1. Low Sulfur Diesel

1.1 Diesel National Environment Protection Measures

With the establishment of the National Environment Protection Council, as a result of the May 1992 Intergovernmental Agreement on the Environment, Australia decided to declare National Environment Protection Measures (NEPMs) so as to enact uniform national environmental standards. Information on NEPMs may be found at the National Environment Protection Council website at www.nepc.gov.au. The NEPMs that relate, either directly or indirectly, to motor vehicles and their emissions are the NEPM for Ambient Air Quality, the National Pollutant Inventory (NPI), the Diesel Vehicle Emissions NEPM, and the proposed Air Toxics NEPM. The NEPM for Ambient Air Quality sets air quality standards for the ambient environment, and does not deal with emissions, as such. Emission controls on new vehicles are achieved through Australian Design Rules (ADRs). The NPI requires industry to report on emissions.

1.1.1 Diesel vehicle emissions

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

Motor vehicles, particularly those with diesel engines, are significantly disproportionate contributors of fine particle pollution and oxides of nitrogen in urban areas. Since 1996 diesel vehicle emission standards in the ADRs (http://www.dot.gov.au/land/environment/envrev99.htm) have placed limits on the emission of particles for new vehicles. Before 1996, diesel vehicles sold in Australia were required to meet a smoke opacity standard. Amendments to Australian ADRs for diesel vehicle emissions, gazetted in 1999, will bring about the introduction of Euro2, Euro3 and Euro4 standards from 2002.. These standards are described in more detail in section 1.3, below.

1.2 Diesel Fuel and the Diesel Engine

1.2.1 Introduction

Most heavy vehicles over 10 tonnes gross vehicle mass (GVM) use turbocharged, four-stroke compression ignition engines. Smaller vehicles use normally aspirated engines. All are commonly referred to as ‘diesel engines’. Fuel is injected into the diesel engine at over 1000 atmospheres pressure and ignited by the heat of compression, whereas in the petrol engine the fuel is ignited by a spark from a spark plug.

1.2.2 Fuel quality review

In 1999, Environment Australia commissioned a comprehensive review of possible new fuel specifications for Australia, designed to reduce emissions of greenhouse gases and air pollutants from Australian road transport. In addition to modelling emissions reductions, the project assessed the impact on Australian refineries, vehicle manufacturers, consumers and the economy-wide effects of changing fuel specifications for petrol and diesel. The reports (Environment Australia, 2000a, 2000b) of the fuel quality review are available at http://www.ea.gov.au/atmosphere/transport/fuel/index.html .

Low sulfur diesel (LSD) is diesel fuel that meets either the Euro2 fuel specifications for diesel fuel, or the fuel specifications for LSD proposed by the Commonwealth for implementation in 2002.

Table 1.1
Diesel fuel quality specifications (Environment Australia, 2000a, 2000b)

Fuel parameter	Euro2 (EN590:1993)	Commonwealth (1 January 2002)[1]
Sulfur (ppm)	500	500
Cetane index	46 (min)	46 (min)
Density at 15°C (kg/m^3)	820 – 860	820 – 860
Distillation T95 (°C)	370 (max)	370 (max)
Ash & suspended solids (ppm)	-	100 (max)
Viscosity (cSt)	-	2.0 – 4.5

Diesel fuel is generally derived from light virgin gas oil that is produced from the distillation of crude oil. The distillation is conducted in Australian refineries. LSD is produced in refineries with a hydro-desulfurisation unit. As at March 2001, Western Australia and Queensland had passed legislation mandating a diesel sulfur content of 500 ppm or less.

1.2.3 Emission factors

A CO_2 emission factor of 69.7 g/MJ for diesel fuel (of energy density 38.6 MJ/L) may be found in Workbook 3.1 on transport of the Australian Greenhouse Gas Inventory methodology (National Greenhouse Gas Inventory Committee, 1998), whereas, for other emissions, the default emission factors are as given in Table 1.2.

Table 1.2
Emission factors for diesel vehicles expressed as g/km

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

Source: National Greenhouse Gas Inventory Committee (1998)

1.3 Upstream and Tailpipe Emissions

1.3.1 Upstream

Diesel fuel is manufactured using crude oil as a feedstock. Depending on the characteristics of the crude oil(s) used, a number of different refinery streams may be blended to produce diesel fuel complying with the relevant specification. These streams most commonly include straight run distillate and light cycle oil (LCO) produced from heavier fractions in a fluid catalytic cracker. The sulfur content of these fractions depends on the feedstock crude oil used and may be as high as 2%; their boiling range falls between 150°C and 380°C.

Diesel fuel currently used in Australia has a sulfur content of around 1300 ppm. As from 31 December 2002, new LSD specification will apply, requiring sulfur content of diesel fuel to be 500 ppm or lower.

High levels of sulfur in diesel fuel are undesirable, as during combustion they are converted to volatile sulfur oxides (SOx). These are corrosive and lead to increased engine wear. They also contribute directly to acid rain and produce solid sulfates, which add to the particulate matter in the exhaust gases.

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[1] The sulfur specification takes effect 31 December 2002.

Hydro-desulfurisation is the process that is most commonly used to reduce sulfur in fuel. The process involves catalytic hydrogenation, which converts chemically bound organic sulfur into hydrogen sulfide (H_2S). It also improves the cetane number.

To meet the 500 ppm limit, a single-stage hydro-desulfurisation unit using a Cobalt-Molybdenum (Co-Mo) catalyst, and sometimes Nickel-Molybdenum (Ni-Mo) catalyst, under moderate severity, is adequate. Further sulfur removal — down to <15 ppm in the case of ultra-low sulfur diesel (ULSD) — requires a two-stage, high severity hydro-desulfurisation unit using both the Co-Mo and Ni-Mo catalysts.

Energy use for oil and gas production and transportation, and refinery processing, is taken from the National Greenhouse Gas Inventory for 1998 (NGGIC, 2000) and shown in Table 1.3. This excludes exploration activity.

Note that oil and gas are assumed to be produced together and emissions and extraction energy are allocated between them based on the energy content of each fuel. Similarly, refinery products, such as diesel, petrol, LPG and so on, are treated as co-products with the energy consumption, and consequent emissions being allocated to the output products (diesel, petrol, LPG), based on the energy content of each fuel.

In addition to the energy use detailed in table 1.3, energy and emissions for transportation of crude oil imported into Australia are taken into account. Assumptions for oil imports are also taken from the National Greenhouse Gas Inventory, with 58% of crude taken to be transported 10,000 km predominantly from Malaysia and the Middle East.

Table 1.3
Energy use data for oil and gas production and refinery processing

	Fuel	Energy Use	Production 1998[3]	Energy Use to production energy ratio
		PJ	PJ	GJ/PJ produced
Oil and gas production and field processing	Petroleum	0.9[1]	2528.6	0.36
	Gas	141.1[1]	2528.6	55.80
Natural gas transmission	Gas	8.6[1]	688.5	12.49
Gas production and distribution	Gas	2.4[1]	371.5	6.46
Petroleum Refining	Petroleum	87.2[2]	1663.8	52.41
	Gas	11.6[2]	1663.8	6.97

[1] Fuel Combustion Activities 1A-2 (sheet 1): Emissions from manufacturing industries and construction (all sources) (NGGIC)
[2] Fuel Combustion Activities 1A-1 (sheet 2): Emissions from Energy Industries (all sources) (NGGIC)
[3] Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas (NGGIC)

Emissions from combusted fuels and fugitive emissions are also taken from the National Greenhouse Gas Inventory and are shown in Table 1.4.

No Australian aqueous emissions or solid wastes data was available for the crude oil, natural gas production or transport sectors, so data from European studies (Boustead, 1993) was used as a proxy. This data is detailed in Table 1.5 and Table 1.6.

Table 1.4
Fugitive greenhouse emission data for oil and gas production and refinery processing

		Fuel Quantity	CO_2	CH_4	N_2O	NOx	CO	NMVOC
		(PJ)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)
Oil	Exploration (for both oil and gas)	1257	14.8	0.2				0.1
	Crude oil production	298		0.3				0.3
	Crude oil transport: domestic	1664		0.2				1.3
	Crude oil refining and storage	1102	153	1.9		0.1	0.5	34
	Petroleum product distribution							57.9
Gas	Production and processing	1272		1.6				1
	Transmission	689		4.9				0.1
	Distribution	372	10.4	171.7				25.5
Venting and flaring for oil and gas production	Venting at gas processing plant	1272	2814	119.6				42.3
	Distributed venting	860	749					
	Flaring	2646	2188	26.6	0.1	1.1	6.6	11.4

Source: Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas

Table 1.5
Aqueous emissions for Oil and Natural Gas Production data from APME data for Europe

Emissions	mg/MJ Natural Gas	mg/MJ Crude Oil
Acid as H+	1.56	0.53
metallic ions	0.19	0.09
CxHy	0.19	0.09
suspended solids	1.56	0.71
dissolved solids	1.36	0.18
dissolved organics	0.78	0.36
oil	1.36	0.53
phenol	0.02	0.02

Source: Boustead (1993)

Table 1.6
Aqueous emissions for oil and natural gas production data from APME data for Europe

Emissions	mg/MJ Natural Gas	mg/MJ Crude Oil
industrial waste	0.78	0.71
mineral waste	0.08	0.07
slags/ash	11.70	10.67
inert chemicals	0.39	0.36

Source: Boustead (1993)

For refineries, data on trace metals and volatile organic fugitive emissions was taken from the National Pollutant Inventory Guide book (Environment Australia, 1999b), together with data submitted by refineries to the National Pollutant Inventory.

The controlled emission factor for particle emissions from Fluid Catalytic Cracking Units is taken as 0.128 kg/m^3 feed to the unit (page 19, Table 10 (Environment Australia, 1999b). From this data, trace metal emission data is estimated using emission factors provided in the NPI guidebook (Environment Australia, 1999b: Table 11, p.20), which are shown in Table 1.7.

Table 1.7
Metal emissions to air for particulate matter from refinery operations

Metal emission	Controlled emission factor as weight % of total particulate matter
Nickel	0.031
Copper	0.003
Zinc	0.006
Selenium	0.003
Antimony	0.002
Lead	0.01
Cadmium	0.002
Mercury	0.001

Source: Extracted from Environment Australia (1999b: Table 11 page 20)

Volatile organic emissions were estimated using emission factors related to total volatile organic compound (VOC) emissions from fugitive emissions in refineries, given in the NPI guidebook (Environment Australia, 1999b: Table 15 p. 31). Data was given for a range of fugitive leaks such as flanges, valves, drains and pump seals. The lowest and most common was the data for flanges and valves, so this data was used to breakdown the VOC emissions reported in the National Greenhouse Gas Inventory into different organic species as shown in Table 1.8.

