bureau of transport economics

Alternative Fuels in Australian Transport

Information Paper

This Paper reviews the physical characteristics of alternative fuels, technical and economic aspects of production of alternative fuels and alternative fuel vehicles, environmental, safety and health issues associated with alternative fuel use, factors influencing market acceptance, and policy issues. The emphasis is on the extent of environmental benefits which might result from alternative fuel and the costs involved in making these fuels available. The discussion covers reformulated gasoline, diesel, liquefied petroleum gas, ethanol, methanol, vegetable oils, natural gas, electric vehicles and hydrogen.

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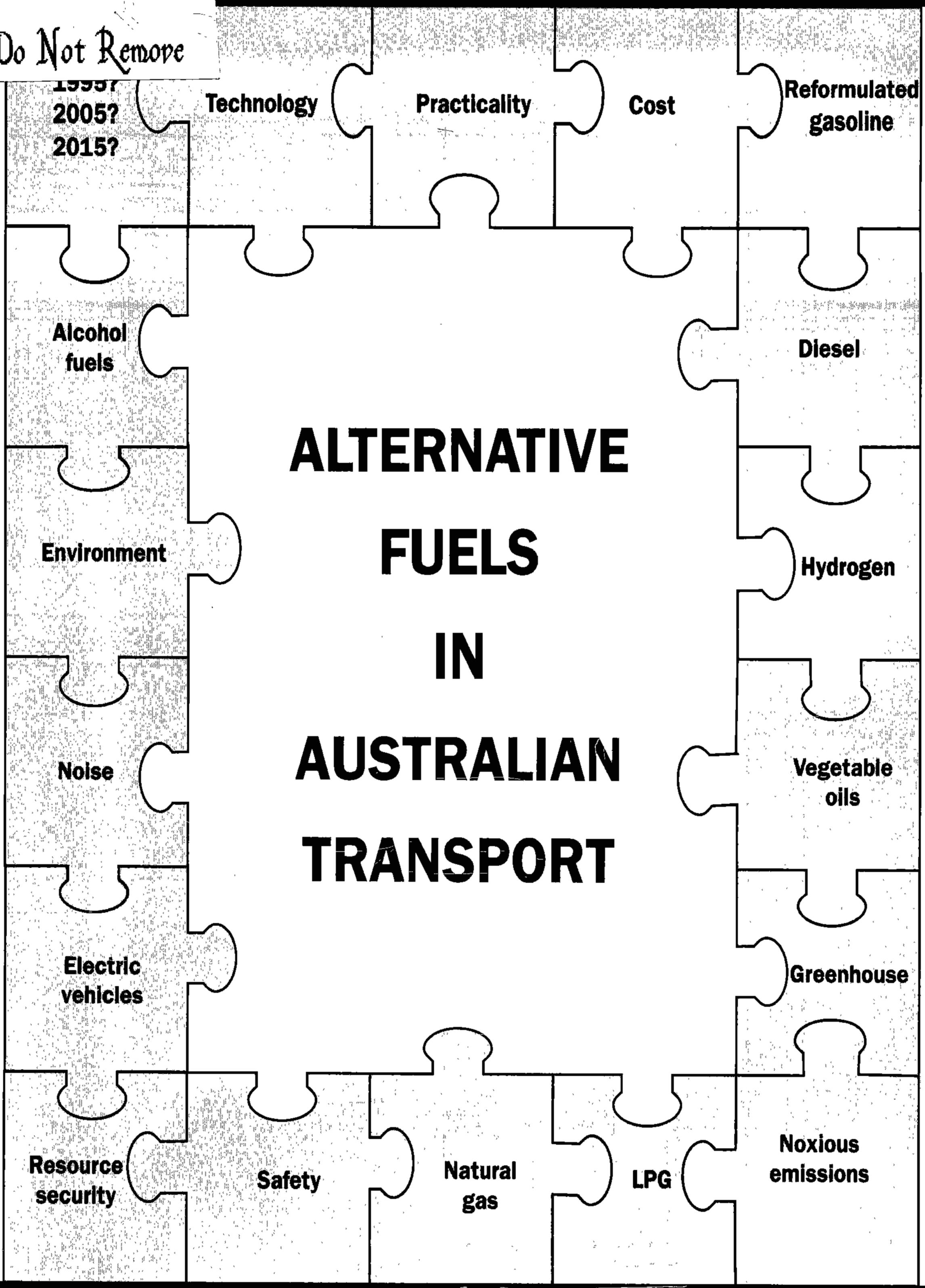

ALTERNATIVE FUELS IN AUSTRALIAN TRANSPORT

INFORMATION PAPER 39

FOREWORD

The use of various alternative fuels is often proposed in order to reduce greenhouse gases or noxious emissions in the transport sector. The large range of different fuels supported with apparently equal vigour suggested that it would be worthwhile to investigate a number of issues more closely. These include the relative efficacy of each fuel in reducing greenhouse and noxious emissions, safety, relative prices, and the costs of introduction and usage. Numerous studies have already examined many of these aspects, but the lack of a comprehensive overview, particularly from an Australian point of view, led to the decision to review the issues and the literature in some detail in a single publication.

The study forms part of the BTCE's continuing research into environmental aspects of the transport sector. It was prepared by a team led by Beryl Cuthbertson. Members of the team were Neil Kelso, Ken Thomas, and David Cosgrove. Anita Scott-Murphy assisted in the final stages of the study.

During the course of the project, the study team received much valuable assistance. I would like to thank: Professor David Trim, Professor Brian Milton, Professor Peter Rogers, Professor Noel Dunn and Professor Mark Wainwright of the University of NSW; Doug Munro of the Victorian Environmental Protection Authority; Russell Wakefield and Bill Armitage of Australian Gas Light Company; Alan Kain of NGV Australia; John Bamford of the Australian Gas Association; Phil Happ of the Australian Electric Vehicle Association; Roy Leembruggen of Elroy Engineering; Fred Darby of the Renewable Energy Authority of Victoria; Ron Mendelsohn of the Strategic Research Foundation; John Moll and Graeme Sheahan of Ford Australia; Basil Hancock of the NSW State Transit Authority; Darryl Meade and Dan Davies of the Victorian Public Transport Commission; George Cornwall and Andrew Warr of BP Australia; Colin Holmes, Ian McFarlane, Bruce McIver and Barry Sampson of Shell Australia; Ian Brumby and Murray Radestock of Gogas; Peter Elliot of Linfox; Cliff Kavonic and Mark Burfield of BHP; Professor Alan Seawright of the University of Queensland; and Dr John Begg of CSIRO. I would especially like to thank Dr Jim Le Cornu, Ken Hodgkin, Professor Geoff Sergeant, Dr Ian Walker, Professor Peter Rogers, Professor David Gosden, Dr Hien Ly, John Bamford and Noel Trompp for comments on drafts of the paper. Any errors in the paper remain, of course, the responsibility of the project team.

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ABSTRACT

This paper reviews the physical characteristics of alternative fuels, technical and economic aspects of production of alternative fuels and alternative fuel vehicles, environmental, safety and health issues associated with alternative fuel use, factors influencing market acceptance, and policy issues. The emphasis is on the extent of environmental benefits which might result from alternative fuel use, and the costs involved in making these fuels available. The discussion covers reformulated gasoline, diesel, liquefied petroleum gas, ethanol, methanol, vegetable oils, natural gas, electric vehicles and hydrogen.

SUMMARY

Natural gas, ethanol, methanol, vegetable oils, hydrogen, electricity and some petroleum-based fuels (reformulated gasoline, liquefied petroleum gas (LPG) and diesel fuel in light duty vehicles) are potential alternatives to gasoline. These fuels accounted for around 4 per cent of Australian transport fuel use in 1991–92. The share of LPG was 2.5 per cent.

This paper reviews the physical characteristics of alternative fuels, technical and economic aspects of their production and of alternative fuel vehicles, associated environmental, safety and health issues, factors influencing market acceptance, and selected policy issues. The focus is on the costs and the extent of environmental benefits which might result from alternative fuel use.

Alternative fuels are being promoted, to varying degrees, in many countries around the world. They are featured as 'clean fuels', both for greenhouse and urban pollution reasons. It is sometimes held that alternative fuels can provide a secure domestic fuel supply, and relieve pressures on exchange rates.

Some countries have adopted vigorous support programs. In the USA in particular, an extensive array of tax concessions and regulatory schemes has been employed to influence fuel and vehicle choice. Regulations mandate the use of low emission vehicles in fleets, and the increased use of zero or ultra-low emission vehicles. High pollution taxes on gasoline and diesel in Sweden, for example, also favour alternative fuels. Other countries, including Australia, provide a more modest level of assistance.

Reformulated gasoline (RFG) has been developed in the USA to reduce air pollution. It involves adjustments to refinery processes and refinery inputs to improve fuel combustion, reduce evaporation and remove impurities. It is not currently available in Australia, and could involve considerable investment in refinery capabilities.

Liquefied petroleum gas (mainly propane or butane) is now available from a network of some 2000 refuelling stations around Australia. In contrast, natural gas tends to be used by fleet vehicles with access to central refuelling facilities. Natural gas has the potential to become a significant transport fuel, with the development of an adequate public refuelling infrastructure. Australia's reserves

are large, and the technology is relatively well developed. Natural gas is mostly methane, and is used in road transport mainly in its compressed (CNG), rather than liquefied (LNG), form. At present most LPG and CNG vehicles are dual-fuel vehicles, converted after purchase. The trend towards original manufacture (OEM) of dual-fuel or dedicated fuel vehicles will result in more efficient vehicles with improved marketability.

Ethanol and methanol may be used in blends with gasoline or diesel, or as pure fuels. Use of these alcohol fuels in low level blends is possible without extensive vehicle modification. In high level blends, adjustments are required, and may involve significant costs. Trials will be necessary to ensure compatibility of fuel and vehicles under Australian conditions. The most likely development is use in blends of 10 per cent with gasoline and 15 per cent with diesel. Ethanol in gasoline can replace lead as an octane-enhancer. Both fuels require a technological breakthrough in production from the lignocellulosic fraction of crops to permit low-cost production on a large scale.

Electric vehicles may operate on electricity only, or may be hybrids. Hybrids are intended to overcome problems associated with limited range and refuelling, by providing supplementary power directly to the vehicle, or to recharge the batteries. Electric vehicles have no tailpipe emissions and are quiet, and are thus ideal for urban areas. Market acceptance, however, is likely to be limited until battery limitations are resolved and production costs reduced.

Hydrogen is seen as a viable transport fuel only in the very long term. It has the potential to reduce noxious emissions to negligible levels, but would reduce greenhouse gas emissions only if produced from non-fossil fuel sources. To compete with other fuels it will need to be produced from cheap solar electricity.

Economic viability

With the possible exception of diesel in cars, alternative fuels are at present not commercially viable in Australia, and probably not in any other country, without some form of government intervention. The cost of using these fuels is high relative to gasoline, and those which currently compete in Australia — principally natural gas and LPG — receive an implicit subsidy through exemption from the Commonwealth excise and State taxes (between 29 and 39 cents per litre from August 1993) that apply to gasoline and diesel.

Even diesel might be regarded as not financially viable for light duty vehicles because of the relatively high vehicle cost. In most countries where diesel car numbers are significant, their use has been encouraged by substantial financial incentives to offset the higher capital costs.

However, alternative fuels can have environmental benefits when compared with gasoline. The central issue is how important these benefits are, and how they compare with the additional costs to society incurred as a result of using alternative fuels.

Environmental benefits

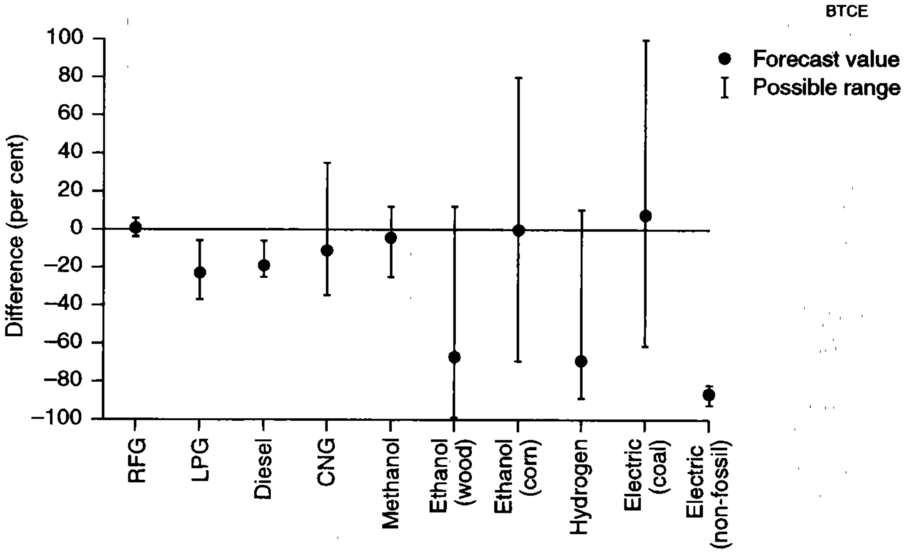
Environmental benefits from use of alternative fuels can be gained through reductions in greenhouse gas emissions, mainly carbon dioxide (CO_2), or noxious emissions in urban areas. Noise levels can also be lower. Unfortunately, the value of the environmental benefits from using alternative fuels rather than gasoline is extremely difficult to assess. Estimates of achievable reductions in emissions vary widely. In particular, the same fuel produced in different ways can result in very different emissions. Also, there are significant difficulties in assigning monetary values to any reduction in emissions.

Emissions from alternative fuels

Tailpipe emissions of CO_2 from alternative fuels can be estimated fairly accurately from the carbon content of the fuel and the amount of fuel used per kilometre. Fuel use per kilometre varies with the energy content of a fuel and the engine type. For example diesel engines are more efficient than gasoline engines. However, fuel use can vary unpredictably. It depends on the efficiency with which a particular vehicle uses a fuel, and hence on the type and condition of test vehicles, as well as on test conditions, such as temperature and the way the vehicle is driven. The new Holden and Ford LPG vehicles, for example, have shown quite different percentage reductions in emissions when compared with their new gasoline equivalents.

Comparisons based solely on tailpipe emissions, however, can provide a distorted picture. Hydrogen burns without producing CO_2, but the electricity used to produce the hydrogen through electrolysis would produce CO_2 (except where power from non-fossil fuel is used). In the case of electric vehicles, use of hydro-electricity as opposed to coal-fired power will give a very different overall greenhouse emissions result. Natural gas requires energy for compression prior to use in a vehicle, and can be distributed using pipelines rather than by freight vehicles. It is therefore important to estimate greenhouse emissions on a full fuel cycle basis, taking into account emissions from all energy used in achieving a given transport task with a particular fuel. Some estimates are made on a life cycle basis taking into account emissions in vehicle manufacture and vehicle life.

The variation in full fuel cycle emissions due to different production, distribution and refining processes, and different vehicle and test conditions, results in different estimates of the reduction in greenhouse gas emissions arising from use of alternative fuels. Available estimates sometimes relate to new vehicles, sometimes to future vehicles, and sometimes to averages for a vehicle fleet. The conversion factors used to express the various greenhouse gas emissions in CO_2 equivalents can also affect estimates of potential reductions. For example, estimates of greenhouse gas reductions from use of CNG are partly



Sources International Energy Agency 1993, *Cars and Climate Change*; De Luchi, M. 1993, 'Greenhouse-gas emissions from the use of new fuels for transportation and electricity', *Transportation Research*, 27A, no. 3; BTCE estimates.

Figure A **Life cycle greenhouse gas emissions from alternative fuel vehicles relative to gasoline vehicles (carbon dioxide equivalents)**

dependent on the values assumed for the global warming effect of methane. If a short time horizon is used (10 years as opposed to 100 years), methane emissions from use of CNG are relatively more important, giving a less favourable result for CNG. An indication of the range of estimates for various alternative fuels is presented in figure A.

Figure A relates to exclusive use of fuels. If ethanol is used as a 10 per cent blend with gasoline, a greenhouse gas emission reduction of about 4 to 5 per cent could be expected, based on a 60 per cent lower emission rate than from gasoline. In a 15 per cent blend with diesel and an assumed 50 per cent lower emission rate, the greenhouse saving would be around 5 per cent.

Reductions in life cycle greenhouse gas emissions (relative to gasoline) estimated by the International Energy Agency for new cars in 2000 in North America are: LPG 23 per cent, diesel 19 per cent, CNG 11 per cent, RFG –1 per cent, ethanol from lignocellulose 68 per cent, methanol from gas 4 per cent, electric cars using hydro-power 86 per cent, and hydrogen from non-fossil fuel 70 per cent.

