Increasing cetane number and decreasing polyaromatics are the two most significant variables in reducing heavy-duty diesel engine emissions. As Faiz et al. (1996) note, the absence of any effect on PM emissions from changes in cetane number is different from the results of a number of US studies. This difference most likely is due to the higher cetane number of the EPEFE fuels (50 to 58) compared to the diesel fuels in the United States. Increasing cetane number from 50 to 58 seems to have little effect on PM emissions, but increasing it from 40 to higher levels such as 45 or 50 has a significant effect.

Table 1.6

Measurement-based Average Exhaust Emissions Data for HDV (g/MJ)

Fuel	Ref	FE (L/100km)	CO_2	CH_4	N_2O	Particles	NO_x	VOC	CO
Diesel	1	44.6	73.8			0.05	0.04	0.58	0.47
Diesel	2	29.9	73.8	0.006	0.003	0.86	0.19	1.00	2.09
Diesel	3	urban							
Diesel	3	44.4	73.8			1.21	0.38	1.04	0.10
Diesel	3	rural							
Diesel	3	39.7	73.8			0.52	0.19	1.07	0.10
Diesel	3	highway							
Diesel	3	35.6	73.8			0.335	0.189	1.081	0.102
Diesel	4		73.8			0.029	0.792	0.048	0.288
LSD			73.8						
ULSD			73.8						
Biodiesel	4								
BD20	4								
CNG	4		53.9			0.001	0.488	0.277	0.214
E93	4		125.2			0.021	0.305	0.000	0.581
E95	4		122.5			0.018	0.647	0.399	1.173
LPG	4		62.9			0.001	1.540	0.200	0.429
NG	4		55.5	0.101	0.001		1.2	0.001	0.2

refs 1: Corinair, 1990; 2: Corinair, 1994; 3: Yanowitz et al. (1999); 4: Motta et al. (1996)

Table 1.7

Change (percent) in heavy-duty diesel vehicle emissions with variations in diesel fuel properties

Fuel property	CO_2	Particles	NO_x	VOC	CO
Density 855 to 828 g/L	+0.07	-1.59	-3.57	+14.25	+5.0
Polyaromatics 8 to 1 percent	-0.60	-3.58	-1.66	-4.02	0.08(NS)
Cetane number 50 to 58	-0.41	0(NS)	-0.57	-6.25	-10.26
T95 370 to 325°C	+0.42	0(NS)	-1.75	+13.22	+6.54
Sulfur 2000 to 500 ppm	-	-13.0	-	-	-

Source: Faiz et al. (1996) -not applicable; (NS) not significant; positive values indicate an increase in emissions; negative values indicate a decrease in emissions.

1.4 Greenhouse Gases and Other Emissions

Australia is committed to a target for national greenhouse emissions of no more than eight percent above 1990 levels by 2008-2012 under the Kyoto Protocol to the United Nations Framework Convention on Climate Change.

In 1997, transport emitted about 24% of the national anthropogenic CO_2 emissions of 287.5 Mtonnes, but only 17% of total greenhouse gas emissions of 431 Mtonnes CO_2-equivalents (National Greenhouse Gas Inventory Committee, 1999). About 87% of these emissions come from road transport, including cars, trucks and buses. Table 1.8 gives a breakdown of the relative greenhouse gas emissions from transport and road transport.

Table 1.8

Australian greenhouse gas emissions from the transport sector and the road sub-sector in 1997

	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	CO_2-equiv. (Gg)
Transport	68488	23.38	11.32	72487
Road Transport	59886	20.68	11.07	63752

Source: National Greenhouse Gas Inventory Committee (1999)

In terms of the types of fuel used, current consumption is about 18,000 ML of automotive gasoline and 12,600 ML of automotive diesel, with aviation using nearly 5,000 ML of turbine fuel. LPG and aviation gasoline consumption is relatively low. Strong growth is anticipated for aviation and road freight. Rail currently accounts for about 56% of non-urban freight (in net tonne-kms), of which over 1/3 is carried by private operators.

The greenhouse gases considered in this review are carbon dioxide, nitrous oxide, hydrofluorocarbons, methane, sulfur hexafluoride, and perfluorocarbons. This particular group of greenhouse gases is sometimes called the Kyoto Protocol group of greenhouse gases, because they comprise the list of greenhouse gases specified in that protocol. The transport sector generates both 'direct' and 'indirect' greenhouse gases. Direct gases are radiatively active. Those emitted by transport include carbon dioxide, methane, nitrous oxide, and CFCs. The indirect greenhouse gases include carbon monoxide, other oxides of nitrogen and non-methanic volatile organic compounds. These do not have a strong radiative effect in themselves, but influence atmospheric concentrations of the direct greenhouse gases by, for example, oxidising to form CO_2 or contributing to the formation of ozone, a potent direct greenhouse gas. Present international agreement is to ignore such gases in the calculation of CO_2-equivalent greenhouse gases.

The concept of a global warming potential (GWP) has been used to enable different greenhouse gases to be compared to each other and expressed in CO_2-equivalents. The GWP factors reflect the different extent to which gases absorb infrared radiation and the differences in the timescales on which the gases are removed from the atmosphere. The GWP is used in the National Communications required by the UN Framework Convention on Climate Change. The Kyoto Protocol has adopted GWPs (with a 100-year time horizon) as the basis for defining equivalences between emissions of different greenhouse gases during the 2008-2012 commitment period. These GWPs are given in Table 1.9.

The Kyoto Protocol requires calculations of greenhouse gases to be made on the basis of fossil-fuel derived carbon dioxide or net exchange of carbon with the long lived biosphere. Carbon dioxide that is generated as a result of the combustion of a renewable fuel (such as canola oil) is not to be included in greenhouse gas inventories.

Table 1.9

100 year global warming potentials

Gas	GWP
Carbon dioxide	1
Methane	21
Nitrous Oxide	310
Sulfur Hexafluoride	23900
CFC-11	3800*
CF_4	6500
C_2F_6	9200

*Direct only. Other estimates include indirect effects

With vegetable oils and ethanol derived from biomass, carbon dioxide emitted during combustion of the fuel is offset by that absorbed by the plant from the atmosphere during growth. However, greenhouse debits arise in the path from crop to canola or ethanol consumption in vehicles. The use of agricultural chemicals, fuelling of farm machinery, transport of the crop, processing of the crop, drying of liquid wastes and transport of canola or ethanol may all involve the use of fossil fuels and hence emissions of CO_2. Denitrification of fertilisers applied to the crop is also a major problem because N_2O, which has a high GWP, will be emitted.

These greenhouse debits are site specific because they depend on the crop grown, the source of fuel used to process the crop and any additional release of greenhouse gases from the soil above natural levels.

Air Pollutants

The air pollutants to be considered are carbon monoxide, oxides of nitrogen, sulfur dioxide, non-methanic volatile organic compounds (VOC), visible smoke and particles. These air pollutants are generated by transport vehicles in varying amounts, depending on the nature and composition of the fuel that is used, the type and age of the vehicle, the nature of the drive cycle, and the degree to which the vehicle is properly tuned. Most of the VOC exhaust emissions from conventional vehicles are composed of hydrocarbons (compounds containing carbon and hydrogen only). VOC emissions from alcohol-based vehicles contain a greater proportion of very reactive compounds called aldehydes. Particles and smoke are composed of a mixture of many different compounds. Some of these gaseous and particulate compounds are toxic. Examples are benzene, formaldehyde, lead, chromium and benzo-a-pyrenes.

1.5 Life-Cycle Assessment (LCA)

A general introduction to life-cycle assessment may be found in Graedel & Allenby (1995). When LCA is applied to the emissions from the use of different transport fuels, both combustion and evaporative emissions need to be included, as well as the full life-cycle of the fuel. A full life-cycle assessment of emissions takes into account not only the direct emissions from vehicles, but also those associated with the fuel's:

- Extraction
- Production
- Transport
- Processing
- Conversion
- Distribution.

Bureau of Transport and Communications Economics (1994) use the term 'full fuel-cycle' for the situation that takes into account emissions from all energy used in achieving a given transport task with a particular fuel. This contrasts with tailpipe emissions, which can be estimated fairly accurately from the carbon content of a particular fuel and the amount of fuel used per kilometre. A life-cycle basis for estimating fuel emissions for a particular fuel takes into account emissions in vehicle manufacture and vehicle life, whereas a full life-cycle assessment sets the system boundaries much wider and incorporates emissions from the associated infrastructure.

Emissions related to vehicle manufacture, maintenance and disposal, and road building are relevant to total transport emissions, but they are not likely to vary significantly with the nature of the fuel used. The infrastructure associated with refuelling will, however, vary with the different alternative fuels.

The method of analysis (Beer et al. 1996) consists of flowcharting each of the above steps. Then, on the basis of the life of the plant infrastructure used in each of the four steps, one determines a weighting factor to apply to the energy usage (the embodied energy), to the greenhouse gases, and to the air pollutants emitted during that particular step. Because the greenhouse gases have been emitted, rather than embodied, the term in-process greenhouse gases has been used to refer to the greenhouse-gas emissions during the whole life-cycle.

Analysis of the production requires knowledge of the collection system used for the particular fuel. Certain fuels are processed on-site. Other fuels are transported to refineries or processing plants. Further transport may then be needed before the fuel is ready for distribution to the commercial vehicles that will use the fuel.

Quantification of the life-cycle then consists of estimates of the:

- Plant-life for the equipment used in each of the steps, and the use of these plant-life estimates to determine weighting factors
- Energy usage in each of the steps
- Greenhouse gases associated with each of the steps
- Air pollutants (if any) associated with each of the steps.

The quantified estimate obtained from each step will be multiplied by the appropriate weighting factor, and the final result summed to produce the embodied energy, the in-process greenhouse gases, and the in-process air pollutants.

For example, a life-cycle assessment of greenhouse gas emissions from road transport considers both the direct and the in-process greenhouse gas emissions involved in manufacturing and using a motor vehicle. It also needs to consider the greenhouse gases emitted in constructing and maintaining the physical infrastructure of the roads, traffic lights, and street lights. Finally, it needs to consider the administrative infrastructure involved in maintaining serviceable roads and traffic flow.

All of these calculations are non-trivial. Consider the issues separately. The first issue is that of the greenhouse gas emissions involved in the life-cycle of a motor vehicle. European studies (Kuhndt and Bilitewski, 1999) and Japanese studies (Toyota Motor Corporation, 1999) find that approximately 80% of the energy consumption (and thus the greenhouse gas emissions) is in the actual driving of the vehicle. Fig. 1.1 shows the break-up of the resulting in-process and direct greenhouse gas emissions from a European Golf III vehicle. Even the final disposal of the vehicle, shown in the figure as recycling, consumes energy and hence emits greenhouse gases. Similar Australian studies indicate that the direct emissions as a result of automobile utilisation are only 57% of the total life-cycle energy, which is a much lower percentage of the total than in the European or Japanese case (Fewchuk et al. 1998).

The second issue is that of the in-process greenhouse gases involved in maintaining the administrative infrastructure of a government authority to oversee transport issues. In the case of the NSW Roads and Traffic Authority (RTA), the largest source of their in-process greenhouse gas emissions is in their road-making operations (Fig. 1.2). The large greenhouse gas emissions involved in the manufacture of cement for concrete roads, and their steel reinforcing, mean that in many situations bitumen roads are less greenhouse-gas intensive. Typical calculations for Sydney indicate that total in-process greenhouse gases associated with asphalt roads comprise 650 Mg CO_2 per km of road, whereas total in-process greenhouse gases associated with reinforced concrete roads comprise 3,017 Mg CO_2 per km of road. These are indirect greenhouse gas emissions arising from in-process activities. The largest direct source of the RTA greenhouse gas emissions arises from the energy use in their buildings and warehouses (Fig. 1.2).

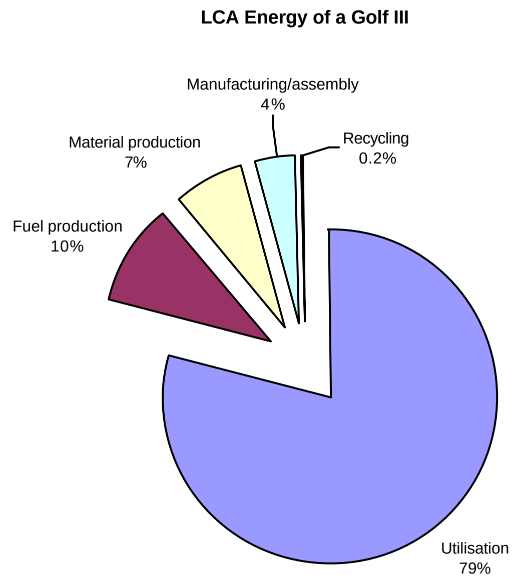


Figure 1.1

The in-process and direct greenhouse gas emissions (0.0356 Gg CO_2) during the life-cycle of a Golf III for a life of 150,000 km and a fuel consumption of 12.3 km/L (Kuhndt and Bilitewski, 1999)

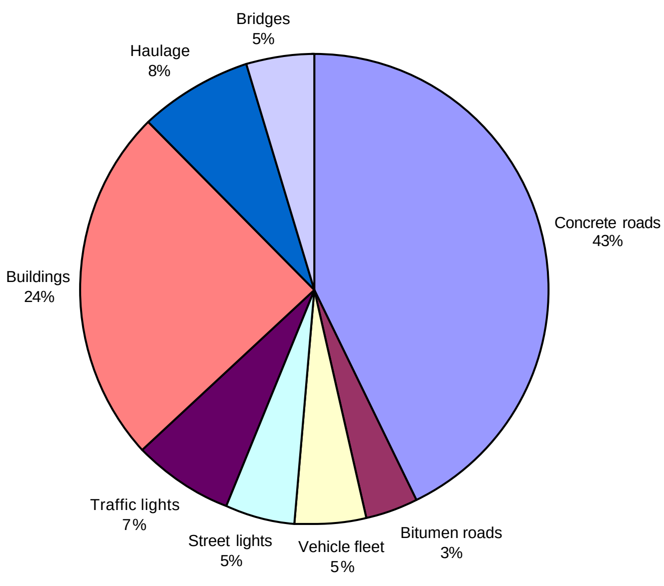


Figure 1.2

The in-process and direct greenhouse gas emissions (441 Gg CO_2) of all activities associated with the annual operations of a government road and traffic authority (RTA, 1998; Beer et al. 1996)

Life-cycle assessment modelling

Life-cycle assessment was done with the assistance of commercial LCA software package, SimaPro 4.0 software. SimaPro 4.0 is an open structure program that can be used for different types of life-cycle assessments. The production stage, the use stage and the end of life scenario can be specified in as much detail as necessary by selecting processes from the database and by building process trees, which can be drawn by the program. The results are presented in scores or graphs, varying from a list of substances (inputs and outputs), characterised scores, normalised scores or evaluated scores.

The foreground system for this study (tailpipe emissions and fuel production) has been mostly entered into the database from existing reports and studies. Much of the background data (minor material inputs, process heat, and fuel transportation) have been taken from existing Australian data and international data from the SimaPro database, with modifications made to fit the Australian context. The output from SimaPro consists of the priority pollutants - CO_2, CH_4, N_2O, NOx, CO, NMVOC and particles. For these pollutants, data have been specifically sought from the literature. In addition to the priority pollutants, we have provided a small number of broader environmental indicators that draw largely on the other life-cycle inventory data contained in the background systems for fuel production. Data have not specifically been sought for these indicators and before making any judgements on these data, they would need to be checked and verified in a more detailed LCA analysis. The reason for providing the data is to alert readers to other indicators may be of consequence, and may need to be investigated further. The indicators include CO_2-equivalents, embodied energy, photo-oxidant potential, heavy metals, carcinogenic substances, and solid waste. Indicators that are not included here, but should be included in any future study, are land-use impacts, biodiversity, and water-use.

The database of SimaPro has been updated with the information obtained during the course of this study. SimaPro contains several methods to evaluate the outcomes of the inventory stage of an LCA (the list of substances).

1.6 Structure of the Report

This report examines each of the ten alternative fuels with respect to their life-cycle emissions of greenhouse gases and air pollutants. Each fuel is considered in a separate chapter. Wherever possible the emissions are provided on a quantitative basis as a result of values available in the literature.

We have used a hierarchy of data quality to assess the data on emission profiles from different vehicle types. There are no Australian experimental data available on emissions from heavy vehicles, (other than buses), though the National Greenhouse Gas Inventory provides default values for emission factors and for fuel economy. A number of other Australian studies have relied on overseas data on heavy vehicles. Such data have been reviewed and, where appropriate, used in the SimaPro model.

The report consists of three parts. Part I consists of the introductory chapter, a second chapter that reviews the literature and data relating to emissions, and a final chapter that summarises the results. Part II consists of six chapters that examine each of the alternative fuels in detail. Part III consists of appendices.

The comparison between different fuels is done on the basis of the mass of emissions per kilometre of distance travelled. Arriving at such a figure involves three steps:

1. Life-Cycle Analysis of Emissions.
   This first step produces an estimate of the greenhouse gas and air quality emissions from each fuel expressed as the mass of emissions per unit of energy - kg/MJ.
2. Fuel Efficiency.
   This characterises the fuel in terms of its energy per unit volume in units of MJ/L
3. Performance.
   This characterises the fuel in terms of the per-kilometre emissions.

An alternative way of considering this is to examine the units associated with the quantities:

$$\text{g/km} = (\text{g/MJ}) \times (\text{MJ/kg}) \times (\text{kg/L}) \times (\text{L/km}) \quad (1)$$

The first term (g/km) is the final performance result that this report examines; the emissions expressed on a per kilometre basis. One arrives at this by considering the product of the engine emissions (g/MJ), the fuel combustion characteristics (MJ/kg), the fuel density (kg/L) and the vehicle fuel economy (L/km). Each one of these four terms displays variability, so that the uncertainty associated with the emissions will be the sum of the percentage uncertainties associated with each of the four terms. This report compares emissions on a g/km basis. Appendix 4 gives the equivalent g/MJ results.

Whereas the first two steps given above can be undertaken on the basis of static tests of motors and theoretical calculations on fuel properties, performance is determined in this study on the basis of fuel economy, expressed in units of L/km. Ideally this is based on road tests using vehicles with alternative fuels. Such on-road tests are very difficult and expensive to carry out so that most emission tests are actually carried out either as static tests or on a chassis dynamometer.

Static tests require the engine to be removed from the chassis, and then tested over a lengthy test protocol. Chassis dynamometer tests involve the drive wheels of the vehicle being placed over a set of rollers, and the vehicle being driven in a representative test cycle while the emissions are collected and then analysed. The dynamometer must have sufficient rotating inertia to simulate the mass of the vehicle in acceleration and deceleration manoeuvres. Most tests are performed on unladen vehicles because of limited dynamometer inertia. Figure 1.3 shows the mobile dynamometer of the Department of Mechanical and Aerospace Engineering at West Virginia University, who worked with the US Department of Energy to build a mobile dynamometer capable of testing up to 20 tonnes.

The data collected with the dynamometer of Fig. 1.3 for trucks, snow ploughs, garbage trucks and buses using conventional and alternative fuels are available on the world wide web.

Figure 1.3

West Virginia University Mobile Heavy-vehicle Chassis Dynamometer Facility

1.7 Web-based General Information Sources

National Environment Protection Measures
http://www.nepc.gov.au

Alternative fuels
The alternative fuels data center is at
http://www.afdc.doe.gov

The USEPA Office of Transportation and Air Quality information on fuels is at
http://www.epa.gov/oms/fuels.htm

Diesel exhaust emissions
http://www.dieselnet.com

The USEPA Office of Transportation and Air Quality certification information on emissions from heavy vehicle engines is at http://www.epa.gov/oms/certdata.htm

Alternative fuel technologies
http://www.ott.doe.gov

Greenhouse Gases
http://greenhouse.gov.au

Chapter 2

National And International Studies On Alternative Fuels And Heavy-Vehicle Emissions

2.1 Tailpipe Emissions

2.1.1 Buses

There has been substantial activity in relation to the use of alternative fuels in truck and bus fleets around the world. In Australia, Sydney Buses has a fleet of 104 Scania CNG buses operating out of the Kingsgrove depot, and has ordered a fleet of new Mercedes-Benz CNG buses. The new CNG buses are being introduced into service at a rate of 10 per month so that there will be 150 Mercedes-Benz buses in operation by September 2000. The new buses will operate from the Ryde depot (75 buses) and the Port Botany depot (75 buses).

By contrast, the expert reference group examining fuel for Transperth's new bus fleet opted for low sulfur diesel (Expert Reference Group, 1998). The conclusion from the report was that

"It is not possible to offer a recommendation for a fuel-technology combination which meets the combined requirements of (1) lowest full cycle greenhouse gas emissions, (2) lowest air toxic emissions, (3) least contribution to population-weighted exposure to PM10, and (4) least contribution to population-weighted exposure to smog produced."

These conclusions were based on the emission rates given in Table 2.1. It appears, based on examination of the report, and the supporting material, that these emission rates were obtained from dynamometer tests conducted by London Transport on one of their bus fleet (Brown, 1997; Williams, 1998) using a simulated urban bus cycle for inner London.

The Expert Reference Group report continues:

"LPG meets the first two requirements but not the last two. CNG is close to meeting the third and fourth, but is a little behind low sulfur diesel on the first two. However, it is evident that low sulfur (0.05%) diesel with an oxidation catalyst can meet the third, and is close to meeting the first, second and fourth."

Table 2.1

Emission rates[4] (g/km) used in the Transperth Bus report based on Millbrook trials

	CO_2	CO	NOx	HC[5]	PM10
Existing fleet	1868	5	20	4.5	2.025
Euro2 Diesel	1500	2	16	1.2	0.5
LSD	1386				
LSD+OXC	1330	0.3	14	0.4	0.2
ULS	1351				
ULS+OXC	1288				
ULS+CRPT	1282				
LPG+3C	1309	0.13	5.4	0.03	0.02
CNG+OXC	1344	0.6	10	3	0.05

OXC – Oxidation catalyst; 3C – 3 way catalyst; LSD - Low sulfur diesel (< 500 ppm sulfur)
CRPT-continuous regenerating particulate trap; ULS Ultra low sulfur diesel (< 50 ppm sulfur)
Source: Expert Reference Group (1998)

Cope & Katzfey (1998) have revised some of the values given in Table 2.1 and their updated estimates are given in Table 2.2. In addition, they presented a comparison with US emissions on CNG buses obtained from the report of Motta et al. (1996).

Table 2.2

Revised Millbrook trials emission rates (g/km)

	CO	NOx	HC	PM10
Existing fleet	33	22	3.7	1
Euro2 Diesel	5.76	15	1.62	0.23
LSD+OXC	1.23	14.1	0.87	0.11
CNG+OXC	0.66	9.9	3.61	0.05
CNG (US)	0.71	7.2	9.82	0.01

Source: Cope & Katzfey (1998)

The reduction in CO_2 emissions as the sulfur is removed from the diesel fuel is surprising and requires further examination. We would not expect the reduction in sulfur to alter the emissions when measured on an engine dynamometer and this is confirmed by data supplied by Daimler Chrysler (D. Graham, *pers. comm.* 2000), which are reproduced in Table 2.3.

The results of Table 2.3 indicate consistency in CO_2 emissions (when expressed in g/MJ) as the sulfur content of the fuel varies. Although the actual value is very high compared to the typical value of 69.7 g CO_2/MJ discussed in the previous chapter it, in fact, refers to the engine mechanical output rather than the primary energy input of the fuel.

[4] These all refer to tailpipe emissions. The Expert Reference Group report incorrectly claims that the CO_2 emissions are full cycle emissions.
[5] HC refers to total hydrocarbons emissions, which includes methane.

Table 2.3

Emission rates (g/MJ) for diesel and CNG buses used in NSW buses[6]

Fuel	Manufacture	CO_2	CO	NOx	HC	PM10	Source
Diesel (200 ppm)[7]	Mercedes-Benz	203	0.13	1.78	0.100	0.030	Daimler-Chrysler
Diesel (50 ppm)[4]	Mercedes-Benz	203	0.01	1.81	0.003	0.008	Daimler-Chrysler
CNG	Scania	-	0.56	0.97	.097	<0.03	State Transit
CNG[8]	Scania	-	0.78	3.31	.820	-	Brown et al. (1999)
CNG	Mercedes-Benz	-	0.56	0.56	.139	0.014	State Transit
CNG[4]	Mercedes-Benz	174	0.55	0.24	.033	-	Daimler-Chrysler

Re-examination of the supporting material for the Expert Reference Group report reveals that the LSD emission of 1386 g CO_2/km actually refers to a Euro 1 engine, so that the apparent improvement in fuel economy (to 1351 g CO_2/km) as a result of using ULS fuel is not a result of the change in fuel but a result of a change in vehicle technology. We suspect the same to be true in relation to the apparent decrease from 1500 g/km to 1386 g/km when switching from diesel to LSD. As will be shown later in this chapter, 73 US buses using diesel fuel have average CO_2 emissions of 1737 g/km. However, the tested values ranged from 1436 g/km to 2313 g/km. Certainly when US data on emissions from heavy-duty (non-bus) vehicles are examined the tailpipe CO_2 emissions per kilometre of low sulfur fuel (California Diesel) are, on average, higher than the equivalent average for diesel fuel.

When contact was made with Australian bus companies known to be using alternative fuels, the emission figures that were provided were those obtained from the vehicle manufacturers. Table 2.3 reproduces the figures used by Sydney Transit in relation to the emissions of their existing CNG fleet of Scania buses and the expected emissions from the new Mercedes-Benz CNG buses. These figures comply with the Euro3 emission standards. The NSW EPA (Brown et al. 1999) chassis dynamometer tests on Scania CNG buses are also given.

Some emission testing work has been conducted by the NSW EPA (Scott et al. 1995; Brown et al. 1999). Joseph (1996) reports on the field trials of the six Renault PR100-2 diesohol buses used by the Canberra-based ACTION buses. The conclusion was that there is a considerable reduction in the level of smoke emissions and oxides of nitrogen (NOx) compared to diesel buses. There were no significant differences in gross carbon dioxide, unburned hydrocarbons or aldehyde emissions. However, there was an increase in carbon monoxide emissions when diesohol was used in unmodified Renault engines.

2.1.2 Trucks

The situation with trucks is similar to that of buses. Though there are over 80 natural gas trucks in use in Australia there are few data in relation to their emissions. One of the best documented studies on the development of LNG as a heavy-duty vehicle fuel was that of Zingarelli (1997), yet this study was focussed on LNG supply and utilisation and undertook no emissions testing, relying instead on visual observations of white and black smoke emissions.

---

[6] Values were supplied as g/kWh and have been converted
[7] ECE R 49 13 mode steady state test
[8] Chassis dynamometer tests

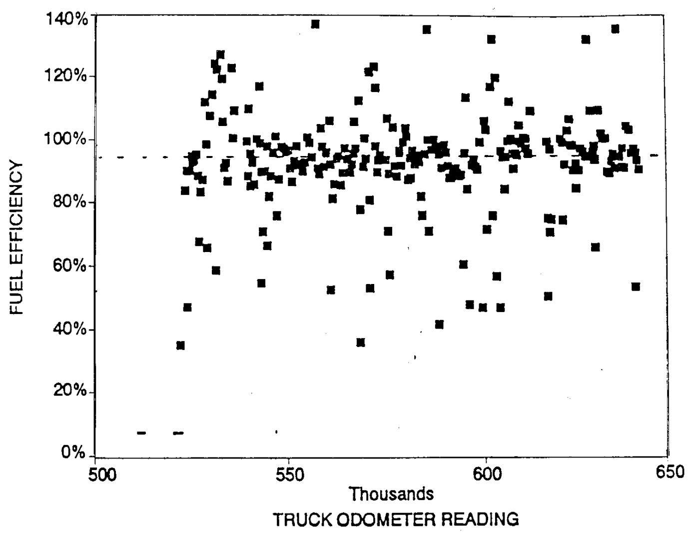


Figure 2.1.

Fuel economy of LNG operation of a heavy truck as a percentage of all-diesel operation (Zingarelli, 1997)

Greenhouse gas emissions can be indirectly inferred from measurements of fuel economy. Figure 2.1 reproduces the fuel economy results given by Zingarelli (1997). The LNG truck, in this case, was a Volvo NL12 prime mover and tipper trailer that operated in a dual fuel mode so that it reverted to diesel operation when the LNG fuel system was out of service. The diesel fuel economy of 1.75 km/L is taken as 100%. The calculated fuel efficiency of the gas operation, as a percentage of that achieved with all-diesel operation, is markedly variable. On average, the fuel efficiency of the gas operation was around 95% of that of all-diesel operation. That is, gas operation consumed around 5% more energy for the same distance travelled.

The relative efficiency between gas and diesel varies markedly depending on the particular operations that the vehicle is undergoing. These results parallel those of Sun et al. (1997) who examined tailpipe emissions of trucks operating on CNG and LPG. They found that when measured relative to diesel fuel, emissions would vary from less than the diesel to more than the diesel, depending on whether the vehicle was tested under a cold start or a hot-start.

Bureau of Transport and Communications Economics (1995) presents a range of greenhouse gas emission estimates from the use of alternative fuels in trucks (compared with diesel fuel). These are reproduced in Table 2.4. The table illustrates the large variability that is found when individual results are examined. In many cases this variability is so large that it is difficult to determine whether the alternative fuel emissions are better or worse than that of diesel. This indicates that, wherever possible, comparison between alternative fuels needs to be done on a statistical basis.

Table 2.4

Range of greenhouse gas emission estimates for trucks (compared with diesel fuel)

Fuel	Worst: % change	Best: % change
LPG	+15	-11
CNG or LNG	+45	-13
Ethanol from corn/coal	+100	-56
Ethanol from wood	+35	-100

Source: Bureau of Transport and Communications Economics, 1995: Table VI.3

2.2 *Life-Cycle Emissions*

There have been a number of studies designed to examine fuel-cycle emissions and energy use, and recently there have been studies on life-cycle emissions and energy use of alternative fuels. However, most of these (Delucchi, 1991, 1993, 1997; Darrow, 1994a, 1994b; Acurex Environmental Corporation, 1996) relate to cars and not to heavy vehicles. The UK has published preliminary work on a life-cycle study of alternative fuels (ETSU, 1996). The International Energy Agency has published a five volume survey of automotive fuels (IEA/AFIS, 1996a, 1996b, 1998, 1999a, 1999b), which examine the well-to-wheel greenhouse gas emissions, and air quality implications, of alternative and conventional fuels.

Australian Transport

Lenzen (1999) has used the Apelbaum (1997) data to provide a "top-down" estimate of total greenhouse gas emissions as a result of Australian transport.

Total greenhouse gases were estimated by using calculated Australian fuel usage, and adding estimated operating and infrastructure emissions on the basis of their costs. Thus the in-process greenhouse gases associated with the vehicle and the roads have been incorporated through their costs.

Table 2.5

Calculated energy intensity and greenhouse gas intensity of the Australian urban bus fleet

Bus Location	Average occupancy	Energy Intensity (MJ/km) Fuel	Operation	Total	Greenhouse gas intensity (kg CO_2-e/km) Fuel	Operation	Total
Sydney	12	20.4	9.6	28.8	1.44	0.96	2.4
Melbourne	8	25.6	5.6	30.4	1.84	0.56	2.4
Brisbane	10	21	10	31	1.5	1.1	2.6
Adelaide	11	22	6.6	28.6	1.54	0.66	2.2
Perth	12	19.2	6	25.2	1.44	0.6	2.04
Canberra	7	14	4.2	18.9	1.05	0.42	1.54
Hobart/Launceston	6	21.6	7.8	29.4	1.56	0.78	2.34
Darwin	18	16.2	14.4	32.4	1.26	1.62	2.7
Newcastle	11	18.7	7.7	26.4	1.43	0.77	2.09

Based on data from Lenzen (1999)

2.2.1 Buses

Table 2.5 summarises the results of Lenzen (1999) for Australian buses. The energy intensity of the fuel can be converted to fuel economy by using an energy content of 38.6 MJ/L. For Sydney this produces a value of 1.89 km/L, which is in agreement with the typical fuel economy for a Sydney diesel bus of 1.62km/L (State Transit, *pers. comm* 2000.). The National Greenhouse Gas Inventory (1996) advocates 3.2 km/L as an average Australian value for diesel buses.

The "top-down" approach has underestimated tailpipe emissions. For example, Table 2.1 indicates that Western Australian Government estimates of the Perth bus fleet are 1.87 kg CO_2/km, whereas Table 2.5 has a much lower figure (1.44 kg CO_2-e/km) even with the inclusion of CH_4 and N_2O to produce CO_2-equivalents.

2.2.2 Trucks

Table 2.6 summarises the results of Lenzen (1999) for Australian trucks, divided into three classes. Articulated trucks (which we take as heavy trucks), rigid trucks (which we take as medium trucks) and light commercial vehicles (LCV, which we take to be light trucks).

Table 2.6

Calculated energy intensity and greenhouse gas intensity of the Australian road freight fleet

	Tonnage t/veh	Energy intensity MJ/km			GHG intensity kg CO_2-e/km		
		Fuel	**Operation**	**Total**	**Fuel**	**Operation**	**Total**
Articulated	16.87	23.52	5.04	28.56	1.848	0.504	2.184
Rigid	3.6	12.6	3.96	16.56	0.936	0.396	1.332
LCV	0.17	5.44	2.856	8.296	0.3808	0.2822	0.663

based on data from Lenzen (1999)

The assumed fuel economies based on the energy intensity appear to be reasonable. Data supplied by Australia Post for inter-city freight show an average fuel consumption of 45L/100 km for B doubles (Parsons Australia, *pers. comm.*). However, the assumed greenhouse gas emission factor that ranges from 70 to 79 g CO_2-e/MJ seems very high for diesel vehicles.

2.2.3 US Transport

In 1998, the US National Renewable Energy Laboratory (NREL) completed a study for the US Department of Agriculture and Department of Energy to evaluate fuel-cycle energy and emission impacts of using biodiesel (BD) in place of diesel in urban buses (Sheehan et al. 1998a,b)

The study consists of a detailed evaluation of the use of soybean biodiesel. The diesel fuel-cycle in this study included stages from petroleum recovery to diesel combustion on buses.

The major operations within the boundary of the petroleum diesel system include:

- Extract crude oil from the ground
- Transport crude oil to an oil refinery
- Refine crude oil to diesel fuel
- Transport diesel fuel to its point of use
- Use the fuel in a diesel bus engine,

whereas the biodiesel cycle included stages from soybean farming to biodiesel combustion on board diesel buses. For the biodiesel system, major operations include:

- Produce soybeans
- Transport soybeans to a soy crushing facility
- Recover soybean oil at the crusher
- Transport soybean oil to a biodiesel manufacturing facility
- Convert soybean oil to biodiesel
- Transport biodiesel fuel to the point of use
- Use the fuel in a diesel bus engine.

The study included fossil energy use, petroleum use, CO_2 emissions, and emisions of five criteria air pollutants. The study also estimated, though less thoroughly, the amount of waste water and the amount of solid waste generated during production of biodiesel. The study used a life-cycle model developed by Ecobalance Inc. (a consulting company in Virginia), which provided a wealth of detailed information on energy use and emissions for each stage involved in the two fuel-cycles.

2.2.4 European Transport

Franke & Reinhardt (1998) examined the ecological impact of biofuels in Europe on the basis of a pre-combustion life-cycle analysis. Their work built on the comprehensive life-cycle analysis of Kaltschmitt et al. (1996) and Kaltschmitt & Reinhardt (1997) who examined all of the possible

European bioenergy carriers, including rapeseed oil (canola), and rapeseed methyl ester (RME, a form of biodiesel). Their comparison of RME and diesel for Germany is reproduced in Table 2.7.

Table 2.7

Pre-combustion life-cycle comparison of German canola and biodiesel as compared to diesel

	CO_2–equ. (kg/GJ)	N_2O (g/GJ)	SO_2 (g/GJ)	NOx (g/GJ)
Canola	-70	42	-49	-140
Biodiesel	-72	58	-25	+110

Source: Franke & Reinhardt (1998)

Eriksson et al. (1996) and Blinge (1998) have looked at the life-cycle of alternative fuels used in Sweden, including the Swedish bus fleet. The gas that is used in Sweden comes from the Danish gas fields in the North sea. It has low sulfur content and is transported to Sweden in pipelines under its own natural "self-pressure". This makes the refining operations comparably energy efficient and clean. Sweden also claims to have the cleanest diesel oil in the world (10 ppm sulfur). One of the results of their work is that it is impossible to present LCA-data on motor fuels that are valid world-wide. One has to study the "site-specific" systems. It is also clear, at least for fossil fuels, that the major part of the emissions originates from the operation of the vehicle.

