9. Liquefied Natural Gas

9.1 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 NG used in Melbourne in 1997/98 was 91.6% methane, 5.0% ethane, 0.4% propane, 0.1% butane, 0.8% nitrogen and oxygen, and 2.1% carbon dioxide. NG is consumed in the residential, commercial, industrial, and utility markets.

The interest in NG as an alternative fuel stems mainly from its clean burning qualities, its domestic resource base, and its commercial availability to end-users. Because of the gaseous nature of this fuel, it must be stored on board a vehicle in either a compressed gaseous state (CNG) or in a liquefied state (LNG). In Australia, CNG is compressed to around 20 MPa for on-board storage. Methane liquefies at –161^{o}C. LNG is generally refrigerated to –180^{o}C for liquefaction, and requires vacuum-insulated cryogenic tanks to maintain it in liquid form for storage.

9.1.1 Natural gas manufacture

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

9.1.2 Natural gas market

The chapter on compressed NG includes a description of the pipeline system that is used to distribute NG throughout Australia.

LNG has long been used as a substitute for marine diesel fuel and is starting to be used as a heavy vehicle fuel. The low temperature facilities that are needed are expensive, and their manufacture, installation and operation increases the life-cycle emissions of greenhouse gases. The life-cycle emissions of LNG are likely to be comparable with those of CNG, as summarised above, except that the CO_2 emissions will be higher. The LNG market niche is centrally fuelled, heavy-duty fleet vehicles with high fuel consumption, where fuel cost savings can amortise equipment capital costs. LNG vehicle life-cycle costs will be lower than those for diesel vehicles when LNG equipment prices decrease and/or financial benefits such as emission reduction credit sales are realised. While there are no severe LNG vehicle technology problems, improvements are needed in areas such as accurate fuel level and flowrate instrumentation. The safety record is good, but it is difficult to quantitatively rate the LNG safety relative to gasoline and diesel vehicles because the statistical data needed does not yet exist. According to news reports at (http://www.lngexpress.com/japa.htm), Japan has a research program focussing on the use of

LNG in heavy-duty trucks and buses. Because Japan imports large quantities of LNG by sea, the cheapest fuel for a vehicle would be the imported LNG without any treatment. Japan therefore hopes to convert its diesel trucks and buses to LNG. The Australian situation is substantially different. Most NG is piped in gaseous form, not shipped. Centralised LNG facilities exist near Perth, Melbourne and Alice Springs. They are all relatively small scale. According to the Australasian Natural Gas Vehicle Council, recent developments also mean that smaller scale on-site liquefaction plants are likely to become more viable in Australia in the near future.

9.1.3 Fuel characteristics

NG has very different fuel characteristics from the fuels normally used in internal combustion engines. Louis (2001) cites a lower heating value of 52.9 MJ/kg. According to Perry's Chemical Engineering Handbook (5^{th} edition, 1973: p. 9–13) the higher heating value of LNG, at –164^{o}C is 23.9 MJ/L (when converted from imperial units). This corresponds to a lower heating value of 21.7 MJ/L, which is below that of automotive diesel (38.6 MJ/L). These two results indicate that LNG has a density of 0.41 kg/L. For comparison, as a gas its density, at 0.70 g/L, is lower than that of air.

9.1.4 Implications for engine conversions

According to a submission from Wesfarmers LNG:

"LNG as a heavy duty vehicle fuel is a recent development; improvements in vehicle tanks, storage vessels and dispensers have all contributed to its adoption by heavy vehicle fleets, and bus and locomotive operators. OEM manufacturers such as Cummins, Caterpillar and Detroit have greatly assisted by providing the heavy duty vehicle engines for NG. LNG gives these operators' vehicle range and refuelling times comparable to diesel without any power to weight disadvantages. Vacuum-insulated vehicle tanks are designed to replace the diesel units without any vehicle modifications. So, off-road down-time for truck/bus conversion is minimal.

It is estimated that there are 2,300 plus LNG vehicle globally, all currently in the northern hemisphere. An indication of the growth of this fuel is that a third vehicle tank manufacture is setting up to produce 1000 tanks per annum.

LNG will shortly be available from Wesfarmers Plant, North West Shelf Gas are to construct a domestic terminal supplying gas retailers from their existing facility and the possibility exists of LNG being available from the Victorian plant.

The first dedicated LNG truck is in Australia and will be shown to the industry at the Asia Pacific Natural Gas Vehicle Summit in Brisbane in April 2001."

9.2 Full Fuel-Cycle

9.2.1 Tailpipe

Collison et al. (1997) review the Maryland Mass Transit (MTA) pilot study of LNG buses using Cummins L10-240G NG engines. In this case the use of LNG, rather than CNG, arose because the heavy tanks needed to withstand CNG pressures meant that the extra weight (1,300 kg) put the buses close to their gross vehicle rating with just a modest passenger load. Using LNG resulted in a practical operating range. The MTA diesel buses averaged about 1.02 km/L and the

MTA LNG buses averaged about 1.02 km/L per diesel equivalent litre (based on the energy content of the fuels). Collison et al. (1997) claim that newer versions of the engines will improve fuel economy by using oxygen sensors and closed-loop computer controls during driving. However, idle fuel consumption consistently remains higher than that of diesel engines.

Table 9.1 shows the emissions obtained from the use of LNG buses. The measurements originally given in units of g/hp-h have been converted to g/kWh and g/MJ.

Table 9.1
Emissions from LNG buses using Cummins L-10 240G engines

	g/hp-h	g/kWh	g/MJ	LNG bus g/km	1998 Diesel bus g/km
NOx	2	2.68	0.74	5.1	10.7
PM	0.02	0.03	0.007	0.05	0.13
VOC	0.6	0.8	0.22	1.53	3.5

Source: (Collison et al. 1997)

In Table 9.2 we compare these to the emissions from the Cummins L-10 260G engines.

Table 9.2
Emissions from LNG buses using Cummins L-10 260G engines

	g/kWh
NOx	2.3
PM	0.03
NMHC	0.3
CO	0.5

Source: (Nylund and Lawson, 2000: Table 7.2))

Battelle (2000) provides a comprehensive evaluation of the Dallas Area Rapid Transit (DART) LNG bus site. These buses used the same Cummins L-10 G series of engines (Cummins L-10 280G in this case) even though Cummins discontinued the L-10G engine for NG operation in early 1999. Cummins continues to offer the C8.3G and B5.9G engines for transit and truck operation. Table 9.3 reproduces its data after conversion to metric units.

Table 9.3
DART LNG vehicles compared to diesel baseline vehicles (g/km)

Fuel	CO	NOx	THC	CH_4	NMHC[c]	PM	CO_2	km/L	MJ/km
LNG	0.146	13.28	8.56	7.81	0.03	a	1397	1.412[b]	25.49
Diesel	2.76	15.83	0.72		0.72	0.20	1640	1.641	22.20

a. Below limit of detection.
b. The fuel consumption mpg and km/L for the LNG are not the actual consumption figures. They are based on a miles per equivalent gallon using 137 cubic feet of NG at STP being equivalent to 1 gallon of ordinary (high sulfur) diesel.
c. The report claims that NMHC is calculated using THC-CH_4. The numbers in the report, reproduced in this table, do not obey this formula.

The Australasian Natural Gas Vehicle Council kindly provided emissions data from the latest generation of engines taken from various studies including UK test data on a CNG 113M engine using Mobil CNG (Andrew, 2001), data from Cummins on their 8.3 litre diesel and C8.3G engine with and without catalyst (Lyford-Pike, 2001) and data from a 9.8 L Transcom modified Renault 620-45 NG engine (AEC Limited), as well as data from South Australian CNG buses (ANGVC, 2001). The data in Table 9.4 was used in the quantitative analysis.

Table 9.4
Scania diesel and CNG test results (g/kWh) in the UK (Andrew, 2001)

	HC	CO	NOx	PM	CO_2
Diesel	0.864	1.442	7.014	0.373	756.3
CNG	0.212	0.018	0.962	0.007	674
LNG	0.18	0.017	1.532	0.013	698

Table 9.4 provides results of a test of the present generation of diesel engines (Scania DSC 11-21) as tested at the Millbrook Proving Ground in January 2001 (Andrew, 2001). The drive cycle was not specified. However, as the European Community requires Euro3 standards for heavy vehicles as from January 2000, we expect that both the engines and the test regime corresponded to Euro3. The specific fuel consumption during the test of the CNG vehicle was 190 g/kWh at 1100 to 1800 rpm. The minimum range of the CNG truck was 560 km. The truck achieved a range in excess of 640 km by increasing the CNG pressure from 200 bar to 250 bar.

9.2.2 Upstream emissions

Most LNG production facilities are located in north-western WA. At present all LNG produced is exported using purpose-built tankers. In case of the use of LNG in Australia as fuel for heavy vehicles, the production and delivery scenario of Figure 9.1 needs to be considered (IEA, 1997). There is no data on fugitive emissions of LNG trucked from the North West Shelf to appropriate distribution points, especially as vehicles powered by LNG will use LNG boil-off as part of their power source.

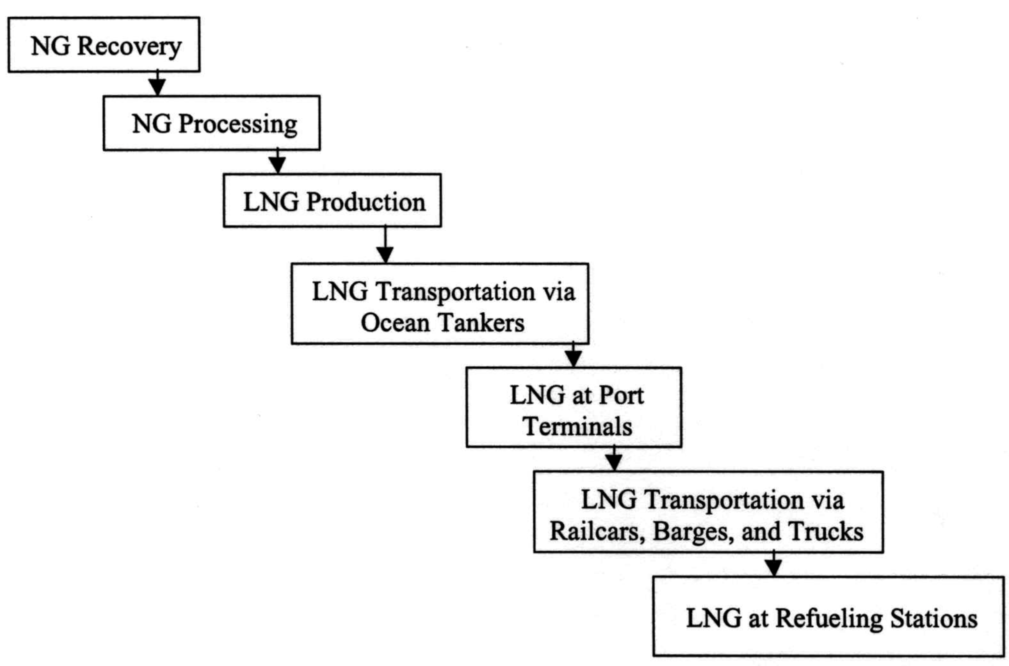


Figure 9.1
LNG production and delivery flowsheet.

Part 2 Details of Fuels

The composition of the NG considered in this study is given in Table 9.5.

Table 9.5
Composition of the NG considered in this study

Component	Mol% (dry basis)
Methane (C1)	86.6
Ethane (C2)	5.8
Propane (C3)	3.1
Iso Butane (iC4)	0.8
Normal butane (nC4)	0.5
Pentane (C5)	0.5
Hexane plus (C6+)	0.1
Nitrogen (N_2)	0.4
Carbon dioxide (CO_2)	2.0
	100.0

Before liquefaction the gas is dried and the carbon dioxide removed. Carbon dioxide is removed using an amine wash system and exhausted into the atmosphere. Sulfur and all components likely to freeze during liquefaction (moisture, higher hydrocarbons) are also removed.

The liquefaction plant is modelled on the Air Products & Chemical multi-component refrigerant process with propane pre-cooling, which is the most common technology used in recent years. The refrigerant compressors consume the bulk of the power needed to operate the plant.

Transport calculations are based on a ship capacity of 75000 m^3. A full vapour return system is assumed to be operative at the loading jetty and the reception terminal. This means that any boil-off during loading and unloading operations is recovered.

Cargo boil-off during the sea voyage is used for powering ship’s utilities and for the vessel’s propulsion. Any shortfall of fuel is made up by fuel oil.

LNG can be delivered from port terminals to bulk terminals and refuelling stations via rail or road. Storage of LNG as cryogenic liquid in insulated storage vessels at pressures between 4 and 10 Bar is a standard practice. Any boil-off at storage facilities is recovered and used as fuel.

Data on liquefaction is taken from an International Energy Agency report on the existing state of the art facility in Sarawak (Malaysia) with corrections appropriate for the North West Shelf LNG facility. Inputs to LNG production are shown in Table 9.6

Table 9.6
Energy use in NG liquefaction

Fuel	Efficiency	Value in MJ	Comment
Energy from NG	94.6%	2686	90.5 MJ per 1000 MJ Gas (51.3 MJ/kg) compressed

Source : IEA Report No. PH2/12 “LNG Full Fuel Cycle: Emissions & Private Costs”, October 1997.

Production data for NG and emission data from energy from NG are shown in the CNG section.

For the shipping of LNG a total fuel use of 0.16 MJ per tonne.kilometre of gas transported is derived from the IEA data (Executive Committee of IEA Greenhouse Gas R&D Programme, 1997). Emissions are taken to be the same as those for NG usage in boilers, which is detailed in the CNG section.

