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Life-Cycle Emissions Analysis of Fuels for Light Vehicles

REPORT
(HA93A-C837/1/F5.2E)
to the
AUSTRALIAN GREENHOUSE OFFICE
by

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Acronyms

ABARE	Australian Bureau of Agricultural and Resource Economics
ADR	Australian Design Rule
AGA	Australian Gas Association
AGO	Australian Greenhouse Office
AIP	Australian Institute of Petroleum
ALPGA	Australian Liquefied Petroleum Gas Association
ANGVC	Australasian Natural Gas Vehicles Council
AUC	Australian Urban Cycle
BRS	Bureau of Resource Science
BTCE	Bureau of Transport and Communications Economics
BTRE	Bureau of Transport and Regional Economics
CADC	Common Artemis Drive Cycle
CBD	Central Business District
CFC	Chlorofluorocarbons
CH_4	Methane
CI	Compression ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DI	Direct injection
DOTARS	Department of Transport and Regional Services
DSA	Duncan Seddon and Associates
ECE	Economic Commission for Europe
EDC	European Drive Cycle
EETP	European Emissions Test Program
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
FC	Fuel consumption
FFC	Full-fuel cycle
FORS	Federal Office of Road Safety
FQR	Fuel Quality Review

FTP	Federal Test Protocol
FVI	Fuel Volatility Index
GCV	Gross Calorific Value
GJ	Gigajoule; unit of energy; 1 GJ = 1 x 10^9 J
GHG	Greenhouse Gas/Gases
GVM	Gross Vehicle Mass
GWP	Global Warming Potential
HC	Hydrocarbons. In this report, HC is used for non-methanic hydrocarbons.
HCU	Hydro-Cracking Unit
HDU	Hydro-Desulfurisation Unit
HD5	Standard for LPG such that it is primarily propane.
HDV	Heavy Duty Vehicle
HEV	Hybrid Electric 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	Liquid Natural Gas
LP	Leaded Petrol
LPG	Liquefied Petroleum Gas
2G LPG	Second generation LPG vehicles (air/fuel continuously mixed in inlet tract or ports, computerised fuel management system with closed loop feedback)
3G LPG	Third generation LPG vehicles (timed, sequential multi-port injection—dry gas or liquid fuel—with computerised fuel management system and closed loop feedback)
LS	Low sulfur
LSD	Low sulfur diesel
MJ	Megajoule; unit of energy; 1 MJ = 1 x10^6 J
MON	Motor Octane Number
MTBE	Methyl tertiary butyl ether
MVEC	Motor Vehicle Environment Committee
NAFC	National Average Fuel Consumption
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
NRMA	NSW Road and Motoring Association
NSW	New South Wales
OEM	Original equipment manufacturer
OXC	Oxidation catalyst
OHS	Occupational health and safety
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
PM10	Particulate matter below 10 μm diameter
PULP	Premium unleaded petrol
RMIT	Royal Melbourne Institute of Technology
RON	Research Octane Number
RTA	Roads and Traffic Authority (NSW)
SAE	Society of Automotive Engineers
SI	Spark ignition
SO_2	Sulfur dioxide
SO_x	Oxides of sulfur
SOF	Soluble Organic Fraction
THC	Total hydrocarbons, being the sum of NMHC and methane.
TSP	Total suspended particles
TTVS	Trans Tasman Vehicle Standards
ULP	Unleaded petrol
ULS	Ultra-low sulfur (less than 50 ppm sulfur) in diesel or petrol.
US	United States of America
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compounds
XLS	Extra low sulfur (less than 10 ppm sulfur) in diesel or petrol.

Acknowledgements

We acknowledge the assistance and guidance of the Project Manager for this work, Mr Ziggy Durek of the Australian Greenhouse Office. We also acknowledge the financial contribution towards this work of the Australian Greenhouse Office, and also the Victorian EPA and DSE, which participated in the project under an initiative of the Victorian Greenhouse Strategy.

Executive Summary

This study extends the work done for the Australian Greenhouse Office (AGO) on the life-cycle assessment of emissions from heavy vehicles. It does so by using the same methodology and applying it to light vehicles. Petrol, diesel, LPG (dual-fuel) and CNG fuels and a number of vehicle technologies were examined.

On a full-fuel cycle basis, when vehicles are normalised to remove mass differences, the lowest greenhouse gas (GHG) emissions are from hybrid electric vehicles. Diesel vehicles emit less exbodied GHG (exbodied emissions are the sum of the pre-combustion emissions and the tailpipe emissions) than petrol, LPG or CNG vehicles, which also means that a diesel-hybrid would have lower exbodied GHG emissions than a petrol-hybrid. Diesel vehicles also have lower exbodied emissions of carbon monoxide and non-methanic volatile organic compounds (NMVOC) than petrol, LPG, and CNG. However, diesel vehicles emit more particulate matter than any other fuel class.

Exbodied LPG emissions are below those of the equivalent class of petrol vehicle for all types of fuels (propane and autogas) and for all emissions except for carbon monoxide. The equivalent class of petrol vehicle means that second generation LPG vehicles[1] are compared with ULP vehicles, whereas third generation LPG vehicles are compared with PULP vehicles. These findings refer to dual-fuel LPG vehicles manufactured on the production line or post-equipped under the control of the car manufacturer. We expect after-market conversions to LPG to perform more poorly, but would also expect dedicated single-fuel LPG to perform better.

CNG vehicles have lower GHG emissions than petrol and second generation LPG vehicles, but higher emissions than diesel and third generation LPG vehicles. Third generation LPG vehicles have the lowest NMVOC, NO_x and PM emissions. CNG emissions of NO_x and PM are comparable with third generation LPG whereas CNG emissions of NMVOC are slightly higher.

However, these results depend on the drive cycle used to examine the emissions. The above conclusions are based on the European Drive Cycle (EDC) that is required under ADR 79. Under the Artemis Drive Cycle recently introduced as a test drive cycle in Europe, the GHG tailpipe emissions of CNG are less than those of diesel vehicles, whereas the reverse is the case under the EDC and the Australian Urban Drive Cycle (AUDC). This indicates that vehicle technology and catalytic converter technology need to be very tightly designed for optimum performance and minimum emissions. It is for this reason that we expect that dedicated LPG vehicles should be able to be more tightly designed and thus have lower emissions than dual-fuel vehicles.

Present day health concerns associated with motor vehicle emissions are predominantly focussed on particulate matter (PM10, PM2.5, PM1). LPG (third generation) vehicles have the lowest tailpipe emissions of PM10, but on a life-cycle basis the PM10 emissions from LPG and CNG are comparable, and are less than those from diesel, petrol or even hybrid vehicles.

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[1] Second generation LPG vehicles have electronic control, and the third generation LPG combine advanced fuel injection technology with advanced electronic management features. For more details, the reader can consult Anyon (2002).

We examined the effect of vehicle mass by examining the exbodied emissions to be expected from a compact-sized vehicle of approximately 1000 kg — compared with the reference family-sized vehicle of 1,700 kg mass. The same relativities hold in both cases, but the absolute values of the emissions are much lower in the case of smaller cars. Thus the reference ULP (less than 150 ppm sulfur) vehicle emits 349 g CO_2-e per km on a full-fuel cycle basis; the equivalent Euro 4 PULP vehicle (with less than 50 ppm sulfur) emits 289 g CO_2-e per km, whereas a petrol hybrid of the same mass emits 200 g CO_2-e per km. However, a compact Euro 4 PULP vehicle of 1130 kg emits 191 g CO_2-e per km, a petrol hybrid such as the 2003 Prius emits 128 g CO_2-e per km, whereas the Honda insight (950 kg) emits only 101 g CO_2-e per km.

A comparison of exbodied emissions is provided in charts ES.1–ES.5, and is also presented in Section 7.2 of the report. The bar charts show the emissions per km for family vehicles (1,700 kg).

The effects of vehicle mass are most marked in the case of fuel consumption and GHG emissions. Emissions of the criteria pollutants are more dependent on vehicle technologies and emission control systems.

A summary of the results of the analysis of emissions per km is presented in Table ES.1.

Table ES.1 – Relative performance of fuels analysed in the study (ULP Euro 3 as baseline)

Fuel	**GHG**	**CO**	**NO_x**	**NMVOC**	**PM**
PULP Euro 4	–	–	—	–	–
ULS PULP Euro 4	–	–	—	–	–
LS Diesel Euro 4	–	—	—	—	++
ULS Diesel Euro 4	—	–	—	—	++
LPG Autogas 2nd gen.	–	–	+	–	—
LPG Propane 2nd gen.	–	–	–	—	—
LPG Autogas 3rd gen.	—	–	—	—	—
LPG Propane 3rd gen.	—	–	—	—	—
CNG	—	–	—	—	—
Hybrid PULP	—	–	–	–	—
Hybrid Diesel	—	—	—	—	—

Legend: — significantly lower[2] (than the reference fuel); – lower; = much the same; + higher; ++ significantly higher.

Numerous data gaps were revealed during this study. There were:

- insufficient particulate matter emissions data for LPG vehicles. We draw conclusions about PM10 particulate emissions on the basis of steady-state constant speed testing
- insufficient emissions data for CNG vehicles. Our results are based on one data set from a Volvo V70
- insufficient air toxics emissions data for us to determine the effects of different fuel types on air toxics emissions

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[2] Significantly lower is < 0.5*base value; lower is below 0.95 of the base value; about the same is within 0.95 and 1.05 of the base value; higher means >1.5*base value; significantly higher means > 2*base value.

- no data on the performance of dedicated LPG vehicles. All of the LPG emissions data that we were able to obtain related to dual-fuel[3] vehicles
- no test data to examine the differences (if any) in tailpipe emissions from direct injection light vehicles as a result of the sulfur content of petrol (i.e. 50 ppm, 10 ppm). Some results show that reduced-sulfur fuels enhance the performance of vehicle technologies designed to use them, thus reducing all emissions. A summary is provided in section 7.4.

These findings suggest that further investigation is necessary. The statistical inference is confined to very few data under Australian conditions. This is an area of future research and we recommend testing the requisite vehicles on the same drive cycle, with the four fuels examined in the present study.

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[3] Dual-fuel vehicles (in Australian terminology) are known as bi-fuel vehicles in the UK.

Family-sized Australian car

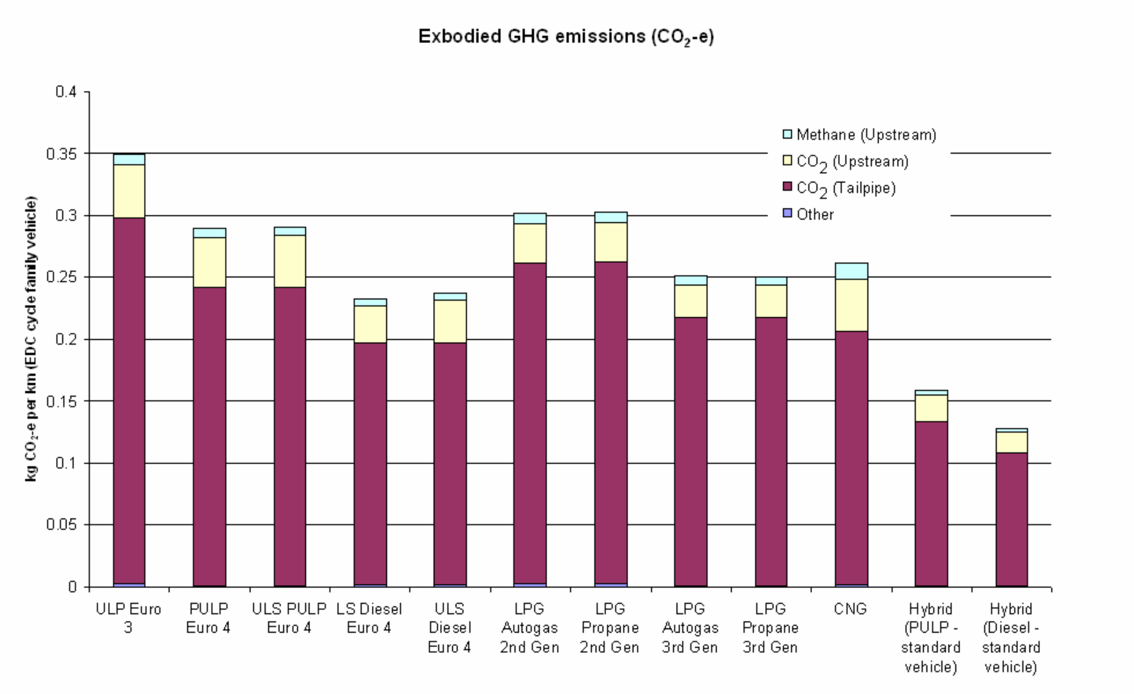


Figure ES.1 – Exbodied greenhouse emissions from family-sized vehicles (European Drive Cycle)

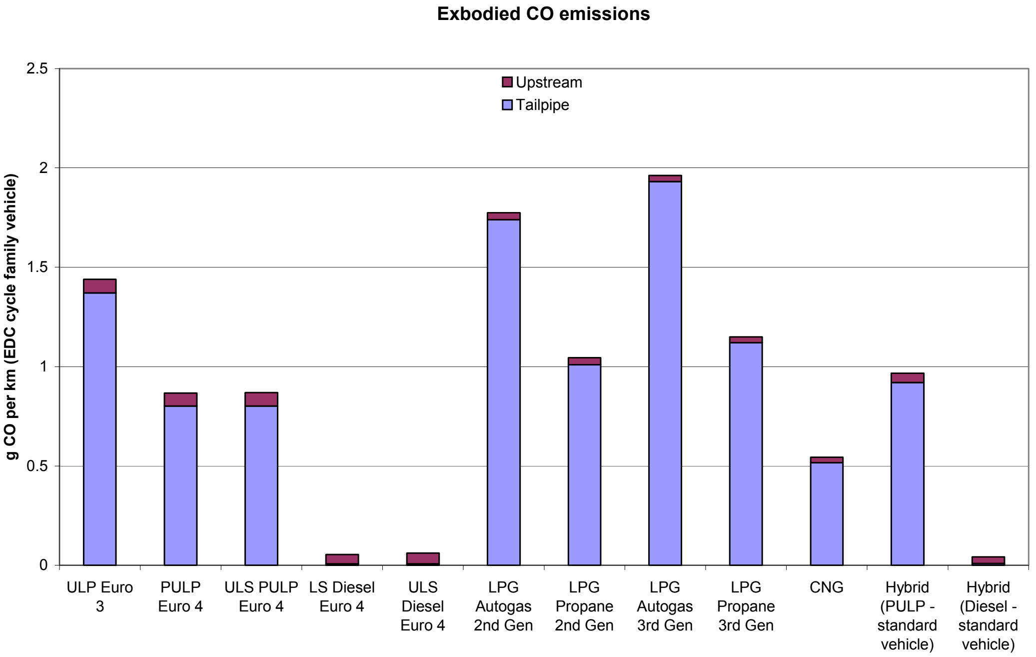


Figure ES.2 – Exbodied carbon monoxide emissions from family-sized vehicles (European Drive Cycle)

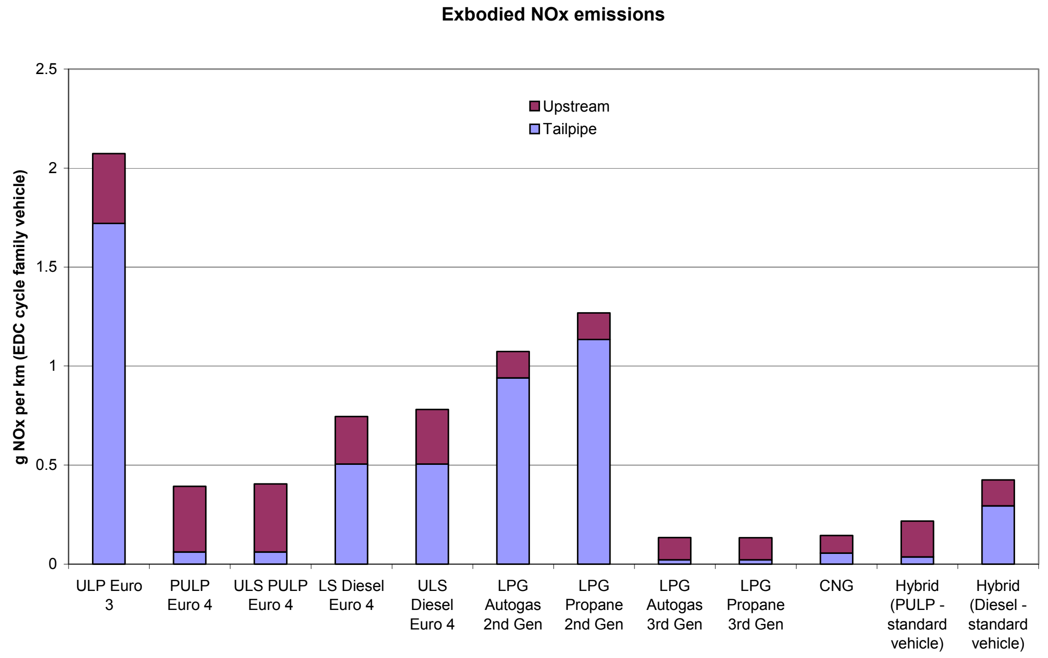


Figure ES.3 – Exbodied NO_x emissions from family-sized vehicles (European Drive Cycle)

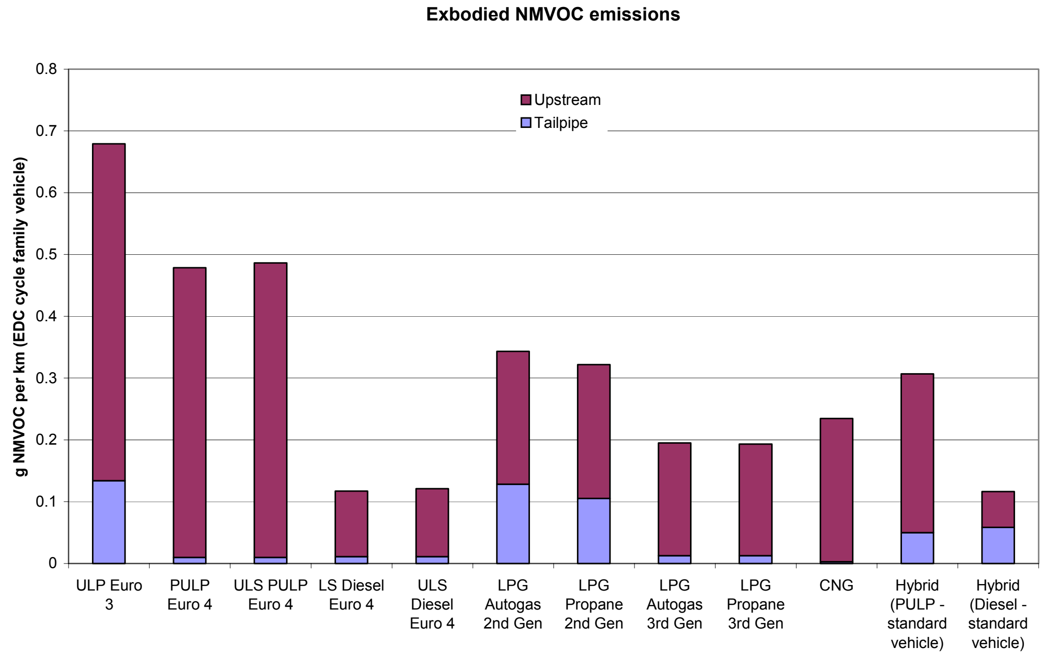


Figure ES.4 – Exbodied hydrocarbon (NMVOC) emissions from family-sized vehicles (European Drive Cycle)

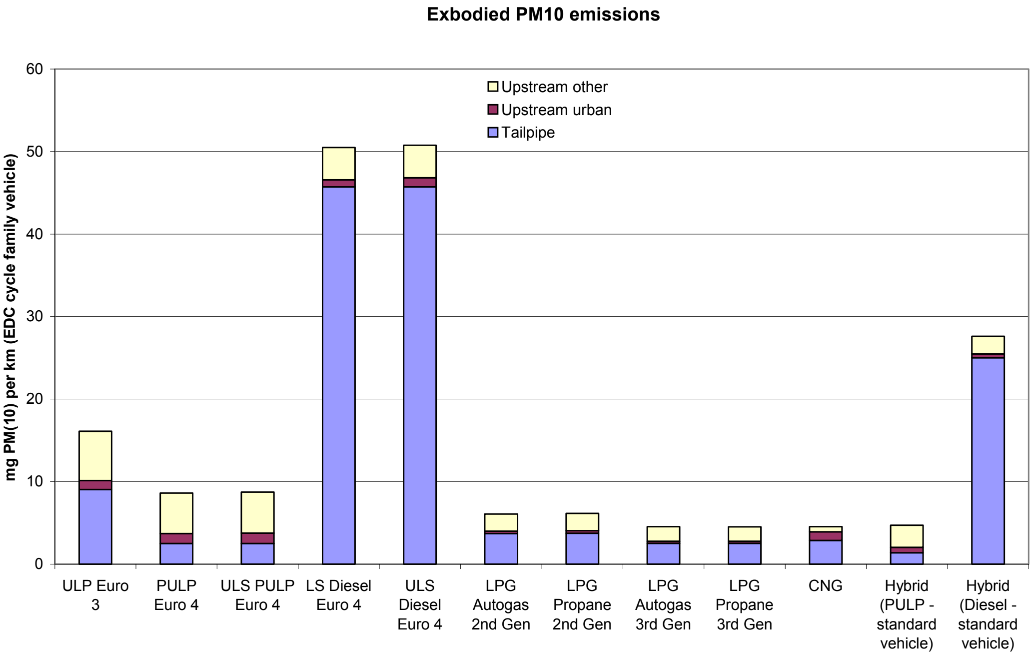


Figure ES.5 – Particle (PM10) emissions from family-sized vehicles (European Drive Cycle)

1. Background

1.1. Introduction

In 2001 CSIRO, in conjunction with RMIT, the University of Melbourne, Parsons Australia Pty Ltd and the Southern Cross Institute of Health Research undertook a study for the AGO entitled *Comparison of Transport Fuels*, which examined the full-fuel cycle of emissions from alternative fuels used in heavy vehicles. This report responds to a brief from the AGO to undertake a comparison of road transport fuel emissions for light vehicles (less than 3.5 tonne) by using a similar methodology to that adopted in the earlier study. The most notable difference between the studies is that the light vehicles study factors in different motor vehicle technologies.

The Terms of Reference are given in Appendix A.

Table 1.1 identifies fuels and motor vehicle technologies that are to be included in the study.

Table 1.1 – Matrix depicting fuels and motor vehicle technologies included in this study

Fuel	Conventional Technology	New Technology	Dual-fuel	Hybrid
ULP containing <150 ppm of sulfur	SI			
PULP containing <150 ppm of sulfur	SI			SI
PULP containing <50 ppm of sulfur	SI	DI		SI
LPG (Autogas)	SI	Liquid Phase Injection-3rd Generation	ULP	
LPG (HD5)	SI	Liquid Phase Injection-3rd Generation	ULP	
CNG	SI			
Diesel containing <50 ppm of sulfur	CI–DI			CI
Diesel containing <10 ppm of sulfur	CI–DI			CI

ULP = Unleaded petrol (91 RON, 81 MON)

PULP = Premium unleaded petrol (95 RON, 85 MON)

CNG = Compressed Natural Gas

LPG (liquefied petroleum gas) — autogas from any source meeting the voluntary Australian Liquefied Petroleum Gas Association Ltd specification or European standard EN589.

LPG (HD5) – HD5 grade autogas from any source. Refer to Californian Air Resources Board specifications http://www.arb.ca.gov/regact/lpgspecs/lpgspecs.htm

SI = Spark Ignition Engine

CI = Compression Ignition Engine

DI = Direct Injection (into combustion chamber)

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 eight fuels. Four classes of fuels are considered—petrol, diesel, LPG and CNG. Also, three classes of emissions are considered:

- GHG, which are global pollutants that comprise carbon dioxide, nitrous oxide, hydrofluorocarbons, methane, sulfur hexafluoride, and perfluorocarbons.
- Criteria air pollutants that are more local in their effect, which comprise carbon monoxide, oxides of nitrogen, sulfur dioxide, non-methanic volatile organic compounds, and particles.
- Air toxics, which include compounds such as benzene, aldehydes (formaldehyde and acetaldehyde), 1,3 butadiene, polycyclic aromatic hydrocarbons (PAH), toluene, and xylene.

1.2. Structure of the report

This report examines life-cycle emissions of GHG and air pollutants by light vehicles running on alternative fuels. It continues a program of assessment of the life-cycle emissions of alternative fuels (Beer et al. 2000, 2001, 2002, 2003; CSIRO, ABARE and BTRE 2003). In these studies, wherever possible, the emissions are provided on a quantitative basis as a result of values available in the literature. However, the above reports have already detailed many of the upstream processes required to produce fuels. As a consequence, the major thrust of this report is the collation of data related to the tailpipe emissions from the vehicles. Descriptions of upstream emissions are given only where they are not given in the earlier reports, as in the case of unleaded petrol, or where there has been a substantial re-analysis of the allocation methods used in the earlier reports, as in the case for LPG.

Fuels are compared on the basis of the mass of emissions per kilometre travelled, for vehicles normalised in such a way that their masses are comparable. The mass of emissions per kilometre travelled is the environmentally most meaningful figure, though it is subject to greater variability than the mass per unit energy. Arriving at the emissions per kilometre involves three steps:

1. Life-cycle analysis (LCA) of emissions

   This first step produces an estimate of the GHG and air quality emissions from each fuel expressed as the mass of emissions per unit of energy—kg/MJ.

2. Fuel combustion

   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 examining this is to examine the units associated with the quantities:

$$g/km = (g/kWh) \times (1/\text{engine efficiency}) \times (kWh/MJ) \times (MJ/kg) \times (kg/L) \times (L/km) \quad (1.1)$$

The first term (g/km) is the final performance result that this report examines. The emissions are expressed on a per kilometre basis. One arrives at this by considering the product of the engine emissions (g/kWh), the fuel combustion characteristics (MJ/kg), the fuel density (kg/L) and the vehicle fuel economy (L/km). Each one of these four elements will display variability so that, if the variables are independent then, the uncertainty associated with the emissions will be the sum of the percentage uncertainties associated with each of the four terms.

We have retained the use of g/kWh (even though it is dimensionally equivalent to g/MJ) to emphasise that the output of an engine dynamometer refers to the usable work, rather than the energy content of the fuel.

The theoretical efficiencies of petrol engines (which follow an Otto cycle) and diesel engines depend on the compression ratio. For typical values of these, the theoretical Carnot efficiencies range from 64% to 67%, though the efficiencies of actual engines are lower (Zemansky 1957).

Whereas the first three elements given above can be calculated 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 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 placing the drive wheels of the vehicle 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.

The quantitative results provide an estimate for the mean emission factor. Because of the large variability in the results of emission tests on conventional and alternative fuels, a statistical approach needs to be adopted. The uncertainty for each fuel needs to be estimated, and comparison with the reference fuel made on the basis of the statistical variability. The method of uncertainty analysis adopted is explained in Appendix C.

1.3. Sources of quantitative information

The quantitative calculations in the report are based on a variety of sources for upstream emissions, summarised in Table 1.1 of Beer et al. (2001). These sources were used for the upstream (pre-combustion) process calculations, in conjunction with the extensive data set held by RMIT Centre for Design. This data set consists of emissions and energy use involved in Australian manufacturing.

Two main sources of data were used to provide the quantitative tailpipe emissions information. These were:

- The Comparative Vehicle Emissions Study undertaken by DOTARS. The report and Excel spreadsheets of the data obtained in this study are available at: http://www.dotars.gov.au/mve/index.htm

- The European Emissions Testing Program (EETP) undertaken by the LPG Association of the UK. A summary of the data obtained in this study is available in the report LPG: *A bridge to the future* available at: http://www.lpga.co.uk/ai_mem/secure/pdf/Road%20Fuel%20Gases%20Consultation%20Response.pdf

In addition, the Australian LPG Association provided clarification and further information on the data.

1.4. Greenhouse gases and other emissions

In 2002, transport emitted about 19.26% of the national anthropogenic CO_2 emissions of 384.6 Mtonnes, but only 14.4% of total GHG emissions of 550 Mtonnes CO_2-equivalents (National Greenhouse Gas Inventory 2002, 2004). About 88.2% of these emissions come from road transport, including cars, trucks and buses. Table 1.2 gives a breakdown of the relative GHG emissions from transport and road transport.

Table 1.2 Australian GHG emissions (in CO_2-e) from the transport sector and the road sub-sector in 2002

Sector	**CO_2 (Gg)**	**CH_4 (Gg)**	**N_2O (Gg)**	**CO_2-e (Gg)**
Transport	74,087	656	4,467	79,210
Road transport	64,887	597	4,385	69,869

Source: National Greenhouse Gas Inventory 2002 (2004), Table A17, p.27.

In terms of the types of fuel used, current annual consumption is about 18,400 ML of automotive gasoline and about 8,100 ML of automotive diesel, with aviation using around 6,000 ML of turbine fuel. LPG and aviation gasoline consumption is relatively low.

The GHG considered in this report are carbon dioxide, methane and nitrous oxide. The concept of a global warming potential (GWP) has been used to enable different GHG to be compared with each other and expressed in CO_2-e. The GWP factors reflect the different extent to which gases absorb infrared radiation and the differences in the time scales 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 100-year time horizon) as the basis for defining equivalences between emissions of different GHG during the 2008–2012 commitment period. These GWPs are given in Table 1.3.

Table 1.3 100-year GHG warming potentials

Gas	**GWP**
Carbon dioxide	1
Methane	21
Nitrous oxide	310

Figure 1.1 plots the annual variation from 1988 to 2002 (inclusive) of the vehicle kilometres travelled (VKT, in billions of km), the energy usage (PJ), and the emissions of CO_2, CH_4 and N_2O, and the CO_2-e, all in Gg.

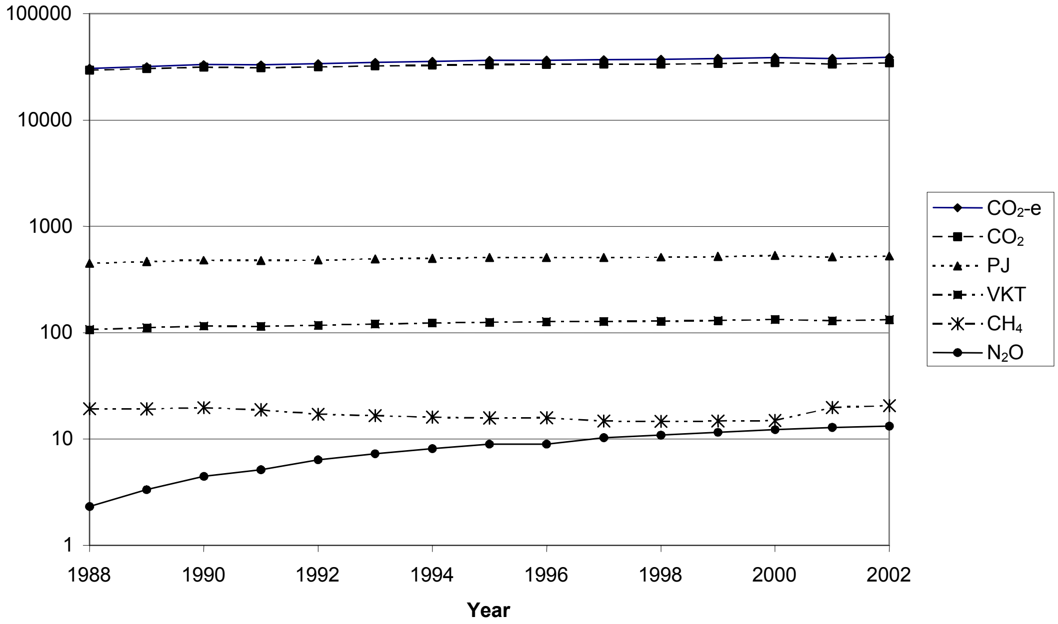


Figure 1.1 – Time series of energy use (in PJ), VKT (in Tm) and GHG emissions (in Gg) of Australian petrol-driven passenger cars

It is noticeable in Figure 1.1 that, despite the upward creep in VKT (from 106.7 billion km in 1988 to 132.5 billion km in 2002), there has been only a slight increase in energy usage from 449.5 PJ to 525.2 PJ. Methane emissions have declined during this period but nitrous oxide (N_2O) emissions have increased as a result of the use of three-way catalytic converters. Beer (1995) has shown that stringent emission controls are successful in decreasing atmospheric loads in the short term, as old vehicles are replaced by newer vehicles with lower emissions. In the longer term all of the vehicle fleet consists of lower emission vehicles and then the increase in passenger car numbers and in VKT leads to an increase in atmospheric loads.

1.4.1 Criteria air pollutants

The air pollutants to be considered are carbon monoxide, oxides of nitrogen, sulfur dioxide, non-methanic hydrocarbons (NMHC), and particles with diameter less than 10 μm (PM10). Emission loads of some of these are given in Table 1.4. These air pollutants are generated by transport vehicles, 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.

Table 1.4 – Australian energy use, GHG emissions and air pollution loads for 2002 for major petrol-driven passenger car classes

Period	**Energy use (PJ)**	**CO_2 (Gg)**	**CH_4 (Gg)**	**N_2O (Gg)**	**NO_x (Gg)**	**CO (Gg)**	**NMVOC (Gg)**	**SOx (Gg)**
Post-1997	152.83	9985	2.32	4.78	27.19	195.3	12.16	2.31
1986–1997	305.48	19960	15.58	8.33	143.65	1418.7	81.79	4.62
1976–1985	56.97	3723	2.16	0.05	31.61	452.5	33.82	0.86
Pre-1976	9.90	647	0.55	0.01	5.61	104.2	8.59	0.15
Total	525.17	34315	20.6	13.17	208.06	2170.7	136.35	7.94

Source: National Greenhouse Gas Inventory 2002 (2004)

Elevated concentrations of sulfur dioxide are not an issue in urban Australia (Manins et al. 2001). The only population centres to exceed the one hour standard of the ambient air quality NEPM (National Environment Protection Measure) are Mount Isa and Kalgoorlie, and in those locations the exceedances are caused by industrial emissions, not transport emissions. Sulfur dioxide emissions from motor vehicles will further decrease as more stringent fuel quality standards come into effect. Accordingly, this report does not quantify sulfur dioxide emissions.

NMHC exhaust emissions from conventional vehicles consist primarily of simple hydrocarbons (excluding methane). Particles, smoke and NMHCs are composed of a mixture of many different compounds, including benzene, formaldehyde, lead, chromium and benzo-a-pyrene. Many of these compounds are highly toxic.

There are a relatively small number of studies on air toxics in Australia compared with the criteria pollutants. A greater difficulty is that there is no agreed Australian methodology for evaluating health risks associated with air toxics. This study reviews work on air toxics emissions from the fuels where such work exists.

1.5. Drive cycles

In this study we obtained data from vehicles with the following drive cycles:

a. The Japanese 10–15 mode drive cycle

   i. **10-Mode Cycle**

   Urban driving cycle used for light-duty vehicles, later replaced by the 10–15 mode cycle. It represented a route of 3.32 km, completed in 675 s. The maximum speed is 40 km/h.

   ii. **10–15 Mode Cycle**

   Urban driving cycle that is currently used in Japan for emission certification of light-duty vehicles. It is derived from the 10-mode cycle by adding another segment of a maximum speed of 70 km/h. The total distance is 4.16 km, completed in 660 s.

b. **ADR 37/01**, which is the same as the **FTP** cycle of the US EPA.

c. **ECE R83/04** (the test procedure required under Euro 2 emission regulations). This is the test cycle that has been required in Australia since 2003 under **ADR 79/00**. It is also known as the ECE15 + EUDC, or EDC (European Drive Cycle) test.

d. **ECE R101** (Revised ECE R83/04), is the test cycle required in Australia under ADR 81/01 to measure fuel consumption. It will be required in Australia from 2005 under ADR 79/01 (to measure emissions). It is the same as ECE R83/04 except that there is no 40 second idle at the start. Since 2000 the ECE15 + EUDC, or EDC (European Drive Cycle) test in Europe has been modified to eliminate the 40 s engine warm-up period.

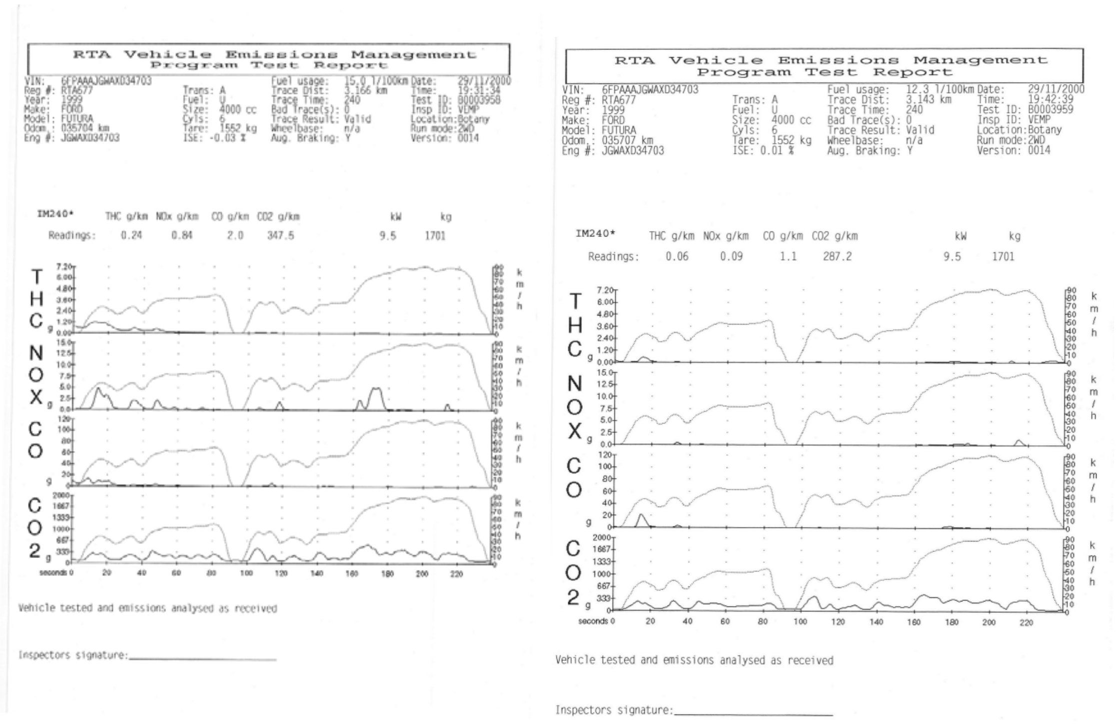
e. **AUC** (Australian Urban Cycle)

   This cycle was developed for the CVES study (Department of Transport and Regional Services 2001) to characterise the normal urban driving pattern of the Australian motorist.

f. **CADC** (Common Artemis Drive Cycle)

   This cycle, used in the European Emission Testing Program, is described in: http://www.umwelt-schweiz.ch/imperia/md/content/luft/fachgebiet/d/au/AU25.pdf.