The most comprehensive study of the life-cycle of alternative fuels is that of the IEA, as summarised in IEA (1999c). Their results for heavy-duty vehicles in terms of tailpipe emissions and well-to-wheel emissions are summarised in Table 2.8 and 2.9 respectively. The actual diesel emissions are given in the last row in g/km, whereas all other values refer to percentages based on diesel having a value of 100.

Table 2.8

European tailpipe emissions for heavy-duty vehicles as a percentage of diesel emissions

Fuel	NOx	CO	HC	PM	CO_2
Diesel	100	100	100	100	100
LPG	20-25	200-500	200-209	24	98-100
NG	15-34	100-620	150-646	15	87-103
Ethanol	81-90	107-400	140-145	19	83-100
Biodiesel	106-115	67-100	80-96	67	102-106
Diesel (g/km)	14.1-16.0	0.5-4.3	0.4-0.5	1.1	885-1195

Source: IEA/AFIS (1999)

Table 2.9

European well-to-wheel lifecycle emissions for heavy-duty vehicles as a percentage of diesel emissions

Fuel	NOx	CO	HC	PM	CO_2
Diesel	100	100	100	100	100
LPG	22-32	199-445	69-177	24	94
NG	16-35	99-530	255-588	15	87
Ethanol (cellulose)	94-103	577-1075	160-256	N/D	16-26
Ethanol (sugar)	103-104	119-891	114-235	55	34-67
Biodiesel	118-127	81-212	68-120	90-98	28-44
Diesel (g/km)	14.-16.7	0.6-4.3	1.1-1.8	1.1	977-1363

N/D = No Data
Source: IEA/AFIS (1999)

2.3 Statistical Variability

The above review of the literature highlights the extreme variability in the results that various researchers have found. Some of the reasons for this variability include specific geographic factors, the age and condition of the vehicles, the experience with the technology, the exact use to which the vehicle is subject, and the drive cycle used to mimic the use. Thus, for example, it is not clear whether the variations in CO_2 emissions shown in Table 2.1 indicate genuine improvements as one moves to low sulfur fuels, or reflect statistical variability in the results, or are influenced by a hidden change in engine technology.

The above review also demonstrates the scarcity of Australian data on heavy vehicle emissions, both with conventional and with alternative fuels. A further difficulty is that even when such data are available (Joseph, 1996) they are based on so few vehicles that it is difficult to gauge the statistical variability that is associated with the results. As a result of these considerations we undertook a search of the literature for data on alternative fuel emissions from heavy vehicles that could be used to examine the issues related to variability.

We are particularly interested in the performance of heavy vehicles when fuelled with conventional fuel (i.e. diesel) and with alternative fuels. Such vehicles have three major regions of use: urban, highway, and off-road. We have obtained and used data on buses as being the archetypical urban heavy vehicle. Trucks comprise the archetypical highway heavy vehicle and, where possible, we have used truck data to represent highway vehicles. Off-road vehicles are primarily used in industrial applications. They are not considered in this report, though the California Air Resources Board has, on 17th February, 2000, made available an emissions inventory of off-road large compression-ignited engines (see http://www.arb.ca.gov/toxics/diesel/diesel.htm).

2.3.1 Buses

Motta et al. (1996) tested a range of alternative fuels with at least 10 buses using each alternative fuel (along with 10 corresponding statistical controls). All buses were tested on the mobile dynamometer shown in Figure 1.3 - emissions data obtained from these, and subsequent, tests are available on the world wide web, via the Alternative Fuels Data Centre web site, at http://www.afdc.doe.gov/afv/emissions.html. The data are summarised in Table 2.10 in terms of the average values obtained, as well as the maximum and minimum values observed for each of the pollutants for each fuel. There is a large variation evident for every one of the emissions being considered, which explains the large range shown in Table 2.10 and why it is so difficult to determine whether a particular fuel has more or less, emissions than the equivalent diesel vehicle.

Table 2.10

Average, maximum, and minimum values of the tailpipe emissions (g/km) recorded for buses undergoing an urban (CBD) drive cycle on a dynamometer

Fuel		CO_2	CO	THC	NOx	PM	C_2H_5OH	HCHO	CH_3CHO
Biodiesel	**Average**	**1948.35**	**11.41**	**1.21**	**25.66**	**0.90**			
	Max	2120.00	17.63	1.44	35.63	1.93			
	Min	1755.00	6.50	0.94	9.75	0.45			
BD20	**Average**	**1965.00**	**6.38**		**35.06**	**0.56**			
	Max	2113.75	11.50		49.25	0.88			
	Min	1883.13	3.31		19.81	0.24			
CNG	**Average**	**1343.51**	**5.33**	**6.90**	**12.17**	**0.02**			
	Max	1873.13	28.81	43.88	43.19	0.11			
	Min	1156.25	0.25	0.88	2.88	0.01			
Diesel	**Average**	**1736.97**	**7.72**	**1.30**	**21.26**	**0.79**			
	Max	2313.75	28.94	1.75	36.75	1.77			
	Min	1436.88	2.50	0.81	11.50	0.06			
E93	**Average**	**2119.17**	**9.84**		**5.16**	**0.36**	**1.27**		
	Max	2256.25	13.88		6.63	0.46	2.86		
	Min	1986.88	1.56		4.13	0.15	0.03		
E95	**Average**	**2154.10**	**20.62**	**7.02**	**11.37**	**0.31**	**4.60**	**0.20**	**1.06**
	Max	3611.88	38.31	21.04	20.94	0.61	21.17	0.40	2.42
	Min	1481.88	0.69	0.69	5.00	0.04	0.11	0.01	0.03
LNG	**Average**	**1496.68**	**10.21**	**4.76**	**36.68**	**0.02**			
	Max	1706.25	36.75	4.81	53.38	0.04			
	Min	1332.50	0.06	3.09	19.38	0.01			

BD-biodiesel; BD20 – 20% biodiesel, 80% diesel; E93 – 93% ethanol blend, C_2H_5OH - ethanol emissions
HCHO - formaldehyde emissions CH_3CHO - acetaldehyde emissions. Blanks indicate no data.
Source: www.afdc.doe.gov/afv/emissions.html

Table 2.11

Average, maximum, and minimum values of the tailpipe emissions (g/km) recorded for heavy-duty vehicles.

Vehicle Type, Fuel and Number of Vehicles		CO_2	CO	THC	NOx	PM	C_2H_5OH	HCHO	CH_3CHO
Tractor	**Average**	1059	5.81	0.70	9.37	0.44			
BD	Max	1271	18.06	1.41	12.19	1.06			
8	Min	874	2.19	0.13	6.69	0.14			
Tractor	**Average**	1563	3.70		14.48	0.43			
BD35	Max	2779	6.06		24.44	0.87			
8	Min	1103	2.06		10.50	0.24			
Truck	**Average**	1346	2.03		12.20	0.35			
BD35	Max	1414	2.31		12.75	0.37			
4	Min	1266	1.81		11.50	0.34			
Tractor Truck	**Average**	1102	3.59		8.11	0.45			
LSD	Max	1246	10.00		9.13	1.32			
8	Min	891	1.75		6.94	0.23			
Tractor Truck	**Average**	930	11.90		6.42	0.28			
CNG	Max	960	13.63		9.81	0.35			
7	Min	904	10.19		4.63	0.22			
Tractor	**Average**	1155	4.57	0.80	10.49	0.46			
Diesel	Max	1393	17.44	1.75	12.88	1.01			
21	Min	941	1.94	0.18	7.31	0.19			
Tractor Truck	**Average**	1036	1.31		15.73	0.60			
Diesel	Max	1058	1.44		22.00	1.11			
5	Min	1015	1.06		10.69	0.26			
Truck	**Average**	1296	2.65		11.02	0.51			
Diesel	Max	1370	4.75		12.63	0.58			
6	Min	1221	1.88		9.06	0.46			
Snow Plow	**Average**	1320	2.56	0.75	9.25	0.43			
Diesel	Max	1320	2.56	0.75	9.25	0.43			
1	Min	1320	2.56	0.75	9.25	0.43			
Snow Plow	**Average**	1680	14.17	4.04	7.94	0.32	1.72	0.14	0.71
E100	Max	2584	72.63	10.33	9.25	0.89	3.57	0.55	2.19
10	Min	1279	3.19	2.41	6.88	0.07	0.44	0.05	0.27
Tractor	**Average**	1350	8.60	4.23	7.95	0.18	4.65	0.12	0.54
E95	Max	1582	12.44	4.91	8.63	0.26	5.02	0.14	0.80
6	Min	1141	5.75	3.38	7.19	0.09	4.37	0.09	0.39
Tractor Truck	**Average**	1117	4.91		3.23	0.04			
LNG	Max	1262	7.5		8	0.08			
18	Min	993	4.06		1.94	0.01			

Source: www.afdc.doe.gov/afv/emissions.html. Blanks indicate no data

.

2.3.2 Trucks

The Alternative Fuels Data Centre web site also contains tailpipe emissions data for a range of heavy-duty vehicles that were examined as part of the US Department of Energy alternative fuels program. These vehicles included tractors, garbage trucks, snowplows, and line-haulage trucks. The data are again supplied on the accompanying floppy disk and are also summarised, in Table 2.11 in terms of the average values obtained, as well as the maximum and minimum. Unlike the case of the buses, in which relatively uniform vehicles were examined on the same drive cycle, the vehicles of Table 2.11 comprise a heterogeneous fleet. The type of vehicle and the fuels that were examined are given in Table 2.12.

We have excluded heavy vehicles that were tested in an urban drive cycle (such as garbage trucks) and grouped the data in Table 2.11 in terms of type of vehicle and fuel.

Table 2.12

Vehicle types and fuels used to generate values given in Table 2.11

Fleet Location	Application	Engine Manufacturer	Engine Model	Fuel System
New York City - Dept of Sanitation	Garbage Packers	Cummins	L10-240G	CNG
		Caterpillar	3306	CNG
		Detroit Diesel	Series 60	CNG
Sheldon IA - AG Processing	Line - Haul	Cummins	L10	Bio-diesel
		Detroit Diesel	Series 60	Bio-diesel
		Mack Truck, Inc.	E6	Bio-diesel
Peoria, IL - Archer Daniels Midland	Line - Haul	Detroit Diesel	6V92	Ethanol
			6V92	Diesel
Hennepin County, MN	Snow Plow/Dump Truck	Detroit Diesel	6V92	Ethanol
			6V92	Diesel

2.4 Methodology

Mindful of the fact that a life-cycle estimate of alternative fuel emissions is applicable only within the country in which it is generated we have developed a procedure to generate life-cycle estimates that is sensitive to Australian conditions. Accordingly we have reviewed the situation applicable to each alternative fuel in terms of its use in Australia, and the requirements to extract, transport, process, distribute and use the fuel. The energy used and the emission generated for each of these sub-components have been estimated on the basis of Australian data (if available), or overseas data, if Australian data were not available. The SimaPro4 software was used to model the total life-cycle. The web site at http://simapro.rmit.edu.au/ contains further details about the software.

Where a particular fuel is not used in Australia we have based the calculations on realistic scenarios as to its likely use. Thus, for example, ultra-low sulfur (ULS) diesel is presently not manufactured in Australia. However, assume that Australian refineries producing such ULS diesel, rather than importing it.

Because this study constituted a desk study and literature review, we have estimated the emissions associated with the fuel extraction, production, transport and distribution. We have followed the terminology of the life-cycle assessment community and called all of these stages pre-combustion, whereas the fuel conversion stage is called combustion. The quantitative estimates of the energies and emissions associated with the pre-combustion stage are based on the best estimates that we were able to obtain supplemented by the international data-base held by the RMIT Centre for Design, as part of the Australian Data Inventory Project.

The results of the life-cycle assessment are given in the subsequent chapters that deal with each fuel individually. They are presented as a spreadsheet that gives the pre-combustion and the fuel combustion emissions and also as a flow chart of the greenhouse gas emissions and how they arise in both the combustion and pre-combustion stages.

Chapter 3

Comparative Emissions and Analysis

3.1 Full fuel-cycle emissions

3.1.1 Buses

The life-cycle calculations given for each fuel in Part II have been collated and the results summarised in Table 3.1. There are enough overseas studies that have been done on buses to provide more quantitative indicators for this type of vehicle compared to the other categories.

The comparisons that have been undertaken are based on the values given in Table 2.1, as modified in Table 2.2. We have assumed an engine fuel efficiency equivalent to that of the Euro2 case in Table 2.1 as the reference case. In the calculations it has been assumed that each of the fuels is suitable for such an engine. The data on LNG and biodiesel are taken from Table 2.10, but are normalised (on the basis of the fuel consumption) to be equivalent to the values in Table 2.1.

The fossil-fuel greenhouse gas results are shown in Figure 3.1, and are reproduced in Table 3.2. They indicate that the renewable fuels have substantial greenhouse-gas emissions associated with their pre-combustion phases, but this is more than offset by combustion of non-fossil carbon. Consequently, they have the lowest greenhouse gas emissions. Gaseous fuels are comparable with diesel. LNG appears to have fuel-cycle emissions about the same as diesel fuel with CNG a little less. However, there is considerable uncertainty associated with the estimate of the LNG, and the result is dependent on the assumption made with respect to methane emissions from an LNG bus, about which very little is known. Subsequent sections of this chapter will quantify the uncertainties to enable a ranking to be made that incorporates uncertainties.

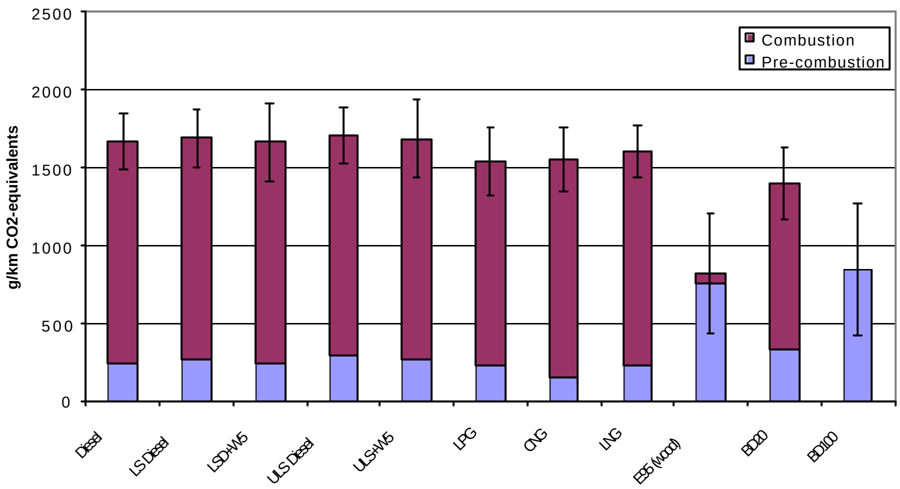


Figure 3.1
Total fossil-fuel greenhouse gas emissions (CO_2 - equivalents) in g/km for buses

Table 3.1

Full fuel-cycle (g/km) emissions for buses

		Diesel	LSD	* LSD+ W5	ULS Diesel	* ULS+ W5	LPG	CNG	LNG	E95 (wood)	BD20	BD100
CO_2	Precombustion	227	246	231	274	249	210	144	234	744	300	708
	Fossil fuel Combustion	1413	1404	1409	1406	1411	1310	1336	1326	73	1050	0
	Total	1640	1650	1640	1680	1660	1520	1480	1560	817	1350	708
	Renewable combustion									1394	262	1306
	Grand total	1640	1650	1640	1680	1660	1520	1480	1560	2211	1612	2004
CH_4	Precombustion	0.69	0.70	0.65	0.73	0.67	0.64	0.26	2.54	0.11	0.48	0.20
	Fossil fuel Combustion	0.02	0.01	0.01	0.01	0.01	0.12	2.50	2.23	0.00	0.00	0.00
	Total	0.71	0.71	0.66	0.74	0.68	0.76	2.76	4.77	0.11	0.48	0.20
	Renewable combustion									0.10	0.00	0.02
	Grand total	0.71	0.71	0.66	0.74	0.68	0.76	2.76	4.77	0.21	0.48	0.22
N_2O	Precombustion	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.08	0.42
	Fossil fuel Combustion	0.04	0.04	0.04	0.04	0.04	0.01	0.02	0.02		0.02	0.00
	Total	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.00	0.10	0.42
	Renewable combustion									0.02	0.005	0.025
	Grand total	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.105	0.445
CO	Precombustion	3.73	3.74	3.5	3.89	3.54	3.45	0.09	2.85	2.00	3.01	3.52
	Combustion	1.88	1.32	1.34	1.41	1.38	0.12	0.66	9.05	14.60	4.28	7.68
	Total	5.61	5.06	4.84	5.30	5.01	3.57	0.75	11.90	16.60	7.29	11.20
NOx	Precombustion	1.10	1.18	1.10	1.28	1.16	1.02	0.63	1.60	0.34	1.19	2.70
	Combustion	15.00	14.72	14.53	14.32	13.80	5.31	9.87	32.50	7.83	23.51	17.20
	Total	16.10	15.90	15.63	15.60	14.96	6.33	10.50	34.10	8.17	24.70	19.90
NMVOC	Precombustion	2.00	2.01	1.87	2.09	1.90	1.85	0.28	2.84	0.38	1.64	2.02
	Combustion	1.10	0.50	0.53	0.52	0.54	0.02	2.75	2.45	4.85	1.05	0.84
	Total	3.10	2.51	2.40	2.61	2.44	1.87	3.03	5.29	5.33	2.69	2.86
Particles	Precombustion	0.16	0.17	0.16	0.26	0.24	0.14	0.01	0.08	0.15	0.25	0.84
	Combustion	0.47	0.22	0.24	0.16	0.17	0.02	0.05	0.01	0.21	0.38	0.60
	Total	0.62	0.39	0.40	0.42	0.41	0.16	0.06	0.09	0.36	0.63	1.44

* Based on a 5% blend of waste oil with the specified fuel. Calculations based on weighting emissions from waste oil by 5% and that from the diesel by 95% except in the case of particulate emissions where calculations are according to Appendix A in the chapter on waste oil.

Table 3.2

Fuel-cycle fossil fuel greenhouse gas emissions (g/km) for urban buses in CO_2-equivalents

	Diesel	LSD	LSD+ W5	ULS	ULS+ W5	LPG	CNG	LNG	E95 (wood)	BD20	BD100
Pre-combustion	245	264	246	293	266	227	149	288	754	335	847
Combustion	1425	1426	1419	1417	1419	1313	1401	1382	73	1065	0
Total	1670	1690	1665	1710	1685	1540	1550	1670	827	1400	847

3.1.2 Heavy vehicles other than buses

We have estimated emissions from heavy vehicles other than buses by using similar data to that used for buses, except that there is better fuel economy due to operation over a highway type cycle more pertinent to long-distance freight operations. The tailpipe emissions of pollutants other than CO_2 are also likely to be less due to less transient engine operation. To enable equivalent calculations to be done for low-sulfur diesel, we re-examined the heavy-vehicle data set, and used the results for California diesel as being representative of low-sulfur diesel. According to the Californian Air Resources Board: (http://www.arb.ca.gov/toxics/diesel/fs/ Equilon/sld007.htm) California diesel contains less than 200 ppm sulfur, and has a cetane number of 53.8.

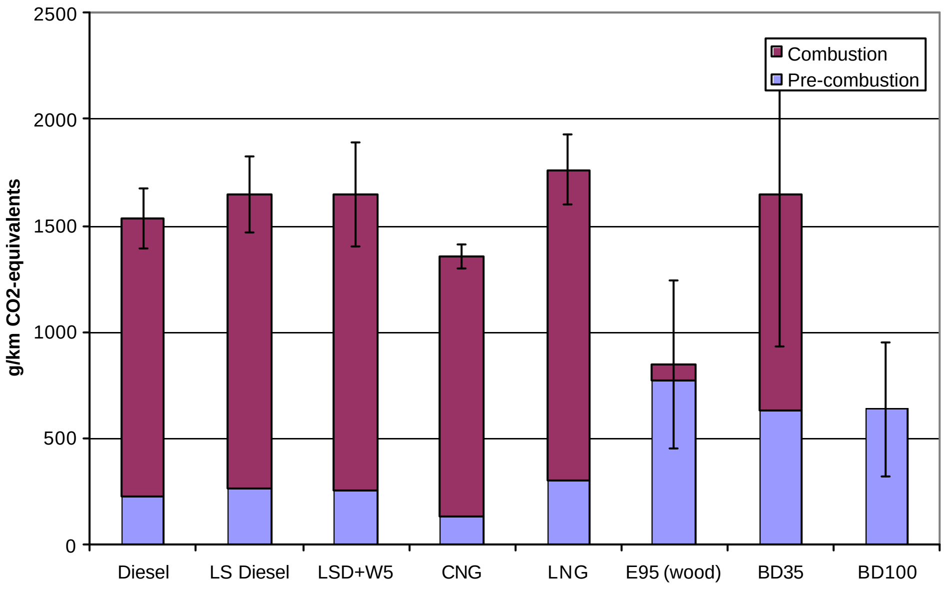


Figure 3.2

Total greenhouse gas emissions (CO_2-equivalents) in g/km for non-bus heavy vehicles

Table 3.3

Greenhouse and air pollutant emissions (g/km) for non-bus heavy vehicles

Trucks		Diesel	LSD	* LSD+W5	CNG	LNG	E95 (wood)	BD35	BD100
CO_2	Precombustion	208	242	241	125	247	768	587	512
	Foss.Comb	1296	1379	1376	1164	1397	76	1008	0
	Total	1504	1621	1617	1289	1644	844	1595	512
	RenewCom						1439	542	1189
	Total	1504	1619	1617	1289	1644	2283	2137	1834
CH_4	Precombustion	0.635	0.687	0.685	0.223	2.7	0.12	0.563	0.178
	Foss.Comb	0.025	0.01	0.011	2.5	2.5	0.005	0.001	
	Total	0.66	0.697	0.696	2.723	5.2	0.125	0.564	0.178
	RenewCom						0.1		0.018
	Total	0.76	0.694	0.66	2.756	5.2	0.225	0.564	0.196
N_2O	Precombustion	0.012	0.011	0.011	0.000	0.001	0.002	0.097	0.38
	Foss.Comb	0.025	0.025	0.025	0.025	0.025	0.001	0.016	
	Total	0.037	0.036	0.036	0.025	0.026	0.003	0.113	0.38
	RenewCom						0.023	0.008	0.025
	Total	0.037	0.036	0.036	0.025	0.026	0.027	0.122	0.405
CO	Precombustion	3.42	3.66	3.66	0.09	3.03	2.12	3.56	3.21
	Combustion	2.98	4.49	4.41	14.89	6.14	9.65	3.09	6.52
	Total	6.40	8.15	8.07	14.98	9.17	11.77	6.65	9.73
NOx	Precombustion	1.01	1.15	1.15	0.55	1.7	0.36	1.41	2.46
	Combustion	12.89	10.14	16.08	8.03	4.04	8.92	14.22	10.51
	Total	13.90	11.29	17.23	8.58	5.74	9.28	15.63	12.97
NMVOC	Precombustion	2.12	1.96	1.97	0.28	2.99	0.40	1.94	1.84
	Combustion	0.82	0.49	0.51	0.25	0.25	4.74	0.80	0.79
	Total	2.94	2.45	2.48	0.53	3.24	5.14	2.74	2.63
Particles	Precombustion	0.165	0.165	0.165	0.0122	0.087	0.164	0.312	0.767
	Combustion	0.55	0.56	0.57	0.35	0.05	0.2	0.41	0.5
	Total	0.715	0.725	0.735	0.3622	0.137	0.364	0.722	1.27

* Based on a 5% blend of waste oil with the specified fuel. Calculations based on weighting emissions from waste oil by 5% and that from the diesel by 95% except in the case of particulate emissions where calculations are according to Appendix A in the chapter on waste oil. Waste oil precombustion and combustion emissions obtained from Tables 3 and 1 in the chapter on waste oil.

Table 3.4

Fuel-cycle fossil fuel greenhouse gas emissions (g/km) for heavy vehicles in CO_2-equivalents

	Diesel	LSD	LSD+ W5	CNG	LNG	E95 (wood)	BD35	BD100
Pre-combustion	225	260	259	130	304	771	629	634
Combustion	1304	1387	1384	1224	1457	76	1013	0
Total	1529	1647	1643	1354	1761	848	1642	634

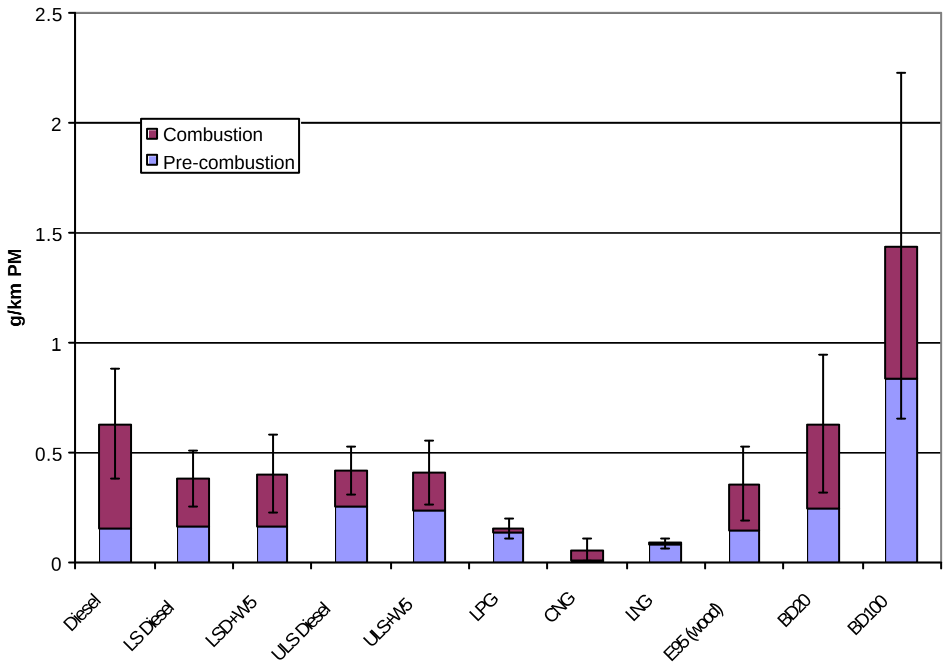


Figure 3.3

Particulate matter emissions (g/km) for urban buses

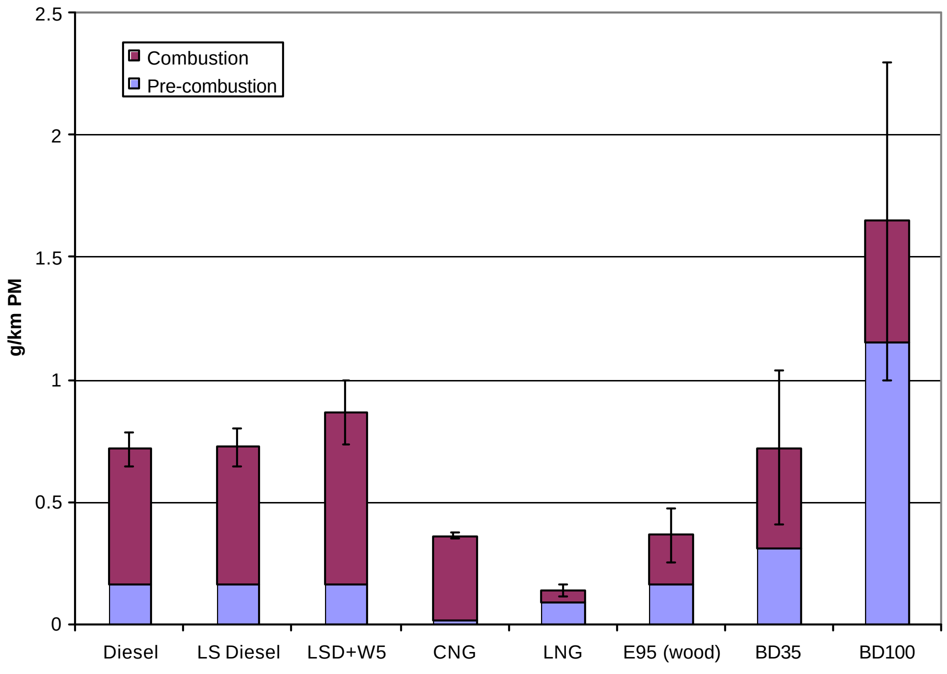


Figure 3.4

Particulate matter emissions (g/km) for non-bus heavy vehicles

The method that was used to estimate the values for the non-bus heavy vehicles was to use the data of Table 2.9, normalised to the diesel truck data for CO_2 (1296 g/km). Thus, for example, as a diesel tractor emits 1155 g CO_2/km, all tractor readings were multiplied by a factor of 1296/1155. Similar considerations apply for the other fuels. After this procedure, all the results for the vehicles that used the same fuels were averaged.

3.2 Full-life-cycle Emissions

The calculations that have been undertaken to date have examined the fuel-cycle in terms of the energy expended, and the greenhouse gases and air pollutants emitted as a result of the extraction, transport and refining of oil, and the production, transport, and conversion of renewable fuels.

We have omitted the emissions related to vehicle manufacture, maintenance and disposal, and road building because they are not likely to vary significantly with the nature of the fuel used. Representative estimates are given by Lenzen (1999) and have been reproduced in Table 2.5.

The infrastructure associated with refuelling will, however, vary with the different alternative fuels, but a proper analysis of the life-cycle emissions resulting from differences in infrastructure that will be needed to install new distribution and fuelling systems, as opposed to using the existing diesel fuelling system, are beyond the scope of this report. The reason for this is that two possible approaches can be taken and it is not clear how to determine the base-lines for greenhouse gas calculations. The traditional life-cycle analysis would compare both existing and new infrastructure on a cradle-to-grave basis in which case the emissions associated with both the diesel infrastructure and any requisite new infrastructure are subject to comparison.

An alternative approach focuses attention on the Kyoto Protocol, which requires Australia to meet greenhouse gas emission targets based on the year 1990. Thus any greenhouse gas emissions that were undertaken before the year 1990 have been completely discounted, whereas the greenhouse gas emissions involved in the construction of any new alternative fuels infrastructure, no matter how climate-friendly the resulting technology, may make it harder for Australia to meet the Kyoto commitments. Accordingly, we have not attempted to provide quantitative estimates of the infrastructure components.

3.3 Uncertainty analysis

We have used the range of estimates for tailpipe emissions, shown in Tables 2.6 and 2.7. We have assumed that the maximum and minimum values correspond to the 100/*N*th and the 100-(100/*N*)th percentiles, where N is the number of data points. If the data points are normally distributed then the standard deviation, s, is given by

$$s = R / f \quad (1)$$

where R is the range, namely, the difference between the maximum value and the minimum value and f is determined from the area under the normal curve. We have calculated the uncertainty, U, of the tailpipe emissions using

$$U = s / X \quad (2)$$

where X is the mean value of the quantity. Further details are given in Appendix 2.

3.3.1 Buses

The uncertainties, as given in Equation 2, have been tabulated for buses in Table 3.5.

Table 3.5

Uncertainties (in percent) of tailpipe emissions for buses

Fuel	*N*	*f*	CO	THC	NOx	PM	CO_2
BD	11	2.7	37	15	38	61	7
BD20	8	2.3	55		36	50	6
CNG	90	4.6	22	136	72	108	12
Diesel	73	4.4	78	17	27	50	11
E93	6	1.9	66		26	45	7
E95	47	4.0	46	73	35	46	13
LNG	22	3.4	106	11	28	46	8

The smallest uncertainties are associated with CO_2 emissions. This is to be expected because CO_2 can be estimated from fuel usage, which is determined by the engine technology and the mechanical energy required to accomplish the test cycle. The other emissions are trace, unwanted side products. In general, the lowest uncertainties are associated with THC and NOx emissions, and the highest with CO and particulate emissions. The large uncertainties associated with air pollutant emissions from CNG are particularly noticeable. As this fuel is in widespread use in Australian bus fleets, it appears that further analysis is required to reduce the uncertainties associated with CNG emissions and hence enable a more accurate assessment of their air pollution potential.

3.3.2 Heavy vehicles other than buses

The uncertainties, as given in Equation 2, have been tabulated for heavy vehicles other than buses in Table 3.6.

Table 3.6

Uncertainties (in percent) of tailpipe emissions for heavy vehicles other than buses

Fuel	*N*	*f*	CO	THC	NOx	PM	CO_2
BD	8	2.3	106	71	23	81	15
BD35	12	2.8	49		35	54	39
CNG	7	2.2	11		29	17	2
Diesel	33	3.8	144	50	30	39	9
E95	6	1.9	36	17	8	45	15
LNG	18	3.2	18		47	48	6
LSD	8	2.3	80		9	84	11

3.4 Other greenhouse gases and smoke

Emissions of sulfur hexafluoride are associated only with the manufacture of magnesium. Similarly, perfluorocarbons are associated only with the manufacture of aluminium. The amount of magnesium and aluminium in heavy vehicles is so small that this source of greenhouse gases has been estimated as being negligibly small despite their very high GWP factors.

Hydrofluorocarbons are associated with automobile air conditioning. These are closed systems and thus there should be no emissions from hydrofluorocarbons in relation to heavy vehicle usage.

Sulfur dioxide has not been considered in this review because it is not an air pollutant of concern in Australian cities. Emissions of sulfur dioxide from vehicles is proportional to the amount of sulfur in the fuel, and if the existing 1500 ppm diesel is replaced by 500 ppm diesel then sulfur dioxide emissions will be reduced to one-third of present levels. The alternative fuels that were considered contain no sulfur and hence have no sulfur dioxide emissions.

We have found it difficult to obtain quantitative estimates of smoke emitted from heavy vehicles using either conventional or alternative fuels. Watkins (1991) points out that smoke is defined as suspended particulate air pollutants, with a diameter of less than 15 µm, arising from the incomplete combustion of fossil fuels. As most diesel particles have sizes that are less than 1 µm in diameter, the estimates of PM have been used as a surrogate for smoke.

3.5 Eco-indicators

The international agreement on the use of the GWP as a weighting factor for different greenhouse gases means that it is straightforward to calculate the greenhouse gas emissions in CO_2-equivalents, and this measure can be used to compare the greenhouse gas emissions performance of different alternative fuels. There is no similar agreement in relation to the other gases that we have considered, which fall under the general category of air pollutants.

On a life-cycle basis, the renewable fuels such as ethanol and biodiesel indicate lower greenhouse gas emissions than conventional diesel, or gaseous fuels because the combustion of the non-fossil fuel is not counted for greenhouse gas inventory purposes, and the pre-combustion emissions, which do use fossil fuel, are substantially less than the total emissions of the fossil fuels. Nevertheless, it must be acknowledged that there are very large uncertainties associated with the analysis of the gaseous fuels. The uncertainties in the tailpipe emissions have already been quantified in Tables 3.4 and 3.5, but there are equally large, if not larger, uncertainties associated with the pre-combustion emissions. The possibility of fugitive methane emissions during the transport and distribution of natural gas is the source of the large uncertainty associated with CNG and LNG.

Emissions of carbon monoxide do not cause problems in Australia, so that we believe that it does not need to be considered in evaluating alternative fuels. NOx and THC together are important because they are the precursor chemicals that are the ingredients of smog. Particulate matter is of concern because of the epidemiological evidence that particulate matter has short term and long term health effects, including mortality such that a 10 $\mu g/m^3$ increase in PM10 is associated with a 1% increase in mortality.

These air pollution and health considerations indicate that we should really consider heavy vehicles in two classes – those used primarily in urban areas (e.g. buses), and those used primarily in rural areas (e.g. trucks). Urban vehicles need to have low emissions of NOx, THC and particulate matter. However, as smog is not a problem in rural areas, the THC and NOx levels of emission are not as important as the particulate emissions. This is especially the case as the NEPM for Ambient Air Quality seeks equal protection for all Australians. Though it may be argued that rural particulate emissions are not important because of the occurrence of natural dust, there are theories that health effects arising from inhalation of particulate matter arise only when carbonaceous particles, such as those from combustion, are inhaled. Accordingly we recommend that rural and highway air quality evaluation include particles, particularly as many small country towns sit aside major transport routes.

On this basis we note that the gaseous fuels, CNG, LNG and LPG perform particularly well. They have very low particulate emissions, and their THC and NOx emissions are comparable with other fuels. Nevertheless, the uncertainties associated with CNG and LNG are large, as shown in Tables 3.4 and 3.5.

Other eco-indicators are discussed in Appendix 5.

3.6 Ranking (including uncertainty)

The output of this study is to be a ranking of the fuels in terms of their greenhouse gas and air quality aspects, for both city driving, and highway driving conditions. We believe that any ranking method that is used must take into account the uncertainties associated with the data. Accordingly, we have devised a ranking scheme that incorporates uncertainty, which is described in the following paragraph, and in Appendix 3.

We rank the emissions according to their average characteristics in terms of global warming and pollution impact, and assign each gas as a score its rank value. We then rank the gases for one standard deviation above and below their average emissions and again score them. The three scores are summed, and the final ranking is based on this sum.

