25th Australasian Transport Research Forum
Incorporating the BTRE Transport Policy Colloquium
Canberra 2-4 October 2002

The role of LPG in reducing vehicle exhaust emissions

Damon Honnery, J Ghojel and Patrick Moriarty
Monash University

Abstract

Examination of the Australian vehicle fleet leads to the conclusion that the time required for a significant penetration of forced change, for example the switch from leaded to unleaded petrol, largely depends on the average age of the vehicle type and vehicle use. Thus vehicle groups with high turnover, as represented by a high scrappage rate or low average age, will be populated by technologically, and hence environmentally, superior vehicles, compared with groups with lower turnover rates. A significant question for these vehicle groups is what to do with older vehicles as Australia harmonises its emission standards with those in Europe. Heavy duty vehicles are one such group. They are typically diesel powered, and of greater average age and cost than other vehicles. Thus many were introduced into Australia before any rigorous exhaust emission standards for this class of vehicle were in place. Because of their cost, many are unlikely to be replaced until the cost of operation forces change. Since they don't have to meet any new or recently introduced emission standards, environmental factors are rarely considered important. One possible solution to the environmental problems these vehicles cause may lie in the conversion of the diesel power plant to a cleaner fuel such as propane. In this paper we look at the potential within the heavy duty vehicle sector for conversion to propane and the improvements in emissions, both local and global, that may result. Our analysis is based on a series of instrumented chassis dynamometer tests carried out on both diesel and propane fuelled heavy vehicles.

Contact author

Dr Damon Honnery
Senior Lecturer, Dept of Mech. Engineering
Monash University
Dept. of Mech Engineering
PO Box 31
Monash University
Clayton VIC 3800
Telephone: 03 9905 1988
Fax: 03 9905 1825
E-mail: damon.honnery@eng.monash.edu.au

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Introduction

Urban road transport in Australia, whether passenger or freight, faces three major environmental/resource challenges. The first is oil depletion; Australian oil and condensate production is expected to peak soon (Australian Bureau of Statistics (ABS) 2002). ABARE projects that Australia will need to import 60% of its petroleum by the year 2010, compared with under 10% in 2001 (Anon 2002). The world as a whole will experience similar difficulties. A US Geological Survey official, Les Magoon, sees cumulative global oil production passing 50% of total discovered and undiscovered reserves by around 2007 (the 'turning point', as he describes it), after which he sees a sellers' market prevailing (Anon 2001). Australia will increasingly need to compete with the rest of the world for its imported oil from the small handful of Gulf states which will still have oil for sale.

The other two problems, urban and global air pollution, are the main concerns of this paper. Global air pollution from greenhouse gases, chiefly CO_2, is not uniquely an urban problem. But like oil depletion, it is in large urban areas that solutions must be found first, since alternatives to oil-based fuels, or alternative transport modes, are easier to introduce in cities than in more thinly populated areas. Air pollution is also usually more serious in cities in Australia, which is a further reason for focussing on cities. Transport emissions are the dominant sources for urban carbon monoxide (CO), oxides of nitrogen (NO_X) and hydrocarbons (ABS 1996). They are also therefore an important contributor to urban photochemical smog, which is a serious problem in Melbourne and Sydney.

All these pollutants, together with PM10s (particulate matter smaller than 10 micrometres), have adverse health effects (Beer, Grant, Brown, Edwards, Nelson, Watson and Williams 2000; Lloyd and Cackette 2001; Yencken and Wilkinson 2000). Further, the solution to Australia's urban pollution lies firmly in our own hands, since very little of it is generated in other countries. While urban air pollution may be declining in most of our large cities on a ppm basis, its adverse health effects are probably growing. Not only are our city populations increasing, but over the past decade there has been a move back to the inner city and adjacent suburbs (ABS 2001a), where traffic densities and congestion are highest.