Cold start testing can be significantly more stringent than warm start testing. We demonstrate this (Figure 1.2) with chassis dynamometer results obtained for two identical tests undertaken by the NSW RTA on a Ford Futura. The cold start behaviour is evident in the traces on the left side of the figure, where the high initial emissions of THC and NO_x, as well as the blips indicating NO_x emissions, indicate the cold start emissions. In the second test, undertaken 11 minutes later (and thus the car engine had warmed up for 11 minutes) there are substantially lower emissions of all of the certification pollutants THC, NO_x and CO as well as lower emissions of CO_2.



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VIN:    6FPAAAJGWAXD34703                 Fuel usage:    15.0 l/100km Date:     29/11/2000
Reg #:  RTA677           Trans: A         Trace Dist:    3.166 km     Time:     19:31:34
Year:   1999             Fuel:  U         Trace Time:    240          Test ID:  B0003958
Make:   FORD             Size:  4000 cc   Bad Trace(s):  0            Insp ID:  VEMP
Model:  FUTURA           Cyls:  6         Trace Result:  Valid        Location:Botany
Odom.:  035704 km        Tare:  1552 kg   Wheelbase:     n/a          Run mode:2WD
Eng #:  JGWAXD34703      ISE: -0.03 %     Aug. Braking:  Y            Version:  0014

IM240*     THC g/km  NOx g/km  CO g/km  CO2 g/km        kW     kg
 Readings:   0.24      0.84      2.0     347.5          9.5    1701

Vehicle tested and emissions analysed as received

Inspectors signature:______________________
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```
RTA Vehicle Emissions Management
      Program Test Report
VIN:    6FPAAAJGWAXD34703                 Fuel usage:    12.3 l/100km Date:     29/11/2000
Reg #:  RTA677           Trans: A         Trace Dist:    3.143 km     Time:     19:42:39
Year:   1999             Fuel:  U         Trace Time:    240          Test ID:  B0003959
Make:   FORD             Size:  4000 cc   Bad Trace(s):  0            Insp ID:  VEMP
Model:  FUTURA           Cyls:  6         Trace Result:  Valid        Location:Botany
Odom.:  035707 km        Tare:  1552 kg   Wheelbase:     n/a          Run mode:2WD
Eng #:  JGWAXD34703      ISE: 0.01 %      Aug. Braking:  Y            Version:  0014

IM240*     THC g/km  NOx g/km  CO g/km  CO2 g/km        kW     kg
 Readings:   0.06      0.09      1.1     287.2          9.5    1701