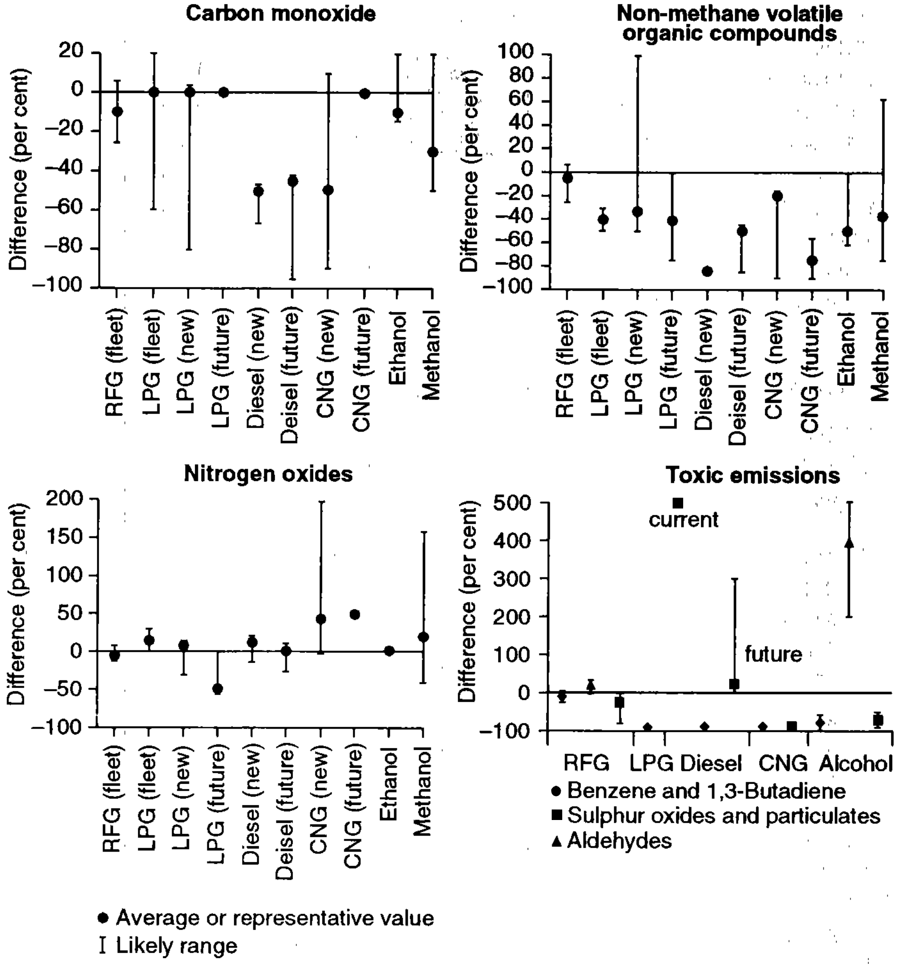
Noxious emissions causing local air pollution include carbon monoxide (CO), volatile organic compounds (VOCs) (mainly hydrocarbons), nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulates, including smoke and lead. Test results for these emissions from alternative fuels are even more variable than those for greenhouse gases. Noxious emissions depend not only on fuel use, but also on use of pollution control equipment, engine management systems, the efficiency of the combustion process, driving patterns, the length of trips, and weather conditions. Vehicles designed to operate on lean-burn mixtures can achieve good emissions results, but if operated at higher than the air-to-fuel ratios they were designed for, to increase power output, emissions performance can be very poor.

Specific noxious gases may be reduced with an alternative fuel, while others will increase. But there is no ready basis for comparing the noxious effect of various combinations of gases. For example, it is difficult to be definitive about diesel, which produces much lower levels of CO and hydrocarbons than gasoline, but more particulate and SO_x emissions. The smog forming potential of NO_x emissions depends on the concentrations in the atmosphere of other gases with which NO_x reacts. Carbon monoxide may be a problem in one part of a city, but not in another, depending on weather conditions.

Technological progress, particularly relative improvements in the fuel efficiency of gasoline vehicles, and the introduction of progressively more stringent emission standards for all vehicles (both new and on-road) may reduce the potential for achieving emission benefits from alternative fuel use. This can aggravate the difficulties of comparison.

Figure B shows the range of estimates of reductions in noxious emissions from use of alternative fuels. Generalisations are clearly difficult. Good results for most fuels can be achieved under 'design' conditions or with increased costs. When particular emissions need to be addressed more urgently than others, use of some fuels could give beneficial results. RFG can give better results with more costly reformulations. Noxious emissions from diesels could be very low if SO_x and particulate emissions can be controlled with engine management systems or particulate traps, and removal of sulphur from the fuel. LPG noxious emissions may be no better than those from gasoline in existing vehicles where conversions have been unsatisfactory, but show promise of good reductions in new vehicles. If a long time-frame is adopted, CNG in light vehicles appears to offer good reductions overall, with the possible exception of NO_x. In comparison with diesel, emissions could be lower overall if CNG vehicles were operated under lean-burn conditions to reduce NO_x. Alcohol fuels may improve urban air quality, but emissions results are quite variable.

Alcohol fuels provide a good example of the complexity of estimating reductions in both greenhouse and noxious emissions. The full fuel cycle greenhouse gas emissions from use of alcohol fuels depend crucially on the source of energy for producing the fuels, and on the nature of the feedstock. For example, in producing ethanol from sugarcane, emissions are reduced more if bagasse can



Source International Energy Agency 1993, *Cars and Climate Change* 1993, *Phase I Final Report*; Carnovale, F. et al., 1991, *Air Emissions Inventory, Port Phillip Region; Planning for the Future*, Report SRS 91/001, Environmental Protection Authority of Victoria, Melbourne; BTCE estimates

Figure B Noxious emissions from alternative fuel vehicles relative to the emissions from gasoline vehicles using comparable levels of technology

be utilised as an energy source rather than, for example, coal. There is not likely to be any greenhouse benefit in substituting ethanol produced from corn using coal power, for gasoline. If plants used to produce alcohol replace other plant matter with a high CO_2 absorption rate, the emission advantages will be much less than they could have been if additional plant growth had occurred. If an old forest or municipal waste were used to produce alcohol, rather than left to rot, there could be significant greenhouse benefits.

Alcohol fuels have lower tailpipe emissions of VOCs than gasoline, but higher evaporative emissions. Overall VOC emissions would tend to be higher from alcohol fuels in terms of weight. However, the composition of the VOC emissions differs from those produced by gasoline. Alcohol fuels contain no benzene, which is carcinogenic. Aldehyde emissions are higher, but only until vehicle engines are warm, and the health effects of these are uncertain. In addition, emissions from low level alcohol blends may not be consistent with those from high level blends, or from pure fuels. Good emission results have been claimed from use of 'diesohol', but results have yet to be confirmed. The ACTION bus trials in Canberra are expected to provide useful information.

Costs of alternative fuels

Use of alternative fuels can result in additional costs to society. These include the net effect of any additional capital and operating costs, and any 'inconvenience' costs to consumers.

For LPG and CNG, retail fuel prices may be a fraction above or below the pre-tax gasoline price for an equivalent amount of energy. (Differences in fuel costs will also arise due to the different efficiencies with which various vehicles use different fuels.) The cost of converting a vehicle is of the order of $1500 to $2000. The additional capital cost of a diesel passenger car might be even higher, though the more efficient diesel engine can make diesel competitive with gasoline for cars overall. This might not be so if diesel were to be used on a much larger scale, as diesel fuel costs could increase with increased demand.

RFG would cost perhaps 5 to 10 cents per litre more than gasoline to produce, and would need to be subsidised in some way if its use were to be encouraged. RFG would be more expensive to produce in Australia than in the USA. Australian distribution systems contain water and may require modification for use with RFGs containing additives with an affinity for water.

Alcohol fuels and vegetable oils have high production costs at this stage. If alcohol fuel can be produced as a by-product of other processes (utilising existing capital equipment), it has a chance of being more competitive, though there would be limits to the amounts that could be supplied from such sources. There is confidence in some quarters that production from lignocellulose will permit low-cost alcohol fuels once the technology is established. Some Australian estimates, in 1992 values, are as low as 14 Australian cents per litre of ethanol, ranging to 40 cents (20 to 58 cents per litre of gasoline equivalent). Estimates of current production costs of ethanol from corn, cereal or sugar are mainly in the range 40 to 70 cents per litre (58 cents to $1.02 per litre of gasoline equivalent). Distribution costs for alcohol fuels would be higher because the much lower energy content of alcohol fuels would require a large increase in the amount of fuel transported and stored for a given energy supply. The affinity of ethanol and methanol for water can cause corrosion, and hence problems with fuel and distribution systems.

Electric vehicles, while ideal for urban areas in that they have virtually no noxious emissions, are as yet high cost. The Australian Huntington *Mira* conversion, at a quoted price of $16 000 plus sales tax, would cost about twice as much as the gasoline *Mira*. In large-scale production electric vehicles could become a lot cheaper, but large-scale production will depend especially on improved battery technology. Gasoline or natural gas cars offering similar service characteristics to electric vehicles, such as power, space or range, may have lower costs and environmental performance almost as good. For example, the CNG Honda *Today*, built for the Japanese urban market, is capable of under 2.8 litres (gasoline equivalent) per 100 kilometres, and long distances without refuelling.

Infrastructure costs involved in providing refuelling facilities for new fuels can be significant. The Australian Gas Association (AGA) has estimated refuelling requirements for a 10 per cent penetration of the gasoline market by CNG at $700 million. These costs are included in the estimated fuel price of around 35 cents per cubic metre of gas. (A cubic metre of natural gas (NG) is roughly equivalent to one litre of gasoline in energy content terms.) Natural gas costs can be much lower when supplied from private depots or when resources of existing service stations can be employed than when new public retail outlets are required. Prices for natural gas in the USA vary by around 10 cents per cubic metre between the cheaper traditional fuel outlets and the more expensive new natural gas outlets.

Alternative fuels do not always offer the same convenience characteristics as gasoline. Lower range, limited passenger or boot space, limited pay-loads, longer refuelling times, restricted refuelling availability and some apprehension about safety, vehicle performance and the expertise of vehicle service personnel effectively impose additional costs on users of alternative fuels. Uncertainty about the continuing excise free status of alternative fuels, and about resale values of alternative fuel vehicles, is also likely to constrain market acceptance.

In the case of LPG these limitations have been largely overcome. Refuelling infrastructure enables travel in all but remote areas of Australia without resort to the dual-fuel capacity, and recent factory-produced conversions are reported to have no problems with range or boot space. Other alternative fuel vehicles still have drawbacks compared with gasoline unless used for special purposes in niche markets; for example, where refuelling facilities can be centralised. Electric vehicles require the commercial availability of battery types allowing much higher range and faster recharging than the lead–acid battery.

The relatively limited number of conversions to LPG (about 250 000) and natural gas (over 600) in Australia, despite apparently short payback periods on initial capital outlays for vehicles performing high mileages, suggests that the residual unpriced costs to consumers may be considerable. Developments with dedicated and original equipment manufacture (OEM) vehicles should reduce these costs in the future.

Policy issues

The additional costs of alternative fuels mean that, at least at present, they require assistance to penetrate the transport fuel market. Despite the implicit 'subsidy' they now receive through exemption from Commonwealth excise and State taxes, they have achieved only a limited market share. This suggests that increased assistance may be required for a substantial level of market penetration, most likely including an assurance of continuing support beyond the current five-year period announced in 1992.

The main policy issue relating to alternative fuels is the level of 'subsidy' warranted for the industry. Any justification of assistance would need to be based on positive externalities or other social benefits that are not already reflected in the price the industry receives commercially for these fuels.

Because of the lack of a clear picture of the physical amount of emission reduction potentially available from alternative fuel use, and because it is not possible to assess accurately the environmental costs of transport emissions, these social benefits cannot be reliably valued in monetary terms. There is also insufficient information on the costs of achieving emission reductions in other ways to enable the benefits of alternative fuel use to be valued on a 'control cost' basis. Some rudimentary estimates of the costs of achieving greenhouse gas emission reductions with various alternative fuels have been provided.

Nevertheless, the order of reductions in emissions which might be expected from alternative fuel use (figures A and B) suggests that the environmental costs of emissions would need to be substantial to justify the additional costs which would be involved in supporting these fuels. Available estimates of emissions costs are reviewed.

It is sometimes argued that the ability of alternative fuels to provide resource security (avoiding the costs of disruptions to oil supply, or of large price increases), to replace oil imports and improve the balance of trade, and to generate employment and increase national product, provides sound reasons for encouraging their use.

To support the 'balance of trade', or 'balance of payments' argument on economic grounds, it would need to be demonstrated that Australia has a chronic problem with earning adequate foreign exchange, or that the existing exchange rate does not reflect the social cost of imports and exports with which domestic energy supplies compete. It would also have to be demonstrated that utilising fuels such as natural gas as a substitute for oil imports would be a cost-effective way of generating additional foreign exchange.

Similarly it would need to be demonstrated that expansion of a domestic alternative fuels industry would be a cost-effective way of increasing employment in the economy.

There are costs involved in maintaining or developing self-sufficiency in resources. These costs would need to be weighed against the probable costs that might be incurred as a result of short- or long-term disruptions to international trade. Global oil supply and demand projections are favourable in the long term. Combined with historical experience of sanctions busting and continued supply of materiel during wars, it is unlikely that the benefits of self-sufficiency would outweigh the costs.

Conclusions

Use of alternative fuels imposes additional costs on society. A major policy issue is the extent to which these costs are offset by social benefits not provided by gasoline.

Most alternative fuels do possess some environmental advantages over gasoline, and some level of price differential or government support may be desirable to reflect these social benefits. The difficulty lies in determining how much.

The extent of benefits varies among fuels. The same fuel produced with different inputs can be environmentally good or bad. These fuels, ideally, should be treated differently. There is uncertainty about achievable physical emission reductions, and there is no accurate method for valuing emission reduction benefits. In addition, it would be difficult to establish a fuel price differential that would reflect noxious emission benefits. These are not particularly well related to fuel consumption. Technological change and increasingly stringent emission standards mean that estimates today could be a poor guide to the likely future benefits of alternative fuels.

Given the difficulty of determining price differentials to reflect environmental benefits, it could be preferable to opt for some other means of having environmental factors influence transport fuel choices. Rather than assist specific fuels, common emission standards could be set for all fuels and/or vehicles, tradeable rights to generate emissions could be established, or incentives could be provided for research. With regard to standards, a clearly specified target date would need to be set to allow manufacturers and consumers adequate time to plan responses and so minimise costs. Those fuels or vehicles able to meet the standards more easily would have a market advantage.

There also appears to be a role for government in establishing quality standards for alternative fuel vehicles and equipment, in providing information to improve consumer knowledge and to protect consumers from product defects or adverse safety and health consequences, and in ensuring that current gasoline vehicle emission standards are broadened to apply also to vehicles using alternative fuels.

Of the various alternative fuels, use of diesel or CNG in passenger vehicles appears, at present, to offer the most socially cost-effective means of reducing emissions of greenhouse gases. Both fuels could also prove socially cost-effective in reducing noxious emissions, depending on the cost of particulate traps in diesel vehicles. However, a more comprehensive analysis of these and other options is required to identify the cheapest strategies overall. The BTCE's current research program is directed towards this end.

CHAPTER 1 INTRODUCTION

In October 1990 the Australian Government, and State, Territory and local governments adopted an interim planning target for greenhouse gas emissions, subject to certain conditions.[1] The target involved stabilising emissions of those greenhouse gases not controlled by the Montreal Protocol at 1988 levels by the year 2000, and reducing these emissions to 20 per cent below 1988 levels by 2005. In June 1992 Australia also signed the framework convention agreed to at the UNCED conference in Rio de Janeiro. This convention commits signatory countries to formulate national programs to mitigate climate change (United Nations Framework Convention on Climate Change, Article 4, Commitments, 1b). The objective of the Rio Convention is to reduce greenhouse emissions to 1990 levels by 2000, and, ultimately, to stabilise greenhouse gas concentrations in the atmosphere.

A National Greenhouse Response Strategy (NGRS), endorsed by the Council of Australian Governments on 7 December 1992, contains measures directed towards the achievement of the greenhouse targets. A strategy for Ecologically Sustainable Development (ESD), also endorsed by the Council of Australian Governments on 7 December, contains measures directed towards alleviating air pollution and noise levels in local environments.