Table 1.8
Speciation data for NPI Substances from Equipment Fugitives[1]

Compound	Compound Weight Percent in VOCs Released
n-hexane	4.76
Cyclohexane	0.14
Xylenes	0.28
Benzene	0.14
Toluene	0.7

Source: Extracted from Environment Australia (1999b: Table 15 page 32)
[1] Emission factors are for flange and valves

Organic and trace metal emissions to water were also determined from data in the NPI Guide. Metal emissions are provided per cubic metre of waste water (Environment Australia, 1999b: Table 20 p. 41), while organic emissions are provided as a weight percent of dissolved organic carbon (Environment Australia, 1999b: Table 19 p. 40. Waste water effluents and DOC loads per tonne of production was estimated from reported emission data from refineries to the National Pollutant Inventory. The data was conservatively estimated by dividing total flow by capacity, rather than production. This would reduce the result on a per tonne basis. Emission factors for organics to water are presented in Table 1.9, while factors for metals emitted are provided in Table 1.10. The calculated average wastewater emission for Australian refineries was 30 L per tonne of product and dissolved organic carbon (DOC) was calculated to be around 0.79 g per tonne of product.

Table 1.9
Default Speciation Factors for Organics in Refinery Effluent

Organic substance	NPI Substance Weight Percent of DOC
Toluene	0.00092
Benzene	0.00091
Xylenes	0.00140
Phenol	0.00069
1,2-Dichloroethane	0.00027
Hexachlorobenzene	0.00000
Polycyclic aromatic hydrocarbons	0.00160
Styrene	0.00010
Ethylbenzene	0.00012
1,1,2-trichloroethane	0.00004
Chloroform	0.00250

Source: Environment Australia (1999b: Table 19 p. 40)

Figure 1.1 provides an overview of how the unit processes are put together in the LCA inventory, with flows from each process shown for 1 kg of diesel production.

Table 1.10
Default Emission Factors for Trace Elements and Inorganics in Refinery Effluent

Trace Elements	NPI Substance Emission Factors (kg/m^3 of flow)
Zinc	4.40E-04
Phosphorous	4.10E-07
Arsenic	6.70E-06
Chromium(VI)	7.70E-06
Selenium	3.10E-06
Nickel	3.60E-06
Copper	2.90E-06
Antimony	5.80E-07
Cobalt	1.60E-06
Mercury	1.10E-08
Cadmium	3.30E-07
Lead	1.90E-06
Cyanide	7.60E-09
Ammonia	1.30E-06

All energy use throughout fuel processing is assumed to have a greenhouse emission profile as of standard fuel combustion, as described in the National Greenhouse Gas Inventory in Fuel Combustion Activities 1A-1 (sheet 1): Emissions from Energy Industries (all sources) (NGGIC, 1998). Air emissions of organic and inorganic substances, and particles, are taken from the National Pollutant Inventory Emission Estimation Technique Manual for Combustion in Boilers (Environment Australia, 1999a). Grid-supplied electricity data were taken from the Australian LCA inventory data project, described in (Grant, 2000).

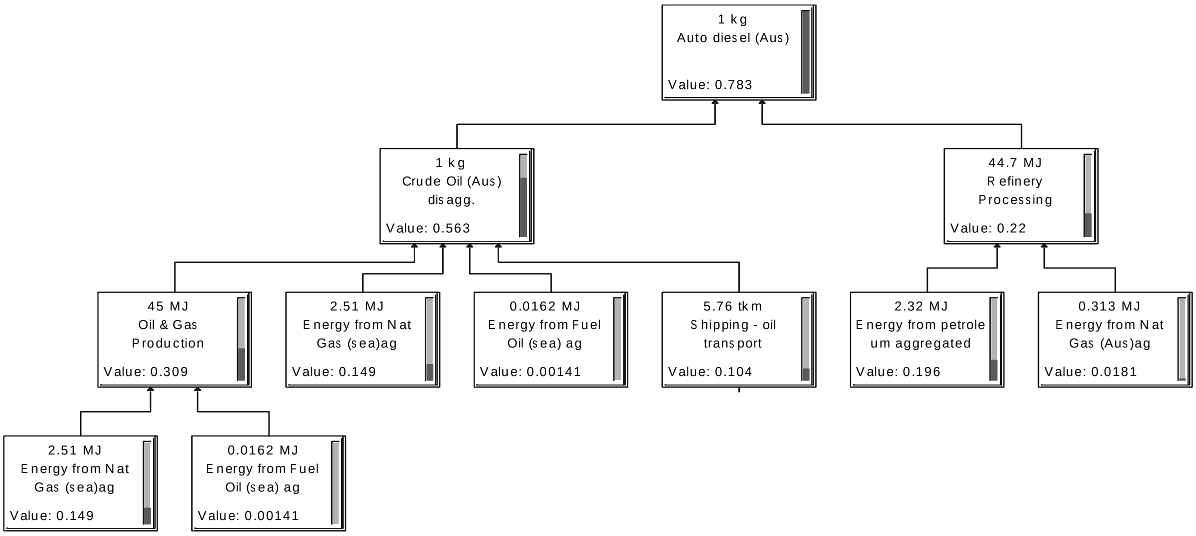

Figure 1.1
Processes leading into diesel production as modelled in LCA software.
(The diagram shows the energy flows per kilogram of LSD. The lower value in each box is set to display cumulative greenhouse gas emissions in kg CO_2-eq.)

Assumptions for Production of LSD

Discussions with Mr Mark Sanders of BP, an expert in refinery operation, updated the previous assumptions that were made regarding additional processing to produce lower sulfur diesel. For LSD (500 ppm S) a hydro-desulfurisation unit would be required on top of current refinery operations. Beer et al. (2000) assumed that for ULSD a hydro-cracking unit would be required on top of normal refinery operations. More recent information indicates that existing hydrofiners can be used to produce ULSD by employing more active catalysts, increased hydrogen purity, and reduced space velocities. In the absence of better data, information on the two processes has been taken from standard equipment specifications. The data for this is shown in Table 1.11.

Table 1.11
Additional inputs to produce 1 tonne LSD and ULSD from 1 tonne current diesel

	Equipment	Electricity	Energy from gas oil	Steam
		kWh	MJ	kg
Low sulfur	Hydro-desulfurisation unit	7.3	577	0
Ultra low sulfur	Hydro-cracking unit	50.3	1578	95

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

1.3.2 Tailpipe emissions

There have been two major investigations conducted in Australia of the tailpipe emissions from LSD. Brown et al. (1999) used a four-mode steady-state chassis dynamometer based test derived from the SAE 13-mode test to examine four vehicles — a medium-duty truck with Euro1 engine technology (1992 Ford Trader of 7,075 kg gross vehicle mass), a Euro1 engine technology bus (1987 Mercedes Mark 4 of 16,000 kg GVM), a Euro2 technology bus (1996 Scania 11L Turbo of 19,100 kg GVM), and a Euro1 engine technology heavy duty truck (1991 Volvo NL12 Heavy Tipper of 25,000 kg GVM). The vehicles were examined using diesel fuel, with (D+C) and without (D) a fitted catalytic converter, and using LSD fuel, with (LSD+C) and without (LSD) a fitted catalytic converter. The catalytic converters were oxidation catalysts on metallic or ceramic substrates. The emission results for the main pollutants are given in Table 1.12 to Table 1.15.

Table 1.12
Tailpipe emissions of CO (g/kWh) for various types of diesel

	MD	Bus	Euro2	HD
	Ford Trader	Mercedes Mk4	Bus Scania	Truck Volvo
D	5.96	7.11	0.54	2.68
LSD	5.97	7.95		2.39
D+C	0.63	3.56	0.2	1.51
LSD+C	0.57	3.31	0.1	0.95

Source: Brown et al. (1999)

Table 1.13
Tailpipe emissions of NOx (g/kWh) for various types of diesel

	MD	Bus	Euro2	HD
	Ford Trader	Mercedes Mk4	Bus Scania	Truck Volvo
D	8.23	14.1	9.2	9.77
LSD	8.76	13.9		10.5
D+C	7.89	11.9	8.84	10.6
LSD+C	7.41	12.5	9.02	11

Source: Brown et al. (1999)

Table 1.14
Tailpipe emissions of THC (g/kWh) for various types of diesel

	MD Ford Trader	Bus Mercedes Mk4	Euro2 Bus Scania	HD Truck Volvo
D	1.45	1.7	0.42	0.4
LSD	1.62	1.84		0.39
D+C	0.21	1.14	0.2	0.24
LSD+C	0.15	1.12	0.09	0.22

Source: Brown et al. (1999)

Table 1.15
Tailpipe emissions of PM (at rated speed, 75% power) (mg/kWh) for various types of diesel

	MD Ford Trader	Bus Mercedes Mk4	Euro2 Bus Scania	HD Truck Volvo
D	194	133	19	92
LSD	221	155		127
D+C	366	193	27	138
LSD+C	451	167	43	104

Source: Brown et al. (1999)

Parsons Australia Pty Ltd (2000) examined the emissions from two vehicles using the Australian Composite Urban Emissions Drive Cycle (CUEDC, pronounced Q-DC). Their results, using six different diesel fuels of varying sulfur content, are given in Table 1.16 and Table 1.17. The values in Table 1.17 have been used to determine tailpipe emissions in Table 1.23.

Table 1.16
Emissions from a Euro 1 technology (ADR70) Light Commercial Vehicle (1993 Toyota Hilux) using a range of diesel fuels.

	S content mg/kg	CO_2 g/km	CO g/km	NOx g/km	HC g/km	PM (filter) mg/km	FC L/100 km
Base Fuel	1700	464	3.16	1.62	0.04	741	18.21
Euro2	480	444	1.15	1.47	0.02	353	18.22
Euro3	210	435	0.74	1.49	0.04	293	17.53
Euro4	39	439	1.24	1.48	0.04	331	17.86
WorldWide	24	452	1.29	1.42	0.05	301	18.52
CARB	264	439	1.69	1.28	0.04	419	17.68

Source: Parsons Australia Pty Ltd (2000: Table 5.3)

Table 1.17
Emissions from a Euro 1 technology (ADR70) Rigid Truck (1995 Isuzu 900SUR) using a range of diesel fuels.