Vehicle tested and emissions analysed as received

Inspectors signature:______________________
```

Figure 1.2 – Cold start (left) and warm start (right) testing of a vehicle under the IM240 drive cycle. Note the higher emissions as a result of the cold start.

1.5.1 Methodology for converting ADR 37 to ADR79

The drive cycle plays an important role in the determination of emissions. We illustrate this by an analysis of the differences in carbon dioxide emissions associated with the National Average Fuel Consumption if the fuel consumption is measured using ADR 79 instead of ADR 37.

We have examined the correlations between fuel consumption determined by ADR 37 (based on AS2877) and the emissions to be expected from both ADR 79/00 and ADR 79/01. These are summarised in Table 1.5 and Table 1.6.

Table 1.5 – Equivalent fuel consumption (FC) corresponding to 6.8 L/100 km based on correlations of vehicle fuel consumption

Drive cycle	Regression equation	Equivalent L/100 km	CO_2 emissions (g/km)
ADR 79/00	1.0911 FC	7.42	166
ADR 79/00	0.9675 FC + 1.3362	7.92	177
ADR 79/01	1.0703 FC	7.28	163
ADR 79/01	0.8429 FC + 2.5483	8.28	185

Alternatively, Table 1.6 uses the correlations of vehicle carbon dioxide emissions to arrive at slightly different estimates.

Table 1.6 – Equivalent carbon dioxide emissions corresponding to 152 g/km CO_2 from ADR 37 based on correlations of vehicle carbon dioxide emissions

Drive cycle	**Regression equation**	**Carbon dioxide**	**CO_2 emissions (g/km)**
ADR 79/00	1.0816 FC	152	164
ADR 79/00	0.9408 FC + 34.214	152	177
ADR 79/01	1.0556 FC	152	160
ADR 79/01	0.8087 FC + 61.79	152	184

1.6. Life-cycle analysis

A general introduction to LCA may be found in Graedel and Allenby (1995), while the international standards on LCA, contained in the 14040 series (International Standards Organisation 1998) provide a basic framework in which to undertake LCA. 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 analysis of emissions (which we refer to as exbodied emissions) takes into account not only the direct emissions from vehicles (which are referred to as downstream emissions) but also those associated with the fuel's:

- extraction
- production
- transport
- processing
- conversion
- distribution.

These are referred to as upstream emissions. In the context of automobile fuels they are also referred to as pre-combustion emissions. Further details and examples of life-cycle analysis are given in Appendix D.

1.7. The automobile life cycle

Much of the material in this section is taken from Kuhndt and Bilitewski (1999), supplemented by material found on the Toyota website.

Today vehicles consist of approximately 15,000 parts. Steel, iron, plastic and nonferrous metal dominate automobile construction. They account for more than 80% of material used for current vehicles. A common trend in the material composition of a car is toward increasing use of lightweight materials, especially towards the use of numerous types of plastics and non-ferrous metals such as aluminium, copper and magnesium. Table 1.7, taken from Kuhndt and Bilitewski (1999), shows the material composition of current vehicles.

The generic European vehicle shows a downward trend in metal content, which now accounts for about 65% of the total weight. The plastic content of current models has increased fourfold over the last twenty years and it is expected that this will continue to increase before levelling off at about 15% by the year 2000 (Peters 1996). The Golf III has already achieved this level of plastic content.

The *utilisation* of an automobile consumes about 80% of the total primary energy consumption of the life cycle of an automobile. This refers to the energy involved in production, utilisation and disposal of the vehicle itself. The LCA of the Golf III confirms that the 'use phase' is the dominant phase (Figure 1.3).

Table 1.7 – Passenger Car's Material Ratio

Material	**Material ratio (% by weight)**			
	Generic US vehicle[1]	**Generic Japanese vehicle[2]**	**Generic EU compact vehicle[3]**	**Golf III[3]**
Steel and iron	67	72.2	65	64
Plastic	8	10.1	12	16
Glass	2.8	2.8	2.5	3.1
Rubber	4.2	3.1	6	4
Fluids and Lubricants	6	3.4	2.5	5
Non-ferrous metal	8	6.2	8	1.6
Electric cable				1.3
Insulation				1.1
Paint				0.9
Other materials	4	2.2	4	3
Total weight (kg)	1438	1270	1210	1025

Source: [1] Keoleian et al. (1997): [2] Kobayashi (1996): [3] Schweimer and Schuckert, M. (1996)

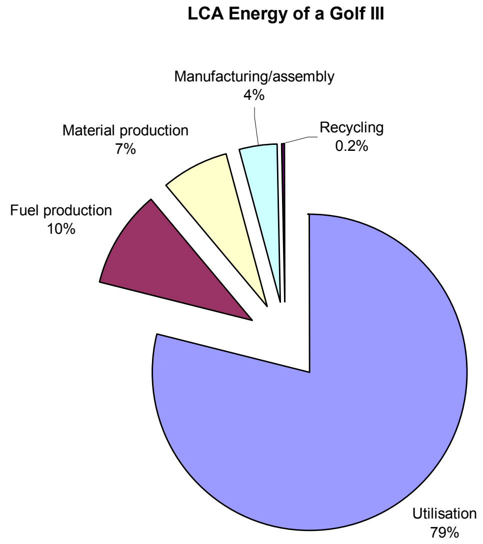

Figure 1.3 – The in-process and direct GHG emissions (0.0356 Gg CO_2) during the life cycle of a Golf III for a life of 150,000 km, primary energy consumption of 540 GJ and a fuel consumption of 12.3 km/L (Kuhndt and Bilitewski 1999)

The main pollutants from automobile exhausts, for conventional gasoline and diesel engines, are carbon dioxide, carbon monoxide, nitrogen oxides, hydrocarbons and fine particles. Carbon dioxide is the most significant GHG.

Carbon dioxide emissions are directly related to fuel consumption, and for each kilometre travelled, can be reduced only by increasing vehicle efficiency, or switching to alternate fuels such as natural gas. Every 60-litre fill up at the gas station results in about 135 kg of carbon dioxide being released into the atmosphere. Globally, automobile emissions are directly responsible for close to 10% of man-made carbon dioxide emissions. If gasoline refining and processing, as well as automobile manufacturing are considered, automobiles are responsible for 15–20% of global carbon dioxide emissions.

One of the items in the Toyota Corporation (1998) Environmental Report[4] is a chart, reproduced in Figure 1.4, which compares the life-cycle analysis of the energy consumption in a typical gasoline vehicle, with that of a hybrid vehicle. The important aspect to note is that, although there is a substantial energy saving in the drive cycle, the energy consumption in material production and in vehicle production is slightly higher for the hybrid vehicle.

Toyota also published figures for the fuel efficiency and the CO_2 emissions (in g/km) of its vehicles in 1997. These values are based on a Japanese drive cycle referred to as the 10–15 mode. Toyota's hybrid vehicle, the Prius, emitted 84 g of CO_2 per km of travel, corresponding to a fuel efficiency of 28 km per litre of fuel. The Toyota Australia website provides fuel efficiency and CO_2 emission values for the second generation of Prius. With a city cycle (ADR81/01), the fuel consumption is 4.4 L/100 km and the CO_2 emissions are 106 g/km, 50% lower than a conventional car of similar size.

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[4] We reproduce this chart, and that of Figure 1.5, because they contain data on the Prius. Toyota is expected to release data on the 2003 Prius in August 2004.

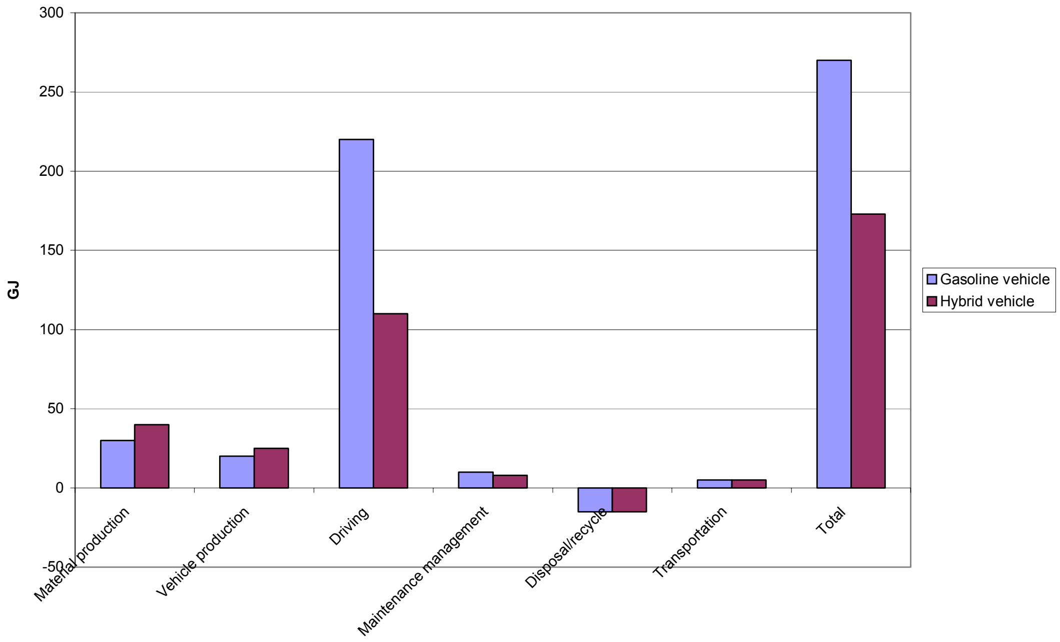
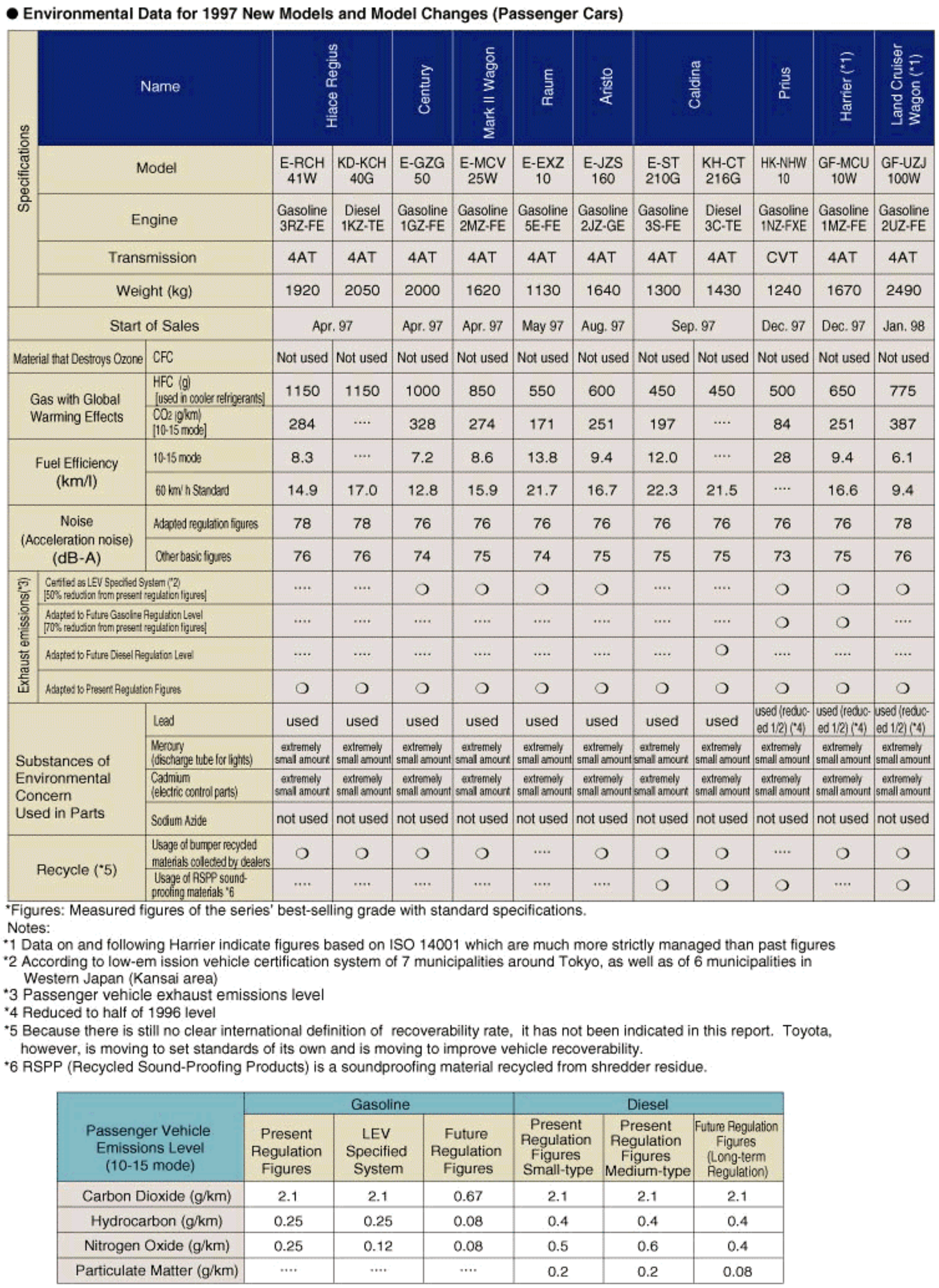


Figure 1.4 – Toyota Corporation estimates of the LCA of its hybrid vehicle

Source: Toyota Motor Corporation (1998)

The first generation Prius is listed as having a fuel efficiency of 28 km/L, and as emitting 84 g of CO_2/km (Japanese 10–15 drive cycle). Multiplying the two figures yields an emission factor of 2,352 g CO_2/L of fuel. If we use the National Greenhouse Gas Inventory Committee (1996b) energy density given in section 1.5, of 34.2 MJ/L, then the emission factor for the Prius is 68.8 g CO_2/MJ, which is slightly higher than the Australian default value shown of 66 g/MJ. For the second generation of Prius, the emission factor is 2,409 g CO_2/L of fuel, with an equivalent emission factor of 70.4 g CO_2/MJ, again higher than the Australian default value.

These calculations again indicate that carbon dioxide emissions are directly related to fuel consumption. For each kilometre travelled, emissions can be reduced only by increasing vehicle efficiency, or switching to alternative fuels such as natural gas.



● **Environmental Data for 1997 New Models and Model Changes (Passenger Cars)**

Specifications	Name	Hiace Regius		Century	Mark II Wagon	Raum	Aristo	Caldina		Prius	Harrier (*1)	Land Cruiser Wagon (*1)
	Model	E-RCH 41W	KD-KCH 40G	E-GZG 50	E-MCV 25W	E-EXZ 10	E-JZS 160	E-ST 210G	KH-CT 216G	HK-NHW 10	GF-MCU 10W	GF-UZJ 100W
	Engine	Gasoline 3RZ-FE	Diesel 1KZ-TE	Gasoline 1GZ-FE	Gasoline 2MZ-FE	Gasoline 5E-FE	Gasoline 2JZ-GE	Gasoline 3S-FE	Diesel 3C-TE	Gasoline 1NZ-FXE	Gasoline 1MZ-FE	Gasoline 2UZ-FE
	Transmission	4AT	4AT	4AT	4AT	4AT	4AT	4AT	4AT	CVT	4AT	4AT
	Weight (kg)	1920	2050	2000	1620	1130	1640	1300	1430	1240	1670	2490
Start of Sales		Apr. 97		Apr. 97	Apr. 97	May 97	Aug. 97	Sep. 97		Dec. 97	Dec. 97	Jan. 98
Material that Destroys Ozone	CFC	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used
Gas with Global Warming Effects	HFC (g) [used in cooler refrigerants]	1150	1150	1000	850	550	600	450	450	500	650	775
	CO_2 (g/km) [10-15 mode]	284	····	328	274	171	251	197	····	84	251	387
Fuel Efficiency (km/l)	10-15 mode	8.3	····	7.2	8.6	13.8	9.4	12.0	····	28	9.4	6.1
	60 km/ h Standard	14.9	17.0	12.8	15.9	21.7	16.7	22.3	21.5	····	16.6	9.4
Noise (Acceleration noise) (dB-A)	Adapted regulation figures	78	78	76	76	76	76	76	76	76	76	78
	Other basic figures	76	76	74	75	74	75	75	75	73	75	76
Exhaust emissions(*3)	Certified as LEV Specified System (*2) [50% reduction from present regulation figures]	····	····	○	○	○	○	····	····	○	○	○
	Adapted to Future Gasoline Regulation Level [70% reduction from present regulation figures]	····	····	····	····	····	····	····	····	○	○	····
	Adapted to Future Diesel Regulation Level	····	····	····	····	····	····	····	○	····	····	····
	Adapted to Present Regulation Figures	○	○	○	○	○	○	○	○	○	○	○
Substances of Environmental Concern Used in Parts	Lead	used	used	used	used	used	used	used	used	used (reduced 1/2) (*4)	used (reduced 1/2) (*4)	used (reduced 1/2) (*4)
	Mercury (discharge tube for lights)	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount
	Cadmium (electric control parts)	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount	extremely small amount
	Sodium Azide	not used	not used	not used	not used	not used	not used	not used	not used	not used	not used	not used
Recycle (*5)	Usage of bumper recycled materials collected by dealers	○	○	○	○	····	○	○	○	····	○	○
	Usage of RSPP sound-proofing materials *6	····	····	····	····	····	····	○	○	○	····	○

*Figures: Measured figures of the series' best-selling grade with standard specifications.

Notes:

*1 Data on and following Harrier indicate figures based on ISO 14001 which are much more strictly managed than past figures

*2 According to low-em ission vehicle certification system of 7 municipalities around Tokyo, as well as of 6 municipalities in Western Japan (Kansai area)

*3 Passenger vehicle exhaust emissions level

*4 Reduced to half of 1996 level

*5 Because there is still no clear international definition of recoverability rate, it has not been indicated in this report. Toyota, however, is moving to set standards of its own and is moving to improve vehicle recoverability.

*6 RSPP (Recycled Sound-Proofing Products) is a soundproofing material recycled from shredder residue.

Passenger Vehicle Emissions Level (10-15 mode)	Gasoline			Diesel		
	Present Regulation Figures	LEV Specified System	Future Regulation Figures	Present Regulation Figures Small-type	Present Regulation Figures Medium-type	Future Regulation Figures (Long-term Regulation)
Carbon Dioxide (g/km)	2.1	2.1	0.67	2.1	2.1	2.1
Hydrocarbon (g/km)	0.25	0.25	0.08	0.4	0.4	0.4
Nitrogen Oxide (g/km)	0.25	0.12	0.08	0.5	0.6	0.4
Particulate Matter (g/km)	····	····	····	0.2	0.2	0.08

Figure 1.5 – Toyota Corporation (1998) data for 1997 passenger cars[5]

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[5] The smaller table at the foot of Figure 1.5 gives passenger vehicle emissions levels for 'carbon dioxide'. We assume it should read 'carbon monoxide'

One of the most noticeable differences is in the estimate of the total life-cycle energy consumption of a Japanese gasoline vehicle, which is about 270 GJ and the estimate of the total life-cycle energy consumption of the Golf III, which is 540 GJ. Part of this discrepancy is due to the shorter assumed life of the Japanese vehicle (98,000 km) compared with the European vehicle (150,000 km). However, as shown below, the mileage is not sufficient to account for the discrepancy. The assumed fuel efficiency of the generic Japanese gasoline vehicle must be superior to that of the Golf III, and the figures available to us confirm this assumption. The caption of Figure 1.3 notes the fuel consumption of the Golf III to be 8.1 L/100 km, which is equivalent to 12.3 km/L. Figure 1.5 lists fuel efficiencies of new Toyota vehicles, and only the Landcruiser has fuel efficiency lower than that of the Golf III. We suspect that the Golf III fuel efficiency and life-cycle estimates are based on an urban drive cycle, whereas the Toyota fuel efficiency and life-cycle estimates are based on the Japanese 10–15 drive cycle, which is a mixed urban and highway cycle. For comparison, Table 1.8 provides fuel consumption figures for an Australian car, the Holden Commodore VT Executive, provided by the Royal Automobile Club of Queensland (1999). Comparison between the Golf III values and those in the table indicate that the quoted fuel consumption is intermediate between the city and highway cycles of the Commodore and because the Golf III, at 1025 kg, is lighter than the Commodore (1551 kg) we will assume that the quoted fuel consumption of the Golf III refers to an urban cycle, and infer a fuel consumption for the Golf III of 4.86 L/100 km for a highway cycle for an automatic, and 4.86 L/100 km for a manual.

Table 1.8 – Fuel consumption (L/100 km) for Holden 1998 VT Commodore Executive

Cycle	Manual	Automatic
City cycle	11.0	12.0
Highway cycle	7.2	7.2

Source: Royal Automobile Club of Queensland (1999)

The differences in weight, and in assumed life, play an important role in the energy estimates for the car. Fewchuk et al. (1998) examined the life-cycle energy analysis of the original concept car and compared it with the life-cycle energy consumption associated with an upper-medium class Australian car (a Ford Falcon), with a mass of 1,750 kg driven over 225,000 km. They estimate the total life-cycle energy consumption of the upper-medium class car to be 1,637 GJ. This corresponds to about 1200 GJ if based on 150,000 km. This is about five times the estimate for the Japanese Prius, and about twice the estimate for the Golf III.

It is not, however, clear that the life-cycle calculations of the European and Japanese groups use the same system boundaries as the Australian group. Fewchuk et al. (1998) include fuel processing in their calculations, which they estimate to be 21% of the total life-cycle energy, whereas it appears that the European groups do not. If we remove fuel processing then the Australian estimate of fuel utilisation, which is only 60% of total life-cycle energy, increases to 75%, which is comparable with the 80% estimated by the Europeans.

Beer (2000b) extended these life-cycle calculations to incorporate the emissions associated with road building and the operations of the road administration.

1.8. The fuel life cycle

There have been a number of American and European studies of the fuel life cycle. In many situations these are known as well-to-wheel studies. We prefer not to use this term because many of the fuels that we examine do not come from oil wells.

The most recent comprehensive study of light vehicles in the United States is that of General Motors Corporation et al. (2001). It focuses on the U.S. light-duty vehicle (LDV) market after 2005; it compares 13 fuels, selected from 75 fuel pathways in their well-to-wheel energy use and greenhouse emissions. The study considers 15 vehicles, including conventional and hybrid electric vehicles with both spark-ignition and compression-ignition engines, as well as hybridised and non-hybridised fuel cell vehicles; the benchmark vehicle is the Chevrolet Silverado full-size pick-up.

General Motors was also involved in an analogous European study (GM–LBST Study 2002). The objective was to identify potential fuels with technical and environmental ability to complement, and eventually substitute, gasoline and diesel on the European passenger car market. It followed the American study and compared the two regions. The GM–LBST Study (2002) investigated 44 upstream pathways (88 variants) and selected 16 pathways to derive the full fuel-cycle energy use and GHG emissions. The fuels selected for analysis were based on crude oil, natural gas, electricity and biomass, and they were combined with the following vehicle propulsion systems: internal combustion engine, fuel cell, and hybrids, considered technically available by 2010. The base vehicle was the 2002 Opel Zafira minivan using 1.8 16V gasoline internal combustion engine and a 5-speed manual transmission. The findings were consistent with those of the American study, but absolute values were lower due to a smaller reference vehicle.

The most recent study is that of a consortium of EUCAR, CONCAWE and the Joint Research Centre of the European Commission (2004). This study builds on the earlier GM work, using much of the same input data. The major differences are first, that the tank to wheel data (which we refer to as the upstream or the pre-combustion data) used in the EUCAR et al. study is a consensus position from the equipment manufacturers, while that used in the GM study was only from GM. Second, the CONCAWE study covers costs in addition to GHG and energy.

This chapter presented the structure of the report, the main sources of data, and an overview of the traffic, energy requirements and emissions resulting from road transport in Australia. It also discussed the concept of LCA, not only for fuels, but also for automobiles, providing an example for Toyota. The results show that GHG emissions are significantly correlated with fuel efficiency. As the tailpipe emissions are highly dependent on the drive cycles, a presentation of the drive cycles and a method to convert between them is given.

2. Normalisation

Because it is impossible to find a single study of tailpipe emissions from all the relevant fuels, it has been necessary to use data from different studies using different fuels in different vehicles. To make such studies comparable with each other, it is necessary to normalise the data.

The methodology used in this study requires data obtained where the alternative fuel under consideration is tested in a vehicle for which test data using the reference fuel (unleaded petrol in this case) is also available. This provides a constraint on acceptable tailpipe emissions data.

The ratio of emissions between the alternative fuel and the reference fuel are then calculated. These ratios are then applied to the reference vehicle used for the study.

The reference vehicle used in this study was the Ford Falcon tested as part of the Comparative Vehicle Emissions Study (Department of Transport and Regional Services 2001). On the basis of the fuel consumption (12.76 L/100 km) under the ADR37 cycle, and the energy density of the petrol (34.2 MJ/L) we calculate the vehicular force to be 4.36 MJ/km. On the basis of the normalisation methods explained below, under the EDC this corresponds to 4.194 MJ/km.

The work (MJ) expended by the fuel in propelling a car is given by:

$$W = F\ d = q\ m\ a\ d \qquad (2.1)$$

where F is the vehicular force, d is the distance travelled (km), m is the vehicular mass, q is a measure of the efficiency of the vehicle that combines the mechanical and thermal efficiencies, and a is the acceleration involved. The acceleration will depend primarily on the drive cycle used to test the vehicle. This report uses the drive cycle of ADR 79/01, also known as EDC, as the basis of comparison.

2.1. Emission regulations

Table 2.1 lists the emission standards required for certification of light vehicles under Australian Design Rules.

Table 2.1 – Emission limits and timing for vehicles to meet Euro standards in Australia

Passenger cars and light commercial	**In force**	**CO ($g\ km^{-1}$)**	**HC ($g\ km^{-1}$) [exhaust]***	**NO_x ($g\ km^{-1}$)**	**PM ($g\ km^{-1}$)**
ADR37/01 (Petrol)	1997/9	2.1	0.26	0.63	N/A
ADR79/00 (Petrol, LPG, CNG) (Euro 2)	2003	2.2	0.28	0.22	0.08
ADR79/01 (Petrol, LPG, CNG) (Euro 3)	2005/6	2.3	0.2	0.15	0.05
ADR79/01 (Diesel) (Euro 4)	2006/7	0.5	0.3 (NO_x + HC)	0.25	0.025

* HC [evaporative] 2 g per test

Source: http://www.dotars.gov.au/mve/emission_requirements.htm

2.2. Effects of the vehicle mass

The aim of this section of the study is to examine how the vehicle and fuel mix determines and characterises the carbon dioxide emissions. As a basis for comparison, we examine the transport emissions of large, locally made, six cylinder family-sized vehicles. The baseline vehicle is an average of Ford Falcon and Holden Commodore, being the LPG vehicles tested in the CVES 2001. The data for these vehicles is given in Table 2.3.

Having settled on a baseline vehicle, there are four test cycles to choose from in the CVES study:

- ADR37/01 (FTP)
- ADR79/00 (Euro 2)
- ADR79/01 (Euro 3)
- Australian Urban Drive Cycle.

The Australian Urban Drive Cycle (AUDC) aims to represent real-world emissions expected from Australian vehicle operation in cities.

The ADR79/00 (Euro 2) and ADR79/01 (Euro 3) cycles are the same except the latter does not include a forty second engine warm up before the test.

For the purpose of comparability with the European Emission Testing Program (2003) data (a major source of detailed emission for third generations LPG vehicles, Euro 4 engine technology and PULP designed vehicles), we chose ADR79/01 test cycle as the baseline test for comparing fuels and technologies. The disadvantage of this is that in the CVES study the ADR79/00 tests were repeated in triplicate while the ADR79/01 tests were based on single tests. However, the variation between these two test cycles is small enough that the data from the ADR79/00 test may be used to predict uncertainty in the ADR79/01 tests.

Having settled on a standard vehicle type (large family vehicle mass of 1594 kg), and a common test cycle (ADR79/01, also known as Euro 3 Drive Cycle or EDC), a methodology for comparing carbon dioxide emissions across different test data sets is required. Two important data sets for the study are the CVES (Department of Transport and Regional Services 2001) and the European Emission Testing Program data, EETP (LP Gas Association 2003).

The CVES study provides data on ULP, some data on PULP in ULP vehicles, and LPG data. It is based on a range of vehicle sizes from small 4 cylinder vehicles up to light commercial vehicles and recreation vehicles. Its also has a mix of European, Asian and Australian built vehicles.

The EETP program gives data on PULP vehicles conforming to Euro 4 emission standards, third generation LPG vehicles, a CNG vehicle and a range of new diesel vehicles. The two data sets share a common test cycle (ADR79/01) but no identical vehicles were used in both tests, and the average size of vehicles tested in the European data set is smaller than that used in the CVES data set. To make a fair comparison, the emissions measured in the EETP data set can be adjusted to account for heavier vehicles used as the baseline for this study. To achieve this, the relationship between vehicle mass and CO_2 emissions was established for the two tests (i.e. CVES and EETP) and is shown in Figure 2.1.

Unfortunately, vehicle masses are not provided in EETP test data, although vehicle inertia settings are provided, which are close to the reference mass of vehicles (the mass of the vehicle plus 100 kg to account for fuel and passenger). The problem with using inertia as a measure, rather than vehicle mass, is that standard inertia categories are used for vehicles of wide mass range as shown in Table 2.2. For the CVES study all vehicles apart from two, fit into three inertia categories. Despite this, a reasonable correlation is obtained with an R^2 value of 0.847. Figure 2.3 shows the same data for the CVES study but includes the CO_2 correlation against reference mass; almost the same relationship is obtained with a substantial improvement in the R^2 value to 0.94. Taking this into consideration, vehicle inertia is taken as a reasonable proxy for vehicle reference mass in this instance.

Having obtained the relationships shown in Figure 2.1, the data from the EETP program has been mass corrected to represent a 1594 kg vehicle. This is subsequently referred to as an Australian family-sized vehicle. Similar relationships have been developed from diesel and LPG data in the EETP data sets shown in Figure 2.3 with the original PULP correlation.

Table 2.2 – ECE Settings for inertia on dynamometer

Reference mass (kg)	Equivalent inertia (kg)	Road power (kW)
850 to 1,020	910	5.6
1,020 to 1,250	1,130	6.3
1.250 to 1,470	1,360	7
1,470 to 1,700	1,590	7.5
1,700 to 1,930	1,810	8.1
1,930 to 2,150	2,040	8.6
2,150 to 2,380	2,270	9
2,380 to 2,610	2,270	9.4
> 2610	2,270	9.8

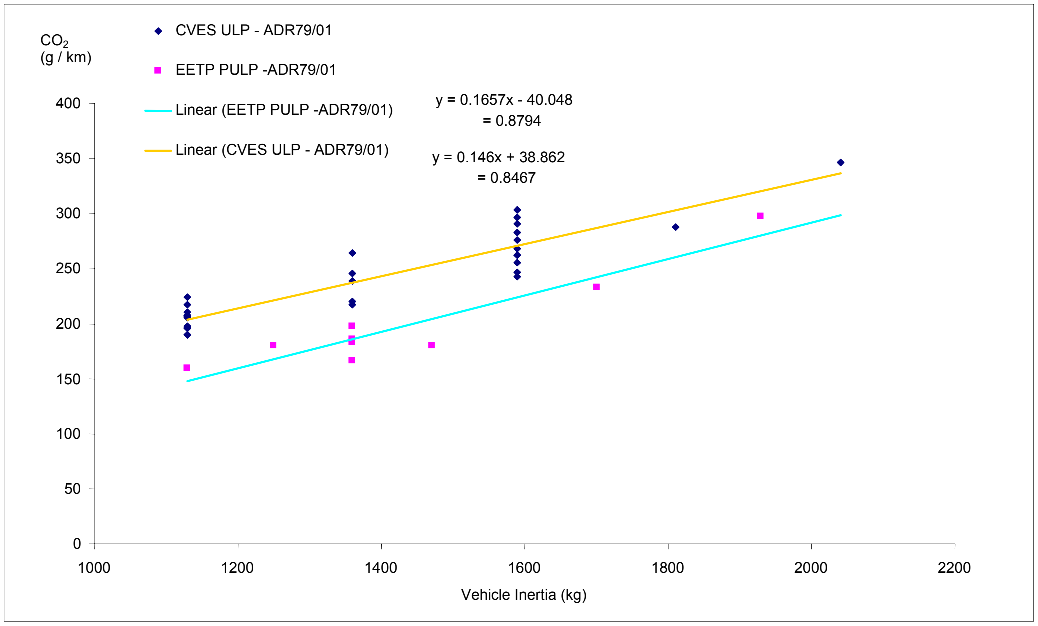

Figure 2.1 – Relationship between vehicle inertia and CO_2 emissions for EETP and CVES data

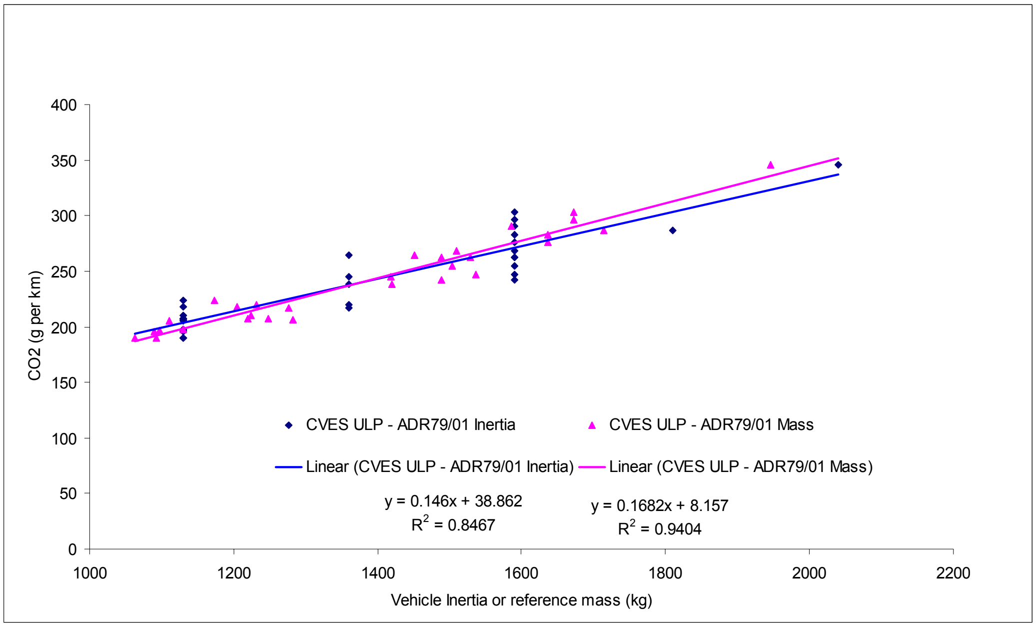

Figure 2.2 – relationship between vehicle inertia, vehicle reference mass and CO_2 emissions for CVES study

Table 2.3 – CVES Test data for LPG vehicles

Attribute	Test		Average for baseline
CVES Vehicle Number	64	61	
Make	Ford	Holden	
Model	AU Falcon	Commodore	
Build Date	October 1998	August 1998	
ADR Level	01	01	
Vehicle Mass (kg)	1615	1571.5	1594
Fuel Type	ULP	ULP	
Odometer Reading	4433	7250	
Drive Type	RWD	RWD	
Condition	OK	OK	
Tyres Make	Dunlop Monza	?	
Size	205/65R15	?	
Engine Displacement	4.0 L	3.8 L	
Number of Cylinders	6	6	
Engine Configuration	Inline	Vee	
Transmission Type	Auto	Auto	
No. of Gears	4	4	
Tested In	Economy	Economy	
Fuel System	MPI	MPI	
A/C	Yes	Yes	
Engine Oil	OK	OK	
Trans. Fluid	NA	OK	
Radiator	OK	Top up	
Battery Level	OK	OK	
Charge	OK	OK	
EEMS	Yes	Yes	
Catalyst Type	3 way	3 way	
Special vehicle options fitted	Nil	Nil	
Safety	OK	OK	
Euro 3 Test CO_2 (g/km)	287.083	303.487	295.2
Euro 3 Test CO (g/km)	1.605	1.137	1.37
Euro 3 Test NO_x (g/km)	2.28	1.161	1.72
Euro 3 Test HC (g/km)	0.146	0.225	0.185
Euro 3 Test FC (L/100km)	12.69	13.344	13.02
Euro 2–3 test Reference Mass (kg)	1715	1672	1694
Euro 2–3 test Inertia (kg)	1810	1590	1700

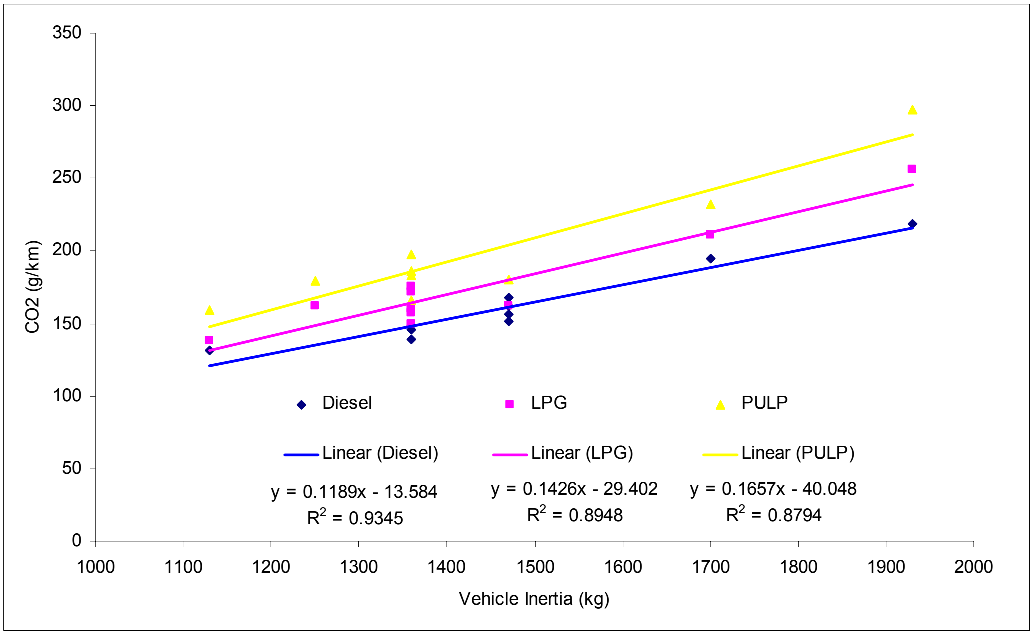

Figure 2.3 – Relationship between vehicle inertia and CO_2 emissions for PULP, Diesel and LPG vehicles in EETP data

Table 2.4 – Determining mass increase in third generation LPG vehicles and diesel vehicles compared with PULP counterparts

Vehicle	**Diesel**		**LPG**		**Petrol**	
	Engine type	**Inertia**	**Engine type**	**Inertia**	**Engine type**	**Inertia**
Ford Transit	2.4L DI 4 cylinder	1930	2.3L 16V 4 cylinder	1930	2.3L 16V 4 cylinder	1930
Kangoo	1.5L DCi 4 cylinder	1130	1.2L 16V 4 cylinder	1130	1.2L 16V 4 cylinder	1130
Nissan Primera	2.2L 4 cylinder	1470	1.8L 16V 4 cylinder	1360	1.8L 16V 4 cylinder	1360
Peugeot 406	2.0L 4 cylinder	1470	1.8L 16V 4 cylinder	1360	1.8L 16V 4 cylinder	1360
Renault Scenic	1.9L 16V 4 cylinder	1360	1.6L 16V 4 cylinder	1360	1.6L 16V 4 cylinder	1360
Vauxhall Astra	1.7L 4 cylinder	1360	1.6L 16V 4 cylinder	1360	1.6L 16V 4 cylinder	1250
Vauxhall Vectra	2.0L 4 cylinder	1470	1.8L 16V 4 cylinder	1470	1.8L 16V 4 cylinder	1470
Volvo V40	1.9L 4 cylinder	1470	1.8L 16V 4 cylinder	1470	1.8L 16V 4 cylinder	1360
Volvo V70	2.4L 20V 5 cylinder	1700	2.4L 20V 5 cylinder	1700	2.4L 20V 5 cylinder	1700
Average Mass		1484.4		1460		1435.6

Vehicle	Diesel		LPG		Petrol	
	Engine type	Inertia	Engine type	Inertia	Engine type	Inertia
Mass increase from petrol vehicle		3.4%		1.7%		

Table 2.5 – Procedure for adjusting CO_2 and fuel efficiency according to vehicle mass from EETP data to baseline vehicle for this study

Vehicle mass conversion factor	Units	PULP	Diesel	LPG 3rd generation
Average inertia vehicle in EETP test	kg	1436	1,472	1436
Average mass increase in equivalent vehicle from EETP study	% from PULP	–	3.4%	1.7%
Inertia of reference vehicle	kg	1700	1758	1729
Multiplication factor for relationship of vehicle CO_2 to inertia[1]		0.166	0.119	0.143
Offset factor for relationship of vehicle CO_2 to inertia[1]		-40.05	-13.58	-29.40
CO_2 from EETP EDC data sets (average)	g/km	197.9	161.4	174.2
CO_2 adjusted to CVES vehicle inertia	g/km	241.6	195.4	217.1
Inferred vehicle fuel consumption from new CO_2 value	MJ/km	3.5396	2.8081	3.5569

[1] The values in this row are taken from the relationships developed in Figure 2.1.