9.2.3 Fugitive emissions

NG can contain significant quantities of naturally occurring CO_2, which in the past has often been vented to the atmosphere at the well-head. Le Cornu (1989) pointed to Cooper Basin gas as having up to 35 per cent by weight (12.7 per cent by volume) of naturally occurring CO_2. On a state-by-state basis, vented CO_2 accounts for between 3 and 15 per cent of full fuel-cycle CO_2 emissions from NG combustion (Wilkenfeld, 1991). Fugitive emission data used for NG production is described in the CNG section. A process tree for LNG production is shown in Figure 9.2 with the methane emission shown in grams as the lower value in each process box. The largest fugitive emission is in the assumed loss in fuel distribution, which is discussed in more detail below.

9.2.4 Methane emissions from vehicles

There is no data on fugitive emissions of LNG trucked from the North West Shelf to appropriate distribution plants, especially as vehicles powered by LNG will use LNG boil-off as their power source. Methane, the principal component of NG, has a greenhouse radiative forcing of 21 over a 100-year period. It is therefore important that tailpipe losses of unburnt fuel and fugitive/evaporative losses are minimised.

Because methane is a non-reactive hydrocarbon, tailpipe emissions of methane are less well controlled by catalytic converters than the emissions of more reactive hydrocarbons (BTCE, 1994).

Experience with the LNG road train built to operate between Alice Springs and Yulara over a decade ago suggests that fugitive losses from LNG boil-off in intermittent use may not be a major problem. The LNG tanks, filled to 90 per cent of their volume, stood without use for 10 days before the pressure opened a relief valve. Stakeholders have suggested that today periods up to 14 days can easily be sustained.

9.2.5 Methane fugitive losses in distribution

Quantification of fugitive losses from methane distribution depends on the scenario adopted for transport and liquefaction of the LNG. On-site liquefaction and transport (via ship or truck) results in negligible fugitive losses. Pipeline distribution of the NG and subsequent liquefaction in urban liquefaction facilities will introduce much greater fugitive emissions. These emissions, emanating from high pressure distribution, will be lower than losses from low pressure urban gas distribution.

(Kadam 1999) has emission from gas processing plants at 0.1%, while the 1998 NGGI has total distribution losses for low pressure gas supply at 0.25%. In the final modelling, a figure of 0.1% has been used for fugitive emission of methane from LNG 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 (this is the same figure used for CNG distribution). A sensitivity analysis showing the effect of different levels of fugitive emissions is presented in Figure 9.3. It shows that up to 0.25% emission, the greenhouse gas emission results are still lower than the baseline diesel fuel, while at 10% the full fuel-cycle emission is substantially above the diesel baseline. The exbodied emissions and the baseline are the same at approximately 4% fugitive emissions.

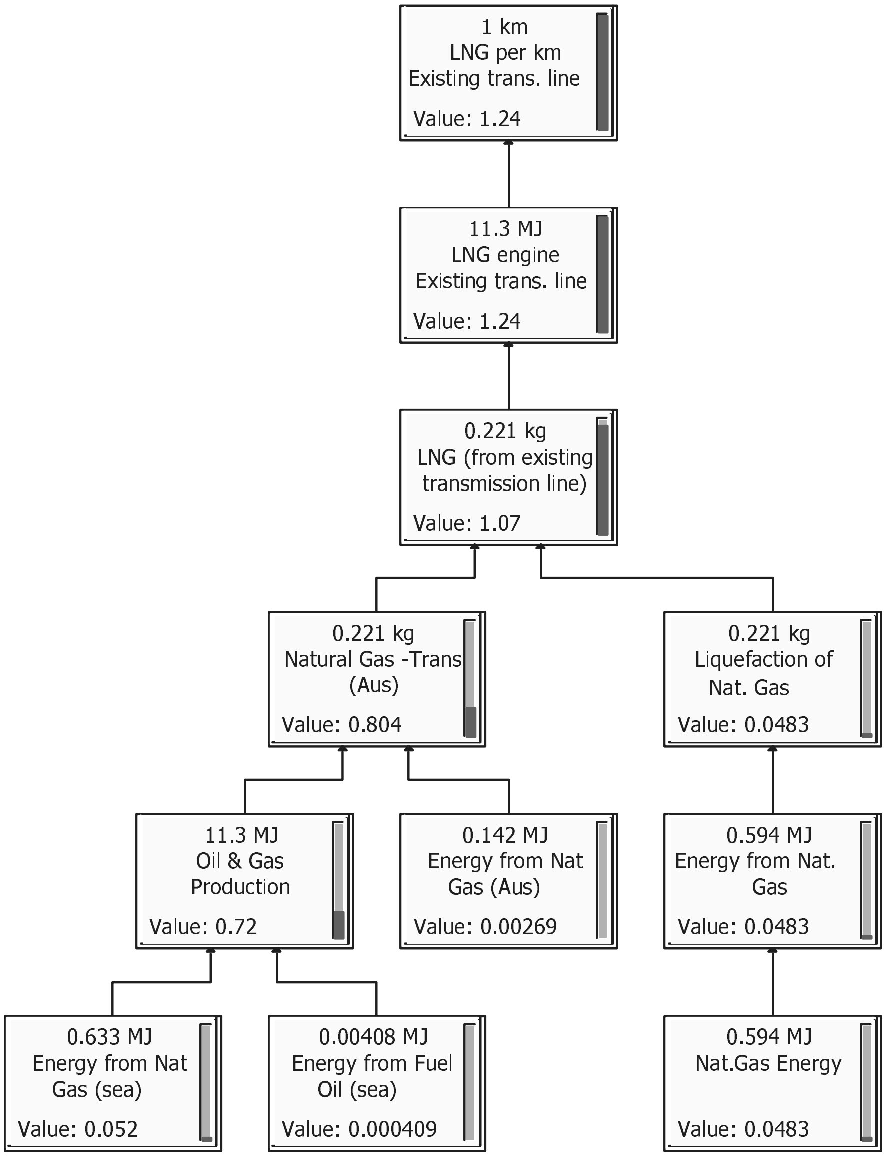
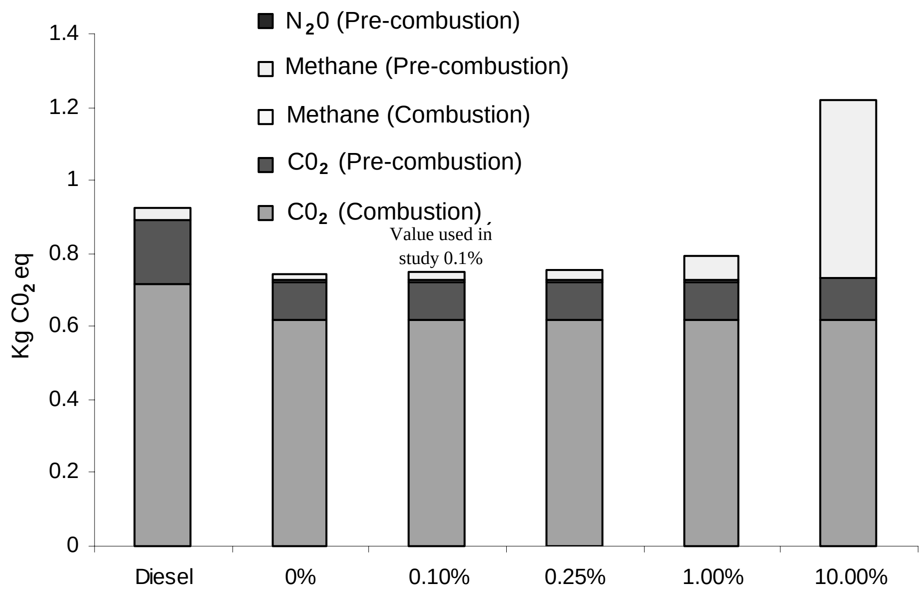


Figure 9.2
Methane emission in grams across LNG life cycle per km truck transport

Figure 9.3



Effect of different fugitive emission assumptions on full fuel-cycle greenhouse emission per km of truck travelled

We have estimated the fugitive emissions during bulk transfer and storage operations, on a g/MJ basis, as given in Table 9.7.

Table 9.7
Estimates (g/MJ) of fugitive CNG/LNG emissions during bulk transfer and storage

LNG losses at filling	Value	Comment
Spillage capacity on disconnect in mL	2.4	Parker Alternative Fuel Product Catalogue 3850
LNG density kg/m^3	420	See section 9.1.3
LNG lost per fill kg	0.001	per fill
g/km given 300 km between fills	0.0033	
g/MJ	0.000133	given fuel consumption in buses at 25 MJ/km
Diesel losses at filling		
Diesel g/l	0.006	from NGGIC workbook 2.1 1998
g/MJ	0.000167	given 36 MJ/litre for diesel
LNG loss as a percentage of diesel losses	80%	

9.2.6 Exbodied emissions

Modelling of the LNG scenarios for Australia is difficult in the absence of any substantial infrastructure operation for local transport. LNG production facilities are located in north-western WA which are used to produced export LNG. For LNG production in Australia three scenarios have been considered. The main scenario is based on production of LNG from urban gas supplies in Australian cities. This has been used as the baseline as there are facilities being built at Kwinana WA to supply local LNG. The other scenarios are based around use of the North West Shelf gas fields using ships to transport the LNG to east coast Australia, and road transport of LNG to Perth. The three scenarios are outlined in Figure 9.4.

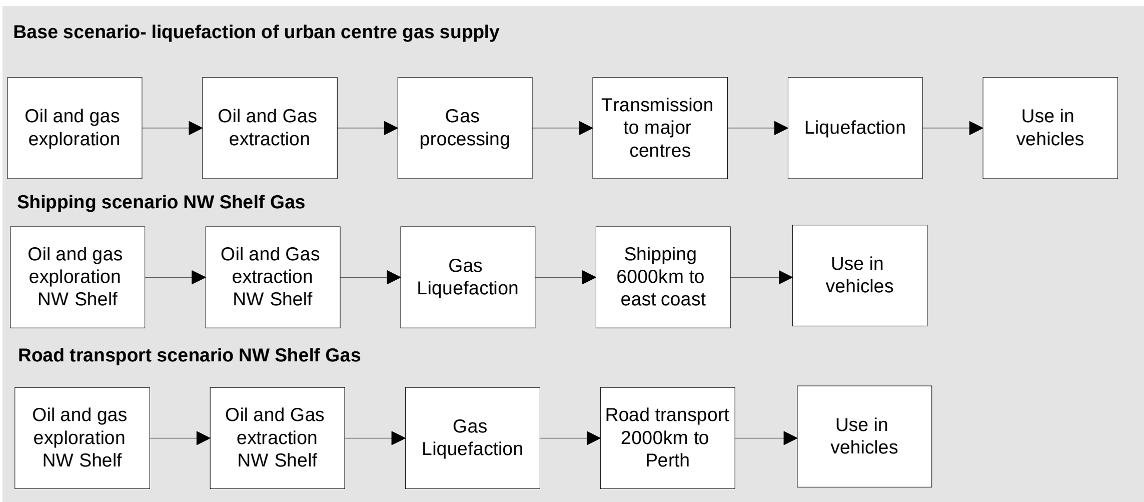


Figure 9.4
Different scenario for LNG production modelled in the study

The calculations in this section are the same as those for CNG, with an extra allowance for the emissions involved in liquefying the NG.

9.3 Results

Table 9.8
Urban and rural life cycle emissions calculated for diesel and LNG

Full life cycle	Units (per MJ)	LS diesel	LNG	LNG NW shelf to east coast	LNG NW shelf to Perth
Greenhouse	kg CO_2	0.0858	0.0660	0.0666	0.0691
NMHC total	g HC	0.140	0.028	0.028	0.030
NMHC urban	g HC	0.111	0.002	0.002	0.003
NOx total	g NOx	1.044	0.204	0.206	0.242
NOx urban	g NOx	0.987	0.190	0.175	0.178
CO total	g CO	0.253	0.012	0.012	0.014
CO urban	g CO	0.242	0.006	0.003	0.004
PM10 total	mg PM10	40.7	0.5	0.5	2.3
PM10 urban	mg PM10	39.3	0.3	0.1	0.3
Energy Embodied	MJ LHV	1.18	1.11	1.11	1.14

Table 9.9
Urban and total precombustion emissions per MJ for diesel and LNG

Precombustion	Units	LS diesel	LNG	LNG NW shelf to east coast	LNG NW shelf to Perth
Greenhouse	kg CO_2	0.0191	0.0113	0.0119	0.0144
NMHC total	g HC	0.0565	0.0262	0.0263	0.0284
NMHC urban	g HC	0.027	0.001	0.000	0.001
NOx total	g NOx	0.100	0.029	0.031	0.067
NOx urban	g NOx	0.043	0.015	0.000	0.003
CO total	g CO	0.023	0.009	0.009	0.011
CO urban	g CO	0.012	0.003	0.000	0.001
PM10 total	mg PM10	5.42	0.4	0.423	2.14
PM10 urban	mg PM10	4	0.208	0.00636	0.209
Energy Embodied	MJ LHV	1.18	1.11	1.11	1.14

Table 9.10
Urban and total combustion emissions per MJ for diesel and LNG

Combustion	Units	LS diesel	LNG
Greenhouse	kg CO_2	0.067	0.055
NMHC total	g HC	0.084	0.002
NMHC urban	g HC	0.084	0.002
NOx total	g NOx	0.944	0.175
NOx urban	g NOx	0.944	0.175
CO total	g CO	0.230	0.003
CO urban	g CO	0.230	0.003
PM10 total	mg PM10	35.26	0.12
PM10 urban	mg PM10	35.26	0.12
Energy Embodied	MJ LHV	0	0

Table 9.11
Summary of life cycle emissions from alternative fuels

		LS diesel	LNG	LNG NW shelf to East Coast	LNG NW shelf to Perth
Greenhouse	Precombustion	0.0191	0.0113	0.0119	0.0144
Greenhouse	Combustion	0.0667	0.0547	0.0547	0.0547
NMHC total	Precombustion	0.0565	0.0262	0.0263	0.0284
NMHC total	Combustion	0.0835	0.0016	0.0016	0.0016
NMHC urban	Precombustion	0.0271	0.0008	0.0001	0.0012
NMHC urban	Combustion	0.0835	0.0016	0.0016	0.0016
NOx total	Precombustion	0.1000	0.0293	0.0310	0.0668
NOx total	Combustion	0.944	0.175	0.175	0.175
NOx urban	Precombustion	0.043	0.015	0.000	0.003
NOx urban	Combustion	0.944	0.175	0.175	0.175
CO total	Precombustion	0.0225	0.0089	0.0093	0.0107
CO total	Combustion	0.2301	0.0031	0.0031	0.0031
CO urban	Precombustion	0.0123	0.0028	0.0001	0.0008
CO urban	Combustion	0.2301	0.0031	0.0031	0.0031
PM10 total	Precombustion	5.42	0.40	0.42	2.14
PM10 total	Combustion	35.26	0.12	0.12	0.12
PM10 urban	Precombustion	4.00	0.21	0.01	0.21
PM10 urban	Combustion	35.26	0.12	0.12	0.12
Energy Embodied	Precombustion	1.18	1.11	1.11	1.14

Units as in previous tables.