	S content Mg/kg	CO_2 g/km	CO g/km	NOx g/km	HC g/km	PM (filter) mg/km	FC L/100 km
Base Fuel	1700	782	3.45	10.63	1.01	447	32.92
Euro2	480	719	2.48	10.17	0.9	380	30.18
Euro3	210	746	2.75	10.47	0.95	313	31.22
Euro4	39	718	3.13	8.66	0.73	284	30.53
WorldWide	24	692	2.81	8.4	0.73	283	29.6
CARB	264	775	2.63	8.57	0.84	300	31.56

Source: Parsons Australia Pty Ltd (2000: Table 5.4)

1.4 Full Fuel-Cycle Analysis of LSD Emissions

Coffey (2000) conducted modelling studies to estimate life-cycle emissions as a result of improved fuel quality, tighter emission controls on petrol and diesel vehicles, and a lower growth in transportation as the Kyoto Protocol commitments are met. The results may be found at: http://www.ea.gov.au/atmosphere/transport/fuel/index.html .

Diesel vehicles reduce their emissions of sulfur dioxide when using low and ultra-low sulfur fuels. The increased processing at the refinery indicates that the life-cycle greenhouse gas emissions are liable to increase. There are strong theoretical arguments to indicate that reducing fuel sulfur, *per se*, will not alter the fuel economy of an engine. Nevertheless, the recent fuel economy results of Parsons Australia Pty Ltd (2000) confirm that there is an approximate 10% increase in fuel efficiency when LSD is substituted for diesel as in Table 1.17.. This confirms the results obtained on London buses that were noted in Table 2.1 of Beer et al. (2000). Desulfurisation produces changes to fuel properties such as the cetane value.. It is likely that the fuel economy will vary among LSDs from different sources.

The pre-combustion estimates for LSD were based on the assumption that existing Australian refineries will need to install a hydro-desulfurisation unit to produce LSD. The Stage 1 report (Beer et al. 2000) assumed that a hydro-cracker was needed to produce ULSD. Recent analyses (M. Sanders, pers. comm.) indicate that Australian refineries may be able to produce

ULSD using hydro-desulfurisation units by modifications as described earlier, or for new units by increasing the operating pressures.

1.4.1 *Emissions on a mass per unit energy basis*

The results obtained by using the SimaPro life-cycle model along with the upstream and tailpipe emissions data is given in Table 1.18 for the full life cycle for greenhouse gases and criteria pollutants. The upstream emissions and the tailpipe emissions that comprise these totals are given in Table 1.19 and Table 1.20, respectively. They have also been used to represent bus emissions by using the Leung and Williams (2000) model to represent emissions from a bus generating the same tractive force as the truck.

Table 1.18
Urban and total life-cycle emissions calculated for LSD

Full Lifecycle	Units (per MJ)	LS Diesel engine
Greenhouse	kg CO_2	0.0858
NMHC total	g HC	0.140
NMHC urban	g HC	0.111
NOx total	g NOx	1.044
NOx urban	g NOx	0.987
CO total	g CO	0.253
CO urban	g CO	0.242
PM10 total	mg PM10	40.7
PM10 urban	mg PM10	39.3
Energy Embodied	MJ LHV	1.18

The results separate urban and rural emissions, rural being the difference between total emissions and urban emissions. Emissions were assumed to occur in urban areas unless they were produced by a known rural or maritime activity.

The apparent discrepancies in certain values, when compared with tabulations earlier in this report, arise because many of the values reported in the main text are in terms of g/MJ measured as useable energy from the engine driveshaft (normally represented as g/kWh), whereas the life-cycle calculations are consistent in setting all the calculations in terms of g/MJ, based on the inherent chemical energy of the fuel. On average, this reduces quoted engine dynamometer values by a factor of 3.

Table 1.19
Urban and total upstream emissions (per MJ) for LSD

Precombustion	Units	LSD
Greenhouse	kg CO_2	0.0191
NMHC total	g HC	0.0565
NMHC urban	g HC	0.027
NOx total	g NOx	0.100
NOx urban	g NOx	0.043
CO total	g CO	0.023
CO urban	g CO	0.012
PM10 total	mg PM10	5.42
PM10 urban	mg PM10	4
Energy Embodied	MJ LHV	1.18

Table 1.20
Urban and total tailpipe emissions (per MJ) from LSD

Combustion	Units	LSD
Greenhouse	kg CO_2	0.067
NMHC total	g HC	0.084
NMHC urban	g HC	0.084
NOx total	g NOx	0.944
NOx urban	g NOx	0.944
CO total	g CO	0.230
CO urban	g CO	0.230
PM10 total	mg PM10	35.26
PM10 urban	mg PM10	35.26
Energy Embodied	MJ LHV	0

1.4.2 Vehicle emissions - trucks (g/km)

This section gives the calculated values for the emissions from trucks, on a per-kilometre basis.

Table 1.21
Urban and total life-cycle emissions (per km) for trucks calculated for LSD

Full LC	Units	LSD
Greenhouse	kg CO_2	0.9250
NMHC total	g HC	1.509
NMHC urban	g HC	1.192
NOx total	g NOx	11.250
NOx urban	g NOx	10.638
CO total	g CO	2.723
CO urban	g CO	2.612
PM10 total	mg PM10	438.4
PM10 urban	mg PM10	423.1
Energy Embodied	MJ LHV	12.70

Table 1.22
Urban and total precombustion emissions (per km) for trucks calculated for LSD

Precombustion	Units	LSD (Aus)
Greenhouse	kg CO_2	0.2060
NMHC total	g HC	0.609
NMHC urban	g HC	0.292
NOx total	g NOx	1.080
NOx urban	g NOx	0.468
CO total	g CO	0.243
CO urban	g CO	0.132
PM10 total	mg PM10	58.4
PM10 urban	mg PM10	43.1
Energy Embodied	MJ LHV	12.7

Table 1.23
Urban and total tailpipe emissions (per km) for trucks calculated for LSD

Combustion	Units	LSD (Aus)
Greenhouse	kg CO_2	0.719
NMHC total	g HC	0.900
NMHC urban	g HC	0.900
NOx total	g NOx	10.170
NOx urban	g NOx	10.170
CO total	g CO	2.480
CO urban	g CO	2.480
PM10 total	mg PM10	380.00
PM10 urban	mg PM10	380.00
Energy Embodied	MJ LHV	0

1.4.3 *Vehicle emissions - buses (g/km)*

This section gives the calculated values for the emissions from buses, on a per-kilometre basis.

Table 1.24
Urban and total life cycle emissions (per km) for buses calculated for LSD

Full LC	Units	LSD
Greenhouse	kg CO_2	1.66
NMHC total	g HC	2.71
NMHC urban	g HC	2.14
NOx total	g NOx	20.20
NOx urban	g NOx	19.10
CO total	g CO	4.89
CO urban	g CO	4.69
PM10 total	mg PM10	787
PM10 urban	mg PM10	760
Energy Embodied	MJ LHV	22.8

Table 1.25
Urban and total precombustion emissions (per km) for buses calculated for LSD

Precombustion	Units	LSD (Aus)
Greenhouse	kg CO_2	0.37
NMHC total	g HC	1.09
NMHC urban	g HC	0.52
NOx total	g NOx	1.94
NOx urban	g NOx	0.84
CO total	g CO	0.44
CO urban	g CO	0.24
PM10 total	mg PM10	104.9
PM10 urban	mg PM10	77.4
Energy Embodied	MJ LHV	22.8

Table 1.26
Urban and total tailpipe emissions (per km) for buses calculated for LSD

Combustion	Units	LSD (Aus)
Greenhouse	kg CO_2	1.2910
NMHC total	g HC	1.616
NMHC urban	g HC	1.616
NOx total	g NOx	18.270
NOx urban	g NOx	18.270
CO total	g CO	4.453
CO urban	g CO	4.453
PM10 total	mg PM10	682.3
PM10 urban	mg PM10	682.3
Energy Embodied	MJ LHV	0.00

1.4.4 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 1.27.

Table 1.27
Estimated one standard deviation uncertainties (in percent) for LSD emissions

	g/MJ	g/t-km	g/p-km
CO_2	10	9	11
NMHC	34	50	17
NOx	29	30	27
CO	111	144	78
PM10	45	39	50

1.5 Viability and Functionality

LSD is diesel fuel that meets either the Euro2 fuel specification for diesel fuel, or the fuel specification for LSD proposed by the Commonwealth for implementation in 2002. Reformulation of diesel to LSD requires no change to the current diesel distribution system or engines.

Changing diesel fuel composition and exhaust treatment can reduce emissions of toxic substances. Low sulfur content reduces emissions of PM. Reducing the polycyclic aromatic hydrocarbons and aromatic content reduces the emissions of some, but not all polycyclic aromatic hydrocarbon compounds. For heavy vehicles these changes do not reduce emissions of gaseous toxics such as formaldehyde, benzene, and 1,3 butadiene (different results are obtained from light vehicle emissions). Particle traps in conjunction with low sulfur fuels reduce emissions of organic compounds and particulate matter, but not always to the same degree. Although the emissions of toxics are lower, the limited data does not indicate that the kind of substances emitted, or the profile of toxic substances, are altered.

According to a news report in the Australian Financial Review (8 January 2001, page 4) the Royal Automobile Club of Queensland advised owners of affected diesel-engined vehicles to lodge compensation claims for fuel pump seal leaks resulting from the use of LSD refined in Brisbane. We are advised (M. Sanders, pers. comm.) that the problem was due to lowering of the aromatics content of the fuel. The rubber oil seals in pre-1994 Japanese diesel vehicles use a type of rubber that expands with high aromatic content. The sudden drop in aromatics associated with the transition to LSD caused the seals to shrink and led to fuel leakage. Similar problems also occurred with certain pieces of agricultural machinery.

BP will rectify the problem by paying for new seals. The problems did not arise as a result of the lowering of the sulfur content as such, but because of the use of a hydro-cracker instead of a hydro-refiner.

1.6 Health and OHS

1.6.1 Production and transport

Estimated trace metal emissions to air for particulate matter from refinery operations are shown in Table 1.7. The emitted metals include nickel, copper, zinc, selenium, antimony, lead, cadmium and mercury.

Estimates of organic (including benzene, toluene and xylene) and trace metal emissions to water in refinery effluent are in Table 1.9 and Table 1.10.