We have used the bus data as representative of city driving, and the truck data as representative of highway driving. The standard deviations for the combustion mode are assigned on the basis of the results derived in Tables 3.5 and 3.6. The standard deviations for the pre-combustion modes are assigned on the basis of our expert judgement. Thus for existing and known technology, such as that of diesel fuels, we have assigned a 10% uncertainty. For gaseous fuels we have assigned 25% uncertainties, and for renewable fuels we have assigned 50% uncertainties.

This method is straightforward when calculating the rankings on the basis of greenhouse gases (expressed in CO_2-equivalents) and produces the results in Table 3.7 However, some caution should be exercised as the uncertainties used in producing these rankings, that magnify the differences in emissions as portrayed in Figure 3.1, may be related to the vehicles rather than the fuel.

Table 3.7

Fuel ranking in relation to greenhouse gases;
the lowest value denotes the lowest greenhouse gas emissions

Fuel	CityGHG Score	CityGHG Rank	HwyGHG Score	HwyGHG Rank
Diesel	24	**8**	13	**4**
LSD	28	**10**	20	**7**
LSD+W5	23	**7**	17	**6**
ULS	31	**11**		
ULS+W5	27	**9**		
LPG	12	**4**		
CNG	15	**5**	10	**3**
LNG	20	**6**	23	**8**
E95	4	**1**	6	**2**
BD20/35	9	**3**	16	**5**
BD100	5	**2**	3	**1**

+W5 denotes the use of 5% waste oil   Blanks indicate no data

In relation to air quality, the ranking was less straightforward. Because of the concern for human health and well being, particulate matter is believed to pose the greatest health risk. Hydrocarbons pose a health risk in the long term, as a number of compounds are carcinogenic. In addition hydrocarbons are one of the precursors for the formation of ozone, and reductions in hydrocarbon are the most effective way of reducing ozone. Oxides of nitrogen are also ozone precursors, and NO_2 poses a health risk at high concentrations (which are rarely found in Australian cities). Finally, carbon monoxide poses a health risk at concentrations that do not occur in Australia.

It was thus decided to weight the air pollutants on the basis of their health risk.

Air Pollution Health Risk

The NEPM for Ambient Air Quality (National Environment Protection Council, 1998) provides estimates of the short-term health effects of the criteria pollutants.

CO – Loss of 1 day's earning for 50,000 people at a cost of $6M. (National Environment Protection Council, 1998: p.52)

NO_2 – 10 to 15% of the population display respiratory symptoms at a cost of $5 million. (National Environment Protection Council, 1998: p. 61)

O_3 – Up to 10 deaths per year in Australia, with total costs up to $810 million. (National Environment Protection Council, 1998: p.75-76)

PM - Up to 2,400 deaths per year in Australia, with an associated health cost of $17.2 billion. (National Environment Protection Council, 1998: pp.122 & 127)

In the absence of more detailed information, the health effects related to ozone (O_3) are ascribed equally to NOx and hydrocarbons. (National Environment Protection Council, 1998: p. 78)

In addition, hydrocarbons have long-term health effects that have been examined by Hearn (1998) for Melbourne. If we extrapolate his figures to all of Australia then there are approximately 1250 to 1785 deaths per annum as a result of hydrocarbons (excluding deaths ascribed to the particulate matter in the hydrocarbons).

The main health risk for Australians arises from particulate matter and from hydrocarbons. Given the considerable uncertainties associated with these estimates of mortality, and the costs of morbidity, we have developed health risk weighted air quality rankings as follows:

The summed score for particulate matter was multiplied by 2, the summed score for hydrocarbons was multiplied by 1, the summed score for NOx was multiplied by 0, and the summed score for carbon monoxide was multiplied by 0, and the totals added together to produce a final air quality score, as shown in Table 3.8.

Table 3.8

Fuel scores and final ranking in relation to air quality; the lowest value denotes the lowest emissions

Fuel	CityPM	CityHC	CityNOx	CityAQ	CityAQ	HwyPM	HwyHC	HwyNOx	HwyAQ	HwyAQ
	weight=2	weight=1	weight=0	Score	**Rank**	weight=2	weight=1	weight=0	Score	**Rank**
Diesel	28	25	24	81	**10**	14	17	17	45	**5**
LSD	15	15	20	45	**4**	16	10	15	42	**4**
LSD+W5	21	10	19	52	**5**	20	11	24	51	**7**
ULS	18	19	14	55	**7**					
ULS+W5	21	14	13	56	**8**					
LPG	9	4	4	22	**1**					
CNG	3	18	7	24	**2**	7	3	7	17	**1**
LNG	6	32	33	44	**3**	3	18	3	24	**2**
E95	15	24	7	54	**6**	8	24	8	40	**3**
BD20/35	29	17	30	75	**9**	16	14	20	46	**6**
BD100	33	20	27	86	**11**	24	11	14	59	**8**

3.6.1 Overall Ranking

On the basis of greenhouse gas considerations, the renewable fuels, ethanol and biodiesel – either in the form of canola, or as an esterified biofuel - are the lowest emitters because they combust non-fossil fuels. This is true for both city and highway driving. Of the fossil fuels, LPG was the lowest greenhouse gas emitter for the city cycle, whereas for the highway cycle (for which LPG data were not found), CNG was the lowest emitter and came second to biodiesel.

With respect to air quality considerations, the gaseous fuels – LPG, CNG and LNG – are the lowest emitters, primarily because their particle emissions are low. We were unable to obtain sufficient data on LPG to determine whether this is true for both city and highway driving. However, LPG was the lowest emitter under a city drive cycle, and CNG was the second lowest. Under highway conditions, for which we lacked LPG information, CNG was the lowest emitter. It is also worth noting that because of its large particle emissions, biodiesel is the worst fuel in relation to air quality for both city and highway driving.

3.7 Discussion

It is difficult to compare and rank "like-with-like" when examining the emissions (in grams emitted per kilometre travelled) from different fuels. In the case of LPG, few heavy vehicles use it so that data concerning its emissions are scarce. In the case of other fuels it is rare for individual studies to have examined similar engines using similar pollution control equipment. This means that there is extreme variability in the available emissions data, and it is possible to produce misleading comparisons where the best result from one fuel is compared to the worst result from another fuel. We have, wherever possible, used a statistical approach to try to minimise such problems.

Nevertheless, there are certain situations in which it is very difficult to obtain a statistically significant population of emission data. We have already mentioned that LPG data are scarce. As pointed out in Chapter 6, two technologies can be adopted for LPG engines, lean burn, or stoichiometry, but we have emission results only for the latter.

In an analogous situation pure canola oil can be used in an unmodified diesel engine, but the performance is sub-optimum. To improve performance, one can either modify the engine, or modify the fuel. The latter approach is the one most commonly adopted, so that there are more data available on biodiesel emission than on emissions from vehicles using pure vegetable oils. In fact, we could find no data on emissions from heavy vehicles using canola, though there are data on emissions from the closely related rapeseed oil. However, the results that we have used for the quantitative evaluation and rankings were all based on soy-biodiesel.

There are also data gaps in relation to emissions from light heavy-duty vehicles. Emissions from buses have been extensively studies. To a lesser degree, emissions from trucks have also been studied. Studies that report on alternative fuels and their emissions from light heavy-duty vehicles are scarce, and are only now starting to appear in the literature (Durbin et al. 2000).

It is also possible to reduce air pollutant emissions, from vehicles by incorporating increasingly sophisticated emission control devices. Thus, it may be argued, that the high particle emissions from biodiesel are not representative, because more sophisticated emission control devices would be installed if biodiesel were to become a commonly used fuel. This study has compared alternative fuels used with current emission technologies. Future emission technologies seek to reduce particulate matter emissions. Diesel vehicles can greatly reduce their particle emissions through the installation of particulate traps, but these can only be used with ultra-low sulfur fuels. This means that:

i) the attainment of Euro4 emission standards for diesel vehicles is tied to the reduction of sulfur in the diesel fuels,

ii) the results of this study are unlikely to be valid after three years, because by that time there will be a widespread adoption of the Euro3 standard in Australia, and the Euro4 standards overseas. We also assume that substantial new vehicle technologies will develop over the next three years.

The statistical approach that we have adopted in this report has used tailpipe emissions data from a heterogeneous vehicle fleet in terms of their emission control technology. Some of the buses whose results are summarised in Table 2.10 were fitted with catalytic converters. Some were not. Some were fitted with diesel particulate traps. Most were not. The data needed to examine the effects of such emission technologies are available on the web from the Alternative Fuels Data Centre web site.

During the course of this study, it was noted that the final results were particularly sensitive to some of the assumptions made. In particular:

- We have assumed CNG and LNG are compressed using gas. If it is assumed that electricity is used then the life-cycle emissions of greenhouse gases from CNG and LNG exceed those of diesel.
- We have assumed that LNG is shipped in sea-going vessels using gas, whereas CNG is piped. If diesel powered ships are used then substantial particulate matter is emitted, and the life-cycle air quality aspects of LNG are substantially reduced.
- Fugitive emissions from filling and servicing of CNG and LNG have been incorporated into the analysis. However, no allowance was made for possible fugitive emissions as a result of leakage from reticulated gas supplies.
- The high methane emissions from LNG pre-combustion assume LNG "boil-off" when the evaporated fuel is vented.
- We have assumed that the ethanol to be used in heavy vehicles is derived from wood as this method offers the only possibility for the widespread economic production of ethanol.

- Biodiesel results are based on soy-biodiesel. The single study that compares canola-biodiesel with soy-biodiesel (Spataru and Romig, 1995) indicates that canola-biodiesel has lower greenhouse gas emissions, but comparable air quality emissions.
- We have assumed LPG production requires similar energy to the production of diesel. Some studies treat LPG to be a "free" by-product of diesel refining and ignore its production energy.

A number of observations also became evident.

1. The emissions of the Australian heavy-duty vehicle fleet are not well represented in available data. Those data that exist are often default data, such as those in the National Greenhouse Gas Inventory. Current studies should partly correct this situation.
2. It is of concern that top-down estimates of heavy-duty vehicle emissions, such as those of Apelbaum (1997) and Lenzen (1999), do not agree with bottom-up estimates. We have not had sufficient time to determine the reason for the discrepancy. Current IPCC guidelines for good practice in the generation of greenhouse gas inventories require the implementation of both top-down and bottom-up estimates wherever possible. The topic is therefore an important one, but should be examined over a three year time scale.
3. The data that we have used are based on a number of different drive cycles: the US - CBD cycle, the US - 5 peak truck cycle, and the London transport urban inner London cycle. None of these approximates the CUEDC drive cycle proposed for the diesel NEPM.
4. The criteria that are used to determine and rank emissions have changed drastically over the years as Australian urban air quality improves and pollutants that were once serious, and thus required regulation, have diminished in concentration. We advocate that a regular re-analysis of Australian emissions be undertaken after three years to determine whether the criteria used in this report remain valid.
5. There are few published data on emissions from light heavy-duty vehicles, or from articulated vehicles.

3.8 Recommendations

1. Biodiesel fuels are the lowest greenhouse gas emitters. We recommend that the information that has been collected on biodiesel be documented in a separate report that incorporates a quantitative uncertainty analysis. This is particularly relevant for the Australian context because of the perceived discrepancy between the US and the European estimates of life-cycle energy usage in the production of biodiesel.
2. We recommend that emission testing on imported biodiesel used in Australian vehicles be conducted. In particular, whether its use in Australian vehicles is accompanied by the large particulate emissions observed during its use elsewhere.
3. LPG has not been a serious contender for use with heavy vehicles, but it looks very good on greenhouse gas and air pollution criteria. There appears to be a lack of data on emissions from LPG trucks under highway conditions. We recommend that this data gap be addressed.
4. There are considerable uncertainties associated with the emissions of methane and non-methanic hydrocarbons from CNG and from LNG. In addition, there is a lack of data on actual methane and nitrous oxide from heavy vehicles. Because there are numerous CNG buses in operation in Australian cities, we recommend that a program of testing be undertaken to determine the factors responsible for the emission of methane, nitrous oxide and non-methanic hydrocarbons from CNG buses. During such testing the effect of exhaust catalysts needs to be determined as these increase some unregulated emissions.
5. The apparent decrease in CO_2 emissions quoted by the Expert Reference Group when low sulfur diesel and ULS is used does not appear to agree with US results. As CO_2 emissions are related to fuel economy we recommend that three identical vehicles, one using diesel, one using LSD and one using ULS be tested over an identical route and their relative fuel economies and CO_2 emission determined.
6. It is of concern that top-down estimates of heavy-duty vehicle emisisons, such as those of Apelbaum (1997) and Linzen (1999), do not agree with bottom-up estimtes. Identifying the cause of this discrepancy is important and we recommend that this be done through the award of a post-doctoral fellowship.
7. We recommend that this study be repeated after three years. There are rapid technological developments taking place in heavy vehicle emission controls and in heavy-vehicle, fuel specifications and we expect that the emission characteristics of vehicles in three years time will differ substantially from those of the current fleet.
8. This study has concentrated on emissions from alternative fuels. We recommend that a separate study be commissioned to examine heavy-vehicle emission-control technologies on individual fuels.
9. The use of waste oil blended into diesel offers a slight reduction in greenhouse gases, but leads to increased air pollution. The most favorable use of waste oil is as recycled lubricating oil.

Part 2

Fuels

Chapter 4

Diesel

4.1 Background

Diesel fuel is produced from the distillation of crude oil to produce light virgin gas oil, which then becomes diesel fuel as the final product. The distillation is conducted in Australian refineries. Table 3.1 is reproduced from the fuel quality review document (http://www.environment.gov.au/epg/fuel/review.rtf) produced by the Environment Protection Group of Environment Australia.

Table 4.1

Australian Refineries: 1997 Average Pool Qualities of Diesel[1]

Company	All	Caltex		BP		Mobil		Shell	
Refinery Location	Aust Avg.	Lytn. QLD	Kurn NSW	Bulw QLD	Kwin WA	Altona VIC	S'vac SA	Geel VIC	Clyde NSW
On-road Diesel :									
Production M.tpa	1.27	1.4	1.2	0.9	2.1	1.2	0.8	1.6	1.1
Sulfur ppm	1500	380	1400	2100	2100	1000	900	1600	2200
Cetane Index	51.1	50.2	50.0	50.4	49.5	51.9	58.8	48.6	51.0
PAH % m	3.5	n/a	n/a	2.2	4.0	n/a	n/a	n/a	n/a
T-95 deg.C	349	339	343	n/a	n/a	357	366	n/a	n/a
Viscosity, 40 °C, mm^2/s	3.2	3.1	3.2	n/a	1.9	3.2	3.2	2.9	3.5
Density kg/m^3	847	843	852	842	845	847	835	850	855

1: AIP (1997).
Aust avg: Australian average
Lytn: Lytton
Kurn: Kurnell
Bulw: Bulwer
Kwin: Kwinana
S'vac: Port Stanvac
Geel: Geelong

Diesel fuel currently has a sulfur content that averages 1500 ppm, although there are substantial regional variations.

Greenhouse gas emission factors for diesel fuel may be found in Workbook 3.1 on transport of the Australian Greenhouse Gas Inventory methodology (National Greenhouse Gas Inventory Committee, 1998)

CO_2 emission factor 69.7 g/MJ
SO_2 emission factor 0.116 g/MJ
Energy density 38.6 MJ/L,

whereas, for other emissions, the default emission factors are as given in Table 4.2.

Table 4.2

Emission factors for diesel vehicles expressed as g/km

Vehicle	CH_4	N_2O	NOx	CO	NMVOC
Light trucks	0.01	0.014	1.18	1.11	0.53
Medium trucks	0.02	0.017	3.1	1.82	0.99
Heavy trucks	0.07	0.025	15.29	7.86	3.78
Buses	0.03	0.025	4.9	2.88	1.56

Source: National Greenhouse Gas Inventory Committee (1998)

The NSW EPA (Brown et al. 1999) conducted tests on nine diesel-powered heavy vehicles using both ordinary and low sulfur diesel.

Particle sizes

According to Eldering & Cass (1996) all of the particles emitted by a diesel engine are less than 10 µm in diameter, with virtually all particles being below 1 µm in diameter. They suggest that appropriate ratios of PM1:PM2.5:PM10 for emissions from diesel engines are 12.8:13.4:14.1.

4.2 Life-cycle Analysis of Diesel

Apelbaum (1997) claims an energy performance of 12.89 MJ/km (2.99 km/L) for a diesel bus under urban conditions. In the light of the CO_2 emissions measured in the US and the UK, and in the light of the discussion in Chapter 2, this figure appears to be too low. Our work has been conducted on the basis of 27 MJ/km, (1.43 km/L) based on the estimated CO_2 emissions from the current Perth bus fleet as quoted in Table 2.1. We have then used these figures to calculate the fuel-cycle emissions of a typical Perth bus, along with the revised emissions in Table 2.2. The results are given in Table 4.3

Table 4.3

Fuel-cycle emissions (in g/km) of an average Perth diesel bus

Class	Fuel Production	Combustion	Total
CO_2	227	1,413	1,640
CH_4	0.69	0.02	0.71
N_2O	0.01	0.04	0.05
CO	3.73	1.88	5.61
NOx	1.10	15.00	16.10
NMVOC	2.00	1.10	3.10
Particles	0.155	0.469	0.624

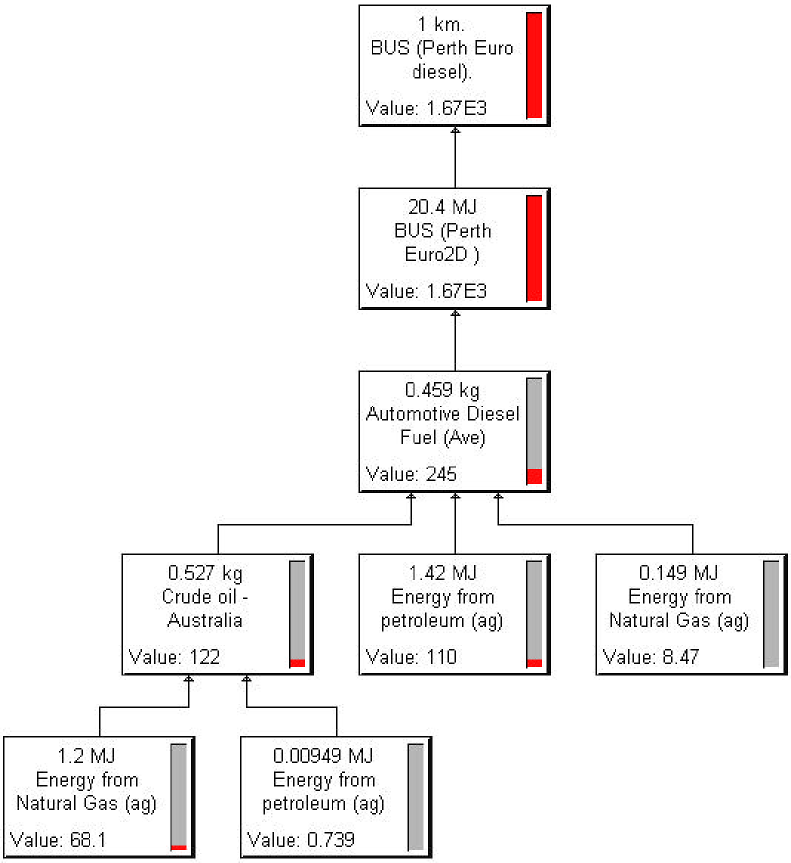


Figure 4.1

Value = grams CO_2 eq

Process tree of estimated CO_2 equivalent emissions per kilometre from the existing Perth diesel bus fleet

Figure 4.1 illustrates the flow chart used to arrive at the pre-combustion values. The pre-combustion emissions include the production and extraction of crude oil, transport to refinery, and refinery processing. These data have been extracted from interim data of the Australian Data Inventory Project being co-ordinated by the Centre for Design at RMIT. The process tree shows the value (in g CO_2) for the emissions of the fuel specified in the box. The value at the top of the box is the quantity of the fuel that is consumed at that stage of the tree.

To interpret Figure 4.1, we start at the top of the tree and note that the value ($1.67x\ 10^3$) refers to a final quantity of 1 km as specified at the top of the box. The value in this case, is grams of CO_2-equivalent. To travel this 1 km requires the expenditure of 20.4 MJ, as shown at the top of the second box down. The bottom of this box shows that 1670 grams of CO_2-equivalent are emitted in producing this 20.4 MJ.

The third box down refers to the diesel fuel before it is combusted. It constitutes 0.459 kg of fuel. To produce this fuel, 245 gram of CO_2-equivalent have been emitted. This is shown as a value in the bottom of the box, but is also pictorially represented by the bar on the right, which is filled to 245/1670 of its length.

The 0.459 kg of diesel requires for its production 0.527 kg of crude oil, 1.42 MJ of energy from petroleum, and 0.149 MJ of energy from natural gas as depicted by the three boxes in the fourth row. The respective CO_2 -equivalent emissions (122 g, 110 g, 8g) are also given.

Finally, the production of 0.527 kg of crude oil requires 1.2 MJ of energy from natural gas and 0.095 MJ energy from petroleum.

4.3 Conventional Low Sulfur Diesel and Ultra-Low Sulfur Diesel

Low sulfur diesel is diesel fuel that is below 500 ppm. This is slightly above the Euro3 specifications, which require sulfur to be below 350 ppm, the cetane index to be above 46, and the density to be below 845 kg/m^3. The Caltex refinery in Lytton, Queensland was recently commissioned to produce low sulfur diesel fuel (Sanders, 1999). To be able to produce low sulfur diesel, most Australian refineries need to treat the fuel through a hydro-desulfurization process (Davies, 1999).

Ultra-low sulfur diesel meets Euro4 specifications that require sulfur to be below 50 ppm. To accomplish this most Australian refineries need to treat the fuel through a hydro-cracker. Barnes (1999) estimates that the weighted average cost of upgrading Australian refineries to produce Euro4 diesel will add 1.5 cents per litre to the base cost of diesel fuels. Diesel in Victoria retails presently at 81 cents per litre, which includes an excise duty of 43.355 cents (Parliamentary Library, 1999), although 35.027 cents per litre rebate is available for diesel used in primary production.

In Europe there is an even lower sulfur diesel fuel available known as Citydiesel (see www.greenergy.com/products/faq.html). The Citydiesel concept was originally developed in Sweden in 1989. Today Citydiesel accounts for more than 95% of the market in Sweden and other Nordic countries. Table 4.4 gives the properties of Citydiesel.

Table 4.4

Comparison of Citydiesel and Low Sulfur Diesel

Specification	Unit	Low sulfur Diesel	Citydiesel	Principal effect
Poly Aromatic Compounds	Volume%	> 1.5	Trace	Reduced particulates
Sulfur	ppm wt	500	10	Reduced acid rain and particulate matter
Cetane Index		50	54	Increased combustion efficiency, reduced emissions
Aromatics	Volume%	> 30	< 15	Reduced toxicity
Final Boiling Point of Fuel	degreesC	> 370	310	Reduced visible smoke

Source: www.greenergy.com/products/faq.html

4.4 *Life-cycles of Low and Ultra-Low Sulfur Diesel.*

Modelling studies are presently underway to estimate life-cycle emissions as a result of improved fuel quality, tighter emission controls on petrol and diesel vehicles, and a lower growth in transportation as the Kyoto Protocol commitments are met. Preliminary results of these studies were reported by Best (1999) and indicate declines in air pollutant emissions, primarily because of the tighter emission controls on petrol-driven vehicles. Final results may be found at: www.environment.gov.au/epg/fuel/

Although diesel vehicles will reduce their emissions of sulfur dioxide when using low and ultra-low sulfur fuels, the increased processing at the refinery indicates that the life-cycle greenhouse gas emissions are liable to increase. The fuel economy estimates are conflicting. Best (1999) indicates that the Cetane Index will decrease in going from Australian diesel to Australian LSD (from 51 to 46) but then increases to a value of 52 in going to ULS. It is therefore difficult to see how the results depicted in Table 2.1 can indicate a 10% increase in fuel efficiency when LSD is substituted for diesel in a Euro2 engine. Nevertheless, in the absence of other data, we have used the results shown in Table 2.1 in our fuel-cycle estimates.

The pre-combustion estimates for LSD and ULS emissions have been based on the assumption that existing Australian refineries will need to install a hydro-desulfurization unit to produce LSD, and a hydro-cracker to produce ULS. Thus the extra emissions are associated with running these units. Tables 4.3 and 4.6 give the life-cycle emission results.

Table 4.5

Low Sulfur Diesel Bus – emissions in g/km

Class	Fuel Production	Combustion	Total
CO_2	246	1,404	1,650
CH_4	0.70	0.01	0.71
N_2O	0.01	0.04	0.05
CO	3.74	1.32	5.06
NOx	1.18	14.72	15.90
NMVOC	2.01	0.50	2.51
Particles	0.169	0.224	0.393

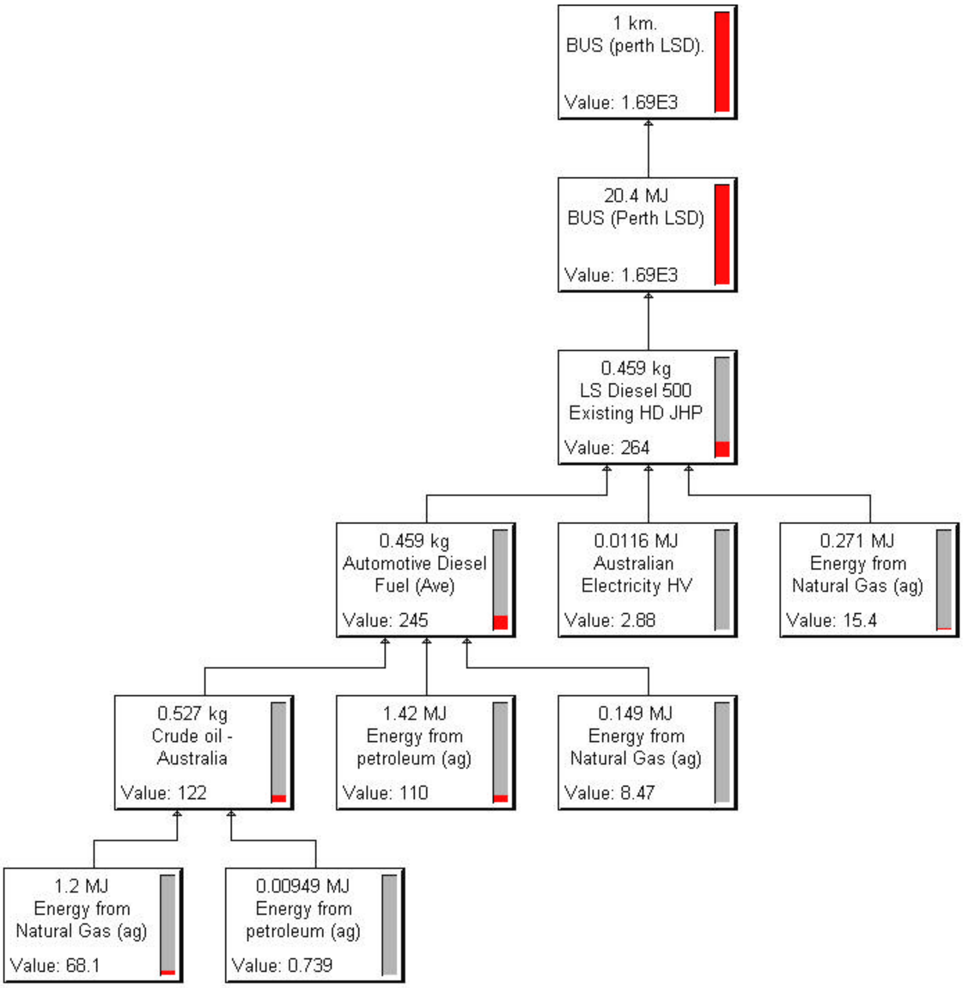


Figure 4.2

Value = grams CO_2 eq

Process tree of estimated CO_2 equivalent emissions per kilometre from low sulfur diesel (LSD)

Table 4.6

Ultra Low Sulfur Diesel Bus – emissions in g/km

Class	Fuel Production	Combustion	Total
CO_2	274	1,406	1,680
CH_4	0.73	0.01	0.74
N_2O	0.01	0.04	0.05
CO	3.89	1.41	5.30
NOx	1.28	14.32	15.60
NMVOC	2.09	0.52	2.61
Particles	0.261	0.155	0.416

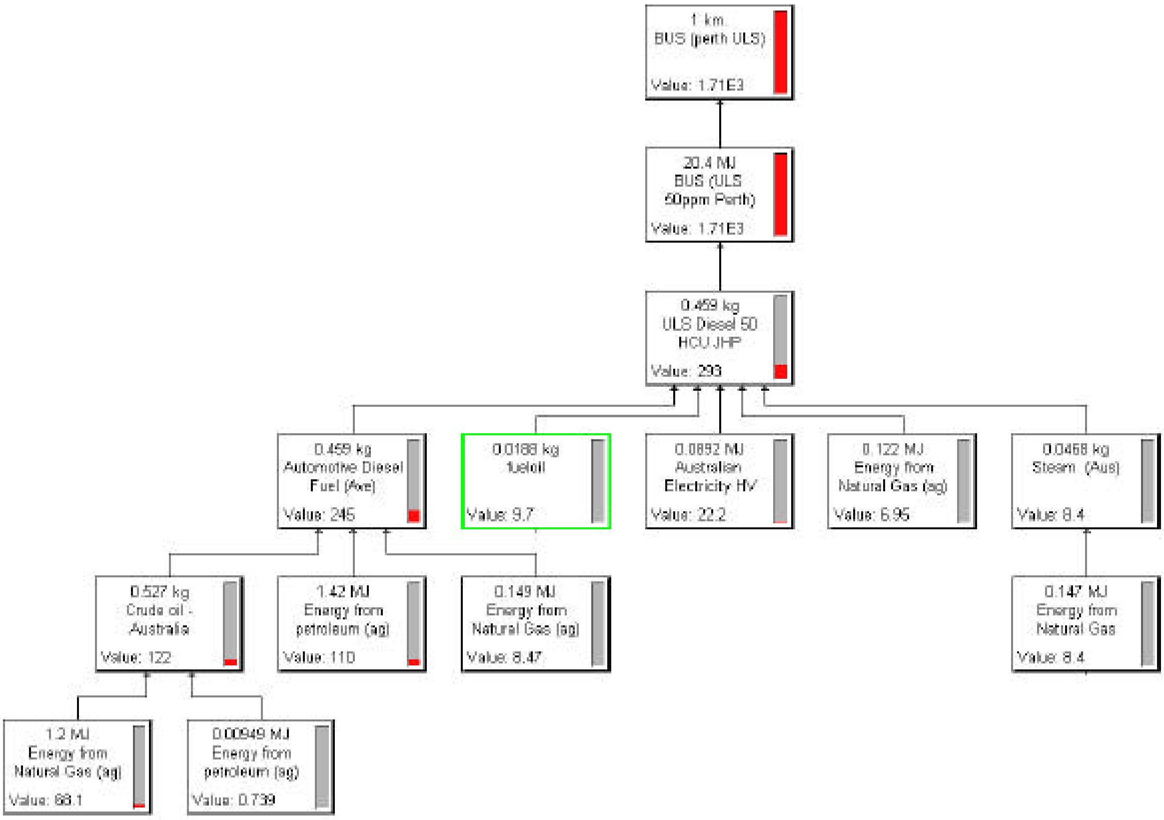


Figure 4.3

Value = grams CO_2 eq

Process tree of estimated CO_2 equivalent emissions per kilometre from ultra-low sulfur diesel (ULS)

Table 4.7 gives the life-cycle emission results that apply to the use of oxygenating catalysts, as compared to a bus that is not equipped with such a catalytic converter.

Table 4.7

Comparison of emissions with oxygenating catalysts on buses

	BUS (Perth LSD).	BUS (Perth LSD oxycat).	BUS (Perth ULS)	BUS (Perth ULS oxycat)
CO_2	1,620	1,560	1,600	1,530
CH_4	0.68	0.66	0.69	0.66
N_2O	0.01	0.01	0.01	0.01
CO	4.88	4.68	4.98	3.67
NOx	15.50	15.20	14.80	14.00
NMVOC	2.41	2.70	2.45	2.14
Particles	0.38	0.87	0.39	0.31

Chapter 5

Natural Gas

5.1 Background

Natural gas (NG) is a mixture of hydrocarbons, mainly methane (CH_4), and is produced either from gas wells or in conjunction with crude oil production. The composition of natural gas used in Melbourne in 1997/98 was 91.6 percent methane, 5.0 percent ethane, 0.4 percent propane, 0.1 percent butane, 0.8 percent nitrogen and oxygen, and 2.1 percent carbon dioxide. Natural gas is consumed in the residential, commercial, industrial, and utility markets.

The interest for natural gas as an alternative fuel stems mainly from its clean burning qualities, its domestic resource base, and its commercial availability to end-users. Because of the gaseous nature of this fuel, it must be stored onboard a vehicle in either a compressed gaseous state (CNG) or in a liquefied state (LNG). In Australia, CNG is compressed to around 20 MPa for on-board storage. Methane liquifies at -161^{o}C. LNG is generally refrigerated to -180^{o}C for liquefaction, and requires vacuum-insulated cryogenic tanks to maintain it in liquid form for storage. LNG is vaporised before combustion. At this time LNG is not widely developed in the Australasian area, due to the cost of the infrastructure, and in many areas natural gas is readily available by pipeline. The advantage of LNG is that such gas can be stored in a relatively small space. Australia exports huge amounts of NG to Japan every year from the North West shelf project (located in northern Western Australia). All of this gas is exported, by ship, as LNG.

The Gasex NGV Working Group (1996) points out that Australia has abundant reserves of natural gas that are linked to major markets by over 12 000 km of high pressure transmission pipelines and over 64 000 km of reticulation lines. According to this document, proven and probable reserves amounted to 99 715 PJ as at the end of 1994, which equals 89 years supply at the 1996 production levels. This does not include coal-bed methane, which is estimated to amount to a similar level, (Bureau of Transport & Communications Economics, 1994). According to the Australian Natural Gas Industry website (http://www.gas.asn.au/) the BRS estimate was 124,314 PJ as at December 1997. Australia's major natural gas reserves are located in Bass Strait (10 per cent), the Cooper-Eromanga Basin (6 per cent) and the basins of the North-west Shelf of Western Australia (83 per cent). A trans-Australia pipeline to connect the basins of Western Australia with the major consuming areas of the south-east is expected to be required by around the years 2009 to 2015.

5.1.1 Natural Gas Manufacture

Natural gas consumed in Australia is domestically produced. Gas streams produced from reservoirs contain natural gas, liquids and other materials. Processing is required to separate the gas from petroleum liquids and to remove contaminants. First, the gas is separated from free liquids such as crude oil, hydrocarbon condensate, water, and entrained solids. The separated gas is further processed to meet specified requirements. For example, natural gas for transmission companies must generally meet certain pipeline quality specifications with respect to water content, hydrocarbon dewpoint, heating value, and hydrogen-sulfide content. A dehydration plant controls water content; a gas processing plant removes certain hydrocarbon components to hydrocarbon dewpoint specifications; and a gas sweetening plant removes hydrogen sulfide and other sulfur compounds (if present).

5.2 *Natural Gas Market*

Natural gas is distributed throughout Australia in pipeline systems (Figure 5.1) that extend from the well-head to the end user.