THE GREENHOUSE EFFECT

The greenhouse effect refers to the warming of the earth and its lower atmosphere by the action of certain gases present in the earth's atmosphere. These radiatively active, or 'greenhouse gases', absorb and re-emit radiation from the earth's surface. Greenhouse gases occur naturally, but concentrations of some are being substantially increased as a result of human activity. This has resulted in the so-called 'enhanced', or 'anthropogenic' greenhouse effect (IPCC 1992; NGAC 1992).

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[1] '...that Australia would not implement response measures that would have net adverse economic impacts nationally or on Australia's trade competitiveness, in the absence of similar action by major greenhouse producing countries' (Commonwealth of Australia, 1992).

The transport sector generates both 'direct' and 'indirect' greenhouse gases. Direct gases are radiatively active. Those emitted by transport include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs). The 'indirect' greenhouse gases — including carbon monoxide (CO), other oxides of nitrogen (NO_x) and non-methane hydrocarbons (NMHC) — do not have a strong radiative effect themselves, but influence atmospheric concentrations of the direct greenhouse gases by, for example, oxidising to form CO_2, or contributing to the formation of ozone (O_3), a potent direct greenhouse gas.

To facilitate comparisons, emissions of the various direct and indirect greenhouse gases are often expressed in terms of CO_2 equivalent emissions. These indicate the mass of CO_2 having the same radiative or global warming effect as a given mass of a particular greenhouse gas. The Intergovernmental Panel on Climate Change conversion factors (IPCC 1990, 1992) for a 100-year time horizon have been used in this report in deriving CO_2 equivalent emissions (appendix I). Due to the incomplete scientific understanding of atmospheric chemistry, there is still considerable uncertainty underlying conversion factors for the indirect gases. This should be borne in mind when interpreting the results in this paper. Although conversion factors are likely to be revised in the future, the relative ranking of various alternative fuels in terms of their greenhouse contributions is not expected to change (appendix I).

Carbon dioxide is the major gas associated with the enhanced greenhouse effect. Increases in CO_2 concentrations are expected to contribute over 60 per cent of the induced global warming projected for the next century (IEA 1992a). Disregarding the contribution of CFC emissions from vehicles (which derive from air-conditioner releases and not from fuel use), around 85 per cent of the transport sector's contribution to the enhanced greenhouse effect is due to CO_2 emissions.

LOCAL AIR POLLUTION

In contrast to the global impact of the greenhouse gases, some emissions from transport and other industries directly pollute the local environment where they are concentrated.

The primary local air pollutants generated by transport vehicles, either directly or by subsequent reactions, are CO, NO_x, sulphur oxides (SO_x), a range of volatile organic compounds (VOCs), photochemical oxidants (primarily O_3) and particulates, including smoke. Most of the VOC exhaust emissions from conventional vehicles are composed of hydrocarbons (HCs). VOC emissions from alcohol-fuelled vehicles contain a greater proportion of very reactive compounds called aldehydes. Several members of the VOC, oxidant and particulate pollutant groups are acutely toxic. Examples are benzene, formaldehyde, lead and chromium.

EMISSION REDUCTION AND ALTERNATIVE TRANSPORT FUELS

Various measures could be adopted to reduce greenhouse gas emissions and local air pollution from the transport sector. These include, for example, fuel taxes, changes in urban form, charges for road use, imposition of emissions standards on vehicles, and changes in engine technology.

The objective of this paper is to examine the potential for reducing emissions through the use of alternative fuels.

Alternative fuels have been broadly defined to include natural gas, ethanol, methanol, vegetable oils, electricity and hydrogen (all of which currently have little or no usage in Australian transport), and reformulated gasoline (RFG), liquefied petroleum gas (LPG) and diesel (in so far as expanded use of these petroleum based fuels also provides an alternative to current gasoline use).

In determining emissions from the use of different transport fuels, both combustion and evaporative emissions need to be included, and the assessment should be based on the full fuel cycle (FFC). Full fuel cycle emissions take into account not only the direct emissions from vehicles, but also those associated with the distribution of fuel to retailers, energy used in the refining process, transportation of refinery feedstocks, and extraction of the feedstocks. Emissions from vehicle manufacture, maintenance and disposal, and road building are also relevant to total transport emissions, but they are not likely to vary significantly with the nature of the fuel used. A possible exception is the case of diesel cars, which have longer lifetimes than other vehicles.

An analysis of alternative transport fuel use involves many aspects and some very complex technical and economic issues. Technical issues include fuel chemistry and emissions, fuel production and distribution technology, vehicle technology, and health and safety matters. Economic aspects include fuel and vehicle prices, taxes and subsidies, the costing of externalities resulting from emissions, market acceptance, and macroeconomic implications — including effects on the balance of payments. Resource security arguments also need to be considered.

AUSTRALIAN TRANSPORT FUEL USE

Australian transport is fuelled predominantly by petroleum based fuels. In 1991–92, fuels other than those derived from petroleum or petroleum related sources comprised only 16.5 petajoules (PJ), or about 1.6 per cent of the 1017 PJ consumed by the transport and storage sector of the Australian economy. The fuels used in this sector in 1991–92 are shown in table 1.1.

Table 1.2 shows transport sector energy consumption[2] by sector and by transport mode for 1987–88 (the base year for the Government's interim

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[2] Australian energy consumption is reported officially in terms of gross calorific values, and energy use data in this paper are also in these terms. Conversion factors used to calculate emissions from fuel use based on net calorific values are therefore adjusted before being applied to the Australian energy consumption data.

TABLE 1.1 CONSUMPTION OF AUSTRALIAN TRANSPORT FUELS, 1991–92

Fuel	*PJ*	*Per cent*
Petroleum based		
Leaded gasoline	359.5	35.4
Unleaded gasoline	219.5	21.6
Liquefied petroleum gas (LPG)	25.5	2.5
Automotive diesel oil (ADO)	225.7	22.2
Industrial diesel fuel (IDF)	4.9	0.5
Aviation turbine fuel (avtur)	126.9	12.5
Aviation gasoline (avgas)	3.3	0.3
Fuel oil	35.2	3.5
Major non-petroleum fuels		
Black coal	4.0	0.4
Natural gas	5.7	0.6
Electricity	6.8	0.7

PJ Petajoule (10^{15} joules)

Source ABARE (1993).

planning target) together with the major fuels used. About 86 per cent of transport energy is used in road vehicles, and the bulk of current development work in alternative fuels is directed to this segment. This paper therefore focuses on the road transport sector. However, the scope for using alternative fuels in other modes is touched on where appropriate.

VEHICLE FUEL EFFICIENCY IMPROVEMENTS

One important caveat relevant to any analysis of alternative fuels is that there is significant potential for improvement in the fuel efficiency of vehicles using gasoline and diesel fuels. Realisation of this potential could substantially alter the relative attractiveness of alternatives. Significant gains may yet be realised for cars from engine and transmission developments, and through weight and drag reduction. For trucks, engine developments such as turbocompounding, use of ceramic components, and the adiabatic (zero heat loss) diesel engine may become important in the near future. Such technical advances for conventionally fuelled vehicles may be available also for alternatively fuelled vehicles. However, unless the emissions savings from technological improvements were equal in absolute rather than relative terms for both conventional and alternatively fuelled vehicles, the benefits of switching to various alternative fuels would be reduced.

Whether significant improvements in the fuel efficiency of conventional vehicles can be achieved in a relatively cost-effective way, and greenhouse gases and noxious emissions reduced as a result, is clearly an unknown at this stage. Such uncertainty will make comparison of the cost-effectiveness of alternative

TABLE 1.2 AUSTRALIAN TRANSPORT FUEL USE, 1987–88

Sector and mode	*Energy[a] (PJ)*	*Major fuels*
Urban passenger		
Car	384	Gasoline
LCV[b]	26	Gasoline, ADO[c]
Bus	7	ADO
Rail	11	Electricity, ADO
Subtotal	433	
Non-urban passenger		
Car	143	Gasoline
LCV	19	Gasoline, ADO
Bus	9	ADO
Rail	4	ADO, electricity
Airline	50	Avtur[d]
Subtotal	232	
Urban freight		
LCV	44	ADO, gasoline
Rigid truck	52	ADO
Articulated truck	24	ADO
Subtotal	120	
Non-urban freight		
LCV	32	ADO, gasoline
Rigid truck	27	ADO
Articulated truck	63	ADO
Non-bulk rail	11	ADO
Government bulk rail	15	ADO, electricity
Private bulk rail	4	ADO, electricity
Air	9	Avtur[d]
Non-bulk sea	3	Fuel oil, IDF[e], ADO
Bulk sea	16	Fuel oil, IDF, ADO, Coal
Subtotal	181	
Total	964	

PJ Petajoule (10^{15} joules)

a. Full fuel cycle energy consumption basis.
b. Light commercial vehicle.
c. Automotive diesel oil.
d. Aviation turbine (ie jet) fuel.
e. Industrial diesel fuel.

Source BTCE (1991).

strategies for reducing greenhouse gas and noxious emissions from transport (including the use of alternative fuels) very hazardous.

STRUCTURE OF THE REPORT

Part I of this report examines supply-side considerations including technical aspects, emissions, and costs of alternative fuels. Chapters 2 to 4 cover reformulated gasoline, LPG and diesel, providing a basis for comparison with the non-petroleum alternative fuels discussed in subsequent chapters.

Part II examines demand considerations. In chapter 10, market acceptance aspects of alternative fuels and vehicles are examined, and conclusions are drawn regarding the most promising areas for change in the pattern of fuel use and the introduction of new fuels.

In Part III the policy implications for governments of alternative fuel use are discussed, and arguments often presented for facilitating the introduction and increased use of alternative fuels are addressed.

PART I: TECHNICAL AND SUPPLY CONSIDERATIONS

CHAPTER 2 REFORMULATED GASOLINE

BACKGROUND

Reformulated gasoline (RFG) is the term used to describe a variety of improved gasoline blends which have recently been developed to improve urban air quality. Development of RFG is occurring primarily in the North American market because of legislation aimed at reducing pollutants from motor vehicles. The initial impetus for its production came from US oil companies, in an attempt to provide a petroleum based 'clean' fuel alternative to counter the adoption of M85 (a blend of 15 per cent gasoline and 85 per cent methanol) in California.

When applied to petroleum fuels, the term *reformulation* generally means the control of refinery inputs and conversion processes to produce fuels that meet certain specifications. RFGs have been specified so as to reduce the effect of gasoline evaporation and combustion on the environment.

Improved vehicle emission characteristics are achieved through the selection of appropriate gasoline components, fuel additives, and the degree of fuel processing and purification. Examples include reducing volatile ingredients (to lower evaporative emissions), the addition of combustion enhancers (to lower CO emissions) and the removal of sulphur impurities (to reduce SO_x emissions).

Gasoline characteristics and production

Automotive gasoline (commonly called petrol in Australia) is a complex mixture of hundreds of volatile hydrocarbons (compounds containing only carbon and hydrogen atoms). Most components fall in the molecular size range of C_4H_{10} to $C_{10}H_{22}$. Gasoline is a less dense fuel than diesel, which is comprised mainly of hydrocarbons containing between 9 and 18 carbon atoms per molecule. Gasoline has become the preferred automobile fuel because of its high combustion energy, capacity to mix readily with air and resistance to engine knocking.

Gasoline combustion properties depend on ambient temperature, so refiners vary the precise composition of gasoline both by time of year and by region. On average, both leaded and unleaded Australian gasoline consist approximately of 57 per cent alkanes (hydrocarbons with chains of carbon atoms joined by single bonds), 1 per cent alkenes (hydrocarbons containing carbon to carbon double bonds), and 42 per cent aromatics (hydrocarbons containing stable six-membered rings of carbon atoms joined together by alternating single and double bonds) (Carnovale et al. 1991). Gasolines, both reformulated and standard, also contain a range of additives such as dyes, corrosion inhibitors, ignition improvers and detergents (to reduce engine deposits).

In a spark ignition automobile engine, a mixture of air and gasoline is ignited by a spark when the air–fuel mixture inside the cylinder has been compressed by the piston. The burning of the mixture should create a strong, smooth expansion of gas in the cylinder, forcing the piston outward evenly. If the air–fuel mixture ignites too rapidly (ahead of the flame front), a sharp pressure rise occurs, and the piston receives a single hard jolt rather than a strong smooth push. This causes the characteristic pinging sound termed *engine knock*. A reduction in the efficiency of converting the gasoline combustion energy to useful work within the engine results. Under severe conditions engine damage can occur.

The quality of a particular gasoline mixture as a fuel for the internal combustion engine is rated according to its *research octane number* (RON), or anti-knock index. Gasolines with high octane numbers burn more slowly and smoothly, and are more effective fuels. The octane number of a fuel is obtained by comparing its knock characteristics with those of two reference compounds, iso-octane (C_8H_{18}) and heptane (C_7H_{16}). Iso-octane is considered to have very good anti-knock qualities and is assigned an octane number of 100. Heptane has poor anti-knock properties and is assigned an octane number of zero. Gasoline with the same anti-knock characteristics as a mixture of 95 per cent iso-octane and 5 per cent heptane would be rated as 95 octane. Australian regular unleaded gasoline has an octane number between 91 and 93. Premium unleaded is between 95 and 98 octane, and leaded gasoline is around 97 octane.

The usual first step in petroleum refining is the separation process of *distillation*, where the crude oil is separated into a number of fractions. Fractions commonly separated include (in ascending order of average molecular weight) petroleum gas, naphtha, kerosene, gas oil, fuel oil, intermediate feedstocks for lubricant and wax manufacture, and asphalt. From the naphtha is derived the simplest grade of the gasoline blending components, known as straight-run gasoline. Straight-run gasoline effectively consists of hydrocarbons having a straight carbon chain structure, and it has a low octane number.

Gasoline accounts for more than half of all transport fuel demand. Refineries consequently seek to maximise the yield of gasoline from crude oil. A higher level of gasoline production may be achieved by using secondary refining processes, to convert some of the residual distillation products to gasoline, or to improve the quality of the various gasoline blending components.

A process called *isomerisation* uses catalysts to convert the straight chain compounds in straight-run gasoline into branched chain molecules, significantly improving octane ratings.

Another process, called *catalytic reforming*, supplements isomerisation as a means of converting low octane hydrocarbons into high octane components. Catalytic reforming allows the formation of molecules containing carbon ring structures — especially aromatic hydrocarbons (the major components of which are six-member rings of carbon atoms), which have very high octane ratings. However, Australian standards constrain one of these aromatics, benzene (C_6H_6), to below 5 per cent of gasoline by volume, since it is argued to be carcinogenic (Streeton 1990) and a scheduled poison.

Yet another process to manufacture gasoline components is known as *catalytic cracking*. This process converts the heavy molecular weight fractions from distillation (such as fuel oil) into (catalytically cracked) gasoline. The feedstocks are heated to very high temperatures in the presence of catalysts, breaking down (cracking) the longer chain molecules into lighter products. These are then separated by further distillation and used as gasoline components.

Petroleum gas fractions (mainly arising from the catalytic cracking process) can also be converted into gasoline components by processes known as *alkylation* and *polymerisation*.

The various gasoline components are then blended (or *formulated*) to meet the particular product requirements of finished gasoline (such as octane number, vapour pressure, boiling point range, or sulphur and benzene content).

The octane number of a given gasoline blend can also be improved by the addition of an octane enhancer (or anti-knock agent), a substance that helps control the burning rate of the gasoline. The most widely used and effective of these is tetraethyl lead (TEL, $C_8H_{20}Pb$). Although such lead compounds are undoubtedly effective in improving gasoline performance, their use is being increasingly curtailed by governments because of the toxicity of lead emissions. From 1986 all new Australian cars have been required to use unleaded gasoline.

Lead in gasoline also interferes with control of exhaust pollutants via a catalytic converter. Three-way catalytic converters[1] (so called because they deal with three pollutant types using three distinct chemical pathways) contain catalysts that promote the conversion of CO, HCs and NO_x into CO_2, water (H_2O) and nitrogen (N_2), thereby reducing noxious exhaust emissions. Since the catalysts used are deactivated by lead, cars with these converter systems must be run on unleaded gasoline.

The introduction of unleaded gasoline to the Australian market in 1985 involved a substantial level of fuel reformulation by Australian refineries. Current unleaded gasolines tend to achieve their octane ratings by using a greater proportion of high octane components (typically the aromatic hydrocarbons from the catalytic reforming process) in the blends than leaded gasoline.