9.3.1 Emissions per unit distance

Table 9.12
Urban and total exbodied emissions per km for diesel and LNG

Full life cycle	**Units (per km)**	**LS diesel**	**LNG**	**LNG NW shelf to east coast**	**LNG NW shelf to Perth**
Greenhouse	kg CO_2	0.9250	0.748	0.755	0.784
NMHC total	g HC	1.509	0.315	0.316	0.340
NMHC urban	g HC	1.192	0.027	0.019	0.032
NOx total	g NOx	11.250	2.317	2.335	2.741
NOx urban	g NOx	10.638	2.153	1.989	2.017
CO total	g CO	2.723	0.136	0.140	0.156
CO urban	g CO	2.612	0.067	0.036	0.044
PM10 total	mg PM10	438.4	5.9	6.1	25.6
PM10 urban	mg PM10	423.1	3.7	1.4	3.7
Energy Embodied	MJ LHV	12.7	12.50	12.60	12.90

Table 9.13
Urban and total pre-combustion emissions per km for diesel and LNG

Precombustion	Units (per km)	LS diesel	LNG	LNG NW shelf to East Coast	LNG NW shelf to Perth
Greenhouse	kg CO_2	0.2060	0.128	0.135	0.186
NMHC total	g HC	0.609	0.297	0.298	0.322
NMHC urban	g HC	0.292	0.009	0.001	0.014
NOx total	g NOx	1.080	0.333	0.351	0.757
NOx urban	g NOx	0.468	0.169	0.004	0.033
CO total	g CO	0.243	0.101	0.105	0.121
CO urban	g CO	0.132	0.032	0.001	0.010
PM10 total	mg PM10	58.4	4.53	4.8	24.3
PM10 urban	mg PM10	43.1	2.36	0.0721	2.36
Energy Embodied	MJ LHV	12.7	12.5	12.6	12.9

Table 9.14
Urban and total combustion emissions per km for diesel and LNG

Combustion	Units	LS diesel	LNG
Greenhouse	kg CO_2	0.719	0.620
NMHC total	g HC	0.900	0.018
NMHC urban	g HC	0.900	0.018
NOx total	g NOx	10.177	1.984
NOx urban	g NOx	10.177	1.984
CO total	g CO	2.480	0.035
CO urban	g CO	2.480	0.035
PM10 total	mg PM10	380.00	1.33
PM10 urban	mg PM10	380.00	1.33
Energy Embodied	MJ LHV	0	0

Table 9.15
Summary of life cycle emissions per km from diesel and LNG

		LS diesel	LNG	LNG NW shelf to east coast	LNG NW shelf to Perth
Greenhouse	Precombustion	0.2060	0.128	0.135	0.186
Greenhouse	Combustion	0.7190	0.6200	0.6200	0.6200
NMHC total	Precombustion	0.6090	0.2970	0.2980	0.3220
NMHC total	Combustion	0.9000	0.0180	0.0180	0.0180
NMHC urban	Precombustion	0.2920	0.0091	0.0008	0.0136
NMHC urban	Combustion	0.9000	0.0180	0.0180	0.0180
NOx total	Precombustion	1.0800	0.3330	0.3510	0.7570
NOx total	Combustion	10.170	1.984	1.984	1.984
NOx urban	Precombustion	0.468	0.169	0.004	0.033
NOx urban	Combustion	10.170	1.984	1.984	1.984
CO total	Precombustion	0.2430	0.1010	0.1050	0.1210
CO total	Combustion	2.4800	0.0348	0.0348	0.0348
CO urban	Precombustion	0.1320	0.0320	0.0008	0.0096
CO urban	Combustion	2.4800	0.0348	0.0348	0.0348
PM10 total	Precombustion	58.40	4.53	4.80	24.30
PM10 total	Combustion	380.00	1.33	1.33	1.33
PM10 urban	Precombustion	43.10	2.36	0.07	2.36
PM10 urban	Combustion	380.00	1.33	1.33	1.33
Energy Embodied	Precombustion	12.70	12.50	12.60	12.90

9.3.2 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, as given in Table 9.16.

Table 9.16
Estimated one standard deviation uncertainties (in per cent) for low sulfur diesel emissions

	g/MJ	g/t-km	g/p-km
CO_2	5	6	8
NMHC	10	11	11
NOx	35	47	28
CO	60	18	106
PM10	45	48	46

9.4 Viability and Functionality

Kleenheat Gas informs us that one chassis-mounted HLNG-119 (410 L capacity) LNG tank is equivalent to seven CNG fibre-wrapped roof mounted tanks, so that there is more room available in an LNG vehicle than a CNG vehicle because the tanks occupy less space. LNG buses are about 400 kg heavier than equivalent diesel buses. A general rule is that a full LNG tank is 10% heavier than a full diesel tank for the same vehicle. They also point out that current LNG refuelling rates of 378 L per minute are common, and they consider this to be comparable to diesel refuelling rates.

Engines designed for CNG are used with LNG, by heating and vaporising the liquid fuel before it is fed to the engine. All commercially available LNG buses use engines that were originally designed for CNG, because the fuel enters the engine in a gaseous state. The liquid storage of the fuel is the only difference between CNG and LNG buses. This means that the emission characteristics, and most aspects of viability and functionality, will be the same for both CNG and LNG buses.

The Los Angeles Transit Authority (LACMTA) notes that LNG buses have the same reliability and operating cost issues as CNG buses. In addition, on-board cryogenic fuel pumps in the previous generation of LNG vehicles experienced short operating lives and high replacement costs. All modern LNG fuel systems are pump-less.

It is instructive to note the summary of the Dallas Area LNG Bus Fleet trials (Batelle, 2000), known as DART. The major conclusions from the evaluation of DART's LNG experience include the following:

- DART has had significant problems with startup of LNG operations, especially range. The buses were specified to have a 400 mile (640 km) range and were able to achieve only 277 miles (440 km) at the beginning of operation. A fourth LNG tank was added for on-board storage of LNG. This fourth tank provided enough fuel to make a range of 380 miles (600 km) which was deemed acceptable by DART. Several other problems with early failure of components in the engines (turbocharger, spark plugs, exhaust valve, cylinder head, and wastegate) fuel system (leaks), the fuelling station nozzle, and other systems have nearly all been resolved through a team effort at DART and with the vendors.

- The drivers report that the LNG buses are well matched in performance to diesel; it is difficult to tell them apart.
- The range problem caused reduced usage of the LNG buses at the start of operation. The range problem has been resolved by the fourth LNG tank. Today, the LNG buses are treated the same as the diesel buses in meeting the daily pullout requirements.
- The fuel economy has been steady at 1.62 miles per LNG gallon (0.685 km/L) or 2.70 miles per diesel equivalent gallon (1.14 km/L). DART along with ZF (the transmission vendor) and Cummins continue to explore ways to increase fuel economy with a goal of a 5–10% improvement.
- Some engine problems continue to be an issue for the DART LNG buses. Cummins continues to work on these problems even though the L10 engine has been discontinued as a commercial product. The resolution of problems with the L10 are applicable to the C8.3G, which is Cummins current heavy-duty NG engine for the transit market. Cummins is working on issues with spark plugs and wires, cylinder head design, turbo actuator, coils, and wastegate.
- Emissions testing from West Virginia University showed that the diesel engines at DART were very clean. The LNG emissions were cleaner. This emission testing at DART was a state-of-the-art comparison for transit with 1998 technology.
- Total operating costs for the LNG buses were only 3% higher than the diesel buses. However, the maintenance costs for the engine/fuel related systems were 33% higher for the LNG buses compared to the diesel buses. The fuel costs were 32% higher for the LNG buses compared to the diesel buses.
- Miles between roadcalls (on-road failure of an in-service bus) for the LNG and diesel buses overall were about the same. The LNG buses had 50 per cent lower miles between roadcalls for the engine/fuel rated systems compared to the engine/fuel related system roadcalls on the diesel buses.
- The LNG and NG vehicle (NGV) industry were challenged with making the DART operation a success due to the problems with range. The consortium of industry partners worked together and overcame the problems working through an “LNG Taskforce”. Today, all 139 LNG buses make pullout nearly every day.
- The two LNG fuelling station are working well for DART. Some problems have been experienced with fuelling nozzle leaks and driveaways with damage to the dispensing system. The nozzle has been redesigned and seems to be working better in managing leaks. DART is still exploring breakaway fitting and hose designs. The new LNG station at South Oak Cliff does not have the extensive length of piping (300 feet) from the storage tanks to the fuelling island that Northwest has. This has resulted in a much higher available fuelling rate, up to 70 gpm (265 L/min).

9.4.1 Safety

The safety regulations for all fuels - whether liquid or gaseous - will generally ensure that the risk of a fire under normal operating conditions is small. It is generally in the event of a crash or equipment failure that a hazard will occur. As with most fuels, the main fire hazard comes from leakage either during refuelling operations or during operation of the equipment, or a vehicle crash.

Three requirements must be met before there is a fire or an explosion. First, leakage of the fuel. Second, mixing of the fuel with air to give a mixture in the flammable range. Third, a source of ignition.

The likelihood of a flammable mixture occurring is less for NG than for LPG, since NG is lighter than air and rises. LPG vapour is heavier than air and tends to form 'pools' near the ground. It is generally accepted that the various automotive fuels range in safety from diesel (safest) to LPG as the most hazardous, with alcohol fuels, methane and petrol in the middle of the range.

9.4.2 Warranty

The Cummins base engine warranty on a C8.3G+ engine is 2 years, 250,000 miles (402,338 km), or 62590 hours of operation, whichever occurs first.

9.5 Health Issues

Emissions of particulate matter, some of which is carcinogenic, are almost eliminated with NG use (see Table 9.11). The IANGV (1990) noted that the NGV engine's lubricating oil appeared to be the source of remaining particle emissions.

The life-cycle emissions of LNG are liable to be comparable with those of CNG, except that the CO_2 emissions will be higher. The major determinant of the life-cycle greenhouse gas emissions from the use of NG is the consideration of fugitive methane.

9.5.1 Production and transport

Particulate matter
The LCA estimate for LNG urban precombustion (truck) PM10 emissions of 2 mg/km is substantially less than the LSD estimate of 43 mg/km.

Air toxics

The LCA estimate for LNG urban precombustion (truck) NMHC emissions of 0.009 g/km is substantially less than 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. The disk accompanying this report provides details of air toxic emissions from upstream activities.

9.5.2 Use

NGVs have the potential to significantly reduce local air pollutants such as CO, NMHCs, SOx, particles, smoke and odour. The situation with regard to NOx is less clear cut although LNG has a lower adiabatic flame temperature than diesel, which implies lower NOx emissions. LNG has nearly zero sulfur levels and, thus, negligible sulfate emissions.

Particulate Matter

Research consistently shows that gaseous fuels in general, with their simple chemistry and very low sulfur content, emit extremely low levels of particles (Anyon, 1998).

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

The LCA estimate for LNG combustion (truck) PM10 emissions of 1 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air Toxics

CNG produces much lower emissions of the main air toxics such as benzene, 1,3 butadiene, formaldehyde and acetaldehyde, compared with diesel (Anyon, 1998). It is reasonable to assume LNG would have similarly low toxics emissions.

As with CNG, LNG contains no benzene, so refuelling and running losses of this toxic would be zero. (US EPA, 1993).

The LCA estimate for LNG combustion (truck) NMHC emissions of 0.0180 g/km is less than the LSD estimate of 0.900 g/km.

9.5.3 Summary

LNG upstream emissions of both particles and air toxics are substantially less than LSD. LNG tailpipe emissions of particles are substantially less than LSD. LNG tailpipe emission of NMHC as well as benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

No comparative emissions data for CNG and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH)
- toluene
- xylene.

9.6 OHS Issues

LNG is much lighter than air and thus it is safer than spilled diesel. Refuelling is considered to be the ‘least-safe’ moment of its use.

The OHS issues in the lifecycle of CNG are covered by a range of State and Commonwealth OHS provisions. While there will be different OHS issues involved in the production process associated with LNG compared with LSD, no OHS issues unique to the production and distribution of LNG have been identified.

9.7 Vapour Pressure Issues

Different views are held on evaporative emissions. One is that LNG vehicles do not have any, due to their sealed pressurised fuel system. BTCE (1994), on the other hand, refers to ‘frequent leaks’ as a technical problem to be solved for NGVs. Experience with the LNG road train built to operate between Alice Springs and Yulara suggests that fugitive losses from LNG boil-off in intermittent use may not be a major problem

9.8 Environmental Impact and Benefit

LNG is a gaseous fuel at normal temperature and pressure. It thus exhibits the same environmental benefits as CNG, namely lower greenhouse gas and air pollutant emissions than diesel, with no land or water pollution. Anecdotal evidence suggests that both drivers and passengers appreciate the lower noise levels of LNG vehicles, compared to diesel vehicles.

ESD principles

Noise levels from NG buses are less than those of diesel buses. LNG buses produce fewer air pollutants and greenhouse gases than diesel buses do. The potential for water and soil pollution is effectively eliminated by the use of NG.