Particles
The estimated PM bus emissions during production and transport taken from Beer et al. (2000) is 0.17 g/km. The use of more recent Australian data (Table 1.25) has reduced this figure to 0.10 g/km. The urban precombustion (truck) PM10 estimate from this LCA is 43 mg/km, as given in Table 1.22.

Air Toxics
Refinery equipment fugitive emissions leaks for NPI estimated as a percentage of total VOC released are in Table 1.8. The estimated percentages of VOC are:

Xylene: 0.28

Benzene: 0.14

Toluene: 0.7.

The LSD upstream emissions estimate of non-methanic volatile organic compounds (NMVOC) taken from Beer et al. (2000) is 2.01 g/km. The use of more recent Australian data (Table 1.25) has reduced this figure to 1.09 g/km. The urban precombustion (truck) NMHC estimate from the LCA is 0.292 g/km, as given in Table 1.22.

An accompanying disk to this report provides details, on a per km basis, of air toxics emissions from upstream activities.

1.6.2 Use

Particulate matter
Beer et al. (2000) found that PM combustion emissions from LSD from a Swedish Euro2 bus were 0.200 g/km. The use of more recent Australian data (Table 1.26) has led to an estimate of 0.68 g/km. The combustion (truck) PM10 estimate from this LCA is 0.038 g/km, as given in Table 1.23.

Air Toxics
The use of more recent Australian data (Table 1.26) has led to an estimate for buses of 1.62 g/km of NMVOC. Emissions are given for the other air toxics, however, no data was available for toluene and xylene combustion emissions. There is a substantial difference between the APACE 1999 Sydney bus results for HC and those reported in the Stage 1 Report of Beer et al. (2000). The combustion (truck) HC (assumed to be equivalent to NMVOC) estimate from the LCA is 0.900 g/km as given in Table 1.23.

1.6.3 LSD emissions summary

The LCA emissions analysis given in Section 1.4 indicates that:

- The primary source of CO emissions is during the fuel production phase.
- The primary source of NOx emissions is during the combustion phase.
- The primary source of NMHC emissions is during the fuel production phase.
- The primary source of PM emissions is during the combustion phase. The combustion (truck) PM10 estimate of 38 mg/km will be used in comparisons with the other fuels.
- There is considerable variability in estimates of combustion HC emissions for LSD. This complicates comparisons between LSD and the various fuels in the absence of more detailed air toxics data. The combustion (truck) HC (assumed to be equivalent to NMVOC) estimate from the LCA of 0.900 g/km will be used in comparisons with the other fuels.
- Benzene emissions are estimated at 0.002 g/km
- 1,3 butadiene emissions are estimated at 0.017 g/km
- Formaldehyde and acetaldehyde emissions are very variable.
- polycyclic aromatic hydrocarbon emissions are estimated at 0.076 g/km

1.6.4 OHS issues

Diesel is hazardous according to Worksafe Australia criteria, with moderate toxicity, a moderate hazard in relation to body contact, and a moderate hazard in relation to chronic effects. It is less hazardous than petrol, but as refineries produce both petrol and diesel from crude oil, many of the precautions needed to guard against the high flammability of petrol are also needed during the manufacture of diesel.

Long-term occupational exposure of workers in refineries can lead to lympho-haematopoietic cancers, which include leukaemia, multiple myeloma, and non-Hodgkin’s lymphoma. The Health Watch study of refinery workers (Bisby, 1993) found that the incidence of these diseases in ex-refinery workers was twice that expected in the general population.

The OHS issues in the lifecycle of LSD are covered by a range of State and Commonwealth occupation health and safety provisions.

Vapour Pressure Issues

There are minimal evaporative emission issues during the transport and use of LSD due to its relatively low volatility.

Evaporative emissions are a considerably more important issue for petrol- or gasoline-fuelled vehicles, compared with diesel vehicles. There is evidence (see for example NRC, 1991) that evaporative emissions from petrol vehicles have been consistently under-estimated, and recent studies have continued to demonstrate the importance of evaporative emissions.

1.7 Environmental Impact

Ecologically sustainable development is based on the principles of equity, efficiency and ecological integrity. The modern western economy is based on petroleum products, of which diesel is one. Though substantial arguments can be advanced that such an economy is not sustainable, in the sense that fossil fuels constitute a non-renewable resource, over the past three decades exploration activity has continually discovered new hydrocarbon reserves. In addition, the current concern over climate change has highlighted the burning of fossil fuels as one of the main causes. Thus even if one argues that the fossil fuel economy is economically efficient, it is more difficult to argue that it encourages equity or ecological integrity.

Diesel is refined from crude oil. Spills of crude oil, especially during transport in oil tankers at sea, pose an environmental hazard that contaminates marine life and bird life. Environmental damage from diesel itself can also occur, especially from leaks at service stations and refuelling depots that have been known to contaminate groundwater supplies.

1.8 Process trees

Figure 1.2 and 1.3 indicate process trees obtained from the SimaPro software used to undertake the quantitative life-cycle components of the study. These trees indicate, in an abbreviated form, the upstream components used to evaluate each component of the life-cycle.

To interpret the process tree, one starts at the top. Thus, in Figure 1.2, the values in the box refer to the mass (in kg) of CO_2-equ. To travel 1 km using LSD, there is a total of 0.926 kg emitted, as shown in the top box and summarised in Table 1.21. The fuel energy expended in travelling this 1 km is 10.8 MJ, as depicted in the second box down. The box below, which we shall call the fuel box, indicates that prior to combustion, the fuel tank contained 0.251 kg of fuel and that the upstream emissions of CO_2-equ to manufacture this fuel amounted to 0.207 kg CO_2-eq., as shown in Table 1.22.

Two separate process trees are depicted below the fuel box. The left hand side shows the upstream emissions involved in refining crude oil to produce diesel fuel. The process tree on the right shows the upstream emissions involved in hydro-processing to reduce the sulfur content of the fuel. For clarity, not all upstream processes are shown. If various upstream processes are not included, this is apparent by examining the bottom of the box. Small lines (tick marks) indicate that the full analysis consists of upstream processes feeding in to that box.

The computer software produces output in colour. On the right of each box there is a green line, with a red lower portion. The red lower proportion represents the proportion of the total value (0.926) accumulated up to that point. This can be seen by carefully examining the fuel box. The bottom 20% of the bar on the right of the box is darker than the remainder. The two top boxes have bars that are completely red.

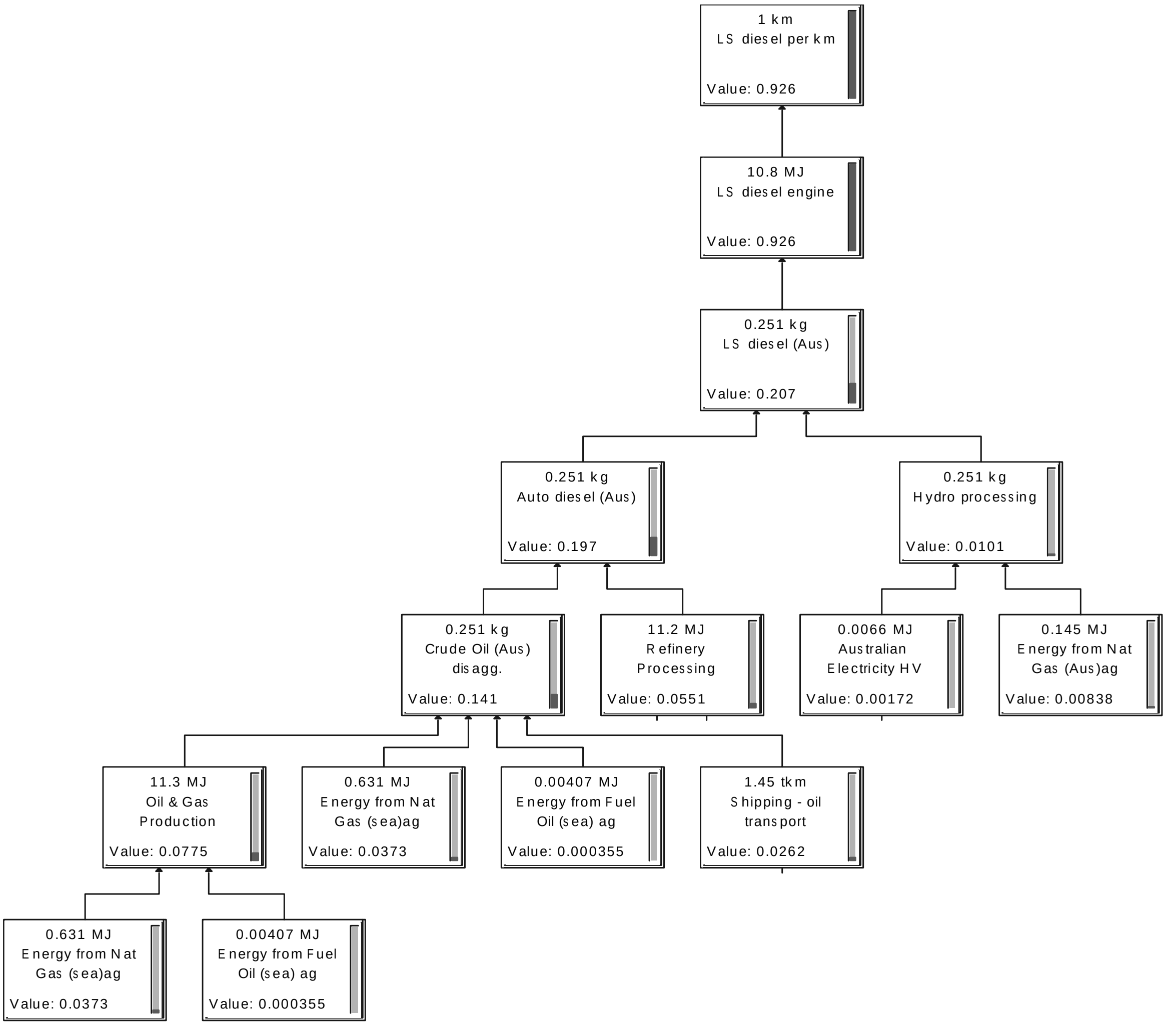

Figure 1.2
Exbodied greenhouse gases emissions (kg CO_2-eq) from LSD production, processing and use in vehicle. The value is given in the bottom of each box.