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1. For the Australian vehicle fleet, around 80 per cent of cars manufactured after 1986 are fitted with three-way catalytic converters.

CHARACTERISTICS OF REFORMULATED GASOLINE

The first reformulated gasoline was introduced in 1989 by Atlantic Richfield Co. (ARCO). The current ARCO formulation (called EC-X), first produced in 1991, is considered to represent 'state of the art' reformulated fuels (EPA 1991b). It is an unleaded 95 octane reformulated gasoline with reduced aromatics and sulphur. It contains 15 per cent by volume of the oxygenate methyl tertiary butyl ether (MTBE), which is derived from methanol (CH_3OH) and isobutylene ($C_3H_6CH_2$).

The addition of the oxygenate improves fuel combustion, and CO and HC exhaust emissions resulting from incomplete fuel combustion are therefore reduced. The three compounds currently being considered for major use as gasoline oxygenates are MTBE, ethyl tertiary butyl ether (ETBE) (derived from ethanol and isobutylene), and tertiary amyl methyl ether (TAME). These compounds all have similar properties but MTBE is the most widely used. The use of MTBE raises the octane rating of the fuel without requiring higher levels of aromatics.

A program of research and development on reformulated fuels, the Auto/Oil Air Quality Improvement Research Program (AQIRP), has been undertaken by 14 oil companies in conjunction with three major US carmakers. This research program has found that, in general, adding oxygenates to gasoline reduces the amount of exhaust emissions — hydrocarbons and carbon monoxide (AQIRP 1993a). However, the ultimate form of RFG is far from decided and will depend on further research efforts into emission characteristics and implementation costs. Gasoline components may undergo radical chemical transformations inside the engine, and the precise reformulation required can only be determined through extensive in-vehicle testing.

As the decade progresses, the trend in US refining is expected to be towards an average fuel that combusts more completely and has less evaporative emissions (Unzelman 1991b) than current gasolines. The composition of this fuel will depend largely on the costs of improving the various gasoline properties and on the requirements of tighter vehicle emission standards.

EMISSIONS AND SAFETY

Gasoline vehicle emissions that contribute to urban air pollution (so-called noxious emissions) and to the enhanced greenhouse effect are considered below.

Noxious emissions

The introduction of reformulated gasolines in the USA was driven by the extent of local air quality problems in almost 100 cities (Sinor Consultants 1992e).

Serious levels of CO and ozone (O_3) pollution are encountered in many of the larger US cities (Sinor Consultants 1992a). Ozone is the main constituent of photochemical smog, and is a harsh irritant that poses a public health concern in many urban areas. Ozone is not emitted directly from motor vehicles, but is formed in the atmosphere as the result of a series of complex reactions between emissions of VOCs and NO_X.

Recent amendments to the US Clean Air Act require that only RFGs that meet certain standards for oxygen content, vapour pressure, benzene content and heavy metal content can be sold from 1995 in the 10 US cities with the most severe levels of O_3 pollution (Sinor Consultants 1992b). About 40 US cities with serious CO pollution levels are required to establish oxygenated fuels programs by the end of 1992, with a view to having all US cities meet the federal air quality standard for CO by the year 2000 (Sinor Consultants 1992b). The cities where legislation requires the use of RFG account for around 27 per cent of the US gasoline market (Unzelman 1991a). Future use of RFG in the USA could be widespread, since those states that fully comply with federal standards for both ozone and CO consume less than 9 per cent of US gasoline sales (Sinor Consultants 1992c).

The primary air pollutants emitted by gasoline vehicles are CO, NO_X, SO_X, and various VOCs. HC species make up the bulk of gasoline VOC exhaust and evaporative emissions; the remainder consist mostly of carbonyl compounds. Carbonyls (which include aldehydes and ketones) are very reactive compounds that consist of an HC structure with one (or more) of the carbon atoms double bonded to an oxygen atom.

Due to their acute toxicity, several organic emission species are often monitored separately from total VOC volume. Airborne toxic substances from gasoline include formaldehyde (a carbonyl, H_2CO), benzene (an aromatic hydrocarbon, C_6H_6) and butadiene (an alkene, C_4H_6) (Carnovale et al. 1991).

Evaporative hydrocarbon emissions from the vehicle fuel system occur under three main conditions: *running, diurnal* and *hot soak*. Running losses occur while the vehicle is being driven. Diurnal losses result from normal daily temperature changes causing the air–fuel mixture in the fuel tank to expand and expel gasoline vapour. Hot soak losses occur at the end of each vehicle trip, where engine heat causes evaporation from the carburettor and gasoline tank. Of the HC emissions from the current Australian vehicle fleet, around 10 per cent could be from running losses, 30 per cent from other evaporative losses, and 60 per cent from the exhaust (based on Carnovale et al. 1991).

All reformulated gasolines exhibit lower exhaust emissions of CO, compared with conventional gasoline. Evaporative HC emissions, both from the vehicle and from fuel distribution, also tend to be lower, because of the lower fuel vapour pressures and the reduced content of low boiling point compounds (IEA 1992a). The total mass of HC exhaust emissions is reduced by most reformulations, but the extent of the reduction is highly vehicle-model-specific. NO_X emissions are generally similar for conventional gasoline and common blends of RFG, but can be reduced with appropriate reformulation (such as reducing fuel sulphur and alkene content).

ARCO has claimed that average reductions of over 20 per cent in exhaust emissions of CO, HC and NO_X, up to 36 per cent in vehicle evaporative HC emissions, 47 per cent in total emissions of toxic compounds (EPA 1991b) and 80 per cent in SO_X (OTA 1990) are possible when its reformulations are used in place of conventional gasoline. ARCO has not yet marketed its cleanest RFG (EC-X) because of its additional production cost of 15 to 20 US cents per gallon (Nadis & MacKenzie 1993).

Emission reductions achieved, however, will be vehicle-specific, and reductions from the total fleet will therefore depend on its vehicle composition. Compared with vehicles without modern emission controls, only small absolute emission benefits can be expected from vehicles fitted with catalytic converters (*Oil & Gas Journal* 1991). Also, modern vehicles have engine management systems with oxygen sensors. These sensors detect the amount of oxygen in exhaust gases, and the air–fuel ratio in the engine is controlled on the basis of these oxygen levels. This would tend to counter the effects produced by oxygenates, and smaller reductions in HC and CO emissions would be expected from using RFG in cars with these 'closed-loop' sensor systems (EPA 1991b).

The view that the emissions benefits of RFG are vehicle-specific is supported by a number of studies, including those of AQIRP (1993a) and the Chevron Research and Technology Company (CRTC) (Hoekman 1992). The initial phase of AQIRP tested various fuel composition and vehicle combinations, and their effects on emissions. Two fleets of vehicles, current (1989) and older (1983 to 1985) model US production cars, were tested with respect to various gasoline changes:

- adding oxygenates;
- decreasing aromatic content;
- decreasing alkene content;
- decreasing sulphur content;
- reducing the temperature at which 90 per cent of the fuel evaporates (denoted by T90).

The AQIRP results revealed considerable differences in emissions depending on the vehicle and type of reformulation (Unzelman 1991a). They imply that reducing fuel aromatic content tends to reduce HC exhaust emissions from newer vehicles while increasing HC from older vehicles. Reducing alkene content reduced NO_X emissions, but increased HC exhaust emissions. Adding 15 per cent MTBE reduced average CO emissions by over 10 per cent, but was more effective in the older vehicles. Reducing T90 caused lower HC exhaust emissions, especially from the new cars, but increased NO_X and CO output, especially from the older vehicles. Only in the case of reduced sulphur content were all exhaust components lowered, since a reduction in sulphur content improves the functioning of catalytic converters (Colucci & Wise 1992).

For evaporative HC emissions, AQIRP found that oxygenated fuels have lower diurnal emissions but higher hot soak emissions (Colucci & Wise 1992). AQIRP exhaust emission tests show that, on average, reductions of 21 per cent in HCs and 26 per cent in CO were typical for 1989 model US cars using available RFGs rather than conventional gasoline. On the other hand, NO_x levels typically increased by 3 per cent. For pre-1986 US cars, the reductions were around 6 per cent in CO and 14 per cent in NO_x, with an increase of 7 per cent in HC emissions (EPA 1991b).

The tests conducted at CRTC (Hoekman 1992) involved a fleet of vehicles covering a range of model years (from 1970 to 1990), makes (both US and imported) and sizes. The vehicles were selected to encompass the four main emission control technologies which are found in cars. These are, in order of increasing sophistication:

- non-catalyst systems, which include modifications to ignition timing and air–fuel ratios;
- oxidation catalyst systems, which include a two-way catalytic converter to oxidize HCs and CO;
- early three-way catalytic converters, to reduce HC, CO and NO_x emissions;
- advanced three-way catalyst systems, using electronic fuel injection under computer control.

The CRTC program tested a reformulation similar to ARCO EC-X, containing 11 per cent MTBE, against average premium unleaded gasoline. The tests revealed modest emission reductions in total HCs (between 5 and 18 per cent, depending on vehicle type) and in CO (11 to 21 per cent), but no change for NO_x. Total VOC emissions were reduced with the reformulated fuel by around 6 per cent across the vehicle fleet, but emissions of reactive aldehyde and alkene compounds increased.

Regarding ozone abatement, even though the RFG tested exhibited lower total VOC emissions, these gains were largely offset by higher emission levels of reactive gases. As a group, all vehicle VOC emissions are contributors to ozone pollution. However, there are considerable differences in the ozone-forming potential (or *reactivity*) of the many components of vehicle exhaust emissions. Total reactivity of the test fleet's exhaust emissions (in terms of grams of ozone formed per vehicle-kilometre) indicated no statistically significant difference between the two fuels. Ozone contribution for non-catalyst vehicles did show an 8 per cent decrease with RFG, but reactivity-weighted VOC emissions from advanced three-way catalyst vehicles actually increased slightly (by 2 per cent) when using RFG.

Hoekman (1992) reports that RFG use causes increased emissions of some toxic VOC species. When burned, MTBE can give off formaldehyde (Taschner 1991). Hoekman measured formaldehyde increases from the use of RFG for all categories of vehicle pollution control technology. Vehicles equipped with oxidation catalysts, in particular, exhibited formaldehyde emission increases of nearly 30 per cent over those from conventional gasoline use. Hoekman's analysis goes on to show that the reformulated fuel tended to reduce total toxic emissions from vehicles with early three-way catalysts, but increased net toxics from other vehicle types. Emission of benzene was, however, consistently reduced by an average of 7 per cent.

Testing by AQIRP has also shown that fuels containing MTBE and ETBE have increased emissions of formaldehyde and reduced emissions of benzene (Colucci & Wise 1992). AQIRP has found that addition of another oxygenate, TAME, yields even higher formaldehyde emissions than MTBE (Sinor Consultants 1992c).

BTCE estimates (based on Sinor Consultants 1992c, IEA 1992a and Hoekman 1992) are that overall noxious vehicle emissions from a typical RFG could be 5 to 10 per cent lower than those from current Australian blends (appendix II). This will vary according to the vehicle type and the particular fuel reformulation chosen. Many of the fuel attributes yielding the greatest emission benefits (such as heavily reduced fuel sulphur content) are the most costly to implement.

Greenhouse gas emissions

The International Energy Agency (IEA) has compared FFC greenhouse gas emissions from a 95 octane reformulated gasoline (akin to the ARCO reformulations and containing 15 per cent MTBE by volume) with a non-reformulated 95 octane unleaded gasoline. The IEA analysis deals with emissions from new cars (with an assumed fuel efficiency of 6.8 litres per 100 kilometres). The results were generated using a computer model developed by Dr Mark DeLuchi of the University of California, and 'must be considered indicative and relative rather than real or absolute' (IEA 1992a).

Due to the presence of MTBE, the carbon content per litre for RFG is around 3 per cent lower than for conventional gasoline, and the energy content per litre is also lower by around 3 per cent. RFG use therefore requires slightly higher fuel consumption, but not quite as high as the energy per litre difference implies, because there is an engine efficiency gain from the cleaner burning fuel. The consumption of larger volumes of RFG, with a lower carbon content, leads to tailpipe CO_2 emissions per kilometre only 1.4 per cent less than from regular gasoline (IEA 1992a). Data on fuel characteristics in the literature imply that average tailpipe CO_2 emissions from RFG would be of the order of 2 per cent below those of conventional gasoline (and should fall between 1 per cent above and 3 per cent below) (appendix II).

On the basis of DeLuchi's model, use of the RFG led to reductions in emissions of other greenhouse gases, CH_4, CO, NO_x and particularly non-methane hydrocarbons. N_2O from cars is mostly formed in post-combustion reactions between exhaust products and atmospheric nitrogen, and N_2O output was the same for both fuels. The IEA (1992a) results have overall tailpipe greenhouse gas emissions from RFG at around 6 per cent lower than from regular gasoline on a per kilometre basis. The manufacturing of RFG (including the production of MTBE) is about 5 to 10 per cent more energy intensive than the manufacture of standard gasoline. The result of the IEA (1992a) analysis is that RFG yields a net FFC reduction of around 3 per cent in greenhouse gas emissions compared with conventional gasoline (appendix II).

The IEA (1992a) calculations did not, however, take account of the differing reactivity of the NMHCs emitted by conventional and reformulated fuels (as is allowed for by Hoekman 1992). If the IEA results are adjusted for this effect, the potential net reduction in FFC greenhouse gases offered by current RFGs falls to less than one per cent. The latest IEA (1993) calculations provide an estimate of greenhouse gas emissions[2] from the vehicle fleets of North America and OECD Europe in the year 2000. For North America, it was estimated that RFG emissions (in grams of CO_2 equivalents per kilometre) would be 1.1 per cent higher than from gasoline, and for Europe, 0.4 per cent lower.

DeLuchi's own analysis (reported in Sinor Consultants 1992c) shows that RFG has FFC greenhouse gas emissions roughly equivalent to those from standard gasoline. Emissions were derived for a range of scenarios spanning the 'most and least favourable' cases. This sensitivity analysis revealed that RFGs would contribute between 6 per cent less and 10 per cent more (with an average of 1 per cent more) total greenhouse gas emissions than standard gasoline.

BTCE estimates (based on Sinor Consultants 1992c, IEA 1992a and Hoekman 1992) indicate that greenhouse gas emissions from a typical RFG could be 1 to 2 per cent lower than those from current Australian blends on a FFC basis (appendix II). As indicated earlier, noxious emissions will vary according to vehicle type and the particular fuel reformulation chosen, but might be expected to be some 5 to 10 per cent lower from RFG (appendix II). While it is technically possible to develop fuels giving more significant emission reductions, such fuels are at present not being marketed because of high production costs.

Health effects

MTBE was approved by the United States Environmental Protection Agency (USEPA) in 1979 for use in fuel in concentrations up to 11 per cent, and has been included in European fuel since 1973 (Sivak & Murphy 1991).

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[2] IEA emissions from cars are based on life cycle (FFC plus vehicle manufacture) emissions. It has been possible to make FFC comparisons with IEA (1992a) data from details provided.

Any difference in the health effects from RFG as distinct from existing gasolines relates essentially to the possible toxicity of the added oxygenate and its combustion products. Apart from the oxygenate, RFG and standard gasoline have roughly equivalent chemical compositions and emission species. Any health implications besides those from the oxygenate would relate to the reductions or increases in some gasoline emission species. RFG would:

- reduce CO emissions
  - which impair perception and muscle response;
- slightly reduce total VOC and consequent ozone pollution
  - which cause respiratory disorders and aggravate allergies;
- reduce benzene emissions
  - which are carcinogenic, but
- increase emissions of aldehydes
  - which are irritants and possibly carcinogenic.

USEPA data imply that fuel containing 10 per cent MTBE would emit MTBE in the exhaust gases in an amount equal to 2 per cent of tailpipe VOC emissions (Sivak & Murphy 1991). Hoekman (1992) found MTBE to account for around 4 per cent of VOC exhaust emissions from old (non-catalyst) vehicles and around 1 per cent from new (three-way catalyst) cars. Concerning evaporative emissions, evaporation of MTBE from the vehicle fuel tank only accounts for about 10 per cent of total MTBE emissions (Sivak & Murphy 1991). The USEPA reports that ambient concentrations of MTBE at service stations using RFG have been measured at values ranging from 0.28 to 1.0 part per million (Sivak & Murphy 1991).