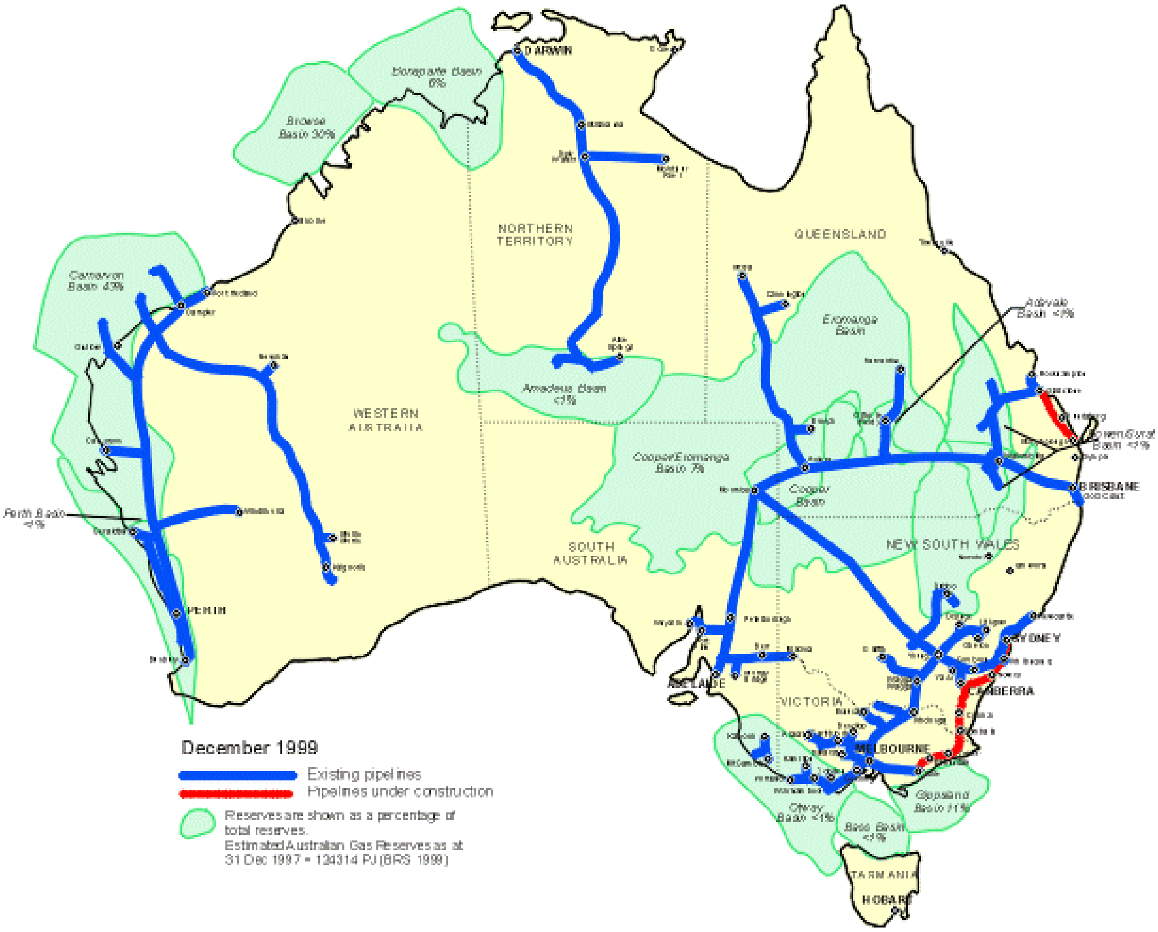


Figure 5.1

Australian gas fields and pipelines

Every State has access to natural gas through pipelines. The pipeline system consists of long-distance transmission systems, followed by local distribution systems. Some underground storage is also used to help supply seasonal peak needs.

According to the California Energy Commission, (http://www.energy.ca.gov/) costs for a "slow fill" system or "quick fill" system to handle public or private fleets can cost $250,000 or as much as $3 million for a bus fleet. A compressor station typically costs $2,000 to $4,000 per vehicle served. Refuelling can be done easily by trained drivers. Costs for a compressor for use with a single vehicle in private homes averages about $3,500. Individual home compressors use a slow-fill system for overnight refuelling. The small compressor would usually be located in a home's garage area and would be connected directly to the natural gas supply in the house.

Natural gas has many benefits, which relate to economics, emissions, greenhouse gases, safety, job creation, and domestic abundance. The Australasian Natural Gas Vehicles Council web site at http://www.ozemail.com.au/~angvc/ provides more information.

5.3 Vehicles

Table 5.1 shows there has been a steady growth in the Australian NGV market in the 1990s, particularly in buses, taxis and forklifts.

Table 5.1

Number of Natural Gas Vehicles in Australia 1991 and 1995

Vehicle Type	1991	1995	% Growth
Buses	72	300	317
Trucks	43	81	88
Cars/Vans/Utes	185	422	128
Taxis	8	28	250
Forklifts	169	770	356
Ships	1	1	–
Total	477	1602	236
Refuelling Stations*	22	70	218

*around 11 percent are available for public refuelling

5.4 Fuel Characteristics

Natural gas has very different fuel characteristics from the fuels normally used in internal combustion engines.

The energy content of CNG varies from 38.8 megajoules per cubic metre at atmospheric pressure in New South Wales and South Australia to 38.5 in Victoria, 37.5 in Western Australia and 41.9 in the Northern Territory (National Greenhouse Inventory Committee, 1998)). The average energy content is similar to that of one litre of automotive diesel oil (38.6 megajoules), and about 12 per cent above that of one litre of gasoline (34.2 megajoules) (ABARE, 1991). Pressurised storage of a cubic metre of CNG, however, requires a volume of 4 to 5 litres.

The energy content of LNG from the North-West Shelf is 25.0 megajoules per litre, about 65 per cent of that of automotive diesel oil (see Chapter 3.1). This low energy content, together with the special low temperature storage requirements, results in particularly high storage costs for LNG.

The effective cetane number of natural gas is low, indicating a high auto-ignition temperature (BTCE, 1994).

5.5 Implications for Engine Conversions

Because of its characteristics, natural gas can be used in spark ignition engines, but in compression ignition engines a proportion of diesel fuel is usually required to trigger ignition. Alternatively, diesel engines can be converted to spark ignition for natural gas use.

For diesel engines (primarily HDVs in Australia), the conversion to a compression ignition dual (mixed) fuel configuration involves use of a pilot supply of diesel to ignite the natural gas. This requires the addition of a gas fuel system alongside the existing diesel fuel system, together with a mechanism for regulating the proportion of diesel and gas for the engine speed and load conditions. According to the IEA (1993) engine efficiency for this configuration is about the same as that for a diesel engine. BTCE (1994) states that the efficiency of dual (mixed) fuel systems can be equal to or higher than for diesel at high loads, but lower at part loads. For this reason, the overall efficiency in service is lower than for diesel.

Conversion of diesel engines to spark ignition engines running solely on natural gas requires more extensive modification, in that the diesel fuel injectors in the cylinder head will be replaced by spark plugs, and an ignition system added to the engine. A compression ratio lower than that of the diesel is likely to be required. Also, a larger cylinder capacity than that required for a dual (mixed) fuel system may be needed, to provide the same energy content (see Section 5.4).

5.6 Emissions

Table 5.2 reproduces the emission factors for heavy vehicles fuelled by natural gas that are given by the National Greenhouse Gas Inventory Committee (1998).

Table 5.2

Emission factors (g/MJ) for heavy vehicles fuelled by natural gas

Gas	Emission factor
CO_2	54.4
CH_4	0.101
N_2O	0.001
NOx	1.2
CO	0.2
NMVOC	0.01

We note that an estimate of tailpipe emissions of 1344 g CO_2/km for a CNG bus (based on the results in Table 2.1) corresponds to a fuel efficiency of 24.7 MJ/km. As a typical energy content for natural gas is 39 MJ/m^3 our results are based on an assumed fuel economy of 1.58 km/m^3. According to NSW State Transit (Hardy, *pers. comm*. 2000) the known fuel consumption of the CNG buses is 1.6 km/m^3.

Using these default figures we have taken the methane emission to be 2.5 g/km and the N_2O emissions for a natural gas fuelled urban bus to be 0.0247 g/km. Emissions of the other gases and particles are based on the dynamometer results given in Tables 2.1, 2.2, 2.10 and 2.11.

Tables 2.1, 2.2, 2.10 and 2.11 provide representative emissions for CNG and LNG vehicles. These results are compatible with the tests on two CNG buses undertaken by the NSW EPA (Brown et al. 1999). However, we have not been able to find literature reports of direct chassis dynamometer measurements of CH_4 and N_2O. This discussion highlights the large uncertainty in the natural gas results as a result of methane emissions, possibly as a result of leakage or venting rather than as a result of combustion.

We note that the CH_4 to NMVOC ratio in Table 6.2 is 10 to 1, with most of the emissions being in the form of methane. However, examination of Tables 2.1 and 2.10 indicates that the total hydrocarbon emissions are comparable in magnitude to the assumed methane emissions.

5.6.1 Fugitive emissions

Natural gas can contain significant quantities of naturally occurring CO_2, which in the past has often been vented to the atmosphere at the well-head. Le Cornu (1989) pointed to Cooper Basin gas as having up to 35 per cent by weight (12.7 per cent by volume) of naturally occurring CO_2. On a state by state basis, vented CO_2 accounts for between 3 and 15 per cent of full fuel-cycle CO_2 emissions from natural gas combustion (Wilkenfeld, 1991).

5.6.2 Methane emissions from vehicles

Methane, the principal component of natural gas, has a greenhouse radiative forcing of 21 (Table 1.4) over a 100-year period. It is therefore important that tailpipe losses of unburnt fuel and fugitive/evaporative losses are minimised.

As methane is a non-reactive hydrocarbon, tailpipe emissions of methane are not as well controlled by catalytic converters as are more reactive hydrocarbons. (BTCE, 1994).

Different views are held on evaporative emissions. One is that CNG vehicles do not have any, due to their sealed pressurised fuel system. BTCE (1994), on the other hand, refers to 'frequent leaks' as a technical problem to be solved for NGVs. According to the IEA (1993), existing CNG cars have methane emissions of around 1 gram per kilometre (over six times that typical for gasoline cars), adding around 10 per cent to life-cycle greenhouse gas emissions (in CO_2 equivalents).

Experience with the LNG road train built to operate between Alice Springs and Yulara suggests that fugitive losses from LNG boil-off in intermittent use may not be a major problem. The LNG tanks, filled to 90 per cent of their volume (Hatfield, 1990), stood without use for 10 days before the pressure opened a relief valve (Yorke, 1991).

5.6.3 Methane fugitive losses in distribution

Fugitive losses would have the potential to reduce substantially any advantages that natural gas may have in terms of emissions. Gas supply authorities considered that fugitive losses would be less than 2 per cent, and concentrated entirely on the old town-gas reticulation systems. Refuelling depots or retail gas reticulation systems would be serviced by new medium or high pressure lines, and fugitive losses from this form of distribution might be expected to be very low. A Swedish study estimated methane leakages from new supply lines at only 0.05 per cent (Sinor Consultants, 1992). BTCE (1994) point out that fugitive losses may be exaggerated through a lack of understanding of the term 'unaccounted for gas,' which is the overall accounting error including metering over a vast distribution network.

We have estimated the fugitive emissions of CNG during bulk transfer and storage operations, on a g/MJ basis, as given in Table 5.3.

Table 5.3

Estimates (g/MJ) of fugitive CNG/LNG emissions during bulk transfer and storage

CNG/LNG losses at filling		
Volume of space in filling if filling nozzle is 25 mm ID and distance between tap and filling valve is 20 mm	0.00000981	Estimate
LNG density kg/m^3	637	Wegrzyn and Gurevick 1996
LNG lost per fill kg	0.0062	per fill
g/km given 300km between fills	0.0208	
g/MJ	0.000833	given fuel consumption in buses at 25 MJ/km
Diesel losses at filling		
Diesel g/l	0.006	from NGGIC workbook 2.1 1998
g/MJ	0.000167	given 36 MJ/litre for diesel
CNG loss as a percentage of diesel losses	500%	

5.6.4 Overall greenhouse emissions from heavy vehicles

The General Manager of the AGA in a submission to the Senate Standing Committee on Industry, Science and Technology (AGA, 1990) stated:

"*In the greenhouse debate we are about line ball. So we cannot wave the flag and say that compressed natural gas replacing diesel is a saviour…*

Similary, Wilkenfeld (1991, 142-3) concluded:

"The heavy vehicle market segments where NGV penetration is most cost effective are those where it will make the least difference to greenhouse emissions…there would be very little reduction in greenhouse gas emissions from converting the heavy vehicle market from diesel to CNG or LNG…"

Moreover, methane emissions from NGVs would reduce the overall greenhouse advantage. In dual (mixed) fuel natural gas vehicles, high methane emissions could negate or reverse the CO_2 advantage (Milkins, 1989, p. 15).

Information on the use of CNG buses in Australia, UK and the US is that reductions in tailpipe CO_2 emissions can be significant. Tests of South Australian State Transit Authority buses indicate a saving of 15 per cent (*Public Transport International,* April 1993). In Canada also, tests on comparable diesel and natural gas buses on city cycles have shown CO_2 emissions to be 15 per cent lower from the natural gas buses (BTCE, 1994). These values accord with those in Table 2.10.

The reduction in tailpipe emissions of CO_2 (compared to diesel) is also markedly evident in the results shown in Tables 2.10 and 2.11. When the CNG emissions for buses are examined in terms of engine type then the statistical variability can be substantially reduced. Table 5.4 displays the results for two different versions of the Cummins engine.

Table 5.4

Emission results (g/km) for CNG buses (based on data in Motta et al. 1996)

Cummins Engine	CO	THC	NOx	PM
L-10 260G	0.71	9.82	7.2	0.01
L-10 240G	11.75	9.38	19	0.005

Source: Motta et al. (1996)

5.7 Local Air Pollution and Noise

The major environmental effects of NGVs could be on local air quality rather than on global warming. Noise levels from HDVs could also be reduced.

NGVs have the potential to effect a significant reduction in local air pollutants such as CO, NMHCs, SO_x, particulates, smoke and odour. The situation with regard to NO_x is less clear cut, and the effects of traces of formaldehyde in NGV exhausts (though less than from alcohol fuels) have yet to be determined.

The level of emissions from NGVs is strongly affected by the state of tune of the engine (IANGV, 1990); also, purpose-designed OEM NGVs can have different emission levels from conversions. For example a Chrysler OEM NGV van has been officially certified as an ultra-low emission vehicle (ULEV) by the California Air Resources Board (BTCE, 1994), whereas Ford now has a natural gas truck certified as a super ultra-low emission vehicle (SULEV) (Vermiglio et al. 1997).

Carter et al. (1992) reported comparative CO emission rates for three gasoline and three NGV versions of cars and light trucks in the USA. Two out of the three NGV cars showed higher emissions than those from the comparable gasoline versions, but two of the three still met the Californian ‘low emission vehicle’ (LEV) standard for CO (3.4 grams per mile). All three NGV light trucks met the LEV standard for CO, and one the ultra ‘low emission vehicle’ (ULEV) standard. However, two of the trucks, including the one meeting the ULEV standard, had CO emissions higher than from their comparable gasoline versions. Sun et al. (1997) also found different trends in CO emissions from different vehicles depending on the details of the engine design and fuel system.

One problem with certification procedures based on engine dynamometers is that they may report values that substantially differ from those calculated by chassis dynamometers. We have already noted this in Table 2.3. The NSW EPA (Brown et al. 1999) also tested the CNG buses for their performance with, and without, a catalyst. The results are reproduced in Table 5.5.

Table 5.5

Methane and non-methanic hydrocarbon emissions (g/kWh) from CNG buses

		THC	Methane	NMVOC
Without catalyst	Bus #1	2.86	2.64	0.22
Without catalyst	Bus #2	3.37	2.92	0.45
With catalyst	Bus #1	1.88	1.85	0.03
With catalyst	Bus #2	3.02	2.78	0.24

Carter et al. (1992) have also compared NMVOC emissions for US gasoline and natural gas versions of cars and light trucks. All three NGV cars met the Californian TLEV standard (0.04 grams per mile), while one met the ULEV standard for NMVOC. In 1992 two of the three NGV light trucks met their ULEV standard, but the other exceeded the Californian standard (Carter et al. 1992), but by 1997 all trucks met the standards (Sun et al. 1997) and vehicles met SULEV standards of 0.005 g/km HC (Vermiglio et al. 1997).

5.8 Particles

Emissions of particulate matter, some of which is carcinogenic, are almost eliminated with natural gas use (see Table 2.10). The IANGV (1990) noted that the NGV engine's lubricating oil appeared to be the source of remaining particulate emissions.

5.9 Summary

According to the Australasian Natural Gas Vehicles Council (ANGVC, undated), a 1996 study by the Department. of Transport and Logistics of Chalmers University, who undertook a life-cycle study on natural gas and diesel fuel in city buses produced the following results for a Volvo B10M Mk IV THG 103KF Natural Gas Bus:

NO_x 66% less
CO 46% less
NMHC 62% less
PM 76% less
SO_2 99% less
CO_2 9% less

when the fuels were compared to an equivalent diesel bus in Sweden (Blinge, 1998).

5.10 CNG

The major determinant of the life-cycle greenhouse gas emissions from the use of natural gas is the consideration of fugitive methane. Methane, over a 100-year time horizon, has a global warming potential of 21, so that small losses of natural gas during extraction, processing, distribution or usage will greatly increase the greenhouse gas emissions when expressed in CO_2-

equivalents. Studies that have attempted to include this produce CO_2-equivalent life-cycle emissions that range up to 45% greater emissions than from an equivalent diesel vehicle.

We have used the tailpipe emissions data for CNG fuelled buses with oxidation catalysts, as given in Table 2.1 for CO_2, and as given in Table 2.2 for other emissions, to calculate full fuel-cycle emissions (see Table 5.6).

Table 5.6

CNG Bus emissions in g/km

Class	Fuel Production	Combustion	Total
CO_2	144	1,336	1,480
CH_4	0.26	2.50	2.76
N_20	0.00	0.02	0.02
CO	0.09	0.66	0.75
NOx	0.63	9.87	10.50
NMVOC	0.28	2.75	3.03
Particles	0.012	0.050	0.062

The pre-combustion emission of methane are based on the default values given in Appendix Table 1(1B-2) of the 1997 National Greenhouse Gas Inventory (1999) for methane emissions as a result of the transmission of natural gas. 4.9 Gg of methane is emitted in the transmission of 632 PJ of energy in the form of natural gas. This is .00775 g/MJ of natural gas. Each kilometre of travel by a CNG bus consumes 24.8 MJ energy, so that there are 0.19 g of fugitive methane emissions per kilometre of travel as a result of losses during transmission. The estimate in National Greenhouse Gas Inventory (1999) is that the fugitive losses during distribution are 55 times as large on a g/ MJ basis.

It may be argued that these distribution figures are overestimates because they are based on estimated losses from the residential natural gas pipelines, and are unlikely to reflect losses from commercial gas systems. We note the quote from Anyon (1998):

"Because they have completely sealed systems, CNG and LPG vehicles should have effectively zero evaporative emissions, and fugitive emissions should be limited to the small release of gas when the fuelling coupling is attached and removed.

In practice, however, most gaseous-fuelled light vehicles have dual fuel capability, so that they still are prone to losses through the gasoline side of the fuel system. The recent Australian LPG study also found leaks in the joints of some LPG fuel lines."

Distribution losses will occur as a result of poor maintenance or operator error. There have been no studies to estimate the magnitude of this and thus we follow the assumption of Wang & Huang (1999) that such losses will be zero.

Figure 5.3 gives the expected flow-chart for methane emissions from CNG.

Value = grams CO_2eq

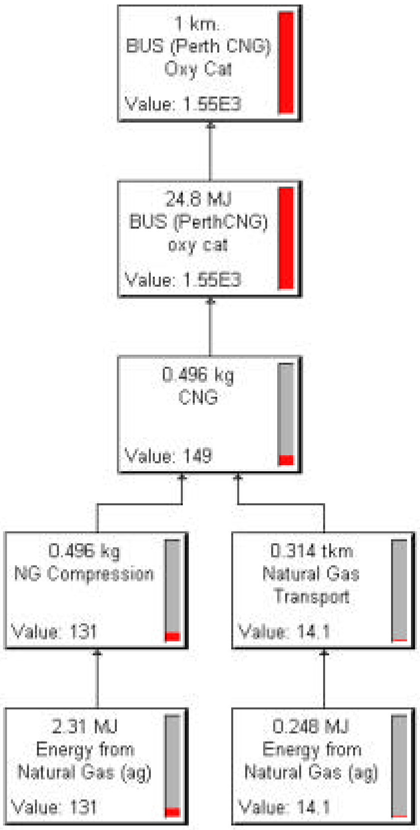


Figure 5.2

Process tree of CO_2 equivalent fuel-cycle emissions for a hypothetical Perth bus using CNG

Schmidt and Pütz (1999) have compared CNG and diesel buses. They claim full fuel-cycle emissions of 950 g CO_2-equivalent per km for the diesel bus, and 1050 g CO_2-equivalent per km for the CNG bus. The high CNG emissions arise because of the assumption that electricity was used for the gas compression. Fuel consumption for CNG buses was 0.55 Nm^3/km for solo buses, and 1.75 Nm^3/km for articulated buses. The fuel has a calorific value of 10kWh/Nm^3. Diesel buses by comparison, use 0.4 L/km (solo buses) and 0.53 L/km (articulated) of fuel with a calorific value of 10 kWh/L.

Table 5.7

Comparison (g/kWh) of diesel and CNG buses

Fuel	THC	PM
Low sulfur (360 ppm) diesel	0.33	0.121
LSD + oxidation Catalyst	0.14	0.11
ULS (10 ppm) + CRT	0.02	0.01
ULS + SCRT	0.02	0.01
CNG + 3 way catalyst	0.5	0.02
CNG + Oxidation catalyst	0.6	0.02

Table 5.7 compares the particulate matter and hydrocarbon emissions reported by Schmidt and Pütz (1999). These German results are considerably lower than the Australian results shown in Table 5.5.

Value = grams CH_4

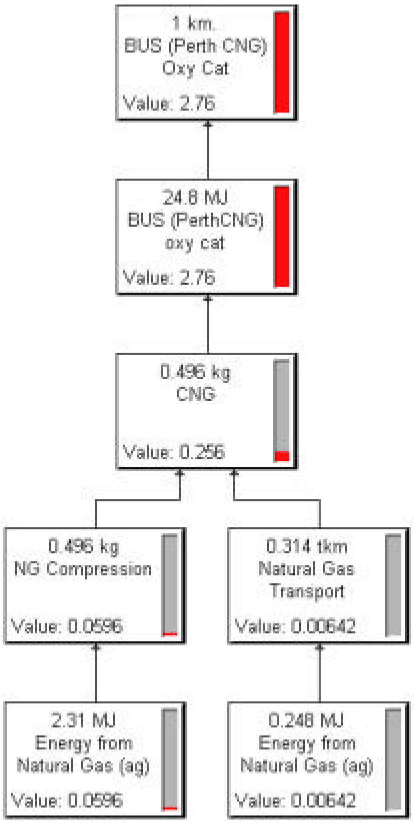


Figure 5.3

Process tree of CH_4 fuel-cycle emissions for a hypothetical Perth bus using CNG

5.11 LNG

Liquified Natural Gas has been used as a substitute for marine diesel fuel, but its low energy content, together with the special low temperature storage requirements, have precluded its use for heavy vehicles. The low temperature facilities that are needed are expensive, and their manufacture, installation and operation increases the life-cycle emissions of greenhouse gases. The life-cycle emissions of LNG are liable to be comparable with those of CNG, as summarised above, except that the CO_2 emissions will be higher. The LNG market niche is centrally fuelled heavy-duty fleet vehicles with high fuel consumption, where fuel cost savings can amortize equipment capital costs. LNG vehicle life-cycle costs will be lower than those for diesel vehicles when LNG equipment prices decrease and/or financial benefits such as emission reduction credit sales are realized. While there are no severe LNG vehicle technology problems, improvements are needed in the areas such as on-vehicle high pressure fuel supply systems, accurate fuel level and flowrate instrumentation, and non-venting refuelling facilities. The safety record is good, but it is difficult to quantitatively rate the LNG safety relative to gasoline and diesel vehicles because the needed statistical data do not yet exist. According to news reports (http://www.lngexpress.com/japa.htm) Japan has a research program focussing on the use of crude LNG in heavy-duty trucks and buses. Because Japan imports large quantities of LNG by sea, the cheapest fuel for a vehicle would be the imported LNG without any treatment. Japan therefore hopes to convert its diesel trucks and buses to LNG. The Australian situation is substantially different. Most natural gas is piped, not shipped, so that centralised LNG facilities located near urban areas do not exist in Australia.

Collison et al. (1997) review the Maryland Mass Transit (MTA) pilot study of LNG buses using Cummins L10-240G natural gas engines. In this case the use of LNG, rather than CNG, arose because the heavy tanks needed to withstand CNG pressures meant that the extra weight (1,300 kg) put their buses close to exceeding their gross vehicle rating with just a modest passenger load. Using LNG resulted in a practical operating range. The MTA diesel buses averaged about 1.02 km/L and the MTA LNG buses averaged about 1.02 km/L per diesel equivalent litre (based on the energy content of the fuels). This indicates that even on the basis of tail-pipe emissions, greenhouse gas emissions of LNG buses are comparable to, or slightly above, diesel buses[9]. Incorporating the full life-cycle, and the possible methane emissions, will further increase the LNG greenhouse gas emissions. Collison et al. (1997) claim that newer versions of the engines will improve fuel economy by using oxygen sensors and closed-loop computer controls during driving. However, idle fuel consumption consistently remains higher than that of diesel engines.

Table 5.8 shows the emissions obtained from the use of the buses. The measurements originally given in units of g/hp-h have been converted to g/kWh and g/MJ, so that the values may be compared to those in Tables 2.3 and 2.7.

Table 5.8

Emissions from LNG buses using Cummins L-10 240G engines

	g/hp-h	g/kWh	g/MJ	LNG bus g/km	1998 Diesel bus
NO_x	2	2.68	0.74	5.1	10.7
PM	0.02	0.03	.007	.05	0.13
VOC	0.6	0.8	0.22	1.53	3.5

Source: (Collison et al. 1997)

[9] The results of Motta et al. (1996) reproduced in Appendix 6 indicate that this is the case for dual fuel LNG buses, but not for spark ignition LNG buses.

5.11.1 Fuel-cycle calculations

Table 5.9

LNG fuelled bus – emissions in g/km

Class	Fuel Production	Combustion	Total
CO_2	144	1,336	1,480
CH_4	0.26	2.50	2.76
N_2O	0.00	0.02	0.02
CO	0.09	0.66	0.75
NOx	0.63	9.87	10.50
NMVOC	0.28	2.75	3.03
Particles	0.012	0.050	0.062

Value = grams CO_2 eq **Value = grams CH_4**

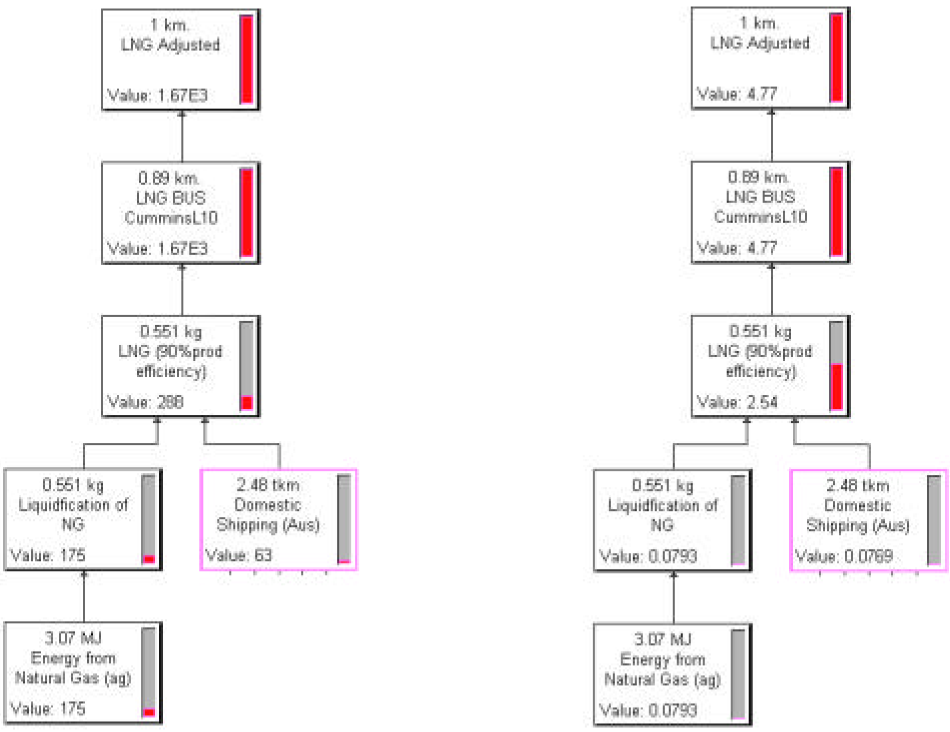


Figure 5.4

Process tree of CO_2 equivalent and CH_4 fuel-cycle emissions for a LNG fuelled bus

Chapter 6

Liquefied Petroleum Gas (LPG)

6.1 Background

Liquefied petroleum gas (LPG) a petroleum industry by-product, consists mainly of propane, propylene, butane, and butylene in various proportions according to its State or origin. The components of LPG are gases at normal temperatures and pressures, but can easily be liquefied for storage by an increase in pressure to about 8 atmospheres or by a reduction in temperature. In Australia, LPG is stored on board the vehicle in a steel cylinder in liquid form, but is converted to gaseous form via a regulator before supply to a gas-air mixer (the equivalent of a carburettor) for intake to the engine.

LPG is a by-product from two sources: natural gas processing and crude oil refining. Most of the LPG used in Australia is produced domestically, though a small quantity is imported. Natural gas, as extracted at the well-head, contains methane and other light hydrocarbons. The light hydrocarbons are separated in a gas processing plant using high pressures and low temperatures.

The natural gas liquid components recovered during processing include ethane, propane, and butane, as well as heavier hydrocarbons.

Propane and butane, along with other gases, are also produced during crude oil refining as a by-product of the processes that rearrange and/or break down molecular structures to obtain more desirable petroleum compounds.

More than 500,000 Australian vehicles, mostly in fleets, travel the nation's highways using LPG. LPG powers all taxis in Victoria, and many other taxi fleets around the country.

6.1.1 LPG in heavy vehicles

According to BTCE (1994) Linfox, the transport operator, used LPG trucks as well as gasoline-fuelled trucks in its fleet in the early 1970s. However, use of the LPG trucks was discontinued, as they had tended to become unreliable after about a year or so. Boral also conducted trials of a truck operating on a blend of diesel and LPG vapour, with the vapour replacing 35 percent of diesel. In theory, diesel vehicles could run on 80 percent LPG and 20 percent diesel mixed in liquid form. To run on 100 percent LPG, heavy vehicle engines require conversion to spark ignition and a reduction in compression ratios.

In 1994 ALPGA saw LPG as being more suitable for the passenger car market, and natural gas more suited to heavy vehicles (BTCE, 1994). The higher energy density of LPG compared with natural gas allows a reasonable range while retaining more of the luggage capacity in the boot of a car. This view may be changing as a result of the recent environmental concern in relation to the health effects of particulate matter (Abramson & Beer, 1998) and especially particulate matter of diameter less than 10 µm, known as PM10. Particulate matter emitted by diesel is all PM10. Anyon (1998) points out that LPG, like CNG, has much lower emissions than diesel, and LPG has particularly low particulate levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particulate emissions reduce to Euro4 levels this advantage may be lost.

According to the Dutch AutoLPG association (http://www.autolpg.com/autocom/busses.htm) DAF, the Dutch vehicle maker, considers CNG (natural gas) to be very well suited for use in a stationary engine, but autogas (i.e. LPG) to be the best fuel for a bus. Their reasons for this choice are: no need for such a big tank, the composition is clearly defined and there is no need to have the gas compressed in an expensive compression station. Once you have the right fuel, you have to select the correct combustion principle. DAF prefers the stoichiometric process over lean burn. The advantage of the stoichiometric combustion principle is that it allows the use of a three-way catalyst, which is impossible in lean burn. With a three-way catalyst the emission of all polluting compounds can be reduced, resulting in extremely low emission rates. If a two-way catalyst is used, the NO_x is not removed. The stoichiometric process reduces the emission rate of particulate matter to one twentieth of Euro2, whereas lean burn only comes to half of Euro2. The drawback of the stoichiometric process is that it loses the efficiency advantage of lean burn and correspondingly increases CO_2 emissions.

6.2 Emissions Tests

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emission characteristics. The London Transport study, conducted at the Millbrook Proving Ground in Bedfordshire, is one of the few studies for which data are available. Even though the results themselves still remain unpublished, a number of Australian public documents, (Anyon, 1998; Expert Reference Group, 1998) have quoted them, and we have reproduced them in Table 2.1 of this report. LPG with a three-way catalytic converter has the lowest emissions of CO, NO_x, PM10 and hydrocarbons. Anyon (1998) points out that only the ultra-low sulfur diesel with a continuously regenerating particulate trap came even close to the extremely low LPG particulate emissions performance. This is also true when studies on earlier technology vehicles are examined. Anyon (1998) also points out that US tests on medium-large engines also confirm that LPG has lower emissions of air toxics than CNG and diesel. The toxics examined were 1,3-butadiene (LPG emissions of 0.1 mg/kWh), acetaldehyde (3.8 mg/kWh), formaldehyde (16.5 mg/kWh) and benzene (0.2 mg/kWh).

Anyon (1997) in a review of alternative fuels for the urban air inquiry quotes heavy-vehicle results from SAE 952442 for LPG which yield 0.2 g/km for CO, 1.42 g/km for NO_x, and 4.2 g/km for THC - which is composed of 4.26 g/km methane and 0.02 g/km NMVOC.

As is evident from Table 2.1, LPG does not appear to fare so well against diesel with respect to tailpipe emissions of CO_2. Although the LPG emissions of CO_2 per kilometre were lower than those of CNG and diesel, they were slightly more than for ULS diesel engines fitted with a catalyst or particulate trap.

We say that it does not appear to fare so well because it is not clear whether the small variations in CO_2 emissions for different fuels shown in Table 2.1 are statistically significant. Although the carbon content on a volume basis, and hence CO_2 emissions, of diesel appear on paper to be greater than for LPG, the higher intrinsic thermal efficiency of diesel engines, primarily through their higher compression ratios, tend to counterbalance this advantage.

Recent compilations of air pollutant emissions from light trucks (pick-up trucks) are given by Anyon (1998), Sun et al. (1997) and by Brasil (1999). BTCE (1995) reproduce in their Appendix VI projected life-cycle greenhouse gas emissions from North American Passenger Vehicles in 2000 on a grams CO_2 equivalent per km basis and obtain a value of 201 for LPG compared to 210 for diesel. These figures apply to passenger vehicles. Another table in the same appendix gives a range of greenhouse gas emission estimates for the use of alternative fuels in trucks (compared with diesel fuel) and obtain a range for LPG from +15% to –11%. The same table gives a range for CNG/LNG from +45% to –13%. Presumably the large range again reflects the assumptions made with respect to fugitive emissions of methane.

Table 6.1

Properties of LPG (NGGIC, 1996, 1998)

Property	Value
Energy Density	25.7 MJ/L
CO_2 Emission Factor	59.4/MJ
SO_2 Emission Factor	0.008 g/MJ

Table 6.2

Default Emission Factors (g/km) for LPG (NGGIC, 1996)

	Buses	Light Trucks	Medium Trucks	Heavy Trucks
CH_4	0.12	0.089	0.13	0.22
N_2O	0.011	0.008	0.011	0.02
CO	24.00	21.99	24.00	24.00
NMVOC	2.41	1.72	2.46	4.21
NOx	2.76	1.98	2.82	4.83

The default emission factors in the methodology for the Australian National Greenhouse Gas Inventory are given in Tables 6.1 and 6.2. We note that our estimate of tailpipe emissions of 1310 g CO_2/km (based on the Millbrook trials in Table 2.1) corresponds to a fuel efficiency of 22 MJ/km and a fuel economy of 0.86 km/L (116L/100km). Such a poor fuel economy presumably reflects the fact that the London Transport buses were using a simulated inner-London drive cycle.

6.3 Fuel-Cycle Results

Table 6.3

Fuel-cycle emissions (g/km) for a bus using LPG

Class	Pre-combustion	Combustion	Total
CO_2	210	1310	1520
CH_4	0.64	0.12	0.86
N_2O	0.01	0.11	0.12
CO	3.45	0.12	3.57
NOx	1.02	5.31	6.33
NMVOC	1.85	0.02	1.87
Particles	0.14	0.02	0.16

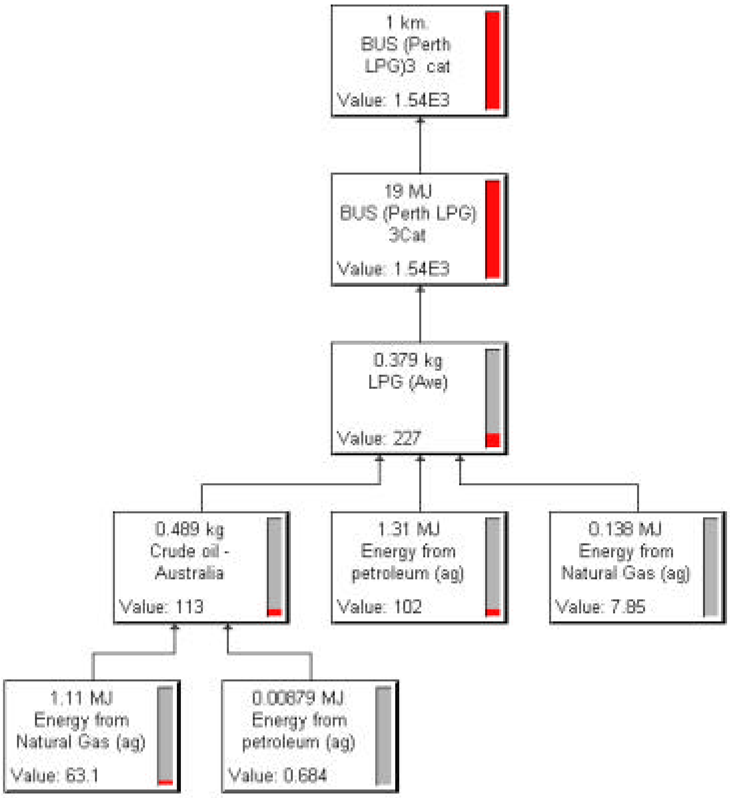


Figure 6.1

Value = grams CO_2 eq

Process tree for LPG emissions of CO_2 equivalents

Chapter 7

Alcohol Fuels: Ethanol And Diesohol

7.1 Background

Development and use of alcohol fuels in transport have, for the most part, been driven by the desire in many countries to find substitutes for imported petroleum based fuels. Alcohol fuels have also been used as additives to conventional fuels to improve fuel characteristics. More recently they have been the focus of attention as a possible means of reducing greenhouse gas emissions and noxious urban emissions from transport.