Table 2.5 displays the procedure used (based on vehicle mass) to adjust CO_2 and fuel efficiency from EETP data to baseline vehicle for this study. The results of Table 2.5 indicate that the carbon dioxide emissions to be expected from a typical Australian family car of 1,594 kg mass undergoing the ADR 79/01 drive cycle, are 242 g/km for a petrol vehicle, 195 g/km for a diesel vehicle, and 217 g/km from an LPG vehicle. The inferred fuel energy loads to which these emissions correspond are 3.54 MJ/km, 2.81 MJ/km and 3.56 MJ/km respectively.

2.3. Effects of the mix of vehicles in the fleet

The discussion in the previous chapter (section 1.6) indicated some of the complex issues that arise when a fleet of vehicles with a different fuel mix needs to be analysed. The proportion of kilometres travelled by petrol and non-petrol vehicles is given in Table 2.6 (based on values in the National Greenhouse Gas Inventory 2001).

Table 2.6 – Distances (billion km) travelled by petrol and non-petrol vehicles in Australia

Fuel	Cars	Light trucks
Petrol	129.38	19.47
Diesel	4.65	8.77
LPG	11.55	3.96
Natural gas	0	0

The carbon dioxide emissions (g/km) corresponding to NAFC of 6.8 L/100 km are given in Table 2.7, whereas the inferred fuel energy loads in MJ/km corresponding to these emissions are given in Table 2.8.

Table 2.7 – The carbon dioxide emissions (g/km) corresponding to NAFC of 6.8 L/100 km

Fuel	CO_2 (g/L)	CO_2 (g/km) based on NAFC of 6.8 L/100 km
Petrol	2,234	152
Diesel	2,663	181
LPG	1,511	103

Table 2.8 – The inferred fuel energy loads (MJ/km) corresponding to NAFC of 6.8 L/100 km

Fuel	Energy load based on NAFC of 6.8 L/100 km
Petrol	2.30
Diesel	2.60
LPG	1.73

The point to be noted is that the relativities between petrol, diesel and LPG vehicles given in Table 2.5, Table 2.7 and Table 2.8 all differ. This means that if the end goal is to minimise carbon dioxide emissions, then the choice of:

- a fixed value of fuel consumption
- a fixed value of carbon dioxide emissions
- a fixed value of fuel energy load,

for a fixed drive cycle will each lead to different achievement strategies for non-petrol vehicles. The easiest way to meet a fixed target for fuel consumption is to convert all diesel and petrol vehicles to LPG. Table 2.7 indicates that LPG vehicles emit 1511 grams of CO_2 per litre of fuel used, which is lower than the per litre emissions of either petrol or diesel.

The easiest way to meet a fixed carbon dioxide emissions target (say 174 g/km carbon dioxide) would be to use diesel vehicles, because the results of Table 2.5 indicate that they have the lowest carbon dioxide emissions on the ADR 79/01 drive cycle.

The data in Table 2.5 also indicates that the choice of a fixed fuel energy load (say 2.63 MJ/km) would also be most easily met by using diesel vehicles — because a diesel vehicle has the lowest MJ/km value over a fixed drive cycle, when compared with petrol and LPG.

2.4. Light trucks and four wheel drives

The results shown in Figure 2.1 and Figure 2.2 illustrate that carbon dioxide emissions vary linearly with mass. Figure 2.1 examines this for the European Drive Cycle and the ADR79/01 drive cycle; whereas Figure 2.2 shows that the relationship is better for vehicle mass than for vehicle inertia (see Table 2.2). To a certain extent this is also true for fuel consumption, and for fuel energy load.

Light trucks and four wheel drives are usually heavier than cars. Table 2.4 gives the inertia for a Ford Transit van as 1930 kg. Values for Toyota Landcruiser and Chrysler Jeep were obtained from the NRMA road test website[6].

The Toyota Landcruiser Prado RV has a mass of 1,721 kg and a fuel consumption of 13 L/100 km; the Toyota Landcruiser Prado GXL has a mass of 1,848 kg and a fuel consumption of 14.7 L/100 km; and the Chrysler Jeep Grand Cherokee Laredo has a mass of 1810 kg and a fuel consumption of 15 L/100 km kg.

Table 2.5 provides CO_2 values adjusted to the inertia of LPG vehicles tested in the CVES study. These inertias are 1,700 kg for PULP vehicles, 1,758 kg for diesel vehicles, and 1,729 kg for LPG vehicles. The carbon dioxide and fuel energy load values in Table 2.5 are correspondingly higher than those given in Table 2.7 and Table 2.8, indicating that vehicles have not yet attained the NAFC target.

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[6] http://www.mynrma.com.au/motoring/cars/buying_and_selling/new_car/reviews/roadTest.shtml

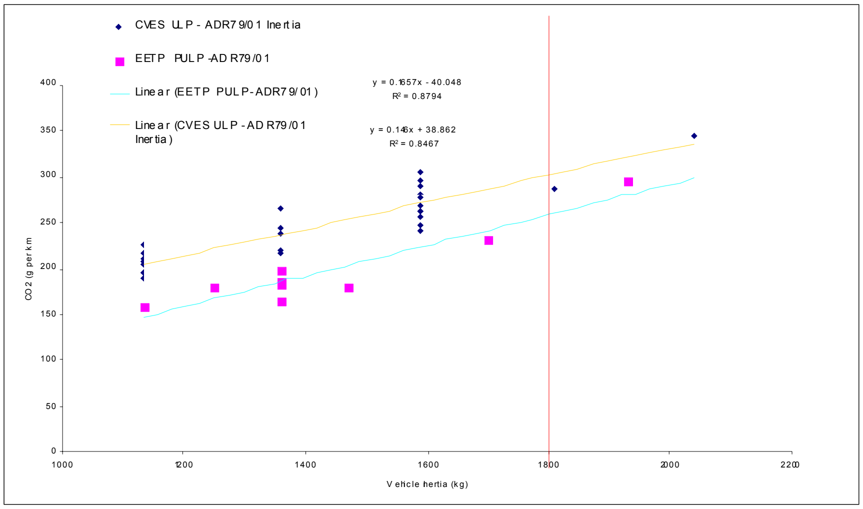

Figure 2.4 – Using a mass to CO_2 relationship to remove vehicle size difference (petrol cars)

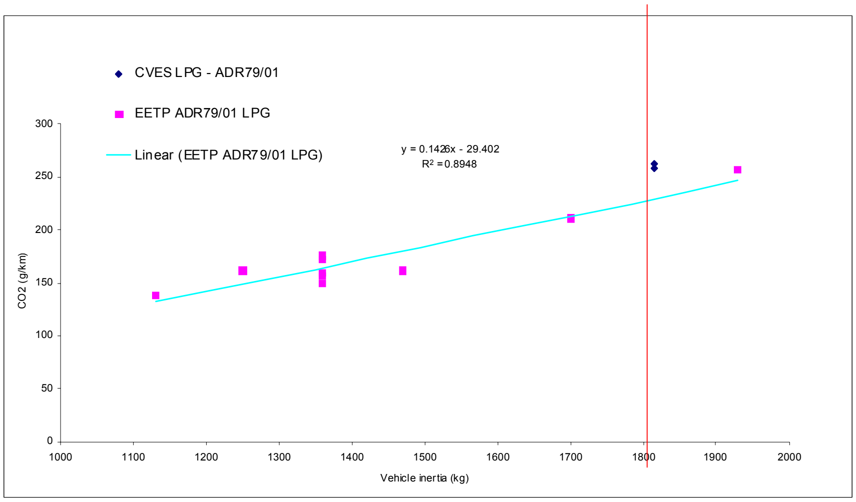

Figure 2.5 – Using a mass to CO_2 relationship to remove vehicle size difference (LPG cars)

2.5. Comparison between fuels (tailpipe emissions)

Our methodology for the earlier reports (Beer et al. 2001) and in this report requires data that compares vehicles that are identical in all respects except for the fuel. Thus, the ideal data set would consist of an Australian vehicle that exists in petrol, diesel, LPG and CNG fuelled versions that is tested under the same drive cycle using each of these fuels. No such vehicle and no such data set exist.

However, in examining the data set for the EETP test program (LP Gas Association 2003) we noticed that a Volvo V70 had been tested in petrol, diesel, LPG and CNG versions in Europe, using the Artemis (CADC) drive cycle. The report on the testing program does not give CNG data, but the Australian LPG Association obtained this testing data and provided it for this study. It is reproduced in Tables 2.9a and 2.9b.

Table 2.9a – Emissions (g/km) from Volvo V70 when using different fuels (Artemis Drive Cycle)

Raw data reported—emissions	**Units**	**PULP**	**Diesel**	**LPG**	**CNG**
CO_2	g/km	222.30	188.60	201.50	170.70
CO	g/km	0.6100	0.0100	1.6700	0.2270
NO_x	g/km	0.0200	0.8900	0.0100	0.0100
HC	g/km	0.0084	0.0100	0.0100	0.0130
PM10	g/km	0.0020	0.0400	0.0020	0.0020

Table 2.9b – Emissions (g/km) from Volvo V70 when using different fuels (European Drive Cycle)*

Raw data reported—emissions	**Units**	**PULP**	**Diesel**	**LPG**	**CNG**
CO_2	g/km	232.50	194.30	210.70	197.70
NO_x	g/km	0.0100	0.4500	0.0200	0.0090

* CO, HC and PM not measured in EDC.

This data set forms the raw data for this study. However, to utilise it in this comparative study of light vehicle emissions the following transformations are required:

- The results from the Artemis need to be converted to equivalent data under the EDC—which is equivalent to ADR 79/01. The EETP undertook EDC testing on the Volvo V70 for only CO_2 and NO_x, so we inferred emissions of the other pollutants on the basis of the ratio of energies applied.
- The results from the Volvo V70 need to be normalised to apply to the representative vehicle(s) that are being examined.
- The results for the Volvo V70 need to be extrapolated to determine the equivalent emissions if ULP was used instead of PULP, if petrol and diesel of different sulfur levels were used, and if LPG–HD5 (Propane) was used instead of Autogas.

The results shown in Table 2.9a and b indicate, once again, the importance of the drive cycle in determining fuel emission characteristics. Under the Artemis Drive Cycle, the lowest CO_2 emissions were from the CNG vehicle. Under the EDC, the lowest CO_2 emissions were from the diesel vehicle.

This chapter presented the procedure used for normalisation and the vehicles and associated data used in the analysis. Relationships between CO_2 emissions and vehicle inertia/mass have been established using regression analysis. The comparison between tailpipe emissions for different fuels and a discussion of the modelling issues close the chapter.

3. Petrol and diesel

In this report the upstream processing details for the various fuels are taken to be the same as those in the Comparison of Transport Fuels report (Beer et al. 2001) unless specified otherwise.

The Comparison of Transport Fuels report (Beer et al. 2001: 325–335) gives information and details for premium unleaded petrol (PULP) but does not deal with the difference between PULP and ULP. This section examines the emissions between ULP and PULP separately, so as to estimate the differences in emissions between the two grades of petrol, and between high sulfur (150 ppm) and low sulfur (50 ppm) PULP.

Petrol is manufactured using a number of refinery product streams derived from crude oil. The blending process is usually determined by three major factors: specification requirements, availability of specific process units within a particular refinery configuration, and the properties of the crude oil used.

There are two grades of unleaded petrol manufactured in Australia for use in vehicles—regular unleaded (ULP) and premium unleaded (PULP). Both grades have the same requirement for motor octane number (MON). The research octane number (RON) requirement is higher for PULP. RON and MON are determined with standard test engines under strict conditions defined in the relevant specifications. The RON test reflects anti-knock properties at lighter load, while MON is determined under conditions resembling high power demand under heavy load.

Fuel volatility index (FVI) is related to vapour pressure of petrol at various temperatures. Variations in FVI are seasonal—FVI requirement changes every month and this variation is a reflection of the average ambient temperatures within different geographic regions at different times of the year.

Hydrocarbons constituting petrol can be broadly broken into three categories: paraffins, naphthenes and aromatics. Usually the octane rating of those increases with increasing chain branching, unsaturation and aromaticity. Variation of octane rating and volatility between different hydrocarbon types is the basis for the blending process. The objective is to produce petrol up to the specification while maximising efficiency of the refining process and feedstock utilisation.

An example of crude oil processing is presented in the chapter describing diesel fuel production. The first stage of crude oil processing is atmospheric pressure distillation. The fraction boiling between 90°C and 220°C, called “straight run naphtha” (gasoline), is the basic feedstock used in petrol production. It consists of predominantly straight chain aliphatic hydrocarbons. Its octane rating is usually below specification and needs to be adjusted by further processing. The first processing step is usually hydro-treating, which lowers sulfur contents and reduces unsaturation.

A number of processes are used to produce blending components. These typically include:

- Reforming—thermal catalytic isomerisation and aromatisation of paraffins and naphthenes, which increases octane rating.
- Isomerisation—conversion of paraffins to isoparaffins in the presence of hydrogen and the catalyst.

- Cracking—thermal catalytic breaking of heavy fractions, which produces a broad range of highly aromatic fractions.
- Alkylation/polymerisation—catalytic oligomerisation of light olefines producing isoparaffins.

The difference between ULP and PULP is determined by differences in octane rating. PULP blend typically contains a larger proportion of high octane streams, i.e. those containing aromatics, isoparaffins and naphthenes.

The site http://www.aeat-env.com/Sulphur_Review/Downloads/sr-UKDETR2.doc, p.4, indicates that producing XLS petrol and diesel (at less than 10 ppm sulfur) will require additional desulfurisation capacity and for some refiners, hydrogen manufacturing units.

Upstream emissions in petrol production arise from oil recovery, transportation and processing. Further emissions derive from distribution through the retail network.

3.1. Introduction

Table 3.1 gives some of the regulated parameters for petrol under the Fuel Standard (Petrol) Determination 2001[7], for lead replacement petrol (LRP), unleaded petrol (ULP) and premium unleaded petrol (PULP).

Table 3.1 – Current and future petrol properties

Attribute	**LRP**	**ULP**	**PULP**
Minimum Research Octane Number (RON)	96	91	95
Maximum sulfur (ppm)	500	500	150
Maximum benzene (% by volume)	1 (by 1 Jan 2006)	1 (by 1 Jan 2006)	1 (by 1 Jan 2006)
Maximum aromatics (% by volume)	48	48	48
Olefins (% by volume)	20 (from 1 Jan 2004)	20 (from 1 Jan 2004)	20 (from 1 Jan 2004)

At present, the Motor Vehicle Environment Committee (MVEC 2003) is conducting a consultation process to determine (among other things) whether the sulfur content of petrol should be reduced to 50 ppm, as required by the European Community from 2006.

3.1.1 Effects of changing octane number

Octane is a measure of a petrol's ability to resist auto-ignition, which can cause engine knock. There are two laboratory test methods to measure petrol octane number: one determines RON and the other MON. RON correlates best with low speed, mild-knocking conditions and MON correlates with high-temperature knocking conditions and with part-throttle operation. RON values are typically higher than MON and the difference between these values is the sensitivity, which should not exceed 10.

Vehicles are designed and calibrated for a certain octane value. When a customer uses petrol with an octane level lower than that required, knocking may result, which could

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[7] http://scaleplus.law.gov.au/html/instruments/0/33/0/2003070101.htm

lead to severe engine damage. Engines equipped with knock sensors can handle lower octane levels by retarding the spark timing; however, fuel consumption and power suffer and at very low octane levels, knock may still occur. Using petrol with an octane rating higher than that required will not improve the vehicle's performance.

However, vehicles designed to operate with premium unleaded petrol usually also operate with different compression ratios, increasing their engine efficiency. In many cases these advantages are lost because of a tendency to increase the weight of such vehicles. Thus, for example, the BMW 5 series that uses PULP has a mass of 1743 kg, whereas the BMW 3 series that uses ULP has a mass of 1388 kg. These factors have been accounted for in our normalisation procedure.

Coffey Geosciences (2000) estimated that the additional costs to domestic refiners of producing Euro IV standard fuel (95 RON and 50 ppm sulfur) would entail capital costs of $A175m per refinery (although the cost would vary across refineries) and additional operating costs of $A17m per annum per refinery. Retail prices would increase by around 1.1 cents per litre. Coffey Geosciences (2000) also estimated that the cost of moving to fuel standards for Euro III compliant vehicles (95 RON and 150 ppm sulfur) would result in an increase in fuel prices of 0.5 cents per litre, with ongoing production costs of 0.15 cents per litre.

Table 3.2 provides Coffey's (2000) estimates of the additional capital and production costs of increasing fuel quality standards and Table 3.3 provides estimates of the average cost per litre of fuel sold of the additional capital and production costs. The estimates show the additional cost of 95 RON is around 1.2 cents per litre.

Table 3.2 – Australian refinery costs to produce fuel quality improvements

Fuel quality improvement	**Average cost estimate**		**Comments**
	Capital ($M/refinery)	**Operating (c/L)**	
Octane enhancement	75	Not provided	Only information in relation capital cost for two refineries was provided. Not used for cost benefit analysis as it applies to all four options. Provided for information.
35% aromatics	115	0.35	Limiting aromatic content of petrol to 35 % while increase octane levels was considered very difficult or impracticable. Capital cost indications were provided in relation to two refineries.
50 ppm S in PULP	34	0.475	Information provided in relation to four refineries.
10 ppm S in PULP	80	0.65	Information provided in relation to four refineries. Cost to reduce sulfur content from 150 ppm to 10 ppm.
10 ppm S in diesel	20	0.4	Information provided in relation to four refineries. Cost to reduce sulfur content from 50 ppm to 10 ppm.

Source: Coffey Geosciences Pty Ltd (2003, Table 6.1, p. 93).

Table 3.3 – Australian refinery costs of fuel quality improvements (cents per litre)

Fuel Quality Improvement	Combined capital and operating cost ($m)	Comments
Octane enhancement	1.2	Applied to the total volume of premium (RON95) production assumed (1.3 GL/yr). For information only, not part of option assessment.
35% aromatics	1.2	Applied to total petrol volume. For information only, not part of option assessment.
Reduction from 150 ppm to 50 ppm S in PULP	1.0	Applied to assumed production of 1.3 GL/yr per refinery.
Reduction from 150 ppm to 10 ppm S in PULP	1.9	Applied to assumed production of 1.3 GL/yr per refinery.
Reduction from 50 ppm to 10 ppm S in diesel	0.7	Applied to assumed transport diesel production of 1.4GL/yr per refinery. Production based on projections contained in Coffey Geosciences (2000).

Source: Coffey Geosciences Pty Ltd (2003, Table 6.2, p. 94).

The use of octane-enhancing compounds, such as ethanol, instead of upgrading refinery processes will depend on the relative capital and operating costs of the two alternatives. It is not clear that the use of ethanol would be the cheapest alternative. The California Energy Commission study (CEC 1999), for example, estimated that switching from MTBE to ethanol would cost motorists between 1.9 and 2.5 US cents per gallon more over the long term. This may be compared with an additional cost of between 0.9 and 3.7 cents per gallon if no oxygenates were used. However, other environmental impacts are associated with MTBE, such as ground water pollution, which determined the removal of MTBE.

DSA (2000) suggests that any move to mass produce 98 RON fuels in Australia, would probably require the use of octane enhancers in the fuel.

3.2. Upstream emissions

3.2.1 Oil and gas production

For the purpose of this LCA, oil and gas are assumed to be co-produced in Australia, for the following reasons:

- In many cases oil and gas are derived from the same well or field.
- Data on energy and emissions from oil and gas production are aggregated for the purpose of national reporting.
- Data on individual energy and emissions from specific oil and gas operations are not available.

Options for allocating emissions and energy use for oil and gas production are:

- mass
- energy content
- cost
- some mix of the above.

Energy based allocation is undertaken in this study, as both oil and gas are principally energy products. Table 3.4 shows the volume of product produced in primary oil and gas production (column 2), the energy contained in each of those product fractions (column 6) and the overall percentage share (column 7).

The energy usage in primary oil and gas production is then split across the different products based on energy shares (last three columns). The table is broken into two sections: the first allocates between oil and gas products, the second allocates between the different gas products. This is done separately so that venting emissions from gas processing products are allocated only across the gas products and not to crude oil and condensate production. The rationale is that, while the two products are co-produced, there is substantial scope to increase gas production without increasing oil production, and the venting of CO_2 in particular is mainly associated with natural gas production.

Emissions from this fuel production (main greenhouse emissions are listed in Table 3.5 and Table 3.6) and production fugitives are split on the same basis.

Table 3.4 – Energy allocation of primary energy production from petroleum refineries 2000–01

Attribute	Volume	Energy content	Energy PJ	Energy share (%)	Petroleum PJ	Gas PJ	Total PJ
Allocation of oil and gas			Volume*energy content				
Crude oil and condensate	38,705 ML	38.7 MJ/L	1,497.9	50.84	0.54	73.41	73.95
Natural gas including ethane and LPG	–	25.7 MJ/L	1,448.4	49.16	0.52	70.98	71.50
Total			2,946.3		1.06	144.39	145.45
Total per MJ of product					0.000360	0.0490	
Gas products allocation							
LPG	4, 558 ML	25.7 MJ/L	117.1	8.09	0.04	5.74	5.78
Natural gas	33.32 TL	39 MJ/kL	1,299.6	89.73	0.47	63.69	64.16
Ethane	0.48 TL	66 MJ/kL	31.6	2.18	0.01	1.55	1.56
Total			1,448.4		0.52	70.98	71.50

Table 3.5 Energy (PJ) and emissions (Gg) for oil and gas production during 2000–01

Item	Fuel	Fuel use (PJ)	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	NO_x (Gg)	CO (Gg)	NMVOC (Gg)
Oil and gas production and field processing	Petroleum	1.06	69.87	0	0	1.06	0.34	0.05
	Gas	144.39	7,386.05	1.05	0.01	25.46	6.16	0.33
Natural gas transmission	Gas	10.69	546.85	0.08	0	2.01	0.49	0.03
Gas production and distribution	Gas	1.9	97.37	0.02	0	0.36	0.09	0

Table 3.6 Fugitive emission from petroleum and natural gas products for 2000–01

Attribute	Fuel quantity (PJ)	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	NO_x (Gg)	CO (Gg)	NMVOC (Gg)
Exploration (for both oil and gas)	2,817.13	169.85	2.08	0.01	0	0.56	0.9
Crude oil production	1,432.1	NA	0.9	NA	NA	NA	8.75
Crude oil transport: domestic	306	NA	0.2	NA	NA	NA	1.29
Crude oil refining and storage	1,676.55	230.81	2.07	0.01	0.13	0.73	34.56
Petroleum product distribution	1,124.65	NA	NA	NA	NA	NA	58.6
Production and processing	1,385.03	NA	1.49	NA	NA	NA	0.39
Transmission	756	0.47	8.11	NA	NA	NA	1.75
Distribution	418.67	9.39	164.1	NA	NA	NA	29.52
Venting at gas processing plant	1,385.03	3,666.63	110.15	NA	NA	NA	71.24
flaring in oil and gas production	2,817.13	2,846.61	35.31	0.08	1.51	8.78	15.13

3.2.2 Refinery production

For basic refinery production, a similar approach has been taken, using energy-based allocation for co-production from a refinery. However, it is recognised that energy content is only one property of a fuel and that, for transport fuels, increased octane (or cetane in the case of diesel) and lowering of sulfur content is also significant value.

To resolve this problem, basic petroleum products are allocated on energy content, and the refined versions of those products have been given additional allocations of process input to account for processing of these fuels into higher, cleaner grades.

Table 3.7 shows the volume of product produced in refineries (column 2), the energy content of each of those product fractions (column 4) and the overall percentage share (column 5). The energy usage in oil refining is then split across the different products based on energy shares (last two columns). Emissions from this refinery production (main greenhouse emissions are listed in Table 3.8), and production fugitives are split on the same basis.

Table 3.7 – Allocation by energy content for refinery co-products 2000–01

Product	**2000–01 (ML)**	**Energy content (MJ/L)**	**Energy (TJ)**	**% by energy**	**Refining energy gas (PJ)**	**Petroleum (PJ)**
Automotive gasoline	17887	34.2	612	35.1	6.64	29.75
Automotive diesel oil	13212	38.6	510	29.2	5.53	24.80
Aviation turbine fuel	5836	36.8	215	12.3	2.33	10.44
Fuel oil	1951	39.7	77	4.5	0.84	3.77
Liquefied petroleum gas	1795	25.7	46	2.7	0.50	2.24
Industrial and marine diesel fuel	98	39.6	4	0.2	0.04	0.19
Bitumen	693	44	30	1.7	0.33	1.48
Lubricants	641	38.8	25	1.4	0.27	1.21
Aviation gasoline	137	33	5	0.3	0.05	0.22
Heating oil	194	37.3	7	0.4	0.08	0.35
Other	5715	37.3	213	12.2	2.31	10.37
Total products	48160		1744	100.0	18.93	84.82

Table 3.8 – Energy (PJ) and Emissions (Gg) for refinery operations during 2000–2001

Fuel	**Energy Use**	**CO_2**	**CH_4**	**N_2O**	**NO_x**	**CO**	**NMVOC**
Petroleum	84.82	5760.47	0.07	0.05	32.55	4.58	0.07
Gas	18.93	968.36	0.02	0	13.68	1.07	0.02

3.3. Allocating emissions to petrol variants

An economic allocation has been used to determine the relative split between ULP and PULP. The refinery price for ULP has been taken as 35c per litre (Shell website Feb 2004 http://www.shell.com.au/petrolpricing/). The crude oil cost component of that is expected to be around 24.3c per litre (US$30 per barrel and assuming around 1 litre of crude will lead to approximately 1 litre of petrol). This leaves a refinery cost of 10.7 cents. The differential between ULP and PULP of 4 c/L (prices observed at service stations) means that there is a 37% increase in refining cost for PULP. Note that Coffey Geosciences (2003) suggests 3.5c for producing premium petrol. These calculations are set out in Table 3.9.

Table 3.9 – Calculation of ULP and PULP production energy

Attribute	Crude	ULP	PULP
Price		84	88
Refinery Price	24.3	35	39
Net costs		10.7	14.7
Increased refining cost			37%

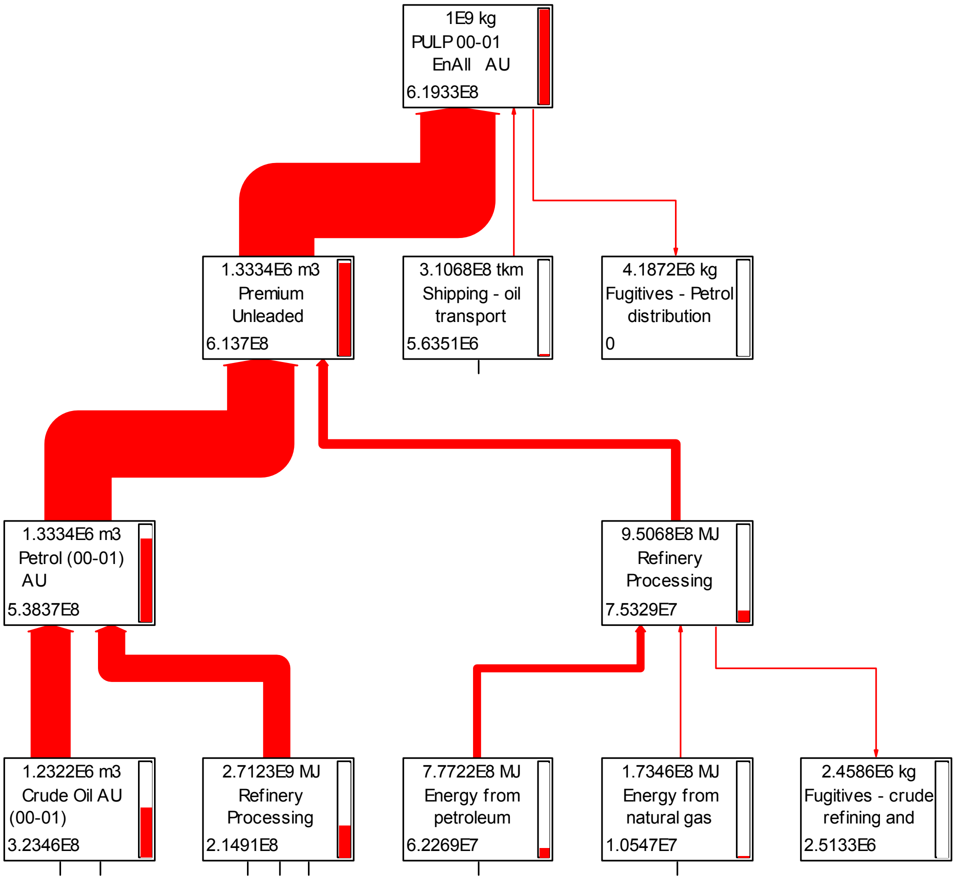

Figure 3.1 – Process flow diagram showing greenhouse emissions for PULP production (kg CO_2-e in lower value of process box)

3.3.1 Ultra low sulfur (50 ppm) PULP

Coffey Geosciences (2003) indicated that fuel production costs would increase by approximately 0.475 c/L to reduce the sulfur in PULP from 150 ppm to 50 ppm. Using the same allocation approach applied for PULP production, an additional refinery burden is calculated in Table 3.10.

Table 3.10 – Calculation of ULS PULP production energy (% changes)

Product	Price (cents)	Refinery Price (cents)	Net costs (cents)	Increased refining cost (%)	Increased energy requirements (%)
Crude		24.3			
ULP	84	35	10.7		
PULP	88	39	14.7	37% of the ULP cost	37
ULS PULP			15.2	41.8% of the ULP cost	41.8

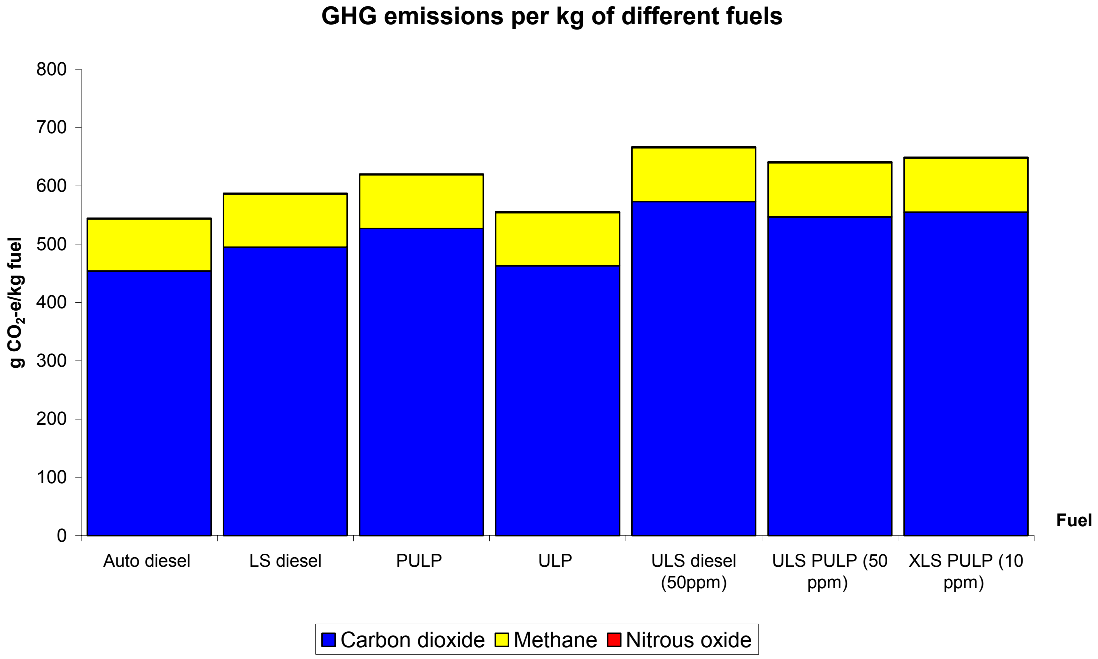

Figure 3.2 – Relative GHG per kg for production of different petroleum based fuels

3.3.2 Low sulfur diesel

The Fuel Quality Review (Coffey Geosciences 2000) states that for low sulfur diesel all crude product will need some form of treatment, probably hydro treating, to achieve a reduction of sulfur levels from 1500 to 500 ppm. The refining costs for this reduction is estimated at approximately 0.5 c/L. In the comparison of transport fuels (Beer et al. 2001), additional processing of diesel is estimated using standard equipment specification for hydro-desulfurisation units, assuming all fuel would be treated by such as a unit. Table 3.11 gives the additional energy use for these processes and the resultant greenhouse emissions are shown in Figure 3.3 and Figure 3.4 for LS and ULS diesel respectively.

Table 3.11 – Additional inputs to produce 1 tonne LSD and ULSD from 1 tonne current diesel

Fuel	Equipment	Electricity (KWh)	Energy from gas oil (MJ)	Steam (kg)	Total energy refinery processing (MJ)	Additional energy requirement (MJ)	Additional energy requirement (%)
Current diesel		0	0	0	2,714		
Low sulfur	Hydro-desulfurisation unit	7.3	577	0	3,317.3	603.3	22.2
Ultra low sulfur	Hydro-cracking unit	50.3	1578	95	4,473	1,759	64.8

Source: J. Hydrocarbon Processing as supplied by M. Sanders (pers comm. 8 Feb. 2000)

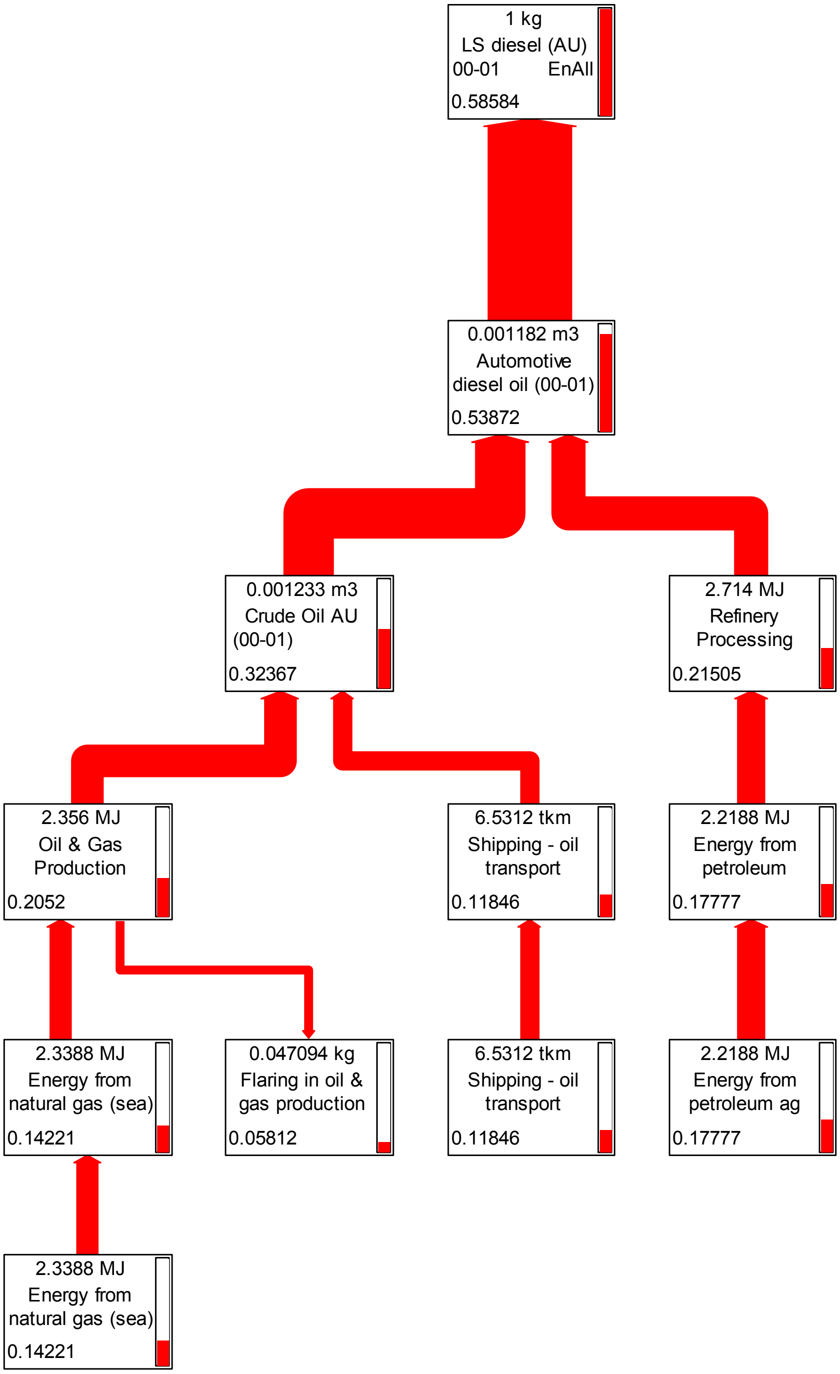

Figure 3.3 – Process tree showing contribution to greenhouse emissions (in lower value of process box) for LS diesel production (based on hydro-desulfurisation operation)

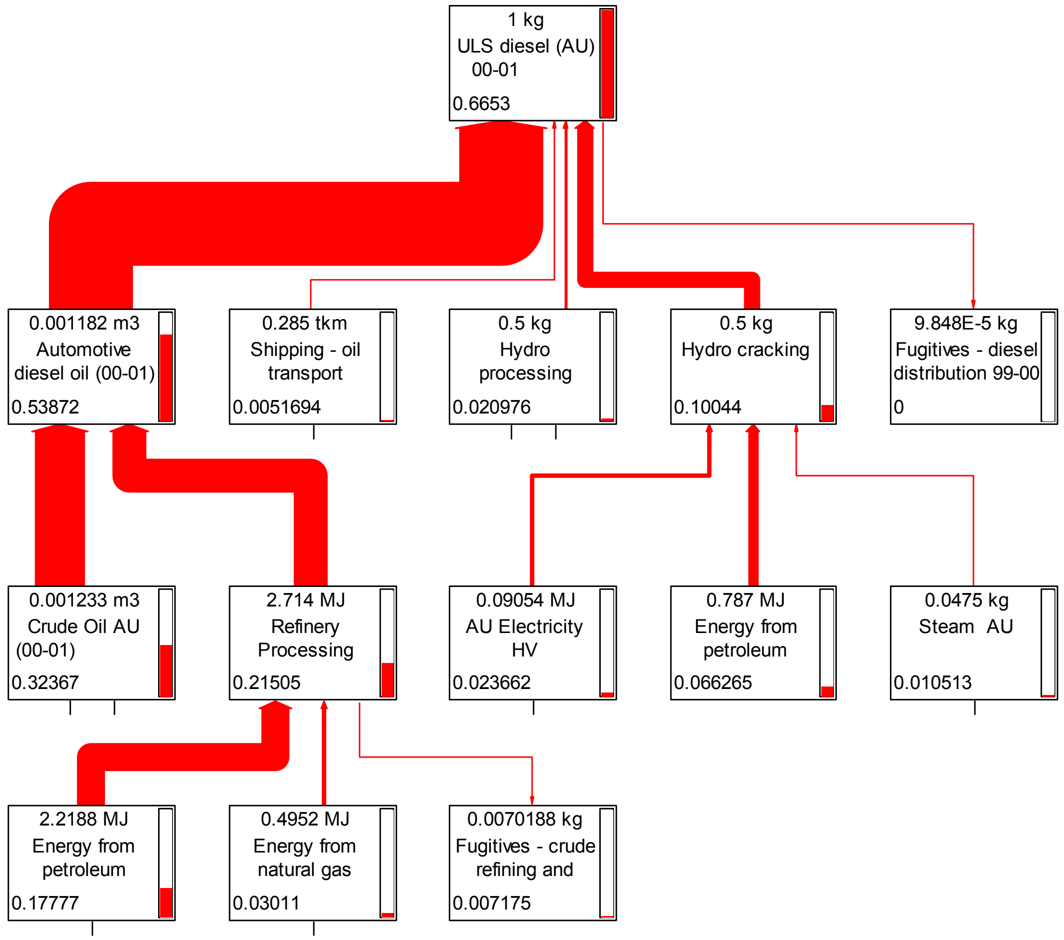

Figure 3.4 – Process tree showing greenhouse emissions (in lower value of process box) for ULS diesel production (based on hydro-desulfurisation and hydro-cracking operations)

An alternative approach is to use the same costing equation used for PULP. Based on the 0.5 c/L additional refinery running costs for low sulfur diesel and an additional 0.5 c/L for ultra low sulfur diesel, the additional energy inputs have been calculated in Table 3.12.

Table 3.12 – Calculation of ULS PULP production energy

Attribute	**Crude**	**Diesel**	**LS diesel**	**ULS**
Price (c)		90	88	
Refinery price (c)	26.7	39	39	
Net costs (c)		12.3	12.8	13.3
Increased refining cost (%)			4% from current refining cost	8.1% from current refining cost

Assuming around 1.1 litre of crude per litre of diesel output

The net result of this allocation is to get lower production energy and greenhouse emissions from the LS and ULD diesel as shown in Table 3.13.

Table 3.13 – Comparison of greenhouse impacts (kg CO_2-e) of 1 kg of fuel production using different estimation techniques for LS and ULS diesel

Total	Diesel	LS Diesel (with HDU)	LS Diesel – Refinery Cost Allocation	ULS Diesel (50% HDU & 50% HCU)	ULS Diesel – Refinery Cost Allocation
CO_2 (Upstream)	0.45442	0.49475	0.46299	0.57259	0.4709
Methane (Upstream)	0.089499	0.091091	0.089768	0.092716	0.09002
N_2O (Upstream)	0.001175	0.001226	0.001199	0.001461	0.001221
Total	0.545094	0.587067	0.553957	0.666767	0.562141

HCU = Hydro-cracking unit, HDU = Hydro-desulfurisation unit

3.4. Tailpipe emissions from petrol engines

Emissions from light vehicles resulting from different fuels are shown in Table 3.14.

Table 3.14 – Change in catalyst equipped vehicle emissions with variations in petrol properties

Fuel property	NO_x	CO	HC	Benzene	1,3 Butadiene	Aldehydes	Evaporatives