Sivak and Murphy (1991) have reviewed MTBE toxicity studies relating to inhalation, ingestion and skin exposure. These studies ranged over acute, subchronic, reproductive and genetic effects. The toxicity studies and the emission measurements compared by Sivak and Murphy indicate that the level of acute toxicity for MTBE by inhalation is at least 18 000 times greater than the expected exposure of RFG users. They also indicate that subchronic MTBE inhalation exhibits no toxicity at levels even 1000 times greater than anticipated exposure. Sivak and Murphy concluded that exposure to MTBE under normal use (essentially driving and refuelling vehicles) provides little likelihood of a human hazard. However, no chronic toxicity studies were included in their review and they did note that the 'complete metabolic pathway of MTBE remains to be elucidated'.

Shell (pers. comm. 1992) cautions that the introduction of a chemical such as MTBE, with the potential for widespread exposure, needs detailed and intensive scrutiny — particularly with regard to long-term effects.

PRODUCTION AND DISTRIBUTION COSTS

To produce RFG, existing Australian refineries would need to change operational processes and modify hardware, possibly incurring substantial capital costs. In general, production of RFG would require additional facilities for greater fractionation and desulphurisation of gasoline feedstocks, manufacture of ethers (such as MTBE and TAME), and increased hydrogen production (Baliker & Forrest 1992).

Baliker and Forrest estimate that RFG production would entail expenditure of US$20 million to US$100 million for an existing 100 000 barrels per day refinery in the USA, depending on refinery configuration. A Bechtel Corporation study estimated the cost at between US$27 million and US$133 million (Sinor Consultants 1992c).

At a return on investment of 15 per cent, Baliker and Forrest estimate that pump prices of RFG would be 9 to 10 US cents higher per gallon than gasoline prices. The Bechtel study (Sinor Consultants 1992c) estimated that meeting California Air Resources Board (CARB) requirements for RFG would require a price increase of 9.2 US cents per gallon, assuming a 15 per cent after tax return on capital investment. AQIRP results indicate that the incremental manufacturing costs for RFG are in the range 2 to 12 US cents per gallon. AQIRP estimates the cost of reformulations to control individual fuel properties as follows (AQIRP 1993b):

	US cents per gallon (1989 $)
Reduction of 20 per cent in aromatics	2.3–4.7
Inclusion of 15 per cent MTBE	1.3–4.0
Reduction of 5 per cent in alkenes	2.2–3.1
Lowering boiling range (T90)	5.0–8.8
Reducing sulphur content	2.1–4.6

The energy content per litre of an oxygenated RFG is slightly lower than that of current gasoline blends because of its dilution with MTBE. Fuel consumption would therefore be higher (IEA 1992a), possibly by about 3 per cent. The additional cost to the consumer of the extra fuel required would be between 2 and 5 US cents per gallon (Sinor Consultants 1992b).

On the basis of the estimated 2 to 12 cent range, it would cost 4 to 17 US cents extra for RFG that provides the same energy output as one gallon of gasoline. This represents between 1.5 and 6.5 Australian cents extra for the energy equivalent of one litre of conventional gasoline (LGE),[3] at an exchange rate of A$1 to US$0.70. Shell (pers. comm. 1992) notes that estimates of the cost of RFG are commonly up to 5 US cents per litre (7.2 Australian cents) above those of conventional gasoline.

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[3] An LGE, or 'litre of gasoline equivalent', denotes the amount of fuel required to provide the same energy content as a litre of conventional gasoline.

According to BP Australia, the costs of producing RFG in the USA could force many smaller refiners out of business (BP, pers. comm. 1992). Baliker and Forrest (1992) also expect that any change to the US fuels market due to RFG legislation will eventually force the closure of some refinery facilities. Some US refiners (including Shell and Amoco) have announced defensive investment strategies: closing some plants and expanding others (Baliker & Forrest 1992).

Costs of introduction in Australia

Australian oil refiners do not appear to have given detailed consideration to the costs of introducing RFG in Australia. According to BP Australia, cost estimates have not been made, but would be 'huge'. Australian refineries have limited flexibility, having been designed for a given product mix. In addition, the introduction of RFG to Australia could require a change from the existing 'wet' to more 'dry' refining and distribution systems (BP, pers. comm. 1992), resulting in even higher prices than those estimated for the USA, where the systems are relatively 'dry'.

RFG benefits from a 'dry' refining and distribution system because of possible phase separation of the oxygenate in RFG in the presence of water. In Australia petroleum products are normally produced and distributed saturated with water, evidenced by a water layer at the bottom of refinery and service station tanks. Water is used to clear pipelines, which are tested hydrostatically. Wharf pipelines are 'rested on water' (that is, they contain water when not in use), although some harbour authorities are beginning to require 'resting' using diesel. There is water in ships' tanks; and although exchanges among Australian refineries reduce the amount of petroleum transported by sea, this amount is still considerable (BP, pers. comm. 1992).

COSTS OF EMISSION REDUCTION

The costs of reducing greenhouse and local emissions by using RFG would be confined essentially to the additional cost of the fuel itself. Apart from the very minor reduction in maximum range, RFG offers the same potential consumer satisfaction as conventional gasoline. It is conceivable that some minor changes to vehicles could prove necessary. Engine calibration may need to be altered, as RFG could have a different octane number, and durability tests would need to be conducted to assess component compatibility (including that of possible rubber, aluminium and zinc deterioration due to the oxygenates).

ABARE (1993) projects gasoline consumption in the Australian road transport sector to be around 651 PJ in 2005, an increase of about 15 per cent over 1987–88. Unleaded gasoline is predicted to constitute 90 per cent of this amount, in contrast to the 15 per cent in 1987–88. Assuming that Australian refinery costs would be at the upper end of the US cost estimates (1.5 to 6.5 Australian cents per LGE), replacement of the projected consumption of ordinary gasoline with RFG would amount to an additional fuel cost, in the year 2005, of about A$1200 million (1992 $). This cost would be lower to the extent that higher prices induce a reduction in gasoline consumption.

This level of replacement would reduce projected 2005 greenhouse gas emissions by about 0.6 megatonnes (in terms of CO_2 equivalent emissions), and would constitute a reduction of about 0.6 per cent in projected 2005 greenhouse gas emissions from the transport sector. The reduction in noxious emissions would vary for different pollutants, but would be some 10 per cent overall in terms of tonnage. The most significant reduction would likely be in the level of CO emissions.

The reformulation strategies that yield the greatest emissions benefits (such as desulphurisation and lowering volatility) are generally the most expensive to implement. As indicated above, ARCO's EC-X could be expected to achieve noxious emission reductions of the order of 30 per cent at a cost of 15 to 20 US cents per gallon (6 to 9 Australian cents per LGE). An SRI International study has estimated similar costs for producing RFGs that would meet likely future standards for noxious emissions in the USA. These range from 18 US cents per gallon for the 1995 standards to 32 cents per gallon for 2010. These compare with the estimate of 9 US cents per gallon for the RFGs currently on the US market (*Oil & Gas Journal* 1991).

CONCLUSION

The extensive fuel reformulation strategies embarked upon by the USA may not be cost-effective for Australia in reducing emissions. FFC greenhouse gas emissions from current RFGs are of the same order as those from conventional gasolines, typically between 1 and 2 per cent below (and would probably fall in the range of 2 per cent above to 4 per cent below). IEA (1993) estimates that 'reformulating gasoline to current US Clean Air Act standards produces virtually the same life cycle greenhouse gas emissions as the use of premium unleaded gasoline'. For noxious gas emissions, approximate estimates are that typical RFGs offer benefits of around 5 to 10 per cent over current Australian gasoline.

The Shell Briefing Service (1992) states that the wider use of catalytic converters and carbon canisters (which attach to fuel system vents and absorb evaporative emissions) is likely to be more cost-effective in reducing transport emissions than any changes to fuel quality.

Similar opinions have been expressed in US literature, particularly after Hoekman (1992) concluded that current fuel reformulations have an almost indiscernible effect on the reactivity of motor vehicle emissions. Stedman (1992) notes that most studies of on-road emissions in the USA have observed that 50 per cent of total noxious emissions are due to only 10 per cent of the fleet. He estimates that 10 times the improvement in ozone contribution from fuel reformulation could be obtained by repairing this 10 per cent of vehicles to the average emission rate of comparably aged vehicles. Stedman concludes that identification and repair of grossly polluting vehicles is likely to be much more cost-effective than fuel reformulation. The Victorian EPA also notes that cars with malfunctioning catalytic converter systems can have emissions 30 times higher than the fleet average, and stresses the importance of long-term vehicle maintenance programs in achieving air quality improvements (Carnovale et al. 1991).

However, less extensive modifications to current gasoline blends may be justified on emissions grounds. The Victorian EPA (pers. comm. 1992) indicated that even though the introduction of RFG is not at present under consideration, there is scope to improve the quality of existing gasoline, particularly with respect to volatility. Decreasing the sulphur content of fuels would prolong catalyst life in addition to lowering tailpipe emissions.

It is also possible that future research could result in gasoline reformulations that have more significant advantages than current types.

CHAPTER 3 LIQUEFIED PETROLEUM GAS

Liquefied petroleum gas (LPG) is an existing road transport fuel with some emissions advantages compared with gasoline. The use of LPG in vehicles is growing rapidly, albeit from a small base, and there is scope to expand its use.

FUEL CHARACTERISTICS

Automotive LPG is essentially a blend of propane (C_3H_8) and butane (C_4H_{10}), although propylene (C_3H_6) may sometimes be present in minor amounts. Propane and butane are gases at atmospheric pressure and temperature, but can easily be liquefied for storage by an increase in pressure to about eight atmospheres or by a reduction in temperature. In Australia, LPG is stored on board the vehicle in a steel cylinder in liquid form, but is converted to gaseous form via a regulator before supply to a gas–air mixer (the equivalent of a carburettor) for intake to the engine.

Compared with butane, propane is in short supply (Australian LPG Association [ALPGA], pers. comm. 1992). In Victoria automotive LPG has until recently been virtually pure propane, but is now a blend, by volume, of about 60 propane to 40 butane. In New South Wales, LPG is also a 60:40 blend, while in Queensland it is 70:30 (EPA 1991a). A blend of 50:50 is feasible, according to the ALPGA. These changes in blend composition are likely to require only minor, if any, engine retuning.

BACKGROUND

LPG has been used as a transport fuel in Australia since the 1970s, particularly in taxis and vehicles that operate indoors — such as forklift trucks — possibly because of perceptions that it is a 'clean fuel'. Industry figures suggest that, excluding the forklift types, about 250 000 Australian vehicles operate on LPG (Borgas 1993).[1] Of these, around 180 000 are privately owned. Virtually all are

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[1] Accurate statistics on LPG vehicle numbers are unavailable. Australian Bureau of Statistics (ABS) data in the 1991 *Motor Vehicle Census* (ABS 1991) record only about 40 000 LPG vehicles.

light duty vehicles (LDVs),[2] average LPG vehicle weight being less than 3 tonnes (Borgas 1993). About 95 per cent can operate as dual-fuel[3] vehicles, using either LPG or gasoline (*BRW* 1992b).

With the exception of one short-lived example of an OEM LPG car around 1980, Australian LPG road vehicles have had to be converted from gasoline vehicles after purchase. However, the Holden *Commodore* and Ford *Falcon* can now be ordered with a fully warranted ex-factory LPG–gasoline dual-fuel capability. GOGAS (pers. comm. 1992) reports signs of interest by car leasing companies in OEM LPG vehicles with full factory warranty. These companies have traditionally taken a conservative view of LPG conversion.

Conversions have typically occurred at a rate of about 35 000 vehicles per year, reaching a high of about 42 000 in 1990 at the peak of the Gulf war. Conversion rates recently have been somewhat lower, due to the uncertainty (until December 1992) surrounding the continuation of the tax and excise free status of LPG. The exemption of LPG from excise is reported to have been crucial in developing the automotive LPG market (GOGAS, pers. comm. 1992).

Unlike the situation for most alternative fuels, there is already a relatively extensive distribution network for automotive LPG. There were 2155 outlets throughout Australia in early 1993, just over half of which were in metropolitan areas. The number of outlets has doubled in the last five years. Some 65 per cent of automotive LPG is consumed in metropolitan areas (GOGAS, pers. comm. 1992).

Extent of LPG use in Australian transport

Australian LPG use is divided fairly evenly among the transport, heating and petrochemical markets. ABARE's statistics indicate that the Transport and Storage sector consumed 25.4 PJ of LPG in 1991–92, out of a total Australian LPG consumption of 83.8 PJ (ABARE 1993). Shell (pers. comm. 1992) regards ABARE's figures as understating transport LPG use and as overstating chemical industry use. GOGAS (pers. comm. 1992) puts total current annual automotive use of LPG (excluding use by vehicles such as forklifts) at 30 PJ, equal to around 3.5 per cent of total road transport energy use or 5 per cent of gasoline use in road transport.

GOGAS estimates the level of replacement of gasoline by LPG at up to 15 per cent in Melbourne and 8 to 10 per cent in Sydney. The Victorian EPA estimates

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[2] LDVs include cars, station wagons, forward control passenger vehicles, utilities and panel vans (LCVs) and four wheel drive vehicles (4WDs).

[3] In this paper, dual-fuel vehicles are defined as vehicles having two separate fuel systems, with only one fuel being used at a time. Dual (mixed) fuel vehicles are defined as those operating on a variable combination of gas and diesel fuel, but which often retain the capability to operate solely on diesel when the gas supply has been exhausted. In contrast a flexible fuel vehicle operates on a variable mixture of fuels utilising the same fuel system.

that LPG has replaced around 6 per cent of gasoline use in all of Victoria (EPA 1991a). The penetration rates would have been influenced by price differences between New South Wales and Victoria (discussed below).

This level of current use has been the result of recent high rates of growth, much higher than those for all other fuels. LPG use grew on average by 15 per cent per year over the past decade, on the basis of the ABARE data series. According to GOGAS (pers. comm. 1992), automotive LPG use has doubled since 1987. GOGAS considers that the achievement of a 'critical mass' of LPG vehicle numbers and refuelling station locations has facilitated this growth. Such high growth rates are not expected to continue; ABARE's projection is for an average growth rate in LPG use in transport of around 6 per cent per year to 2004–05, the LPG increasingly sourced from imports (ABARE 1991).

LPG vehicles

LPG vehicles form about 2.5 per cent of the total number of Australian road vehicles (GOGAS figures). The high annual mileages of taxis — 95 per cent of which have an LPG option — and the larger-than-average size and annual mileage of cars and LCVs converted, would account for the disproportion between the percentage of fuel use (3.5 per cent) and the percentage of vehicle numbers.

LPG in heavy vehicles

Transport operator Linfox (pers. comm. 1992) used LPG trucks as well as gasoline-fuelled trucks in its fleet in the early 1970s. However, use of the LPG trucks was discontinued, as they had tended to become unreliable after about a year or so.

Boral has conducted trials of a truck operating on a blend of diesel and LPG vapour, with the vapour replacing 35 per cent of diesel. In theory, diesel vehicles could run on 80 per cent LPG and 20 per cent diesel mixed in liquid form (Murray 1989). To run on 100 per cent LPG, heavy vehicle engines would require conversion to spark ignition and a reduction in compression ratios.

The ALPGA sees LPG as being more suitable for the passenger car market, and natural gas more suited to heavy vehicles (ALPGA, pers. comm. 1992). The higher energy density of LPG compared with natural gas allows a reasonable range while retaining more of the luggage capacity in the boot of a car.

LPG COSTS AND PRICES

The cost of using LPG depends on LPG prices, the energy content of LPG and the efficiency of the engine when using LPG (all of which influence fuel costs per kilometre to users), conversion costs, and any costs to consumers in terms of diminished utitlity of the product, for example, from reduced range. The latter costs can influence resale values, and hence returns on investment in LPG vehicles.

In assessing the social cost of expanding the use of LPG over and above a business-as-usual scenario, fuel costs to users would need to based on the opportunity cost[4] of LPG and the fuel replaced.

LPG fuel prices

According to Shell (pers. comm. 1992), LPG pricing is a 'complex, commercially sensitive issue'. Local prices and costs are influenced by a number of factors apart from market structure. There is a preference for matching LPG supply and demand to minimise storage costs. LPG is a joint product along with other refinery outputs, and it is used in three distinct markets: industry, residential and transport.

At present, automotive LPG has a price advantage over gasoline of 35 to 50 cents per litre. On an energy content basis, LPG's price advantage is roughly 30 to 40 cents per litre of gasoline equivalent. LPG is free of excise charges, which were removed in 1979 together with the sales tax on vehicle conversion kits (PSA 1990). The excise free status of LPG and other alternative fuels was guaranteed by the Commonwealth Government for a five-year period in December 1992, with a one-year notice of change.