Sustainability

NG is an indigenous fuel that could replace imported, expensive crude oil.

Groundwater

LNG is a gaseous fuel at normal temperature and pressure. Being a gaseous fuel, it does not impact groundwater.

9.9 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 9.17 lists the estimated emissions factors for CNG. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of CNG. LNG can be expected to meet all future Australian design rules for all pollutants.

Table 9.17
Estimated emission factors for LNG under future technologies (PM is unregulated for gas engines)

Technology	CO	CO	THC	THC	NOx	NOx	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	0.3	**1.0**	0.9	**1.0**	0.2	**1.0**	0.1	1.0	0.9
Euro3	**0.53**	0.2	**0.6**	0.6	**0.71**	0.1	**0.67**	0.1	1.0	0.9
Euro4	**0.38**	0.1	**0.42**	0.4	**0.5**	0.1	**0.2**	0.05	1.0	0.8

9.10 Summary

9.10.1 Advantages

- LNG has very low particle emissions because of its low carbon to hydrogen ratio.
- There are negligible evaporative emissions, requiring no relevant control.
- Due to its low carbon-to-hydrogen ratio, it produces less carbon dioxide per GJ of fuel than diesel.
- It has low cold-start emissions due to its gaseous state.
- It has extended flammability limits, allowing stable combustion at leaner mixtures.
- It has a lower adiabatic flame temperature than diesel, leading to lower NOx emissions.
- It has a much higher ignition temperature than diesel, making it more difficult to auto-ignite, thus safer.
- It contains non-toxic components. The liquefaction process removes impurities so that the LNG is pure methane, which is a non-toxic gas.
- It is much lighter than air and thus it is safer than spilled diesel.

- Methane is not a volatile organic compound (VOC).
- Engines fuelled with NG in heavy-duty vehicles offer more quiet operation than equivalent diesel engines, making them more attractive for use in urban areas.
- It has nearly zero sulfur levels and, thus, negligible sulfate emissions.
- NG pricing is stable and predictable, removing uncertainty to business caused by fuel price fluctuations.
- Where on site liquefaction is used, NG is distributed via underground pipe networks, removing the need for hazardous transportation and transfer processes.
- Where on site liquefaction is used, because of the pipeline delivery, retailers or fleet operators are not required to store large quantities of fuel, usually prepaid, on site.
- NG use does not give rise to issues with groundwater contamination such as those experienced through diesel/petrol spillage or leakage from underwater storage.

9.10.2 Disadvantages

- There is considerable extra infrastructure involved with gas liquefaction.
- It requires dedicated catalysts with high loading of active catalytic components to maximise methane oxidation.
- Its driving range is limited because its energy content per volume is relatively low.
- It requires special refuelling stations and handling of a cryogenic liquid, making it suitable only for fleet operations.
- The energy required to liquefy NG leads to increased greenhouse gas emissions in comparison to CNG.
- Exhaust emissions of methane, a greenhouse gas, are relatively high compared with low sulfur diesel.
- Refuelling is considered to be the ‘least-safe’ moment of its use.
- It can give rise to backfire in the inlet manifold if the ignition system fails in use.

10. Liquefied Petroleum Gas — Autogas

10.1 Background

Liquefied petroleum gas (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. There is very little usage of LPG in Australian heavy vehicles. Kleenheat Gas recently developed a diesel/LPG fuel substitution conversion kit that was used in a three month trial of an articulated Volvo B10M MkIII LPG bus in Darwin in late 2000 (see www.nt.gov.au/ministers/palmer/media00/1213lpgdiesel_darwinbus.shtml). Other manufacturers (Ecotrans, Was Diesel Now Gas) offer a similar capability. The few dedicated LPG engine options in Australia are designed to operate on the LPG-HD5 specification.

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. In 1997, Australia produced 4.1 GL of LPG, of which 1.6 GL was from refineries.

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 550,000 Australian vehicles use LPG. LPG powers all taxis in Victoria, and many other taxi fleets around the country. It is a familiar and widely available light vehicle fuel.

The utilisation of LPG as an automotive fuel varies very widely from one country to another, depending on the cost and availability of the fuel in relation to alternative fuels, notably petrol and diesel, Table 10.1 shows the variation in LPG fuel composition in Europe in 1982.

Table 10.1
LPG Composition (% by volume) as Automotive Fuel in Europe in 1982

Country	Propane	Butane
Austria	50	50
Belgium	50	50
Denmark	50	50
France	35	65
Greece	20	80
Ireland	100	-
Italy	25	75
Netherlands	50	50
Spain	30	70
Sweden	95	5
United Kingdom	100	-
Germany	90	10

Source www.vps.com/LPG/WVU-review.html

Table 1 indicates that there are two different classes of LPG. Autogas grade LPG is a mixture of propane and butane. A European specification (EN589) is presently being prepared to standardise the composition. In eastern Australia Anyon (1998) notes that the LPG mixture supplied is typically around 60-70% propane and 40-30% butane. The addition of butane slows down combustion speed in an engine, so that it reduces NOx emission, while it increases emissions of THC and CO.

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 within Australia. The performance of passenger vehicles using different LPG grades has been documented by Watson and Gowdie (2000).

10.1.1 LPG in heavy vehicles

As a result of the recent environmental concern in relation to the health effects of particulate matter (Beer, 2000) and especially particulate matter of diameter less than 10 μm, known as PM10, LPG is being reconsidered as a heavy vehicle fuel. Particulate matter emitted by diesel is all PM10. Anyon (1998) points out that LPG, like CNG, has much lower emissions than diesel, and LPG has particularly low particle levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particle emissions reduce to Euro4 levels this advantage may be lost, though the LPG industry believes that a fully optimised LPG engine may be capable of producing lower particle emissions than an equivalent Euro4 diesel engine.

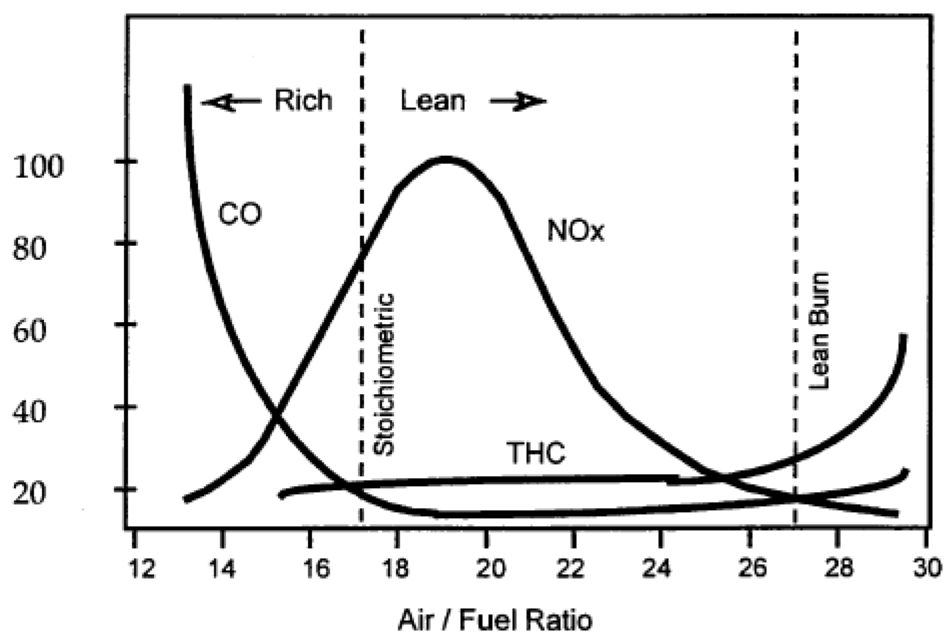


Figure 10.1
Influence of air-fuel ratio on emissions and fuel consumption of a spark-ignition engine. The abscissa is a volume ratio, whereas the ordinate is in ppm (Nylund and Lawson, 2000).

DAF, the Dutch vehicle maker, has developed a dedicated LPG fuelled bus. DAF prefers the stoichiometric process over lean burn. The advantage of the stoichiometric combustion principle is that it allows the use of a three-way catalyst, which is impossible in lean burn. With a three-way catalyst the emission of all polluting compounds can be reduced, resulting in extremely low emission rates. If a two-way catalyst is used, the NO_x is not removed. The stoichiometric process reduces the emission rate of particulate matter to one twentieth of Euro2, whereas lean burn only comes to half of Euro2. The drawback of the stoichiometric process is that it loses the efficiency advantage of lean burn and correspondingly increases CO_2 emissions. Figure 10.1 shows the influence of air-fuel ratios on emissions.

10.2 Exbodied Emissions

10.2.1 Emission tests

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics. There is considerable data in relation to LPG used in cars. (NSWEPA, 1997). In addition, most of the data that we were able to find relates to propane, rather than autogas. Beer et al. (2000) quote values provided by Anyon (1998), and the default values in the Australian NGGI. Nylund and Lawson (2000: Table 10.2) provide emission data for autogas for the DAF LPG 8.65 litre bus operating on a stoichiometric mixture and equipped with a three way catalyst. These are shown in Table 10.2., and were used in the subsequent full-fuel cycle analysis. According to publicity material about these buses the fuel consumption of these LPG buses varies between 0.5 and 0.9 L/km. (CADDET, 1997).

Table 10.2
Autograde LPG emissions

	CO (g/kWh)	THC (g/kWh)	NOx (g/kWh)	PM (g/kWh)	FC (L/km)
DAF GG170LPG	0.25	0.01	0.4	0.015	0.5-0.9
Diesel comparison	4	1.1	7	0.15	0.3-0.5

The properties of LPG, as given by NGGIC are given in Table 10.3.

Table 10.3
Properties of LPG (NGGIC, 1996, 1998)

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

This chapter deals with dedicated LPG vehicles. Dual fuel LPG vehicles operating on LPG (autogas) are expected to have higher emissions than dedicated vehicles, given the results of dual fuel vehicles operating on LPG-HD5 referred to in the chapter on that fuel.

Table 10.4
Default Emission Factors (g/km) for LPG (NGGIC, 1996)

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

The default emission factors in the methodology for the Australian National Greenhouse Gas Inventory are given in Table 10.4.

10.2.2 Upstream

Raw natural gas from gas fields must be processed before being fed into pipelines or liquefied. Raw gas contains vapours and liquids, both hydrocarbons and water, which need to be separated.

In natural gas processing plants, non-hydrocarbon gases such as water, hydrogen sulfide (H_2S), and CO_2 are removed from the gas stream during a gas conditioning stage. Water is removed in a dehydrator through a chemical reaction with solvent or through physical adsorption.

The gas then passes through a processing stage where higher hydrocarbons are stripped from the gas. Stripping may be done by refrigeration (condensation, absorption in hydrocarbon solvent, adsorption on sorbents, compression, or any combination of the above methods. The particular configuration will depend on the composition of natural gas to be processed. Finally, stripped hydrocarbons are separated into ethane, LPG and pentanes plus.

Another source of LPG is crude oil processing at the refinery. LPG fraction is recovered from the top of the atmospheric pressure distillation unit and from various process units such as crackers and hydrotreaters.

Schematic diagram of LPG production and delivery is shown in Figure 10.2.

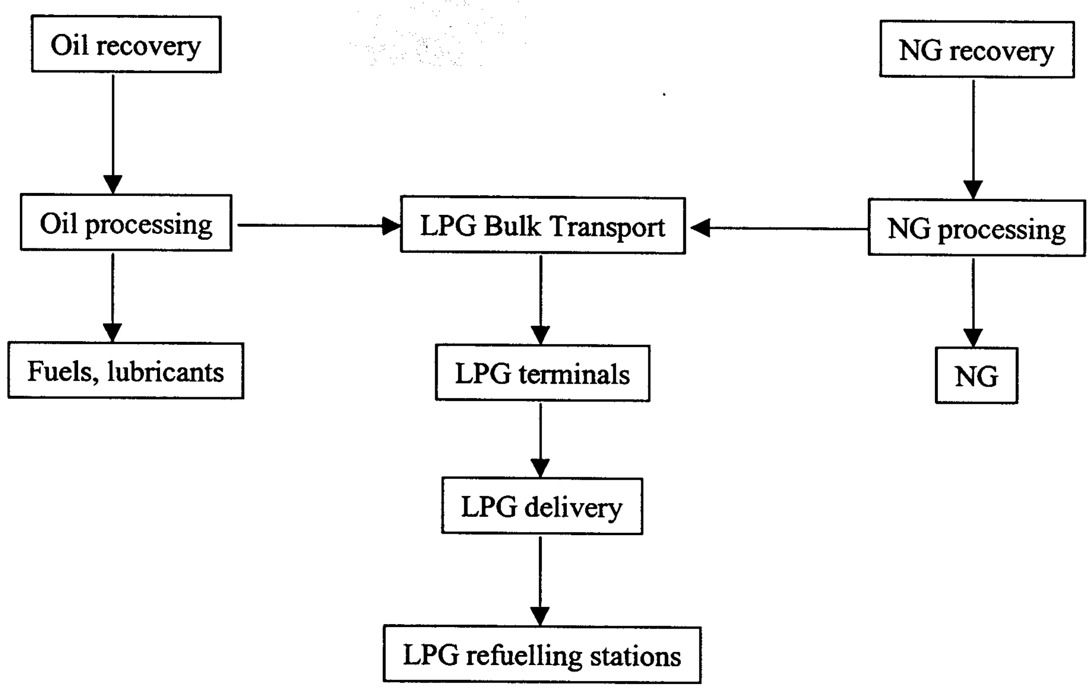


Figure. 10.2
LPG production and delivery flowchart.

Australian annual LPG production is about 6000 ML from combined natural sources and refinery production. Of this approximately 55% is used domestically and 45% exported. Bass Strait is the biggest source of LPG (over 40%), followed by Cooper Basin and the refineries.

Main Australian users are residential (cooking and heating), commercial/industrial (fuel), autogas (petrol/diesel replacement) and petrochemical (as feedstock).