The situation for Australia is further complicated by the move to harmonise our emission standards with those of Europe. For petrol vehicles, this presents a relatively minor challenge, as previous emission regulations have kept pace with change so the gap should be easy to bridge. For diesel vehicles this is not the case. The new Euro emission regulations for diesel vehicles represent a significant improvement over previous standards. Overlaying this is the need, if these standards are to be met, to dramatically improve Australian diesel fuel quality. For example, diesel sulphur levels will need to drop from the existing 1800ppm to less than 50ppm by 2006/7 (Coffey Geosciences 2000). This change alone may require a significant restructuring of the Australian crude oil refining industry (Coffey Geosciences 2000), as appears also to be the case for the US (Loftus, Jones and Huggins 2001). While the changes to emission standards will ultimately lead to improved air quality, this will only take place once newer, less polluting vehicles replace much of the existing fleet. Given the generally longer life of diesel vehicles and their relatively high pollution levels, this may take some time to occur.

There are a number of possible solutions to the problems presented by old diesel vehicles. Old vehicle numbers can be reduced by accelerating their scappage rate through vehicle buy-back programs. Estimates developed by the Bureau of Transport and Communication Economics (BTCE) (1996) suggest that this solution is costly and of limited benefit; for example it would be necessary to scrap virtually all commercial vehicles older than 20 years to obtain a yearly reduction of 1% in emissions. Inspection and maintenance programs combined with emission compliance regimes have also been suggested for in-service vehicles (National Environment Protection Council (NEPC) 2001). However, these would need to rely on improved regulation and enforcement. Another possible solution is to convert these vehicles to an alternative fuel that not only reduces emissions, but also has greater supply security.

In response to these challenges, this paper examines the potential for reducing urban air pollution and greenhouse gas (GHG) emissions by increasing the use of LPG in road transport. At present, LPG is only used in spark ignition engines. This paper first reviews the benefits of light vehicle LPG use, then examines the case for converting old diesel buses and trucks to run on LPG. For this option to be considered useful, the conversion should pay for itself in saved fuel costs, while reducing not only urban air pollution, especially particulates, but also greenhouse gas emissions. Our results show that present LPG conversions can reduce certain urban air pollutants, but not, at present, greenhouse gas emissions.

LPG as an alternative road transport fuel

The GHG (and local air pollution) benefits of LPG may seem very small when compared with the claims often made for biomass fuels, hydrogen fuel cell vehicles, or electric battery vehicles using renewable electricity, with emission reductions ranging up to 100% (Moriarty 2000; Moriarty and Honnery 2002). Further, LPG is still a fossil fuel with a finite resource base, like petrol and diesel. Worldwide, however, LPG is the most important alternative to petrol and diesel in the road transport sector; it is used in almost 7.5 million vehicles in over 40 countries (Australian LPG Association (ALPGA) 2002). This section argues that unlike other alternatives, LPG is not only already well-established in Australia, but has considerable potential for growth as a transport fuel. While not a long term solution, it can help alleviate, in the near and medium term, the supply uncertainties and global and local air pollution problems facing petrol and diesel.

Present use of LPG in Australian road transport

LPG was introduced into Australian road transport in the late 1970s, and according to the latest motor vehicle census (ABS 2001b), is now used in nearly 300,000 road vehicles in Australia, which is 2.4% of the total fleet (Table 1). Of the vehicle types, passenger vehicles and LCVs account for about 98% of all LPG fuelled vehicles. Even higher figures for LPG-fuelled vehicles are reported, with Gogas (2001) giving 500,000, and ALPGA (2001) 'more than 550,000'. Almost all small LPG vehicles have been converted post purchase (whether for LPG use only or as a dual fuel system with petrol) from spark ignition-petrol to spark ignition-LPG. It is only in the last few years that vehicle manufactures have offered LPG variants of popular models.

Table 1 Road fleet by type of vehicle and fuel type in thousands, 2001 (Source: ABS 2001b)

Vehicle type	Petrol	Diesel	LPG/Dual fuel	All fuels
Pass. vehicles	9379	250	207	9836
LCVs	1257	432	81	1770
Buses	15	51	1	67
All trucks	69	345	5	419
All vehicles*	11092	1089	295	12477

*Includes motorcycles and campervans

The share of LPG in total road fuel consumption is much higher than the share of LPG-fuelled vehicles, because LPG is used mainly by vehicles with high kilometres per year. The latest Survey of Motor Vehicle Use (ABS 2001c) gives 1.89 billion litres for the 'LPG/CNG/dual fuel' category, or 7.6% of all road transport fuel by volume. The Australian Institute of Petroleum (AIP) (2002) states that 60% of Australian consumption of 2.3 million tonnes (MT) in 2000 was for 'automotive use', which would imply that LPG's share by volume was already over 10%. Victoria has long had a disproportionate share of LPG vehicles and fuel use: in 1996, 56% of auto LPG was sold in Victoria (AIP 1997). However, as a share of petrol sales, South Australia had a slight lead over Victoria. The other states all had very minor LPG use.