Wholesale prices

The LPG market has been deregulated since 1 January 1991. Prices Surveillance Authority determination of maximum wholesale prices for LPG was ended and export controls were removed. Since then prices have fluctuated considerably, more closely reflecting overseas — especially Saudi Arabian — price movements (*Motor Industry Journal* 1992). For example, BHP propane wholesale list prices have varied in the range $218 to $324 per tonne during the period December 1991 to January 1993 (GOGAS, pers. comm. 1993).

BHP sets its wholesale LPG (propane) prices using a formula based on the Saudi Arabian government selling price adjusted for transport costs (reflecting the cost of importing LPG in 40 000-tonne shipments), insurance, and currency fluctuations (GOGAS, pers. comm. 1993).

According to the *Motor Industry Journal* (1992), wholesale LPG prices in 1991 were lower than those in 1980. The average monthly wholesale price of $253 per tonne for propane in 1992 (GOGAS, pers. comm. 1993), was only marginally higher than the average price of $250 per tonne ruling during the 1980s (based

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[4] Opportunity cost represents the value lost from not using a good or resource in the most valuable alternative use. For LPG or gasoline, which are traded internationally, the import or export price of the fuel would reflect its opportunity cost.

on PSA 1990). GOGAS (pers. comm. 1992) considers that import parity pricing effectively puts a 'floor' under LPG prices. This floor would limit the scope for competition with gasoline through reduced prices were LPG and gasoline to be accorded similar tax treatment.

Retail prices

The Royal Automobile Club of Victoria (RACV) has observed 'clear discount cycles' of four to six weeks in retail prices (*Motor Industry Journal* 1992). For three to four weeks prices edge downwards as discounts are gradually increased, bottom out for one or two weeks, then rebound directly to an undiscounted price (Blythe 1992). These cycles are said to be initiated by independent service station operators seeking to increase their market shares (ALPGA, pers. comm. 1992).

LPG is around 10 cents per litre cheaper in Melbourne than in Sydney. In the first half of 1992 the retail price range was about 28 to 35 cents per litre in Sydney, and usually 20 to 24 cents per litre in Melbourne (*BRW* 1992b), although prices in Melbourne reached 30 cents per litre on several occasions (*Motor Industry Journal* 1992). The GOGAS (pers. comm. 1992) view is that pump prices of LPG per litre in Melbourne are consistently closer to one-third than to one-half of those of gasoline.

The Melbourne–Sydney price differential is long-standing. A 1974 study of LPG as a motor vehicle fuel (BTE 1974) also found that LPG prices were considerably higher in Sydney (6.8 cents per litre) than in Melbourne (4.6 cents per litre).

The ALPGA (pers. comm. 1992) argues that the Melbourne–Sydney price differential is basically the result of shipping Bass Strait LPG from Port Hastings in Victoria to Port Botany in New South Wales. Shell (pers. comm. 1992) believes that transport costs from Victoria to Sydney are only of the order of 5 to 6 cents per litre, and that competition is greater in the Melbourne market because more firms are involved.

The margins between wholesale and retail prices for LPG are said to be generally higher than for gasoline, both because of higher costs of storage, handling, refrigeration and transport, and because of lower volumes sold. However, stated prices of one Victorian retailer showed slim retail margins, at least for the days cited, and illustrated the volatility of LPG prices as a result of discount price cycles. On 12 December 1991, the rack price (or cost price to the retailer) was 18 cents, while the retail price was 19.9 cents per litre. On 8 January 1992 the rack price was 28.0 cents while the retail price was 29.9 cents per litre (*Motor Industry Journal* 1992).

Shell (pers. comm. 1992) put the normal retail margin at about 3 cents per litre in Melbourne and about 5 or 6 cents per litre in country areas. The PSA (1990) has described LPG distribution and marketing as highly concentrated throughout most of Australia with competition most intense in the eastern state capitals.

The price differential between Melbourne and Sydney may have influenced market penetration. Automotive use of LPG in March 1992 was 35.5 megalitres in Victoria but only 13.1 megalitres in New South Wales (including the Australian Capital Territory). Victoria accounted for some 56 per cent of Australian automotive LPG use in this month (DPIE, pers. comm. 1992). Some 60 per cent of LPG use in Sydney is by taxis (GOGAS, pers. comm. 1992). High annual distances travelled by taxis make conversion attractive even with the smaller margin between gasoline and LPG prices in New South Wales.

Costs to users of LPG

Costs of using LPG depend on the cost of fuel and on the costs of vehicle conversion. Fuel costs, as indicated above, depend on the price of fuel, its energy content and the efficiency with which the engine uses the fuel. Costs arising from diminished utility are addressed in chapter 10.

Conversion costs in 1992 varied between $1200 and $1800 for cars (ALPGA cited in *BRW* 1992b), although the National Roads and Motorists' Association (NRMA) had earlier reported the cost of a conversion that complied with all regulatory requirements at $2000 (Haley 1990). GOGAS (pers. comm. 1992) holds that a payback period on conversion outlays of one to two years is required by potential LPG users.[5]

The energy content of a typical automotive LPG blend (25.7 megajoules per litre) is about 25 per cent less than that of gasoline (34.2 megajoules per litre) (ABARE 1993). On this basis LPG vehicles might be expected to consume one-third more fuel per kilometre than gasoline vehicles. While some evidence indicates that vehicles typically consume only 15 to 25 per cent more LPG (*BRW* 1992b), the latest *Fuel Consumption Guide* (DPIE 1993) shows an LPG *Commodore* and an LPG *Falcon* (on a 55:45 city to highway cycle basis) consuming 30 per cent and 45 per cent more fuel respectively, compared with their gasoline equivalents. An NRMA energy test on LPG and gasoline *VN Commodores* travelling between Sydney and Adelaide showed fuel consumption to be 30.7 per cent more for the LPG version (Wallace, pers. comm. 1993).

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[5] Simple (undiscounted) payback periods are commonly used to illustrate the financial viability of conversion to LPG and other alternative fuels. While these may be considered unsuitable, they are widely understood in the transport industry. For this reason, and to facilitate comparison with examples in the literature, the BTCE has made use of simple payback periods at various places in this report. Internal rates of return have also been used where appropriate, for purposes of comparison, and examples of the effects of discount rates on payback periods have been provided.

The BTE's 1974 study of motor vehicle LPG use put the consumption differential at only 10 per cent. Presumably the more recent higher figures reflect the relative improvement in the fuel efficiency of gasoline cars in the interim.

The recent development of liquid-phase LPG injection (as opposed to the conventional vaporiser system) promises improved fuel economy for cars with electronic fuel injection (DPIE 1992b). The Australian company Biocom is considered by GOGAS (pers. comm. 1992) to be at the leading edge in the development of this technology.

Gasoline vehicles may perform more favourably under economical operating conditions, relative to LPG vehicles, than under normal driving conditions. On a recent around-Australia economy run (DPIE 1992a), a Ford *Falcon* achieved 6.6 litres per 100 kilometres on unleaded gasoline, while another *Falcon* using LPG consumed 9.5 litres of LPG per 100 kilometres, some 44 per cent more.

For an equivalent mileage, at 1992 LPG and gasoline prices, the cost of LPG would be around 33 to 75 per cent of that of gasoline, depending on the local price of LPG and the increase in the rate of fuel consumption of the particular vehicle when changing from gasoline to LPG (assumed to range from 15 to 45 per cent). If the excise on LPG were equal to that on gasoline on a per litre of gasoline equivalent basis (22.2 cents per litre compared with the gasoline excise of 29.6 cents per litre from August 1993), the cost of LPG for an equivalent mileage would be between about 70 and 118 per cent of that of gasoline.

FUEL AVAILABILITY

There are opposing views on whether there would be sufficient LPG available — at least from domestic sources — to satisfy any significant increase in demand for its use in transport. Importing LPG would be an option, though the price might be higher.

In 1990, the then Federal Minister for Resources expressed confidence that the deregulation of the LPG market from 1 January 1991, which left the industry free to negotiate market prices, would lead to the infrastructure investment needed to meet future domestic demand for LPG (1990 press release PIE90/202G). ABARE, on the other hand, emphasises the uncertainty of future domestic production. Producers need to choose between investing in plant to extract LPG from oil and gas, or leaving LPG in the major product streams. ABARE (1991) forecasted a decline of about 20 per cent in production of naturally occurring LPG between 1990–91 and 2004–05, and a substantial increase in LPG imports to meet domestic demand for all uses. More recent forecasts are for only a small decline in indigenous LPG production by 2004–05, and no significant increase in imports (ABARE 1993).

GOGAS (pers. comm. 1992) regards domestic supply of LPG as being reasonably sound up to the year 2000, but sees replacement of about 7 or 8 per cent of gasoline use in Australia as being about the limit for expansion of LPG use in transport. This limit, however, is seen as being determined more by demand factors than by restrictions on supply. One limiting factor was that users did not always avail themselves of the full cost savings available from LPG. Both fuel tanks in dual-fuel vehicles tended to be filled, and gasoline used regularly rather than just in emergencies.

LPG production and reserves

The bulk of Australia's LPG supply is captured during oil and natural gas production; the rest is produced during oil refining. Some LPG is imported, for locational reasons, and there are net exports.

Australian reserves of naturally occurring LPG at 31 December 1991 were 1325 million barrels, only half of which had been declared commercial. These reserves would last 60 years at recent production rates. Production was 95 PJ in 1991–92; exports were 42 PJ, imports 1.3 PJ, and domestic consumption amounted to 54 PJ (ABARE 1993).

The question of LPG availability for transport use is complicated by the composition of LPG. As indicated earlier, propane is in shorter supply than butane and the proportion of butane in auto-LPG blends is therefore increasing. While it may be possible to use blends of propane and butane in future in non-automotive use, new burners would be needed in appliances. Butane is now put into gasoline, and some is exported.

Future supply

Increased supplies of LPG for transport could conceivably come from several sources. These include increased domestic production of naturally occurring LPG or refinery output, the removal of more LPG from natural gas, drawing on the current supply of LPG to the petrochemical industry, utilisation of LPG replaced by natural gas in the residential market, use of LPG currently exported, and finally, increased imports of LPG.

Increased domestic production

Forecasts of domestic production have been subject to substantial revision from year to year, with new sources of supply being discovered. ABARE's latest forecasts are for LPG production to peak in 1997–98 at 102 PJ, declining to 88 PJ in 2004–05.

There does not appear to be much scope to increase the supply of LPG by increasing output from refineries, where LPG is essentially a by-product. BP (pers. comm. 1992) has stated that it would not change its refinery input 'diet' to produce more LPG, and Shell tries to minimise LPG production and keep the LPG in gasoline as returns are better. Because of the expense of pressurised containment, storage of LPG is not an economic option. Refineries attempt to match their LPG output with demand, through pricing policies, or by varying the content of LPG in gasoline. LPG in gasoline assists cold starting in cars.

LPG diverted from petrochemical industry use

Almost one-third of LPG goes into the petrochemical market. BP (pers. comm. 1992) stated that there is limited flexibility in the choice of chemical feedstocks for the industry. While switching from LPG to naptha or ethane could conceivably free up almost as much LPG as is currently used in transport (BP, pers. comm. 1992), this is considered by ALPGA (pers. comm. 1992) to be uneconomic at present (1992) LPG prices.

However, ICI has a proposal to pipe ethane from South Australia to its Sydney chemical plant. This would replace the LPG from Bass Strait and imported naptha currently used by ICI to produce ethylene (*Australian Financial Review,* 1 August 1993).

Replacement of LPG by natural gas in residential use

Further replacement of LPG by natural gas in the traditional residential LPG market could free up some LPG for transport use. Natural gas has already made inroads into LPG's heating market (PSA 1990), and it is argued that LPG could not compete with natural gas in this market (BP, pers. comm. 1992). However, natural gas is not available in all locations.

LPG from Australia's natural gas reserves

Australia's resources of natural gas contain small percentages of propane and butane which may be stripped out before export or domestic use of the natural gas. Perth obtains its LPG from natural gas piped to the city from the North-West Shelf. This natural gas contains 2 per cent propane and 0.8 per cent butane, and is thus a suitable source for automotive LPG (Gafcor 1986).

Liquefied natural gas (LNG) exports from the North-West Shelf in 1992 contained LPG equivalent to some 20 per cent of current automotive LPG consumption. Expected production from the North-West Shelf in the year 2007 is such that this source could then conceivably supply 28 PJ of LPG. This would amount to 90 per cent of current automotive LPG use, or 70 per cent of the estimated 2004–05 consumption in vehicles (*BRW* 1992a). This presupposes that the necessary investments in plant are made, and the LPG is channelled into the domestic market rather than exported. Shell (pers. comm. 1992) regarded the expected output of 20 million tonnes per year gas production from the North-West Shelf by 2007 as optimistic.

There is also the possibility that LPG from the Cooper Basin could be carried in the natural gas pipeline to Sydney and then stripped out. Such a strategy could allow the diversion of 15 to 20 PJ of currently exported LPG to domestic automotive use.

There are differences of opinion on the economics of extracting LPG from North-West Shelf natural gas. DPIE opinion (pers. comm. 1992) was that extraction prior to shipment to Japan would currently be uneconomic, though future expansion of processing facilities at the North-West Shelf might include LPG stripping capabilities, depending on the commercial judgments of the companies concerned. The *Australian Financial Review* (1992b) recently announced an investigation by the North-West Shelf project partners of the viability of an export LPG facility to handle some 350 000 tonnes (about 17 PJ) per year, and Shell (pers. comm. 1992) has also indicated that the North-West Shelf Venturers are about to undertake a feasibility study of limited LPG extraction. The BP (pers. comm. 1992) view was that components of natural gas such as propane and butane could be extracted economically if there were a natural gas pipeline to the east coast. However, the Japanese market might prefer that the LPG was not extracted from Australian LNG exports.

Diversion of current LPG exports to domestic use

LPG is currently exported from South Australia and Bass Strait in amounts greater than current usage in transport; hence transport use could expand considerably if exports were diverted to domestic use. Exports were about 42 PJ in 1991–92, compared with 1992 transport consumption estimated as 26 PJ (ABARE 1993) or 30 PJ (GOGAS, pers. comm. 1992). However, LPG exports can be largely in the form of butane, as in 1990–91 (ABARE 1991), and would not then provide the required mix for transport purposes.

LPG exports are forecast to fall to 21 PJ in 2004–05. In that year projected transport consumption of LPG is projected to be 38 PJ (ABARE 1993).

Imports

Imports could be an option to satisfy increased demand for LPG, though the cost of transporting it might influence its competitiveness vis a vis gasoline. Transport costs could be expected to be higher than those for imported gasoline, on an energy equivalent basis, due to the costs of pressurised storage and the lower energy density.

Walker (DPIE, pers. comm. 1992) informed the BTCE that the transport costs of imported LPG would depend on the scale of imports. The PSA (1990) pointed to a freight cost penalty of $50 per tonne from importing LPG in small (8000 to 10 000 tonnes) rather than in large (40 000 to 50 000 tonnes) ships. It held that at existing Australian and overseas LPG prices, the domestic prices would have to have been $100 per tonne — (40 to 50 per cent) higher — for small shipment imports to be economic. BP (pers. comm. 1992) stated that if LPG were to be imported on a large scale, receival and storage facilities would need to be developed to handle 40 000 tonne cargoes.

GOGAS (pers. comm. 1992) is of the opinion that if imports were in large shipments, transport costs of imported LPG would have a minor influence on retail LPG prices — perhaps $20 to $50 per tonne to cover terminal charges. The small effect would result from the import parity nature of current wholesale prices, which include a factor to cover shipping costs. Regarding the required facilities, GOGAS (pers. comm. 1992) alluded to recent plans for a 90 000 tonne LPG storage cavern to be constructed in Sydney.

Regarding availability of LPG for import, BP (pers. comm. 1992) considered that there was 'plenty' of LPG in Saudi Arabian fields. While there might be plenty to satisfy any Australian demand, however, the amount is not large in comparison with overall world demand for transport fuels. The potential supply of LPG for road transport would be around 20 megatonnes annually, equivalent to little more than 5 per cent of current US road fuel consumption (IEA 1992a). Also, US use of LPG in the petrochemical industry is increasing very rapidly (DPIE, pers. comm. 1992).