While the term LPG means broadly a mixture of propane and butane, motor vehicles run on autogas which has to meet relevant specifications. Most important of those are the vapour pressure range required to be between 800 kPa and 1530 kPa at 40°C and minimum motor octane number of 92.

In some overseas countries automotive LPG (HD-5 specification) must contain a minimum of 95% propane, the balance being butane and propylene.

Upstream emissions associated with LPG use arise from energy used in gas and oil recovery and processing. Further emissions result from the delivery to retail outlets.

10.3 Results

Table 10.5
Urban and total life cycle emissions per MJ calculated for diesel and autogas

Full lifecycle	Units (per MJ)	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.0858	0.0764
HC total	g HC	0.140	0.102
HC urban	g HC	0.111	0.075
NOx total	g NOx	1.044	0.140
NOx urban	g NOx	0.987	0.089
CO total	g CO	0.253	0.038
CO urban	g CO	0.242	0.029
PM10 total	mg PM10	40.7	8.9
PM10 urban	mg PM10	39.3	7.6
Energy embodied	MJ LHV	1.18	1.06

Table 10.6
Urban and total precombustion emissions per MJ for diesel and autogas

Precombustion	Units	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.0191	0.0170
HC total	g HC	0.0565	0.101
HC urban	g HC	0.027	0.074
NOx total	g NOx	0.100	0.092
NOx urban	g NOx	0.043	0.040
CO total	g CO	0.023	0.021
CO urban	g CO	0.012	0.012
PM10 total	mg PM10	5.42	5.31
PM10 urban	mg PM10	4	4.02
Energy embodied	MJ LHV	1.18	1.06

Table 10.7
Urban and total combustion emissions per MJ for diesel and autogas

Combustion	Units	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.067	0.059
HC total	g HC	0.084	0.001
HC urban	g HC	0.084	0.001
NOx total	g NOx	0.944	0.048
NOx urban	g NOx	0.944	0.048
CO total	g CO	0.230	0.017
CO urban	g CO	0.230	0.017
PM10 total	mg PM10	35.26	3.55
PM10 urban	mg PM10	35.26	3.55
Energy embodied	MJ LHV	0	0

Table 10.8
Summary of life cycle emissions per MJ from diesel and autogas

		LS diesel	LPG (Autogas)
Greenhouse	Precombustion	0.0191	0.0170
Greenhouse	Combustion	0.0667	0.0594
HC total	Precombustion	0.0565	0.1010
HC total	Combustion	0.0835	0.0007
HC urban	Precombustion	0.0271	0.0742
HC urban	Combustion	0.0835	0.0007
NOx total	Precombustion	0.1000	0.0919
NOx total	Combustion	0.944	0.048
NOx urban	Precombustion	0.043	0.040
NOx urban	Combustion	0.944	0.048
CO total	Precombustion	0.0225	0.0208
CO total	Combustion	0.2301	0.0171
CO urban	Precombustion	0.0123	0.0116
CO urban	Combustion	0.2301	0.0171
PM10 total	Precombustion	5.42	5.31
PM10 total	Combustion	35.26	3.55
PM10 urban	Precombustion	4.00	4.02
PM10 urban	Combustion	35.26	3.55
Energy embodied	Precombustion	1.18	1.06

10.3.1 Emissions per unit distance

Table 10.9
Exbodied emissions per km for diesel and autogas

Full lifecycle	Units (per km)	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.9250	0.8352
HC total	g HC	1.509	1.108
HC urban	g HC	1.192	0.819
NOx total	g NOx	11.250	1.527
NOx urban	g NOx	10.638	0.969
CO total	g CO	2.723	0.415
CO urban	g CO	2.612	0.313
PM10 total	mg PM10	438.4	96.7
PM10 urban	mg PM10	423.1	82.6
Energy embodied	MJ LHV	12.7	11.6

Table 10.10
Precombustion emissions per km for diesel and autogas

Precombustion	Units (per km)	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.2060	0.1860
HC total	g HC	0.609	1.1
HC urban	g HC	0.292	0.811
NOx total	g NOx	1.080	1.000
NOx urban	g NOx	0.468	0.442
CO total	g CO	0.243	0.228
CO urban	g CO	0.132	0.126
PM10 total	mg PM10	58.4	58
PM10 urban	mg PM10	43.1	43.9
Energy embodied	MJ LHV	12.7	11.6

Table 10.11
Combustion emissions per km for diesel and autogas

Combustion	Units	LS diesel	LPG (Autogas)
Greenhouse	kg CO_2	0.719	0.649
HC total	g HC	0.900	0.008
HC urban	g HC	0.900	0.008
NOx total	g NOx	10.177	0.527
NOx urban	g NOx	10.177	0.527
CO total	g CO	2.480	0.187
CO urban	g CO	2.480	0.187
PM10 total	mg PM10	380.00	38.75
PM10 urban	mg PM10	380.00	38.75
Energy embodied	MJ LHV	0	0

Table 10.12
Summary of life cycle emissions per km from diesel and autogas

		LS diesel	LPG (Autogas)
Greenhouse	Precombustion	0.2060	0.1860
Greenhouse	Combustion	0.7190	0.6492
HC total	Precombustion	0.6090	1.1000
HC total	Combustion	0.9000	0.0080
HC urban	Precombustion	0.2920	0.8110
HC urban	Combustion	0.9000	0.0080
NOx total	Precombustion	1.0800	1.0000
NOx total	Combustion	10.170	0.527
NOx urban	Precombustion	0.468	0.442
NOx urban	Combustion	10.170	0.527
CO total	Precombustion	0.2430	0.2280
CO total	Combustion	2.4800	0.1869
CO urban	Precombustion	0.1320	0.1260
CO urban	Combustion	2.4800	0.1869
PM10 total	Precombustion	58.40	58.00
PM10 total	Combustion	380.00	38.75
PM10 urban	Precombustion	43.10	43.90
PM10 urban	Combustion	380.00	38.75
Energy embodied	Precombustion	12.70	11.60

10.3.2 Uncertainties

In the absence of information on the variability and uncertainties associated with LPG emissions, we assume that the uncertainties are the same as those associated with LNG.

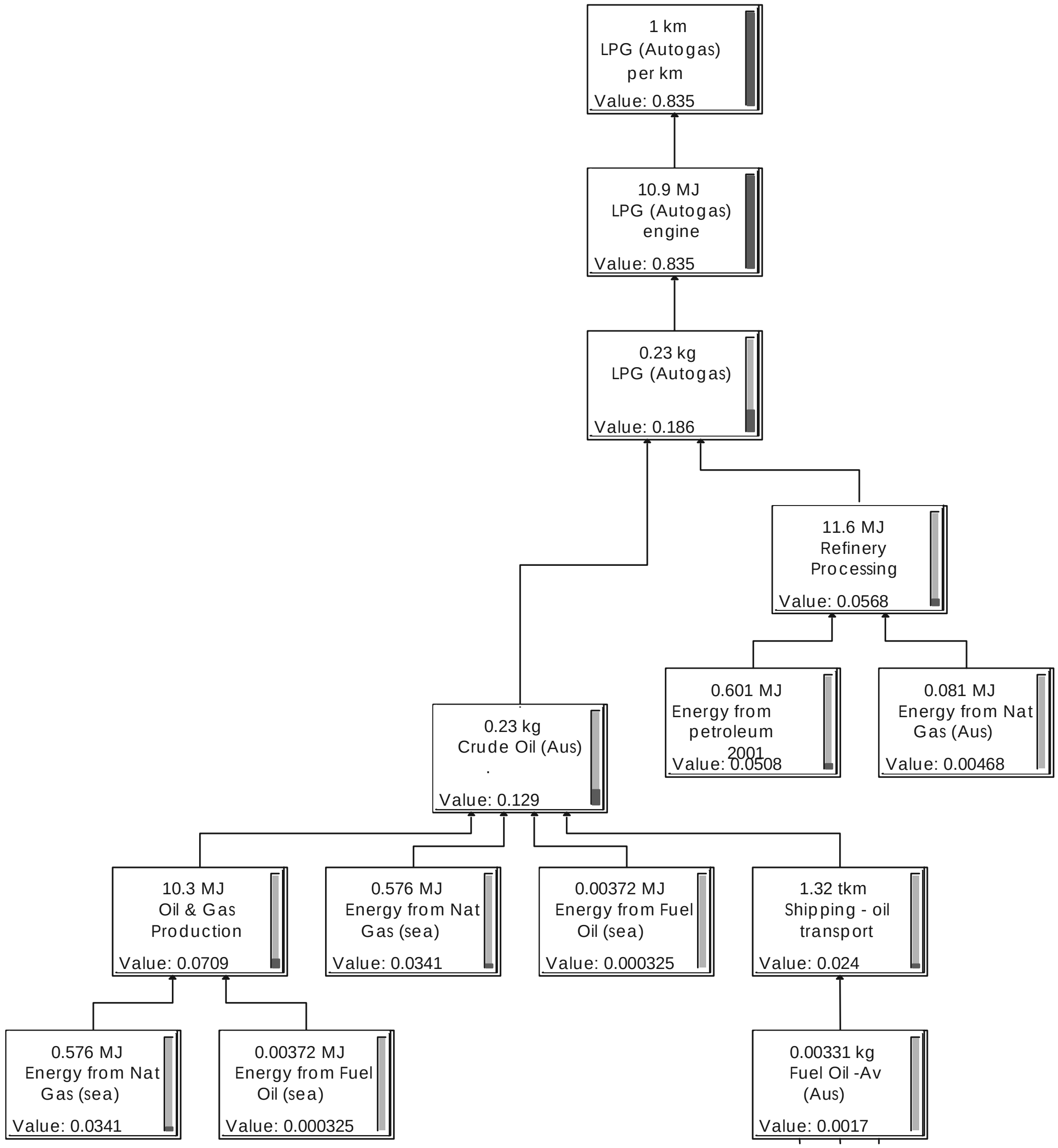


Figure 10.3
Exbodied greenhouse gases emissions (kg CO_2eq) from LPG (Autogas) production and processing and use in vehicle

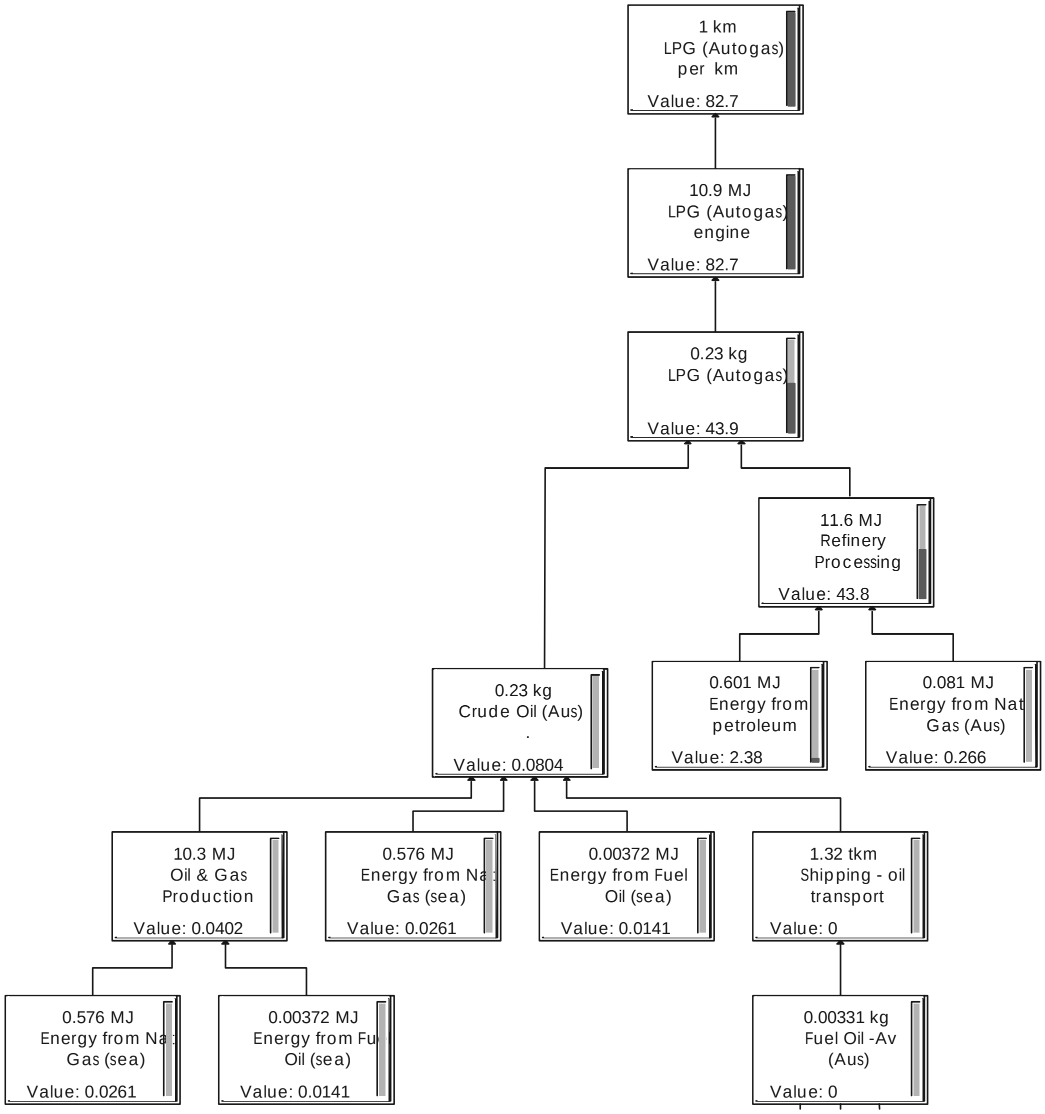


Figure 10.4
Exbodied particulate matter (mg - urban) from LPG (Autogas) production and processing and use in vehicle

10.4 Viability and Functionality

10.4.1 Handling, transport, storage and safety issues

LPG is gas at normal temperatures and pressures. Its physical properties depend strongly on the temperature and pressure at which it is being stored. As the temperature rises, the vapour pressure of LPG increases exponentially. Some ullage space must be left in an LPG tank because the liquid volume expands significantly if the tank encounters increasing ambient temperatures. Between –3^{o}C and 37^{o}C, for example, the liquid volume expands by 13 %. Due to this, and its lower density, LPG requires a 35 % greater storage volume than petrol. LPG systems have a safety device known as an automatic fill limiter (AFL) to ensure no more than 80 % of tank volume fills. This allows room for liquid expansion if the temperature rises after the tank is filled. Due to the low viscosity of LPG and its storage under pressure, it may leak through small cracks, pumps, seals and gaskets. LPG refuelling systems, being totally enclosed and pressure tight, have no refuelling, evaporative, running losses and emissions from the fuel storage system. LPG fuel tank is installed, along with a refuelling port, fuel lines, and pressure safety valves. LPG tanks are constructed of heavy gauge steel, to withstand a pressure of 1000 psi. Common operating pressures are in the range of 130-170 psi. Tanks are equipped with pressure relief valves that will release LPG vapours to the atmosphere to prevent tank explosion under abnormally high pressure conditions.