Proposals for using ethanol as a transport fuel have ranged from using pure alcohol (E100) to using blends of between 3 and 95 per cent alcohol with petrol, often with co-solvents or emulsifiers to assist the blending process. In Australia, both the use and trial of ethanol as a component of gasoline transport fuel have, until recently, occurred primarily in Queensland. All gasoline sold in Queensland from 1929 to 1957 contained 10 per cent ethanol (BTCE, 1994) Gasoline containing 10 per cent ethanol is distributed through a small number of independent fuel retailers in NSW and Victoria. This ethanol is produced from wheat starch at Nowra on the south coast of NSW.

Ethanol will easily blend with gasoline but not with diesel. Alcohols can be used in diesel engines by either modifying the fuel or by extensive engine adaptations. Work in Australia by APACE Research Ltd has produced an ethanol and diesel emulsion called ‘diesohol’. APACE claims that a diesohol emulsion containing up to 30 per cent ethanol will run in a diesel engine, with the engine requiring little or no modification. The ACTION bus fleet in Canberra trialed three new buses running on diesohol (Scott et al. 1995; Joseph, 1996). Sydney buses also used such buses from 1993 to 1998 (Figure 7.1).

Figure 7.1

Diesohol bus used by Sydney Buses from 1993 to 1998.

7.2 Characteristics of Alcohol Fuels

Ethanol (C_2H_5OH) is an alcohol, an oxygenated organic carbon compound. It is the intoxicating component of alcoholic beverages, and is also used as a solvent (methylated spirits). By contrast, diesel is a mixture of a range of hydrocarbon compounds, none of which contains oxygen. In blended fuels, the addition to diesel of the oxygen contained in the alcohol changes a number of important fuel characteristics. These include changes in combustion properties, energy content and vaporisation potential.

The energy content of ethanol is about 23 MJ/L. This compares to 38.6 MJ/L for diesel. The energy content of ethanol depends on whether it is hydrated or anhydrous. Expressed in mass terms the energy content ranges from 24 MJ/kg to 26.7 MJ/kg (http://www.afdc.doe.gov/altfuels.html). Boustead & Hancock (1979) quotes 29.7 MJ/kg. The former values probably represent the lower heating value (net califoric value) whereas the higher value is probably the higher heating value (gross calorific value).

7.3 Production and Distribution

7.3.1 Ethanol production

Ethanol can be manufactured from:

- Biomass via the fermentation of sugar derived from grain starches or sugar crops
- Biomass via the utilisation of the non-sugar lignocellulosic fractions of crops
- Petroleum and natural gas via an ethylene (C_2H_4) intermediate step (reduction or steam cracking of ethane [C_2H_6] or propane [C_3H_8] fractions).

7.3.2 Ethanol from sugar and starch fractions

Starch and sugar crops in Australia have received attention as a potential source of ethanol include cassava in Queensland; sugarcane in Queensland and northern NSW; sweet sorghum in Queensland, NSW and Victoria; Jerusalem artichokes and potatoes in Victoria; sugar beet in Victoria and Tasmania; and cereals in NSW and Victoria. Current research seeks to improve starch yields from grain crops through the application of genetic engineering principles.

Ethanol has traditionally been produced in Australia from molasses, a by-product of the sugarcane industry. CSR supplies around half of the Australian ethanol market with an annual plant capacity of 55 million litres (www.csr.com.au/about/Facts_Distilling.htm). Ethanol is also produced from wheat at Manildra's gluten and starch plant at Nowra (Figure 7.2). The major products of the mill are gluten and starch. The ethanol produced from the waste starch stream with further supplementations of starch is essentially a by-product of the gluten manufacturing process.

Figure 7.2

The ethanol plant at Minaldra's Nowra plant.
(http://www.manildra.com.au/prospectus/prospectus6.html)

There are basically eight steps in the ethanol production process:

1. Milling: The wheat (or corn, barley, etc.) will first pass through hammer mills, which grind it into a fine powder called meal.
2. Liquefaction: The meal will then be mixed with water and alpha-amylase, and will pass through cookers where the starch is liquefied. Heat will be applied at this stage to enable liquefaction. Cookers with a high temperature stage (120-150ºC) and a lower temperature holding-period (9ºC) will be used. These high temperatures reduce bacteria levels in the mash.
3. Saccharification: The mash from the cookers will then be cooled and the secondary enzyme (gluco-amylase) will be added to convert the liquefied starch to fermentable sugars (dextrose), a process called saccharification.
4. Fermentation: Yeast will then be added to the mash to ferment the sugars to ethanol and carbon dioxide. Using a continuous process, the fermenting mash will be allowed to flow, or cascade, through several fermenters until the mash is fully fermented and then leaves the final tank. In a batch fermentation process, the mash stays in one fermenter for about 48 hours before the distillation process is started.
5. Distillation: The fermented mash, now called "beer," will contain about 10% alcohol, as well as all the non-fermentable solids from the wheat and the yeast cells. The mash will then be pumped to the continuous flow, multi-column distillation system where the alcohol will be removed from the solids and the water. The alcohol will leave the top of the final column at about 96% strength, and the residue mash, called stillage, will be transferred from the base of the column to the co-product processing area.
6. Dehydration: The alcohol from the top of the column will then pass through a dehydration system where the remaining water will be removed. Most ethanol plants use a molecular

sieve to capture the last bit of water in the ethanol. The alcohol product at this stage is called anhydrous (pure, without water) ethanol and is approximately 200 proof.

7. Denaturing: Ethanol that will be used for fuel is then denatured with a small amount (0-5%) of some product, like gasoline, to make it unfit for human consumption.
8. Co-Products: There are two main co-products created in the production of ethanol: carbon dioxide and distillers grain. Carbon dioxide is given off in great quantities during fermentation and many ethanol plants collect that carbon dioxide, clean it of any residual alcohol, compress it and sell it for use to carbonate beverages or in the flash freezing of meat. Distillers grains, wet and dried, are high in protein and other nutrients and are a highly valued livestock feed ingredient. Some ethanol plants also create a "syrup" containing some of the solids that can be a separate production sold in addition to the distiller's grain, or combined with it. Minaldra uses this process to produce fructose.

7.3.3 Ethanol from lignocellulose fractions

Lignocellulose is the structural component of plant biomass and can be derived from trees, grasses, and from cereal and paper wastes. Lignocellulose is also a large component of municipal waste. Both the cellulose and hemicellulose portions of the material, which in the case of plants may comprise 65 to 80 per cent of the non-sugar and starch components, can be converted into ethanol. The proportion of cellulose and hemicellulose from various lignocellulose sources is dependent upon the specific biomass crop.

The mass production of ethanol from lignocellulose is still largely in the research and development stage. Production facilities operate mostly at laboratory or pilot scale. The two major research efforts aimed at extracting ethanol from lignocellulose involve technologies using either acid or enzymatic hydrolysis, with the enzymes used being derived from micro-organisms. After hydrolysis the sugars produced are fermented and the ethanol in solution is distilled out, as for ethanol produced from starch and sugar crops.

Ethanol produced from non-lignocellulosic biomass sources is likely to be the only feasible option for the foreseeable future. Production from sugar and grain crops will dominate ethanol production until the lignocellulose process is proved technically and economically more viable.

7.3.4 Supply of biomass feedstock in Australia

Stewart (1990) considered the major potential sources of biomass from the lignocellulosic fraction of crops (cereal straw, sugarcane bagasse, sugarcane field trash, forest residues and energy plantations) to be capable of supplying 235 PJ per year. This is equivalent to about 25 per cent of 1994-95 Australian road transport energy usage (Apelbaum, 1997: Table 4.3 and V.6). Stewart’s estimate takes account of the effects on sustainability of cropping should the total available above ground biomass be collected, and also the feasibility and costs of harvesting crop and forest residues.

By contrast to this conservative outlook of Stewart, APACE has concluded that ‘all of Australia’s transport fuel needs [could be] met by ethanol produced from domestically grown biomass and without interfering with food production or causing land or environmental degradation’ (APACE 1992). The major difference between the projections of Stewart and APACE is that APACE envisages much greater utilisation of crop and forest residues and more extensive planting of tree crops than Stewart.

Bureau of Transport and Communications Economics (1994:Appendix III) contains details of ethanol and methanol production technology and supply constraints, and of the environmental consequences of both crop and fuel production processes.

7.3.5 Ethanol distribution

Difficulties with the distribution of neat ethanol or ethanol blends arise primarily from the solvency effects of ethanol and from ethanol's affinity for water. Ethanol is capable of dissolving substances accumulated in pipelines, storage tanks and other components of the distribution system, thus introducing impurities into the fuel (BTCE, 1994). These substances are insoluble in gasoline. Ethanol's affinity for water can result in phase separation of blended alcohol/gasoline fuels, resulting in engine damage or poor vehicle performance. Phase separation is a function of water content, ethanol content, temperature and properties of the gasoline (BTCE, 1994).

The Australian gasoline production and supply system is a relatively 'wet' system; and use of the existing distribution system for alcohol fuels could result in contamination by water throughout the entire process. BTCE (1994) note claims that it would be necessary to change to a more 'dry' system, at some considerable and as yet unspecified cost, before fuels containing oxygen (oxygenated fuels) could be used in Australia.

By contrast, most US distribution is inland, with greater use of 'dry' pipelines and systems facilitating the handling of oxygenated fuels. In the USA, ethanol is mostly produced in mid-west farm states, by around 50 commercial scale plants. It is shipped by rail car or truck, rather than by pipeline (the least expensive mode), because of the solvency effect problems identified above. Blending occurs in the tanker truck at the distribution terminal prior to distribution to service stations.

7.4 Costs to Users of Alcohol Fuel and Vehicles

7.4.1 Fuel production costs

Ethanol from sugar and starch crops

The price of ethanol depends on the nature and the grade of ethanol being purchased, as well as the quantity. CSR Distillers, over the telephone, quotes an indicative bulk price for anhydrous alcohol of $1.07 per litre, but emphasise that this is for industrial, rather than fuel, use.

Ethanol from lignocellulose

As technology to convert cellulosic feedstocks to ethanol matures, a far wider range of materials, including cereal crop residues, sugarcane bagasse, and forest and sawmill residues, will become feasible feedstocks for ethanol production. The viability of using residues will be influenced by the amount of residue produced and the costs of collection of the residue and transport to the ethanol production plant. Cost estimates for ethanol from lignocellulose depend on the method of production, but the technology still appears to be in the research stage.

7.4.2 Fuel distribution costs

Changes to the existing gasoline distribution system (from a 'wet' to a more 'dry' system, and adjustments to inhibit corrosion), as well as additional infrastructure to transport and store more fuel on an equivalent energy basis, would inevitably increase the cost of alcohol fuels. The extent to which additional refinery and distribution costs would lead to increased fuel costs to the consumer is not known. In the case of changes to the distribution system, while initial capital outlays may be considerable, the additional cost per litre of fuel may be low owing to the volume of fuel transported through the system. On the other hand, it could be expected that additional costs of transport from refineries, and storage costs, might vary roughly in proportion to the relative volumes of fuel being moved.

7.4.3 Greenhouse gas emissions

Tailpipe Emissions

The ability of either methanol or ethanol to contribute to a reduction in greenhouse gas emissions on a FFC basis is very much influenced by the nature of the feedstock and by the source of power used for the production process. CO_2 emissions from the combustion process alone are fairly similar for alcohol and diesel fuels on an energy equivalent basis, assuming complete combustion.[10]

Table 7.1 reproduces the US value for emissions from diesel and ethanol buses given in Table 2.3. These data are based on six data points in the case of 93% ethanol (E93) and 47 data points in the case of 95% ethanol (E95). All of these buses used the same DDC 6V92TA engine. Motta et al. (1996) have analysed a subset of these data and note no relationship between the emissions and the vehicle odometer readings. Ethanol is used as a petrol blend. The petrol needs to be included for safety (flame visibility) and starting purposes.

Table 7.1

Average, maximum, and minimum values of the tailpipe emissions (g/km) recorded for diesel and ethanol buses undergoing an urban (CBD) drive cycle on a dynamometer

Fuel		CO	THC	OMHCE	NOx	PM	CO_2	C_2H_5OH	HCHO	CH_3CHO
Diesel	**Average**	**7.72**	**1.30**		**21.26**	**0.79**	**1736.97**			
	Max	28.94	1.75		36.75	1.77	2313.75			
	Min	2.50	0.81		11.50	0.06	1436.88			
E93	**Average**	**9.84**			**5.16**	**0.36**	**2119.17**	**1.27**		
	Max	13.88			6.63	0.46	2256.25	2.86		
	Min	1.56			4.13	0.15	1986.88	0.03		
E95	**Average**	**20.62**	**7.02**	**7.59**	**11.37**	**0.31**	**2154.10**	**4.60**	**0.20**	**1.06**
	Max	38.31	21.04	22.24	20.94	0.61	3611.88	21.17	0.40	2.42
	Min	0.69	0.69	3.51	5.00	0.04	1481.88	0.11	0.01	0.03

C_2H_5OH – ethanol emissions
HCHO – formaldehyde emissions
CH_3CHO – acetaldehyde emissions

On a gram CO_2 emitted per kilometre travelled basis, the ethanol buses emitted more than the diesel buses, indicating that the fuel economy of the ethanol buses was below theoretical expectations.

For comparison, Table 7.2 reproduces results obtained from the tailpipe emissions during the Stockholm Bus Project (Mansson, 1997) for ethanol buses undergoing both the ECE-R49 drive cycle, and the Braumschweig drive cycle.

[10] Emissions of CO_2 from ethanol are 64.4 g/MJ, and from diesel 69.7 g/MJ. Emissions of CO_2 from the combustion of one litre of fuel are 1.5 kilograms for ethanol, and 2.7 kilograms for diesel.

Table 7.2

Emissions (g/MJ) for Stockholm ethanol and diesel buses

Fuel	CO	THC	NO_x	PM
"1994" Diesel	1.39	0.33	2.5	0.11
Ethanol ECE-R49 cycle	0.014	0.044	1.06	-
Ethanol Braumschewing cycle	0.004	0.039	1.81	0.011

Source: Mansson, (1997)

7.4.4 Full-cycle emissions

Full fuel-cycle estimates of ethanol (Blinge, 1998; IEA 1999c) indicate that the source of the ethanol is crucial in determining whether ethanol is greenhouse-friendly in relation to diesel.

Blinge (1998) has produced full-fuel-cycle estimates of emissions from ethanol buses under three life-cycle scenarios, namely:

Case 1 - raw materials and energy are waste products from pulp production and are, according to LCA allocation rules, regarded as "free".

Case 2 - waste steam used in the process could be used in other applications (e.g. district heating). The steam thus has an economic value and is included in the LCA.

Case 3 - Steam is produced from oil in a thermal power station and all energy is included in the LCA.

The results for energy, the resulting total CO_2 emissions, fossil CO_2 emissions and other emissions reproduced in Table 7.3.

Table 7.3

Life-cycle (g/km) emissions from Stockholm ethanol bus

	Case 1	Case 2	Case 3
Total Energy (MJ/km)	21.6	32.44	38.16
Total CO_2	1505	2258	2660
Fossil CO_2	36.36	36.36	152.4
CO	0.31	0.31	0.32
THC	0.47	0.47	0.48
NO_x	7.94	7.94	8.16
PM	0.09	0.09	0.12

Source: Blinge (1998: Table 4.3, p.88)

The Canadian Renewable Fuels Association claims that if corn farmers use state-of-the-art, energy efficient and sustainable farming techniques, and ethanol plants integrate state-of-the-art production processes, the amount of energy contained in the ethanol and its co-products can be more than twice the energy used to grow the corn and convert it into ethanol (http://www.greenfuels.org/ethaques.html)

Their claim is based on the fact that ethanol contains about 23.6 MJ per litre (high heating value)[11]. The energy content, however, may not be as important as the energy replaced. Due to the higher combustion efficiency of ethanol and its octane credit at the refinery, for example, ethanol can replace 28.1 MJ of gasoline (Levelton Engineering Ltd. and $(S\&T)^2$ Consulting Inc.).

[11] Also known as Gross Calorific Value

Using the displacement value for calculating the energy content of co-products, there is a further 3.9 MJ/litre of energy in ethanol represented by the co-products. The total energy contained in a litre of ethanol is therefore 32 MJ. It takes about 5 MJ of energy to grow the corn required for one litre of ethanol. This is about 15.5% of the energy in the ethanol and the co-product. It takes a further 14 MJ (43.9% of the energy in the ethanol) to process the corn to ethanol using current technology and practices. It is expected that fully optimized plants will be able to lower this to 11 MJ (35.0%) in the near future.

The IEA estimates of FFC greenhouse gas emissions from ethanol are given in Tables 2.8 and 2.9.

Because the major consumer of energy in the ethanol chain is the ethanol processing plant, emissions from the use of ethanol could be improved significantly if there were scope for reducing fossil energy consumption on the plant. Taschner (1991) and Colley et al. (1991) have drawn attention to the effect of using co-products of ethanol production (such as cereal straw) as an energy source, rather than leaving it to release greenhouse gases through decomposition. When ethanol is derived from wastes produced during processing sugar and starch crops for other purposes, a significant greenhouse benefit might be realised, if fossil fuel use could be attributed to the primary product (for example, gluten or starch).

If ethanol substitution for diesel is to provide a major reduction in transport greenhouse gas emissions it will need to be demonstrated that it is both technically and economically feasible to produce ethanol on a large scale from lignocellulose processes.

We have estimated the fuel-cycle emissions from ethanol on the basis of the US E95 bus results, along with the data stored in the RMIT database, and the details given by Kadam et al. (1999) on the life-cycle production of oxygenates from biomass.

Table 7.4

E95 Bus – emissions in g/km

Class	Fuel Production	Combustion	Total
CO_2	-650	1,467	817
CH_4	0.11	0.10	0.21
N_2O	0.00	0.02	0.02
CO	2.00	14.60	16.60
NOx	0.34	7.83	8.17
NMVOC	0.38	4.85	5.23
Particles	0.154	0.209	0.363

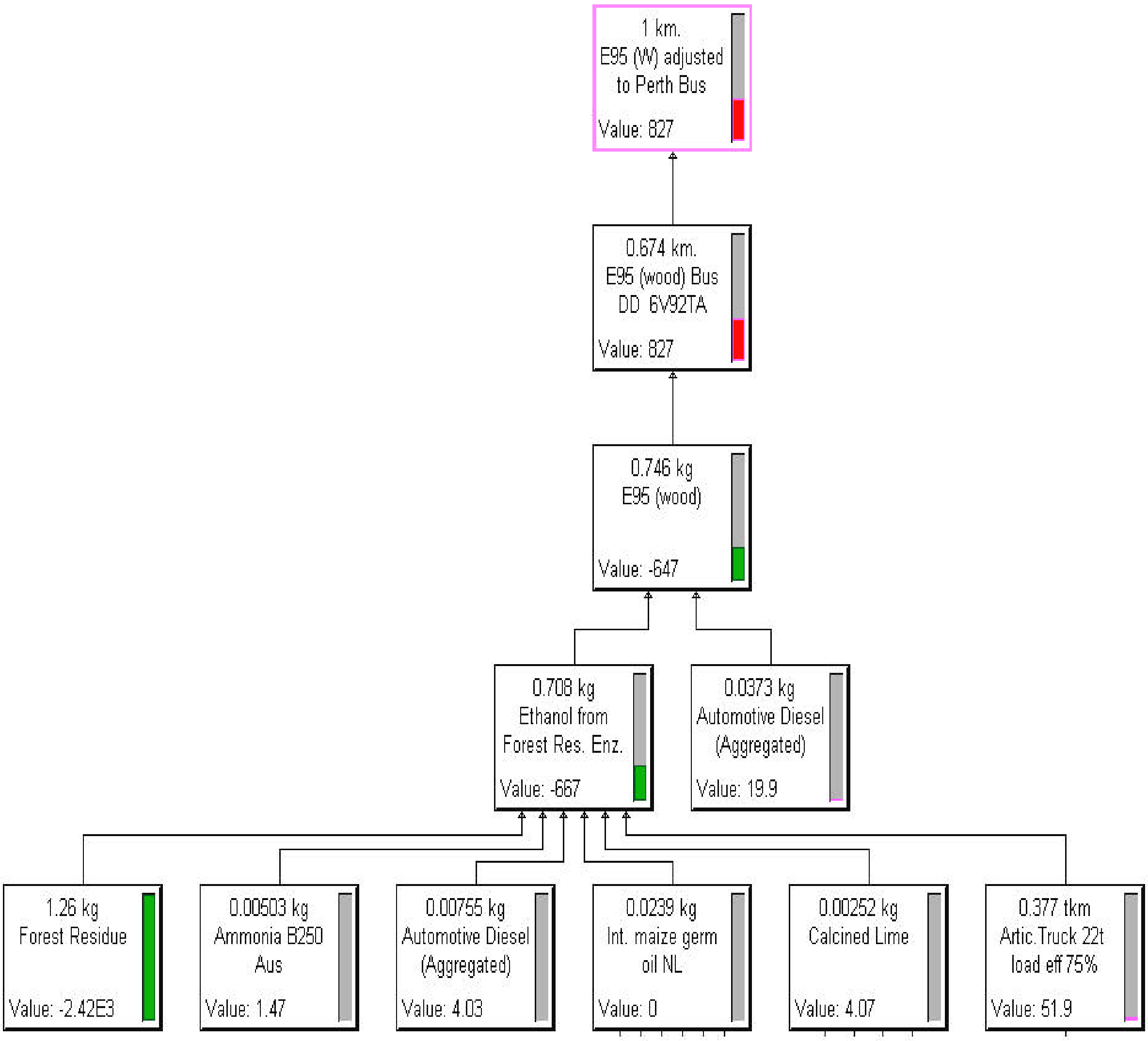
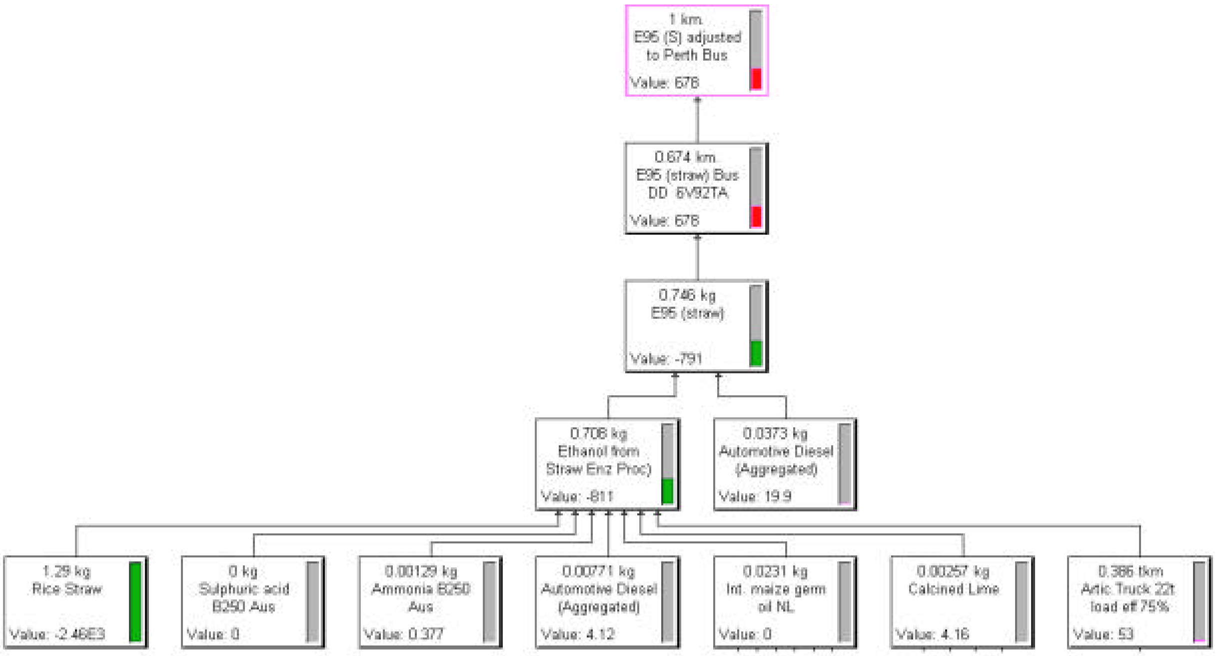


***Figure 7.3**

E95 (wood) Value = grams CO_2 eq

Process tree of fuel-cycle CO_2 equivalent emissions per kilometre travelled for an ethanol bus with ethanol derived from wood

* E95 Detroit diesel (DD6V923A) has been adjusted to match an equivalent fuel consumption of the Perth bus study based on a ratio of the Detroit diesel usage to Perth bus study diesel usage.



[#] Figure 7.4

E95 (straw) Value = grams CO_2 eq

Process tree of fuel-cycle CO_2 equivalent emissions per kilometre travelled for an ethanol bus with ethanol derived from straw

[#] E95 Detroit Diesel (DD6V923A) has been adjusted to match an equivalent fuel consumption of the Perth bus study based on a ratio of the Detroit Diesel diesel usage to Perth bus study diesel usage.

7.5 Carbon Monoxide Emissions

Carbon monoxide (CO), produced from the incomplete combustion of carbon in the fuel, is probably the least important of the noxious vehicle emissions in Australian cities, in that levels of carbon monoxide are generally below accepted levels (State of the Environment Advisory Council, 1996: Chapter 5).

BTCE (1994) quotes reduced CO emissions when ethanol replaced diesel in Swedish buses. This was not the case in the ethanol buses used in the United States, and the IEA (1999c) results quoted in Table 2.8 also do not support it.

7.6 Sulfur Dioxide Emissions

Alcohol does not contain sulfur atoms. An increase in the alcohol content of a fuel will thus automatically reduce emissions of sulfur dioxide. (Vehicles running on 100 per cent ethanol could emit a very small amount of sulfurous compounds via combustion of the lubricating oil.)

7.7 Oxides of Nitrogen

Nitrogen oxides (NO_x) formed during the high temperature combustion of nitrogen and oxygen are involved in a complex series of reactions in the atmosphere leading to photochemical smog. Compounds in smog include respiratory and eye irritants and particulate matter that reduces visibility and affects health.

NO_x emissions from ethanol are lower than from diesel, even without a catalytic converter. This is evident in the results of the US ethanol fleet given in Table 7.1 and 2.7.

7.8 Volatile Organic Compounds (VOCs)

VOCs play a role in the formation of photochemical smog. Some VOCs produce a detectable odour; others are carcinogenic.

7.8.1 Exhaust VOC emissions

Exhaust emissions of VOCs from alcohol vehicles consist mainly of unburnt ethanol, as shown in Table 7.1. Also, comparisons of exhaust emissions of VOCs from different vehicles, or the same vehicle in different tests, should be interpreted cautiously, as results can be influenced by a wide range of specific fuel and vehicle factors. A review by the Victorian EPA (1991b) considered VOC composition to be affected by a large number of factors. These factors included fuel characteristics such as vapour pressure, volatility range, and aromatic, olefin and sulfur content; and vehicle factors including engine ignition timing map and management system, engine design, the efficiency of fuel and air mixing and introduction to the engine, the time required for both engine and catalytic converter to reach efficient operation, catalytic converter efficiency at the time of emissions tests, and the composition of catalyst materials.

7.8.2 Evaporative VOC emissions

Evaporative emissions of VOCs from vehicles increase when the vapour pressure of the fuel is increased or the ambient air temperature rises (Carnovale et al. 1991).

Diesel fuel has very low vapour pressure, but the addition of alcohol to diesel (for example diesohol) creates a fuel with a vapour pressure similar to that of gasoline. While modern gasoline vehicles have some evaporative emission control measures, diesel vehicles do not. Evaporative emissions may be a significant problem from unmodified vehicles using diesohol, but this needs to be tested.

To contain evaporative emissions from vehicles using alcohol fuel, measures may need to be implemented to control fuel vapour pressure, and control evaporative emissions from diesel fuel vehicles.

7.9 Other Emissions from Alcohol Fuels

Particulates from the incomplete combustion of fuel and from the combustion of lubricating oil contribute to the discharge of particles into the atmosphere, reducing visibility and affecting human health. With diesel vehicles, emissions of SO_2 form very fine droplets of sulfuric acid that become visible as particles in the atmosphere.

The utilisation of high alcohol content ignition-improved fuels in heavy-duty engines leads to a reduction in particulate emissions, as shown in Tables 2.11 and 7.1.

7.10 Diesohol

Work in Australia by APACE Research Ltd has produced an ethanol and diesel emulsion called ‘diesohol’. APACE claims that a diesohol emulsion containing up to 30 per cent ethanol will run in a diesel engine, with the engine requiring little or no modification. An unmodified heavy-duty diesel truck running on diesohol containing 15 per cent ethanol attained the lowest 'greenhouse gas index' in the Australian 1992 Energy Challenge sponsored by the New South Wales Office of Energy. The ACTION bus fleet in Canberra trialed three new buses running on diesohol (Scott et al. 1995; Joseph, 1996). Sydney buses also used such buses, until 1998, from their Burwood depot (Figure 7.1)

Diesohol is a blend of diesel fuel (84.5%), hydrated ethanol (15%) and an Australian developed emulsifier (0.5%). Hydrated ethanol is ethyl alcohol that contains approximately 5% water. The emulsifier is an important component in the preparation of the fuel. It has been developed by APACE Research.

The tests on diesohol that were conducted by the NSW EPA (Scott et al. 1995) compared the performance of three ACTION ethanol-fuelled buses with three buses fuelled by diesel. The results are summarised in Table 7.5.

Table 7.5

Results of emission testing of diesohol buses

Pollutant	Result (+ indicates increased emissions)
CO_2	0%
CO	+21%
NOx	-11.5%
Smoke	-50%
HC	0%

7.11 Emissions Summary: Alcohol Fuels

Ethanol has the potential to reduce greenhouse gas emissions from the transport sector, but would need to be produced from biomass (and for the most part from the lignocellulose) to make a significant contribution to reduction in these emissions. However, whether reductions in greenhouse gas emissions will in fact be available from use of ethanol depends on the circumstances of the particular case.

Where the non-lignocellulosic fraction of crops is used, the source of energy for processing and the use made of the lignocellulosic fraction will be important in determining the net emissions. For example, use of crop residue such as bagasse to replace a fossil fuel when it would otherwise be left to decompose (liberating CO_2), would assist in achieving an overall saving in emissions. Use of non-fossil fuel for energy would only be an advantage if it replaced existing crops (rather than forest). Even where lignocellulose is utilised, the potential contribution will vary with the type of feedstock (municipal waste, trees, crops), and the extent to which it displaces other biomass. Land availability, the economics of production, use of fertilisers and transport needs will also influence the outcome.

In the urban environment the situation is uncertain. The results that we have examined indicate reductions in emissions of NOx and particles, but increases in emissions of hydrocarbons and CO.

7.12 Conclusion

To be able to achieve any significant reductions in emissions of greenhouse gases by using alcohol fuels, the ethanol will need to be produced from the lignocellulose fractions of biomass. However, it has yet to be demonstrated that the large-scale production of alcohol from lignocellulose can be technically feasible and economically viable. This was the situation six years ago (BTCE, 1994) and appears still to be the case.

Alcohol fuels in some instances can lead to urban air quality benefits; but it is difficult to generalise. Some emissions increase and others decrease. The Canadian Renewable Fuels Association web site (http://www.greenfuels.org/emissionsimpact.html), for example, claims that all criteria pollutant and hydrocarbons decrease for both low blend and high blend ethanol. The available data do not support such a claim, especially in the case of heavy vehicles. Evaporative emission controls for vehicles would be important if low percentage alcohol blends were to be used especially with gasoline, but probably also with diesel. Ethanol in high percentage blends (or neat) replacing diesel in urban buses offers some air pollution reductions. Emissions from ethanol in low percentage blends replacing diesel (diesohol) confirm the reductions in particle levels, but again some emissions increase while others decrease.

Chapter 8

Fuels from Vegetable Oil

8.1 Canola

Diesel engines initially perform to much the same standard with pure vegetable oil as with diesel (BTCE, 1994). In the past pure vegetable oils have been mainly used in tractors on farms. Pure vegetable oils create problems in turbocharged direct injection engines with charge air coolers, such as those used in trucks.

Table 8.1 compares some of the physical and chemical properties of diesel and canola oil. Vegetable oils have slightly higher density than diesel, but slightly lower energy content (gross calorific value). Vegetable oils have a lower carbon content than diesel, which means lower CO_2 emissions per litre of fuel burnt. CO_2 emissions per kilometre travelled may not be lower, however, due to the lower energy content of the vegetable oils and a higher proportion of multi bonded carbon compounds. The major difference in physical characteristics between canola and diesel is in the viscosity. Canola is over 12 times as viscous as diesel at 20^oC, and remains more than six times as viscous even after heating to 80^oC.

Table 8.1

Comparison of typical properties of diesel, canola oil and biodiesel

	Diesel	Canola	Biodiesel
Density (kg/L)	0.835	0.922	0.88
Gross calorific value (MJ/L)	38.3	36.9	33.3
Viscosity (mm^2/s @ 37.8^oC)	3.86	37	4.7
C:H:O ratio (by mass)	86:14:0	78:10:12	57:9:8
Sulfur (%)	0.15	0.0012	<0.01

Source: Adapted from Table 6.1 of BTCE (1994) and from www.afdc.doe.gov. The C:H:O ratio for biodiesel is taken from http://www.biodiesel.org/fleets/summary.shtml#attributes

These high viscosity levels create problems for the use of canola as a pure fuel. The flow of the fuel from tank to engine is impeded, which can result in decreased engine power. Fuel filter blockages may also occur. The multi-bonded compounds pyrolyse more readily and engines can suffer coking of the combustion chamber and injector nozzles, and gumming, and hence sticking, of the piston rings. A progressive decline in power results. If left unchecked, dilution of the crankcase oil can lead to lubrication breakdown. Long term tests have verified that there is a build-up of carbon deposits in the injection nozzles and cylinder heads.

The viscosity problem can be mitigated by preheating the oil and using larger fuel lines, by blending diesel and canola, or by chemical modification (i.e. producing biodiesel). Canola is completely miscible with diesel. A 50-50 blend of canola and distillate will have a viscosity level less than three times that of pure distillate at 40^oC.

Apart from the viscosity difficulties, canola may result in starting difficulties due to a high temperature being required before the oil will give off ignitable vapours. It also has a relatively slow burn rate as a result of the low cetane rating, which makes canola unsuitable for high speed engines.

According to the Australian Financial Review (Bolt, 1999) canola prices in Australia slumped by 25 per cent during 1999 to a cash price of $280 a tonne. Canola production in Australia soared from 170,000 tonnes in 1991-92 to an estimated 2.1 million tonnes in the year 2000. A similar situation exists in the United States where soybean producers also face an excess of production capacity. Product surpluses and declining prices provided much of the impetus for the current interest in fuel production from oilseeds.

We have been unable to locate emissions data for heavy vehicles using canola, consequently we rely on data for the very similar rapeseed oil. According to BTCE (1994) the presence of oxygen in biodiesel, and its lower viscosity relative to pure vegetable oil, would ensure better combustion in the engine. Available evidence is that, compared with pure vegetable oils, emissions of CO, HCs and particulates are lower for biodiesel.

A detailed study for the Society of Automotive Engineers (SAE) in Germany, comparing engine performance and exhaust emissions from diesel and pure rapeseed oil, was completed in 1991 (Hemmerlein et al. 1991). A range of engines was tested, including those in tractors, underground vehicles, heavy-duty vehicles (HDV), building machines, generators and pumps. All of the combustion systems used in modern diesel engines were covered. The discussion below concentrates on the on-road vehicles. However, the percentage changes in emissions quoted relate to the whole range of engines tested, as separate figures were not provided for each category of on-road vehicle. The figures are clearly influenced by the combustion system, power output and capacity of the various engines, which varied from 40 to 274 kilowatts, and 1.6 to 12 litres respectively.