At the end of 2000, there were 8370 service stations in Australia, and in 2002, nearly 3500 LPG retail outlets (Table 2). Victoria and SA had a higher share of LPG outlets than service stations in general, as expected, but the other mainland states were also well-provided with LPG outlets. Given that the economic benefit of LPG use for high kilometre travel vehicles would be similar to that for Victoria and SA, the low use by the other major states is surprising.

Table 2 Number of service stations and LPG outlets in Australia by state (percentage in brackets) (Source: ALPGA 2002)

State	No. of service stations in year 2000	No. of LPG outlets in year 2002
NSW/ACT	2758 (33%)	926 (26%)
Vic	1966 (24%)	1065 (31%)
Qld	1521 (18%)	517 (15%)
WA	848 (10%)	430 (12%)
SA	807 (10%)	441 (13%)
Tas	361 (4%)	45 (1%)
NT	109 (1%)	64 (2%)
Australian total	8370 (100%)	3488 (100%)

Environmental/resource arguments for LPG use

Australian oil reserves are not large; in 1998/9 the reserves to production (R/P) ratio was 9.5 years for economically demonstrated resources (ABS 2002). Australia’s crude oil and condensate production has probably already peaked, and will drop sharply over the coming years (Anon 2002). In contrast, the comparable R/P ratio for naturally occurring LPG was 46.4 years, and that for natural gas (NG), 44.6 years. Since Australia is a significant net exporter of LPG and NG, while being a net importer of crude oil, the reserves to domestic consumption ratios are even more skewed in favour of LPG and NG. Naturally-occurring LPG in Australia is usually associated with NG, although it is also found with oil. LPG reserves are about 8% of NG reserves (ABS 2002).

How much could transport LPG use be expanded in Australia? Presently, about 1.4 MT are used in light vehicles, or 60% of total local consumption of 2.3 MT. Since total Australian production is around 3.3 MT (AIP 2002), annual auto use could be expanded to around 2 MT if it continued to use 60% of the total, and if (net) exports ceased. Future production of naturally occurring LPG should expand as NG production expands. On the other hand, any reduction in local oil production would partly offset this increase. Refinery LPG could either rise or fall in the future. It will rise if refinery production of higher octane petrol rises (AIP 2002). But, given the uncertain future for oil, future refinery production itself may be uncertain. In summary, if net LPG exports ceased, and NG production grows as planned, transport use for LPG can also be expanded significantly.

Not only are LPG and NG more abundant than conventional petroleum, but, because of their lower carbon content, they produce less CO_2 per megajoule (MJ) during combustion than diesel or petrol. For this reason, as well, they deserve careful consideration as alternatives for vehicle fuels. At 99% combustion, values for the CO_2 produced by various fossil fuels (in gram per MJ of energy released) and their energy density are given in Table 3. (For NG 100% combustion is assumed, and the energy density figure is for LNG).

Table 3 **Energy density and CO_2 emissions for various fuels (Source: Australian Greenhouse Office (AGO) 1998)**

Fuel	MJ/litre	CO_2 g/MJ
NG	25.0	54.4
LPG	25.7	59.4
Petrol	33.0	66.0
Diesel	38.6	69.7

When examining the relative greenhouse gas (GHG) emissions for various fossil fuels it is important to consider GHG emissions other than CO_2 released during combustion, and also emissions that must be assigned to the fuel that are released during fuel production, transport, refining, storage, and distribution. The literature shows that, except for NG, emissions other than CO_2 are a very minor share of both total combustion and upstream GHG emissions (Wang 1996).