10.4.2 Engine manufacturers'acceptance of the fuel for warranty purposes;

Australian cars that are converted to LPG are warrantied by the converter. For example, Sprint Gas provides a 3 year, 100,000 km warranty on new cars (that have travelled less than 2,000km at the time of conversion) and a 2 year, 50,000 km warranty on used cars. (http://www.sprintgas.com.au/pgfive.html). Dedicated LPG cars typically have a 3 year, 100,000 km warranty provided by the manufacturer. Dedicated LPG heavy vehicles will come with similar warranties.

LPG engines are commercially available in the US from two major North American engine manufacturers for buses up to 30 feet in length. The Caterpillar G3306 and the Cummins B5.9-195 LPG engines were developed for mid-sized, heavy-duty vehicles. The Cummins B5.9-195 LPG engine is certified to the EPA 1999 Clean Fuel Fleet Vehicle Low Emission Vehicle (LEV) standard and the California Air Resources Board low NOx standard of 2.5 g/bhp-hr for heavy duty engines. Detroit Diesel discontinued development of an LPG version of the Series 50G and 60G for larger heavy duty vehicles.

In Europe, according to the web page of the Vienna bus fleet, the European manufacturer MAN will provide Vienna with extra LPG buses (http://www.klip.wien.at/english/verkehr/ve_bus.htm). Renault has developed an LPG bus, whereas DAF introduced the stoichiometric process for their LPG buses.

10.4.3 Functionality

Gaseous fuelled engines are generally considered easier to start than petrol or diesel engines in cold weather, because the fuel is vaporized before injection into the engine. Hot starting may, however, produce difficulties. After an engine is shut down, the engine coolant continues to absorb heat from the engine, raising its temperature. If the vehicle is re-started within a critical period after shutdown (when both the coolant and the engine are at high temperature) then the coolant will heat the gas more than normal, lowering its volumetric heating value and density.

10.4.4 Fuel energy density and vehicle operational range;

Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is low. Thus LPG tanks take more space and weigh more than petrol or diesel fuel tanks. The range of LPG vehicles is equivalent to that of petrol or diesel vehicles.

10.4.5 Refuelling requirements;

The time to refuel LPG tanks is similar to that of refuelling times for petrol and diesel. The filling system of LPG tanks is not uniform across Europe, though new CEN standards are being designed to standardise this. In this respect, as with electricity plugs, Australia is ahead of Europe having standardised LPG refill nozzles across the country.

There are small losses of LPG during refuelling.

10.4.6 Issues affecting the availability of fuel

The 60% of Australian LPG that is sourced from natural gas is vulnerable to disruption in the gas supply. This was most evident with the Longford incident in 1998 when gas supplies to Melbourne, and much of the rest of Victoria were halted following the disaster at the Longford plant. During the period of gas shortage, LPG was sourced from interstate and there were no disruptions to LPG supply. The NSW cavern storage provides added security.

10.4.7 Other issues

It is nowadays standard to use a multi-point fuel injection system. If this is not used then there can be back-firing to the inlet manifold. Some manufacturers discontinue fuel supply during deceleration to achieve the same result.

10.5 Health Issues

LPG's low emissions have low greenhouse gas effects and low NOx precursors.

10.5.1 Production and transport

Upstream emissions associated with LPG use arise from energy used in gas and oil recovery and processing. Further emissions result from the delivery to retail outlets.

Particulate matter

The LCA estimate for LPG(Autogas) urban precombustion (truck) PM10 emissions of 44 mg/km is similar to the LSD estimate of 43 mg/km.

Air toxics

The LCA estimate for LPG(Autogas) urban precombustion (truck) HC emissions of 0.811 g/km is greater than 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.

10.5.2 Use

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics.

LPG, like CNG, has much lower emissions than diesel, and LPG has particularly low particle levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particle emissions reduce to Euro4 levels this advantage may be lost. (Anyon 1998)

Anyon (1998) also points out that US tests on medium-large engines also confirm that LPG has lower emissions of air toxics than CNG and diesel. The toxics examined were 1,3-butadiene (LPG emissions of 0.1 mg/kWh), acetaldehyde (3.8 mg/kWh), formaldehyde (16.5 mg/kWh) and benzene (0.2 mg/kWh). Nylund and Lawson (2000: Figure 2.4) provide graphs with values for unregulated emissions at low temperature (-7^{o}C) for 1,3 butadiene of 0.2 mg/km, formaldehyde of 1 mg/km, and benzene of 1 mg/km. Though these results may well refer to HD-5, it is likely that autogas would have similarly low emissions of air toxics.

Particulate matter

Research consistently shows that LPG (and gaseous fuels in general) with its simple chemistry and very low sulphur content, emit extremely low levels of particulate matter. (Anyon, 1998)

The LCA estimate for LPG(Autogas) combustion (truck) PM10 emissions of 39 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air toxics

LPG has very low 1,3 butadiene and benzene emissions, but aldehyde emissions increase substantially, as with alcohol fuels (compared to gasoline vehicles). However, these higher aldehyde emissions would likely be reduced with a catalyst specifically designed for an LPG vehicle. (USEPA, 1993). Compared to diesel vehicles LPG produces much lower emissions of the main air toxics such as benzene, 1,3 butadiene, formaldehyde and acetaldehyde. (Anyon, 1998)

The LCA estimate for LPG(Autogas) combustion (truck) HC emissions of 0.008 g/km is substantially less than the LSD estimate of 0.900 g/km.

10.5.3 Summary

LPG upstream emissions of particulate matter are similar to LSD. LPG upstream emissions of air toxics are greater than LSD. LPG tailpipe emissions of particulate matter are substantially less than LSD. LPG tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are expected to be less than LSD.

No comparative emissions data for LPG and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH)
- toluene
- xylene.

10.5.4 OHS

The release of one unit volume of LPG in air generates a mixture that is around 2.5 times more than the volume of the mixture formed following the release of a similar amount of diesel.

The extent of hazards associated with such a leakage will depend largely on the relative tendency of the fuel to form a combustible mixture and the length of time for this mixture to persist in the vicinity of discharge and away from it either to be ignited from numerous potential ignition sources or feed a fire that may be engulfing the tank.

The tendency for the fuel to disperse in the surroundings from a leak is governed by the role of buoyancy and diffusional effects.

LPG vapour is heavier than air, disperses slowly, and can accumulate in local valleys. LPG, when involved in a leak will discharge in a liquid form requiring a period of time to vaporise and disperse. In the case of CNG leak, because of the gaseous nature of the fuel , the gas will issue as a very high velocity jet into surroundings aiding greatly in the rapid dispersion of the fuel.

It takes a minimum of from over 2 % by volume of LPG in air at ambient conditions to just support a continuous flame propagation, as compared to around 5 % for methane and 1 % for petrol. The ignition energy for LPG , as well as methane and petrol, are sufficiently low that ignition is usually assured in the presence of thermal ignition sources such as sparks, lighted matches, hot surfaces and open flames. The quenching of methane-air flames by cold surfaces, as indicated by quenching distance, is easier than in the case of flames involving LPG-air mixtures. Due to this, flame traps are more successful in suppressing methane fires than those involving LPG.

LPG fires tend to persist within the leakage area due to its liquid and heavier than air state. For fuel line ruptures, pressurised gaseous fuels represent higher hazard levels than petrol.

10.6 Environmental Issues

The environmental issues surrounding LPG are the same as those for CNG and LNG, in that they are gaseous fuels that do not cause land or water pollution.

LPG may be thought of as a natural gas by-product, or as a petroleum refinery by-product. In the former case the upstream environmental issues are those of CNG; whereas in the latter case the environmental issues are those of diesel.

Noise levels from dedicated LPG buses are less than those of diesel buses. LPG buses produce less air pollutants and greenhouse gases than diesel buses. The potential for water and soil pollution is effectively eliminated by the use of LPG.

10.7 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 10.13 lists the estimated emissions factors for LPG. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of LPG. The estimates of Arcoumanis (2000) indicate that LPG can be expected to meet all future Australian Design Rules for all pollutants.

Table 10.13
Estimated emission factors for LPG under future technologies

Technology	CO	CO	HC	HC	NOx	NOx	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	0.4	**1.0**	0.5	**1.0**	0.3	**1.0**	0.3	**1.1**	1.2
Euro3	**0.53**	0.2	**0.6**	0.3	**0.71**	0.2	**0.67**	0.2	**1.0**	1.2
Euro4	**0.38**	0.1	**0.42**	0.1	**0.5**	0.2	**0.2**	0.05	**1.0**	1.1

10.8 Summary

10.8.1 Advantages

- It has low cold-start emissions due to its gaseous state.
- It has lower peak pressure during combustion, which generally reduces noise and improves durability; noise levels can be less than 50% of equivalent diesel engines.
- LPG fuel systems are sealed and evaporative losses are negligible.
- It is easily transportable and offers ‘stand-alone’ storage capability with simple and self-contained LPG dispensing facilities, with minimum support infrastructure.
- LPG vehicles do not require special catalysts.
- It contains negligible toxic components.
- LPG has lower particle emissions and lower noise levels relative to diesel, making it more attractive for urban areas.
- Its low emissions have low greenhouse gas effects and low NOx precursors.
- Relative to other fuels, any increases in future demand for LPG can be easily satisfied from both natural gas fields and oil refinery sources.
- Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles.

10.8.2 Disadvantages

- Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is lower than diesel, which explains why LPG tanks take more space than diesel fuel tanks. They are pressure vessels so that they also weigh more than diesel tanks.
- It is heavier than air, which requires appropriate handling.
- Though the lower flammability limit for LPG is actually higher than the lower flammability limit for petrol, the vapour flammability limits in air are wider than those of petrol, which makes LPG ignite more easily,
- It has a high expansion coefficient so that tanks can only be filled to 80% of capacity.
- LPG in liquid form can cause cold burns to the skin in case of inappropriate use.

11. Liquefied Petroleum Gas — HD5

11.1 Background

HD5 requires a minimum propane (C_3H_8) content of 90% and a propylene content of less than 5% on a volume basis. The remainder is normally n-butane (C_4H_{10}), with isobutane and butanes also present. LPG HD-5 is essentially propane. Table 11.1 gives properties of liquefied petroleum gas (LPG) HD5 based on its main component, propane.

Table 11.1
Properties of LPG HD5 (Propane)

Property	Value
Liquid density	499 kg/m^3
Energy density (LHV)	23.1 MJ/L
CO_2 emission factor	65 g/MJ

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. There is very little usage of LPG in Australian heavy vehicles, though the company Was Diesel Now Gas undertakes conversions of vehicles to run on HD-5. The few dedicated LPG engine options in Australia are designed to operate on LPG-HD5.

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.

The utilisation of LPG as an automotive fuel varies very widely within a country and from one country to another, depending on the cost and availability of the fuel in relation to alternative fuels, notably gasoline and diesel. Table 11.2 shows the variation in LPG fuel composition in Europe in 1982. The performance of passenger vehicles using different LPG grades has been documented by Watson and Gowdie (2000).

Table 11.2
LPG Composition (% by volume) as automotive fuel in Europe in 1982

Country	Propane	Butane
Austria	50	50
Belgium	50	50
Denmark	50	50
France	35	65
Greece	20	80
Ireland	100	-
Italy	25	75
Netherlands	50	50
Spain	30	70
Sweden	95	5
United Kingdom	100	-
Germany	90	10

Source: www.vps.com/LPG/WVU-review.html

Table 11.2 indicates that there are two different classes of LPG. LPG HD5 is used in the United States. Its specifications have been regulated by the California Air Resources Board (http://www.arb.ca.gov/regact/lpgspecs/lpgspecs.htm) under Amendment of Title 13, California Code of Regulations, section 2292.6.

In 1992, the Board adopted section 2292.6, which took effect on January 1, 1993. The Board included a maximum limit of 10% by volume on the propylene content of vehicular LPG. That propylene limit was to have declined to 5% on January 1, 1995. However, in 1994, the Board delayed the effective date of the 5% propylene limit to January 1, 1997, and then in 1997, the Board again delayed the effective date of the propylene limit until January 1, 1999. In the interim, the propylene limit remained at 10% by volume. The Board delayed the effective date of the propylene limit out of concerns raised by the vendors of commercial propane (who supply the motor vehicle LPG used in California) that too little of the commercial propane available to them meets the original specifications set by the Board.

The LPG specifications also include a maximum limit on butanes and heavier species, of 2.5% by volume. This limit is also contained in the specifications for industrial and commercial grade propane.

When the Board adopted the specifications for vehicular LPG, and other alternative fuels, it set essentially identical standards for the motor vehicle fuel sold commercially in California and the fuel used for emission standard certification testing of new motor vehicles. The purpose for the commercial fuel specifications is to ensure that motor vehicles certified on LPG will receive in-use fuel having a quality similar to that of the certification fuel, so that the vehicles will achieve their emission standards in use.