Table 8.2

Comparison of emissions from use of rapeseed oil and diesel fuel

Emissions	HDV
CO	d
HC	d
NO_x	=
Particulates	dd
Aldehydes and ketones	dd
Aromatic hydrocarbons	dd
PAH	d
Exhaust-gas smell	d

= Rapeseed oil equal to diesel fuel
d Diesel fuel better than rapeseed oil
dd Diesel fuel clearly better than rapeseed oil
Combustion system
Direct injection, turbocharged, charge-air cooler (heavy-duty trucks).
Source Adapted from Hemmerlein et al. (1991) and BTCE (1994).

Energy consumption and engine performance from the use of rapeseed oil and diesel were found to be similar (Hemmerlein et al. 1991).

Exhaust emissions were higher from the use of rapeseed oil despite its higher oxygen content. Although oxygenated fuels are believed to burn more completely in an internal combustion engine, this generalisation relies on other fuel properties being the same. This is not the case for vegetable oils. CO emissions were up to 100 per cent higher (this was not dependent on engine size nor the combustion system) and HC emissions up to 290 per cent higher for all engine types, depending on the operating range of the engine. The slower combustion and lower maximum temperature in the combustion chamber from using rapeseed oil reduced NO_x emissions by up to 25 per cent.

Particulates emissions from HDVs were reduced by 90 to 140 per cent. Aldehydes and ketones were 30 to 330 per cent higher with rapeseed oil. Emissions of aromatic hydrocarbons were significantly higher, regardless of engine type and operating conditions. PAH emissions increased by 10 to 140 per cent in both LDVs and HDVs. The intensity of exhaust smell was 10 to 130 per cent higher with rapeseed oil.

The SAE experiments revealed that neither direct injection engines (HDVs) nor swirlchamber engines (cars) are suited to operate with 100 per cent rapeseed oil. These two engines failed because of either sustained engine damage, a deterioration in torque output, or particulate emissions.

8.2 Biodiesel

Biodiesel is a generic name for fuels obtained by esterification of a vegetable oil. This produces a fuel with very similar properties to pure diesel, but with an improved emissions performance. Often biodiesel refers to rapeseed oil methylester (RME), the main European biodiesel. Esterified soybean oil is the main US source of such fuel, called Soy diesel. Figure 8.1 depicts a flow chart of the esterification process.

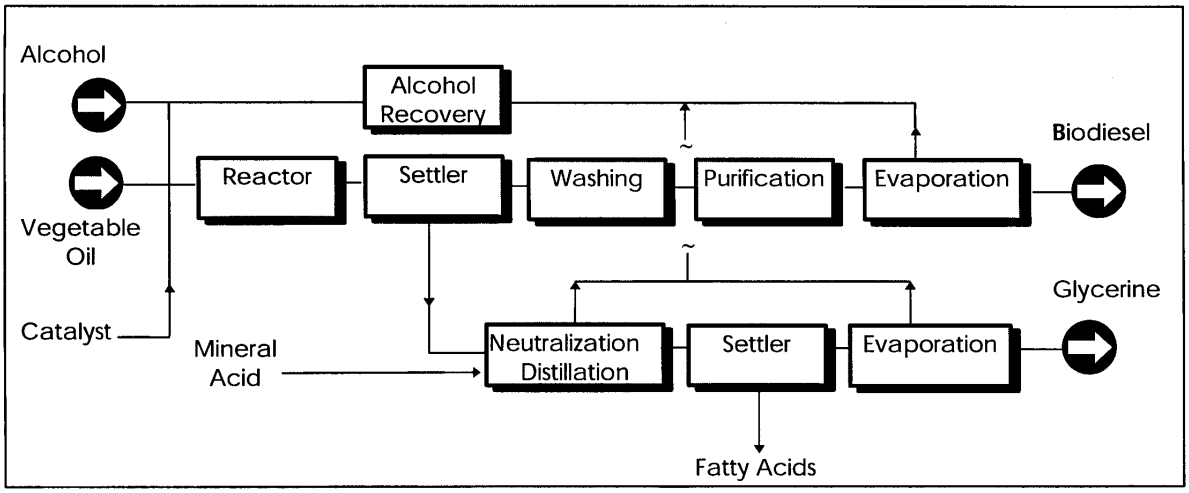


Figure 8.1

Flowchart of the process of esterification to create biodiesel fuel

Biodiesel can be used in a diesel engine without modification. Mittelbach (1998) quotes a cetane number of 48 for pure biodiesel (from rapeseed) but notes that this can be increased to 59 if the biodiesel is made from the ethyl esters of tropical oilseeds. Mann (1998) claims a cetane number of 56 for soydiesel. The fuel consumption of biodiesel per kilometre travelled is very similar to that for diesel. As shown in Tables 2.10 and 2.11 the fuel consumption (as inferred from CO_2 emissions) is higher for buses using biodiesel or 20% biodiesel blend (BD20), but on average was lower for the heterogeneous heavy-duty vehicle fleet. Buckmann & van Malsen (1997) give the relative fuel consumption of diesel and biodiesel on an energy basis, on a volumetric (i.e. per litre) and on a gravimetric (i.e. per kg) basis.

The greenhouse gas emissions arising from the process depicted in Figure 8.1 depend on the amount of fossil-fuel involved in the production of the alcohol. If methanol is used then this process is described by the equation.

$$C_3H_5(OOCR)_3 + 3CH_3OH \text{ ? } 3RCOOCH_3 + C_3H_5(OH)_3$$

(Triglyceride) (Methanol) (Methylester) (Glycerine) as given by Sheehan et al. (1998: p. 147), who assume that 5% (by mass) of the carbon emissions are fossil-fuel carbon. We have assumed that all of the biodiesel is of renewable origin because Australia is more likely to use ethanol in the production of biodiesel than methanol.

8.3 Production of Biodiesel

World-wide production facilities of biodiesel comprise 1.3 million tonnes. The real total production for 1997 is estimated as 660,000 tonnes of biodiesel (Table 8.3).

Table 8.3

Biodiesel Production Worldwide

Country	Capacity [kt/a]	Production [kt/a]
France	315	260
Italy	211	109
Germany	293	105
Czech Republic	63	45
Austria	40	22
USA	136	13
Others	228	107
Total	1,286	661

Source: Mittelbach, (1998)

Austria was one of the first main users of biodiesel. A decentralized plant was built in Mureck in 1991 mainly for the production of rapeseed oil methylesters. Because of the limited availability of rapeseed oil the plant was reconstructed and enlarged also to process used frying oil and other low quality feedstock. The European Commission is funding a study in Graz, to examine the feasibility of collecting waste edible oils and fats within the city and to use the resulting waste oil in a local vehicle fleet (Mittelbach, 1998).

8.4 Tailpipe Emissions

The extensive use of biodiesel fuels in the United States and Europe means that data are available on their emission characteristics during operational performance. Such data, from the United States, are summarised in Tables 2.10 and 2.11. Motta et al. (1996) noted that the large scatter in the data meant that they could claim no significant difference between emissions of diesel and BD20. Tests on extra buses have not altered this situation, as shown in Table 2.10. The data in Table 2.7, however, indicate that the average particulate emissions from the heterogeneous heavy vehicles using biodiesel were higher than those from vehicles using diesel on their own.

Due to the absence of sulfur and the presence of oxygen in biodiesel one would expect theoretically lower particulate emissions. In practice one finds the exact opposite. Variability in the emission of pollutants derived from small amounts of incomplete burnt fuel (CO, VOC and particles) characteristic of emission testing using drive cycles (even between nominally identical vehicles) may mask such changes.

Spataru and Romig (1995) examined emissions from a DCC 6V92TA motor on an engine dynamometer, when both soya and canola methyl esters were used in blends with ordinary diesel and low sulfur diesel (California diesel). Their results are given in Table 8.4.

Table 8.4

Engine dynamometer results (g/kWh) of emissions from a 20% blend of various biodiesel with diesel

	CME20/Diesel	CME20/LSD	SME20/LSD
Total PM	0.32	0.34	0.36
Total HC	0.49	0.59	0.64
NO_x	7.87	7.44	6.31
CO	1.40	1.61	1.50
CO_2	875	877	924

Source: Spataru and Romig (1995) CME20 = 20% Canola methylester; SME20 = 20% Soy methylester

On the basis of the results in Table 8.4 it appears that biodiesel made from canola emits less greenhouse gases than soy-biodiesel.

The European data lead to slightly different conclusions to the US study (Buckmann and van Malsen, 1997). Figure 8.2 compares the results of different studies and gives a graphical representation of the values in Table 2.8. It gives an indication of the effect on the tailpipe emissions if diesel fuel were substituted by pure biodiesel. The European data support two conclusions:

- Biodiesel gives a reduction in hydrocarbon emissions
- Vehicular CO_2 emissions are not affected significantly by use of biodiesel.

However the US data do not give the same results.

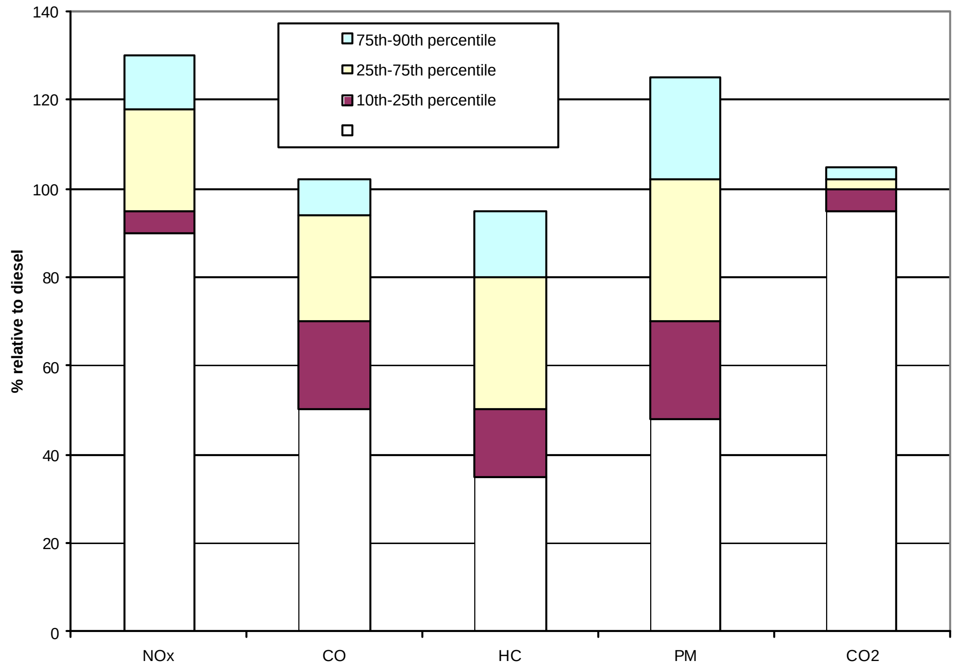


Figure 8.2

Emissions of biodiesel relative to diesel
(Based on Buckmann & van Malsen, 1997)

CO tends to be lower for biodiesels, NOx tends to be slightly higher. Particulate emissions could also be a little lower, but the results of different tests give a range of different values. The sulfur content is also much lower than that of regular diesel oil. Thus, in terms of vehicular use, biodiesel and conventional diesel do not differ much. Application of biodiesel shows only minor problems; application of conventional diesel is more favourable on an energy basis; biodiesel on the other hand has the advantage of lower emissions (except for NOx). However, when looking at the main advantage of biodiesel, the reduced greenhouse gas emissions, the whole fuel chain should be considered - from production of the fertilisers used in farming to the use of the fuel in the vehicle. In other words, one has to consider the fuels on a well-to-wheel basis.

8.4.1 Air Toxics

The US National Biodiesels Board has summarised studies on the air toxics emitted during biodiesel combustion, compared to diesel combustion. These results, given on the web site (http://www.biodiesel.org/fleets/summary.shtml#attributes), are reproduced in Table 8.5.

Table 8.5

Gaseous PAH levels (μg/cycle) of diesel fuel and a 50% biodiesel diesel blend.

	Diesel	**50% Biodiesel**
Naphthalene	331,654	384
Methyl-2 Naphthalene	10,289	329
Fluorene	1,864	368
Anthracene	4,301	873

8.5 Life-Cycle Emissions

8.5.1 European work

Studies show that, on an energy basis, biodiesel is 6.5 to 10 times as expensive as diesel from crude oil (IEA, 1995; Heinrich et al. 1992) This means that the competitiveness of biofuels depends on government intervention, whether by taxation, subsidy or legislation. Beside the costs per litre, there is a second reason why driving on biodiesel is not the most economical choice: its lower calorific value causes an increase in fuel consumption - 8% more fuel (by volume) must be used, which is approximately 13% more by mass.

There are three important factors influencing the energetic comparison of diesel oil and biodiesel (see Table 8.6): the energy input for biodiesel, the energy input for fossil diesel and the energetic value of the by-products of biodiesel production.

Table 8.6

Comparison of the energy input for biodiesel and diesel oil

Biodiesel	**Diesel oil**
Production of seed, fertiliser and pesticides	Extraction of crude oil
Production of crop (cultivating land, sowing, harvesting)	Transport
Transport	Production of diesel oil (refinery)
Oil extraction	Distribution (transport)
Esterification	
Distribution (transport)	

8.6 By-Products

During the production of biodiesel, by-products are formed. Straw, for instance, is a by-product of the production of rapeseed and the esterification of rapeseed oil produces glycerine. These by-products have a certain energetic value, the magnitude of which depends very much on the method used to determine energy-content. One way to express energy content is the calorific value of the by-product; another way is in terms of substitute energy - that is the energy saved when a certain fuel is replaced by use of the by-product. Thus the energy stored in the by-products cannot be compared directly with the energy value of biodiesel. The energy contents of, for instance, straw cannot serve directly as a diesel combustion fuel. For this reason, the energy stored in by-products is considered of lower quality than the energy stored in biodiesel or diesel oil.

8.7 Energy Balance

The energy balance can be used to determine life-cycle CO_2 emissions. The energy input required for the production of biodiesel is shown in Table 8.7, based on the comparison of 26 studies reported in the literature (Scharmer & Gosse, 1996)

Table 8.7

Energy balance for biodiesel.

	[GJ/ha]
Input	26-35
Output (RME)	42-50
Output (by-products)	31-37

There is a significant range of values; differences arise through different assumptions, for instance, about the yield per acre or the energy needed for esterification.

Table 8.7 shows that the energy needed for the production of biodiesel is very high. When all input energy is accounted to the biodiesel, this amounts to 0.62 to 0.70 MJ/MJ biodiesel while for conventional diesel this is only 0.10-0.14 MJ/MJ diesel. If fossil fuels are used to produce biodiesel, this is mostly a matter of fuel substitution, yielding only 15 to 16 GJ per hectare (RME). Thus the by-products (31- 37 GJ/hectare) can, in fact, be regarded as the main product of the process. They only contain however low-grade energy.

8.7.1 Other greenhouse gases

CO_2 is not the only greenhouse gas to be considered - other gases such as nitrous oxide and methane should also be taken into account. Table 8.8 reproduces the in-process greenhouse gas emission estimates of Buckmann & van Malsen (1997). Nitrous oxide, especially, plays a significant role in the comparison of diesel oil and biodiesel as it is emitted during the production of biodiesel but not during the production of diesel oil (Reinhardt 1994).

Table 8.8

Well-to-wheel greenhouse gas emissions (kg CO_2 - equivalent per GJ diesel and biodiesel)

kg CO_2 equivalent/GJ	Diesel	Biodiesel (RME)
CO_2 emissions	80-82	19-33
Other greenhouse gases	2	26-37
Total greenhouse gas emissions	82-84	59-70

Compared on a well-to-wheel basis the reduction in greenhouse gas emissions of biodiesel (per energy unit) from Table 8.8 is only 17% to 29%.

8.8 US Work

Sheehan et al. (1998a) undertook a comprehensive life-cycle analysis of the use of biodiesel in a bus, and compared this to the life-cycle analysis of the use of diesel in the same bus. They concluded (Sheehan, 1998b) that the benefit of using biodiesel is proportional to the blend level of biodiesel used. Substituting BD100 for diesel in buses reduces the life-cycle consumption of petroleum by 95%. A 20% blend of biodiesel and petroleum diesel (BD20) causes the life-cycle consumption of petroleum to drop 19%.

Biodiesel and petroleum diesel production processes are almost equally efficient at converting raw energy resources (in this case, petroleum or soybean oil) into fuels. Biodiesel's advantage is that its largest raw resource (soy oil) is renewable. So biodiesel requires less fossil energy (only 0.31 units) to make 1 unit of fuel. Biodiesel yields 3.2 units of fuel product energy for every unit of fossil energy consumed in its life-cycle. The production of BD20 yields 0.98 units of fuel product energy for every unit of fossil energy consumed. These US results appear to be in conflict with the European results of Table 8.7.

8.8.1 Reductions in CO_2 emissions

Because biodiesel production requires such small amounts of fossil fuel, its CO_2 life-cycle emissions are, not surprisingly, much lower than those of petroleum diesel. Displacing petroleum diesel with biodiesel in urban buses is an extremely effective strategy for reducing CO_2 emissions. Biodiesel reduces net CO_2 emissions by 78% compared to petroleum diesel. For BD20, CO_2 emissions from urban buses drop 16%.

8.8.2 Air pollutant emissions

Using BD100 in urban buses substantially reduces life-cycle emissions of total particulate matter (32%), CO (35%), and SO_x (8%), relative to petroleum diesel's life-cycle according to the US work (Sheehan et al. 1998).

Biodiesel reduced particulate, carbon monoxide, and sulfur dioxide emissions compared to diesel fuel. Tailpipe emissions of particulates smaller than 10 microns were 68% lower for buses that run on biodiesel (compared to petroleum diesel). Tailpipe CO emissions were 46% lower. Biodiesel completely eliminated tailpipe SO_x emissions.

These reductions in air emissions reported here are proportional to the amount of biodiesel in the fuel. Thus, for BD20, users can expect to see 20% of the reductions reported for BD100.

NO_x is one of three pollutants implicated in the formation of ground-level ozone and smog in urban areas (NO_x, CO, and HCs). Biodiesel increases tailpipe NO_x emissions, and these emission sources dominate its life-cycle NO_x emission levels.

The use of BD100 in urban buses increases NO_x life-cycle emissions by 13%. Blending biodiesel with petroleum proportionally lowers NO_x emissions. BD20 exhibits a 3% increase in life NO_x cycle emissions. Most of this increase is directly attributable to increases in NO_x tailpipe emissions. BD100, for example, increases NO_x tailpipe levels by 9%.

Their results are based on the performance of current fuel and engine technologies.

The biodiesel life-cycle also produces more hydrocarbon (HC) emissions compared to the diesel fuel life-cycle. Most of the biodiesel life-cycle emissions are produced during farming and soybean processing operations. Tailpipe HC emissions are actually lower for biodiesel than for diesel fuel. Total life-cycle emissions of HCs are 35% higher for BD100 than for petroleum diesel. However, HC emissions at the bus's tailpipe are 37% lower.

8.9 Our Estimates

We have used the tailpipe emissions observed in the US bus study of Table 2.6, and combined this with the distribution of life-cycle emissions studies by Sheehan et al. (1998a, b) to produce estimates of the fuel-cycle emissions of 100% biodiesel, and 20% biodiesel.

8.10 100% Biodiesel

Table 8.9

Fuel-cycle emissions,(g/km), of a bus using 100% bio-diesel

Class	Pre-combustion	Combustion	Total
CO_2	512	1189	1701
CH_4	0.219	0.018	0.237
N_20	0.443	0.025	0.468
CO	3.76	6.25	10.28
NOx	3.02	10.51	13.53
NMVOC	2.16	0.79	2.95
Particles	1.15	0.5	1.65

8.11 20% Biodiesel

Table 8.10

BD20 Bus – emissions in g/km

Class	Fuel Production	Combustion	Total
CO_2	37.7	1,312	1,350
CH_4	0.48	-	0.48
N_20	0.08	0.02	0.10
CO	3.01	4.28	7.29
NOx	1.19	23.51	24.70
NMVOC	1.64	-	1.64
Particles	0.250	0.378	0.628

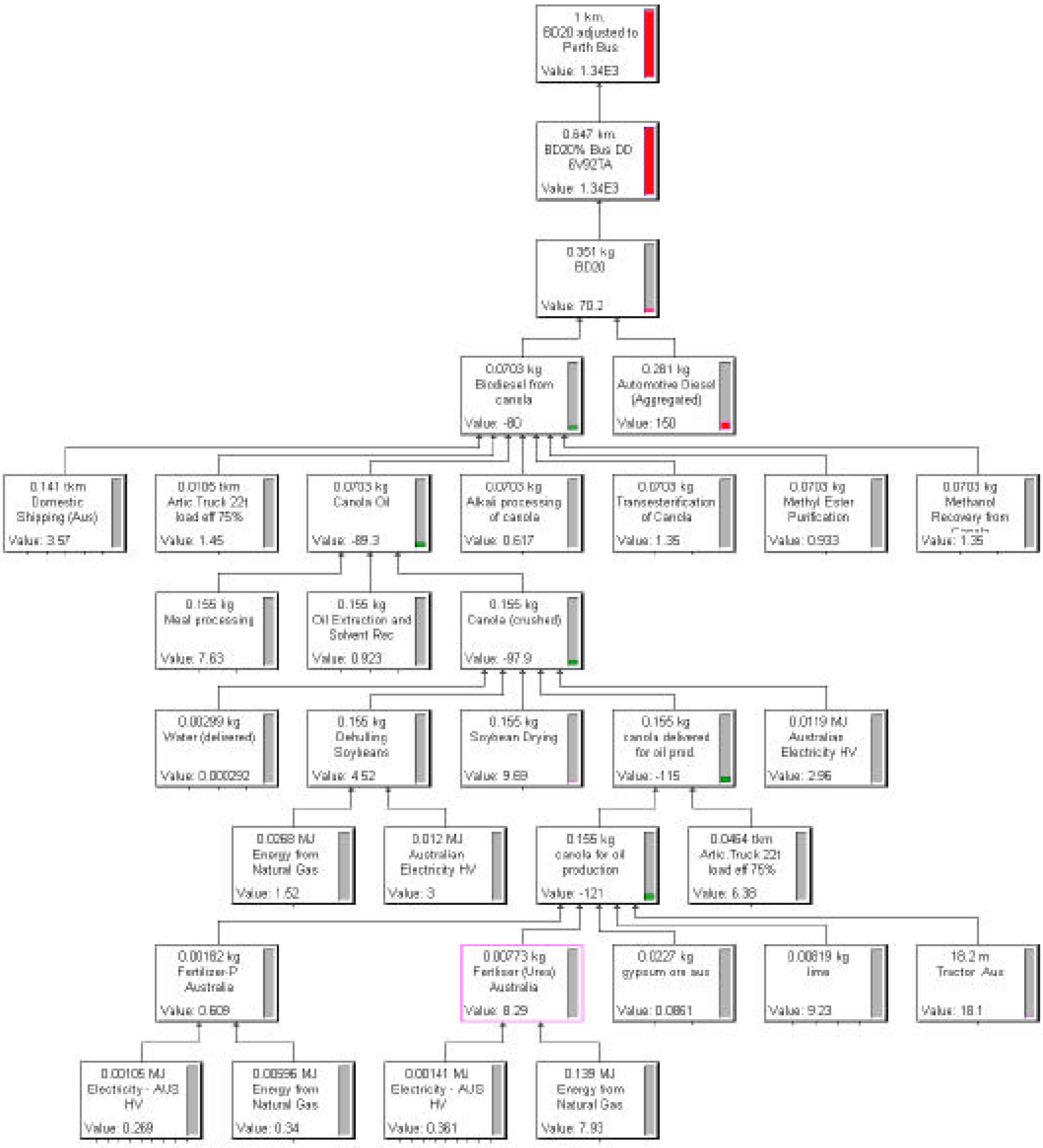


Figure 8.3

Process tree of 20% biodiesel emissions of greenhouse gases
§ BD20 Value = grams CO_2 equivalents

♣ BD20 Detroit diesel (DD6V923A) has been adjusted to match an equivalent fuel consumption of the Perth bus study based on a ratio of the Detroit diesel usage to Perth bus study diesel usage

BD100 Value = grams CO_2 eq

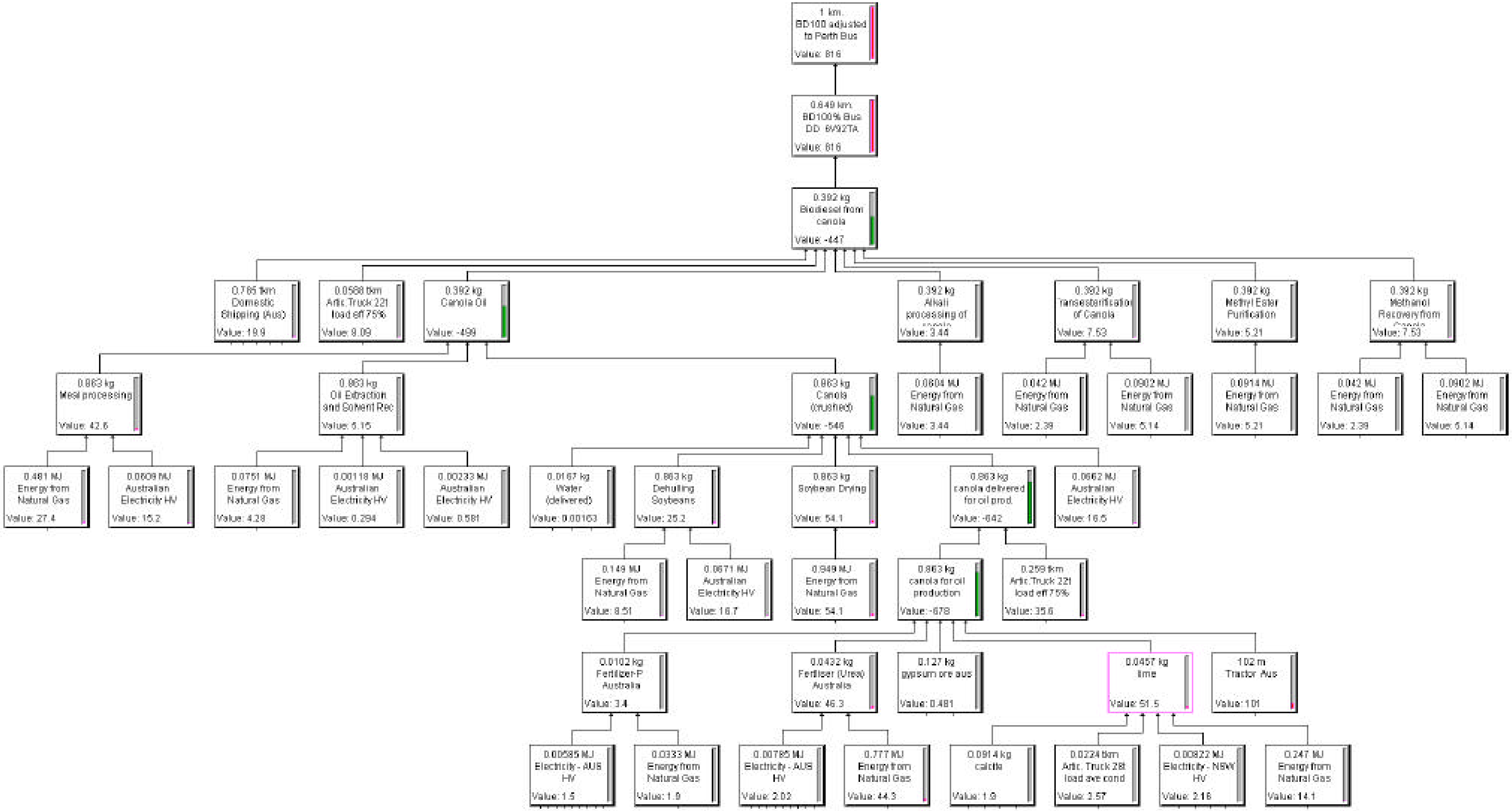


Figure 8.4

Process tree of greenhouse gas emissions from a biodiesel powered bus*

*BD100 Detroit Diesel (DD6V923A) has been adjusted to match an equivalent fuel consumption of the Perth bus study based on a ratio of the Detroit Diesel usage to Perth bus study diesel usage

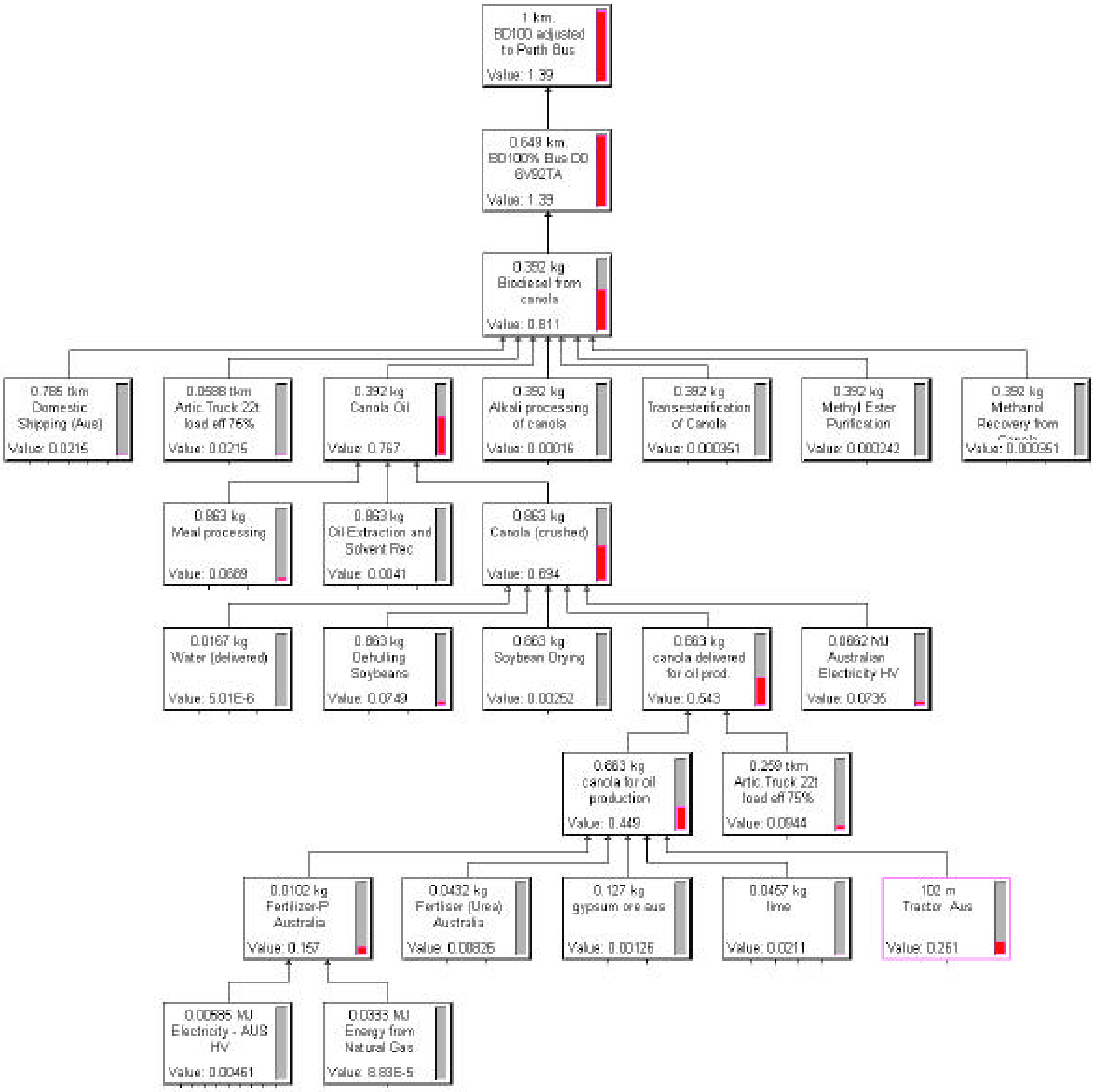


Figure 8.5

Process tree of particulate matter emissions from a 100% biodiesel powered bus
[♠] BD100 Value = grams particles

♠ BD100 Detroit Diesel (DD6V923A) has been adjusted to match an equivalent fuel consumption of the Perth bus study based on a ratio of the Detroit Diesel diesel usage to Perth bus study diesel usage.

8.12 Biodiesel Extenders

In the United States, various biodiesel products are also sold as diesel extenders. Figure 8.6 reproduces the web page of Soy Shield a product of Schaeffer Manufacturing. Similar products are also sold by other companies and are generically known as premium biodiesel.

Figure 8.6

Example of US advertising for biodiesel as diesel extender

Chapter 9

Waste Oil

9.1 Sources and Usage of Waste Oil in Australia

The total production of lubricating oil over the last decade in Australia has been between 631 and 811 ML per annum (Marshall et al. 1999). Part of this oil is exported and the remainder is consumed locally at the relatively static rate of approximately 520 ML per annum for the last decade. Of this oil consumed in Australia about half is lost to the system through uses such as combustion (two-stroke oils), process and spray oils, spills and leaks. The remainder is recoverable waste oil, which has its main origin from automotive sources as shown in Table 9.1.

Table 9.1

Sources of recoverable waste oil in Australia

	'000 tonnes (%)	
Use	**1991 (IC, 1991)**	**Marshall et al. (1999)**
Automotive	161 (67%)	#
Industrial	52 (22%)	#
Other lubricants	14 (6%)	#
Other transport	11 (5%)	#
Total available for collection	239 (100%)	200 (100%)

More detail not given by Marshall *et al.* (1999).

Table 9.2

Uses of uncollected waste oil

	'000 tonnes (%)	
Use	**1991 (IC, 1991)**	**Marshall et al. (1999)**
Dust and vegetation control	83 (53%)	#
*On-site fuel, lubricating	17 (11%)	#
Tip	49 (32%)	#
Illegal dumping	6 (4%)	#
Total	155 (100%)	320 (100%)

* Part of this waste oil is blended with diesel for transport fuel

More detail not given by Marshall et al. (1999).

Of the waste oil available for collection IC (1991) indicates that 65% is not collected and is used as shown in Table 9.2 and 35% is collected and is used as shown in Table 9.3. Calculations based on the Marshall et al. (1999) data seem to give similar percentages, however, the categories used are different and so it is difficult to make a comparison directly. A significant proportion of uncollected waste oil is released into the environment. The impact of such use is mixed giving the benefit of dust and vegetation control but the corresponding cost of oil pollution, for example waste oil in water-ways or ground water, and the long time for oil be break down biologically. Marshall et al. (1999) has noted that it takes only 1 litre of oil to contaminate 1,000,000 litres of drinking water. Most collected waste oil, on the other hand, is not released into the environment directly, but indirectly through combustion (approximately 95%) as fuel in various forms, as shown in Table 9.3.

Table 9.3

Uses of centrally collected waste oil

	'000 tonnes (%)	
Use	1991 (IC, 1991)	1999 (Marshall et al 1999)
* Cement/lime kilns	23.7 (28%)	
* Fuel oil	18.3 (22%)	
* Coal bulk density	11.8 (14%)	
* Brickworks	9 (11%)	96 (75%)
* Sugar mills	1.8 (2%)	
* Oil companies (blended & used as fuel oil)	14.6 (18%) #	
Diesel extender		28 (20%)
Recycled lubricating oil	2.7 (3%)	4(3%)
Dust Suppression	0.5 (0.5%)	
Hydraulic	0.5 (0.5%)	
Other	0.9 (1%)	1 (2%)
Total	84 (100%)	128 (100%)

* Indicated waste oil is used as a fuel with minimal processing.
# This study did not differentiate between waste oil used as fuel oil or as diesel extender.

The recent report by Marshall et al. (1999) attempted to describe and quantify the uses of waste oil and is reproduced with permission in Figure 9.1. In relation to the diagram we note that Group II to V are types of lubricating oils, defined in Marshall et al. (1999, p.16), classified according to methods of production. Most feedstock for lubricating oil is Middle Eastern in origin. The report notes that the recycled oil industry is subject to sudden changes due to market forces and exact quantities are hard to estimate accurately.

Waste oil is of variable quality and chemical composition due to the particular application it was used for. Table 9.4 shows concentrations of various metallic and other materials commonly found in waste oil from some typical applications. Though some of the data are dated, the concentrations are not expected to change significantly, with the exception of sulfur and lead. Diesel fuel is shown for comparison only. It can be seen that concentrations of contaminants vary considerably in the three oils shown in the table.