Lower aromatics level	+	–	–	–	0/+	0/+	–
Increase oxygenate level	–/0/+	–	–	–	–/0	+	0/+
Lower olefins	–	0	+	0	–	0	–/0
Lower sulfur	–	–	–	–	0	0	0
Lower T90	0/+	0	–	–	–	–/+	0/+
Increase E100	+	0	–	–	0	?	0
Lower RVP	0	–/0	–	–/0	0	0/+	–/0

Source: van Walwijk et al. (1996) – a decrease of the emissions; 0 no influence on the emissions; + an increase of the emissions; ? influence is unclear or unknown. The effect of aromatic levels on NO_x emissions depends on the type of catalyst. Oxygenates have little effect on NO_x but it can be in either direction.

A subsequent program, the European Automobile Fuels Programme (see http://europa.eu.int/comm/environment/autooil/), re-examined the Euro 2 emissions data and extrapolated the results to estimate the performance of alternative fuels in Euro 3 and Euro 4 engines (Arcoumanis 2000).

3.4.1 ULP and PULP tailpipe emissions

Tables 3.14 and 3.15 reproduce the emission results (in g/km) for the Ford Falcon and a 1998 and 1999 Holden Commodore obtained under the Comparative Vehicles Emissions Study. All three of these vehicles used ULP and were certified under ADR37/01. The results of the vehicles under the ADR testing are given in Table 3.15 and the results of the vehicles under Euro 2 testing are given in Table 3.16.

These tables also give results for a 1998 BMW using PULP.

Table 3.15 – Emission results (g/km) for ADR37 compliant vehicles under ADR37 test cycles

ADR37 FTP test	**1999 Ford Falcon AU**	**1998 Holden Commodore**	**1999 Holden Commodore**	**BMW 5 Series**
Fuel	ULP	ULP	ULP	PULP
CO	1.183	0.51	0.51	0.38
HC	0.051	0.10	0.086	0.03
NO_x	0.181	0.19	0.139	0.04
FC (L/100 km)	14.28	13.13	12.18	14.89

Table 3.16 – Emission results (g/km) for ADR37 compliant vehicles under ADR79/00 test cycles

ADR79/00 Euro 2 Test	**1999 Ford Falcon AU**	**1998 Holden Commodore**	**1999 Holden Commodore**	**BMW 5 Series**
Fuel	ULP	ULP	ULP	PULP
CO	1.412	0.92	0.658	0.04
HC	0.059	0.20	0.174	0.02
NO_x	0.1291	1.17	0.851	0.04
FC (L/100 km)	13.934	12.76	11.83	14.77

3.4.2 ULS–PULP

The emissions data obtained from the Euro 4 petrol vehicles tested under the EETP are given in Table 3.17

Table 3.17 – Emission results (g/km) for Euro 4 compliant vehicles under Artemis test cycles

Artemis Drive Cycle	**Average of EETP vehicles tested**
Fuel	Euro 4 Petrol
CO	0.97
HC	0.012
NO_x	0.093
CO_2	193.4

3.4.3 Particulate matter emissions from petrol vehicles

There have been very few measurements of particulate matter emissions from petrol vehicles in Australia. The Victorian EPA uses emission factors derived from the MOBILE5 and MOBILE6 models. These are reproduced in Table 3.18 for both TSP (total suspended particles) and for PM10. The speciation factor is the proportion of TSP that are less than 10 µm in size. It may be noted that these emission factors do not differentiate between ULP and PULP, or acknowledge the potential for reduced PM10 emissions as the sulfur in PULP is reduced.

Table 3.18 – Emission factors for TSP and PM10 from petrol fuelled passenger vehicles

Period	TSP (g/km)	Speciation factor	PM10 (g/km)
Pre-1986	0.0186	0.9	0.01674
1986–1997	0.00963	0.97	0.00934
Post-1997	0.00267	0.97	0.00259

3.4.4 Tailpipe emissions from diesel vehicles

Though it is possible to find data from Australia (Zito and Marquez 2002) and New Zealand (Ministry of Transport 1998) on emissions from cars and other light vehicles using high sulfur diesel, the EETP results provide the only test data that we were able to obtain on emissions from the present generation of diesel vehicles using low sulfur fuels. We were not, however, able to differentiate between emissions from LSD and ULS diesel and have, therefore, assumed on the basis of MVEC (2003) results given below, that the tailpipe emissions are decreased by 5% with ULS diesel. It is normally assumed that the removal of sulfur from fuel will reduce PM emissions. However, a greater reduction in PM emissions is associated with the installation of particulate traps when the sulfur level is sufficiently low to enable them to function efficiently.

For heavy vehicles, the differences (if any) between tailpipe emissions of LSD and ULS are contentious (Beer et al. 2003) and therefore uncertain. The same may be the case with LSD and ULS emissions from light vehicles, but we have been unable to source any light vehicle data to investigate the matter.

Even if it would be possible to provide estimates of emissions from XLS diesel (< 10 ppm sulfur) on a similar basis we felt that such a procedure would not be valid. If XLS diesel were to be introduced, it would be done so as to enable more stringent emission controls to be placed on diesel vehicles—especially in relation to particulate matter. The effects of such controls on emissions and on fuel consumption are presently not known. However, the addition of such controls is likely to lead to changes in emissions compared with the present situation. MVEC (2003) claims that reduction in sulfur will lead to fuel efficiency benefits of 2% for diesel vehicles (and 3% for petrol vehicles) because vehicles with NO_x storage traps are more fuel efficient for very low sulfur content fuels (MVEC 2003: p.40). In addition, there will be a reduction in particulate matter emissions that MVEC (2003: p.37) estimates to be 5%.

Hence it was not considered valid to extend the analysis to XLS until test data is available on vehicles that use the emission controls likely to apply with XLS vehicles.

3.5. Results

The upstream emission results are based on the energies involved in typical refining operations (as evaluated for low sulfur diesel). A process tree for particulate matter is given in Figure 3.5. Process trees for GHG are given in Chapter 0; tabulations of the results can be found in Appendix E.

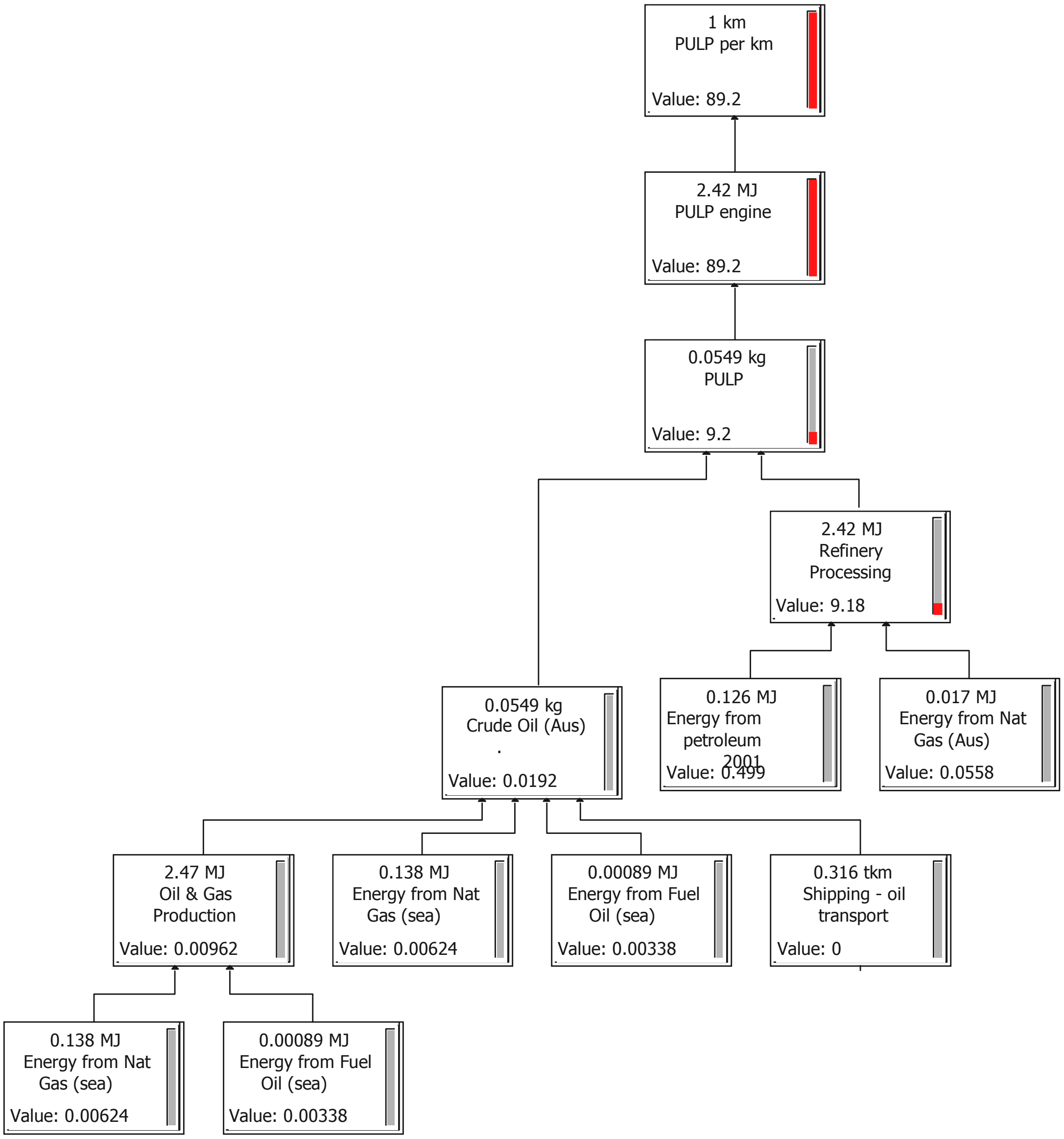

Figure 3.5 – Exbodied particulate matter (mg, urban) from PULP production and processing, and use in vehicles

This chapter analysed the upstream and combustion emissions resulting from production, transport, and use of petrol and diesel.

The main difficulties in this analysis arise from the paucity of data on sulfur content of the fuel. For upstream emissions, economic allocation was used to determine the energy requirements and associated GHG and pollutant emissions for ultra- and extra-low sulfur petrol and diesel. For tailpipe emissions, qualitative and quantitative assessments present in the literature have been used.

4. LPG

4.1. LPG in Australia

LPG has been used as an automotive fuel in Australia since the 1960s. It is the most widely available ‘alternative fuel’ in this country, and it has been claimed (Anyon 2002) that Australia has the best refuelling infrastructure in the world. There are over 3,500 service stations across Australia that are equipped with LPG dispensing systems, allowing vehicles operating on LPG virtually unrestricted travel through most of Australia. In 2003, the Census of Motor Vehicles (ABS 2003) registered 225,700 LPG or dual-fuel passenger vehicles, representing 2.2% of the passenger vehicles fleet, 95,334 LPG or dual-fuel LCVs (5.1% of total LCVs), and a total of 329,592 LPG or dual-fuel motor vehicles (2.5% of the fleet).

4.2. Literature review

The following works provide an overview of LPG emissions testing undertaken in Australia.

4.2.1 Motor vehicle pollution in Australia

This study (Brown et al. 1997) published in May 1997 by the NSW Environment Protection Authority for Environment Australia and the Federal Office of Road Safety, gives emission information pre-tune and post-tune for ADR 27 and ADR 37 vehicles. When this study was undertaken, the LPG vehicles used were converted, not OEM.

4.2.2 Comparative vehicle emissions study

This study published in February 2001 by the Department of Transport and Regional Services (2001), gives emission information for the certification pollutants (CO, HC, NO_x) for ADR 37/01 vehicles when tested under three drive cycles—the FTP cycle, the Euro 2 cycle (applicable to ADR 79/00) and the Euro 3 cycle (applicable to ADR 79/01).

These two studies provide much, but not all, of the information needed to characterise fully ADR 37 vehicles.

4.2.3 Greenhouse gas emissions from motor vehicles in Australia

This paper by Weeks et al. (1996) was published in the Proceedings of the 13th International Clean Air & Environment Conference. It provides results of measurements of the GHG emissions of methane and nitrous oxide from LP, ULP and LPG vehicles, and compares the results with the default emissions given in the National Greenhouse Gas Inventory.

4.2.4 Emissions from passenger vehicles on unleaded petrol and LPG

This paper by Ristovski et al. (2002) in the Proceedings of the 15th International Clean Air & Environment Conference provides results of measurements of emissions of PM and carbonyls and PAH from ULP and LPG vehicles.

The above group of reports and papers provide all of the information needed to characterise the emissions from an ADR 37 LPG vehicle and to compare it with an equivalent ULP vehicle.

4.2.5 Systematic evaluation of twelve LP gas fuels for emissions and fuel consumption

This paper by Watson and Gowdie (2000) is part of the SAE Technical Papers series (SAE 2000–01–1867). It provides an analysis of the different emissions that arise from the different composition of LPG in terms of propane (C_3H_8) and butane (C_4H_{10}) and the olefins propylene (C_3H_6) and butylene (C_4H_8). The results of this study are reproduced in Appendix B. These results can be used to determine the properties of LPG composed of a different mix of propane and butane.

4.2.6 LPG as an automotive fuel—an environmental and technical perspective

This booklet by Anyon (2002) is an update of an identically titled report published in 1998. It provides an excellent review of the literature related to LPG vehicles within the Australian context, including their emission characteristics and how these emission characteristics integrate with present and future technological developments.

4.2.7 LPG: A bridge to the future

This report (LP Gas Association 2003[8]) gives the results of the EETP program. Appendix 1.3.1 and Appendix 1.3.2 of that report provide emission results for the testing program. The test program obtained European passenger vehicles such that the model was available in three different fuel types: petrol, diesel and autogas. Ten vehicles were tested—details are given in Appendix 1.2—and the emissions data for CO_2, NO_x, HC and CO are given (in g/km) for the Artemis Drive Cycle. Data for the EDC is also given but only for CO_2 and NO_x.

The study concludes (p.4) that CO_2 emissions with autogas are 1.8% lower than diesel, and 20.3% lower than petrol. NO_x emissions for autogas are lower with 120–180% than petrol and 2000% than diesel. The PM emissions of autogas are 120 times lower than diesel (urban driving cycle).

4.3. Structure of the Chapter

This chapter examines LPG with respect to its life-cycle emissions of GHG and air pollutants when used as a fuel for light vehicles. The use of LPG as autogas is examined in two vehicle types: second generation (2G) LPG vehicles that have electronic control, and third generation (3G) LPG vehicles that combine advanced fuel injection technologies with advanced electronic management features. Anyon (2002: Appendix A) provides more details on the differences between first, second, third and fourth (future) generation LPG technologies.

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[8] http://www.lpga.co.uk/ai_mem/secure/pdf/Road%20Fuel%20Gases%20Consultation%20Response.pdf

We have used a hierarchy of data quality to assess the data on emission profiles from different vehicle types. Australian experimental data is used wherever possible. Recent overseas data is reviewed and, where appropriate, used in the SimaPro model.

Fuels are compared on the basis of the mass of emissions per kilometre of distance travelled, which is the environmentally most meaningful figure, though subject to greater variability than mass per unit energy. Arriving at emissions per kilometre involves three steps.

This first step produces an estimate of the GHG and air quality emissions from each fuel, expressed as the mass of emissions per unit of energy — kg/MJ. The second step characterises the fuel in terms of its energy per unit of volume (MJ/L), and the last step calculates the performance of the vehicle expressed as fuel consumption (in L/km).

4.4. Life-cycle analysis of emissions

This first step produces an estimate of the GHG and air quality emissions from each fuel expressed as the mass of emissions per unit of energy — kg/MJ.

4.4.1 Production life cycle for LPG

4.4.1.1 Background

LPG 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 used in motor cars 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 330,000 Australian vehicles use LPG, either as a dedicated fuel or in dual-fuel[9] vehicles. LPG powers all taxis in Victoria, and many other taxi fleets around the country. It is a familiar and widely available light vehicle fuel.

For eastern Australia, Anyon (1998) notes that the LPG mixture supplied is typically around 60–70% propane and 40–30% butane. The addition of butane reduces NO_x emission, while it increases emissions of THC and CO.

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[9] Australian usage is for 'dual-fuel' to refer to a vehicle that can operate either on LPG or on petrol. Such a vehicle is called a bi-fuel vehicle in the UK.

In January 2000 the ALPGA published performance-based specifications for LPG. These are widely perceived to be more stringent than the European standards and have become a de facto standard in Australia. The performance of passenger vehicles using different LPG grades has been documented by Watson and Gowdie (2000).

4.4.1.2 Calculations

As noted above, LPG is produced as a by-product of refinery processes (1,795 ML) and as a by-product of natural gas processing (4,558 ML). Table 4.1 shows that Australia is more than self sufficient in LPG production, exporting 2,785ML and importing 633ML in the year 2000–2001.

Because LPG is produced as a by-product, (in both refineries and natural gas production) some form of allocation is required to determine the impacts of LPG production.

4.4.1.3 Attributional allocations for LPG

For the two production routes for LPG (refinery and natural gas processing) allocations have been calculated based on energy and mass, while a price-based allocation has also been undertaken for LPG from refineries (no conclusive data on the comparative price of LPG and natural gas products was found). The refinery allocations also change the environmental profile of other refinery product including the unleaded petrol, so this has also been calculated for comparing LPG and petrol vehicles.

4.4.1.4 LPG from oil and gas production

Table 4.2 reproduces Table 3.4, which shows the volume of product produced in primary oil and gas production (column 2) and the energy contained in each of those product fractions (column 6) and the overall percentage share (column 7). The energy usage in primary oil and gas production is then split across the different products based on energy shares (last three columns). The table is broken into two sections: the first allocates between oil and gas products the second allocates between the different gas products. This is done separately so that venting emissions from gas processing products are allocated only across the gas products and not to the crude oil and condensate production. Emissions from this fuel production (main greenhouse emissions are listed in Table 4.8) and production fugitives are split on the same basis.

Table 4.1 – Production and consumption of LPG (ML) in Australia

Attribute	1993–4	1994–5	1995–6	1996–7	1997–8	1998–9	1999–00	2000–01
Refinery product	1057	1205	1448	1605	1518	1691	1674	1795
Bonaparte	108.18	114.7	118.9	81.1	54.4	25.3	19.7	21.7
Carnarvon	0.181	0.196	0.22	0	0	0	0	0
Barrow Island	0	0	385.519	780.44	1,279.9	1,354.9	1,564.4	1,493.3
Queensland	930.88	935.6	897.24	803.26	810.25	889.84	894.64	816.25
Gippsland	2,661.5	2,558	2,247.46	2,124.6	2,292.1	1,634.3	1,888.9	1,725.1
Total	3,700.7	3,609	3,649.4	3,789.4	4,436.8	3,904.3	4,367.6	4,056.4
Not listed	314.11	360	464	464	464	464	464	502
Total production from NG	4,015	3,969	4,113	4,253	4,901	4,368	4,832	4,558

Attribute	1993–4	1994–5	1995–6	1996–7	1997–8	1998–9	1999–00	2000–01
Total (refinery and NG)	5,072	5,174	5,562	5,859	6,419	6,060	6,506	6,353
Consumption	4,110	4,477	4,448	4,160	4,386	4,400	4,456	3,979
Export	1,290	1,189	1,469	2,421	2,824	2,486	2,857	2,785
Import	164	266	415	588	511	496	519	633

Table 4.2 – Energy allocation of primary energy production including LPG 2000–2001

Attribute	Volume	Energy content	Energy (PJ)	Energy share	Petroleum (PJ)	Gas (PJ)	Total (PJ)
Allocation of oil and gas			Volume* energy content				
Crude oil and condensate	38,705 ML	38.7 MJ/L	1,497.9	50.84%	0.54	73.41	73.95
Natural gas including ethane and LPG	–	25.7 MJ/L	1,448.4	49.16%	0.52	70.98	71.50
Total			2,946.3		1.06	144.39	145.45
Total per MJ of product					0.000360	0.0490	
Gas products allocation							
LPG	4,558 ML	25.7 MJ/L	117.1	8.09%	0.04	5.74	5.78
Natural Gas	33.32 TL	39 MJ/kL	1,299.6	89.73%	0.47	63.69	64.16
Ethane	0.48 TL	66 MJ/kL	31.6	2.18%	0.01	1.55	1.56
			1,448.4		0.52	70.98	71.50

Table 4.3 shows the volume of product produced in primary oil and gas production (column 2) and the mass of each of those product fractions (column 6) and the overall percentage share (column 7). The energy usage in primary oil and gas production is then split across the different products based on mass shares (last three columns). Emissions from this fuel production, and production fugitives, are split on the same basis (main greenhouse emissions and fugitives are listed in Table 3.5 and Table 3.6).

Table 4.3 – Mass allocation of primary energy products including LPG

Attribute	Volume	Density	Mass (kton)	Mass share (%)	Petroleum (PJ)	Gas (PJ)	Total (PJ)
Allocation of oil and gas			Volume*density				
Crude oil and condensate	38,705 ML	38.7 kg/L	1497.9	98.12	1.04	141.68	142.72
Natural gas including ethane and LPG	–		28.6	1.88	0.02	2.71	2.73
Total			1,526.5		1.06	144.39	145.45
Total per MJ of product					0.000694	0.0946	
Gas products allocation							
LPG	4,558 ML	0.52 kg/L	2.4	8.28	0.00	0.22	0.23
Natural Gas	33.32 TL	0.77 kg/m^3	25.7	89.58	0.02	2.43	2.44
Ethane	0.48 TL	1.28 kg/m^3	0.6	2.14	0.00	0.06	0.06
Total			28.6		0.02	2.71	2.73

4.4.1.5 LPG from refinery production

The main difficulty in undertaking economic allocations is finding comparable prices between products that reflect the value of the product to the producer (which is the entity with the choice of whether to increase or decrease output of the products). Table 4.4 gives economic data based on import and export markets, and is therefore free of most taxes and levies, and has thus been used as the basis of the economic allocation. An alternate source of data is from the economic input–output tables from the ABS, which are shown in Table 4.5. However these data are older, less complete, and have some overlap in definitions of fuel product groups, and so are provided only for comparison.

Table 4.6 shows the volume of product produced in refineries (column 2) and the value of that production for each of those product fractions (column 4) and the overall percentage share by value (column 5). The energy usage in oil refining is then split across the different products based on economic value (last two columns). Emissions from this fuel used in refineries (main greenhouse emissions are listed in Table 3.8), and production fugitives, are split on the same basis.

Table 4.4 – Economic data on import and export value of refinery products for 2000–2001

Fuel	ML traded	$m-value	$/L
Exports			
Automotive gasoline	1,278	494	0.387
Automotive diesel oil	1,157	446	0.385
Aviation turbine fuel	755	301	0.398
Fuel oil	724	183	0.253

Fuel	ML traded	$m-value	$/L
Exports			
Industrial and marine diesel fuel	119	52	0.436
Aviation gasoline	28	17	0.585
Kerosene	10	5	0.449
Lubricants	278	238	0.856
Other	226	114	0.505
Total refined products	4,577	1,849	0.404
Liquefied petroleum gas	2,785	830	0.298
Bunkers	2,291	899	0.392
Crude oil and other refinery feedstock	24,030	8,131	0.338
Imports			
Automotive gasoline	1,189	432	0.363
Diesel fuel	1,129	438	0.388
Aviation turbine fuel	387	154	0.397
Fuel oil	814	222	0.272
Lubricants	33	60	1.816
Liquefied petroleum gas	633	160	0.253
Other	561	314	0.561
Total refined products	4,746	1,780	0.375
Crude oil and other refinery feedstock	26,237	8,680	0.331

Table 4.5 – 1996–97 economic data on Australian refinery production

Fuel	Volume 1996–97 (ML)	Energy content 1996–97 (TJ)	Basic prices from input-output data ($)	Ratio price/ energy content ($/MJ)	Price ($/L)
Automotive petrol; gasoline refining or blending; motor spirit (incl. aviation spirit)	18,221	622,999	5,128,300,000	0.00823	0.281
Automotive diesel oil	12,968	500,567			
Aviation turbine fuel	5,284	194,450			
Fuel oil	1,796	71,282			
Liquefied petroleum gas	1,605	41,261	267,000,000	0.00647	0.166
Industrial and marine diesel fuel	45	1,764			
Bitumen	638	28,087	207,600,000	0.00739	0.325
Lubricants	788	30,587			

Fuel	Volume 1996–97 (ML)	Energy content 1996–97 (TJ)	Basic prices from input-output data ($)	Ratio price/ energy content ($/MJ)	Price ($/L)
Heating oil	243	9,062			
Other	5,284	197,079			
Total products	46,872	1,697,139	10,554,800,000	0.00622	0.225

Table 4.6 – Allocation by price for refinery co-products 2000–2001

Attribute	2000–2001 (ML)	Price ($/l)	Value	% by value	Refining energy gas (PJ)	Petroleum (PJ)
Automotive gasoline	17,887	0.387	6917	34.86	3.00	30.13
Automotive diesel oil	13,212	0.385	5089	25.65	2.21	22.17
Aviation turbine fuel	5,836	0.398	2326	11.72	1.01	10.13
Fuel oil	1,951	0.253	493	2.48	0.21	2.15
Liquefied petroleum gas	1,795	0.298	535	2.70	0.23	2.33
Industrial and marine diesel fuel	98	0.436	43	0.22	0.02	0.19
Bitumen	693	0.375	260	1.31	0.11	1.13
Lubricants	641	1.816	1164	5.87	0.51	5.07
Aviation gasoline	137	0.585	80	0.40	0.03	0.35
Heating oil	194	0.253	49	0.25	0.02	0.21
Other	5,715	0.505	2887	14.55	1.25	12.58
Total products	48,160	0.412	19842	100.0	8.62	86.43

Table 3.7 shows the volume of product produced in refineries (column 2) and the energy content of each of those product fractions (column 4) and the overall percentage share (column 5). The energy usage in oil refining is then split across the different products based on energy shares (last two columns). Emissions from this refinery production (main greenhouse emissions are listed in Table 3.8 and reproduced in Table 4.8), and production fugitives, are split on the same basis.

Table 4.7 shows the volume of product from refineries (column 2) and the mass of each of those product fractions (column 4) and the overall percentage share (column 5). The energy usage in oil refining is then split across the different products based on mass shares (last two columns). Emissions from this refinery production (main greenhouse emissions are listed in Table 3.8 and reproduced in Table 4.8), and production fugitives, are split on the same basis.

Table 4.7 – Allocation by mass for refinery co-products 2000–2001

Fuel	Volume (ML)	Density (kg/L)	Mass (kt)	% by mass	Refining energy gas (PJ)	Petroleum (PJ)
Automotive gasoline	17,887	0.735	13,152	34.72	6.57	29.45
Automotive diesel oil	13,212	0.846	11,178	29.51	5.59	25.03
Aviation turbine fuel	5,836	0.793	4,628	12.22	2.31	10.37
Fuel oil	1,951	0.901	1,758	4.64	0.88	3.94
Liquefied petroleum gas	1,795	0.519	931	2.46	0.47	2.09
Industrial and marine diesel fuel	98	0.881	86	0.23	0.04	0.20
Bitumen	693	1.019	706	1.86	0.35	1.58
Lubricants	641	0.893	572	1.51	0.29	1.28
Aviation gasoline	137	0.708	97	0.26	0.05	0.22
Heating oil	194	0.808	157	0.41	0.08	0.35
Other	5,715	0.808	4,616	12.19	2.31	10.34
Total products	48,160	0.787	37,882	100.00	18.93	84.82

Table 4.8 – Energy (PJ) and Emissions (Gg) for refinery operations during 2000–2001

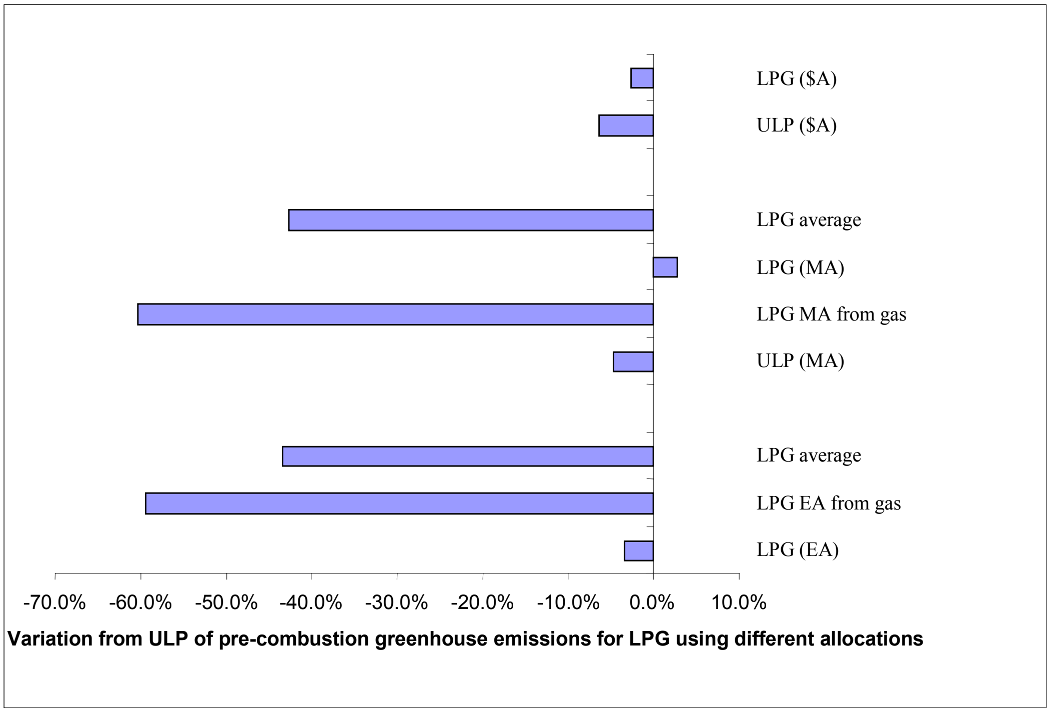
Item	Fuel	Energy use	CO_2	CH_4	N_2O	NO_x	CO	NMVOC
Petroleum Refining	Petroleum	84.82	5,760.47	0.07	0.05	32.55	4.58	0.07
	Gas	18.93	968.36	0.02	0	13.68	1.07	0.02

Table 4.9 shows the resulting pre-combustion emission from different refinery allocation techniques (energy-, mass- and price-based allocation) that are also graphed for CO_2, NO_x and PM10 in Figures 4.1 to 4.3. It shows that emissions from LPG produced from natural gas are consistently lower than those produced by refineries, and that in refineries the emissions attributed to LPG are usually lower than those for an equivalent amount of unleaded petrol.

Table 4.9 – Comparison of pre-combustion emissions from different attributional allocation approaches based on 1 kg of LPG and 1.065 kg of ULP

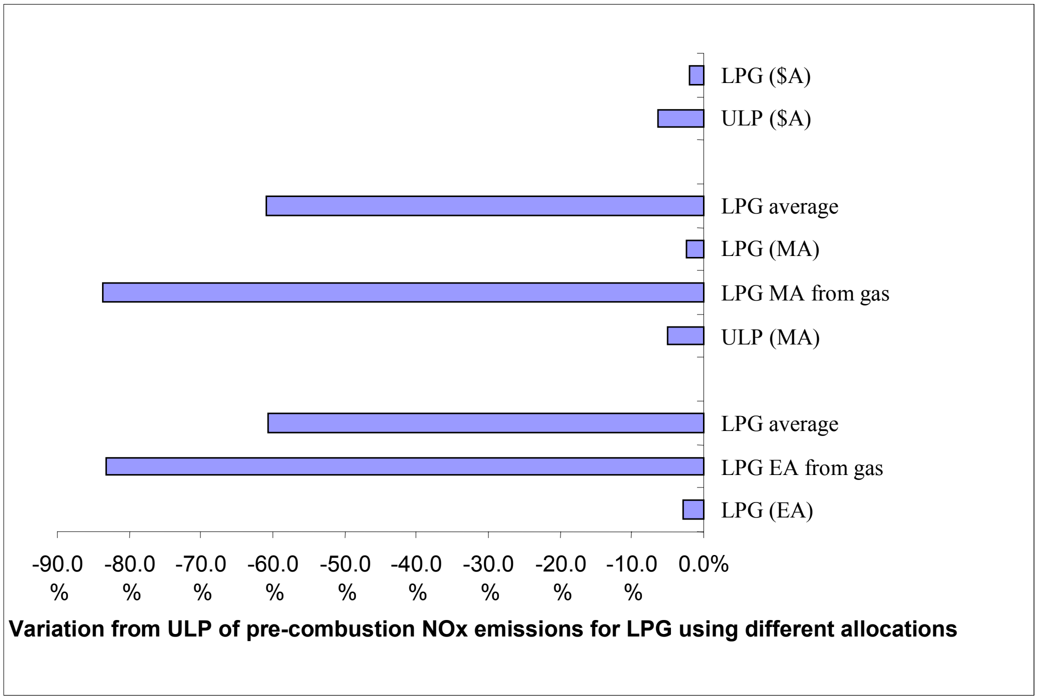
Fuel	Greenhouse (kg CO_2)	NMVOC total (g HC)	NO_x total (g NO_x)	CO total (g CO)	PM10 total (mg PM10)
ULP (EA) refinery	0.497	4.04	3.6	0.678	242
LPG (EA) refinery	0.48	3.57	3.5	0.663	239
LPG (EA) from gas (2003)	0.202	0.328	0.602	0.257	7.94
LPG average (EA)	0.281	1.24	1.42	0.371	73.2
ULP (MA) refinery	0.474	3.92	3.42	0.635	224

Fuel	Greenhouse (kg CO_2)	NMVOC total (g HC)	NO_x total (g NO_x)	CO total (g CO)	PM10 total (mg PM10)
LPG (MA) refinery	0.511	3.56	3.51	0.692	228
LPG MA from gas (2003)	0.197	0.318	0.585	0.249	7.71
LPG average (MA)	0.285	1.23	1.41	0.374	69.8
ULP ($A) refinery	0.465	3.78	3.37	0.634	226
LPG ($A) refinery	0.484	3.59	3.53	0.671	242



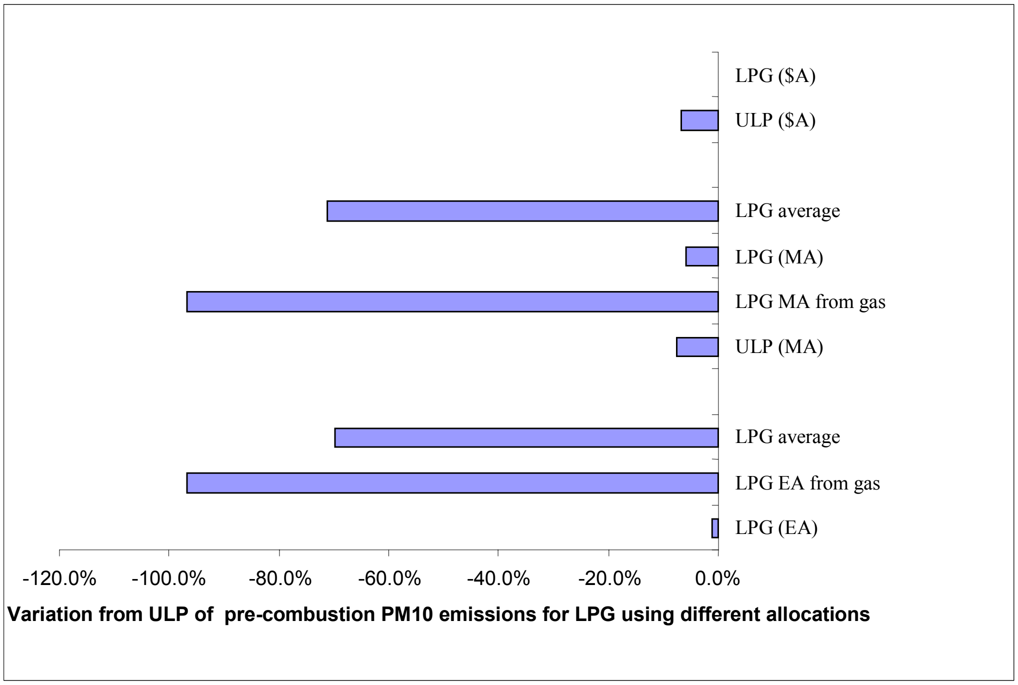
EA = Energy allocation, MA= Mass allocation, $A = economic allocation

Figure 4.1 – Comparison of pre-combustion emission from different attributional allocation approaches for CO_2



EA = Energy allocation, MA= Mass allocation, $A = economic allocation

Figure 4.2 – Comparison of pre-combustion emission from different attributional allocation approaches for NO_x emissions



EA = Energy allocation, MA= Mass allocation, $A = economic allocation

Figure 4.3 – Comparison of pre-combustion emission from different attributional allocation approaches for PM emissions

4.4.1.6 Expanded system boundary allocation

Data from LPG usage in the Australian economy was obtained from national input–output data for 1996–7 and is presented in Table 4.10 for LPG from natural gas, Table 4.11 for LPG from refineries and Table 4.12 for combined LPG usage. These tables show that the largest users of LPG (aside from the petroleum industry) are industrial process industries such as metal production, cement and lime production and basic chemical production. This is followed by private consumption, which would include vehicle and household usage.

Exports are the largest single use of LPG, accounting for 16% and 45% of natural gas-derived and petroleum production-derived LPG, respectively. Discussion with the LPG industry reveals that this export material could be the most sensitive user-sector of LPG (i.e. the use that would increase or decrease as usage in the Australian transport sector is decreased or increased). The effects of increasing or decreasing LPG exports, predominantly into Asia particularly Japan, can only be speculative in this report. Again, from discussions with LPG industry experts, Australian LPG could be substituted by LPG from other countries, ultimately from new plant capacity to separate LPG from current refinery and gas processing operations, or from LNG in Australia, Malaysia or elsewhere around the world. Australia exports around 2/3 of its annual natural gas production as LNG to Asia, so there is scope to expand and contract this to absorb small changes in LPG supply.

However, one problem with this approach is that the substitution allocation leads back to the original production system (LPG from natural gas being substituted by natural gas co-produced with LPG). Because of this, a system boundary expansion has not been used in the study.

Table 4.10 – Usage of LPG (from gas production) by value 1996–67

Economic sector	**LPG (gas) usage (A\$000[1])**	**Total % of supply (%)**
Petroleum and coal products	91,288	13
Basic non-ferrous metal and products	87,658	12
Basic chemicals	41,585	6
Iron and steel	34,053	5
Communication services	28,649	4
Gas supply	26,948	4
Defence	23,899	3
Private final consumption expenditure	23,766	3
Government administration	21,258	3
Retail trade	17,509	2
Accommodation, cafes and restaurants	16,143	2
Road transport	15,063	2
Meat and meat products	13,999	2
Poultry	13,107	2
Other services	8,402	1
Community services	8,345	1

Economic sector	**LPG (gas) usage (A$000[1])**	**Total % of supply (%)**
Pulp, paper and paperboard	7,030	1
Dairy products	6,672	1