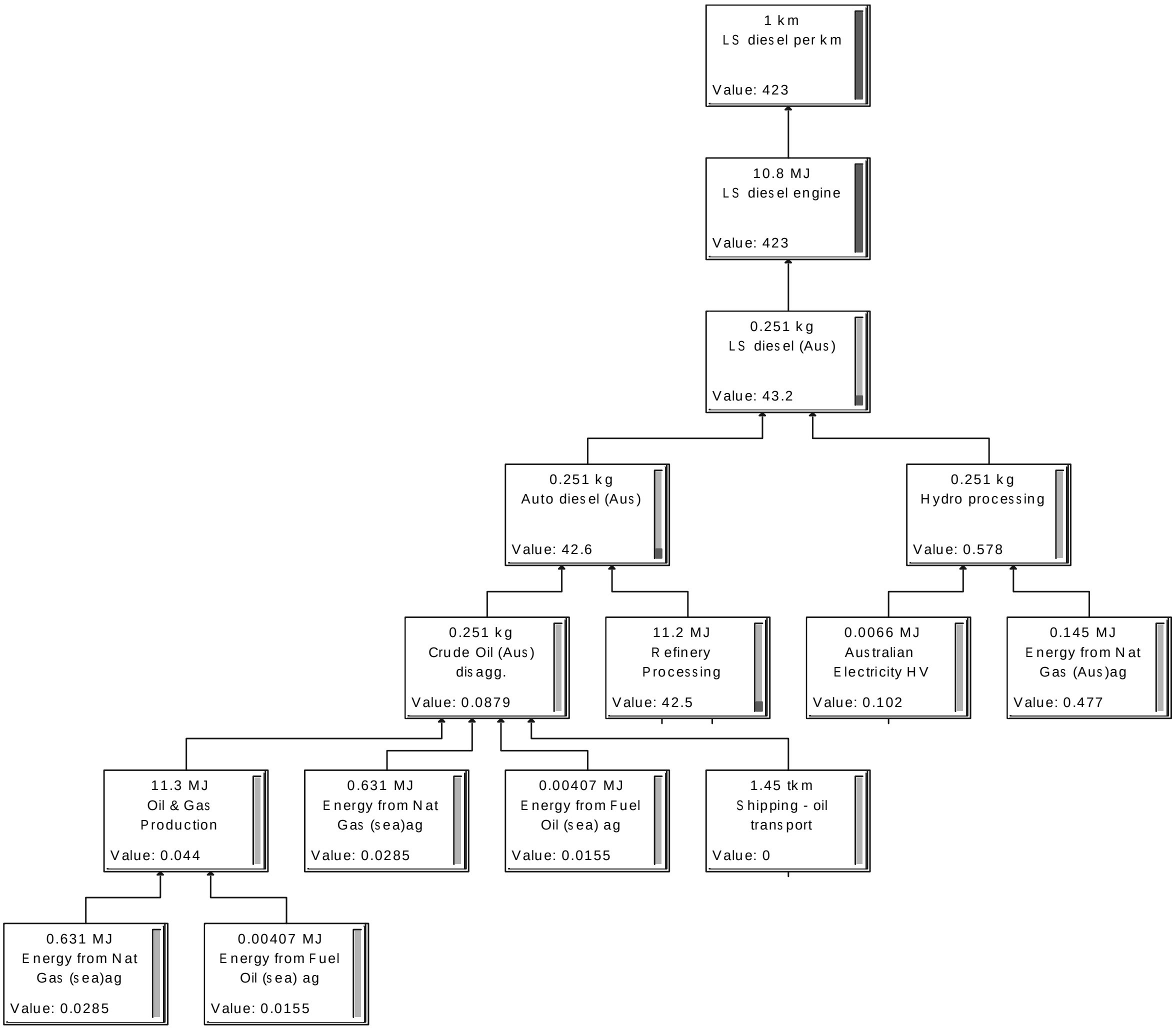

Figure 1.3
Exbodied particulate matter (mg - urban) from LSD production, processing and use.
The value is given in the bottom of each box.

2. Ultra-Low Sulfur Diesel

2.1 Background

Ultra-low sulfur diesel (ULSD) is diesel fuel that meets either the Euro4 fuel specifications for diesel fuel, or the fuel specifications proposed by the Commonwealth for implementation in 2006. To date, the only Euro4 fuel specification that has been established is for sulfur. Directive 98/70/EC of the European Communities in 1998 set the maximum sulfur level from 2005 as being 50 ppm. Euro3 specifications for other parameters such as the cetane number, cetane index, density, T95, and PAH levels, apply until replaced by revised specifications. These limits are shown in Table 2.1.

Table 2.1
Ultra-low sulfur diesel fuel quality specifications (Environment Australia, 2000a, 2000b)

Fuel parameter	Euro 3 (applicable from 2000)	Euro 4 (applicable from 2005)	Commonwealth (1 January 2006)
Sulfur (ppm)	350 (max)	50	50 (max)
Cetane number	51 (min)	-	-
Cetane index	46 (min)	-	50 (min)
Density at 15°C (kg/m^3)	845 (max)	-	820 to 850
Distillation T95 (°C)	350 (max)	-	360 (max)
PAH (% by mass)	11 (max)	-	11 (max)

Diesel fuel is generally derived from light virgin gas oil that is produced from the distillation of crude oil. The distillation is conducted in Australian refineries. Low sulfur diesel is produced in refineries with a hydro-desulfurisation unit. ULSD requires either a hydrocracker, or the use of higher pressures in the hydro-desulfurisation unit (hydrofining).

Greenhouse gas emission factors for diesel fuel may be found in Workbook 3.1 on transport of the Australian Greenhouse Gas Inventory methodology (National Greenhouse Gas Inventory Committee, 1998). A CO_2 emission factor of 69.7 g/MJ for diesel fuel (energy density of 38.6 MJ/L) is given in Workbook 3.1, whereas, for other emissions, the default emission factors are as given in Table 2.2.

Table 2.2
Emission factors for diesel vehicles expressed as g/km

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

Source: National Greenhouse Gas Inventory Committee (1998)

The values given in the Australian Greenhouse Gas Inventory are typical values representative of the Australian situation. They do not incorporate the possible changes to fuel properties arising from the different cetane values of LSD and ULSD produced by different refineries.

2.2 Upstream and Tailpipe Emissions

2.2.1 Tailpipe emissions

Parsons Australia Pty Ltd (2000) examined the emissions from a heavy truck using the CUEDC drive cycle using different diesel fuels of varying sulfur content. The results are given in Table 2.3, and these results are used in the subsequent calculations.

Table 2.3
Emissions and fuel consumption (FC) from a Euro 1 technology (ADR70) Rigid Truck (1995 Isuzu 900SUR) using a range of diesel fuels.

	S content mg/kg	CO_2 g/km	CO g/km	NOx G/km	HC g/km	PM (filter) mg/km	FC L/100km
Base Fuel	1700	782	3.45	10.63	1.01	447	32.92
Euro2	480	719	2.48	10.17	0.9	380	30.18
Euro3	210	746	2.75	10.47	0.95	313	31.22
Euro4	39	718	3.13	8.66	0.73	284	30.53
WorldWide	24	692	2.81	8.4	0.73	283	29.6
Californian diesel (CARB)	264	775	2.63	8.57	0.84	300	31.56

Source: Parsons Australia Pty Ltd (2000: Table 5.4)

The latest (and only other) Australian study of the heavy vehicle emissions from the use of ultra-low sulfur fuel was provided by BP Australia, namely that of Morawska et al. (2001). This report looked at the emission characteristics of LSD and ULSD used in a Volvo FL12 truck engine at constant speed. Three trucks were examined. Truck T3 had a catalytic converter, whereas trucks T1 and T2 did not. Table 2.4 summarises the Mode 5 data (50% load), by averaging the Western Australian and Queensland lower sulfur and ultra-low sulfur fuels for Trucks 1 and 2 for LSD and ULSD, and using the single reading for truck 3 for LSD+C, and ULSD+C.

Table 2.4
Emissions from Volvo FL12 trucks using low and ultra-low sulfur diesel fuel without and with (+C) a catalytic converter

	PM10 (mg/km)	CO_2 (g/km)	NOx (g/km)
LSD	729	1927	12
LSD+C	479	1677	7
ULSD	576	1958	11.5
ULSD+C	509	2009	9

2.2.2 Upstream

Production of low sulfur and ultra-low sulfur diesel

Diesel fuel is manufactured using crude oil as a feedstock. Depending on the characteristics of the crude oil(s) used, a number of different refinery streams may be blended to produce diesel fuel complying with the relevant specification. These streams most commonly include straight run distillate, light cycle oil (LCO) produced from heavier fractions in a fluid catalytic cracker (FCC) and vacuum gasoil (VGO). Sulfur contents of these fractions depends on the feedstock crude oil used and may be as high as 2%, and their boiling range falls between 150°C and 380°C. Refineries may be configured in many ways, depending on the properties of the crude oil feedstock and desired products spectrum. An example flow diagram of crude oil processing is presented in Figure 2.1.

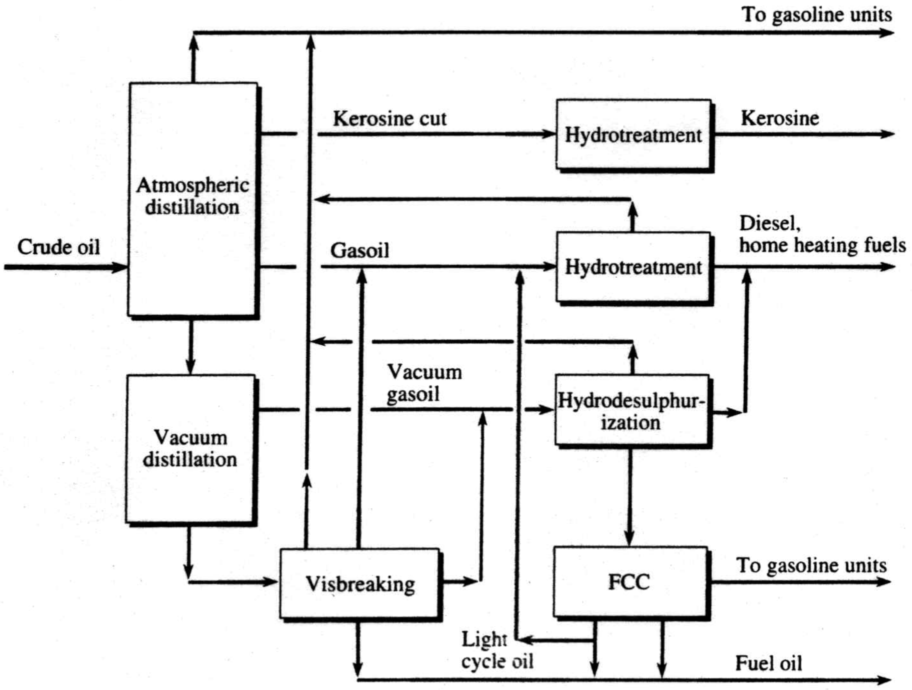

Figure 2.1
Typical flow-chart for crude oil processing

Diesel fuel currently used in Australia has a sulfur content of around 1300 ppm. As from 31 December 2002, new low sulfur diesel specifications will apply requiring the sulfur content of diesel fuel to be lower than 500 ppm. From 1 January 2006 ULSD will be required.