During the combustion of waste oil or any product derived from waste oil, the contaminants shown in Table 9.4 (unless otherwise removed) will be released into the environment. Though the combustion process will significantly change some of these contaminants, reducing their health impacts, health effects from metals will generally be unchanged by combustion.

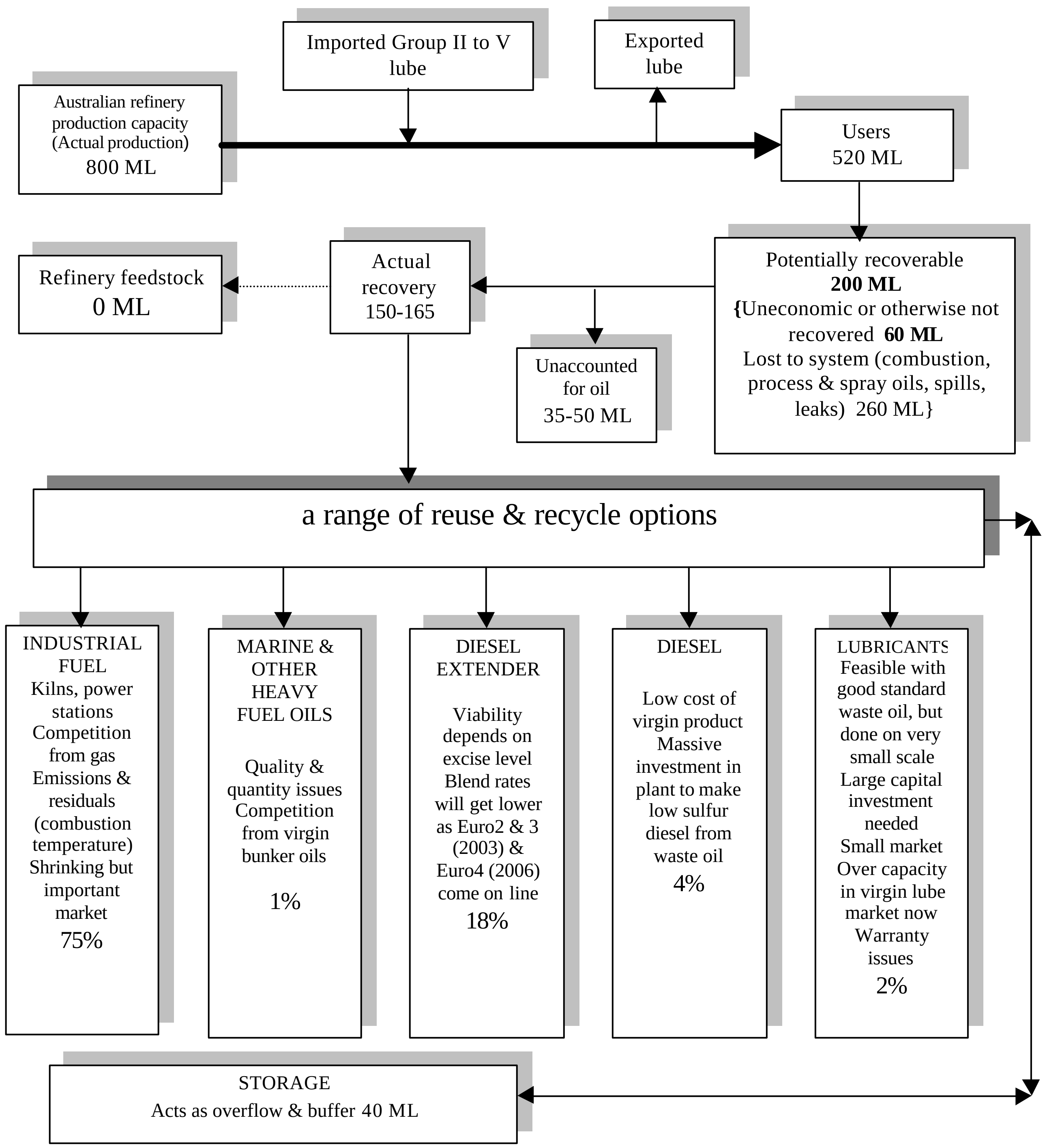


Figure 9.1

Existing flows & volumes of waste oil
(all volumes are best approximations, ? indicates not known) Marshall* et al. *(1999)

Table 9.4

Typical concentrations (ppm) of selected contaminants in diesel and waste oil.

Contaminant	Diesel fuel Aul & Pechan (1993)	Automotive waste oil Blatz (1979)	Locomotive waste oil Blatz (1979)	Centrally Collected Waste oil Aul & Pechan (1993)
Ash	25			6500
Chlorine	100			2200
Nitrogen	300			1000
Sulfur	2400			5000
Aluminium	8			45
Arsenic	0.8			12
Barium	0.5	200	150	66
Cadmium	0.3			1
Chromium	1.3	30	65	6
Iron	12	750	50	240
Lead	1.8		35	1100
Magnesium	6.3	450	20	260
Vanadium	1.6			3
Zinc	3.6	1100	20	800
Copper		50	20	
Tin		20	10	
Calcium		2200	2100	
Phosphorus		950	15	
Boron		50	20	
Sodium		160	310	
Silicon		50	20	
Lead (Gasoline)		7800		

Blank entries indicate no measurement was made, they do not indicate zero reading.

9.2 Methods of Using Waste Oil

This study is concerned primarily with the use of waste oil as a transport fuel. The following two possibilities are available for the use of waste oil in this way.

Use of crankcase waste oil blended directly with diesel fuel

- Option 1.1 Blending at time of vehicle servicing
- Option 1.2 Continuous blending during vehicle operation.

Central collection of waste oil and rerefining to

- Option 2.1 Diesel extender then blended with diesel fuel
- Option 2.2 Diesel quality fuel.

In addition, we consider the following option, which is not a use of waste oil as a transport fuel:

- Option 3 Recycling of waste oil into lubricating oil.

We include Option 3 because the overall objective is to reduce greenhouse gas emissions and recycling waste oil appears to have considerable advantages in this regard.

The term “diesel extender” is used to refer to waste oil that has been rerefined (Option 2) to a level close to that of diesel fuel. Though uses in Option 1 are extending diesel fuel, the term “diesel extender” is not used here because only filtering of the waste oil is necessary. The term “rerefining” is used for Option 2 processes of converting waste oil to diesel extender/diesel but not for Option 1 processes. In Option 3 processes using lubricating oil can be obtained by filtering and centrifuging waste oil so we prefer the term “recycling” in this case.

9.3 *Crankcase Waste Oil Blended Directly with Diesel Fuel*

9.3.1 Option 1.1: Blending at time of vehicle servicing

At present some filtered waste oil collected at the time of servicing is blended with diesel and used as a transport fuel. Only minimal filtering is necessary when waste is used in this way. In the non-transport sector this is common in remote mining locations where oil disposal is difficult. Engine manufacturers give standard instructions for this practice (Caterpillar, 1996). In the transport sector, fleet operators also follow this practice at a central service facility because of the economic benefits of reducing diesel consumption and avoiding waste oil disposal. The exact amount of waste oil used in this way is uncertain but we estimate it to be less than 5% of the total waste oil in Australia. Generally, diesel engines used in transport vehicles can use fuel blended with up to 7% waste oil.

An advantage of using waste crankcase oil in this way is that it is not contaminated by water, engine coolant and grease, typical of the centralised collection system. If stored and blended carefully the waste oil only requires filtering. Care must be taken that additives in the oil such as sulfur compounds do not result in levels of SO_X emissions above allowable levels.

9.3.2 Option 1.2: Continuous blending during vehicle operation

The amount of waste oil used in this way has significantly increased over the last decade due to changes in truck engine technology. Many diesel engines in use in Australian trucks (e.g. Cummins, 2000) use a computerised engine condition monitoring system which continuously blends crankcase oil with diesel fuel and replenishes the crankcase with new oil. This system greatly reduces service intervals and increases engine life. Because the crankcase oil is delivered directly into the same engine there are no problems of contamination. Diesel engines are particularly susceptible to contaminated fuel because the fuel must pass through a high pressure injection pump and then enter the combustion chamber through a very small diameter nozzle. Both of these components may be damaged by contaminants in the fuel or changes in the lubricating properties of the fuel.

Such a system has a number of greenhouse gas emission implications:

- Greenhouse gas emissions from transport of waste oil to a central location are eliminated
- Greenhouse gas emissions due to the extraction, transport and refining of the displaced diesel fuel are eliminated
- Greenhouse gas emissions due to the extraction, transport and refining of virgin lubricating oil will continue to occur
- Greenhouse gas emissions will arise from the manufacture and installation of the on board blending system
- Recycling of the waste oil into new base lubricating oil may contribute less net greenhouse gas emissions than burning the waste oil in a diesel engine. This is because recycling waste oil means that virgin lubrication oil will not have to be made from Middle Eastern crude (with extraction, transport, and refining greenhouse gas emissions). Lubricating oil can not be manufactured from Australian crude oils.

Some facts of relevance are (USEPA, 1996):

- Recycling used oil takes only about one-third the energy of refining crude oil to lubricating quality
- It takes 160 L (42 US gallons) of crude oil, but only 3.8 L (1 US gallon) of used oil, to produce 2.4 L (2.5 quarts) of new, high quality lubricating oil

9.4 *Central Collection of Waste Oil and Processing*

Centrally collected waste oil is generally of low and variable quality and may be contaminated with water and coolant. Waste oil may contain many contaminants as shown in Table 9.4. This oil may be filtered and rerefined into diesel extender or undergo further processing into diesel quality fuel.

9.4.1 *Option 2.1 Diesel extender (derived from waste oil) blended with diesel fuel*

This will require less energy and consequently have lower greenhouse gas emissions than diesel quality fuel. Both diesel extender or rerefined diesel will contain the contaminants in the original waste oil unless they are removed. These contaminants or their derivatives will be released to the environment during the combustion process.

Diesel extender can be blended with diesel up to about 40% depending on its quality.

Diesel extender is obtained from waste oil by one of several rerefining processes (listed in Marshall et al. 1999) and is chemically close to diesel in composition. It generally has a golden colour (unlike the white colour of diesel) and a lower flash point. Thus it cannot be sold as diesel. It also has a stronger odour than diesel.

9.4.2 *Option 2.2. Diesel quality fuel*

Greenhouse gas emissions from production are significantly lower (less than 50%) than for virgin diesel from crude oil as shown in Table 9.7, below. However, to raise the quality of the product from diesel extender to diesel quality fuel, requires extra processing plant. Such a plant involves a high capital cost.

9.4.3 *Option 2.3 Recycling of waste oil into lubricating oil*

Though this is not an option for the use of waste oil as a transport fuel it is included because of significant apparent greenhouse gas emission savings.

Recycling of waste oil was pioneered by the Germans during the early 1940's, and the allied embargo of World War 2). The practice has continued and has been encouraged recently by a levy system on virgin oil, which has been used to subsidise waste oil recovery and recycling. Most lubricating oil sold in Germany now originates from recycled oil. By contrast, in Australia this figure would be only a few percent. South Africa is also a country where a large amount of recycled lubricating oil is sold.

9.5 *Combustion of Hydrocarbons*

Crude oil products are refined primarily on the basis of the length of their hydrocarbon chains. Petrol has a medium length, diesel a longer length and lubricating oil a very long length chain. Hence each of these hydrocarbons have different combustion properties. Longer hydrocarbon chain (and cyclic) products will have the following characteristics compared to shorter chain products

- Higher viscosity
- Lower volatility
- Slower burning rate because long chains must be broken up
- Higher energy content and CO_2 emissions per MJ or per litre
- More unburnt combustion products in emissions, including more particulates

A brief background on the production of particulates during combustion is given below to explain the marked increase in particulates noted in Table 9.5 when oil is blended with diesel fuel. Internal combustion engines have been developed to accommodate these different fuels. Petrol engines are high revving (5,000 r.p.m) and require a quick burning fuel such as petrol. The power of the engine derives from the combustion of the petrol/air mixture at an approximately constant volume. Truck diesel engines are slower revving (1,500-2,000 r.p.m) and derive power from a slower combustion process at approximately constant pressure. It can be shown from the laws of thermodynamics that a diesel engine is inherently more efficient than an equivalent petrol engine. Marine and very large diesel engines are very slow revving (50-500 r.p.m) and use fuel oil that is similar in nature to lubricating oil. Oil is made from hydrocarbon chains that are longer than that of other lighter fuels, which give oil its lubricating properties. The slow combustion of oil (including waste oil) and to a lesser extent diesel is caused by the time required to break up the long hydrocarbon chains before they can react to form CO_2. When this process is not given enough time to complete, carbon (soot) particles result. In a well-run industrial furnace long chain hydrocarbons and particles are maintained at a high temperature for a long time to allow for complete chemical reaction of all carbon to CO_2. Such a long combustion process is not possible in an internal combustion engine.

9.6 Calculations

The focus of this chapter is on the use of waste lubricating oil as a transport fuel. The origin of this waste oil is as follows. About 520,000 tonnes of lubricating oil is sold in Australia each year. About half of this oil is lost to the system and the other half is recoverable. Of the recoverable oil about 35% is actually recovered. Of this recovered recoverable oil about 75% is used as fuel oil, mostly in furnaces, 20% is rerefined into diesel extender, 3% is recycled into lubricating oil and 2% is used for other uses.

Emission factors due to combustion of waste oil in transport vehicles for the gases specified in the consultancy brief are shown in Table 9.5, below. There are only very limited measurements of emissions of diesel/waste oil or diesel/diesel extender blends available. Diesel engine manufacturers such as Cummins and Caterpillar have conducted emission tests on diesel fuel blends in the USA to ensure their engines meet US EPA regulations when they use such blended fuel. The manufacturers have only made very limited information available to the public (Appendix A). In the absence of such direct measurements, we have made use of the fact that waste oil is similar in some petrochemical properties to fuel oil, provided the waste oil is filtered and water removed. We have used the properties of fuel oil from National Greenhouse Gas Inventory Committee (1996; 1998) as approximations for waste oil shown in Table 9.6. Principles of combustion theory have also been used (Glassman, 1987; Dibble, 2000). Many of the gas emissions are unchanged relative to diesel because of the similarities in the properties of waste oil and diesel, however emissions of particulates and, to a lesser extent, visible smoke are particularly sensitive to the addition of oil to diesel fuel. The reasons for this have been explained in Section 9.5 (Combustion of Hydrocarbons).

Table 9.5

Emissions of gas from transport vehicles using specified diesel blends as a percentage of virgin diesel fuel gas emission in the same transport vehicle. All values are best estimates unless otherwise indicated.

Greenhouse	**Diesel/Waste Crankcase Oil Blend**		**Diesel/Diesel Extender**	**Rerefined Diesel**
% blend with diesel	**0.5% + Option 1.2**	**5% Option 1.1**	**40% Option 2.1**	**100% Option 2.2**
Greenhouse Gas				
CH_4	100	100	100	100
CO_2	100*	100.3*	100*	100*
N_2O	100	100	100	100
Non-Greenhouse Gas				
CO	100	100	100	100
NO_X	100	100	100	100
SO_X#	100	100	100	100
(NMVOC)s	100	100	102	100
Visible Smoke	100	110	105	100
Particles	102.5&	125&	103	100

* Calculated by proportioning emissions from Table 9.6 .by blend percentage.

+ Recommended by Caterpillar (1996) for continuous truck engine blending

Since sulfur levels of waste oil can vary considerably we assume that the waste oil or diesel extender has the same sulfur content as the diesel fuel.

& See Appendix A.

Table 9.6

CO_2 emission factors and liquid fuel energy densities by fuel type

Fuel Type	Proportion of Fuel Oxidised	CO_2 Emission Factor (g/MJ)	Energy Density (MJ/L)
Automotive Gasoline	0.99	66.0	34.2
Automotive Diesel Oil	0.99	69.7	38.6
Industrial Diesel Fuel	0.99	69.7	39.6
Fuel Oil	0.99	73.6	40.8
Lubricants & greases		*73.7	

Sources: Abbreviated from National Greenhouse Gas Inventory Committee, 1996, 1998

* http://www.greenhouse.gov.au/inventory/archive/natmethod/energy1/ch2.html#t4

In addition to the emissions due to combustion in Table 9.5 above, the non-combustion life-cycle greenhouse gas emissions of waste oil, diesel extender and recycled lubricating oil are shown relative to virgin diesel in Table 9.7. Prices for diesel extender (64c/L) and rerefined diesel (70c/L) are calculated assuming that the price differences in these products compared to virgin diesel (78c/L) are an indication of the energy (hence emissions) produced. We note that diesel extender is liable for fuel excise at 80% of the rate for virgin diesel. Allowance has been made for large scale efficiencies in the production of virgin diesel. Emissions due to recycling of lubricating oil were inferred from the energy needed (one third) relative to refining virgin lubricating oil as given in USEPA (1996). It has been shown (Scott & Hargreaves, 1991) that recycled lubricating oil is equal in quality and lubricating properties to that of virgin oil.

Greenhouse gas emissions for diesel and waste oil and its derivatives do not vary substantially in Table 9.5, however Table 9.7 shows major differences are evident for non-combustion life-cycle greenhouse gas emissions. The total non-combustion life-cycle emissions shown in Table 9.7 are lowest for waste crankcase oil blended directly with diesel fuel because it requires virtually no treatment storage or handling. However the maximum blend with diesel recommended by most engine manufacturers is only 7%. It is worth noting that substituting waste oil for diesel increases the in-process greenhouse gas emissions associated with the transport of the fuel. Burning waste oil in engines means that virgin lubricating oil must be made from Middle Eastern crude oil instead of being re-refined from waste oil. Bass Straight crude yields only about 0.5% lubricating oil whereas Middle Eastern crude yields about 12% (Scott, 2000).

Table 9.7

Non-combustion Greenhouse life-cycle emissions for diesel, waste oil, diesel extender and recycled lubricating oil. Virgin product total taken as 100%. Best estimates unless otherwise indicated.

Life-cycle step	Virgin diesel or virgin lubricating oil	Waste Crankcase Oil blended		Diesel Extender	Rerefined Diesel	Recycled Lubricating Oil
		directly to engine	At time of vehicle servicing			
		0.5%+ Option 1.2	5% Option 1.1	Option 2.1.	Option 2.2	Option 3
Transport & handling before processing	15*	15	5	5	5	5
Processing	75	0	5	25#	35	25
Transport & handling after processing	10	0	0	10	10	10
Total	100	15	10	40	50	40

* Some of these emissions will be attributed outside Australia.
# USEPA (1996)

9.7 Recommendations for Future Investigation

1. The quantity of waste crankcase oil blended directly with diesel on board trucks is increasing. Measurements need to be made of non-greenhouse gas emissions, visible smoke and particulates for blends of waste crankcase oil (0-10%) and diesel extender (0-100%) with diesel to validate the best estimates made here.

2. Significant differences exist in the relative life-cycle greenhouse gas emissions when waste oil is used to produce recycled lubricating oil or rerefined to produce diesel extender. Further investigation is needed to clarify the difference and determine which option gives the minimum greenhouse gas emissions.

3. Metal contaminants in waste oil need to be measured. Investigation of the health impacts of such contaminants that are released into the atmosphere at the time of combustion should be conducted.

Appendix A: Calculation of Particulate Emissions in Diesel/Waste Crankcase Oil Blends.

Unpublished data from Schneider (2000) regarding the Cummins “Centinel” oil blending system show, that there is an increase of 0.0054 to 0.0081 g/MJ (0.002 to 0.003 g/hp-h) of particulate emissions with a 0.57% oil in fuel blend. The engine-out particulate emissions are around the 0.24 to 0.26 g/MJ (0.090 to 0.095 g/hp-h) level for pure diesel. The increase seen by the addition of Centinel is so small, that it takes several tests to statistically verify the increase.

So from the Cummins data there is approximately a 2.7% increase in particulate matter for a 0.57% blend of crankcase oil. In the absence of other data we assume a linear relationship between percentage blend of crankcase oil and percentage increase in particles. Given the uncertainties in the test data the following formula will be adopted:

(% increase in particulate matter) = 5 x (% crankcase oil blended with diesel)

The values in Table 9.5 are thus calculated.

References*

Andrias, A., Samaras, Z., Zafiris, D. & Zierock, K.H. (1993). CORINAIR Working Group on Emission Factors for calculating 1990 emission from road traffic. Vol 2: Copert: computer programme to calculate emissions from road traffic, user's manual. (Final Report, Document of the European Commission) Brussels: Office for Official Publications of the European Communities. *

Anyon, P. (1998). Liquefied Petroleum Gas as an Automotive Fuel: an environmental and technical perspective. Redfern, NSW: Australian Liquefied Petroleum Gas Association Ltd. *

Anyon, P., chair. (1997). Transport vehicles: report of Task Group 4, Inquiry into Urban Air Pollution in Australia. (Urban Air Pollution in Australia ; Supporting Report; 2) Parkville, Vic.: Australian Academy of Technological Sciences and Engineering. 216 p. *

APACE. (1992). New technology for ethanol production: its use as a transport fuel, presented to the Department of Arts Sports Environment & Territories, 25 February 1992. APACE Research Ltd.

Apelbaum Consulting Group. (1997). The Australian transport task, energy consumed and greenhouse gas emissions. Barton, ACT: Dept. of Primary Industries and Energy. 2 v. *

Australian Academy of Technological Sciences and Engineering. (1997). Urban air pollution in Australia. Parkville, Vic.: Australian Academy of Technological Sciences and Engineering. 224 p. [http://www.environment.gov.au/epg/pubs/urban_air.html] *

Australian Bureau of Agricultural and Resource Economics. (1991). Projections of energy demand and supply, Australia 1990-91 to 2004-05. Canberra: AGPS. ix, 144 p. *

Australian Gas Association. (1990). Reducing the impact of the greenhouse effect: submission by AGA to the Senate Standing Committee on Industry, Science and Technology. Canberra: Australian Gas Association.

Australian Institute of Petroleum. (1997). Refinery Product Characteristics. Melbourne: Australian Institute of Petroleum.

Barnes, P. (1999). PBA role in refinery modelling: assist, audit, review. Paper presented at: Fuel Quality Workshop, Melbourne. Canberra: Environment Australia. *

Beer, T., Weeks, I.A., Gipps, P. & Gu, K. (1996). Greenhouse gas inventory NSW RTA . (SB/1/265F) Aspendale, Vic.: CSIRO Division of Atmospheric Research. vii, 68 p. *

Best, R. (1999). Fuel quality review: background scenario selection, refinery inputs, vehicle emissions. Paper presented at: Fuel Quality Workshop, Melbourne. Canberra: Environment Australia. *

Blatz, F.J. (1979). Rerefined locomotive engine oils and resource conservation. Lubrication Engineering, **35** (II): 618-624.

Blinge, M. (1998). ELM: Environmental assessment of fuel supply systems for vehicle fleets. (Report; 35) Göteborg, Sweden: Dept. of Transportation & Logistics, Chalmers University of Technology. *

Bolt, C. (1999). Canola boom comes to an end. Australian Financial Review, (Thursday 23 December): 7 . *

Boustead, I. & Hancock, G.F. (1979). Handbook of industrial energy analysis. Chichester : Ellis Horwood. 422 p. *

Brasil, T. (1999). Exhaust emissions test results from a 1998 Ford F-150 LPG/gasoline bi-fueled light-duty truck using six LPG fuel blends: a report to the LPG Task Group, Air Resources Board. Sacramento, CA.: California Air Resources Board.

[http://arbis.arb.ca.gov/altfuels/lpg/mvlpge/LDV_Rpt.htm] *

Brown, S., Kadayifci, M., Bryett, C. & Pengilley, M. (1999). Diesel emissions reduction project. (Report ; MV-A-38) Lidcombe, NSW: NSW Environment Protection Authority. *

Brown, S.J. (1997). An experimental investigation of affordable alternative fuel and exhaust aftertreatment options for urban buses. Paper presented at : Trucks and buses: the results of real world testing, Millbrook Proving Ground. England: London Transport. *

Buckmann, M. & van Malsen, A. (1997). Biodiesel: a climate-friendly auto fuel? Greenhouse Issues, (31).

[http://www.ieagreen.org.uk/july31.htm#Biodiesel] *

Bureau of Transport and Communications Economics (Australia). (1994). Alternative fuels in Australian transport. (Information Paper ; 39) Canberra: AGPS. 325 p. *

Bureau of Transport and Communications Economics (Australia). (1995). Greenhouse gas emissions from Australian transport: long-term projections. (Report; 88) Canberra: AGPS. 273 p. *

Carnovale, F., Alviano, P., Carvalho, C., Deitch, G., Jiang, S., Macaulay, D. & Summers, M. (1991). Air emissions inventory Port Phillip control region: planning for the future. (Scientific Series; SRS 91/001) [Melbourne]: Environment Protection Authority. 181 p. *

Carter, S., Heenan, J. & Kozole, K. (1992). NGV meet the LEV brothers. Paper presented to: NGV92: the 3rd Biennial International Conference and Exhibition on Natural Gas Vehicles., Goteborg.

Caterpillar. (1996). Caterpillar Engine Data Sheets. (EDS; 62.0-62.1) Tullamarine, Vic.: Caterpillar of Australia, Ltd. *

Clifford, M. (1991). Gas sparks interest in "lean burn" Louisville. Truck Australia.

Colley, R., Fulton, A., Hall, D.O. & Raymond, W.F. (1991). The environmental effects of large-scale bioethanol production in Europe. In: IX International Symposium on Alcohol Fuels, Firenze. p. 915-921.

Collison, C.E., Bechtold, R.L. & Gibbs, J.L. (1997). Maryland mass transit administration demonstration of liquified natural gas transit buses (SAE 971666). In: State of alternative fuel technologies 1997 [SAE International Spring Fuels & Lubricants Meeting], Dearborn, MI (Special Publication (Society of Automotive Engineers), SP-1274) . Warrendale, PA: Society of Automotive Engineers. p. 111-125. *

Cope, M.E. & Katzfey, J.J. (1998). Air quality impact of the Perth bus fleet (revised) / prepared for the Western Australia Department of Environment Protection and Western Australia Department of Transport. (SB/1/376) Aspendale: CSIRO Atmospheric Research. iii, 37 p. *

Corinair Expert Group. (1994-1995). CORINAIR. Technical annexes volume 2 : Default emission factors handbook. (EUR 13232/EUR 12586) Brussels, Belgium: European Commission, Directorate-General, Environment, Nuclear Safety and Civil Protection. *

Cox, J. & Apelbaum Consulting Group. (1999). The Australian diesel fleet: existing vehicle characteristics and the modelling of transport demand, vehicle populations and emissions. Adelaide, SA: National Environment Protection Council.

[http://www.nepc.gov.au/diesel/diesel_prepare.html#proj_1] *

Cummins Engine Company. (1999). Cummins Centinel Advanced Engine Oil Management System [WWW page]. Columbus, IN: Cummins Engine Company.

[http://cecoewww.cummins.com/partserv/centinel.html] *

Darrow, K.G. (1994). Comparison of fuel-cycle emissions for electric vehicle and ultra-low emissions natural gas vehicle: report prepared by Energy International Inc. Los Angeles, CA: Southern California Gas Company.

Darrow, K.G. (1994). Light-duty vehicle fuel-cycle emission analysis: report prepared by Energy International Inc. Chicago, IL: Gas Research Institute.

Davies, G. (1999). Refinery operation. Paper presented at: Fuel Quality Workshop, Melbourne. Canberra: Environment Australia. *

Delucchi, M.A. (1991). Emission of greenhouse gases from the use of transportation fuels and electricity, Volume 1: Main text. (ANL/ESD/TM-22) Argonne, IL: Center for Transportation Research, Argonne National Laboratory.

Delucchi, M.A. (1993). Emission of greenhouse gases from the use of transportation fuels and electricity, Volume 2: Appendicies A-S. (ANL/ESD/TM-22) Argonne, IL: Center for Transportation Research, Argonne National Laboratory.

Delucchi, M.A. (1997). A revised model of emission of greenhouse gases from the use of transportation fuels and electricity. Davis, CA: Institute of Transportation Studies, University of California, Davis.

Dibble, R.W. (2000). Diesel fuels research. Berkeley, CA : Department of Mechanical Engineering, University of California, Berkeley .

[http://www.me.berkeley.edu/cal/diesel/] *

Durbin, T.D., Collins, J.R., Norbeck, J.M. & Smith, M.R. (2000). Effects of biodiesel, biodiesel blends, and a synthetic diesel on emissions from light heavy-duty diesel vehicles. Environmental Science and Technology, **34** (3): 349-355. *

Earl, W.B., Wickramanayake, W.P. & Poh Chee Lee. (1991). Biomass substitutes for diesel. In: IX International Symposium on Alcohol Fuels, Firenze. p. 117-119.

Edward Aul & Associates, Inc. & E. H. Pechan & Associates, Inc. (1993). Emission factor documentation for AP-42 section 1.11: waste oil combustion. Research Triangle Park, NC: U.S. Environmental Protection Agency. 43 p.

[http://www.epa.gov/ttnchie1/fbgdocs/b01s11.pdf] *

Eggleston, S., Gaudisio, D., Gorissen, N., Joumard, R., Rijkeboer, R.C., Samaras, Z. & Zierock, K.H. (1993). CORINAIR Working Group on Emission Factors for calculating 1990 emission from road traffic. Vol 1: Methodology and emission factors. (Final Report, Document of the European Commission) Brussels: Office for Official Publications of the European Communities.*

Eldering, A. & Cass, G.R. (1996). Source-oriented model for air pollutant effects on visibility. Journal of Geophysical Research, **101** (D14): 19343-19369. *

Energy Technology Support Unit. (1996). Alternative road transport fuels: a preliminary life-cycle study of the UK. (ETSU Report; R92) London: HMSO.

Environment Protection Authority (Victoria). (1991). A comparative study of greenhouse gases and air pollutants from petrol fuelled vehicles and vehicles using natural gas, automotive diesel fuel or liquefied petroleum gas. Melbourne: EPA Victoria.

Environmental Protection Agency (United States). (1996). Managing used oil: advice for small business. (EPA530-F-96-004) Washington, DC: USEPA. 4 p.

[http://www.epa.gov/epaoswer/hazwaste/recycle/usedoil/usedoil.pdf] *

Eriksson, E., Blinge, M. & Lovgren, G. (1996). Life-cycle assessment of the road transport sector. Science of the Total Environment, **190**: 69-76. *

Expert Reference Group (Western Australia). (1998). Euro2 & beyond: fuel for Transperth's bus fleet. Perth, WA: The Group. 80 p.

[http://www.transport.wa.gov.au/euro2] *

Faiz, A., Weaver, C.S. & Walsh, M.P. (1996). Air pollution from motor vehicles: standards and technologies for controlling emissions. Washington, DC: The World Bank. 246 p. *

Fewchuk, D., Lamb, D., Parikh, Y., Brey, S., Charters, W.W.S. & Watson, H.C. (1998). Concept car-life-cycle energy analysis (SAE 981154). Warrendale, PA: Society of Automotive Engineers. *

Franke, B. & Reinhardt, G. (1998). Ecological impacts of biofuels in Europe. In: International Liquids Biofuels Congress proceedings, Curitiba, Parana, Brazil. Jefferson City, MO: National Biodiesel Board.

[http://www.biodiesel.org/ilbc/Berndt_Franke.html] *

GASEX. NGV Working Group . (1996). Natural gas vehicle developments in the Asia-Pacific region. Canberra: Australian Gas Association. 88 p. *

George Wilkenfeld and Associates. (1991). Greenhouse gas emissions from the Australian energy system: the impact of energy efficiency and substitution . (ERDC; 22) Canberra, ACT: Energy Research and Development Corporation. 246 p. *

Glassman, I. (1987). Combustion. 2nd ed. ed. London; Orlando, FL: Academic Press. xix, 501 p. *

Graedel, T.E. & Allenby, B.R. (1995). Industrial ecology. Prentice Hall: Englewood Cliffs, NJ. xix, 412 p. *

Hassall and Associates. (1994). Extended field trials of ethanol blends in vehicles: a report prepared for Energy Research and Development Corporation. Barton, ACT: Hassall and Associates Pty Ltd. viii, 104 p. *

Hatfield, H. (1990). LNG: the long-range alternative? Truck Australia., (October 1990).

Hearn, D. (1995). Health risks due to motor vehicle emissions in Melbourne. Clean Air, **28** (2): 37-44. *

Heinrich, G. & Decker, R.W. (1992). Alternative Kraftstoffe: Chancen und Risiken aus der Sicht von Volkswagen. In: VDI Berichte: Aspekte alternativer Energieträger für Fahrzeugantriebe, number nr. 1020.

Hemmerlein, N., Korte, V., Richter, H. & Schroder, G. (1991). Performance exhaust emissions and durability of modern diesel engines running on rapeseed oil. (SAE Technical Paper; 910848) Detroit, MI: International Congress and Exposition.

IEA Automotive Fuels Information Service. (1999). Automotive fuels for the future: the search for alternatives. Paris: International Energy Agency. 92 p. *

IEA Automotive Fuels Information Service. (1996). Automotive fuels survey: Volume 1: Raw materials and conversion. Netherlands: Innas BV. *

IEA Automotive Fuels Information Service. (1996). Automotive fuels survey: Volume 2: Distribution and use. Netherlands: Innas BV. *

IEA Automotive Fuels Information Service. (1998). Automotive fuels survey: Volume 3: Comparison and selection. Netherlands: Innas BV. *

IEA Automotive Fuels Information Service. (1999). Automotive fuels survey: Volume 4: Innovations or illusions. Netherlands: Innas BV. *

IEA Automotive Fuels Information Service. (1999). Automotive fuels survey: Volume 5: Mobile machinery: Sector analysis. Netherlands: Innas BV. *

Industry Commission (Australia). (1991). Recycling: Vol 2. Recycling of products. (Report (Australia. Industry Commission); no.6) Canberra: AGPS. *

International Association for Natural Gas Vehicles. (1990). A position paper on natural gas vehicles . Auckland: IANGV.

International Energy Agency . (1995). Biofuel costs. The Clean Fuels Report, **7** (3).

International Energy Agency. (1993). Cars and climate change. (Energy and Environment Series) Paris: International Energy Agency. 236 p. *

International Energy Agency. (1992). Energy and the environment: transport system responses in the OECD, greenhouse gas emissions and road transport. Restricted Draft, 21 January, and Restricted Draft of chapters 11 and 12, 8 April 1992. Paris: OECD/IEA.

Joseph, S. (1996). Testing of diesohol fuel buses: synthesis report on the field trials undertaken by ACTION. The laboratory tests undertaken by the N.S.W. EPA and analysis of the program by APACE Research. Canberra: Dept. of the Environment, Sport and Territories. 31 p. *

Kadam, K.L., Camobreco, V.J., Glazebrook, B.E., Forrest, L.H., Jacobson, W.A., Simeroth, D.C., Blackburn, W.J. & Nehoda, K.C. (1999). Environmental life-cycle implications of fuel oxygenate production from California biomass: technical report life-cycles. (Report; NREL/TP-580-25688) Golden, CO: National Renewable Energy Laboratory.

[http://www.ott.doe.gov/biofuels/pdfs/body.pdf] *

Kaltschmitt, M. & Reinhardt, G.A., ed. (1997). Nachwachsende Energieträger: Grundlagen, Verfahren, ökologische Bilanzierung (Biofuels: Basics, processes, ecological balances). Braunschweig: Vieweg. 527 p.

Kaltschmitt, M., Reinhardt, G.A. & Stelzer, T. (1996). LCA of biofuels under different environmental aspects. In: Proceedings of the 9th European Bioenergy Conference, Copenhagen. Oxford: Pergamon/Elsevier.

Kuhndt, M. & Bilitewski, B. (1999). Towards Reduced Environmental Burden of Mobility: Improving the Automobile Life-cycle:a CHAINET Case Study Report: Draft February 1999. Leiden: CHAINET. 51 p.

[http://www.leidenuniv.nl/interfac/cml/chainet/drafaut2.rtf] *

Landgrebe, J. (1994). The environmental risks of biofuels. Presented at: Biofuels in Europe, Tours, France.

Le Cornu, J. (1990). Greenhouse gas emissions from the production and use of alternative transport fuels. In: Greenhouse and energy. D. J. Swaine (editor). East Melbourne: CSIRO Australia. p. 293-303. *

Lenzen, M. (1999). Total requirements of energy and greenhouse gases for Australian transport. Transportation Research Part D: Transport and Environment, **4** (4): 265-290. *

Mann, P. (1998). The production and use of ethyl esters from vegetable oils. In: International Liquids Biofuels Congress proceedings, Curitiba, Parana, Brazil. Jefferson City, MO: National Biodiesel Board.