Health services	5,945	1
Other business services	5,492	1
Other food products	5,253	1
Services to mining	4,778	1
Rail, pipeline and other transport	4,760	1
Motor vehicles and parts; other transport equipment	4,746	1
Plastic products	4,444	1
Scientific research, technical and computer services	4,305	1
Total supply	709,913	100
Exports	111,526	16

[1] Note the full sector description is: Liquefied petroleum gases—natural; coal gas and similar, other than petroleum gases and other gaseous hydrocarbons.

Table 4.11 – Usage of LPG (from refinery production) by value 1996–97

Economic sector	**LPG (refineries) usage (A$000)**	**Total % of supply (%)**
Cement, lime and concrete slurry	19,225	6
Private final consumption expenditure	18,461	6
Basic non-ferrous metal and products	14,885	5
Electricity supply	13,199	4
Fruit and vegetable products	11,724	4
Other mining	7,668	2
Dairy products	7,208	2
Retail trade	6,274	2
Pulp, paper and paperboard	5,061	2
Services to transport; storage	4,924	2
Poultry	4,497	1
Iron and steel	4,105	1
Basic chemicals	4,083	1
Wholesale trade	3,621	1
Dairy cattle	3,437	1
Non-ferrous metal ores	3,310	1
Other construction	3,217	1
Other agriculture	3,181	1
Sheep	2,966	1
Beef cattle	2,902	1

Economic sector	**LPG (refineries) usage (A$000)**	**Total % of supply (%)**
Increase in stocks	2,632	1
Accommodation, cafes and restaurants	2,197	1
Glass and glass products	2,190	1
Coal, oil and gas	1,873	1
Other non-metallic mineral products	1,751	1
Total supply	326,031	100
Exports	149,112	46

Table 4.12 – Usage of LPG (from both gas and refinery production) by value 1996–97

Economic sector	**LPG (gas) usage (A$000)**	**LPG (Refineries) usage (A$000)**	**Total usage (A$000)**	**Total % of supply (%)**
Basic non-ferrous metal and products	87,658	14,885	102,544	10
Petroleum and coal products	91,288	28	91,315	9
Basic chemicals	41,585	4,083	45,668	4
Private final consumption expenditure	23,766	18,461	42,228	4
Iron and steel	34,053	4,105	38,158	4
Communication services	28,649	1,084	29,734	3
Gas supply	26,948	2	26,950	3
Defence	23,899	184	24,083	2
Retail trade	17,509	6274	23,782	2
Government administration	21,258	215	21,473	2
Cement, lime and concrete slurry	1,894	19,225	21,119	2
Accommodation, cafes and restaurants	16,143	2,197	18,340	2
Poultry	13,107	4,497	17,604	2
Road transport	15,063	932	15,995	2
Meat and meat products	13,999	586	14,586	1
Dairy products	6,672	7,208	13,880	1
Fruit and vegetable products	1,922	11,724	13,647	1
Electricity supply	0	13,199	13,199	1
Pulp, paper and paperboard	7,030	5,061	12,090	1
Other services	8,402	79	8,481	1
Community services	8,345	77	8,422	1
Other mining	204	7,668	7,872	1
Increase in stocks	4,268	2,632	6,899	1
Other business services	5,492	849	6,341	1
Health services	5,945	263	6,208	1

Economic sector	LPG (gas) usage (A$000)	LPG (Refineries) usage (A$000)	Total usage (A$000)	Total % of supply (%)
Other construction	2,822	3,217	6,038	1
Non-ferrous metal ores	2,622	3,310	5,931	1
Other food products	5,253	583	5,836	1
Services to transport; storage	884	4,924	5,808	1
Motor vehicles and parts; other transport equipment	4,746	983	5,730	1
Scientific research, technical and computer services	4,305	933	5,238	1
Other non-metallic mineral products	3,451	1,751	5,202	1
Total supply	709,913	326,031	1,035,944	100
Exports	111,526	149,112	260,637	25

4.4.2 Fuel combustion

This characterises the fuel in terms of its energy per unit volume in units of MJ/L. The exact value will depend on the fuel composition, but typical values for energy density of petrol and propane, based on the lower heating value (LHV), are given in Table 4.13.

Table 4.13 – Typical values of energy density (based on LHV) for petrol and propane

Fuel	Calorific Value (LHV) (MJ/kg)	Energy Density (LHV) (MJ/L)
Petrol	41.3	31
Propane	46.2	23.4

Source: van Walwijk et al. (1996)

4.4.2.1 Performance

This characterises the fuel in terms of the per-kilometre emissions. It is obtained from fuel consumption data for individual vehicles.

The quantitative results provide an estimate for the mean emission factor. Because of the large variability in the results of emission tests on conventional and alternative fuels, a statistical approach needs to be adopted. The uncertainty for each fuel needs to be estimated, and compared with the reference fuel on the basis of the statistical variability. The method of uncertainty analysis that was adopted is explained in Appendix C.

4.4.2.2 Tailpipe emissions for LPG

New National Fuel Quality Standards have been legislated. These include LPG for which the proposed standards were promulgated in a Discussion Paper put out by Environment Australia (‘Setting National Fuel Quality Standards Paper 5—Proposed standards for liquefied petroleum gas [autogas]', October 2001) and which final standards entered into force in March 2004[10].

4.4.2.3 ADR 37 vehicles

There is considerable published data on the emission characteristics of LPG used in cars. The data collected during the LPG component of the FORS in-service vehicle emissions study (Federal Office of Road Safety 1997) provides data on ADR27 vehicles tested under the ADR27 test cycles, and the ADR37 test cycles.

However, our interest lies in ADR37 and ADR79 vehicles. The Comparative Vehicle Emissions Study (Department of Transport and Regional Services 2001) examined two dual-fuelled (petrol/LPG) vehicles: a 1999 model Ford AU Falcon utility and a 1999 model Holden VT Commodore.

Table 4.14 gives the ratio between LPG and ULP emissions for 1999 vehicles, and a comparison of the ratios that apply between a 1999 LPG vehicle and a 1998 ULP vehicle.

Table 4.14 – Emission results (LPG to petrol ratio) from ADR 37/01 vehicles

Vehicle	Period	CO	HC	NO_x	CO_2
Falcon	99/98	1.04	1.31	0.60	0.87
Commodore	99/98	1.66	1.01	1.09	0.88
Falcon*	99/99	1.56	1.73	0.93	0.78
Commodore	99/99	1.67	1.19	1.45	0.95

*This was the data used to represent the ADR37 vehicle in this study.

These results indicate that for ADR 37/01 vehicles, the only area in which one can claim an unequivocal benefit for LPG over petrol, in terms of tailpipe emissions, is in carbon dioxide.

4.4.2.4 ADR 79/00 vehicles (Euro 2)

Anyon (2002: page 37) examined the emissions from Euro 2 Petrol and dedicated LPG cars. His results for the Vauxhall Vectra (also known as the Opel Vectra) are given in Table 4.15. Anyon (2002) compared the certification results for a group of eight European manufactured cars. The emission results for petrol and LPG were plotted on a scatter diagram, and the line of best fit determined. His results are shown in Table 3.15.

Table 4.15 – Euro 2 (Vauxhall Vectra) Emission results (g/km)

Fuel	CO	HC	NO_x	CO_2
Petrol*	0.13	0.052	0.038	199
LPG*	0.12	0.024	0.033	170

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[10] http://www.deh.gov.au/atmosphere/lpg/index.html

Fuel	CO	HC	NO_x	CO_2
LPG/Petrol ratio	0.92	0.46	0.87	0.85

*These data are used to characterise an ADR 79/00 vehicle

Table 4.16 – Line of best fit for certification emissions from European Euro 2 vehicles and equivalent LPG to petrol emissions ratios

Pollutant	Line of best fit	Equivalent LPG/petrol ratio	Arcoumanis (2000) average	Vauxhall Vectra
CO	y = 1.7791x	0.562	0.6	0.46
HC	y = 1.6613x	0.602	0.7	0.93
NO_x	y = 1.5529x	0.644	0.8	0.87
CO_2	y = 1.1439x	0.874	0.9	0.85
PM			0.8	1.0

Arcoumanis (2000) provides LPG/Petrol ratios for a number of European vehicles, including the Vauxhall Vectra (for which we also have Euro 3 emission data). These results are also reproduced in Table 4.16. It may be noted that the results of Arcoumanis (2000) agree with those of Table 4.15.

4.4.2.5 Preliminary Australian results

We have been supplied with preliminary ADR79/00 certification data for the new Falcon Barra. This data, along with in-service emission testing undertaken on a prototype BA Falcon using a PRINS vapour injection system (VIS), is given in Table 4.17 as LPG/ULP emission ratios.

Table 4.17 – LPG/ULP emission ratios based on preliminary certification and in-service data for BA Falcon

Fuel	CO	HC	NO_x	CO_2
30/70 Propane/Butane	1.299	0.570	0.608	0.910
30/70 Propane/Butane	0.955	0.451	2.063	0.906
Prins VIS in-service	0.195	0.166	1.636	0.913

The most notable aspect of these results is the extreme variability in the ratio of emissions for all pollutants except for CO_2. We have examined this in more detail in Appendix C, by using the results from the in-service LPG testing of Brown et al. (1997), and examining their variability.

It is evident that the uncertainties associated with the emissions of both petrol and LPG vehicles are very large. Percentage uncertainties range between 50% and 100%. Such large uncertainties appear to arise primarily because of the presence of a few macro-polluters in the vehicles that were tested as part of the LPG in-service vehicle study. Basically, the occasional vehicle that emits excessively large amounts of pollutants produces emission values that would be statistically referred to as outliers. As a result, the emission values are not normally distributed but are skewed, with most values being low and a few being extremely high. This applies to petrol vehicles and LPG vehicles.

4.4.2.6 ADR 79/01 vehicles (Euro 3)

We have been provided with emission test results dated January 2001 from Millbrook for a Euro 3 Vauxhall Vectra. These results are for CO, HC, NO_x and CO_2. We wish to extend these emission results with equivalent Euro 3 emissions for PM, for the other GHG (methane and nitrous oxide) and for air toxics, but despite strenuous efforts, have not been able to do so.

An examination of the US Alternative Fuels Data Centre website, and a search for both LPG and for Propane, revealed that the United States has not conducted systematic studies of emissions from LPG vehicles. In contrast to many other alternative fuels, there are no emissions data available on the web. The one study that we were able to find (*Texas Bi-Fuel Liquefied Petroleum Gas Pickup Study: Final Report, May 1999*) examined only the costs involved in running the vehicles.

Arcoumanis, in his report on the Auto-Oil II Programme, reviews emission factors for Euro 2 vehicles and claims emission ratios (on average) for LPG light duty vehicles of 0.6 for CO, 0.7 for HC (THC), 0.8 for NO_x, 0.8 for PM and 0.9 for CO_2.

Table 4.18 – Euro 3 (Vauxhall Vectra) Emission results (g/km)

Fuel	**CO**	**HC**	**NO_x**	**CO_2**
Diesel	0.063	0.014	0.466	162.1
Petrol*	1.049	0.05	0.007	179.1
LPG*	0.744	0.039	0.006	158.7
LPG/Petrol ratio	0.71	0.78	0.86	0.89

*This data are used to characterise an ADR 79/01 vehicle

Table 4.18 gives the actual measured emissions from the Euro 3 Vauxhall Vectra, and the LPG/Petrol ratio. In this case the results indicate that LPG emits less than an equivalent petrol vehicle.

The Arcoumanis report gives Millbrook Euro 2 emission data for a 1998 Vauxhall Vectra under the ECE 96/99 drive cycle. These data give LPG/petrol emission ratios of 0.46 for CO, 0.93 for HC (THC), 0.87 for NO_x, 0.85 for CO_2 as well as 1.0 for PM. These values (also in Table 4.14) and those of Table 4.18, are reproduced in Table 4.19, for ease of comparison.

Table 4.19 – Emission ratios (LPG/Petrol) for Vauxhall Vectra

Test cycle	**CO**	**HC**	**NO_x**	**CO_2**
Euro 2 (ADR79/00)	0.46	0.93	0.87	0.85
Euro 3 (ADR79/01)	0.71	0.78	0.86	0.89

The Euro 3 emission results are not noticeably better than those for Euro 2, except for HC.

We obtained unpublished test data conducted in December 2000 by TNO (in the Netherlands) on the following dual-fuel vehicles:

- Chrysler Voyager 2.4L
- Mitsubishi Charisma 1.6L
- Renault Scenic 1.6 16V
- Volvo S40/V40 1.8L
- Alfa Romeo 156 1.6T.S.
- Dewoo Leganza 2.0L
- Opel Astra X1.6SZR
- Volkswagen Golf 74kW
- Mazda Primacy 1.8
- Citroen Xsara 1.4L
- Peugot 406 1.8 16V
- Honda Accord 1.8L
- Toyota Picnic 2.0L
- Ford Mondeo 1.8L
- Renault Megane 1.6E
- Renault Megane 1.6 8V.

These data, when averaged over all vehicles and all tests, indicate that emissions of CO_2 from LPG vehicles are 12% lower, and HC emissions are 23% lower, than the emissions from the same vehicle using ULP. However, emissions of CO are 14% higher and NO_x emissions are 60% higher.

The data show that LPG is not the easy clean fuel it was in the time of high emission 'no control' cars. To meet Euro 3, and especially Euro 4, emission specifications requires vehicle and catalytic converter technology to be very tightly designed for optimum performance and minimum emissions. A vehicle designed for optimum petrol performance is very unlikely to be optimised to minimise emissions under LPG use.

From the above list, serious attempts to optimise dual-fuel vehicles have been undertaken only by Volvo, GM, Renault and VW. When the four vehicles from these manufacturers are examined then LPG performance improves. Although emissions of CO_2 from these four LPG vehicles are only 10% lower, HC emissions are 31% lower than the emissions from the same vehicle using ULP. In addition, emissions of CO are now 5% lower, though NO_x emissions are 7% higher.

On the basis of these results we do not consider the data to be representative of the results that can be obtained by dedicated OEM LPG vehicles. We believe that the difference between the results of dual-fuel Holden and Ford vehicles, and these European Euro 3 data are that the former are OEM developed systems (albeit by their suppliers in part, particularly Impco for Holden) while these Euro 3 data are mostly for after-market conversions. Where we know that the vehicle has an OEM system, as in the case of the Vauxhall Vectra, the results are markedly superior.

4.4.2.7 Euro 4 vehicles

The data from the European Test Programme (LP Gas Association 2003) was conducted on the following vehicles, available in petrol, diesel and LPG (dual-fuel) versions:

- Vauxhall Vectra
- Vauxhall Astra
- Peugeot 406

- Peugeot 307
- Renault Scenic
- Volvo V40
- Volvo V70
- Nissan Primera.

These data were tested over two drive cycles: the EDC and the Artemis Drive Cycle (Table 4.20).

Table 4.20 – Emission results (g/km) from European Test Programme (LP Gas Association 2003)

Pollutant	Drive cycle	Diesel emissions	Petrol emissions	LPG (Autogas) emissions
CO_2	EDC	161.5	197.9	174.2
CO_2	Artemis	170.9	193.4	172.6
NO_x	EDC	0.417	0.05	0.018
NO_x	Artemis	0.899	0.093	0.042
HC	Artemis	0.013	0.012	0.015
CO	Artemis	0.009	0.971	1.339

Table 4.21 – Air toxic emission results from European Test Programme (LP Gas Association 2003)

Pollutant	Drive cycle	Diesel emissions (mg/km)	Petrol emissions (mg/km)	LPG (Autogas) emissions (mg/km)
Benzene	Artemis	0.142	0.570	0.162
1,3 butadiene	Artemis	0.000	0.032	0.004
Toluene	Artemis	0.107	0.737	0.104
Xylene	Artemis	0.032	0.290	0.041
Formaldehyde	Artemis	0.789	0.172	0.049

4.4.2.8 Air Toxics and Particles

There are few data on air toxics from LPG vehicles, and even fewer on Australian LPG vehicles. Anyon (2002: Figure 29) notes that US studies using the standard FTP cycle (the same as ADR 37/01) show carbonyl emissions to be 30% of those using petrol. These results also indicate that formaldehyde, and to a much lesser extent acetaldehyde, are the dominant air toxics emitted by LPG.

Faiz et al. (1996: Table 5.7) summarise OECD and USEPA results of the emissions of air toxics. The results are reproduced in

Table 4.22 and may be compared with the results of the European programme given in Table 4.21.

Table 4.22 – Air toxics (mg/km) emitted from petrol and LPG light duty vehicles with spark-ignition engines

Compound	**Petrol**	**LPG**
Benzene	7.95	0.242
Toluene	33.66	0.695
m&p xylene	4.57	0.033
o-xylene	1.95	0.101
1,3 butadiene	0.19–0.50	Not available
Formaldehyde	4.78	4.870
Acetaldehyde	0.94	0.641
Acrolein	1.12	0.118

When the results in

Table 4.22 are compared with the results of the European program given in Table 4.21 it becomes apparent that even though emissions from modern LPG vehicles have fallen, the emissions from modern petrol vehicles have fallen even more. Thus, for example, modern LPG vehicles emit 0.67 of the benzene of their 1996 counterparts, and a modern petrol vehicle emits only 0.07 times the benzene of the earlier vehicle.

4.4.2.9 ADR 37 vehicles

Ristovski et al. (2002) studied the particulate and gaseous emissions from a fleet of six LPG and five ULP in-service new Ford Falcon Forte passenger vehicles. This work was not based on drive-cycle testing but instead was based on measuring emissions at steady speeds of 0 km h^{-1} (idle), 40 km h^{-1}, 60 km h^{-1}, 80 km h^{-1}, and 100 km h^{-1}. Particulate matter (PM) was not tested at idle, and air toxics were tested only at 60 km h^{-1} and 80 km h^{-1} .

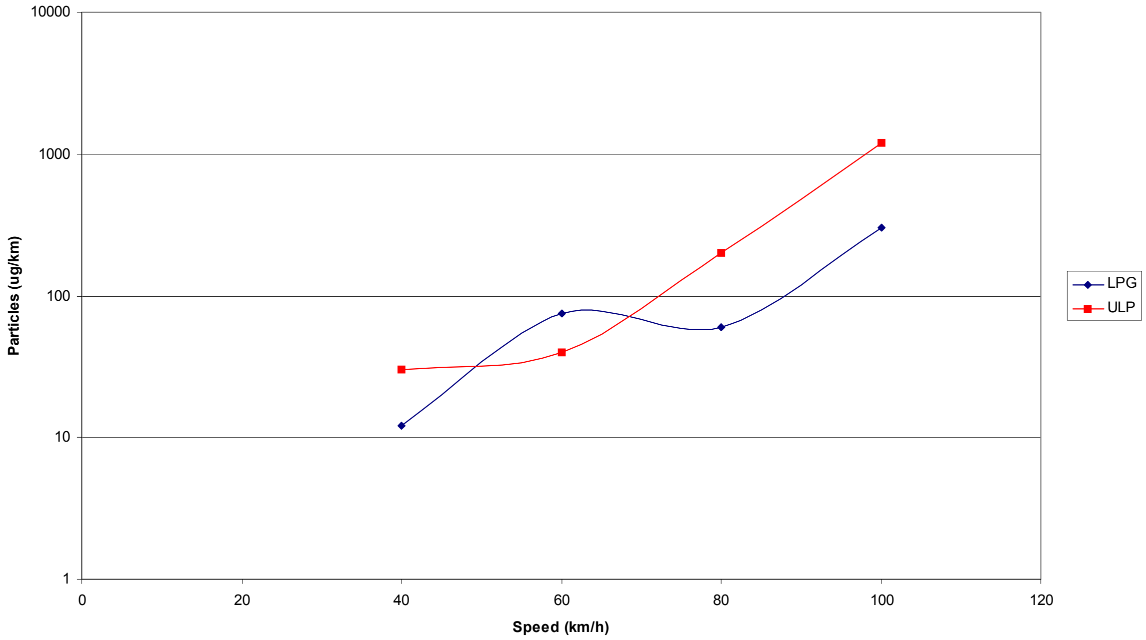

Figure 4.4 – Particle emissions as a function of speed (based on data in Ristovski et al. 2002)

Figure 4.4 plots the particle emissions observed using log-linear axes. The quoted numerical values appear to be anomalously low and have not been used. We have, instead used the observed ratio between the LPG and the ULP. It is noticeable that at high speeds, the particle emissions increase exponentially with speed. It is also noticeable that LPG emissions are lower than those of the equivalent petrol vehicle except in the 50–70 km h^{-1} speed range, which we consider is most likely to be an experimental artefact.

Air toxic emissions were also examined by Ristovski et al. (2002). The results are reproduced in Table 4.23 and Table 4.24. LPG appears to emit less PAH than ULP. LPG also emits less carbonyls than ULP at 60 km h^{-1}, but slightly more than ULP at 80 km h^{-1}.

Table 4.23 – Air toxics (µg km^{-1}) emissions at 60 km h^{-1}

Fuel	**PAH**	**Carbonyl**
LPG	28	4000
ULP	42	5100

Table 4.24 – Air toxics (µg km^{-1}) emissions at 80 km h^{-1}

Fuel	**PAH**	**Carbonyl**
LPG	33	1500
ULP	34	1200

4.4.2.10 Non-CO_2 Greenhouse gas emissions

There is few data available on the emissions of methane (CH_4) and nitrous oxide (N_2O) from LPG vehicles. Weeks et al. (1996) examined 76 vehicles from the Australian in-service passenger fleet and tested them according to ADR 37/00.

The results of this testing program are given in Table 4.25 for methane and in Table 4.26 for nitrous oxide, along with the default emission values recommended by the Australian National Greenhouse Gas Inventory Committee. It is noticeable that the emissions depend on the pollution control device fitted to the car. For both LPG and ULP, the use of three-way catalysts produces the largest emissions of nitrous oxide, but the lowest emissions of methane. When catalysts are used, the emissions from LPG vehicles are always less than those from petrol vehicles. By contrast, an ADR 37 vehicle that lacks a catalyst emits similar amounts of methane and nitrous oxide whether it is powered by petrol or LPG.

Table 4.25 – Methane emission rates (mg/km)

Attribute	LPG	ULP
3-way catalyst	34	24
No catalyst	97	107
NGGIC	87	100

Table 4.26 – Nitrous oxide emission rates (mg/km)

Attribute	LPG	ULP
3-way catalyst	12.9	43
No catalyst	5.3	4.5
NGGIC	7.9	25.0

4.5. Dual-fuel Vehicles

Although the scope of work required us to examine dual-fuel and dedicated LPG vehicles, we do not feel that the data sets available to us are sufficient to enable this to be done. In particular, we do not have data on the same vehicle in dual-fuel and in dedicated mode. As our methodology is based on being able to obtain the ratio between two modes of operation on the basis of such equivalent data, we are not able to apply our methodology in this situation. We recommend that a testing program is needed on the comparative emissions between dual-fuel and dedicated LPG vehicles.

This chapter examines the production of LPG and its use as autogas and propane in two types of vehicles: second generation LPG vehicles with electronic control, and third generation LPG vehicles that combine advanced fuel injection technologies with advanced electronic management features.

The upstream emissions are compared in three allocation situations: energy, mass, and price.

For the combustion emissions, the existing literature is reviewed, and raw data adjusted and normalised for Australian conditions.

Anyon (2002: Appendix A) details the differences between LPG technologies. They can be briefly summarised as follows:

First generation LPG vehicles had carburettors with mechanical ‘open-loop’ systems and no control feedback.

Second generation LPG vehicles have air/fuel continuously mixed in the inlet tract or ports, and have computerised fuel management systems with closed loop feedback.

Third generation LPG vehicles have timed, sequential multi-port injection (dry gas or liquid fuel), with computerised fuel management systems and closed loop feedback.

5. CNG

Information on the Australian gas supply, and its use in vehicles, is given in Beer et al. (2001), which also provides details of the upstream processing of CNG, and an estimate of the sensitivity of the results to fugitive emissions of methane from CNG.

Fugitive losses have the potential to reduce substantially any advantages that natural gas may have in terms of emissions. In Australia, the fugitive emissions for CNG are reduced compared with the US, which is reflected in lower GHG emissions. There are no differences between the emission factors for venting natural gas sourced from Victoria and South Australia. Because of the importance of these fugitive emissions, they are recalculated using the latest information.

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 and in Sydney during 1999/2000, as reported by the Australian Greenhouse Office (2002), is given in Table 5.1. Natural gas is consumed in the residential, commercial, industrial, and utility markets.

Table 5.1 – Composition of natural gas

Attribute	**Longford to Melbourne**	**Moomba to Sydney**
Methane*	90.1	89.9
Ethane*	5.8	7.2
Propane*	1.1	0.1
Butane*	0.2	0.0
Pentane*	0.0	0.0
Hexane*	0.0	0.0
CO_2*	1.9	1.6
MJ/m^3	39.3	38.9
kg CO_2/GJ (content)	0.9	0.8
kg CH_4/GJ (content)	15.5	15.6
kg NMVOC/GJ (content)	2.5	2.4
State sales to end users (PJ)	192.9	198.6
% State sales	100	100
Pipeline sales (PJ)	192.9	198.6
State utility sales (PJ)	177.9	144.9
Pipeline utility sales (PJ)	177.9	144.9
% State utility sales	100	100

* Percentage of natural gas by volume.

5.2. Upstream emissions

5.2.1 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 (1990) 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). In some instances CO_2 recovered from natural gas could be compressed and used in enhanced oil recovery.

Table 5.2 reproduces the venting and flaring values given in the State-based Greenhouse Gas Inventories produced by the Greenhouse Office. These inventories assume that venting provides the natural gas used in subsequent transmission and distribution (see Table 5.3). The salient point to note from the data of Table 5.2 is that the emission factors (in kg/GJ) for venting of natural gas are identical for gas sourced from Victoria and gas sourced from South Australia.

Table 5.2 – Fugitive emissions from venting and flaring in the Bass Strait (Victoria) and the Cooper Basin (South Australia) from oil and gas production

Attribute	**Fuel quantity (PJ)**	**CO_2 (Gg) emissions**	**CH_4 (Gg) emissions**	**CO_2 (kg/GJ) aggregate emission factors**	**CH_4 (kg/GJ) aggregate emission factors**
Victoria 1995					
Oil and Gas Production	831.0	522.0	7.02	0.63	0.01
Venting	262.9	406.9	5.52	1.55	0.02
Flaring	831.0	115.0	1.50	0.14	0.002
South Australia 1995					
Oil and Gas Production	261.4	370.9	5.00	1.42	0.02
Venting	206.7	319.9	4.34	1.55	0.02
Flaring	261.4	51.0	0.66	0.20	0.003
Australia 2000 (used in report)					
Oil and Gas Production	2,722.7	6,170.1	143.2	2.27	0.053
Venting	1,337.2	3,479.8	110.1	2.602	0.082
Flaring	2,722.7	2,690.3	33.1	0.988	0.0121

Source: Energy 1B2 Table on page 9 of National Greenhouse Gas Inventory Committee (1998a, b).

Fugitive emissions of methane occur at the wellhead (production), processing, transmission and end user distribution. Our analysis indicates that average emissions at the production stage in Australia amount to 2.17 kg per tonne of gas, while processing contributes 5.74 kg per tonne of gas.

Australian long distance high pressure (up to 15 MPa) transmission pipelines are relatively modern (the oldest dates back to 1969) and built to high standards. They are well maintained and accidental leaks are rare. It is estimated that at the transmission stage, fugitive emissions are 0.005% of the total network throughput.

Most gas losses from the distribution systems are by leakage from the low pressure network (7 kPa). This includes both the reticulation network and appliances operated by end users. Losses from the distribution network are difficult to estimate as they may occur both upstream and downstream from the meters. It is estimated that emissions from the distribution network, called unaccounted gas, i.e. the difference between the gas issued by the utilities and the gas sold to customers may be as high as 7.5% (National Greenhouse Gas Inventory Committee 1996). We consider this to be an upper bound to likely fugitive emissions. The State-based inventory estimates reproduced in Table 5.3 imply that there is 50% more distribution loss (on a per GJ basis) in South Australia than in Victoria.

Table 5.3 – Fugitive emissions from natural gas (other than venting and flaring) for gas sourced from the Bass Strait (Victoria) and the Cooper Basin (South Australia) from oil and gas production

Attribute	**Fuel quantity (PJ)**	**CO_2 (Gg) emissions**	**CH_4 (Gg) emissions**	**CO_2 (kg/GJ) aggregate emission factors**	**CH_4 (kg/GJ) aggregate emission factors**
Victoria 1995					
Production and Processing	262.9		0.42		0.002
Transmission	217.6	0.0	0.17	0.0	0.001
Distribution	171.8	4.7	68.65	0.03	0.40
South Australia 1995					
Production and Processing	206.7		0.29		0.0
Transmission	84.3	0.0	0.07	0.0	0.001
Distribution	38.5	1.6	24.56	0.04	0.64
Australia 2000 (used in report)					
Production and Processing	1337.2	NE	1.4		0.0015
Transmission	756	0.5	7.9	0.0007	0.010
Distribution	407.1	9.1	158.9	0.022	0.39

The values for fugitive emissions of natural gas used as the basis of comparison in this study are based on data on fugitive emission from natural gas production and also from the National Greenhouse Gas Inventory for 2000 (National Greenhouse Gas Inventory Committee 2002).

A process tree for CNG production is shown in Figure 5.1. The largest emission by far is the assumed loss in fuel distribution, which is discussed in more detail below.

5.2.2 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. BTCE (1994) pointed 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.

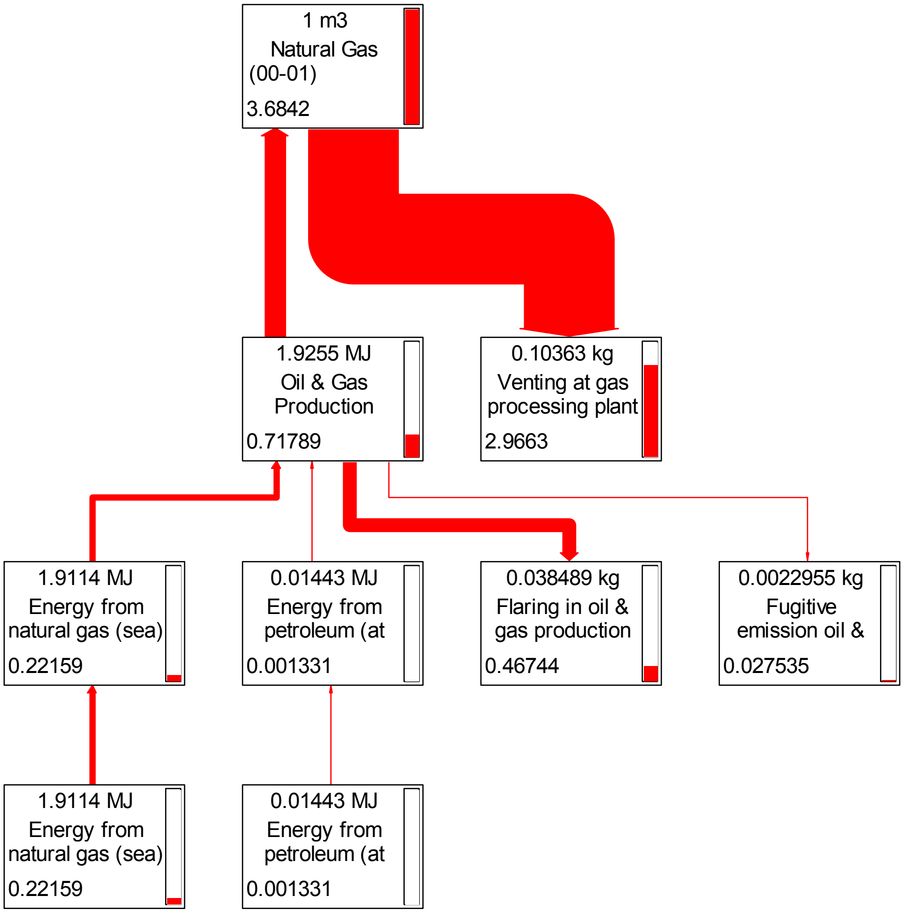

Figure 5.1 – Methane emission in grams from CNG production

Kadam et al. (1999) assumes emissions from gas processing plants are 0.1%, while the 1998 NGGI claims total distribution losses for low pressure gas supply are 0.25%. In the final modelling, a figure of 0.1% has been used for fugitive emission of methane from CNG facilities—including all operations from the point of gas supply to the facility, up to, but not including, the combustion of the gas on board the vehicle. A sensitivity analysis showing the effect of different levels of fugitive emissions is presented in Figure 5.2. It shows that up to 0.25% the GHG emission results are still lower than the baseline diesel fuel, though at 1% the full-fuel cycle emission is substantially above the diesel baseline. Though this sensitivity analysis relates to a truck we believe that the same general results would hold for cars.

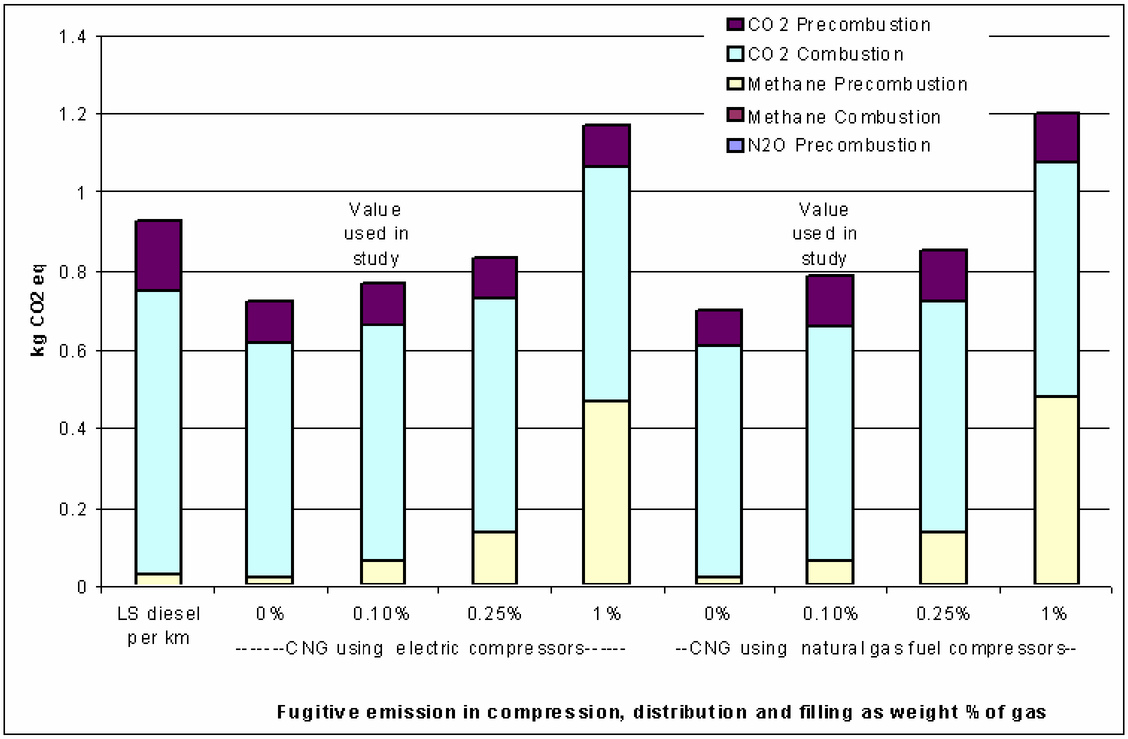

Figure 5.2 – Effect of different fugitive emission assumption of full-fuel cycle greenhouse emission per km travelled (truck)

Two modes of compression were examined: compression using natural gas and compression using electricity.

5.2.3 Release of new data on fugitives and energy in oil and gas processing

New data has been released in the National Greenhouse Gas Inventory for 2000–01 (NGGI 2003), which shows an increase, particularly in oil and gas exploration. The data for 1999–00, and 2000–01 are shown in Table 5.4 with the percentage change in emissions per MJ of fuel. This has an effect on both the emission profile of petroleum products, and natural gas. While the impacts of CNG rise slightly more than diesel fuels, the actual shift in the study results for greenhouse is very small.

Table 5.4 – Change in National Greenhouse Gas Inventory estimates of fugitive emissions for 1999-2000 and 2000-2001

Attribute	**Fugitive emissions**		
	(Gg/PJ) 1999–00	**(Gg/PJ) 2000–01**	**Change 1999–00 to 2000–01 (%)**
Carbon Dioxide Fugitives			
Exploration (for both oil and gas)	0.028207294	0.060291857	114