High levels of sulfur in diesel fuel are undesirable as during the combustion process they are converted to volatile sulfur oxides (SOx). These are corrosive and lead to increased engine wear. They also contribute directly to acid rain and produce solid sulfates, which add to the particulate matter in the exhaust gases.

Hydrodesulfurisation (HDS) is the process that is used to reduce sulfur. The process involves catalytic hydrogenation, which converts chemically bound organic sulfur into hydrogen sulfide (H_2S). It also improves the cetane number.

To meet the 500 ppm limit, a single stage HDS unit using Cobalt-Molybdenum (Co-Mo) and sometimes Nickel-Molybdenum (Ni-Mo) catalyst under moderate severity is adequate. Typical configuration of a HDS unit is shown in Figure 2.2.

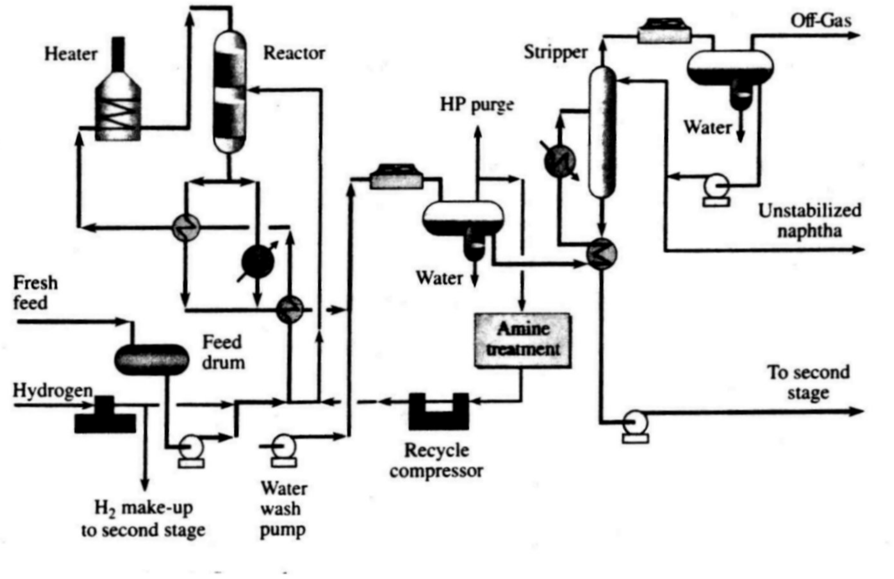

Figure 2.2
Flow diagram of single stage HDS unit

Further sulfur removal (down to below 50 ppm in the case of ULSD) requires a two-stage, high severity HDS unit using the Co-Mo catalyst in the first stage and Ni-Mo catalyst in the second stage. Hydrogenation of diesel over Co-Mo catalyst removes mostly sulfur associated with aliphatic hydrocarbons, while more active Ni-Mo catalyst facilitates hydrogenation of aromatic sulfur as well as saturation of aromatic hydrocarbons thus increasing cetane number and changing physical properties of resulting diesel such as viscosity and cloud point.

Basic assumptions on diesel production

Energy use for oil and gas production and transportation, and refinery processing is taken from the National Greenhouse Gas Inventory for 1998 (NGGIC, 2000) and are shown in Table 2.5.

We assume, based on Australian refinery practice, that the only difference in the energy used to process diesel, LSD and ULSD occurs during hydro-desulfurisation. Thus, we assume oil and gas are produced together and emissions and extraction energy are allocated between them based on the energy content of each fuel. Similarly, refinery products, such as diesel, LSD, ULSD, petrol, LPG and so on, are treated as co-products with the energy consumption, and consequent emissions being allocated to the output products (diesel, petrol, LPG), based on the energy content of each fuel.

Table 2.5
Energy use data for oil and gas production and refinery processing

	Fuel	Energy Use (PJ)	Production 1998[3] (PJ)	Energy use to energy production ratio (GJ/PJ produced)
Oil and gas production and field processing	Petroleum	0.9[1]	2528.6	0.36
	Gas	141.1[1]	2528.6	55.80
Natural gas transmission	Gas	8.6[1]	688.5	12.49
Gas production and distribution	Gas	2.4[1]	371.5	6.46
Petroleum Refining	Petroleum	87.2[2]	1663.8	52.41
	Gas	11.6[2]	1663.8	6.97

1 Fuel Combustion Activities 1A-2 (sheet 1): Emissions from manufacturing industries and construction (all sources) (NGGICf)

2 Fuel Combustion Activities 1A-1 (sheet 2): Emissions from Energy Industries (all sources) (NGGIC)

3 Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas (NGGIC)

Emissions from combusted fuels and fugitive emissions are also taken from the National Greenhouse Gas Inventory and are shown in Table 2.6. No Australian aqueous emission or solid wastes data was available for the crude oil, natural gas production or transport sectors, so data from European studies (Boustead, 1993) has been used as a proxy. This data is detailed in Table 2.7 and Table 2.8

Table 2.6
Fugitive greenhouse emission data for oil and gas production and refinery processing

		Fuel Quantity	CO_2	CH_4	N_2O	NOx	CO	NMVOC
		(PJ)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)
Oil	Exploration (for both oil and gas)	0	168	2.6		0.1	0.5	93.6
	Crude oil production	1257	14.8	0.2				0.1
	Crude oil transport: domestic	298		0.3				0.3
	Crude oil refining and storage	1664		0.2				1.3
	Petroleum product distribution	1102	153	1.9		0.1	0.5	34
Gas	Production and processing	1272		1.6				1
	Transmission	689		4.9				0.1
	Distribution	372	10.4	171.7				25.5
Venting and flaring for Oil and Gas Production	Venting at Gas processing plant	1272	2814	119.6				42.3
	Distributed Venting	860	749					
	Flaring	2646	2188	26.6	0.1	1.1	6.6	11.4

Source: Fugitive Emissions from Fuels 1B-2 (sheet 1): Oil and Natural Gas

Table 2.7
Aqueous emission for oil and natural gas production data from APME data for Europe

Emissions	mg/MJ Natural Gas	mg/MJ Crude Oil
Acid as H+	1.56	0.53
Metallic ions	0.19	0.09
CxHy	0.19	0.09
Suspended solids	1.56	0.71
Dissolved solids	1.36	0.18
Dissolved organics	0.78	0.36
Oil	1.36	0.53
Phenol	0.02	0.02

Source (Boustead, 1993)

Table 2.8
Aqueous emission for oil and natural gas production data from APME data for Europe

Emissions	mg/MJ Natural Gas	mg/MJ Crude Oil
Industrial waste	0.78	0.71
Mineral waste	0.08	0.07
Slags/ash	11.70	10.67
Inert chemicals	0.39	0.36

Source (Boustead, 1993)

For refineries, data on trace metals and volatile organic fugitive emissions was taken from the National Pollutant Inventory Guide book (Environment Australia 1999b), together with data submitted by refineries to the National Pollutant Inventory.

The controlled emission factor for particle emission from fluid catalytic cracking units is taken as 0.128 (Environment Australia, 1999b; Table 10, page 19). From this data, trace metal emission data are estimated using emission factors provided in the NPI guidebook (Environment Australia, 1999b: Table 11, page 20), which are shown in Table 2.9.

Table 2.9
Metal emissions to air for particulate matter from refinery operations

Metal emission	Controlled emission factor as weight % of total particulate matter
Nickel	0.031
Copper	0.003
Zinc	0.006
Selenium	0.003
Antimony	0.002
Lead	0.01
Cadmium	0.002
Mercury	0.001

Source: Extracted from Environment Australia (1999b: Table 11 p. 20)

Volatile organic emissions were estimated using emission factors related to total VOC emission from fugitive emission in refineries, given in the NPI guidebook (Environment Australia 1999b: Table 15 page 31). Data was given for a range of fugitive leaks such as flanges, valves, drains and pump seals. The lowest and most common was the data for flanges and valves, so this data was used to break down the VOC emission reported in the National Greenhouse Gas Inventory into different organic species as shown in Table 2.10.

Table 2.10
Speciation Data for NPI Substances from Equipment Fugitives[1]

Compound	Compound Weight Percent in VOCs Released
n-hexane	4.76
Cyclohexane	0.14
Xylenes	0.28
Benzene	0.14
Toluene	0.7

Source: Extracted from (Environment Australia 1999b: Table 15 page 32)

[1] Emission factors are for flange and valves

Organic and trace metal emission to water were also determined from data in the NPI Guide. Metal emissions are provided per cubic metre of waste water (Environment Australia 1999b: Table 20 page 41), while organic emission are provided as a weight percent of dissolved organic carbon (Environment Australia 1999b: Table 19 page 40. Waste water effluents and DOC loads per tonne of production were estimated from reported emission data from refineries to the National Pollutant Inventory. The data was conservatively estimated by dividing total flow by capacity, rather than production. This would have the effect of reducing the data on a per tonne basis. Emission factors for organics to water are presented in Table 2.11 while factors for metals emitted are provided in Table 2.12. The calculated average wastewater emission for Australian refineries was 30 L per tonne of product and the dissolved organic carbon (DOC) was calculated to be around 0.79 g per tonne of product.