[http://biodiesel.org/ilbc/mann/Paul_Mann.html] *

Månsson, T. (1997). Bio-based fuels for buses, lorries and cars. CADDET Energy Efficiency Newsletter, (3): 4-6. [http://www.caddet-ee.org/newsdesk/nw397_01.htm] *

Marshall, G., Andrews, S., Carter, M. & Dispain, G. (1999). Comprehensive product stewardship system (CPSS) for waste oil. Canberra: Environment Australia, Dept of Environment. *

Merz . (1991). Natural Gas in Transport: Potential for Natural Gas Within the NSW Transport System. Sydney: Department of Minerals and Energy.

Milkins, E.E. (1989). Natural gas in transport: greenhouse effects. Paper presented to: Australian Institute of Energy National Seminar Energy and the greenhouse effect, Melbourne.

Mittelbach, M. (1998). The Importance of Diesel Fuel Substitutes from Non-Edible Seed Oils. International Liquids Biofuels Congress proceedings, Curitiba, Parana, Brazil. Jefferson City, MO: National Biodiesel Board.

[http://biodiesel.org/ilbc/mittelbach/Martin_Mittelbach.html] *

Motta, R., Norton, P., Kelly, K., Chandler, K., Schumacher, L. & Clark, N. (1996). Alternative fuel transit buses: final results from the National Renewable Energy Laboratory Vehicle Evaluation Program. (Report; NREL/TP-425-20513) Golden, CO: National Renewable Energy Laboratory. 40 p.

[http://www.afdc.doe.gov/pdfs/transbus.pdf] *

Narushima, T. (1992). Development of an ultra low emission light duty NGV. Paper presented to: 11th International Electric Vehicle Symposium, Florence.

National Environment Protection Council (Australia). (1998). Ambient air quality: National Environment Protection Measure and revised impact statement for ambient air quality. Adelaide, SA: National Environment Protection Council. 178 p.

[http://www.nepc.gov.au/air/air_nepm.6.98.html] *

National Greenhouse Gas Inventory Committee (Australia). (1998). Australian methodology for the estimation of greenhouse gas emissions and sinks (8 workbooks). [Canberra]: Dept. of the Environment, Sport and Territories. 8 v.

[http://www.greenhouse.gov.au/inventory/methodology/method_content.html] *

National Greenhouse Gas Inventory Committee (Australia). (1996). Energy: workbook for fuel combustion activities (stationary sources): Australian methodology for the estimation of greenhouse gas emissions and sinks. (National Greenhouse Gas Inventory Committee,Workbook; 1.1) Canberra: Dept. of the Environment, Sport & Territories. p. x, 85. p.

[http://www.greenhouse.gov.au/inventory/archive/natmethod/energy1/energy1.html] *

National Greenhouse Gas Inventory Committee (Australia). (1996). Energy: workbook for transport (mobile sources): Australian methodology for the estimation of greenhouse gas emissions and sinks. (National Greenhouse Gas Inventory Committee. Workbook; 3.1) Canberra: Dept. of the Environment, Sport and Territories. xi, 65 p.

[http://www.greenhouse.gov.au/inventory/archive/natmethod/energy3/energy3.html] *

National Greenhouse Gas Inventory Committee (Australia). (1999). National greenhouse gas inventory 1997: with methodology supplements. Canberra, ACT: Australian Greenhouse Office. p. xxxi, 202. p.

[http://www.greenhouse.gov.au/inventory/inventory/inv_content.html] *

Parliamentary Library (Australia). (1999). Bills Digest No. 20 1999-2000, Customs and Excise Amendment (Diesel Fuel Rebate Scheme) Bill 1999. Canberra: Department of the Parliamentary Library. [http://www.aph.gov.au/library/pubs/bd/1999-2000/2000BD020.htm] *

Public Transport International. (1993). Public Transport International -- April 1993. Belgium: International Union of Public Transport.

Reinhardt, G.A. (1994). Umweltautswirkungen der Kraftstoffsubstition durch Pflanzenöle und seine Derivate. (VDI ; 1126) Düsseldorf, Germany: VDI Verlag GmbH.

Road and Traffic Authority of NSW. (1998). Distribution of RTA's contribution to greenhouse gas emissions. In: RTA Environment Report. p. 33.

[http://www.rta.nsw.gov.au/environment/aer1998.pdf] *

Sanders, M. (1999). The Queensland Clean Fuels Project. Paper presented at: Fuel Quality Workshop , Melbourne. Canberra: Environment Australia. *

Scharmer, K. & Gosse, G. (1996). Ecological impact of biodiesel, production and use in Europe. Presented at: 2nd European motor biofuels forum, Graz, Austria.

Schmidt, M. & Pütz, R. (1999). Can the natural gas public service bus also continue in competition? CNG and diesel drive in comparison [English translation]. Der Nahverkehr, **6/99**.

Schneider, V.A., Manager - Engine Certification, Cummins, USA. (2000). Personal communication.

Scott, W., Principal Consultant, Fuchs Tribology Consulting and Education Services, Adjunct Professor (Queensland University of Technology). (2000). Personal communication.

[http://www.fuchslubritech.com.au]

Scott, W. & Hargreaves, D.J. (1991). A case for reclaimed lubricating oils. In: International Mechanical Engineering Congress and Exhibition: preprints of papers., Sydney (National Conference Publication (Institution of Engineers, Australia), 91/10) . Barton, ACT: Institution of Engineers, Australia. *

Scott, W.T., Brown, S.D.A., Kadayifci, M.Z. & Mitchell, A.W. (1995). Exhaust and noise emission testing of diesel and diesohol fuelled buses. (Report. MV-A-29) Lidcombe, NSW: NSW Environment Protection Authority. *

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M. & Shapouri, H. (1998). Life-cycle inventory of biodiesel and petroleum diesel for use in an urban bus. (Report ; NREL/SR-580-24089) Golden, CO: National Renewable Energy Laboratory. xxiv, 284 p.

[http://www.ott.doe.gov/biofuels/pdfs/lifecycle_pdf.html] *

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M. & Shapouri, H. (1998). An overview of biodiesel and petroleum diesel life-cycles. (Report; NREL/TP-580-24772) Golden, CO: National Renewable Energy Laboratory.

[http://www.ott.doe.gov/biofuels/docs/lifecycle.html] *

Sinor, J.E. Consultants Inc. (1992). Canadian survey shows big jump in NGV acceptance. (Clean Fuel Report , April 1992) Colorado.

Spataru, A. & Romig, C. (1995). Emissions and engine performance from blends of soya and canola methyl esters with ARB #2 diesel in a DCC 6V92TA MUI engine. (SAE Technical Paper; 952388) Warrendale, Penn.: SAE International. p. 179-188. *

State of the Environment Advisory Council (Australia). (1996). Australia, state of the environment 1996: an independent report presented to the Commonwealth Minister for the Environment. Collingwood, Vic.: CSIRO Publishing. 1 v. *

Stewart, G.A. (1990). A preliminary evaluation of biomass as a source of renewable energy. Paper presented to: Workshop on Efficiency and Renewable Energy organised by the energy Use and Energy Product Working Groups on Ecologically Sustainable Development.

Sun, X., Wiedmann, T. & Hussein, S. (1997). Fuel management and exhaust emissions of light- and heavy-duty trucks operating on CNG and LPG, (SAE 971661). In: State of alternative fuel technologies 1997 [SAE International Spring Fuels & Lubricants Meeting], Dearborn, MI (Special Publication (Society of Automotive Engineers), SP-1274) . Warrendale, PA: Society of Automotive Engineers. p. 69-82. *

Taschner, K. (1991). Bioethanol: a solution or a new problem. In: IX International Symposium on Alcohol Fuels, Firenze. p. 922-926.

Toyota Motor Corporation. (1999). Environmental Report 1999 . Japan : Toyota Motor Corporation. [http://www.global.toyota.com/globaltoyota/corp_info/envrep/envrep99/index.html] *

Vermiglio, E., Jenkins, T., Kieliszewski, M., Lapetz, J., Povinger, B., Wiley, R., Herber, J., Sahutske, K., Blue, M. & Clark R. (1997). Ford's SULEV dedicated natural gas trucks (SAE 971662). In: State of alternative fuel technologies 1997 [SAE International Spring Fuels & Lubricants Meeting], Dearborn, MI (Special Publication (Society of Automotive Engineers), SP-1274) . Warrendale, PA: Society of Automotive Engineers. p. 83-91. *

Wang, M.Q. & Huang, H.S. (1999). A full fuel-cycle analysis of energy and emissions impacts of transportation fuels produced from natural gas. (ANL/ESD; 40) Argonne, IL: Argonne National Laboratory. xiv, 114 p.

[http://www.transportation.anl.gov/ttrdc/publications/pdfs/esd-40.pdf] *

Watkins, L.H. (1991). Air pollution from road vehicles. London: HMSO. 152 p. *

Watson, H.C. (1991). Future fuels: market penetration and environmental impact. Paper presented to: Conference on Transport and the Environment, Sydney. *

Wegrzyn, J. & Gurevick, M. (1996). Absorbent storage of natural gas. Applied Energy, **55** (2): 71-83. *

Williams, M. (1998). LPG: fresher air for less cash. Coach and Bus, (Week ending 16 April): 8. *

Yanowitz, J., Grabowski, M.S., Ryan, L.B.A., Alleman, T.L. & McCormick, R.L. (1999). Chassis dynamometer study of emissions from 21 in-use heavy-duty diesel vehicles. Environmental Science and Technology, **33** (2): 209-216. *

Yorke, P.L. (1991). Natural gas: an alternative or not. Presented at: 1991 Automotive Manufacturing Congress, Melbourne, Vic. Parkville, Vic.: Society of Automotive Engineers Australasia. *

Zingarelli, J.A. (1997). The development of LNG as a heavy-duty vehicle fuel: main report. (ERDC; 288/2) Canberra: Energy Research and Development Corporation. *

* Asterisk indicates references that have been sighted

PART 3

APPENDICES

Appendix 1	Glossary of Terms
Appendix 2	Uncertainty Analyses
Appendix 3	Scoring and Ranking
Appendix 4	Full Fuel-Cycle (g/MJ) results
Appendix 5	Eco-Indicators
Appendix 6	Commercial Performance

Appendix 1

Glossary of Terms

Aceltaldehyde

CH_3CHO emission component of the exhaust gases of combustion engines, presumably carcinogenic.

Additive

Additives are added to the fuel in small amounts to improve the properties of the fuel. For instance, anti-sludge additives prevent the deposits of carbon and tar on the inlet valves and other engine parts.

Air/fuel ratio

Mass ratio of air to fuel inducted by an engine. See also stoichiometric ratio.

Alcohol

Group of organic compounds, derived from hydrocarbons, which one or more hydrogen atoms replaced by hydroxyl (OH) groups.

Biodegradibility

The capability of a substance to decompose into harmless elements.

Biodiesel

Automotive fuel consisting of esterified vegetable oils such as rapeseed methyl ester and soybean methyl ester

Catalyst

1. Substance that influences the speed and direction of a chemical reaction without itself undergoing any significant change.
2. Catalytic reactor that reduces the emission of harmful exhaust gases from combustion engines.

Canola Oil

A vegetable oil made from canola. It is similar to rapeseed oil but with less crucic acid and glucosinolates.

Cetane number

A measure of the ignition quality of diesel fuel based on ignition delay in an engine. The higher the cetane number the shorter the ignition delay and the better the ignition quality. The cetane number is based on the ignition quality of cetane ($C_{16}H_{34}$) and heptamethylnonane.

Compression ratio

The ratio of the volume of the combustion chamber at the beginning of the compression stroke and the volume of the chamber at the end of the compression stroke.

Compression ignition engine

Internal combustion engine with an ignition caused by the heating of the fuel-air mixture in the cylinder by means of compression. This compression causes a rise in temperature and pressure that make possible the spontaneous reaction between fuel and oxygen. Also called a diesel engine.

Crude; crude oil

Crude mineral oil. Naturally occurring hydrocarbon fluid containing small amounts of nitrogen, sulfur, oxygen and other materials. Crude oils from different areas can vary enormously.

DI-engine

Direct injected engine; combustion engine with a direct injection of fuel into the combustion chamber.

Diesel engine

1. Combustion engine running on diesel oil.
2. Other name for a combustion engine with compression ignition (named after Rudolf Christian Carl Diesel 1858 to 1913), one of the founders of the combustion engine principle.

Diesel (oil)

1. A mixture of different hydrocarbons with a boiling range between 250º and 350º;
2. A fuel for compression ignition or diesel engines.

Diesohol

A blend of diesel fuel, hydrated ethanol and proprietary emulsifier.

Dual-fuel vehicle

Also called bi-fuel vehicle. Vehicle fitted with one engine and two fuel systems. The engine can operate on both fuels. An example is an LPG/Gasoline dual-fuel vehicle.

Evaporative emission

Emission of hydrocarbons of a vehicle from sources other than the exhaust pipe.

Important sources are the venting of the fuel tank and the carburettor. Evaporative losses are subdivided into:

- running losses
- diurnal losses
- hot soak losses.

FFV

Flexible-Fuelled Vehicle. Vehicle able to drive on any mixture of alcohol and gasoline up to 85% alcohol.

Formaldehyde

Aldehyde compound; HCHO; very toxic; probably carcinogenic.

IDI-engine

Indirect-Injection Engine; internal combustion engine (usually a diesel engine) with indirect fuel injection, for instance by way of a pre-combustion chamber or a swirl chamber.

Ignition delay

Expression usually used in connection with compression ignition engine, defined as the time between the start of the injection and the start of the ignition.

Lean mixture

Mixture of air and fuel in a cylinder of a combustion engine containing less fuel than could be burnt by the oxygen present.

Liquefaction

The conversion of a gas to a fluid by lowering the temperature and or raising the pressure. LPG is a liquefied gas; natural gas and hydrogen are sometimes liquefied.

Methylester

An ester resulting from the esterification of oil with methanol, also known as biodiesel.

PAH

Polycyclic Aromatic Hydrocarbon(s). Aromatics of which the molecules contain several linked benzene rings; in several cases carcinogenic.

Pilot injection

Method to ignite fuels that are difficult to ignite. A more easily ignitable fuel is injected into the engine, next to an amount of the real fuel. The added fuel will ignite first and subsequently ignite the real fuel. An example is diesel pilot injection in alcohol engines.

Reformulated fuel

A fuel (especially gasoline or diesel) blended to minimise undesirable exhaust and evaporative emissions.

Rich mixture

An air-fuel mixture in a combustion engine that contains more fuel than can be combusted by the air in the cylinder.

Spark ignition engine

Internal combustion engine with an ignition of the fuel/air mixture by means of a spark; also called otto engine.

Stoichiometric air/fuel ratio

The extact air/fuel ratio required to completely combust a fuel to water and CO_2.

Tailpipe emissions

Emissions of a combustion engine after the catalyst (as distinct from engine-out emissions that are measured before the catalytic converter).

Three-way catalyst

Catalytic reactor for combustion engines, which oxidises volatile organic compounds (VOC) and CO, as well as reduces nitrogen oxides.

Vkm

Vehicle kilometre

VOC

Volatile Organic Compound(s). Collective noun for hydrocarbons that are emitted in the volatile phase by vehicles. Usually described as HC-compounds.

Appendix 2

Uncertainty Analysis

The uncertainty analysis of Chapter 3 has used the maximum and minimum observed values, along with the mean value to estimate the percentage uncertainties. This was done by assuming that the maximum, the minimum and the average are all based on a finite sample taken from a normal distribution. If, for example, ten readings (samples) are taken then the maximum value corresponds to the 10^{th} percentile value, and the minimum to the 90^{th} percentile value. If there are 100 readings then the maximum and minimum correspond to the 1^{st} and 99^{th} percentiles respectively.

There were 11 readings of BD in buses. Thus the maximum and minimum values are the 9th and 91^{st} percentiles. We know, from the properties of the normal distribution that one standard deviation corresponds to the 16^{th} and 84^{th} percentiles. Thus we seek the factor, *f*, that links the range (the difference between the maximum and minimum values) with the standard deviation.

The number that we require is tabulated in tables of the normal probability integral. In the case of BD, for example, we find that the 91^{st} percentile occurs at a value of 1.34 s. Thus the range from the 9^{th} to the 91^{st} percentile covers 2.68 s. Hence the factor, *f*, which we seek equals 2.68, and has been given as *f* = 2.7 in Table 3.5.

Appendix 3

Scoring and Ranking

The study was designed to produce ranked evaluations of the alternative fuels. In most cases this has been done solely on the basis of the average values. We have devised a method that incorporates uncertainty by scoring each alternative fuel on the basis of its rank, repeating the procedure for the ranking incorporating +1 standard deviation and the ranking incorporating -1 standard deviation, then adding the scores and determining a final rank on the basis of the summed scores.

For example, Table A3.1 gives the greenhouse gas emissions (in g CO_2-equivalents/km) for the heavy-duty vehicles of Table 3.4.

Table A.3.1

Ranking and scores of greenhouse gas emissions from heavy-duty vehicles

	Diesel	LSD	LSD+W5	CNG	LNG	E95	BD35	BD100
Total GHG (Average)	1529	1647	1643	1354	1761	847	1642	634
Score	4	7	6	3	8	2	5	1
Total GHG (+1s)	1669	1826	1889	1411	1925	1244	2351	951
Score	4	6	5	3	7	2	8	1
Total GHG (-1s)	1389	1468	1397	1297	1598	450	932	317
Score	5	7	6	4	8	2	3	1
Summed Score	13	20	17	10	23	6	16	3
Final Rank	4	7	6	3	8	2	5	1

Appendix 4

Full Fuel-Cycle (g/MJ) Results

Table A4.1

Full Fuel-Cycle (g/MJ) emissions for buses

		Diesel	LS Diesel	ULS Diesel	LPG	CNG	LNG	E95	BD20	BD100
CO_2	Fuel Production	11	12	13	11	6	9	(29)	2	(41)
	Combustion	69	69	69	69	54	55	65	84	89
	Total	80	81	82	80	60	64	36	87	48
CH_4	Fuel Production	0.034	0.034	0.036	0.034	0.010	0.092	0.005	0.031	0.013
	Combustion	0.001	0.001	0.001	-	0.101	0.102	0.004	-	0.001
	Total	0.035	0.035	0.036	0.034	0.111	0.194	0.009	0.031	0.014
N_2O	Fuel Production	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.005	0.028
	Combustion	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001
	Total	0.003	0.003	0.003	0.001	0.001	0.001	0.001	0.006	0.030
CO	Fuel Production	0.182	0.182	0.190	0.182	0.004	0.103	0.088	0.192	0.239
	Combustion	0.092	0.066	0.069	0.006	0.027	0.382	0.641	0.274	0.521
	Total	0.274	0.248	0.259	0.188	0.030	0.485	0.729	0.466	0.760
NO_x	Fuel Production	0.054	0.058	0.062	0.054	0.026	0.058	0.015	0.076	0.184
	Combustion	0.736	0.720	0.701	0.280	0.398	1.332	0.345	1.504	1.176
	Total	0.790	0.778	0.763	0.334	0.423	1.390	0.360	1.580	1.360
NMVOC	Fuel Production	0.098	0.098	0.102	0.098	0.011	0.103	0.017	0.105	0.137
	Combustion	0.055	0.025	0.026	0.001	0.111	0.113	0.213	-	0.054
	Total	0.790	0.123	0.128	0.099	0.122	0.216	0.230	0.105	0.191
Particles	Fuel Production	0.008	0.008	0.013	0.008	0.000	0.003	0.007	0.016	0.057
	Combustion	0.023	0.011	0.008	0.001	0.002	0.001	0.009	0.024	0.041
	Total	0.031	0.019	0.020	0.009	0.002	0.004	0.016	0.040	0.098

Appendix 5

Eco-Indicators

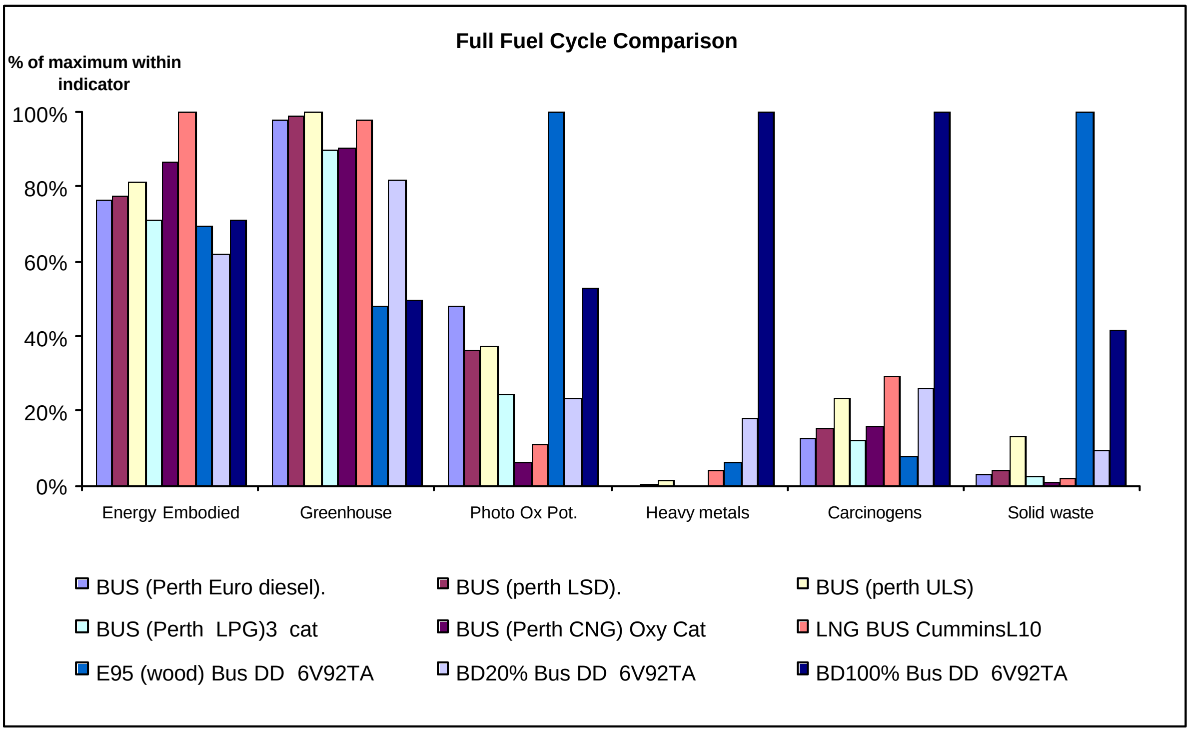


Figure A5.1

The life-cycle indicator presented above draws on some of the non greenhouse data contained in the LCA model for the fuel system. Unfortunately, due to the limitations in the study, combustion emissions other than particles and the direct and indirect greenhouse emissions were not available or collected for the combustion emissions. As a result emissions such as heavy metals and carcinogens are poorly represented in the combustion data. However the table of Appendix 4 does suggest that a number of interesting points should be investigated further. The values for heavy metals from biodiesel are based on lead and other metal emissions in phosphate fertiliser production (see Figure A5.1).

The carcinogens indicator is made up mostly of PAH emission in energy processes during biodiesel production (see Figure 8.1). Again no PAH emissions have been estimated for biodiesel production.

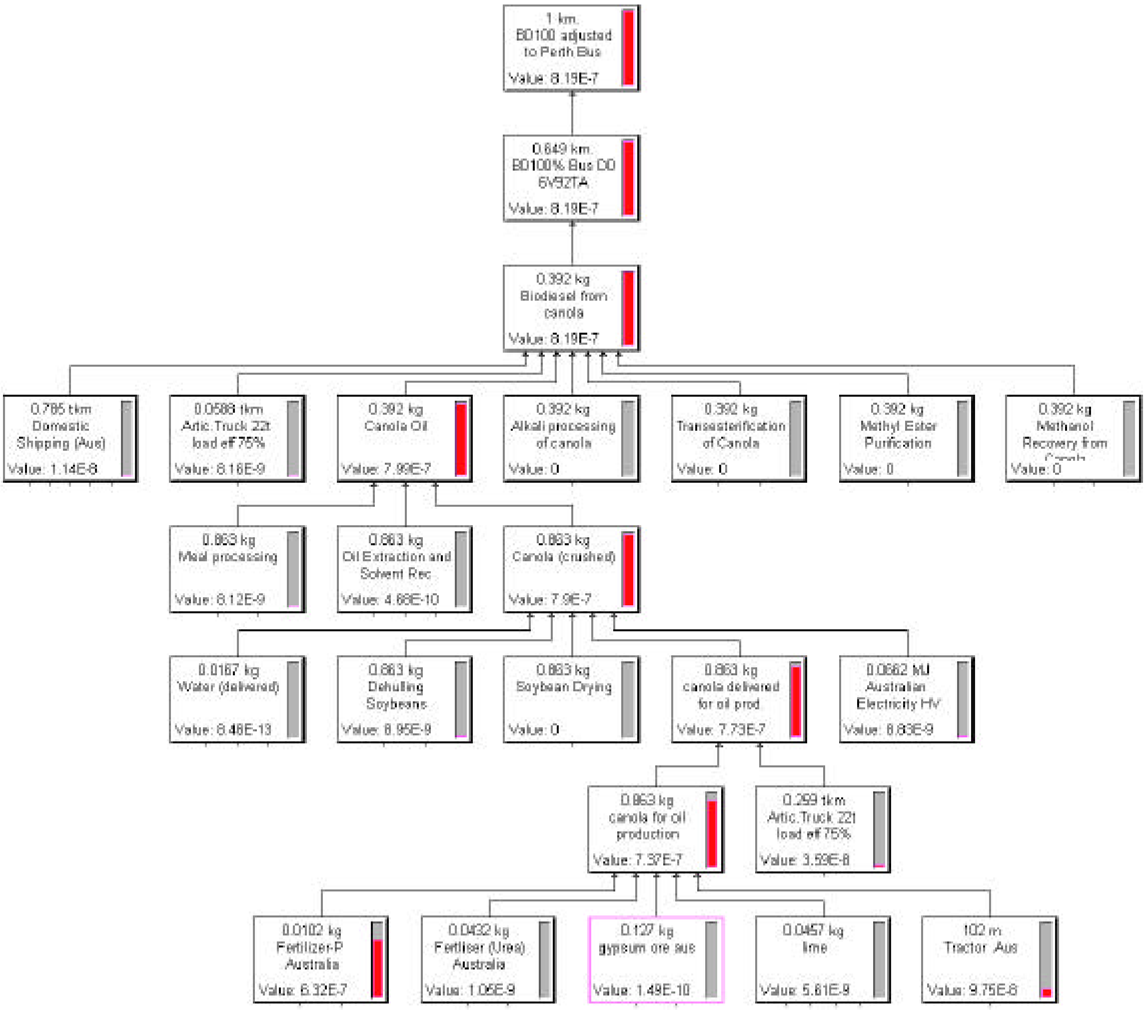


Figure A5.2

BD100 value = Heavy Metals Indicators

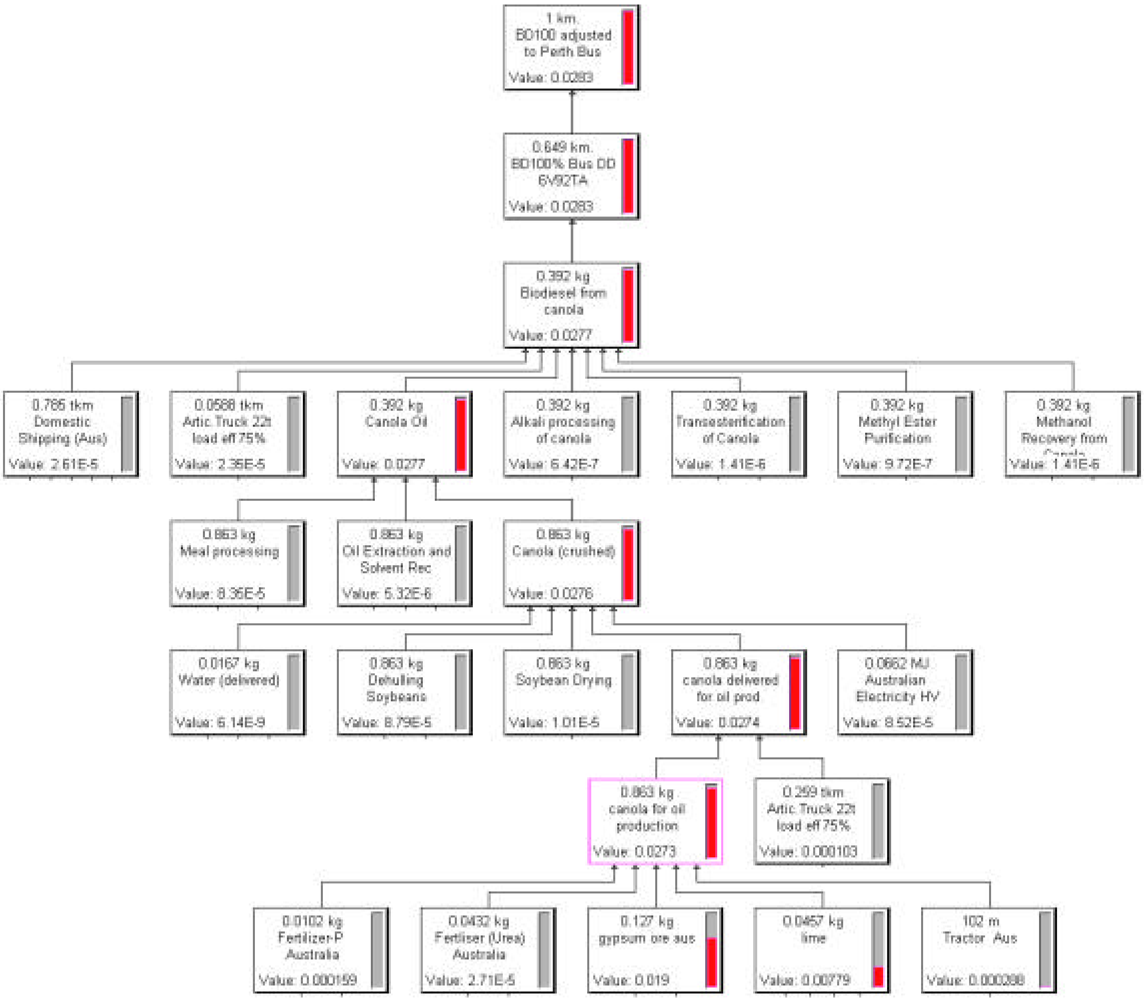


Figure A5.3 -

BD100 value = Carcinogens Indicator

Appendix 6

Commercial Performance of Alternative Fuels

A6.1 US Experience

Motta et al. (1996) document the US experience in relation to the performance of urban buses using alternative fuels. They examined feasibility, fuel economy, fuel cost, maintenance costs and capital costs. Their results are given in Table A6.1. The conclusions drawn from these US data are:

- Only one site (Tacoma buses using CNG) had equal reliability to diesel. Most other sites show some reliability penalty but in many cases the causes are minor, such as the bus out of fuel because the driver is unfamiliar with the vehicle, or appear solvable (e.g. fuel filter plugging at sites where ethanol is used).
- Operating costs of the buses are driven by fuel costs. That is, fuel cost differences (in comparison to diesel) outweigh any maintenance costs between the alternative fuel and diesel bus. Operating costs are lowest for CNG buses and highest for ethanol and biodiesel buses.
- Capital costs are inverse to operating costs. They are highest for CNG/LNG buses and lowest for ethanol and biodeisel buses.

Table A6.1
Summary of commercial performance of US buses using alternative fuels

		LNG/ Dual Fuel	LNG Spark Ignition	CNG	95% Ethanol	93% Ethanol	Biodiesel	LPG
Reliability	Road calls/1000 miles	.39	.22	.12	.12	.12	-	
Diesel Control Reliability	Road calls/1000 miles	.06	.15	.12	.07	.07	-	
Fuel economy	Miles per US gallon	3	2.9	4.3	3.3	3.1	4.0	
Diesel Control fuel economy	Mpg	3.3	4.1	5.7	3.2	3.2	3.9	
Fuel cost	$/1000 miles	200	310	110	500	350	320	
Diesel control fuel cost	$/1000 miles	180	110	110	160	160	120	
Maintenance cost	$/1000 mile	310	410	150	210	210	-	
Diesel control maintenance cost	$/1000 mile	220	280	150	170	170	-	
Capital cost	Increment on diesel base	$55K	$55K	$50K	$20K	$20K	$0K	$40K
Diesel Base	$215K							
Incremental facility cost (fleet of 160 buses)	(million of $)	3.51	3.51	3.75	0.10	0.10	0	0.15

Source: Motta et al. (1996)
All $ figures refer to 1994 US$

A6.2 European Experience

Table A6.2 summarises the European Experience (IEA/AFIS, 1998) in relation to commercial performance of heavy vehicles

Table A6.2

European well-to-wheel fuel costs for heavy-duty vehicles in (US$/GJ vehicle performance)

Fuel	Raw material	Total well to station cost			Total vehicle efficiency [%]	Effective driving cost (US$/GJ vehicle performance)		
		Short[1] term	Medium[2] term	Long[3] term		Short term	Medium term	Long term
Diesel	Crude oil	8.90	11.35	16.30	33.6	26	34	49
LPG	Crude oil	9.90	12.00	16.20	24.4	41	49	66
CNG	Nat. gas	4.30	7.80	14.20	23.9	18	33	59
Ethanol	Grains	26.6	30.60	37.50	33.3	79	92	113
Ethanol	Cellulose	41.10	30.30	25.20	33.3	123	91	77
Biodiesel	Oilseeds	18.9	22.90	29.50	33.3	57	69	89

Source: IEA/AFIS (1998)

[1]Over 1 to 5 years
[2]Over 5 to 15 years
[3]Over 15 to 25 years

A6.3 Summary

COMPARED WITH CONVENTIONAL DIESEL FUELS CUSTOMERS EXPECT:

*	COST - Fuel cost less than conventional for a given task or trip.	
	- Hardware pay back time 15 to 18 months (even though economic break-even may be 3.5 years).	
*	REFUELLING -	- As fast
		- As safe
*	RANGE	- Equal
*	ACCIDENTS	- No increased risk
*	PERFORMANCE	- Equal to that of conventional
*	EMISSIONS	- Comply with any legislation
	COMMUNITY MAY DESIRE:	

- Greenhouse (CO_2) gas emissions lower
- Urban emissions:

  HC (hydrocarbons) lower

  NOx (nitrogen oxides) lower

  PM. (Particles) lower

Table A6.3.1

Fuel LPG
Liquefied Petroleum Gas

	Range	Median	Comment
COST			
- FUEL			Allows for 25% increase in FC.
(Diesel equivalent)	23-45c/L	29c/L*	No excise
- HARDWARE	$1200-$2300	$1800	After-market, mostly dual fuel
REFUELLING			
- TIME	Same-longer	Same	
- SAFETY	Same-better	Same	
RANGE	Worse-same	Worse	Dual fuel to get you home
ACCIDENT RISK	Worse-same	Worse	
PERFORMANCE	Worse-same	Worse	

TIMING Present, but may soon be in short supply
OTHER No evaporative HC or refuelling HC losses
* Crude @ 15c/L Diesel @ 30c/L No excise or Tax

Table A6.3.2

Fuel CNG
compressed natural gas

	Range	Median	Comment
COST			No excise
- FUEL	20-35c/L	26c/L	Stored @ 160 atmospheres
(Diesel equivalent) (includes compressor)			
- HARDWARE	$1800-4000	$2300	
REFUELLING			
- TIME	More-lot more	More	
- SAFETY	Worse-better	Same	
RANGE	130-500 km	Depends	Latest technology high range
ACCIDENT RISK	Better-same	Better	
PERFORMANCE	Worse-same	Worse	

TIMING Present
OTHER No evaporative or refuelling losses, but fugitive methane emissions must be considered

Table A6.3.3

Fuel Ethanol
As blend (@10%, E10) or neat (anhydrous)

	Range	Expected	Comment
COST			No excise or tax
- FUEL	55-75c/L	62c/L	Allows for 50% increase in FC.
(Diesel equivalent)			Original Equipment for diesohol
- HARDWARE BLEND	$0-150	$80	Needs starting aid
Anhydrous	$200-2000	$800	
REFUELLING			For same range
- TIME		+50%	Flame not visible
- SAFETY	Worse-better	Same	Less toxic
RANGE	Worse-same	Same	
ACCIDENTS	Worse-same	Same	
PERFORMANCE	Same-better	Better	With increased compression ratio

Particulates: N.A.

Table A6.3.4

Fuel biodiesel
As blend (@20%, BD20) or neat

	Range	Expected	Comment
COST			
- FUEL	100-300c/L	200c/L	No excise or tax
(Diesel equivalent)			
- HARDWARE Canola	$0-150	$80	
Biodiesel	$200-2000	$800	
REFUELLING			
- TIME		Slightly worse	For same range
- SAFETY	Same	Same	
RANGE	Slightly worse	Slightly worse	
ACCIDENTS	Same	Same	
PERFORMANCE – Canola	Worse	Worse	
- Biodiesel	Same	Same	

Particulates: N.A.