Crude oil production			
Crude oil transport: domestic			
Crude oil refining and storage	0.134978654	0.137669619	2
Production and processing			
Transmission	0.000661376	0.000621693	-6
Distribution	0.02235323	0.022428165	0.3
Venting and flaring oil and gas production	2.266169611	2.31201258	2
Venting at gas processing plant	2.60230332	2.647328939	2
Flaring	0.988100048	1.010464551	2
Methane Fugitives			
Exploration (for both oil and gas)	0.00033	0.0007	123
Crude oil production	0.00014	0.0006	335
Crude oil transport: domestic	0.00081	0.0007	-19
Crude oil refining and storage	0.00123	0.0012	1
Production and processing	0.00105	0.0011	3
Transmission	0.01045	0.0107	3
Distribution	0.39032	0.3920	0.4
Venting and flaring oil and gas production	0.05259	0.0516	-2
Venting at gas processing plant	0.08234	0.0795	-3
Flaring	0.01216	0.0125	3

5.3. Tailpipe emissions

5.3.1 Methane emissions from vehicles

Methane, the principal component of natural gas, has a greenhouse radiative forcing (GWP) of 21 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. According to Nylund and Lawson (2000: p.46) the sulfur-based odorant used in natural gas at very low concentration levels can have a very detrimental effect on the conversion efficiency of oxidation catalysts, bringing their methane conversion down to 30%. When catalysts are optimised for methane, then conversion efficiencies can be as high as 85–90%.

5.4. Discussion

Our results indicate lower GHG emissions than petrol or diesel from tailpipe emissions and upstream emissions. Different results were obtained in earlier studies, such as those reported in the IPCC Second Assessment Report (Watson et al. 1996), the Expert Reference Group (1998) report, or those mentioned at <http://www.hsph.harvard.edu/Organizations/hcra/diesel/diesel.pdf>. As discussed previously, the main reason for this relates to the different treatments of fugitive emissions.

6. Hybrid Vehicles

The life-cycle GHG emissions associated with hybrid vehicles were examined by Beer (2000) in relation to the aXcess concept car developed by CSIRO. More recently, Trigui et al. (2003) examine the tailpipe emissions of the Toyota Prius (1st generation), Nissan Tino and the Honda Insight. Tailpipe emissions of the latest generation hybrid vehicles were obtained from the UK Vehicle Certification Ageny web site[11].

The Toyota Prius and the Honda Insight are both commercially available in Australia. The Honda Insight[12] with a tare mass of 827 kg is lighter than the Prius and, accordingly, is more fuel efficient. The Insight, however, has only two seats and no boot whereas the Prius is a four seater with a boot.

Figure 6.1 – Toyota Prius hybrid electric car

Figure 6.2 – Honda Insight hybrid electric car,

6.1. Hybrid vehicle life-cycle calculations

The Australian Government helped to fund a project to demonstrate Australian capabilities in automotive design and engineering. The project was to design and build an Australian Concept Car, which was called the aXcessaustralia car. It was launched in February 1998. This first car was a conventionally powered car that displayed the innovation Australian carmakers and component manufacturers can exhibit. Fewchuk et al. (1998) estimated the life-cycle energy consumption of this first Concept Car to be 1396 GJ, accompanied by the emission of 126.5 Gg of CO_2.

The second aXcessaustralia Concept Car (aXcess2, or aXcess LEV) was a low emission vehicle based on a common compact sedan with supercapacitors developed by cap-XX Pty Ltd and CSIRO, novel valve-regulated, lead-acid battery technology, as well as innovative switched-reluctance electric motors. Brief information may be found on the web at www.radial.com.au/axcess2.htm, whereas Lamb (2000a) provides more detailed information.

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[11] http://www.vca.gov.uk/carfueldata/index.shtm

[12] www.mynrma.com.au/motoring/cars/buying_and_selling/new_car/reviews/road_test/honda/hondains.shtml

Parallel with the aXcess2 project, Holden and CSIRO developed a hybrid-electric car that approached the hybrid electric challenge from a different perspective. The Holden hybrid car uses a Holden engine, and a slightly modified Holden Commodore body, to drive a CSIRO electric motor/generator in a parallel hybrid configuration and uses the CSIRO/cap-XX supercapacitor and lead-acid battery technology developed for hybrid cars. This is the first application of hybrid technology in a large car (Sparke 2000; Lamb 2000b).

The results of the Toyota Prius will be taken as providing the representative energy usage for a hybrid car. The Prius has a mass of 1240 kg. On the Japanese 10–15 drive cycle, the Prius has a fuel efficiency of 28 km/L compared with 32 km/L for the Insight. It will, however, be necessary to transform the Japanese data and assumptions to Australian conditions.

Our reverse engineering of the values in Figure 1.4 indicates that the Japanese life-cycle calculations for the Prius are based on an assumed vehicle life of 100,000 km. The Prius uses 120 GJ fuel over its life (depicted as the driving energy consumption). Automotive gasoline has an energy density of 34.2 MJ/L (National Greenhouse Gas Inventory Committee 1996a). Thus 120 GJ corresponds to 3500 L of gasoline. The data on the Prius indicate that its fuel efficiency is 28 km/L. Thus 3500 L enables such a vehicle to travel 98,000 km. Such a vehicle life is very short by Australian standards. In 2002 Australian passenger vehicles drove an average distance of 14,200 kilometres (Australian Bureau of Statistics 2002a). The average age of the passenger vehicle fleet in 2002 was 10.1 years (Australian Bureau of Statistics 2002b) so an assumed vehicle life corresponding to 150,000 km seems more realistic.

6.2. Batteries and supercapacitors

Figure 6.3 – The aXcessaustralia Battery Pack

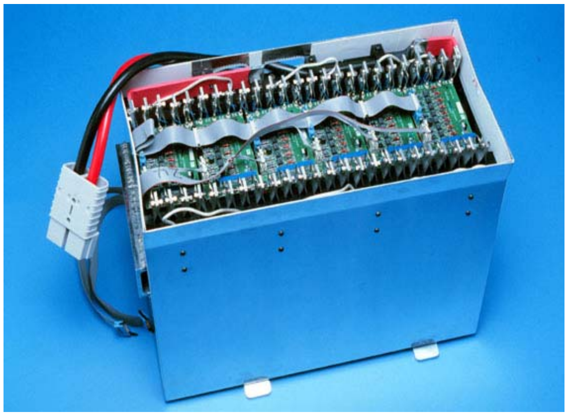

Figure 6.4 – One Half of the Supercapacitor Pack

A typical battery pack (Beer 2000b) has five 12-V batteries. Each battery weighs 11.5 kg. Of this, 7.5 kg is lead, 2.2 kg is lead dioxide, 0.7 kg is sulfuric acid, and 1.1 kg is the case and lids. There is also a small amount of glass wool separator in the batteries but this is minimal in weight and volume. The lead, lead dioxide and sulfuric acid are recyclable. It is estimated that the life of the battery pack is such that 2 packs (i.e. 10 batteries) are needed every 100,000 km. According to information supplied by Tony Vassallo (e-mail dated 5 November 1999 to P. Manins) the supercapacitor pack will weigh approximately 60 kg. The materials in this pack are activated carbon (approximately 7 kg), aluminium foil (approximately 10 kg), electrolyte (approximately 15 kg) of tetraethylammonium tetrafluoroborate in acetonitrile, and a microporous separator. The supercapacitors will be maintenance free, and have a 4000 hour operating life, which should last the life of the car.

In a conventional car, the cost of a battery is approximately 0.5% of the cost of the vehicle. This provides a first order approximation to the likely life-cycle energy involved in the battery. Tony Vassallo (e-mails dated 13 April and 29 May 2000 to T. Beer) estimates that 70 kg of CO_2 is emitted in the manufacture of a conventional 0.7 kWh battery. The HEV batteries are about 0.25 kWh, so that about 27.5 kg of CO_2 is emitted during manufacture. Having a bank of five such batteries will increase the energy requirements compared with a conventional vehicle, but we assume that the life-cycle calculations for the Prius have already taken such factors into account to arrive at the higher energy usage in manufacturing of the Prius compared with a conventional vehicle.

The situation for the supercapacitor (which is not a part of the present generation Prius but is expected to be part of future hybrid vehicles) will be different. The manufacture of aluminium emits substantial quantities of GHG, especially during aluminium smelting when electric currents are used to electrolyse carbon blocks. During this process there are direct emissions of carbon dioxide from the carbon blocks, indirect emissions as a result of the generation of the electricity, and in addition if there are operating problems then quantities of perfluorocarbon will be emitted.

The estimated cost of a supercapacitor pack is about US$1200 when manufactured in volume. This is about 6% of the cost of a VT Commodore Executive. As a first approximation, we will assume that the life-cycle GHG emissions associated with the supercapacitor increase the emissions from the HEV by 6% over a 10-year life, or 0.6% per year

Batteries require equalisation charging once every two weeks to one month. This, however, will require minimal power and will not be a significant power cost (~2–4 kWh per two weeks). The batteries will require a check and clean on a regular basis (once every 6 months to 1 year).

The use of electricity to recharge a battery greatly increases the life-cycle GHG emissions from a hybrid vehicle. The reason for this is that most Australian electricity is produced by burning coal.

Table 6.1 – GHG emissions (kg CO_2-equivalents per kWh) from the use of electricity in various parts of Australia

Location	GHG emissions
Northern Territory	0.69
New South Wales	1.04
Victoria	1.39
Queensland	1.01
South Australia	0.98
Western Australia	1.10
Tasmania	0.06

Source: Sustainable Solutions 1995

Table 6.1 shows the GHG produced for each kilowatt hour of electricity consumed. In Victoria, 1.39 kg of GHG is produced for each kilowatt hour of electricity consumed because Victoria primarily uses brown coal to generate electricity (Sustainable Solutions 1995). In Tasmania, where there is substantial hydro-electric supply of electricity, only 0.06 kg of GHG are emitted for each kilowatt-hour of electricity used.

It is presently unclear how much domestic electricity will be used to recharge and maintain the batteries. Estimates of battery charge rates have ranged from a low of 3 kW to a high of 10 kW (Gates and Westcott 1998). We expect that in most situations the batteries will be recharged during driving. However, even the minimal power involved in battery equalisation is associated with significant GHG emissions. If 4 kW-hour of electricity is used every two weeks to charge the batteries of a vehicle in Victoria, then over a year 143 kg of CO_2 is emitted. This is approximately 8% of the estimated 1.8 tonnes CO_2 that we estimate to be the HEV emissions.

This indicates that electrical charging of batteries may lead to significant GHG emissions, depending on the source of fuel to generate the electricity. Indeed, it raises the specific question: how does electric charging of a battery compare with charging a battery by using petrol while driving a car around?

Table 6.1 gives the GHG emissions per kilowatt hour. To compare this with the use of petrol (by driving a car) for charging a battery, we need to estimate the GHG emissions per unit of energy for automobiles. The National Greenhouse Gas Inventory Committee (1996b) default value for CO_2 emissions is 66 g/MJ, which corresponds to 237.6 g/kWh. The emissions of the other GHG will increase this value, and Sustainable Solutions (1995) estimate it to be 258.9 g CO_2-equivalents/kWh.

However, the values for petrol that have just been quoted refer to the gross calorific value. According to the values quoted by Sparke (2000) only 38% of this energy is available to power the battery. Thus the above emissions, in terms of calorific value, need to be multiplied by 2.63 to estimate the GHG emissions corresponding to battery charging using petrol. This comes to 681 g CO_2-equivalents/kWh.

Comparing this value of 0.68 kg CO_2-e/kWh with the values in Table 6.1, we observe that in most Australian States petrol charging of a battery emits less GHG than electrical charging. The ratios are calculated and depicted in Table 6.2. In Victoria charging an automobile battery using electricity emits 2.04 times the GHG that charging the battery using petrol would emit. By contrast, in Tasmania, which derives much of its electricity from hydro-electricity, electric charging emits less GHG than petrol charging.

Table 6.2 – Ratio of GHG emissions from the use of electricity to the emissions from the use of petrol to charge automobile batteries

Location	**GHG emissions**
Northern Territory	1.01
New South Wales	1.53
Victoria	2.04
Queensland	1.48
South Australia	1.44
Western Australia	1.62
Tasmania	0.09

Even though the electricity industry is undergoing substantial change as a result of electricity reform and the development of a national market with pooled prices, the resulting price volatility does not affect the retail purchaser of electricity. A typical tariff is that of United Energy in Victoria, which charges domestic users 11 c/kWh for the first 1020 kWh, then 12.52 c/kWh. The night rate is 4.47 c/kWh.

Petrol has an energy density of 34.4 MJ/L (National Greenhouse Gas Inventory Committee 1996b) but, as previously indicated, only 38% of this energy is available for charging the battery. Thus each litre of petrol can provide 3.61 kWh to charge the battery. At a typical retail petrol price of 80 c/L, petrol charging of a battery costs about 22.1 c/kWh. This is about double the cost of charging a battery using electricity at the standard domestic tariff, and about five times the cost of using a night tariff.

Because the hybrid electric vehicles use petrol, upstream fuel processing is divided between the full-fuel cycle of the petrol, and the upstream emissions involved in the manufacture of batteries and superconductors. When the emissions from hybrid vehicles are plotted as a function of mass, then the relationship is approximately linear, as depicted in Figure 6.5.

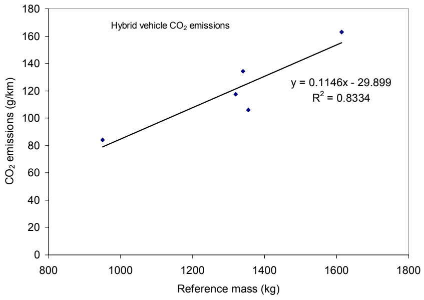

Figure 6.5 – Relationship between GHG emissions from hybrid vehicles and vehicle mass

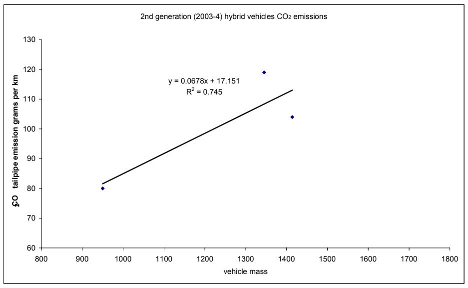

Figure 6.6 – Relationship between GHG emissions from 2nd generation hybrid vehicles and vehicle mass

7. European drive cycle emission results

7.1. Exbodied emission results

This section provides process tree charts, showing the full-fuel cycle for GHG. Instructions on interpreting process trees are given in Appendix D.

7.1.1 Euro 3 vehicles with ULP

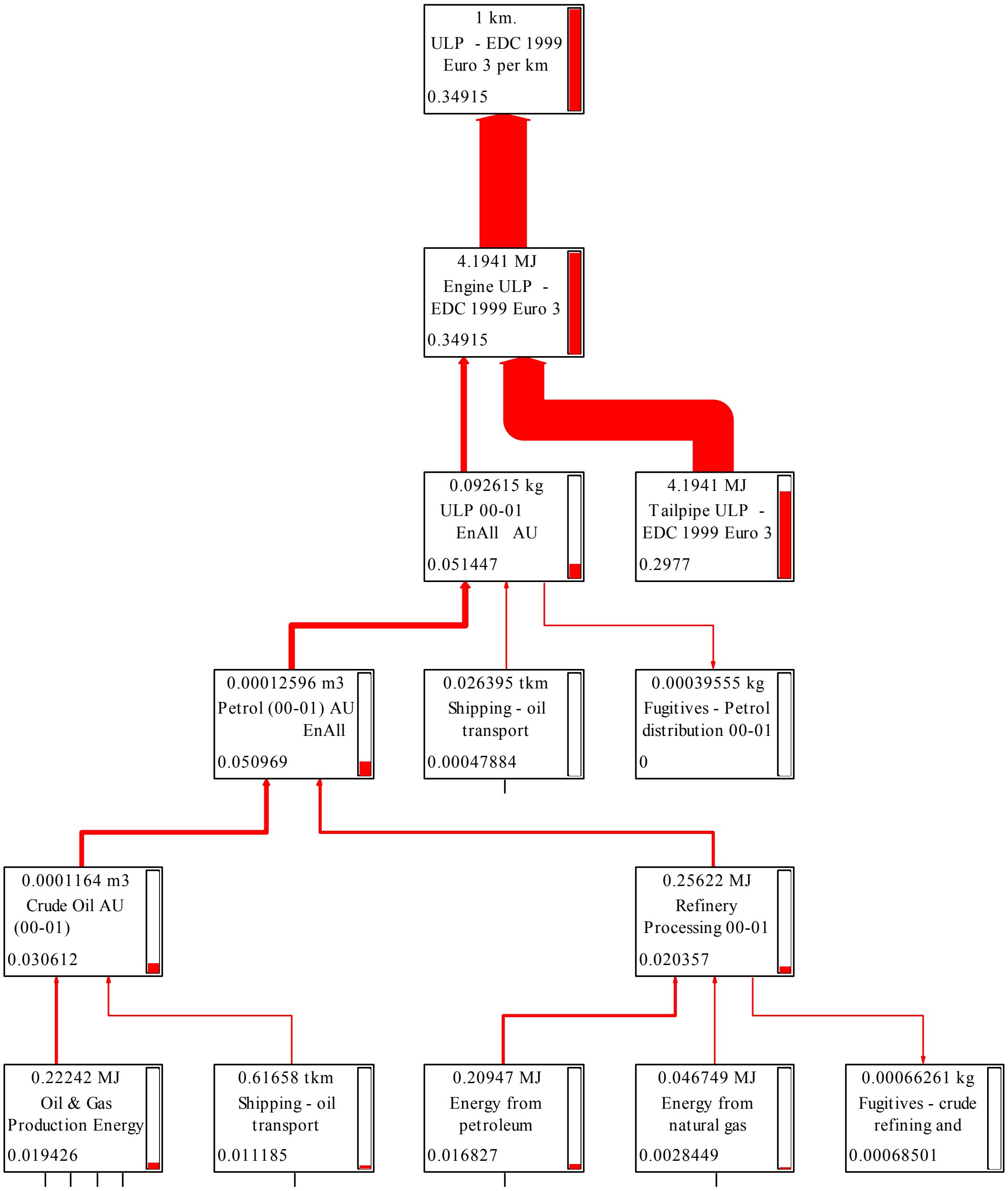

Figure 7.1 – Process tree showing greenhouse emissions from Ford Falcon (ADR 37) on petrol

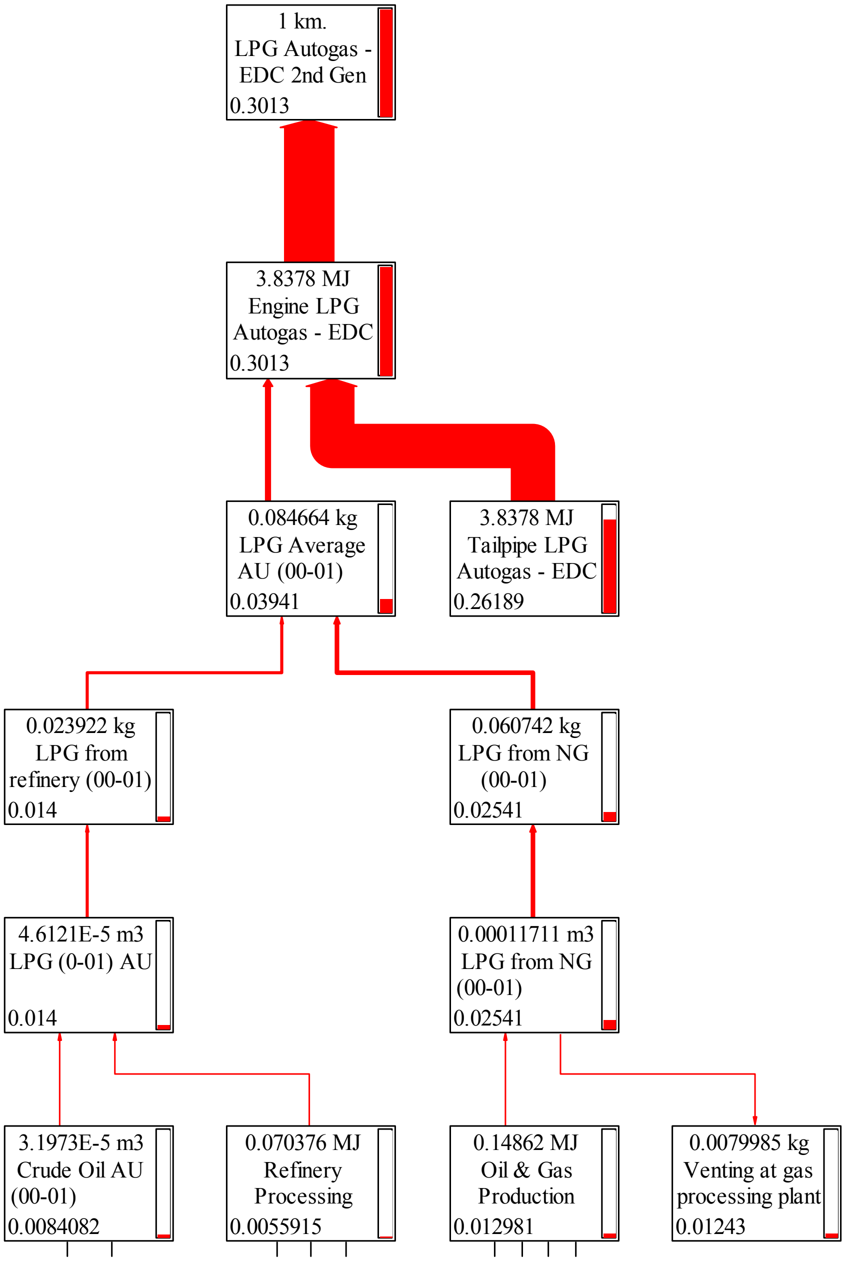

Figure 7.2 – Process tree showing greenhouse emissions from family-sized vehicles with second generation LPG

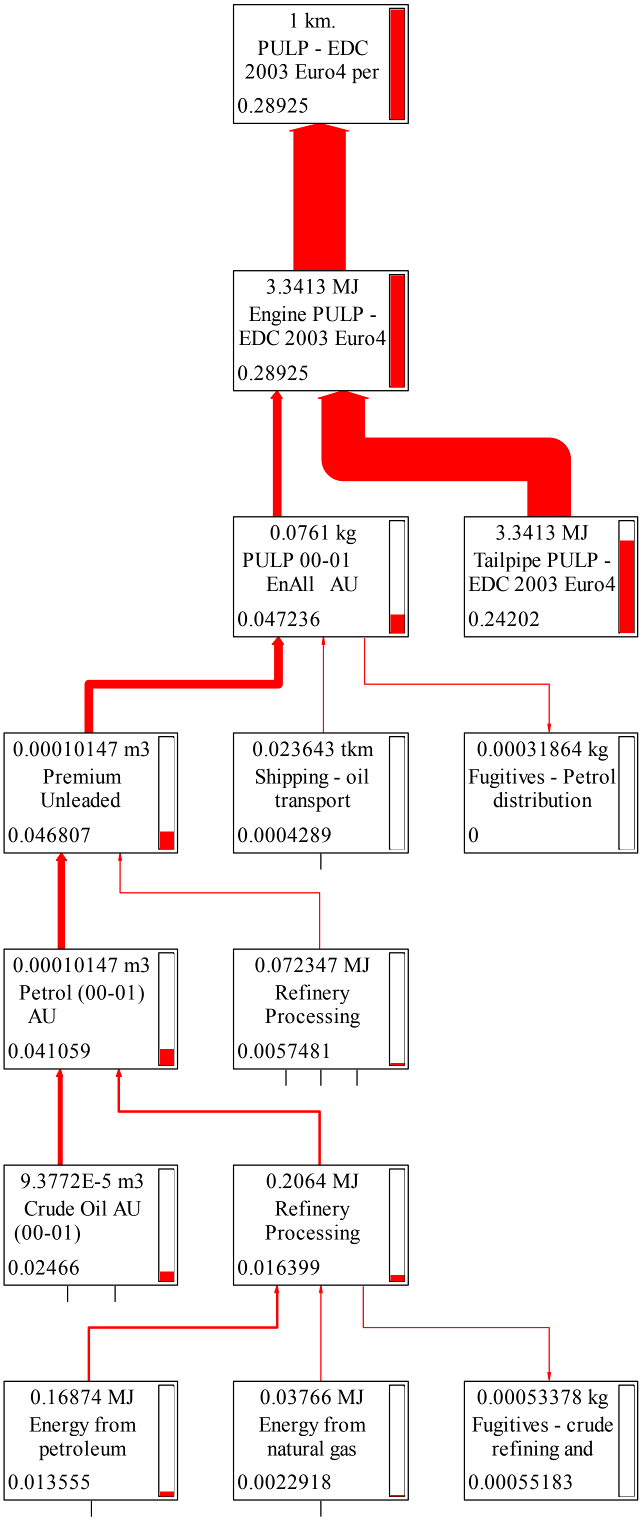

Figure 7.3 – Process tree showing greenhouse emissions from family-sized vehicles with Euro 4 vehicle technology and PULP

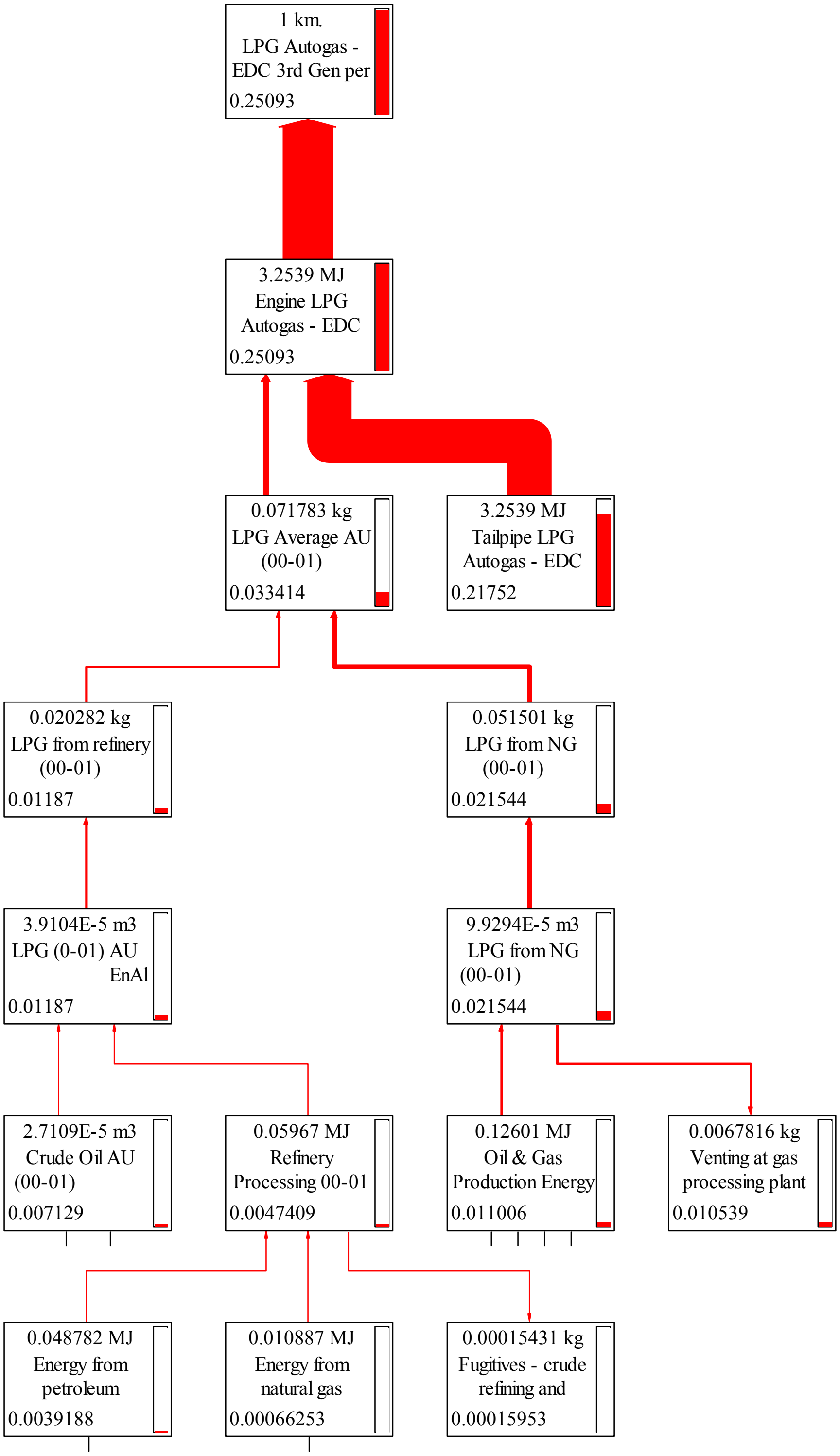

Figure 7.4 – Process tree showing greenhouse emissions from family-sized vehicles with third generation LPG

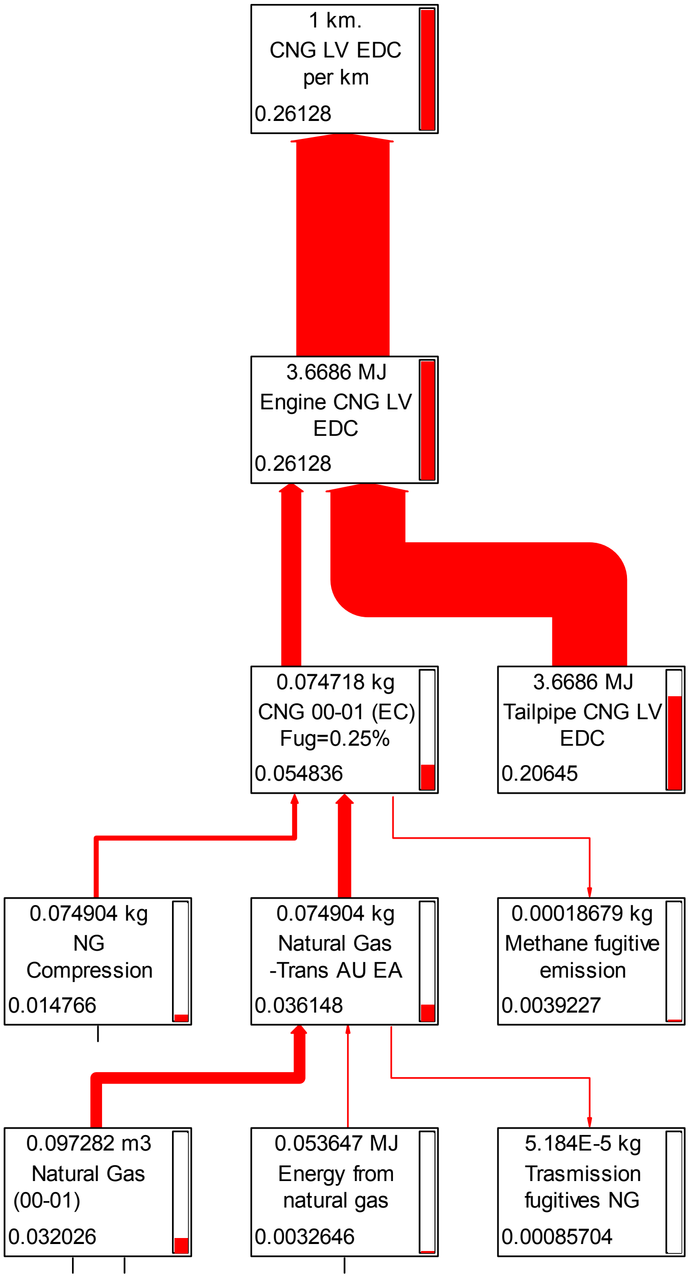

Figure 7.5 – Process tree showing greenhouse emissions from family-sized vehicles with CNG

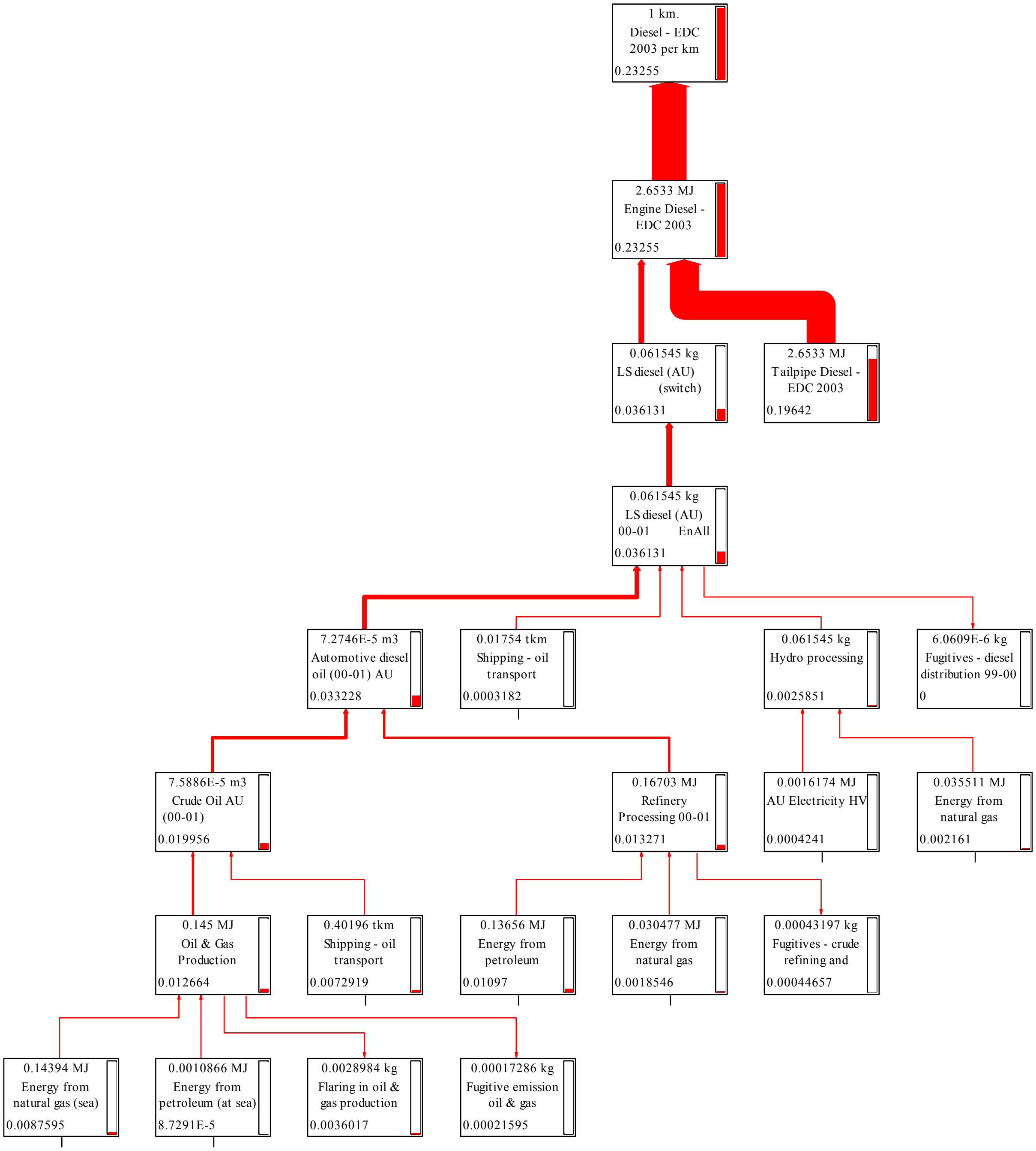

Figure 7.6 – Process tree showing greenhouse emissions from family-sized vehicles with LS diesel

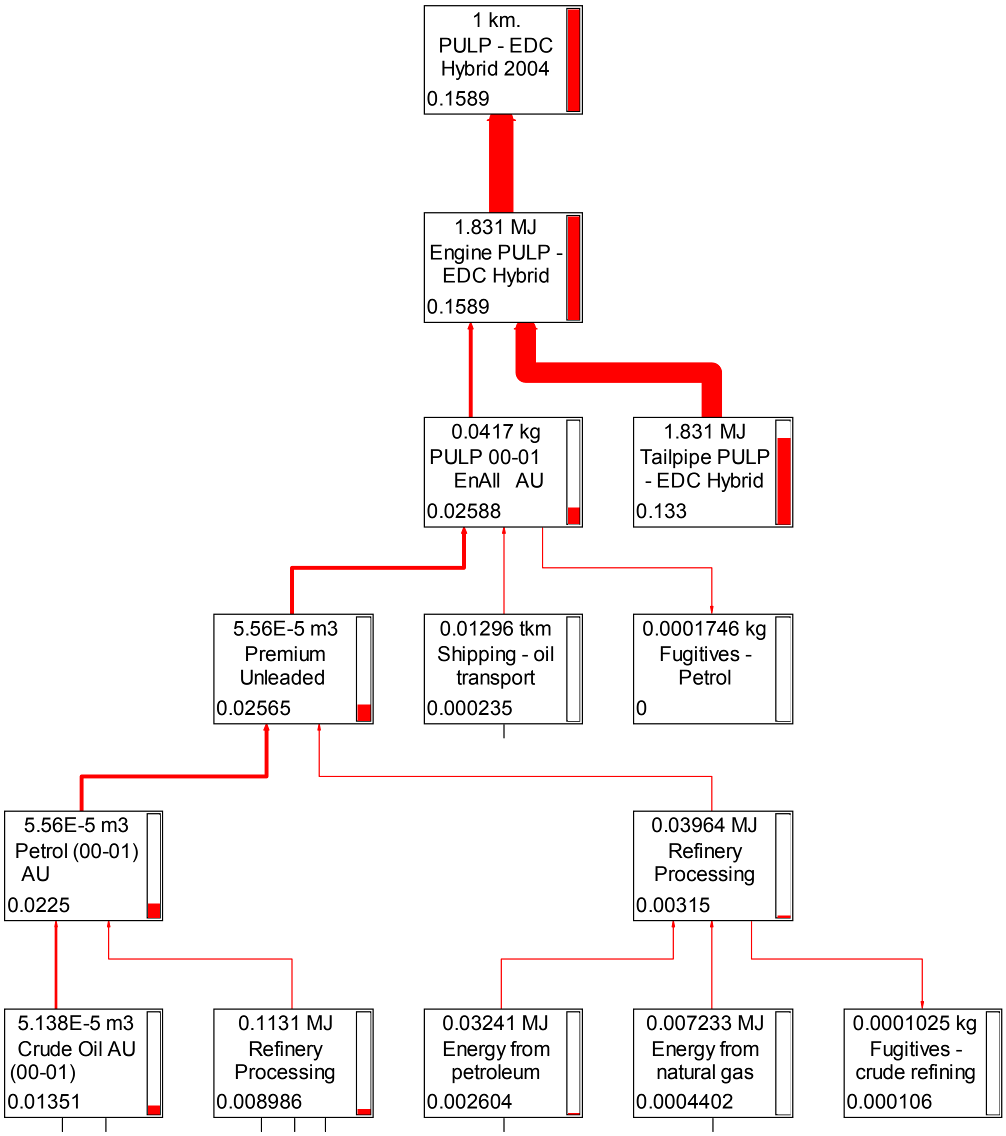

Figure 7.7 – Process tree showing greenhouse emissions from hybrid family-sized vehicles with PULP

7.2. Family-sized Australian car

This section graphs the exbodied emissions from Australian light vehicles. Two classes of vehicles are shown: family-sized vehicles (with a mass of about 1700 kg) and compact vehicles with a mass of about 1000 kg. The data on which these graphs are based is reproduced in Appendix E.

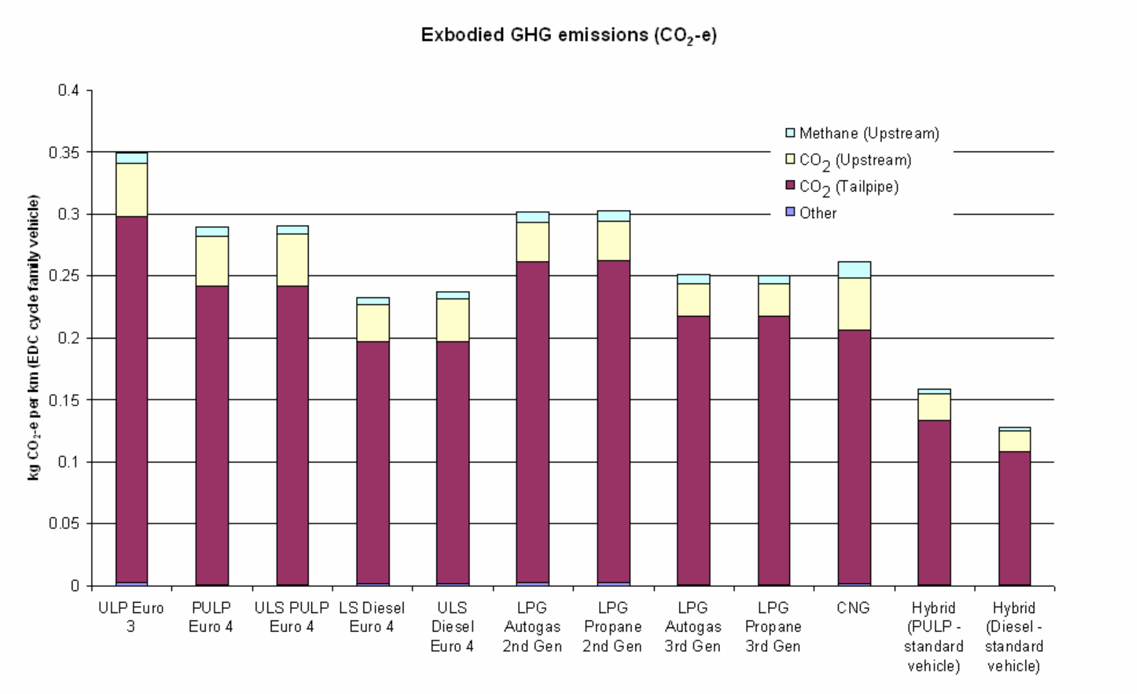

Figure 7.8 – Exbodied greenhouse emissions from family-sized vehicles (European Drive Cycle)

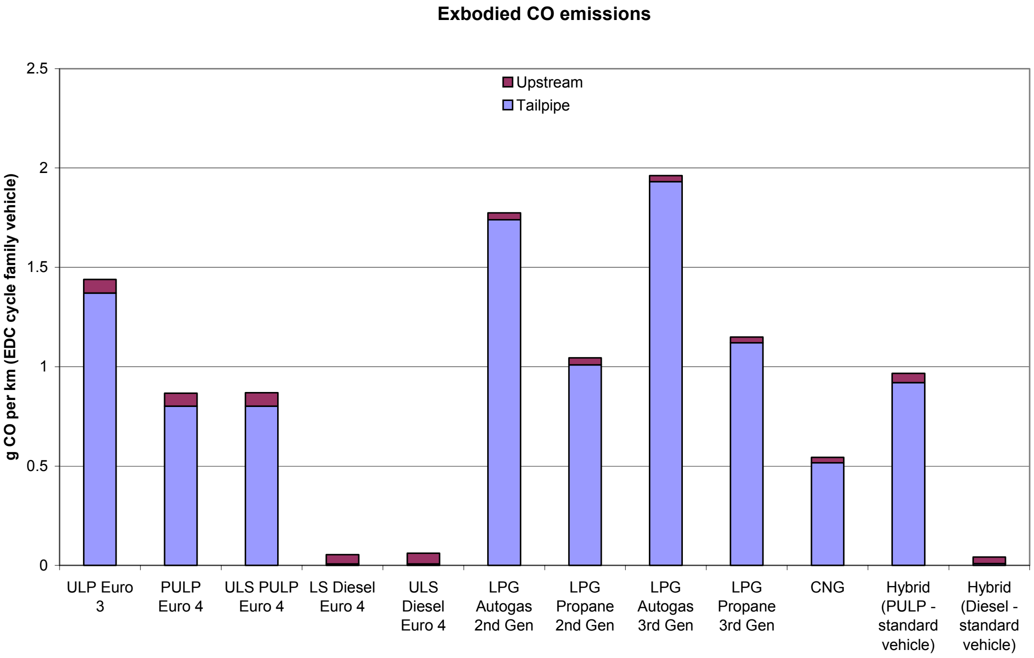

Figure 7.9 – Exbodied carbon monoxide emissions from family-sized vehicles (European Drive Cycle)

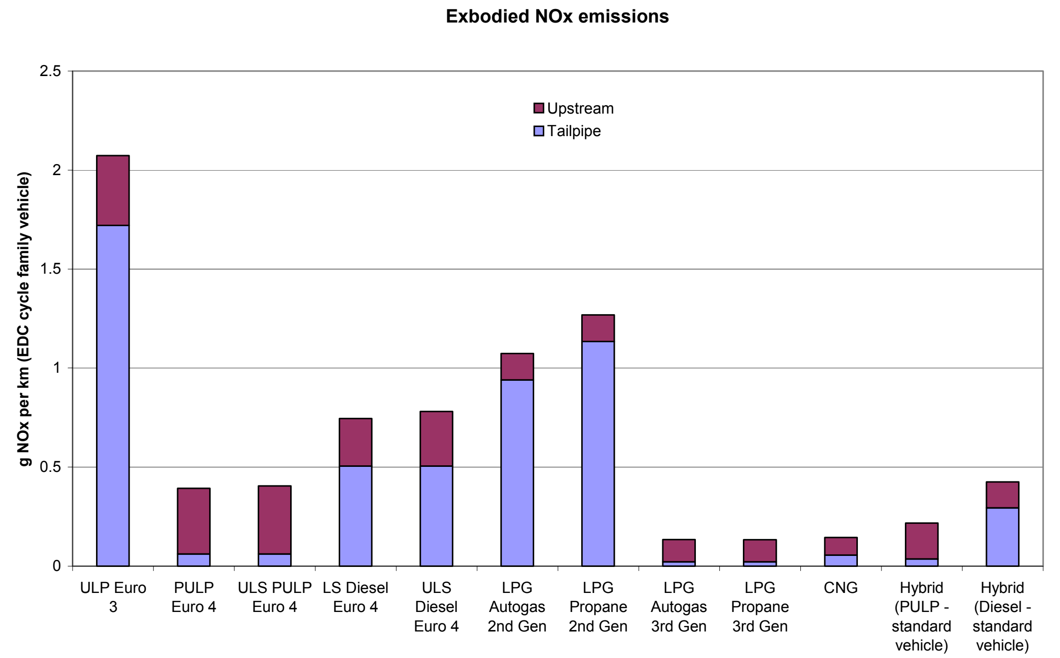

Figure 7.10 – Exbodied NO_x emissions from family-sized vehicles (European Drive Cycle)

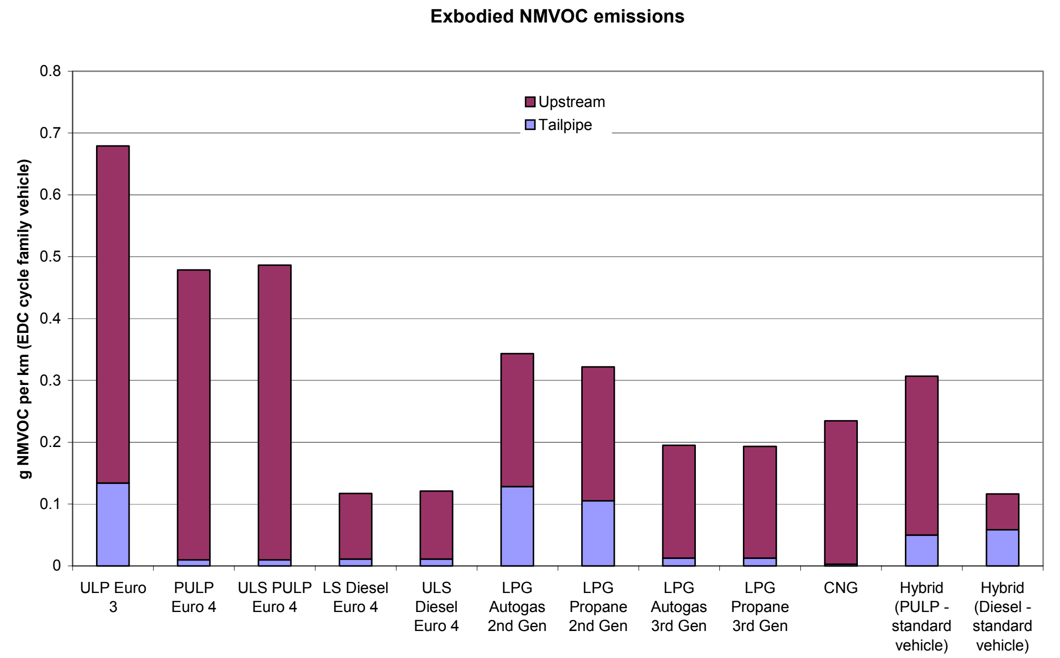

Figure 7.11 – Exbodied hydrocarbon (NMVOC) emissions from family-sized vehicles (European Drive Cycle)

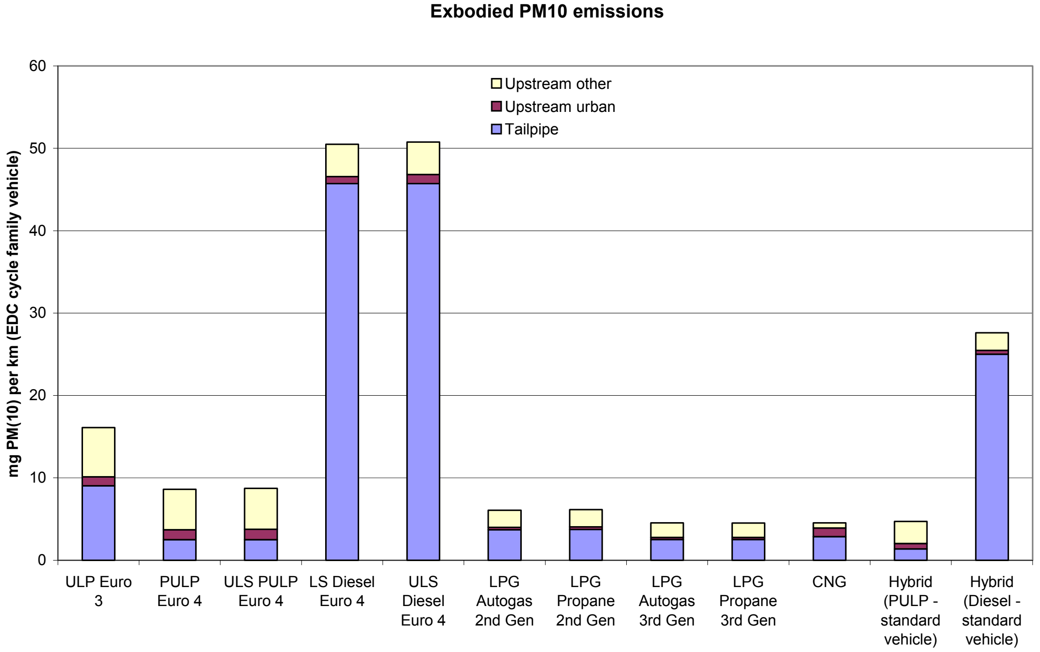

Figure 7.12 – Particle (PM10) emissions from family-sized vehicles (European Drive Cycle)

7.3. Compact-sized Australian car

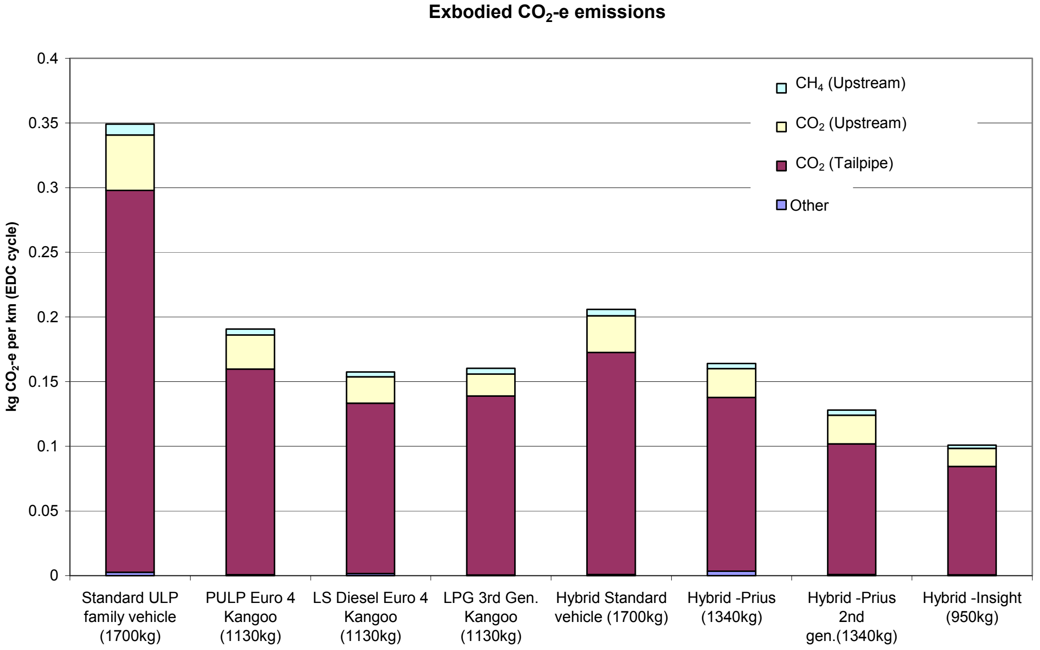

Figure 7.13 – Exbodied greenhouse emissions from compact-sized vehicles (European Drive Cycle)

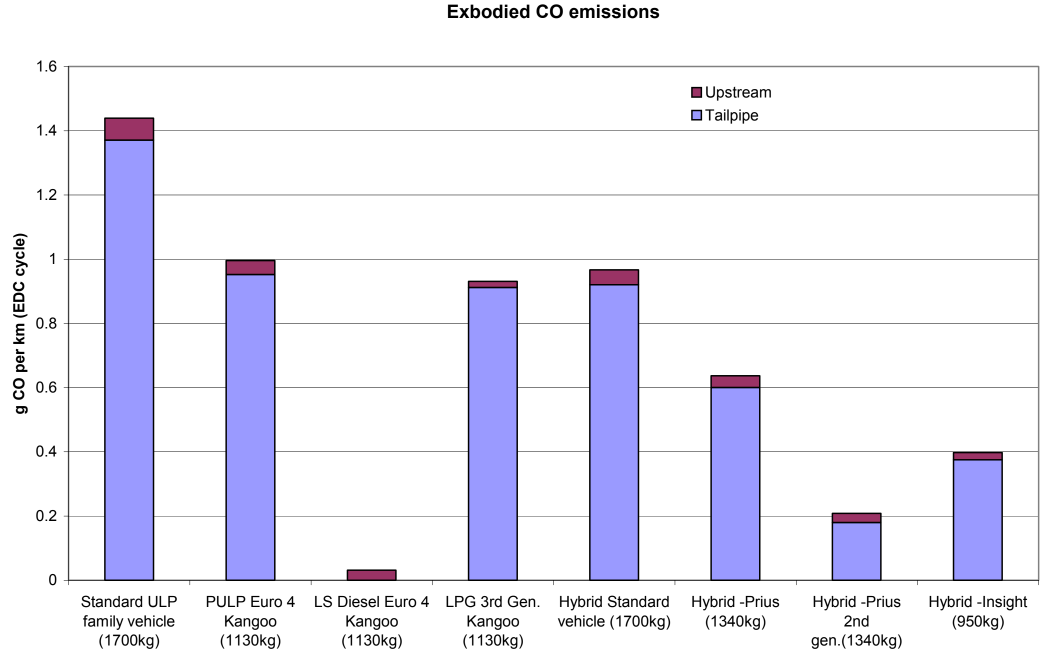

Figure 7.14 – Exbodied carbon monoxide emissions from compact-sized vehicles (European Drive Cycle)

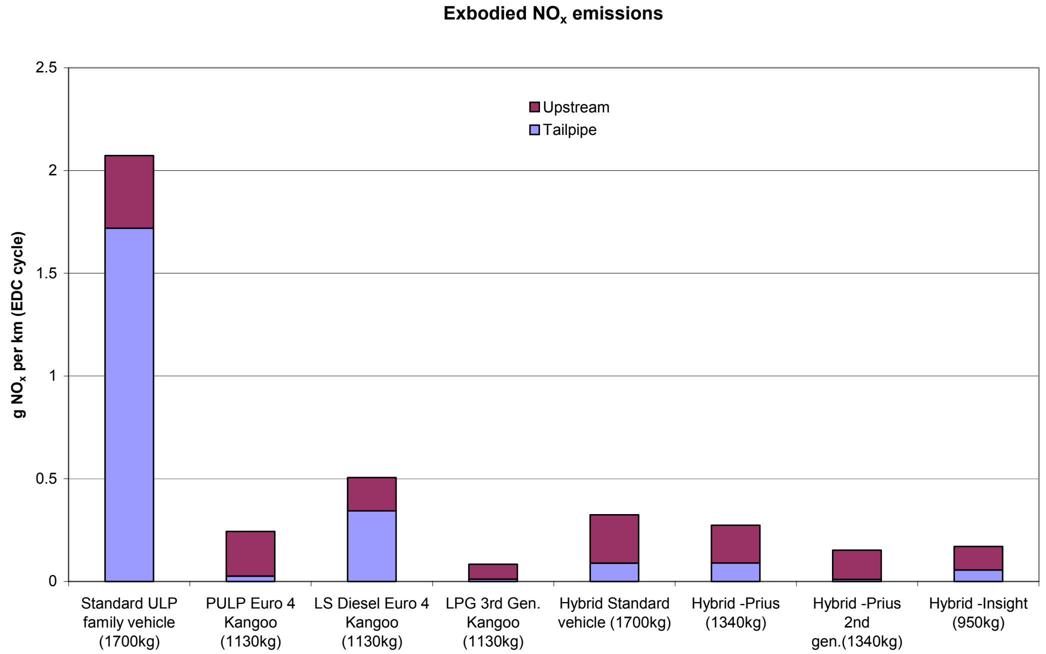

Figure 7.15 – Exbodied NO_x emissions from compact-sized vehicles (European Drive Cycle)

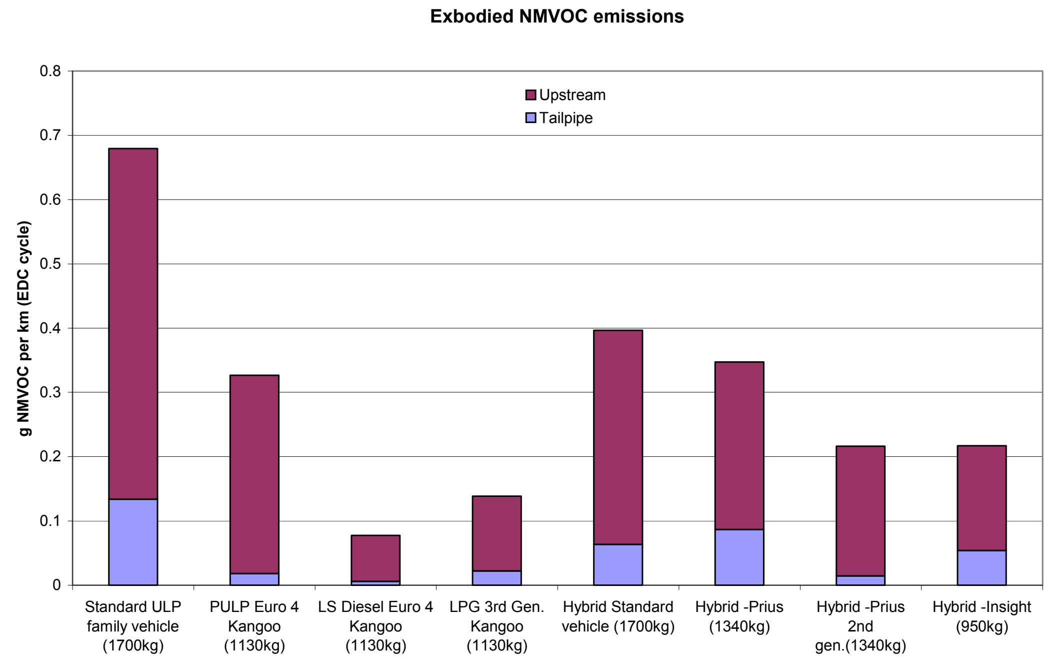

Figure 7.16 – Exbodied hydrocarbon (NMVOC) emissions from compact-sized vehicles (European Drive Cycle)

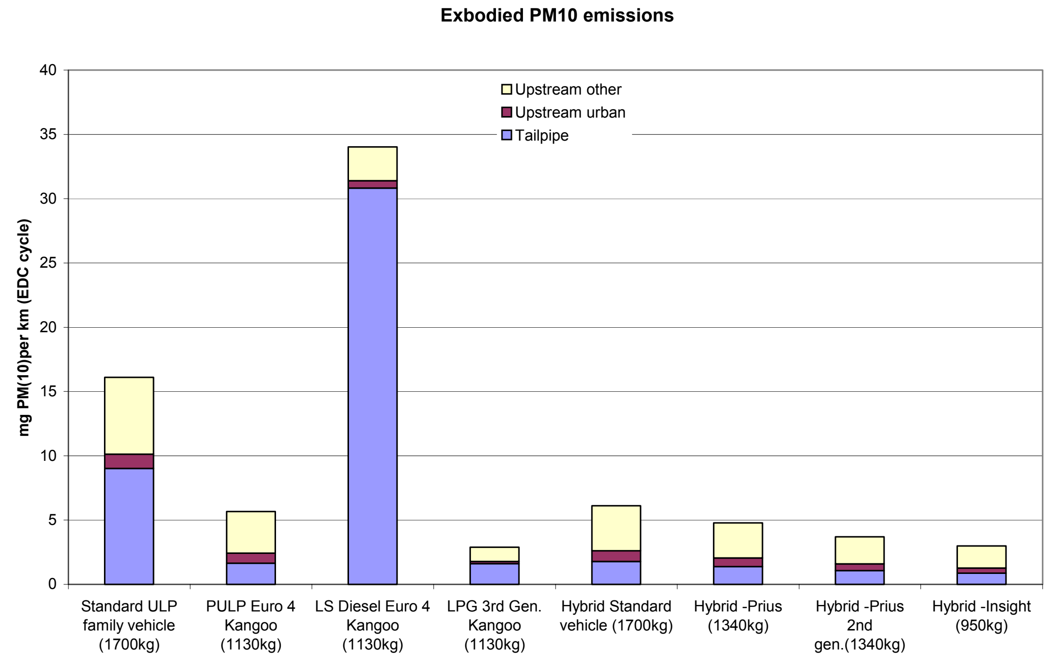

Figure 7.17 – Particle (PM10) emissions from compact-sized vehicles (European Drive Cycle)

7.4. Discussion

This chapter presents the LCA emission results for two sizes of light vehicles fuelled with petrol, diesel, LPG, and CNG. On a full fuel-cycle basis, when vehicles are normalised to remove mass differences, then the lowest GHG emissions are from hybrid electric vehicles. Diesel vehicles emit less exbodied GHG (exbodied emissions are the sum of the pre-combustion emissions and the tailpipe emissions) than petrol, LPG or CNG vehicles, which also means that a diesel–hybrid has lower exbodied GHG emissions than a petrol hybrid. Diesel vehicles also have lower exbodied emissions of carbon monoxide. However, diesel vehicles emit more particulate matter than any other fuel class.

However, these results depend on the drive cycle used to examine the emissions. The above conclusions are based on the European Drive Cycle that is required under ADR 79. Under the Artemis Drive Cycle recently introduced as a test drive cycle in Europe, the tailpipe emissions of CNG are less than those of diesel vehicles, whereas the reverse is the case under the European Drive Cycle (EDC) and the Australian Urban Drive Cycle (AUDC).

Exbodied LPG emissions are below those of the equivalent class of petrol vehicle for all types of fuels (propane, and autogas) and for all emissions except for methane and carbon monoxide. The equivalent class of petrol vehicle means that second generation LPG vehicles are compared with ULP vehicles, whereas third generation LPG vehicles are compared with PULP vehicles.

This finding is different from Anyon (2003), who stated that "current moves towards enhanced emission standards for vehicles (including Euro 3 and Euro 4 standards) still maintain LPG's position as a cleaner fuel than petrol and diesel (even where ultra low sulphur diesel is available)"—p.1 Foreword. Anyon also used data published by Shell (http://www.shellgas.co.uk/site/page/43/lang/en):

LPG compared with ULS Petrol	LPG compared with ULS Diesel
11% to 13% less carbon dioxide	80% to 95% less particulates
15% to 80% less oxides of nitrogen	99% to 99.8% less ultra fine particles
20% to 40% less hydrocarbons	90% to 99% less oxides of nitrogen
30% to 35% less carbon monoxide	

The relatively high GHG emissions from CNG vehicles when compared with diesel, in terms of tailpipe emissions and upstream emissions, appears to arise from a combination of the present maturity of diesel engines, and the present immaturity of CNG engines. EUCAR, CONCAWE and Joint Research Centre of the European Commission (2004) also find that current technology diesel vehicles emit less GHG than CNG vehicles, but estimate a 16% improvement in CNG technology by 2010, compared with only a 2% improvement in diesel engines (with diesel particulate filters).

Present day health concerns are focussed on particulate matter (PM10). LPG (third generation) vehicles have the lowest tailpipe emissions of PM10, but on an exbodied basis the PM10 emissions from LPG and CNG are comparable, and are less than those from diesel, petrol or even hybrid vehicles.

We examined the effect of vehicle mass by examining the exbodied emissions to be expected from a compact-sized vehicle of approximately 1000 kg—compared with the reference family-sized vehicle of 1700 kg mass. The same relativities hold in both cases, but the absolute values of the emissions are much lower for smaller cars. Thus the reference ULP vehicle emits 349 g CO_2-e per km, the equivalent Euro 4 PULP vehicle emits 289 g CO_2-e per km, whereas a petrol hybrid of the same mass emits 206 g CO_2-e per km. However, a compact Euro 4 PULP vehicle of 1130 kg emits 191 g CO_2-e per km, a petrol hybrid such as the 2003 Prius emits 128 g CO_2-e per km, whereas the Honda Insight (with a reference mass of 950 kg) emits only 100 g CO_2-e per km.

The effects of vehicle mass are most marked in the case of fuel consumption and GHG emissions. Emissions of the other criteria pollutants are more dependent on vehicle technologies and emission control systems.

The likely changes in emissions arising from the removal of sulfur from petrol or diesel fuel are contentious. Sulfur-free fuels should enhance the performance of after-treatment technology, with subsequent reductions in all emissions. The following sources have been used in an attempt to estimate the emissions from XLS petrol and XLS diesel (i.e. fuel with less than10 ppm sulfur) for family-sized vehicles (Appendix E). It is important to note that the uncertainties associated with these results are even higher than the uncertainties for emissions from combustion of petrol and diesel with higher levels of S.

MVEC (2003) states that fuel efficiency benefits of 2% (diesel) and 3% (petrol) are associated with sulfur reductions from 50 ppm to 10 ppm; they are linked to the NO_x storage traps (p.40). A 5% reduction in PM for pre-Euro 4 diesel vehicles (p. 37) is also indicated. A UK document published in 2000 suggests that the overall impact on CO_2 emissions from XLS petrol and XLS diesel fuel "could range from being neutral to a small net increase, depending on the assumptions made on future vehicle fuel economy trends and the projected refinery impacts" (p.1)[13]. The same report indicates that reductions in EU fleet emissions of CO, NO_x, and NMVOC due to XLS petrol are 37%, 47%, and 23% respectively compared with only minor benefits for ULS (30 ppm sulfur) fuels (e.g. catalyst efficiency improves by only 15% with 30 ppm sulfur petrol, but by 79% with 8 ppm sulfur petrol). Numerous vehicle manufacturers continue to demonstrate the inadequacy of ULS fuels for lean-burn engines and associated new control devices. Volkswagen, for example, recently completed a test program that showed the conversion efficiency of NO_x storage catalytic converters used with a SIDI (i.e. a direct injection gasoline) engine declined after only 8,000 km from about 85% to less than 50%[14]. DaimlerChrysler tests confirmed as well that conversion efficiency dropped to less than 30% in 7,000 km for the fuel containing 50 ppm sulfur; the 8 ppm sulfur fuel showed some deterioration, but much less than the 50 ppm fuel.

It seems clear that without XLS, the fuel economy potential of gasoline DI engines will not be realised. A news item at http://www.aaireland.ie/news/article.asp?news_Id=287 states that fuel efficiency of Europe's cars will increase by about 5% each year from the introduction of sulfur-free fuels.

A different opinion is found in the study by CONCAWE (2003: p. iv): *"The advanced European vehicles tested showed very little short-term sensitivity to sulphur… The main driver for lower sulphur fuels remains to enable the introduction of advanced exhaust catalyst systems, including regenerative NOx storage systems, while maintaining best fuel*

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[13] http://www.aeat-env.com/Sulphur_Review/Downloads/sr-UKDETR2.doc

[14] http://www.aeat-env.com/Sulphur_Review/Downloads/sr-Ford.pdf, p.24

consumption, CO_2 emissions and long-term durability. Reductions in sulphur level from 150 to 10 mg/kg seem unlikely to bring substantial emissions benefits for current Euro-3 & 4 vehicle technologies"

Numerous data gaps were revealed during this study. There was:

- insufficient particulate matter emissions data for LPG vehicles. We draw conclusions about PM10 particulate emissions on the basis of steady-state constant speed testing
- insufficient emissions data for CNG vehicles. Our results are based on one data set from a Volvo V70
- insufficient air toxics emissions data for us to determine the effects of different fuel types on air toxics emissions
- no data on the emissions of criteria pollutants or air toxics from the latest generation of hybrid vehicles. The tailpipe emissions refer to the first generation Toyota Prius. As a result, the tailpipe emissions for the family-sized car appear high when compared to Euro 4 petrol vehicles. Publicity material from Toyota[15] claims that tailpipe emissions of the new 2003 Prius are the same as, or lower than, the SOx, NOx, and HC pollutant emissions from an equivalent petrol vehicle. This material also claims that exbodied emissions of SOx, NOx, and HC are all lower for the Prius than for an equivalent Japanese petrol vehicle, whereas exbodied emissions of PM are larger.
- no data on the performance of dedicated LPG vehicles. All of the LPG emissions data that we were able to obtain related to dual-fuel[16] vehicles
- no test data to examine the differences (if any) in tailpipe emissions from direct injection light vehicles as a result of the sulfur content of petrol (i.e. 50 ppm, 10 ppm). Results showing that sulfur-free fuels enhance the performance vehicle technologies designed to use them, thus reducing all emissions. A summary is provided in section 7.4.

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[15] www.toyot.co.jp/en/k_forum/tenji/pdf/pgr_e.pdf

[16] Dual-fuel vehicles (in Australian terminology) are known as bi-fuel vehicles in the UK.

8. References

Anyon, P. (1998) Liquefied Petroleum Gas as an Automotive Fuel—an environmental and technical perspective, Australian Liquefied Petroleum Gas Association (ALPGA), Sydney.

Anyon, P. (2002) Liquefied Petroleum Gas as an Automotive Fuel (2nd edition)—an environmental and technical perspective, Australian Liquefied Petroleum Gas Association (ALPGA), Sydney, available at http://www.alpga.asn.au/infonet/publications.asp.

Anyon, P. (2003) LPG—The Clean Transport Alternative: Presenting the Environmental Case, Report commissioned by the Australian Liquefied Petroleum Gas Association (ALPGA), Sydney, September, available at http://www.alpga.asn.au/documents/Paper%203%20-%20LPG%20-%20The%20Clean%20Transport%20Alternative.pdf.

Arcoumanis, C. (2000) A technical study on fuels technology related to the Auto-Oil II Programme, (Volume II: Alternative Fuels) Final Report prepared for the European Commission Director-General for Energy.

Australian Bureau of Statistics (1995) *Motor Vehicle Census Australia*, Catalogue No. 9309.0, Australian Bureau of Statistics, Belconnen, ACT.

Australian Bureau of Statistics (1997) *Motor Vehicles in Australia*, Catalogue No. 9311.0, Australian Bureau of Statistics, Belconnen, ACT.

Australian Bureau of Statistics (2002a) *Survey of Motor Vehicle Use Australia*, Catalogue No. 9208.0, Australian Bureau of Statistics, Belconnen, ACT.

Australian Bureau of Statistics (2002b) *Motor Vehicle Census Australia*, Catalogue No. 9309.0, Australian Bureau of Statistics, Belconnen, ACT.

Australian Bureau of Statistics (2003) *Motor Vehicle Census Australia*, Catalogue No. 9309.0, Australian Bureau of Statistics, Belconnen, ACT, http://www.abs.gov.au/Ausstats/abs@.nsf/lookupMF/06D0E28CD6E66B8ACA2568A900139408.

Australian Greenhouse Office (2002) AGO – GGAP Round Two Default Values for Transport, http://www.greenhouse.gov.au/ggap/internet/transval.html (accessed 15/04/03).

Australian Institute of Petroleum (1997*) Australian Oil Industry*. Melbourne, Australian Institute of Petroleum.

Beer, T. (1995) The predicted impact of revised Australian car design rules on Melbourne air quality trends, *Math. Comput. Modelling, 21*, 99–103.

Beer, T. (2000) *Hybrid Electric Vehicle Greenhouse Gas and Life Cycle Issues*, CSIRO Atmospheric Research Report HEVF5, Aspendale, Vic.

Beer (2000b) Life-Cycle Assessment Of Greenhouse Gas Emissions From Road Transport, *Proceedings 15th International Clean Air & Environment Conference*, 26–30 November 2000, Sydney, Australia, pages 19–23. Clean Air Society of Australia & New Zealand, Mitcham, Vic.