EMISSIONS AND SAFETY

Greenhouse gas emissions

The IEA estimates that for technologically comparable North American vehicles, exhaust and evaporative greenhouse emissions are 15 per cent lower from LPG than from gasoline vehicles per unit of task (IEA 1992a), while life cycle emissions are 24 per cent lower (IEA 1993). BP Oil New Zealand estimated that CO_2 equivalent FFC greenhouse gas emissions from LPG were 16 per cent less than from gasoline (ALPGI 1991). Table 3.1 shows *tailpipe* emission results for CO_2 for a sample of Australian cars tested by the Victorian EPA. These data show CO_2 emission reductions of between 8 and 22 per cent, depending on car vintage, size and test cycle.

Because of the present low level of LPG usage in transport, a large proportionate increase in LPG vehicle numbers would be required to effect even a small reduction in transport greenhouse emissions. For example doubling the current penetration of LPG use in LDVs would raise the level of gasoline replacement from about 5 per cent to about 10 per cent, and would lower total transport greenhouse emissions by around 0.4 per cent, or under 0.3 megatonnes annually.

The cost of effecting such a reduction in emissions over the life of the vehicles would not be small (chapter 11). Conversion costs could be of the order of $800 million, depending on the number of vehicles required to double the penetration of LPG. (This estimate is based on conversion of about 400 000 cars at a cost of $2000 each.) There could be costs for additional refuelling facilities, and possibly some costs resulting from increases in noxious emissions associated with the increased use of LPG. Preventing increases in these noxious emissions with, for example, closed-loop systems, might cost an extra $200 per car.

Noxious emissions

LPG is a cleaner burning fuel than gasoline, which possibly explains its frequent use in vehicles operated indoors. This inherent advantage of the fuel has been reduced, however, and perhaps offset, by improvements to gasoline-fuelled vehicles which have reduced tailpipe emissions, and which have not been matched by similar improvements to LPG vehicles.

To meet the emissions standards set down in Australian Design Rule (ADR) 37, catalytic converters have been incorporated in new Australian gasoline-fuelled cars since 1986, along with some general improvements. These have included, in some cases, sophisticated electronic fuel injection (EFI) systems. There are as yet no standards for emissions from vehicles converted to LPG (McLennan 1993). Gas mixers, which perform the function of carburettors in LPG cars, remain fairly simple devices compared with EFI systems.

Most LPG conversions currently use open-loop systems, which cannot automatically control the air–fuel mixture. While the more sophisticated closed-loop systems can reduce tailpipe emissions (see Australian test results reported below), the additional cost as indicated above would probably be about $200 per vehicle. As there are no benefits in terms of vehicle performance, only a minority of conversions use the closed-loop systems (EPA 1991a). A closed-loop system has been used in the OEM dual-fuel Holden *Commodore*, with an oxygen sensor in the exhaust manifold to allow automatic adjustment of the air–LPG mixture.

Current comparisons of emissions from vehicles using gasoline and LPG may not therefore be indicative of relative emissions from vehicles in the future. OEM vehicles may become more common. More importantly, a focus of the government's action to improve the emissions performance of both new and existing vehicles is the proposal to include LPG (and other alternative fuels) within the scope of ADR 37 (McLennan 1993).[6] Results for tests on LPG vehicles with superior fuel systems would therefore seem to be more meaningful for the purposes of this paper.

For example the introduction in recent years of gasoline cars with substantially lower emission levels has prompted Dutch LPG equipment manufacturers to develop new generation LPG systems. Microprocessor controlled LPG systems are now being used in combination with gasoline injection systems and three-way catalytic converters (Hollemans & Van der Weide 1991). When running on LPG (for both city and freeway cycles) these new engines exhibited reductions in exhaust emissions of around 11 per cent in CO_2, 50 per cent in NO_x, and between 2 and 5 per cent in HC emissions. CO emissions were similar to those from gasoline. IEA (1992a) figures for new European vehicles with equivalent emissions technology show CO and NO_x emissions from LPG vehicles equal to

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[6] ADR 37 places limits on emissions from petrol engined vehicles.

those from gasoline vehicles, and HC emissions 40 per cent lower from LPG vehicles.

There is an additional problem in making comparisons of emissions, in that available test results depend significantly on the equipment included in the vehicles tested, and on whether these vehicles are observed in 'drive-by tests' or in testing stations. Holden *Commodores* and Ford *Falcons*, for example, all now have EFI systems, and these are the type of car most commonly converted to LPG. Comparisons may therefore be made between simple open-loop LPG, and sophisticated gasoline fuel systems.

Emissions from LPG vehicles also vary depending on the propane–butane mix of the LPG itself. The New South Wales State Pollution Control Commission (SPCC) has performed tests on a Ford *EA Falcon* using a variety of LPG compositions. These tests had 100 per cent butane exhibiting 9 per cent better fuel consumption and close to half the NO_x emissions of 100 per cent propane. However, CO emissions with 100 per cent butane were double those of 100 per cent propane (EPA 1991a).

Results of Australian tests

Victorian 'drive-by' emissions tests

Tailpipe emissions from 22 000 cars in Victoria were estimated using instantaneous readings from a remote sensing device. These tests involved the RACV, the Victorian Automobile Chamber of Commerce and the Victorian EPA. They found that LPG vehicles produced twice as much CO on average as equivalent gasoline vehicles (RACV 1992).

This adverse result has been blamed on the inadequate standard of LPG conversions (RACV 1992; GOGAS, pers. comm. 1992), the absence of emissions standards for LPG vehicles, poor servicing of LPG vehicles, and poor state of tune (*Australian* 3 December 1992; GOGAS, pers. comm. 1992). The ALPGA referred to 'too many old vehicles with old equipment and new vehicles which were not correctly converted' (Borgas 1993), while the EPA (pers. comm. 1992) considered that many LPG cars could be running on too rich a mixture, as evidenced by tailpipe odour. The mixture could have been set too rich in an effort to recoup the small power loss likely with LPG.

While Australian Standard 1425 does provide guidelines for the installation of LPG fuel systems, there is no Australia-wide legislation to enforce standards. ADR 44, which requires that LPG fuel systems meet AS1425, and which is enforced, applies only to new dual-fuel LPG vehicles.

Driving cycle tests

Table 3.1 shows test results reported by the Victorian EPA for samples of medium and large pre-1986 cars and small, medium and large post-1986 cars over both city and highway driving cycles.

TABLE 3.1 EXHAUST EMISSIONS FROM LPG CARS

Vehicle type and size, and driving cycle	*Per cent change in exhaust emissions when using LPG instead of gasoline*			
	CO_2	*CO*	*HCS*	*NO_x*
Pre-1986				
Medium				
City	–16	–51	–39	+10
Highway	–8	–42	–35	+6
Large				
City	–15	–60	–34	+24
Highway	–14	+19	–23	+25
Post-1986				
Small				
City	–16	–37	+93	+78
Highway	–14	–95	+129	+59
Medium				
City	–22	–20	+7	+12
Highway	–21	–80	+31	+91
Large				
City	–12	–81	+115	+67
Highway	–15	+515	+367	–24

Note Post-1986 cars have catalytic converters and gasoline cars use unleaded gasoline.

Source EPA (1991a).

The EPA considered that the results for emissions of CO, HCs and NO_x from the post-1986 cars were too variable to draw firm inferences, because of the small sample and dependence on the state of tune of the cars (EPA 1991a). Nevertheless, the variability due to state of tune could indicate what might be expected of the on-road vehicle fleet where the engines of many vehicles are poorly maintained.

This variability of results is evidenced in other tests. In 1988 the EPA and the SPCC conducted emissions tests on dual-fuel (LPG or gasoline) vehicles fitted with catalytic converters. These EPA tests found NO_x and HC emissions were around 30 per cent lower for LPG, but CO was slightly higher. The SPCC also found HC emissions to be reduced by 30 per cent, but its test data showed NO_x increasing by around 10 per cent and CO reducing significantly (ALPGI 1991). Murray (1989) gives as an example the SPCC measurements for a dual-fuel Ford EA *Falcon*. When running on LPG as opposed to gasoline, HC exhaust emissions were one-third lower and CO was 80 per cent lower, but NO_x emissions were 13 per cent higher, although still 20 per cent below ADR 37 limits.

Tests on closed-loop systems

More important from a policy viewpoint are recent ALPGA tests. These were conducted on ten current model vehicles at the Victorian EPA test station, using five types of LPG conversion. All vehicles were equipped with closed-loop systems for both gasoline and LPG operation. The test results demonstrated that such closed-loop LPG conversions met all EPA emission requirements and, on average, gave emission improvements over gasoline (Borgas 1993).

Fleet average emissions

By collating published data on vehicle emissions from Australia and overseas and applying the emission rates to the composition of the Victorian car fleet, the EPA has derived estimates of average emission rates for 1990, split by fuel type. These figures imply that, compared with gasoline-fuelled cars, LPG cars generate, on average, around half the HC emissions (evaporative plus exhaust), 15 per cent more NO_x emissions, and roughly equivalent CO emissions (Carnovale et al. 1991). LPG vehicles also have substantially lower emissions of the toxic gases butadiene and benzene than gasoline vehicles.

Safety

Explosion and fire risk

LPG explosions occur from time to time. For example a recent report (*Age,* 24 October 1992) recorded an LPG car refuelling malfunction which caused an uncontrollable gas leak. This led, via a nearby flame, to a fire and explosion which injured three people and destroyed two vehicles.

The ALPGA considers that most LPG vehicle explosions have been caused by faulty installation (*BRW* 1992b). Murray (1989) points out that 'backyard' fitters have in fact given way to well trained and industry-accredited installers. This may in time reduce concern about LPG safety. (For example, only 28 per cent of respondents to a survey of the general public reported by West in 1986 disagreed with a proposition that there were safety concerns with LPG).

Storage of large quantities of LPG at service stations and in bulk at depots may cause concern. According to Shell (pers. comm. 1992), LPG storage is based on risk analysis procedures developed under the leadership of the New South Wales Department of Planning. Shell regards the storage system as a controlled and acceptable safety situation.

CONCLUSION

LPG appears to have a greenhouse gas emissions advantage over gasoline at present, although estimates of the advantage vary from 6 per cent (Hollemans & Van der Weide 1991) to 25 per cent (IEA 1992a). Australian cars tested showed variable reductions in CO_2 tailpipe emissions, perhaps averaging about 16 per cent (EPA 1991a). To maintain this greenhouse advantage, improvements in fuel economy of LPG vehicles would need to match those likely to occur in gasoline vehicles.

Comparisons of the levels of noxious gas emissions from LPG and gasoline vehicles are inconclusive. NO_x, CO and HC emissions from LPG vehicles have each been shown to be both higher and lower than those from gasoline vehicles, varying in particular with the equipment incorporated (for example, catalytic converters, type of fuel system), and the state of tune of the vehicle.

Some recent tests suggest that noxious emissions are worse from LPG vehicles. These adverse results have been blamed on the poor quality of conversions, and on the lack of standards for LPG vehicles, on poor servicing and use of too rich a mixture. Other tests have been more favourable to LPG. It appears that there is scope for an overall improvement in both greenhouse and noxious emissions from the use of LPG, provided the necessary control equipment is incorporated in LPG vehicles.

In this respect, emissions standards for LPG vehicles may soon be made as stringent as those for gasoline vehicles, both for new vehicles and for in-service vehicles of any given vintage. Another possibility would be to have a requirement that where a vehicle is fitted with a closed-loop engine management system for gasoline, any LPG conversion should also be a closed-loop system. Additional capital costs of about $200 per vehicle would be involved, although these might be recouped from future fuel savings resulting from a closer to optimum fuel-air mixture.

Should it be considered desirable to expand the use of LPG in transport, supply of LPG would not appear to constitute a problem. Imports are likely to be available if required, though the IEA (1992a) considers prices could be volatile. If a trans-Australia natural gas pipeline were to be built in the future, it might be economically feasible to extract LPG on the east coast. Projections are that such a pipeline may be required between 2009 and 2015, depending on the assumptions made about interstate trade in gas and growth of demand (AGA 1992a).

Limitations on increased use of LPG use are, and are likely to remain, more the result of demand factors. LPG industry opinion is that the market share of LPG is not likely to be substantially greater in future than at present. Moreover, any growth is seen as depending on a continuing subsidy, such as the current excise exemption; the more so since users of LPG vehicles, even with the subsidy, do not always fully exploit the cheaper fuel option, but for convenience or insurance purposes utilise both available tanks.

GOGAS (pers. comm. 1992) expects expanded use of LPG to be limited to about two or three percentage points above the current market share. This would represent an increase of about 50 per cent in automotive LPG consumption. BP (pers. comm. 1992) sees LPG as a niche market fuel only, dependent on its present excise free status for any growth, while AGL holds the view that removal of the advantage given by the current excise regime would 'kill' the LPG (and natural gas vehicle) markets (AGL, pers. comm. 1992).

Without the excise free status for LPG, returns on investment in LPG equipment would not appear to be sufficient to encourage large-scale conversion. The scope for price reduction in the industry does not appear to be significant. Some small margin may be available, for example, due to the difference between export and import parity prices.[7] If environmental taxes were introduced to reflect differences in emissions this could increase the available margin. However, it is unlikely that there would be enough leeway to offset the effects of imposition of the excise, and so maintain the incentive for conversion to LPG use.

In assessing the social cost-effectiveness of LPG use as part of a strategy to reduce emissions, fuel costs (measured at opportunity cost), conversion costs, and any inconvenience costs to the consumer all need to be taken into account. This issue is addressed in chapter 11.

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[7] Import parity prices are domestic prices on a par with import prices.

CHAPTER 4 DIESEL

Diesel fuel, sometimes called automotive diesel oil (ADO), is composed primarily of hydrocarbons derived directly from the distillation of crude oil. It is a 'middle distillate', having a boiling point range above that for 'light distillates' such as gasoline, and lower than that for 'heavy distillates' such as fuel oil. As diesel technology is relatively mature, there are not as many technical issues for consideration in this paper as in the case of the other alternative fuels.

BACKGROUND

Diesel is the major road transport fuel used in heavy duty vehicles (HDVs) in Australia, but only a small percentage of light duty vehicles (LDVs) are diesel-engined. Table 4.1 shows the number of diesel-fuelled vehicles in Australia in 1991, and their relative importance in each vehicle category. Overall, about 6 per cent of vehicles were diesel-fuelled.

The rate of growth in diesel vehicle numbers has been high in recent years, almost 8 per cent per annum between 1988 and 1991. In 1991 some 90 per cent of articulated trucks, 60 per cent of rigid trucks and 60 per cent of buses were diesel-engined (ABS 1991).

The increasing use of diesel HDVs has presumably been due to the ready availability of diesel-engined models and the operating cost advantages of diesel engines in terms of fuel costs, engine life and reliability. Because of these advantages, the trend towards increasing proportions of diesel HDVs might be expected to continue, especially where large annual mileages are performed.

COSTS TO USERS OF DIESEL FUEL AND VEHICLES

Diesel for on-road use is subject to the same level of fuel excise per litre as gasoline, and it is currently marketed at prices slightly below those for gasoline per litre. But because diesel fuel contains more energy than gasoline and the thermal efficiency of the diesel engine is greater, energy produced in diesel vehicles is significantly cheaper to the consumer.

TABLE 4.1 DIESEL VEHICLE NUMBERS

Category	*Number of diesel vehicles 1988*	*Per cent of all vehicles in category*	*Number of diesel vehicles 1991*	*Per cent of all vehicles in category*
Passenger vehicles[a]	48 136	0.7	101 580	1.3
LCVs[b]	150 058	13.8	228 540	15.4
Rigid trucks	210 967	40.5	198 228	59.5
Articulated trucks	42 148	91.0	46 015	90.2
Other truck types[c]	10 993	20.6	8 541	18.0
Buses	25 260	27.1	30 175	59.7
Total diesel vehicles[d]	487 573	5.2	613 079	6.1

Note Growth rates for individual vehicle types cannot be inferred from table 4.1 due to reclassification of vehicle categories between the two censuses.

a. Classified as 'cars and station wagons' in 1988. Passenger vehicles include cars, station wagons, 4WD passenger vehicles and forward control vehicles.
b. Light commercial vehicles, classified as 'utilities and panel vans' in 1988. LCVs include utilities and panel vans, cab chassis and forward control load-carrying vehicles not exceeding 3.5 tonnes gross vehicle mass.
c. Classified as 'non-freight trucks' in 1988.
d. 1988 total includes 11 diesel motorcycles.

Source ABS (1991).