Table 2.11
Default Speciation Factors for Organics in Refinery Effluent

Organic substance	NPI Substance Weight Percent of DOC
Toluene	0.00092
Benzene	0.00091
Xylenes	0.00140
Phenol	0.00069
1,2-Dichloroethane	0.00027
Hexachlorobenzene	0.00000
PAHs	0.00160
Styrene	0.00010
Ethylbenzene	0.00012
1,1,2-trichloroethane	0.00004
Chloroform	0.00250

Source: Environment Australia 1999b: Table 19 page 40

Table 2.12
Default Emission Factors for Trace Elements and Inorganics in Refinery Effluent

Trace Elements	NPI Substance Emission Factors (kg/m^3 of flow)
Zinc	4.40E-04
Phosphorous	4.10E-07
Arsenic	6.70E-06
Chromium(VI)	7.70E-06
Selenium	3.10E-06
Nickel	3.60E-06
Copper	2.90E-06
Antimony	5.80E-07
Cobalt	1.60E-06
Mercury	1.10E-08
Cadmium	3.30E-07
Lead	1.90E-06
Cyanide	7.60E-09
Ammonia	1.30E-06

All energy use throughout fuel processing is assumed to have a greenhouse emission profile as of standard fuel combustion as described in the National Greenhouse Gas Inventory in Fuel Combustion Activities 1A-1 (sheet 1): Emissions from Energy Industries (all sources) (NGGIC 1998). Air emissions of organic and inorganic substances, and particles are taken from the National Pollutant Inventory Emission Estimation Technique Manual for Combustion in Boilers (Environment Australia 1999a). Grid supplied electricity data is taken from the Australian LCA inventory data project, described in (Grant 2000).

Assumptions for production of low sulfur diesel

Discussions with Mr Mark Sanders of BP, an expert in refinery operation, updated the previous assumptions that were made regarding additional processing to produce lower sulfur diesel. For low sulfur diesel (500ppm S) a hydro-desulfurisation unit would be required on top of current refinery operations. Beer et al. (2000) assumed that for ultra-low sulfur fuel a hydrocracking unit would be required on top of normal refinery operations. More recent information indicates that existing hydrofiners can be used to produce ULSD by employing more active catalysts, increased hydrogen purity, and reduced space velocities. In the absence of better data, information on the two processes has been taken from standard equipment specifications. The data for this is shown in Table 2.13. The life-cycle calculations have been undertaken for existing Australian conditions with 50% of ULSD from a hydro-desulfurisation unit and 50% of ULSD from a hydrocracking unit. In addition, a second scenario (marked as 100% hydroprocessing) calculates emissions if all Australian refineries use only hydro-desulfurisation units.

Table 2.13
Additional inputs to produce 1 tonne LSD and ULSD from 1 tonne current diesel

	Equipment	Electricity	Energy from Gas oil	Steam
		kWh	MJ	kg
Low Sulfur	Hydro-desulfurisation unit	7.3	577	0
Ultra-low Sulfur	Hydrocracking Unit	50.3	1578	95

Source: J. Hydrocarbon Processing. (supplied by M. Sanders, pers. comm.)

2.3 Results

2.3.1 Emissions per unit energy

Table 2.14
Urban and total life cycle emissions per MJ calculated for low and ultra-low sulfur diesel

Full Lifecycle	Units (per MJ)	LS diesel	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.0858	0.0881	0.0877
NMHC total	g HC	0.140	0.128	0.131
NMHC urban	g HC	0.111	0.097	0.098
NOx total	g NOx	1.044	0.915	0.909
NOx urban	g NOx	0.987	0.855	0.844
CO total	g CO	0.253	0.314	0.313
CO urban	g CO	0.242	0.303	0.301
PM10 total	mg PM10	40.7	31.9	32.2
PM10 urban	mg PM10	39.3	30.4	30.6
Energy Embodied	MJ LHV	1.18	1.27	1.34

Table 2.15
Urban and total precombustion emissions per MJ for low and ultra-low sulfur diesel

Precombustion	Units	LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.0191	0.0222	0.0218
NMHC total	g HC	0.0565	0.0614	0.0642
NMHC urban	g HC	0.027	0.030	0.031
NOx total	g NOx	0.100	0.120	0.114
NOx urban	g NOx	0.043	0.060	0.049
CO total	g CO	0.023	0.027	0.026
CO urban	g CO	0.012	0.016	0.014
PM10 total	mg PM10	5.42	5.84	6.16
PM10 urban	mg PM10	4	4.33	4.55
Energy Embodied	MJ LHV	1.18	1.27	1.34

Table 2.16
Urban and total combustion emissions per MJ for low and ultra-low sulfur diesel

Combustion	**Units**	**LSD**	**ULSD**
Greenhouse	kg CO_2	0.067	0.066
NMHC total	g HC	0.084	0.067
NMHC urban	g HC	0.084	0.067
NOx total	g NOx	0.944	0.795
NOx urban	g NOx	0.944	0.795
CO total	g CO	0.230	0.287
CO urban	g CO	0.230	0.287
PM10 total	mg PM10	35.26	26.08
PM10 urban	mg PM10	35.26	26.08
Energy Embodied	MJ LHV	0	0

Table 2.17
Summary of life cycle emissions per MJ for ultra-low sulfur diesel

		LSD	**ULSD**	**ULSD (100% hydroprocessing)**
Greenhouse	Precombustion	0.0191	0.0222	0.0218
Greenhouse	Combustion	0.0667	0.0659	0.0659
NMHC total	Precombustion	0.0565	0.0614	0.0642
NMHC total	Combustion	0.0835	0.0670	0.0670
NMHC urban	Precombustion	0.0271	0.0297	0.0308
NMHC urban	Combustion	0.0835	0.0670	0.0670
NOx total	Precombustion	0.1000	0.1200	0.1140
NOx total	Combustion	0.944	0.795	0.795
NOx urban	Precombustion	0.043	0.060	0.049
NOx urban	Combustion	0.944	0.795	0.795
CO total	Precombustion	0.0225	0.0270	0.0256
CO total	Combustion	0.2301	0.2874	0.2874
CO urban	Precombustion	0.0123	0.0159	0.0139
CO urban	Combustion	0.2301	0.2874	0.2874
PM10 total	Precombustion	5.42	5.84	6.16
PM10 total	Combustion	35.26	26.08	26.08
PM10 urban	Precombustion	4.00	4.33	4.55
PM10 urban	Combustion	35.26	26.08	26.08
Energy Embodied	Precombustion	1.18	1.27	1.34

2.3.2 *Emissions per unit distance*

Table 2.18

Urban and total life cycle emissions per km calculated for low and ultra-low sulfur diesel

Full Lifecycle	Units (per km)	LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.9250	0.9470	0.9270
NMHC total	g HC	1.509	1.363	1.346
NMHC urban	g HC	1.192	1.036	1.026
NOx total	g NOx	11.250	9.900	9.750
NOx urban	g NOx	10.638	9.275	9.133
CO total	g CO	2.723	3.408	3.376
CO urban	g CO	2.612	3.294	3.264
PM10 total	mg PM10	438.4	344.2	343.1
PM10 urban	mg PM10	423.1	328.6	327.6
Energy Embodied	MJ LHV	12.7	13.1	12.9

Table 2.19
Urban and total precombustion emissions per km for low and ultra-low sulfur diesel

Precombustion	Units (per km)	LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.2060	0.2290	0.2090
NMHC total	g HC	0.609	0.633	0.616
NMHC urban	g HC	0.292	0.306	0.296
NOx total	g NOx	1.080	1.240	1.090
NOx urban	g NOx	0.468	0.615	0.473
CO total	g CO	0.243	0.278	0.246
CO urban	g CO	0.132	0.164	0.134
PM10 total	mg PM10	58.4	60.2	59.1
PM10 urban	mg PM10	43.1	44.6	43.6
Energy Embodied	MJ LHV	12.7	13.1	12.9

Table 2.20
Urban and total combustion emissions per km for low and ultra-low sulfur diesel

Combustion	Units	LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	kg CO_2	0.719	0.718	0.718
NMHC total	g HC	0.900	0.730	0.730
NMHC urban	g HC	0.900	0.730	0.730
NOx total	g Nox	10.170	8.660	8.660
NOx urban	g Nox	10.170	8.660	8.660
CO total	g CO	2.480	3.130	3.130
CO urban	g CO	2.480	3.130	3.130
PM10 total	mg PM10	380.00	284.00	284.00
PM10 urban	mg PM10	380.00	284.00	284.00
Energy Embodied	MJ LHV	0	0	0

Table 2.21
Summary of life cycle per km emissions from ultra-low sulfur diesel

		LSD	ULSD	ULSD (100% hydroprocessing)
Greenhouse	Precombustion	0.2060	0.2290	0.2090
Greenhouse	Combustion	0.7190	0.7180	0.7180
NMHC total	Precombustion	0.6090	0.6330	0.6160
NMHC total	Combustion	0.9000	0.7300	0.7300
NMHC urban	Precombustion	0.2920	0.3060	0.2960
NMHC urban	Combustion	0.9000	0.7300	0.7300
NOx total	Precombustion	1.0800	1.2400	1.0900
NOx total	Combustion	10.170	8.660	8.660
NOx urban	Precombustion	0.468	0.615	0.473
NOx urban	Combustion	10.170	8.660	8.660
CO total	Precombustion	0.2430	0.2780	0.2460
CO total	Combustion	2.4800	3.1300	3.1300
CO urban	Precombustion	0.1320	0.1640	0.1340
CO urban	Combustion	2.4800	3.1300	3.1300
PM10 total	Precombustion	58.40	60.20	59.10
PM10 total	Combustion	380.00	284.00	284.00
PM10 urban	Precombustion	43.10	44.60	43.60
PM10 urban	Combustion	380.00	284.00	284.00
Energy Embodied	Precombustion	12.70	13.10	12.90

2.3.3 Uncertainties

We use the uncertainty estimates given by Beer et al. (2000) on the basis of the tailpipe emissions to estimate the uncertainties associated with the above results to be as given in Table 2.22.