Beer, T., Grant, T., Brown, R., Edwards, J., Nelson, P., Watson, H., and Williams, D. (2000*) Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles*, Stage 1. Report C/0411/1.1/F2 to the Australian Greenhouse Office. CSIRO Atmospheric Research, Aspendale, Victoria, available at http://www.greenhouse.gov.au/transport/publications/pubs/lifecycle.pdf.

Beer, T., Grant, T., Morgan, G., Lapszewicz, J., Anyon, P., Edwards, J., Nelson, P., Watson, H., and Williams, D. (2001) *Comparison of transport fuels: final report (EV45A/2/F3C) to the Australian Greenhouse Office on the Stage 2 study of Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles*. CSIRO Atmospheric Research, Aspendale, Victoria, available at http://www.greenhouse.gov.au/transport/comparison/.

Beer, T., Grant, T., Brown, R., Edwards, J., Nelson, P., Watson, H., and Williams, D. (2002) Full Fuel-cycle Greenhouse Gas Emissions from Alternative Fuels in Australian Heavy Vehicles, *Atmospheric Environment*, *36*, 753–763.

Beer, T., Grant, T., Olaru, D., and Watson, H. (2003) *Shell Aquadiesel Study*, Report to the Australian Greenhouse Office.

Brown, S., Kadayifci, M. and Faber, M. (1997) *Motor vehicle pollution in Australia*, Supplementary Report No. 1—LPG in-service vehicle emissions study, Report to Environment Australia & Federal Office of Road Safety, NSW Environment Protection Authority.

BTCE (1994*) Alternative fuels in Australian transport*, (Information paper 39) AGPS, Canberra ACT.

Carlsson, F., Jahansson-Stenman, O. (2000) *The costs and benefits of electric vehicles*, KFB Report 2000:46, KFB, Stockholm, Sweden.

CEC, (1999), "*Supply and Cost of Alternatives to MTBE in Gasoline*", Staff Report P300-98-013, California Energy Commission, California, February 1999, http://www.energy.ca.gov/mtbe/documents/300-98-013.html.

Coffey Geosciences Pty Ltd (2000*). Review of Fuel Quality Requirements for Australian Transport*. Canberra, Environment Australia.

Coffey Geosciences Pty Ltd (2003). *Report on Fuel Quality and Vehicle Emissions Standards Cost Benefit Analysis*, Department of Environment and Heritage.

CONCAWE (2003) Fuel Effects on Emissions from Modern Gasoline Vehicles. Part 1- Sulphur effects, Report 5/03 prepared by Fuels Quality and Emissions Management Group by its FE/Special Task Force 20, available at http://www.concawe.be/Content/Default.asp?PageID=31.

CONCAWE (2004) Fuel Effects on Emissions from Modern Gasoline Vehicles. Part 2—Aromatics, Olefins, and Volatility Effects, Report 2/04 prepared by Fuels Quality and Emissions Management Group by its FE/Special Task Force 20, available at http://www.concawe.be/Content/Default.asp?PageID=31.

CSIRO, BTRE and ABARE (2003) *Appropriateness of a 350 Million Litre Biofuels Target*, Report to the Australian Government Department of Industry, Tourism and Resources, Canberra, available at http://www.btre.gov.au/urbanpullutants_draft.htm.

Department of Transport and Regional Services (2001) *Comparative Vehicle Emissions Study*, Department of Transport and Regional Services, Canberra, ACT, available at http://www.dotrs.gov.au/land/environment/index.htm.

DSA (2000), "*Octane Enhancing Petrol Additives/Products: Literature Review and Analysis*", Report prepared for Environment Australia, Duncan Seddon and Associates Pty Ltd, Victoria, September.

Ekvall, T. (2002*) Limitations of Consequential LCA*. International Conference on Life Cycle Assessment and Life Cycle Management, Internet.

EUCAR, CONCAWE and Joint Research Centre of the European Commission (2004) *Well to Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context* http://ies.jrc.cec.eu.int/Download/eh/31.

Expert Reference Group (Western Australia) (1998) *Euro 2 and beyond: fuel for Transperth's bus fleet*, Perth, WA: The Group.

Faiz, A., Weaver, C. and M.P. Walsh (1996) *Air Pollution from Motor Vehicles—Standards and techniques for controlling emissions*, World Bank, Washington DC.

Federal Office of Road Safety (1997) *Motor Vehicle Pollution in Australia—LPG In-Service Vehicle Emissions Study*, Report by the Environment Protection Authority of Victoria for the Federal Office of Road Safety (FORS) and Environment Australia, November 1997.

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

Gates, D. & M. Westcott (1998) *Cost calculations for the HEV with battery life included*, Report No. CMIS 98/171, CSIRO Mathematical and Information Sciences, Canberra, ACT.

General Motors Corporation, Argonne National Laboratory et al. (2001). *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems—North American Analysis* http://www.transportation.anl.gov/ttrdc/publications/index.html.

GM-LBST Study (2002), *Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuels/Vehicle Systems—A European Study*, http://www.lbst.de/gm-wtw.

Graedel, T..E. and Allenby, B.R. (1995) *Industrial Ecology*, Prentice Hall: Englewood Cliffs, NJ.

Greenfleet (1999) See: http://www.greenfleet.com.au/Html/greenfleet.html.

International Standards Organisation (1997) ISO 14040 Environmental Management Standard-Life Cycle Assessment, Principles and Framework, Sydney, Australian Standards—Published as AS 14040: 1998.

IPCC (2001) Climate Change 2001: the scientific basis, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Kadam, K.L., Camobreco, V.J., Glazebrook, B.E., Forrest, L.H., Jacobson, W.A., Simeroth, D.C., Blackburn, W.J., and Nehota, K.C. (1999) Environmental life-cycle implications of fuel oxygenate production from California biomass, technical report NREL/TP-580-25688, Golden.

Keoleian, G. A. et al. (1997) *Industrial Ecology of the Automobile—A Life-Cycle Perspective*, Society of Automotive Engineers, Inc, Warrendale, PA, USA.

Kobayashi, O. (1996) *Automobile LCA Study*, in: Proceedings of the Second International Conference on EcoBalance, November 1996, Tuskubla, Japan.

Kuhndt, M. & B. Bilitewski (1999) *Towards reduced environmental burden of mobility: improving the automobile life cycle,* CHAINET Case Study Report 2nd draft—available as at March 2004 at: http://www.leidenuniv.nl/interfac/cml/ssp/projects/chainet/drftcar2.pdf.

Lamb, D. (2000a) *The aXcessaustralia Hybrid Electric Car Project*, Paper presented to the FISITA World Automotive Congress, June 2000, Seoul, Korea.

Lamb, D. (2000b) *Powering the Car of the Future—Emerging Automotive Technologies*, Paper presented at the Holden Hybrid Technology Seminar, 30 March 2000, Melbourne, Australia.

Le Cornu, J.K. (1990) *Greenhouse gas emissions from the production and use of alternative transport fuels,* in Swaine, D. J. "Greenhouse and Energy", pp. 293–303, CSIRO Publishing, East Melbourne.

LP Gas Association (2003*) LPG: A bridge to the future*, http://www.lpga.co.uk/ai_mem/secure/pdf/Road%20Fuel%20Gases%20Consultation%20Response.pdf.

Manins, P., Allan, R., Beer, T., Fraser, P., Holper, P., Suppiah, R. and K. Walsh (2001) *Atmosphere—Australia State of the Environment Report 2001* (Theme Report) CSIRO Publishing on behalf of the Department of the Environment and Heritage, Canberra.

Marsh, G., Hill, N., Sully, J. (2000) Consultation on the Need to Reduce the Sulphur Content of Petrol and Diesel Fuels Below 50 ppm: A Policy Makers Summary, Report produced for the European Commission, DG Environment, Restricted Commercial, AEAT/ENV/R/0372 Issue 5.

Ministry of Transport (New Zealand) (1998) *Vehicle Emissions Testing Programmes: Stage 1 Petrol Vehicles—Stage 2 Diesel Vehicles*, Report, Ministry of Transport, New Zealand.

MVEC (2003) *Draft Regulation Impact Statement for Vehicle Emissions and Fuel Quality Standards for Post 2006*, Report by Vehicle Emissions and Fuel Standards Review Working Group on behalf of the Motor Vehicle Environment Committee, Canberra, ACT.

National Greenhouse Gas Inventory Committee (1996a) *AUSTRALIA-National Greenhouse Gas Inventory 1988 to 1994—Based on Revision 1 Workbooks* (6 volumes), Department of the Environment, Sport and Territories, Australia.

National Greenhouse Gas Inventory Committee (1996b) *Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks, Workbook for Transport (Mobile Sources), Workbook 3.1 (Revision 1)*, Department of the Environment, Sport and Territories, Australia. available as at March 2004 at http://www.greenhouse.gov.au/inventory/methodology/transport.html

National Greenhouse Gas Inventory Committee (1997) *AUSTRALIA-National Greenhouse Gas Inventory 1995 with methodology supplement*, Environment Australia.

National Greenhouse Gas Inventory Committee (1998a) *National Greenhouse Gas Inventory 1996 with Methodology Supplements*, Australian Greenhouse Office, Canberra.

National Greenhouse Gas Inventory Committee (1998b) *Australian methodology for the Estimation of Greenhouse Gas Emissions and Sinks (8 workbooks)*, Australian Greenhouse Office, Canberra. Available as at March 2004 at: http://www.greenhouse.gov.au/inventory/methodology/

National Greenhouse Gas Inventory Committee (2002) *National Greenhouse Gas Inventory 2000 with Methodology Supplements*, Australian Greenhouse Office, Canberra.

National Greenhouse Gas Inventory Committee (2003) *National Greenhouse Gas Inventory 2001 with Methodology Supplements*, Australian Greenhouse Office, Canberra.

National Greenhouse Gas Inventory 2002 (2004) *National Greenhouse Gas Inventory 2002*, Australian Greenhouse Office, Canberra, available as at 12 April 2004 at: http://www.greenhouse.gov.au/inventory/2002/pubs/inventory2002parta.pdf.

Nylund, N.O. and Lawson, A. (2000) *Exhaust emissions from natural gas vehicles*, Report prepared for the IANGV Technical Committee, www.iangv.org/html/sources/sources/reports/IANGV REP part 1 final.pdf.

Peters, T. (1996): *Environmental Awareness in Car Design*, in: Design for Environmentally Safe Automotive Products and Processes, Society of Automotive Engineers, USA.

Royal Automobile Club of Queensland (1999) *Car Reviews* at: http://www.racq.com.au/03_car/reviews_new/holden_vtcommodore_98.htm.

Ristovski, Z.D., Jayaratne, E.R., Lim, M. Ayoko, G.A., Morawska, L., Christensen, E. and G. King (2002) *Comparison of emissions from a selection of passenger vehicles operating on unleaded* *petrol and LPG fuel*, Proc. 16th Clean Air and Environment Conference, Christchurch, 659–664.

Schweimer, G.W and Schuckert, M. (1996) *Sachbilanz eines Golf*, Sonderdruck, Volkwagen AG, Wolfsburg, Germany.

Sparke, L. (2000) *Holden Hybrid Technology*, Paper presented at the Holden Hybrid Technology Seminar, 30 March 2000, Melbourne, Australia.

Sustainable Solutions Pty Ltd (1995) *Australian Home Greenhouse Scorecard*, Environment Protection Authority, Victoria.

Toyota Motor Corporation (1998) *Environmental Report 1998*, Toyota Motor Corporation, Japan.

Trigui, R. et al. (2003) Hybrid Light Duty Vehicles Evaluation Program*, Int. J. Automotive Tech.*, 4 (2), 65–75.

Van Walwijk, M., Bückmann, M., Troelstra, W.P. and Achten, P.A.J. (1996) *Automotive fuels survey Part 2: Distribution and Use*, IEA/AFIS, Netherlands.

Wang, M. (2002) *Greenhouse gas emissions from LP Gas vehicles and appliances: a comparison analysis with other energies*, World LP Gas Association, Paris.

Watson, H. and D.R.R. Gowdie (2000) *The systematic evaluation of twelve LP Gas fuels for emissions and fuel consumption,* SAE 2000-01-1867.

Watson, R.T., Zinyowera, M.C., and Moss, R.H. (1996) *Climate Change 1995* (Contributions of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change), Cambridge University Press, Cambridge.

Weeks, I.A., Galbally, I.E., Ye, Y. and G. Huang (1996) Greenhouse gas emissions from motor vehicles in Australia, *Proc. 13th Clean Air and Environment Conference*, Adelaide, 437–442.

Weidema, B.P. (1999) Systems expansions to handle co-products of renewable materials. Presentation Summaries of the 7th LCA Case Studies Symposium, SETAC-Europe.

Wilkenfeld, G. and Associates (1991) *Greenhouse gas emissions from the Australian energy system: the impact of energy efficiency and substitution.* George Wilkenfeld and Associates with Energetics and Enersonics, for Energy Research and Development Corporation, Canberra, February 1991 (ERDC 22).

Zemansky, M. W. (1957) *Heat and Thermodynamics*, 4th ed., McGraw-Hill, New York.

Zito, R. and Marquez, L. (2002) Assessing impacts of GHG abatement measures on urban freight emissions, *Proc. 24th Conference on Australian Institutes of Transport Research,* Sydney, NSW.

Appendix A. Terms of Reference

A.1 Full-fuel cycle analysis

1. Identify and collect for the specified fuels existing information on emissions from their production and combustion in on-road vehicles up to 3.5 tonnes GVM taking into account:
    1.1 Australian conditions for fuel production
    1.2 impact of vehicle technology for combustion emissions.
2. Critically review and consolidate collected information in the context of the specified combinations of fuels and motor vehicle technologies.
3. Objectively assess the emission characteristics of the specified combinations of fuels and vehicle technologies.
4. Determine whether any combination of fuel and technology has significant potential to compromise vehicles' compliance with gazetted ADR standards for the period to 2010 (inclusive).
5. Examine the viability and functionality of the fuels.
6. Where possible, data specific to the Australian conditions should be used.
7. Where no emissions data is available for a specified fuel/technology combination then the data for the 'as near as possible' fuel/technology combination (for which the data are available) should be used.
8. If no adequate empirical emissions data are available then modelled data can be used to assess identified fuel/technology combinations.

A.2 Fuels and vehicle technologies

The table below identifies fuels and motor vehicle technologies that are to be included in the study.

Table A.1 – Fuels and vehicle technologies

Fuel	Conventional technology	New technology	Dual-fuel	Hybrid
ULP containing <150 ppm of sulfur	SI			
PULP containing <150 ppm of sulfur	SI			SI
PULP containing <50 ppm of sulfur	SI	DI		SI
LPG (Autogas)	SI	Liquid Phase Injection-3rd Generation	ULP	
LPG (HD5)	SI	Liquid Phase Injection-3rd Generation	ULP	
CNG	SI			

Fuel	**Conventional technology**	**New technology**	**Dual-fuel**	**Hybrid**
Diesel containing <50 ppm of sulfur	CI–DI			CI
Diesel containing <10 ppm of sulfur	CI–DI			CI

ULP = Unleaded petrol (91 RON, 81 MON)
PULP = Premium unleaded petrol (95 RON, 85 MON)
CNG = Compressed natural gas
LPG (liquefied petroleum gas) — autogas from any source meeting the voluntary Australian Liquefied Petroleum Gas Association Ltd specification or European standard EN589.
LPG (HD5) – HD5 grade autogas from any source. Refer to Californian Air Resources Board specifications http://www.arb.ca.gov/regact/lpgspecs/lpgspecs.htm
SI = Spark ignition engine
CI = Compression ignition engine
DI = Direct injection (into combustion chamber).

A.3 Other environmental impacts and benefits

Examine significant environmental impacts not included under the fuel cycle analysis resulting from the production, transportation or use of each fuel. This section of the study will include, but not be limited to an examination of:

- the use of technologies or additives associated with the fuel
- spillage or leakage issues including groundwater contamination
- air quality impacts of specified fuels and technologies.

Appendix B. LPG emission results

Watson and Gowdie (2000) examined the emissions (relative to petrol) of eleven blends of LPG with different compositions of C_4 (butane plus butylene) and olefins (propylene plus butylene) for OEM LPG vehicles that are ADR37/01 compliant. Pure propane (blend E) has zero percent of both of these, whereas a typical autogas blend (blend A) would be 55% propane and 45% butane.

Table B.1 reproduces the emission results of Watson and Gowdie (2000).

Table B.1 – LPG fuels emissions compared with petrol as a reference fuel

Blend	C_4 (%)	Olefin (%)	THC (g/km)	CH_4 (g/km)	NMHC (g/km)	CO (g/km)	NO_x (g/km)	CO_2 (g/km)	FC (L/100 km)	Energy intensity (MJ/km)
Petrol			1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
A	45	0	1.024	1.819	0.828	1.564	0.978	0.891	1.302	0.986
B	45	10	1.154	2.610	0.851	1.897	0.918	0.884	1.298	0.978
C	30	20	0.895	1.941	0.678	1.326	1.137	0.897	1.327	0.983
CC	30	30	0.891	1.965	0.664	1.409	1.079	0.916	1.351	1.003
D	0	20	0.844	1,752	0.656	1.069	1.313	0.894	1.387	0.989
E	0	0	0.934	2.131	0.679	0.907	1.180	0.892	1.411	1.004
F	0	30	0.800	1.738	0.603	1.283	1.325	0.908	1.407	1.006
G	30	10	0.930	2.070	0.690	1.339	0.965	0.907	1.345	0.993
H	45	20	0.980	2.317	0.696	1.443	1.003	0.911	1.323	0.998
I	60	20	1.171	2.517	0.892	1.980	1.005	0.896	1.338	1.006
J	60	0	1.440	3.135	1.090	2.634	0.638	0.888	1.286	0.983

Appendix C. Uncertainty analysis

It is possible to determine the uncertainties associated with emissions from LPG vehicles by using the results for ADR37 LPG vehicles given in Brown et al. (1997: Figure 7-6) and the method of uncertainty analysis of Beer et al. (2000: p.35).

The results of Brown et al. (1997) are based on 29 ADR37 vehicles. We assume that the maximum and minimum values correspond to the 100/*N*th and the 100-(100/*N*)th percentiles, where $N = 29$ is the number of data points. If the data points are normally distributed then the standard deviation, σ, is given by

$$\sigma = R / f \qquad (1)$$

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. For $N = 29$, $f = 3.64$.

We can thus calculate the uncertainty, *U*, of the tailpipe emissions using

$$U = \sigma / X \qquad (2)$$

where *X* is the mean value of the quantity.

The uncertainties from Equation 2 are tabulated in Table C.1

Table C.1 – Uncertainties (in percent) of tailpipe emissions for ADR37 vehicles

Fuel	**CO**	**THC**	**NO_x**
LPG pre-tune	110	53	51
Petrol pre-tune	95	104	54
LPG post-tune	80	52	41
Petrol post-tune	107	113	82

It is evident that the uncertainties associated with the emissions of petrol and LPG vehicles are very large. Percentage uncertainties range between 50% and 100%. Such large uncertainties appear to arise primarily because of the presence of a few macro-polluters in the vehicles that were tested as part of the LPG in-service vehicle study. The occasional vehicle that emits excessively large amounts of pollutants produces emission values that would be statistically referred to as outliers. As a result, the emission values are not normally distributed but are skewed, with most values being low and a few being extremely high. This applies to petrol vehicles and to LPG vehicles.

The results of Brown et al. (1997) indicate that tuning reduces the scatter in the data. In so doing it also reduces the mean value of the emissions data, so that Table B.1 indicates that proper tuning does not appreciably reduce uncertainty (expressed as a percentage variability) of the emissions from such macro-polluters.

Appendix D. Process trees

A great advantage of SimaPro is its ability to produce process trees. Figure 7.1 and Figure 7.2 illustrate such trees for the exbodied GHG emissions from ULP and for LPG, respectively, in the case of the 1998 Ford Falcon. These trees indicate, in an abbreviated form, the upstream (pre-combustion) components used to evaluate each component of the life-cycle.

To interpret the process tree, one starts at the top. Thus in Figure D.1 (page 111), the values in the box refer to the mass (in kg) of CO_2-e. To travel 1 km using ULP, there is a total of 0.349 kg emitted, as shown in the bottom left hand corner of the top box. The fuel energy expended in travelling this 1 km is 4.19 MJ, as depicted in the second box at the top. Two separate boxes are depicted below. The left box, which we shall call the fuel box, indicates that before combustion, the fuel tank contained 0.092615 kg of fuel and that the upstream emissions of CO_2-e. to manufacture this fuel amounted to 0.051447 kg CO_2-e.

The box on the right shows the tailpipe emissions involved for unleaded petrol (0.2977). The sum of the emissions shown in the three boxes below the fuel box sum to give the emission value shown in the fuel box. If their sum is less than the emission value shown in the fuel box, then some of the emissions were in the form of fugitive emissions that are not depicted on the process trees.

The computer software produces output in colour. On the right of each box there is a red line. The red line represents the proportion of the total value (0.349) accumulated up to that point. This can be seen by examining the fuel box. The bottom 15% of the bar on the right of the fuel box is red. The bottom 85% of the tailpipe bar is red, indicating the considerable contribution to exbodied GHG. The two top boxes have bars that are completely red.

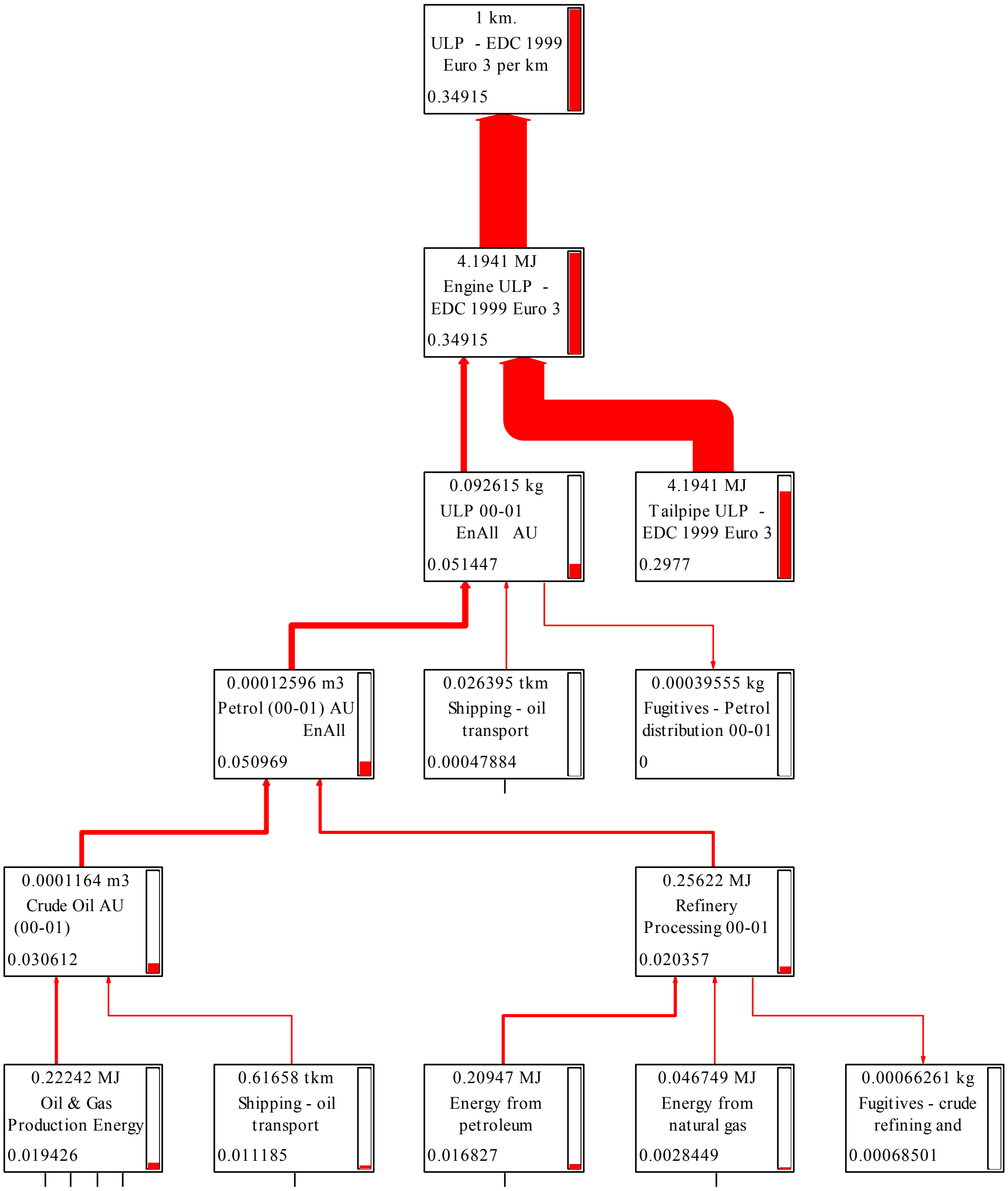

Figure D.1 – Process tree for unleaded petrol when used in a 1998 Ford Falcon complying with ADR79

Appendix E. Exbodied emission results

E.1 Emissions for family-sized vehicles

Table E.1 – Exbodied emissions of criteria pollutants from family-sized vehicles

Impact category	**CO (total) (g CO)**	**NO_x (total) (g NO_x)**	**NMVOC (total) (g NMVOC)**	**Particulate matter (total) (mg PM10)**
ULP–EDC 1999 Euro 3 per km	1.439	2.074	0.679	16.106
PULP–EDC 2003 Euro 4 per km	0.867	0.392	0.479	8.607
ULS PULP–EDC 2003 Euro 4 per km	0.869	0.404	0.487	8.71
XLS PULP–EDC 2003 Euro 4 per km	0.826	0.408	0.49	8.75
LS Diesel–EDC 2003 per km	0.054	0.745	0.117	50.494
ULS Diesel–EDC 2003 per km	0.062	0.781	0.121	50.757
XLS Diesel–EDC 2003 per km	0.071	0.817	0.124	45.7
LPG Autogas–EDC 2nd Gen per km	1.776	1.074	0.343	6.059
LPG Propane–EDC 2nd Gen per km	1.045	1.269	0.322	6.145
LPG Autogas–EDC 3rd Gen per km	1.15	0.134	0.195	4.531
LPG Propane–EDC 3rd Gen per km	1.15	0.133	0.193	4.511
CNG LV EDC per km	0.544	0.144	0.235	4.525
PULP–EDC Hybrid (standard vehicle) per km	0.328	0.217	0.307	4.716
LS Diesel–EDC Diesel (hybrid) per km	0.028	0.425	0.116	27.61

Table E.2 – Exbodied emissions of criteria pollutants from family-sized vehicles separated into tailpipe and upstream emissions

Impact category	**CO**		**NO_x**		**NMVOC**		**Particulate Matter**		
	Tailpipe (g CO)	**Upstream** (g CO)	**Tailpipe** (g NO_x)	**Upstream** (g NO_x)	**Tailpipe** (g NMVOC)	**Upstream** (g NMVOC)	**Tailpipe** (mg PM10)	**Upstream urban** (mg PM10)	**All** (mg PM10)
ULP–EDC 1999 Euro 3 per km	1.371	0.068	1.721	0.353	0.134	0.545	9.023	1.096	16.106
PULP–EDC 2003 Euro 4 per km	0.801	0.066	0.061	0.331	0.010	0.469	2.499	1.184	8.607
ULS PULP–EDC 2003 Euro 4 per km	0.801	0.068	0.061	0.343	0.010	0.477	2.499	1.266	8.710
LS Diesel–EDC 2003 per km	0.008	0.046	0.505	0.240	0.011	0.106	45.732	0.851	50.494
ULS Diesel–EDC 2003 per km	0.008	0.054	0.505	0.276	0.011	0.110	43.445	1.094	48.47
LPG Autogas–EDC 2nd Gen per km	1.740	0.036	0.941	0.133	0.128	0.215	3.683	0.308	6.059
LPG Propane–EDC 2nd Gen per km	1.009	0.036	1.135	0.134	0.105	0.217	3.750	0.310	6.145
LPG Autogas–EDC 3rd Gen per km	1.931	0.030	0.018	0.112	0.015	0.182	2.517	0.261	4.531
LPG Propane–EDC 3rd Gen per km	1.120	0.030	0.022	0.111	0.013	0.180	2.517	0.258	4.511
CNG LV EDC per km	0.517	0.027	0.055	0.089	0.003	0.232	2.862	1.049	4.525
PULP–EDC Hybrid (standard vehicle) per km	0.292	0.036	0.036	0.181	0.050	0.257	1.369	0.649	4.716
LS Diesel–EDC Diesel (hybrid) per km	0.003	0.025	0.294	0.131	0.058	0.058	25.010	0.466	27.61

Table E.3a – Exbodied emissions of GHG from family-sized vehicles

Impact category	**Unit**	**ULP–EDC 1999 Euro 3 per km**	**PULP–EDC 2003 Euro 4 per km**	**ULS PULP–EDC 2003 Euro 4 per km**	**XLS PULP–EDC 2003 Euro 4 per km**	**LS Diesel–EDC 2003 per km**	**ULS Diesel–EDC 2003 per km**
Total	kg CO_2-e	0.3491	0.2892	0.2908	0.28471	0.2325	0.2374
CO_2 (Upstream)	kg CO_2-e	0.04289	0.04013	0.04163	0.0422	0.03044	0.03523
Methane (Upstream)	kg CO_2-e	0.008444	0.007002	0.00705	0.00707	0.005606	0.005706
N_2O (Upstream)	kg CO_2-e	0.00011087	1.05E-04	1.09E-04	0.00011	7.54E-05	8.99E-05

Impact category	**Unit**	**ULP–EDC 1999 Euro 3 per km**	**PULP–EDC 2003 Euro 4 per km**	**ULS PULP–EDC 2003 Euro 4 per km**	**XLS PULP–EDC 2003 Euro 4 per km**	**LS Diesel–EDC 2003 per km**	**ULS Diesel–EDC 2003 per km**
GHG (Upstream)	kg CO_2-e	0.05145	0.04724	0.04879	0.04938	0.03613	0.04104
CO_2 (Tailpipe)	kg CO_2-e	0.2953	0.2416	0.2416	0.234	0.1954	0.1954
Methane (Tailpipe)	kg CO_2-e	0.00108141	5.59E-05	5.59E-05	0.00005	5.14E-05	5.14E-05
N_2O (Tailpipe)	kg CO_2-e	0.00133423	0.00031812	0.00031812	0.000319	0.0009354	0.0009354
GHG (Tailpipe)	kg CO_2-e	0.29770	0.24202	0.24202	0.234369	0.19642	0.19642

Table E.3b – Exbodied emissions of GHG from family-sized vehicles

Impact category	**Unit**	**XLS Diesel: EDC 2003 Euro 3 per km**	**LPG Autogas: EDC 2nd Gen per km**	**LPG Propane: EDC 2nd Gen per km**	**LPG Autogas: EDC 3rd Gen per km**	**LPG Propane: EDC 3rd Gen per km**	**CNG LV EDC per km**	**PULP: EDC Hybrid (standard vehicle) per km**	**LS Diesel: EDC Diesel (hybrid) per km**
Total	kg CO_2-e	0.23449	0.3013	0.3021	0.2509	0.2506	0.2613	0.1589	0.1278
CO_2 (Upstream)	kg CO_2-e	0.04	0.0311	0.03137	0.02639	0.02612	0.04186	0.02199	0.01668
Methane (Upstream)	kg CO_2-e	0.0014	0.008223	0.008289	0.006972	0.006902	0.01288	0.003837	0.003072
N_2O (Upstream)	kg CO_2-e	0.000104	6.65E-05	6.71E-05	5.64E-05	5.58E-05	1.02E-04	5.75E-05	4.13E-05
GHG (Upstream)	kg CO2-e	0.041504	0.03941	0.03973	0.03341	0.03308	0.05484	0.02588	0.01979
CO_2 (Tailpipe)	kg CO2-e	0.192	0.2599	0.2601	0.2171	0.2171	0.2055	0.1324	0.1071
Methane (Tailpipe)	kg CO_2-e	0.000051	8.57E-04	1.00E-03	6.44E-05	6.44E-05	4.87E-04	0.0004033	0.0003706
N_2O (Tailpipe)	kg CO_2-e	0.000936	0.00118214	0.00120372	0.00030803	0.00030803	0.00047766	0.0001743	0.0005093
GHG (Tailpipe)	kg CO_2-e	0.192986	0.26189	0.26235	0.21752	0.21752	0.20644	0.1330	0.1080

E.2 Emissions for compact-sized vehicles

Table E.4 – Exbodied emissions of criteria pollutants from compact-sized vehicles

Impact category	**Unit**	**ULP–EDC 1999 Euro 3 per km (family-sized car)**	**PULP–EDC 2003 Euro 4 Kangoo per km**	**Diesel–EDC 2003 Euro 4 Kangoo per km**	**LPG (Propane) 3rd Gen–EDC 2003 Euro 4 Kangoo per km**	**PULP–EDC Hybrid (2nd gen. Prius) per km**	**PULP–EDC Hybrid (Prius) per km**	**PULP–EDC Hybrid (Insight) per km**
CO Total)	g CO	1.439	0.996	0.031	0.932	0.208	0.636	0.398
NO_x (Total)	g NO_x	2.074	0.244	0.506	0.084	0.153	0.274	0.171
NMVOC (Total)	g NMVOC	0.679	0.327	0.077	0.138	0.216	0.348	0.217
Particulate matter (Total)	mg PM10	16.106	5.663	34.028	2.891	3.704	4.782	2.989

Table E.5 – Exbodied emissions of criteria pollutants from compact-sized vehicles separated into tailpipe and upstream emissions

Impact category	**Unit**	**ULP–EDC 1999 Euro 3 per km (family-sized car)**	**PULP–EDC 2003 Euro 4 Kangoo per km**	**Diesel–EDC 2003 Euro 4 Kangoo per km**	**LPG (Propane) 3rd Gen–EDC 2003 Euro 4 Kangoo per km**	**PULP–EDC Hybrid (2nd gen. Prius) per km**	**PULP–EDC Hybrid (Prius) per km**	**PULP–EDC Hybrid (Insight) per km**
CO (Tailpipe)	g CO	1.371	0.953	0.000	0.912	0.1797	0.600	0.375
CO (Upstream)	g CO	0.068	0.043	0.031	0.020	0.02823	0.036	0.023
NO_x (Tailpipe)	g NO_x	1.721	0.026	0.344	0.012	0.01007	0.090	0.056
NO_x (Upstream)	g NO_x	0.353	0.218	0.162	0.072	0.1425	0.184	0.115
NMVOC (Tailpipe)	g NMVOC	0.134	0.018	0.006	0.022	0.01438	0.087	0.054
NMVOC (Upstream)	g NMVOC	0.545	0.309	0.071	0.116	0.2018	0.261	0.163
Particulates (Tailpipe)	mg PM10	9.023	1.644	30.819	1.606	1.075	1.388	0.868
Particulates (Upstream-Urban)	mg PM10	1.096	0.779	0.573	0.167	0.5097	0.658	0.411
Particulates All	mg PM10	16.106	5.663	34.028	2.891	3.704	4.782	2.989

Table E.6 – Exbodied emissions of GHG from compact-sized vehicles

Impact category	**Unit**	**ULP: EDC 1999 Euro 3 per km (family sized car)**	**PULP: EDC 2003 Euro 4 Kangoo per km**	**Diesel: EDC 2003 Euro 4 Kangoo per km**	**LPG (Propane) 3rd Gen: EDC 2003 Euro 4 Kangoo per km**	**PULP: EDC Hybrid (standard vehicle) per km**	**PULP: EDC Hybrid (Prius 1st gen.) per km**	**PULP: EDC Hybrid (Prius 2nd gen.) per km**	**PULP: EDC Hybrid (Insight) per km**
Total	kg CO_2-e	0.3491	0.1907	0.1575	0.1602	0.2059	0.1614	0.1246	0.1009
CO_2 (Upstream)	kg CO_2-e	0.04289	0.02641	0.02052	0.0168371	0.02850	0.02230	0.01727	0.01393
Methane (Upstream)	kg CO_2-e	0.008444	0.004607	0.00378	0.004449	0.004973	0.003890	0.003013	0.002431
N_2O (Upstream)	kg CO_2-e	0.00011087	6.90E-05	5.08E-05	3.60E-05	7.45E-05	5.83E-05	4.51E-05	3.64E-05
GHG (Upstream)	kg CO_2-e	0.05145	0.03108	0.02435	0.02132	0.03355	0.02624	0.02032	0.01640
CO_2 (Tailpipe)	kg CO_2-e	0.2953	0.159	0.1317	0.139	0.1716	0.1343	0.104	0.08391
Methane (Tailpipe)	kg CO_2-e	0.00108141	7.68E-05	2.71E-05	9.87E-05	4.96E-04	7.00E-04	1.21E-04	4.37E-04
N_2O (Tailpipe)	kg CO_2-e	0.001334	0.0005165	0.00144	0.0002465	0.0002259	0.0001767	0.0001369	0.0001105
GHG (Tailpipe)	kg CO_2-e	0.297701	0.15959	0.13316	0.13891	0.17234	0.13513	0.1043	0.08446