For natural gas, normally used as compressed natural gas (CNG), despite its low CO_2 releases during combustion, full fuel cycle analysis in the US shows that the CO_2-equivalent emissions for a CNG-fuelled car are greater than for an equivalent petrol-fuelled car (Wang 1997). Emissions increased not only because of releases of methane, itself an effective GHG, but also because of the heavier tanks needed to store compressed NG on board. Another issue for CNG is supply quality. At present no fuel quality standard exists for CNG as a road transport fuel in Australia, and it has been shown that the naturally occurring variations in NG from field to field can have a significant effect on performance and emissions (Elder, Jones and Raine 1985). The liquefied form of NG (LNG) suffers even more in greenhouse gas terms than CNG because of the extra energy required to liquefy the gas (Wang 1997). For these reasons, and because of the lack of sales outlets for NG, it will not be considered further in this paper.

A number of researchers, both in Australia and overseas, have published figures on both the upstream energy and greenhouse gas costs of different fuels, including petrol, diesel and LPG (Energetics P/L, 1990; Ecotraffic AB, 1992; Wang, 1996; Lenzen, 1999). To allow comparison, upstream emissions have been expressed as a percentage of emissions during vehicle operation for all the studies. The results are shown in Table 4. As can be seen, there is little agreement on the reported values.

LPG (chiefly a mixture of propane and butane) produced in Australia is mainly obtained directly from the natural gas stream and crude oil. In the year 2000, about 22% of total LPG production was extracted from crude oil in refineries (AIP 2001). Fuel cycle energy and GHG costs will be greater for refined than for naturally occurring LPG, which explains the higher overall values in the US literature (Wang), as well as in Lenzen (1999), who considers LPG only as a refined product. The figures for Energetics are based on naturally occurring Australian LPG; those for Ecotraffic on propane imported to Sweden. To allow for some refined LPG in an Australian context, round figures of 1.10 for the petrol/LPG ratio, and 1.05 for the diesel/LPG ratio have been assumed in this study. Thus, considering the values in both Tables 3 and 4, one MJ of petrol consumed will produce 1.22 times the full fuel cycle CO_2 equivalent emissions of one MJ of LPG. For diesel, the equivalent figure is similar at 1.23.

Table 4 Fuel cycle GHG costs of various transport fuels (combustion CO_2 =1.0)

Author	Country	Petrol	Diesel	LPG
Energetics* (1990)	Australia	1.16	1.10	1.03
Ecotraffic* (1992)	Sweden	1.21	1.14	1.09
Wang (1996)	US	1.26	1.14	1.14
Lenzen (1999)	Australia	1.30	1.29	1.34

*Figures are for CO_2 only. Other GHGs assumed in same ratio.

Experience with LPG in light vehicles

LPG should have an advantage over both petrol and diesel fuels, when full fuel cycle emissions are considered. When used in spark ignition engines, LPG does appear to give GHG reductions compared to petrol. Wang (1996), using the GREET model for 2000 model year cars in 2005, found that for the US, LPG-fuelled cars would lower full fuel cycle GHGs by 7.5% compared with equivalent petrol-fuelled vehicles. However, Wang found no advantage for LPG over diesel-fuelled cars. But as already discussed, Wang's results are biased against naturally occurring LPG. When local air pollution emissions were considered, releases of hydrocarbons (HCs), oxides of sulphur (SOx), and particulates were much lower for LPG vehicles compared with petrol vehicles. Reductions for CO were much smaller, and none were found for NOx. LPG also proved superior to diesel fuel on all local emissions.

On-road experience with LPG differs slightly from the research work. Australian studies (Federal Office of Road Safety (FORS) 1997, Department of Transport and Regional Services (DOTRS) 2001) have shown that LPG use in light vehicles, when compared with equivalent petrol vehicles, resulted in generally slightly elevated CO and HC levels. NOx emission levels varied, although they remained well below the allowable limits set, for example, by ADR37 (DOTRS 2001). Fuel consumption, when expressed in energy terms, was found to be roughly the same for similar petrol and LPG vehicles, a finding confirmed by Gogas (2001) and ABS (2001c) This results in about a 10% saving in GHGs for LPG from combustion alone.

Unlike NG, attempts at developing fuel quality standards for LPG transport fuel have been made (Environment Australia 2001). These standards usually define

LPG as consisting of propane, butane and a variety of trace gases. Studies on the effect of variation in LPG constituent gases on vehicle performance (Elder, Jones and Raine 1985) have shown, for variations typically allowed by fuel quality standards, that power and fuel consumption generally remained unchanged, while emissions (CO for example) change. For LPG vehicles, the most important issue remains the maintenance of the vehicle timing. Significant variation in performance, and hence fuel consumption, can occur should the vehicle become untuned (FORS 1997; Elder, Jones and Raine 1987).