Table 2.22
Estimated one standard deviation uncertainties (in percent) for ultra-low sulfur diesel emissions

	g/MJ	g/t-km	g/p-km
CO_2	10	9	11
NMHC	34	50	17
NOx	29	30	27
CO	111	144	78
PM10	45	39	50

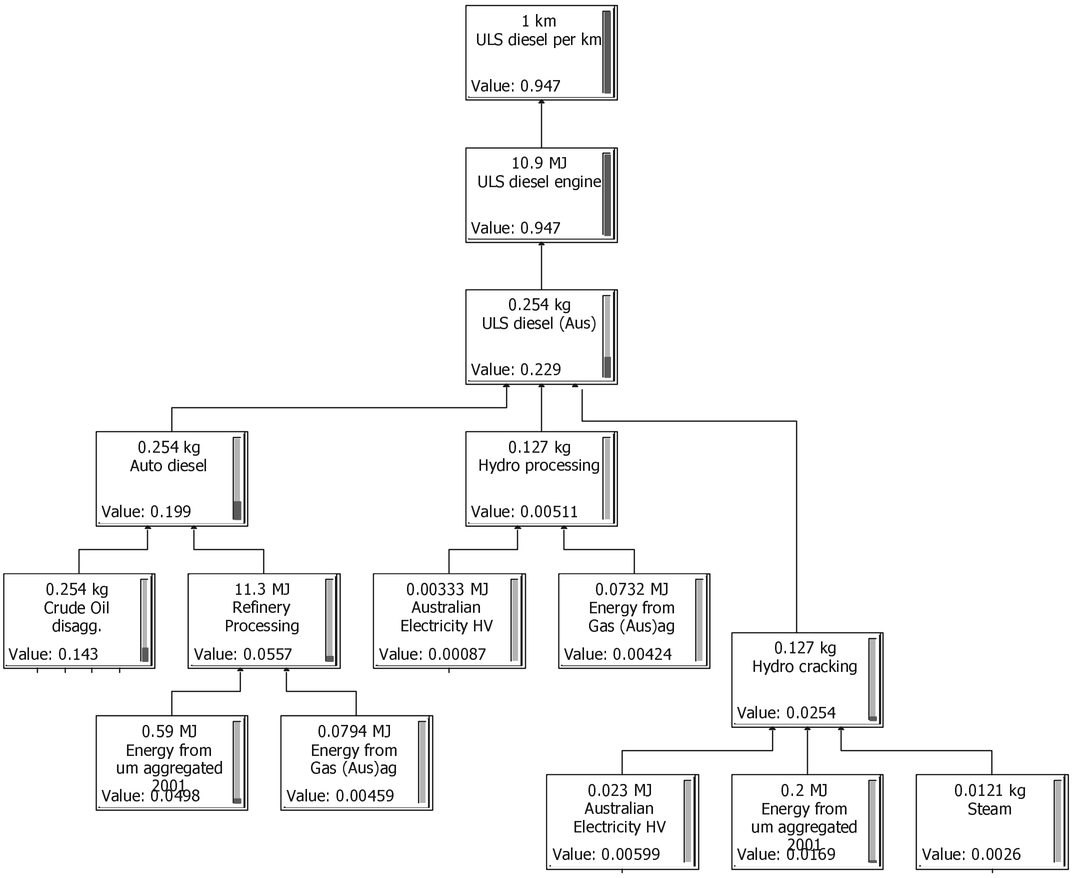

Figure 2.3

Exbodied greenhouse gases emissions (kg CO_2eq) from ULS diesel production and processing and use in vehicle (50% produced using hydro-cracking unit)

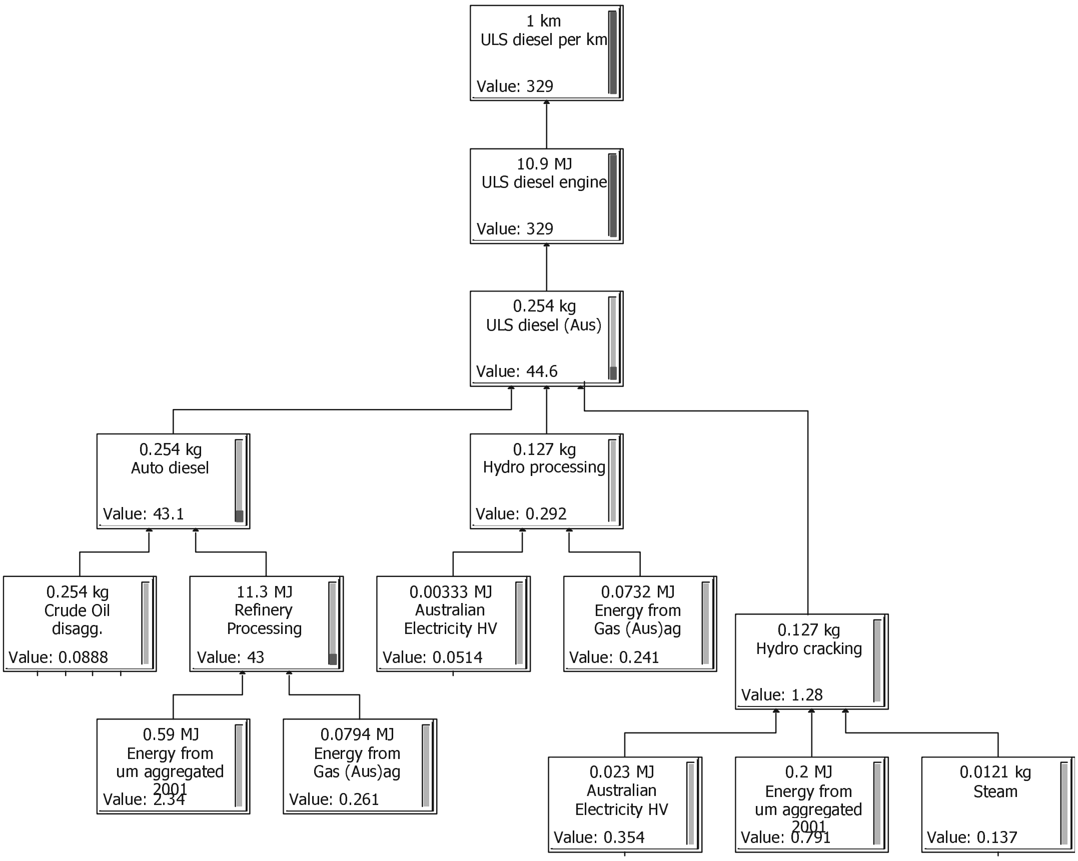

Figure 2.4
Exbodied particulate matter (mg - urban) from ULS diesel production and processing and use in vehicle (50% produced using hydro-cracking unit)

2.4 Viability and Functionality

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on engine performance arising from the introduction of low sulfur diesel and ULSD. The comments in the fuel quality review are echoed by the submissions that were received as part of this study. The Federal Chamber of Automotive Industries (FCAI) notes that in the case of low sulfur diesel 500 ppm is regarded as far too high. Sulfur levels of 100 ppm or less will be needed to ensure that exhaust after-treatment systems function efficiently and allow successful development of clean diesel engines that can realise the inherent fuel efficiency of diesel engines. With respect to ULSD, the FCAI consider the 50 ppm sulfur level as still being too high in terms of providing satisfactory exhaust emissions expected of low emission diesel engines.

BP Australia emphasise the need to match the fuel with the appropriate vehicle technology. They point out that the major benefits of the move to ULSD are provided by the ability to use advanced technology in the engine and the catalyst. These components are often sensitive to sulfur. Therefore it is essential to show the vehicle emissions that are possible with the appropriate Euro4 fuelled engines once both the fuels and the vehicles are available, as is expected to be the case within the next five years. Using ULSD in a Euro2 vehicle will provide only marginal improvement in tailpipe emissions over low sulfur diesel. However, the emissions from a Euro4 vehicle with advanced on-board diagnostics and a particle trap are expected to be dramatically better.

2.5 Health Effects

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on health effects arising from the introduction of low sulfur diesel and ULSD. This report points out that diesel engines are a major source of fine particles – diesel exhaust releases particles at a rate about 20 times greater than that from petrol-fuelled vehicles. Thus the combination of ULSD and particle traps on vehicles using ULSD will reduce the emissions of particles.

The reduction in the number of particles will have two beneficial effects. It will assist in the attainment of the national ambient air quality standard for particles. In addition, diesel engine exhaust contains both small carbonaceous particles and a large number of chemicals that are absorbed onto these particles. The fuel quality review cites studies that have indicated that diesel particles are mutagenic and carriers of compounds that are suspected of contributing to the rise in cancer cases in city areas with a large proportion of diesel-fuelled vehicles.

2.5.1 ***Production and Transport***

The upstream health issues associated with ultra-low sulfur diesel are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

Particulate matter

The LCA estimate for ULSD urban precombustion (truck) PM10 emissions of 45 mg/km is similar to the LSD estimate of 43 mg/km.

Air toxics

The LCA estimate for ULSD urban precombustion (truck) NMHC emissions of 0.306 g/km is similar to the LSD estimate of 0.292 g/km.

The public health effects of air toxics will be mainly associated with combustion emissions in large urban centres. An accompanying disk to this report provides details of air toxic emissions from upstream activities.

2.5.2 ***Use***

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on the environment arising from the introduction of low sulfur diesel and ultra-low sulfur diesel. The combination of ULSD and oxygenating catalysts or “de-NOx” catalysts will enable emissions of smog precursors to diminish, thus improving urban air quality.

2.5.3 ***Particulate matter***

The LCA estimate for ULSD combustion (truck) PM10 emissions of 284 mg/km is less than the LSD estimate of 380 mg/km.

2.5.4 Air toxics

Diesel fuel formulation appears to have little effect on emissions of VOCs and aldehydes, suggesting that the formation of these species in diesel exhaust is controlled by the combustion process. (Parsons Australia Pty Ltd, 2000)

The LCA estimate for ULSD combustion (truck) NMHC emissions of 0.73 g/km is similar to the LSD estimate of 0.9 g/km.

2.5.5 Summary

ULSD upstream particle and NMHC emissions are similar to LSD. ULSD tailpipe NMHC emissions are similar to LSD and have little effect on emissions of VOCs and aldehydes. ULSD reduces particle emissions compared to LSD.

2.6 OHS Issues

The upstream OH&S issues associated with ultra-low sulfur diesel are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

2.7 Vapour Pressure Issues

The vapour pressure issues associated with ultra-low sulfur diesel are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

2.8 Summary

The advantages of ultra-low sulfur diesel are:

- ULSD contains little sulfur and few aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The low sulfur content means that oxidation catalysts will be more efficient.
- The existing diesel infrastructure can be used, unchanged, for ultra-low sulfur diesel.
- Low-sulfur diesel can be used in existing diesel engines.
- Diesel is one of the safest of the automotive fuels.

The disadvantages of ultra-low sulfur diesel are:

- Diesel exhaust (including ULSD exhaust) is treated by the US EPA as an air toxic.
- Because of the extra processing energy, ULSD produces more exbodied greenhouse gases than LSD.

2.9 Environmental Issues

The fuel quality review (Environment Australia, 2000a, 2000b) lists the impact on the environment arising from the introduction of low sulfur diesel and ULSD. The combination of ULSD and oxygenating catalysts or “de-NOx” catalysts will enable emissions of smog precursors to diminish, thus improving urban air quality.

The upstream environmental issues associated with ULSD are the same as low sulfur diesel and are dealt with in the section on low sulfur diesel.

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