On 8 December 1999 the following amendments came into force:

(1) Retain the current interim propylene limit of 10% by volume as a permanent limit.

(2) Establish a new 2.0% by volume maximum limit for butenes.

(3) Establish a new 0.5% by volume maximum limit for pentenes and heavier.

(4) Amend the optional 2.5% by volume maximum limit for butanes and heavier to a 5.0% by volume limit for butanes.

(5) Reduce the maximum sulfur content limit from 120 to 80 parts per million by weight.

Finally, the Board approved an amendment, which requires the staff to review the LPG regulation in five years to determine whether it should be retained, revised, or repealed.

11.1.1 LPG in heavy vehicles

As a result of the recent environmental concern in relation to the health effects of particulate matter (Beer, 2000), especially particulate matter of diameter less than 10 μm known as PM10, LPG is being reconsidered as a heavy vehicle fuel. Particulate matter emitted by diesel is all PM10. Anyon (1998) points out that LPG, like CNG, has much lower emissions than diesel, and LPG has particularly low particulate levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particulate emissions reduce to Euro4 levels this advantage may be lost, though the LPG industry believes that a fully optimised LPG engine may be capable of producing lower particulate emissions than an equivalent Euro4 diesel engine.

DAF, the Dutch vehicle maker, has developed a dedicated LPG fuelled bus. DAF prefers the stoichiometric process over lean burn. The advantage of the stoichiometric combustion principle is that it allows the use of a three-way catalyst, which is impossible in lean burn. With a three-way catalyst the emission of all polluting compounds can be reduced, resulting in extremely low emission rates. If a two-way catalyst is used, the NO_x is not removed. The stoichiometric process reduces the emission rate of particulate matter to one twentieth of Euro2, whereas lean burn only comes to half of Euro2. The drawback of the stoichiometric process is that it loses the efficiency advantage of lean burn and correspondingly increases CO_2 emissions. Figure 1.1 shows the influence of air-fuel ratio on emissions.

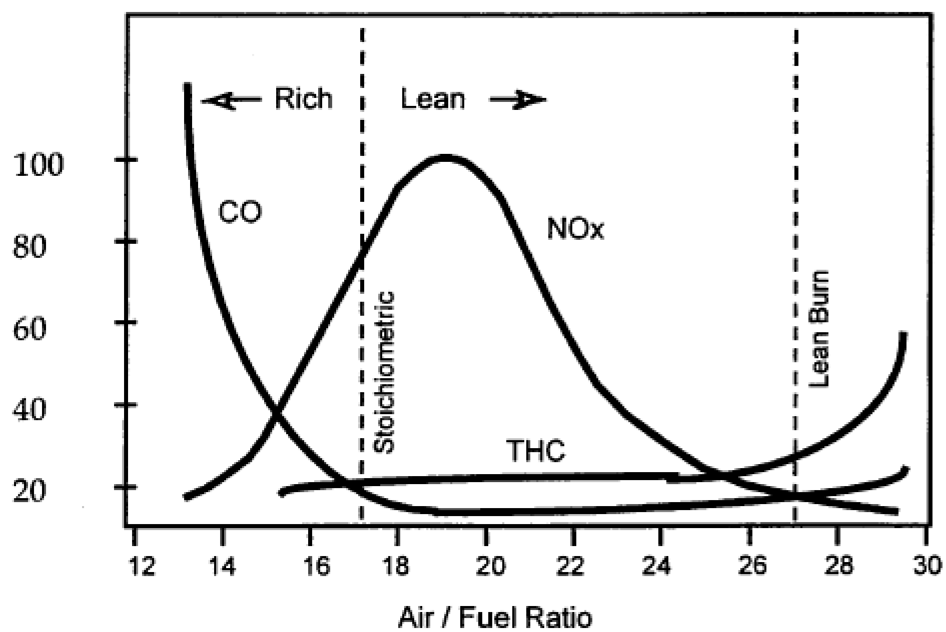


Figure 11.1
Influence of air-fuel ratio on emissions and fuel consumption of a spark-ignition engine. The ordinate is in ppm, and the abscissa is a volumetric ratio (Nylund and Lawson, 2000).

11.2 Exbodied Emissions

11.2.1 Emissions tests

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics. There is considerable data in relation to LPG used in cars. (NSWEPA, 1997).

Beer et al. (2000) quote values provided by Anyon (1998) reproduced in Table 11.3. As a result of stakeholder input, and a further literature search we found further information as given in Table 11.4. The Cummins B5.9LPG data from ADEPT (1998) was used in our analysis.

The LPG sold in the United Kingdom, Ireland, Sweden, Germany and in the United States (when sold as HD5) is propane. As noted by ANGVC (2000) this means that the widely quoted Millbrook trials data, Table 11.3, for the LPG bus in the London Transport Study (Anyon, 1998; Expert Reference Group, 1998; Beer et al., 2000) refers to propane rather than the LPG sold in eastern Australia.

Table 11.3
LPG (Propane) emissions (g/km)

	CO	THC	NOx	PM	CO_2
London LPG Bus with 3 way catalyst	0.13	0.03	5.4	0.02	1309

Table 11.4
LPG (Propane) emissions (g/kWh)

	CO	THC	NMHC	NOx	PM	CO_2	FC
Ford 6.8L V10 engine (Nylund & Lawson, 2000:p105)	3.8		0.15	0.7			
Cummins B5.9LPG with catalyst (ANGVC submission)	1.34		1.09*	3.06*	0.01		
Cummins B5.9LPG (ADEPT, 1998)	0.56	1.185	1.138	3.724	0.008	897.8	315

*These values were from T. Green of Cummins Inc.

Anyon (1998) also points out that US tests on medium-large engines confirm that LPG has lower emissions of air toxics than CNG and diesel. The toxics examined were 1,3-butadiene (LPG emissions of 0.1 mg/kWh), acetaldehyde (3.8 mg/kWh), formaldehyde (16.5 mg/kWh) and benzene (0.2 mg/kWh). Nylund and Lawson (2000: Figure 11.4) provide graphs with values for unregulated emissions at low temperature (-7^{o}C) for 1,3 butadiene of 0.2 mg/km, formaldehyde of 1 mg/km, and benzene of 1 mg/km.

The default emission factors in the methodology for the US Greenhouse Gas Inventory are given in Table 11.5 in terms of pounds per million BTU (the original units), and their conversion into g/MJ, for both controlled (i.e. equipped with catalytic converters) and uncontrolled vehicles.

Table 11.5
Default Emission Factors for LPG (USEPA 1995)

	Controlled HDV (lb/million BTU)	Uncontrolled HDV (lb/million BTU)	Controlled HDV (g/MJ)	Uncontrolled HDV (g/MJ)
CH_4	0.022	0.066	0.0095	0.0284
N_2O				
CO	0.199	3.359	0.0855	1.4438
NMVOC	0.155	1.127	0.0666	0.4844
NOx	0.53	0.796	0.2278	0.3421
CO_2 as C	37.8	37.8	16.2476	16.2476

11.2.2 Upstream

Upstream processing has been dealt with in the description of autogas. The processing of HD5 is identical, except for the rejection of the butane and the subsequent provision of propane gas.

11.3 Results

11.3.1 Emissions per unit energy

Table 11.6
Urban and total life cycle emissions calculated for diesel and propane

Full Lifecycle	Units (per MJ)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.0858	0.0820
HC total	g HC	0.140	0.103
HC urban	g HC	0.111	0.076
NOx total	g Nox	1.044	0.413
NOx urban	g Nox	0.987	0.361
CO total	g CO	0.253	0.036
CO urban	g CO	0.242	0.026
PM10 total	mg PM10	40.7	6.5
PM10 urban	mg PM10	39.3	5.2
Energy embodied	MJ LHV	1.18	1.09

Table 11.7
Precombustion emissions per MJ for diesel and propane

Precombustion	Units (per MJ)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.0191	0.0170
HC total	g HC	0.0565	0.101
HC urban	g HC	0.027	0.074
NOx total	g Nox	0.100	0.090
NOx urban	g Nox	0.043	0.038
CO total	g CO	0.023	0.021
CO urban	g CO	0.012	0.011
PM10 total	mg PM10	5.42	5.05
PM10 urban	mg PM10	4	3.72
Energy embodied	MJ LHV	1.18	1.09

Table 11.8
Combustion emissions per MJ for diesel and propane

Combustion	Units (per MJ)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.067	0.065
HC total	g HC	0.084	0.002
HC urban	g HC	0.084	0.002
NOx total	g NOx	0.944	0.323
NOx urban	g NOx	0.944	0.323
CO total	g CO	0.230	0.015
CO urban	g CO	0.230	0.015
PM10 total	mg PM10	35.26	1.43
PM10 urban	mg PM10	35.26	1.43
Energy embodied	MJ LHV	0	0

Table 11.9
Summary of life cycle emissions per MJ from diesel and propane

		LS diesel	LPG (HD5)
Greenhouse	Precombustion	0.0191	0.0170
Greenhouse	Combustion	0.0667	0.0650
HC total	Precombustion	0.0565	0.1010
HC total	Combustion	0.0835	0.0021
HC urban	Precombustion	0.0271	0.0739
HC urban	Combustion	0.0835	0.0021
NOx total	Precombustion	0.1000	0.0904
NOx total	Combustion	0.944	0.323
NOx urban	Precombustion	0.043	0.038
NOx urban	Combustion	0.944	0.323
CO total	Precombustion	0.0225	0.0205
CO total	Combustion	0.2301	0.0152
CO urban	Precombustion	0.0123	0.0110
CO urban	Combustion	0.2301	0.0152
PM10 total	Precombustion	5.42	5.05
PM10 total	Combustion	35.26	1.43
PM10 urban	Precombustion	4.00	3.72
PM10 urban	Combustion	35.26	1.43
Energy embodied	Precombustion	1.18	1.09

11.3.2 Emissions per unit distance

Table 11.10
Exbodied emissions per km for diesel and propane

Full Lifecycle	Units (per km)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.9250	0.8963
HC total	g HC	1.509	1.133
HC urban	g HC	1.192	0.830
NOx total	g NOx	11.250	4.517
NOx urban	g NOx	10.638	3.939
CO total	g CO	2.723	0.390
CO urban	g CO	2.612	0.286
PM10 total	mg PM10	438.4	70.7
PM10 urban	mg PM10	423.1	56.3
Energy Eembodied	MJ LHV	12.7	11.9

Table 11.11
Precombustion emissions per km for diesel and propane

Precombustion	Units (per km)	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.2060	0.1860
HC total	g HC	0.609	1.11
HC urban	g HC	0.292	0.807
NOx total	g NOx	1.080	0.988
NOx urban	g NOx	0.468	0.410
CO total	g CO	0.243	0.224
CO urban	g CO	0.132	0.120
PM10 total	mg PM10	58.4	55.1
PM10 urban	mg PM10	43.1	40.7
Energy embodied	MJ LHV	12.7	11.9

Table 11.12
Emissions from combustion per km for diesel and propane

Combustion	Units	LS diesel	LPG (HD5)
Greenhouse	kg CO_2	0.719	0.710
HC total	g HC	0.900	0.023
HC urban	g HC	0.900	0.023
NOx total	g NOx	10.177	3.529
NOx urban	g NOx	10.177	3.529
CO total	g CO	2.480	0.166
CO urban	g CO	2.480	0.166
PM10 total	mg PM10	380.00	15.63
PM10 urban	mg PM10	380.00	15.63
Energy embodied	MJ LHV	0	0

Table 11.13
Summary of life cycle emissions per km from diesel and propane

		LS diesel	LPG (HD5)
Greenhouse	Precombustion	0.2060	0.1860
Greenhouse	Combustion	0.7190	0.7103
HC total	Precombustion	0.6090	1.1100
HC total	Combustion	0.9000	0.0231
HC urban	Precombustion	0.2920	0.8070
HC urban	Combustion	0.9000	0.0231
NOx total	Precombustion	1.0800	0.9880
NOx total	Combustion	10.170	3.529
NOx urban	Precombustion	0.468	0.410
NOx urban	Combustion	10.170	3.529
CO total	Precombustion	0.2430	0.2240
CO total	Combustion	2.4800	0.1657
CO urban	Precombustion	0.1320	0.1200
CO urban	Combustion	2.4800	0.1657
PM10 total	Precombustion	58.40	55.10
PM10 total	Combustion	380.00	15.63
PM10 urban	Precombustion	43.10	40.70
PM10 urban	Combustion	380.00	15.63
Energy embodied	Precombustion	12.70	11.90

11.3.3 Uncertainties

In the absence of information on the variability and uncertainties associated with LPG emissions, we assume that the uncertainties are the same as those associated with LNG.