LPG for large vehicles

Scope for LPG in large vehicles

As pointed out earlier, the air pollution problem is largely an urban issue, particularly for Melbourne and Sydney. Given that the coverage of LPG retail outlets is more comprehensive in the capital cities, Table 5 shows, for 1995, the diesel fuel use in all eight capital cities combined, for each vehicle class. Also shown is the number of vehicles registered before 1989, as these vehicles will have higher emissions than newer vehicles in the same category.

Table 5 Diesel fuel use (MLitres) by vehicle type and age for Australian capital cities for 1995 (Source: Cox and Apelbaum 1999)

Vehicle type	All vehicle ages[1]	Vehicles before 1989[1]
Passenger vehicles	216 (46%)	101 (22%)
Light comercial vehicles	219 (27%)	109 (14%)
Rigid trucks	764 (48%)	489 (30%)
Articiculated trucks	485 (20%)	247 (10%)
Other truck types	17 (54%)	11 (33%)
Buses	203 (56%)	126 (35%)
Aust. capital cities total	1904 (33%)	1083 (19%)

[1]Percentages are of 1995 Australian total for vehicle type.

The table shows that 33% of all diesel fuel is used in capital cities, and that 19% of Australian diesel fuel is used by capital city vehicles first registered before 1989. Thus if limited to old vehicles in capital cities, potentially an amount equivalent to 19% of road diesel fuel use in Australia could be converted to LPG. If we further limit conversions to larger vehicles, including all truck categories and buses (which are more likely to recoup conversion costs), this figure drops to 15%.

Experience with LPG in heavy commercial vehicles

On an energy equivalent basis, conversion of 15% of diesel fuel to LPG would result in annual savings of 0.35 Mtonnes of CO_2. However, as has been stated, studies have so far shown little evidence of this saving being realised for light vehicles (Wang 1996). However, few studies have so been done to determine the actual outcomes from LPG use in heavy vehicles (Beer et al 2000).

To examine the performance of LPG use in large vehicles, a series of chassis dynamometer based tests were done on LPG-converted diesel buses and garbage trucks (Honnery *et al* 2002). Conversion of a diesel vehicle to LPG requires major modification of the engine. Not only is conversion to the new fuel required, but conversion of the combustion process to spark ignition is also needed, together with a significant reduction in engine compression ratio. Compression ratio reduction can be achieved by either modification of the piston or cylinder head, or by inserting a spacer plate between the engine block and cylinder head. In the case of the present vehicles, the latter method was used.

To allow a comparative test of performance, LPG-converted vehicles were compared to equivalent diesel vehicles undergoing the same test series. The equivalent diesel vehicles were selected on the basis of make, age, use, and the further requirement of recently having had an engine rebuild. Test vehicle data and typical results are shown in Table 6.

Table 6 Test vehicle details and typical results for diesel and LPG fuel vehicles (Source: Honnery *et al* 2002)

	Buses		Garbage trucks	
Engine type	LPG MAN Mark 1	Diesel MAN Mark 1	LPG Cummins 240	Diesel Cummins 240
Engine size (litre)	11.4	11.4	8.3	8.3
Aspiration	Normal	Normal	Normal	Turbo charged inter-cooled
Gross vehicle weight (tonne)	16	16	15	15
Age (years)	20	20	6	7
DT80 (litre/100km)	101	47	91	49
$CO_{2equivalent}$ (g/km)	1534	1341	1264	1371

Exhaust emissions were measured during the tests in the raw, undiluted gas flow. Exhaust opacity was measured as an indicator of particulate levels (smoke). Exhaust gas rate was determined through use of an inert tracer gas, fuel mass flow, gravimetrically. Diesel fuels used were certified to relevant test fuel standards. For the LPG, 95% pure propane was used because it removed the ambiguity in exhaust emissions that may result from variation in fuel.