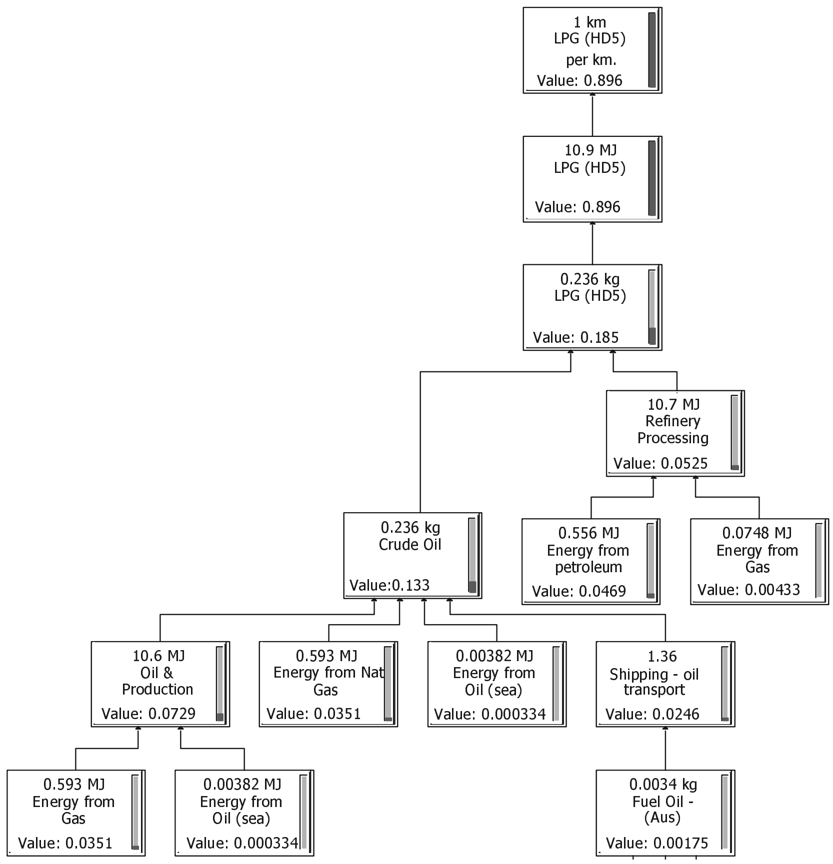


Figure 11.2
Exbodied greenhouse gases emissions (kg CO_2eq) from LPG (HD5) production and processing and use in vehicle

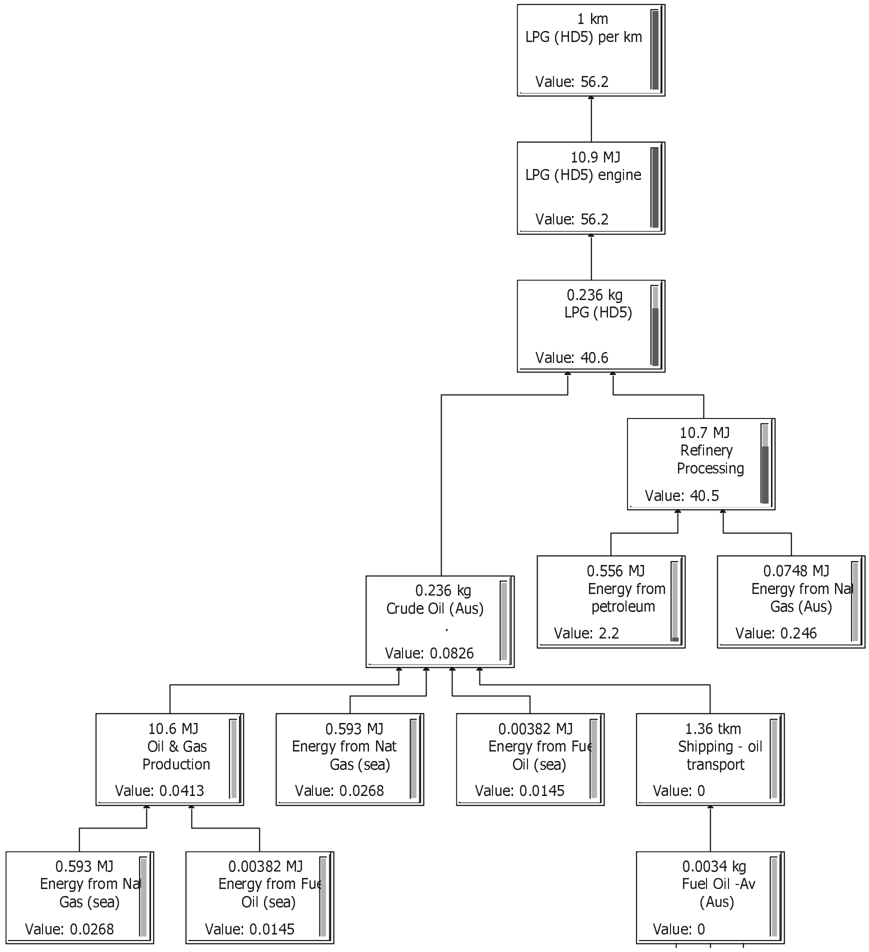


Figure 11.3
Exbodied particulate matter (mg - urban) from LPG (HD5) production and processing and use in vehicle

11.4 Dual fuel and converted vehicles

One relevant issue is a comparison of dual-fuelled vehicles' emissions with those of dedicated LPG only vehicles.

Table 11.14, in the first two columns, gives results reported to the AGO for a 42,000kg GVM 6 cylinder dual fuel (converted) prime mover (when compared to diesel) undergoing tests on the CUEDC drive cycle. Table 11.14 also reproduces the tailpipe results in Table 11.12, in the last two columns. In addition to these results, both maximum power and maximum tractive effort were higher for the dual fuel vehicle.

Table 11.14
Comparative emission (gram per km) for dual fuel and LPG only vehicles

	Dual Fuel		LPG-HD5 only	
	Diesel	**Diesel/LPG**	**Diesel**	**Propane only**
NO_x	18.18	17.67	10.18	3.53
HC	0.69	3.53	0.90	0.023
CO	3.35	8.54	2.48	0.166
CO_2	1296	1359	719	710
PM	0.234	0.227	0.38	0.016

The AGO also provided results (Table 11.15) of tests a Rigid Tray Truck of 13,900 kg GVM that was converted from diesel to a dedicated LPG (HD5) vehicle. The LPG conversion included: modified combustion chambers; reduced compression ratio; sequential port LPG injection; electronic closed loop engine management; and very slight 'lean of stoichiometric' combustion.

The converted vehicle was first tested on the CUEDC cycle. A 3-way catalyst and a turbo boost control valve were then fitted and the vehicle retested in a DT80 test. No testing was done on this vehicle prior to conversion.

Table 11.15
Comparative emission for converted LPG-HD5 only vehicles

	Converted vehicle		Diesel comparison	
	CUEDC (no emission control)	**DT80 (3C+turbo boost)**	**Diesel similar to tested vehicle**	**Generic diesel (Table 11.12)**
NO_x (g/km)	17.1	6.3	4.33	10.18
HC (g/km)	10.6	1.73	0.5	0.90
CO (g/km)	7.16	0.1	2.29	2.48
CO_2 (g/km)	701		763	719
PM (mg/km)	14.1	2.2	453	380
Fuel L/100km	48.3		33.5	
Average opacity (%)	0.1		4.6	

Technical advice communicated by the AGO indicates that the DT80 procedure produces higher emissions than the CUEDC, though the DT80 results correlate well with CUEDC (National Environment Protection Council, 2001). The results for diesel vehicles tested under the CUEDC and DT80 cycles show higher NOx and HC emissions in the DT80 cycle, but substantially lower CO and PM emissions.

Summary

A dedicated LPG vehicle emits lower quantities of all criteria pollutants and greenhouse gases from its tailpipe than an equivalent diesel vehicle. This advantage is lost with dual fuel vehicles and with converted vehicles. On the basis of the two test for which data was available, total hydrocarbon emissions from both types of vehicles are higher than those of the equivalent diesel vehicles. The dual fuel vehicle emitted higher quantities of CO and CO_2 (as well as HC) than the equivalent diesel vehicle.

The three way catalyst and turbo boost reduced NOx, HC, CO and PM emissions. However, the converted propane vehicle emitted higher quantities of NOx, as well as HC, (when compared to an equivalent diesel vehicle) even when fitted with a three way catalyst, though the three way catalyst and turbo boost was very successful in reducing CO emissions. Neverthless, in all cases the change from diesel to LPG – whether from dedicated, converted or dual fuel vehicles - results in lower particulate matter (PM) emissions.

The Australian LPG conversion industry for heavy vehicles is at an early stage in its development. The data from these two tests may not reflect the emissions performance of converted vehicles in the longer term.

11.5 Viability and Functionality

Propane (HD5) viability and functionality issues are identical to those of autogas. The main benefit of propane is that the compression ratio can be altered to suit the higher octane fuel.

Stakeholder input from Cummins noted that when comparing diesel, propane and natural gas in the same engine then the engine performance ratings are highest for diesel, then CNG, then propane. The use of an exhaust brake (guillotine style) is not permitted with the propane or CNG engine, due to the high exhaust temperature. The results, as provided, are reproduced in Table 11.14.

Table 11.16
Relative performance of a Cummins 5.9 L engine

	Maximum bhp rating	Maximum torque
Diesel	260	660
Propane	195	420
CNG/LNG	230	500

Source: J. Bortolussi (pers. comm.)

11.6 Health Effects

Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles. LPG in liquid form can cause cold-burns to the skin in case of inappropriate use. In general, the health effects of autogas and HD5 are the same.

11.6.1 Production and transport

LPG’s low emissions have low greenhouse gas effects and low NOx precursors.

Particulate Matter

The LCA estimate for LPGHD5 urban precombustion (truck) PM10 emissions of 41 mg/km is similar to the LSD estimate of 43 mg/km.

Air Toxics

The LCA estimate for LPGHD5 urban precombustion (truck) HC emissions of 0.807 g/km is greater than 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.

11.6.2 Use

Because it is relatively rare for LPG to be used in heavy vehicles, there is a lack of published data on its emissions characteristics.

LPG, like CNG, has much lower emissions than diesel, and LPG has low particulate levels, which make it an attractive fuel for urban buses and delivery vehicles. However, as diesel particulate emissions reduce to Euro4 levels this advantage may be lost. (Anyon 1998).

Anyon (1998) also points out that US tests on medium-large engines also confirm that LPG has lower emissions of air toxics than CNG and diesel. The toxics examined were 1,3-butadiene (LPG emissions of 0.1 mg/kWh), acetaldehyde (3.8 mg/kWh), formaldehyde (16.5 mg/kWh) and benzene (0.2 mg/kWh). Nylund and Lawson (2000: Figure 11.4) provide graphs with values for unregulated emissions at low temperature (-7^{o}C) for 1,3 butadiene of 0.2 mg/km, formaldehyde of 1 mg/km, and benzene of 1 mg/km.

Particulate matter

Research consistently shows that LPG (and gaseous fuels in general) with its simple chemistry and very low sulphur content, emit extremely low levels of particulates. (Anyon, 1998).

The LCA estimate for LPGHD5 combustion (truck) PM10 emissions of 16 mg/km is substantially less than the LSD estimate of 380 mg/km.

Air Toxics

LPG produces much lower emissions of the main air toxics such as benzene, 1,3 butadiene, formaldehyde and acetaldehyde, compared with diesel (Anyon, 1998).

The LCA estimate for LPGHD5 combustion (truck) HC emissions of 0.023 g/km is substantially less than the LSD estimate of 0.900 g/km.

11.6.3 Summary

LPGHD5 upstream emissions of particulates are similar to LSD. LPGHD5 upstream emissions of air toxics are greater than LSD. LPGHD5 tailpipe emissions of particulates are substantially less than LSD. LPCNG tailpipe emission of benzene, 1,3 butadiene, formaldehyde and acetaldehyde are less than LSD.

No comparative emissions data for LPGHD5 and LSD has been identified for:

- polycyclic aromatic hydrocarbons (PAH)
- toluene
- xylene.

11.7 Environmental Issues

The environmental issues related to propane will be identical to those related to autogas.

Propane may be thought of as a natural gas by-product, or as a petroleum refinery by-product. In the former case the upstream environmental issues are those of CNG; whereas in the latter case the environmental issues are those of diesel.

Noise levels from dedicated LPG buses are less than those of diesel buses. LPG buses produce less air pollutants and greenhouse gases than diesel buses. The potential for water and soil pollution is effectively eliminated by the use of LPG.

11.8 Expected Future Emissions

Arcoumanis (2000) developed a model that examines a given alternative fuel relative to the reference diesel engine (Euro2) in terms of a specific regulated pollutant. A value of 1 implies identical performance to the low sulfur diesel/Euro2 combination. A value greater than 1 implies inferior performance, whereas a value less than 1 indicates superior performance.

Table 11.1 lists the estimated emissions factors for LPG. The columns in bold represent the standards relative to the Euro2 standard. The adjacent column gives the expected performance of LPG. The estimates of Arcoumanis (2000) indicate that LPG can be expected to meet all future Australian Design Rules for all pollutants.

Table 11.17

Estimated emission factors for LPG under future technologies

Technology	CO	CO	HC	HC	NO_x	NO_x	PM	PM	CO_2	LCA CO_2
Euro2	**1.0**	0.4	**1.0**	0.5	**1.0**	0.3	**1.0**	0.3	1.1	1.2
Euro3	**0.53**	0.2	**0.6**	0.3	**0.71**	0.2	**0.67**	0.2	1.0	1.2
Euro4	**0.38**	0.1	**0.42**	0.1	**0.5**	0.2	**0.2**	0.05	1.0	1.1

11.9 Summary

11.9.1 Advantages

- Propane has low cold-start emissions due to its gaseous state.
- Propane has lower peak pressure during combustion than conventional fuels, which generally reduces noise and improves durability.
- LPG fuel systems are sealed and evaporative losses are negligible.
- Propane is easily transportable and offers ‘stand-alone’ storage capability with simple and self-contained LPG dispensing facilities, with minimum support infrastructure.
- LPG vehicles do not require special catalysts.
- Propane contains negligible toxic components.
- LPG has lower particulate emissions and lower noise levels relative to diesel, making propane attractive for urban areas. Noise levels can be less than 50% of equivalent engines using diesel.
- Propane’s emissions are low in greenhouse gases and low in NOx, thus they are low in ozone precursors.
- Increases in future demand for LPG can be easily satisfied from both natural gas fields and oil refinery sources.
- Emissions of PAH and aldehydes are much lower than those of diesel-fuelled vehicles.

11.9.2 Disadvantages

- Although LPG has a relatively high energy content per unit mass, its energy content per unit volume is low which explains why LPG tanks take more space and weigh more than diesel fuel tanks of the same energy storage capacity.
- Propane is heavier than air, which requires appropriate handling.
- Though the lower flammability limit for propane is actually higher than the lower flammability limit for petrol, the vapour flammability limits in air are wider than those of petrol, which makes propane ignite more easily.
- Propane has a high expansion coefficient so that tanks can be filled to only 80% of capacity.
- LPG in liquid form can cause cold burns to the skin in case of inappropriate use.