Drive cycles used to test the vehicles were based on two simple types: unloaded snap acceleration (SAE1667), and combinations of loaded wide-open throttle accelerations and constant speed, constant load conditions. The DT80 test is an example of the later type of test. The DT80 drive cycle consists of two repeats of a loaded acceleration to 80kph, followed by deceleration to idle, completed by a further loaded acceleration to a constant speed of 80kph. Use of the DT80 in these tests is also intended to provide information on in-traffic performance as it has been shown to correlate well with traffic based drive cycles (Parsons 2000). More details on the drive cycles are given in Honnery *et al* (2002).

Fuel consumption results (Table 6) show, for the DT80 test, that the LPG vehicles use about twice the fuel volume per kilometre of diesel vehicles; for the bus the ratio was 2.15, and for the garbage truck, 1.86. When averaged across both vehicle types, the resulting GHG increase, including trace gas contributions, is 3.2%. Consideration of the full fuel cycle GHG costs, Table 4, alters this to a small reduction in GHGs.

Emissions of exhaust gas concentrations of CO and HC were found to be higher for the LPG than the diesel vehicles, but NO_x was lower. As sulphur content in LPG is typically less than 100ppm (Environment Australia 2001), SO_x concentration for the LPG is expected to be far lower than that for the diesel used here which had a sulphur concentration of 1760ppm. Smoke, as measured by opacity, is of course a significant issue for the diesel vehicles, but the LPG vehicles were found to emit none.

A complication in comparing results from the tests is the different performance that may result from conversion of the vehicle engine. Converters of the engine must make a choice about LPG engine compression ratio. There is a competing requirement in that high compression ratio improves performance, but low compression ratio makes for easier conversion. The vehicles tested here were converted to the relatively conservative compression ratio of 8:1. As a result, LPG fuel energy conversion efficiencies were about 5-10% lower than the diesel engines. Propane, the fuel used here, can operate at compression ratios as high as 11:1 and for this value an improvement in fuel consumption of around 5-10% could be expected to result. This would produce a reduction in GHGs still much lower than the 17% expected on an energy equivalent basis (Table 3), or 23% for a full fuel cycle analysis (Tables 3 and 4). It should be noted, however, that the diesel cycle is thermodynamically more efficient than the spark-ignition cycle.

Scope for improvement also exists in the exhaust gas emissions. Catalysts were used in the exhaust systems of the LPG vehicles, but tuning of these to the conditions found in the exhaust was not optimal.

From an operator's perspective, conversion of an engine to a new fuel needs to be at least cost neutral. In the case of conversion to LPG, the fuel volume ratio needs to be lower than about 2.3-2.5, which is the typical LPG/diesel cost ratio.

For the fuel consumption rates found here, the operator could expect savings of around 15-25% in fuel costs. These would have to be weighed against conversion costs, which are far higher than petrol to LPG conversions. (Petrol to LPG conversions only cost $1700-2400 (Gogas 2001)). Large diesel vehicles typically undergo engine rebuilds at scheduled times during their life, so the operator has the choice of converting to LPG during this maintenance period. Conversion at this time would reduce the cost, and so make conversion a more viable option. Running costs for LPG-converted vehicles are typically lower due to the reduced engine load brought about by the lower compression ratios.

Conclusions

LPG is already a major fuel for light vehicles in Australia. When LPG is used in these vehicles, full fuel cycle GHGs can be reduced by up to 20%, as well as improving local air quality. The LPG distribution network is already comprehensive, with about 3500 retail outlets Australia-wide. However, the other states/territories lag far behind Victoria and SA in substituting LPG for petrol, giving LPG potential for further growth in sales in these states.

LPG can also be used as a replacement for diesel. Chassis dynamometer tests on matched LPG and diesel trucks and buses found no GHG benefit for the LPG vehicles. The air pollution benefit was mixed, with much improvement in particulate and NO_X emissions and potentially SO_x, but no benefit for other pollutants. However, there is probably some scope for further improvements in the conversion process, mainly by increasing the compression ratio of the converted engines. At best, such improvement will give a minor GHG benefit and possibly an increased reduction in NO_x, compared with equivalent diesel vehicles. Until such improvements are made, and conversion is economically attractive to operators, it seems best to promote the use of LPG as an alternative fuel for spark ignition engines only.

Acknowledgements

The authors would like to thank the CSIRO for assistance with vehicle emission measurements, Ecotrans P/L Melbourne, for supplying the test vehicles, and the Australian Greenhouse Office, Canberra, for funding this work.

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