The diesel engine's higher potential thermal efficiency is due to the higher compression ratio possible with a diesel engine. The difference in fuel efficiency between diesel and gasoline engines would be higher still at part-load because the diesel engine operates without throttling (of inlet air to maintain a flammable fuel-air mixture) and consequently has lower pumping energy losses than a gasoline engine. According to the IEA, naturally aspirated diesel engines are 15 to 18 per cent more fuel-efficient than modern four-valve gasoline engines for the same performance. For turbocharged diesels the efficiency advantage is estimated at 24 to 28 per cent, and for direct injection turbocharged diesels, 35 to 40 per cent (IEA 1992a).

A comparison of gasoline and diesel fuel consumption and energy use under actual driving conditions is provided by the OECD Compass project (1986) test on a sample of five European cars (data cited in EPA 1991a). Results showed an average fuel consumption rate for diesel versions in urban areas, in litres per 100 kilometres, 39 per cent less than that for the gasoline versions. In non-urban areas, the diesel vehicles' fuel consumption advantage was much smaller, at only 17 per cent. In terms of energy used, the advantages were smaller because of the higher energy content of diesel fuel. The urban energy consumption of the diesels was 32 per cent lower while non-urban energy consumption was 7 per cent lower.

The lower fuel price of diesel per unit of energy relative to gasoline, and higher thermal efficiency of diesel engines, may only provide acceptable returns on the additional outlay for diesel vehicles where high mileages are performed. Payback periods for purchasers of diesel cars are discussed in chapter 10.

FUEL AVAILABILITY

There has been some controversy as to whether diesel could be supplied in sufficient quantities to permit a significant expansion in its use. IEA projections of diesel fuel prices to the year 2005 suggest that availability of diesel may not be a significant problem (IEA 1992a). The IEA projects real prices of diesel to end users to be only 14 per cent higher in 2005 than in 1990, despite a 56 per cent increase in world diesel consumption in road transport. For comparison, gasoline prices are projected by the IEA to be 18 per cent higher in 2005 than in 1990, although world consumption is projected to be only 8 per cent higher. These estimates are based on a projected oil price of US$29.8 in 2005 (1986 $), 43 per cent above the 1990 price (in 1986 $).

In Australia, current refinery configurations and feedstocks constrain the output of diesel and hence the potential to substitute locally produced diesel for gasoline. The properties of diesel are heavily dependent on the crude oil feedstock used, and careful selection of crudes is required to meet fuel quality standards.

Allowing time for adjustment, however, more diesel could be produced from existing refineries or from new capacity. Shell informed the BTCE that Australia's gasoline-to-diesel (distillate) production ratio had changed from the 2.3 of 20 years ago to a current ratio of 1.7. Refiners' plans accommodate further moves in this ratio. If, however, there were to be a substantial increase in diesel use in LDVs, adjustments beyond those now planned would be needed. The crude oil mix could be changed, the cut points in processing could be altered, and middle distillates could be created from other materials, bringing the ratio down to 1.5 or 1.6. Installation of hydrocracking units could result in a further lowering to about 1.2. Hydrocracking involves high pressures and increased refinery energy use. It would be a high-cost option, and diesel could become more expensive to produce than gasoline (Shell, pers. comm. 1992).

BP (pers. comm. 1992) sees potential for current Australian refineries to produce up to 10 per cent more middle distillates. The BP opinion is that most refineries have the capacity to produce more diesel, but that Australian refineries are based on gasoline production, and processing economics go out of balance in substituting diesel for gasoline — at least at current relative prices. Shell's recent refinery investments would increase diesel availability, and BP considered that Australian diesel supplies in the late 1990s could exceed projected demand.

One option to increase the supply of diesel would be to import more diesel rich crudes. Shell (pers. comm. 1992) considers that this would increase prices.

Importing diesel could be a more cost-effective option, at least to 2000, depending on the effects on diesel prices of any growth in overseas demand. Beyond 2000, there should be no problems with obtaining an increased local supply.

Another possibility is the use of ethanol as a diesel extender. As discussed in chapter 5 on alcohol fuels, an emulsion of 85 per cent diesel and 15 per cent hydrated ethanol — which can be used in unmodified diesel engines — has been produced. With ethanol produced from biomass, there is potential for the cost of this fuel to approximate that of ordinary diesel fuel.

While substitution of CNG for diesel in heavy vehicles could increase the availability of locally produced diesel fuel for use in LDVs, using the natural gas directly in the LDVs may be a preferable option from an overall emissions point of view.

Over time, diesel fuel and emissions standards will require the use of cleaner fuels. The increased demand for lighter crudes, suitable for higher quality diesel fuel, will make them more expensive. This could negate the small retail price advantage per litre which diesel fuel now has in Australia, possibly impairing the market acceptance of diesel-engined vehicles in the LDV sector (chapter 10).

EMISSIONS AND SAFETY

Greenhouse gas emissions

Wilkenfeld (1991) estimated total greenhouse gas emissions from diesel and gasoline in terms of CO_2 equivalents on a FFC basis. Results were 201 grams per kilometre for diesel, and 241 grams per kilometre for gasoline. IEA estimates, which include a factor accounting for the longer average lifetime of a diesel engine, are comparable with Wilkenfeld's results. For LDVs, the IEA (1993) has estimated that new diesel powered vehicles in North America, with fuel efficiencies forecast for the year 2000, would have a life cycle greenhouse emissions advantage of 20 per cent over gasoline equivalents using RFG. The advantage over vehicles using conventional gasoline would be 19 per cent. For OECD Europe, the IEA (1993) has estimated a 23 per cent advantage in both cases.

The IEA notes that because much of the greenhouse advantage of diesel arises from lower emissions of HCs and CO, tighter emission regulations for gasoline powered cars would reduce this advantage significantly. It is unlikely that the advantage would be maintained with tighter constraints on emissions from diesels, as these would result in a more energy-intensive diesel fuel production process and would not therefore permit a reduction in emissions parallelling that for gasoline cars. In terms only of CO_2, the IEA (1992a) estimates only an 8 per cent advantage for diesel (Wilkenfeld derives 7 per cent).

The Victorian EPA (1991a) gives results of tests at Victorian and New South Wales vehicle testing stations of emissions from the Mercedes Benz *300D* (3 litre, 6 cylinder diesel car) and the *230E* (2.3 litre, 4 cylinder gasoline car) under the CVS-CH city driving cycle. (Mercedes Benz considers the *230E* to be the gasoline equivalent of the *300D*.) The emissions of CO_2 per kilometre from the *300D* diesel were 10 per cent less than those from the *230E* using unleaded gasoline.

Greenhouse effects of increased penetration in the car fleet

A hypothetical example can be used to illustrate the extent of greenhouse gas emission reduction which might follow use of diesel in LDVs. Assuming diesels were to amount to 15 per cent of the Australian car fleet in the year 2005 (currently 1 per cent), and that the FFC emission reduction from replacing gasoline cars with diesels is 20 per cent, a reduction of almost 3 per cent might then be expected in greenhouse emissions from the car fleet. Based on ABARE's (1993) forecasts for fuel consumption, this would amount to a greenhouse saving of around 1.3 megatonnes of CO_2 equivalent emissions in 2005, depending on the relative progress in fuel economy and emission improvements for gasoline and diesel vehicles. The effect on emissions would be less if Australian refineries were to resort to the energy-intensive hydrocracking refining process in order to produce more diesel fuel.

Such a scenario would, however, require the addition to the fleet of about 1.4 million diesel cars by 2005 (based on Donaldson, Gillan & Jones 1990). The annual addition would be more than the existing diesel car stock, with perhaps 20 to 25 per cent of new car sales being diesels.

There could be impediments to a significant switch to diesel cars in Australia. These include the possible effects on local manufacturers, the perception by the public of diesels as 'dirty vehicles', and the possible higher refinery costs to cater for imported diesel vehicles requiring low sulphur fuel.

Noxious emissions

The Victorian EPA calculations of fleet average emission rates imply that, at present, diesel cars generate 84 per cent less HC (evaporative and exhaust) emissions, 25 per cent less NO_x emissions and 95 per cent less CO emissions than the average for the gasoline fleet (Carnovale et al. 1991).

The EPA's urban cycle tests on the Mercedes Benz *300D* diesel and its *230E* gasoline car found CO emissions per kilometre to be 47 per cent lower for the diesel car, HC emissions 85 per cent lower, but NO_x emissions 13 per cent higher (EPA 1991a).

IEA (1992a) figures relating to new European cars have diesel vehicles emitting 66 per cent less CO than gasoline cars, 80 per cent less total HCs, similar levels of NO_x and ten times the amount of SO_x.

Emissions of polycyclic aromatic hydrocarbons (PAHs) and particulates from diesels, both of which may have adverse health effects, are higher than those from gasoline engines (Streeton 1990). Diesel engines, however, have very low evaporative HC emissions and low exhaust emissions of the toxics benzene, butadiene and formaldehyde (Carnovale et al. 1991). Carnovale et al. (1991) found emission rates for particulates and SO_x to be 3 and 17 times higher respectively than from gasoline cars.

The urban emissions of NO_x and particulates from currently available diesel models, compared with those from gasoline engines, may, despite other emission advantages, make increased use of diesel in cars of doubtful benefit at present. When these emissions can be contained — either by fuel or vehicle modifications such as the lean NO_x catalytic converters currently under development, or particulate traps — diesel could offer significant overall emissions advantages compared with gasoline. Shell (1993) points out that new engine systems available overseas are more cost-effective in reducing particulates than particulate traps. However, these engines, if imported into Australia, would require low sulphur fuel and hence a more costly reformulation process.

Westerholm et al. (1989) found that a diesel oxidation catalytic converter and a particulate trap fitted to a heavy duty truck reduced emissions of CO by 50 per cent, HCs by 70 to 90 per cent, and particulates by 60 per cent. NO_x emissions were found to be unchanged, as was fuel consumption. Volkswagen has developed a turbocharged diesel engine fitted with an oxidation catalyst, a 'Cat-Diesel', that, compared with a naturally aspirated diesel engine, reduces HC emissions by 74 per cent, CO by 90 per cent, NO_x by 13 per cent and particulate emissions by 44 per cent (Klingenberg 1993).

Australian standards for diesel exhaust emissions have been upgraded with the formulation of a new Australian Design Rule (ADR). The new ADR, announced in September 1993, will supplement the existing ADR 30/00 which limits only visible smoke. The new ADR will control emissions of CO, HCs, NO_x and particulates from diesel or combinations of diesel and alternative fuels from 1995. However, certification will be available to vehicles meeting current US or European standards or the 1993/4 Japanese standard. The ADR will be reviewed in 1995, with the present intention of adopting international 'best practice' standards by the end of the decade (Real 1993).

Reformulated diesel fuel

Cleaner diesel fuel can be achieved through reformulation. Reformulating diesel fuel is in fact a more familiar process than reformulating gasoline (Kordel 1991), and there have been gradual improvements in diesel quality. However, there is now increased pressure for more drastic change to reduce the adverse health consequences of diesel emissions.

Particulate emissions depend on a variety of diesel fuel properties — aromatic content, volatility, sulphur content and fuel density (Sinor Consultants 1993a). Recent research (Lange 1991; Betts, cited in Sinor Consultants 1993a) suggests that fuel density is the dominant factor affecting exhaust particulates. Betts found a reduction of 1.2 per cent (0.01 kilograms per litre) in density reduced particulates by the order of 4 per cent. However, lower density also leads to power loss and higher fuel consumption. For example Lange (1991) found that reducing fuel density by 10 per cent (from 0.88 to 0.8 kilograms per litre) reduced the power output and the particulate emissions from a diesel engine by around 11 per cent and 22 per cent respectively. Reducing density by exclusion of the heavier components from diesel fuel would require more intensive fuel conversion, especially hydrocracked components for the diesel fuel pool (Hutcheson & van Paassen 1990).

In Europe the main pressure for improvement in diesel quality is for a reduction in sulphur content. In the USA the 1990 amendments to the US Clean Air Act require that the maximum sulphur content of diesel fuel be gradually reduced to a level of 0.05 per cent by weight (IEA 1992a). The current US and European desulphurisation of diesel results in a sulphur content around 0.2 to 0.3 per cent. In comparison, the sulphur content of Australian diesel fuel is typically around 0.1 per cent and the maximum allowed by Australian standards is 0.5 per cent (Martin 1990).

Hutcheson and van Paassen (1990) have estimated the approximate manufacturing costs for the USA of reducing the sulphur content of diesel fuel to 0.05 per cent by weight at around US$3 billion, or around 1.4 US cents per litre.

Opinions differ as to the choice between reformulation of diesel and the use of control equipment as the better way to reduce emissions. While the available control equipment can achieve much larger reductions, in the short term, reformulation has the advantage of being able to influence the total diesel-fuelled fleet, as opposed to new vehicles only. The Chevron Corporation has developed a reformulated diesel capable of meeting the 1994 US emission standards; in particular, the NO_x, particulate, HC and CO benchmarks (Sinor Consultants 1992e). The reformulation would also meet the 1993 CARB standards.

The effect of adding oxygenates to diesel fuel (for example diesohol, an emulsion of diesel with 15 per cent ethanol) is discussed in chapter 5 on alcohol fuels and briefly in chapter 2.

Future requirements for additional emission control equipment

The head of the Cummins engine manufacturing company has recently stated that major engine producers would be able to meet the 1994 US exhaust emission standards for diesels without having to resort to heavy and expensive catalytic converters or particulate traps (Denniss 1992).[1]

If, however, additional emission control equipment for diesel engines were to be required to meet the 1994 standards, the extra costs involved would affect the market penetration of diesels, especially in LDVs. Kulkarn (1992) has estimated the cost of production of a diesel oxidation catalytic converter for diesels at less than US$1000. Lean NO_x catalytic converters may be more expensive, and particulate traps, which can have efficiencies of up to 95 per cent, could cost upwards of US$2000. Also, the operating life of catalytic converters for vehicles using fuel containing significant amounts of sulphur is open to question, as sulphur in the fuel may poison the catalyst. While Australian crudes are low in sulphur, imported crudes or imported diesel fuel could contain significant amounts.

These control equipment costs, and the costs of producing cleaner diesel fuel, along with some consumer reluctance to accept diesel vehicles, may render diesel cars insufficiently financially attractive to ensure any significant market penetration, unless fuel price differentials between gasoline and diesel are much greater than at present.

Safety

Some particulate emissions from diesels may be carcinogenic (EPA 1991a) or mutagenic. The health effects of PAHs from diesels are as yet unclear (EPA 1991a). PAHs may be involved in photochemical reactions to form very reactive and carcinogenic compounds such as amines (Streeton 1990).

CONCLUSION

Diesel has emissions advantages compared with gasoline. It generates less greenhouse gas emissions and lower levels of most noxious gases. However, particulate emissions are higher. There appears to be potential to expand its use, especially in the LDV segment of the transport fuel market. In the HDV sector the trend is strongly towards diesels in any case, although a growing proportion of the switch away from gasoline is likely to be towards natural gas, provided the exemption of natural gas from Commonwealth excise continues. A switch from diesel to alternatives such as CNG in the HDV sector is also possible.

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[1] These standards for 1994 specify a rate of particulate emissions of 0.1 grams per brake horsepower per hour for trucks and 0.05 for buses, compared with the 1990 standard of 0.6 grams per brake horsepower per hour. NO_x emissions must fall from the 1990 level of 6.0 grams per brake horsepower per hour to 5.0 for trucks and buses by 1994, and to 4.0 for trucks by 1998. CO and HC emission standards are to be unchanged from 1990 to 1994 for buses, and from 1990 to 1998 for trucks.

The indications are that diesel fuel availability would not be a major problem were increased use in LDVs desired for global (greenhouse) environmental reasons. There is scope for increased output from Australian refineries, although imports of diesel fuel might have to be relied on to an increasing extent. In both cases increased costs are likely over time, with consequent effects on diesel's current cost advantage.

There are health considerations involving particulate emissions, primarily from diesels in urban areas. Reductions in particulate emission rates to around the 1994 US truck standards would appear to be required if diesel engines in cars were to be widely adopted for global environmental reasons. To reduce total particulate emissions from transport, given a widespread adoption of diesel engines in cars, emission rates lower than 1994 US standards would be required.

Additional costs of engine and fuel modifications to reduce particulates, or particulate traps, would reduce the market acceptance of diesel cars, as there is currently only a small price differential between gasoline and diesel fuel. The market acceptance of diesel LDVs, especially cars, is likely to be limited to some extent by perceptions of inferior vehicle performance (considering factors such as acceleration, noise, odour and smoothness), unless actively supported by government policy.

The factors influencing market acceptance of diesel cars are discussed in detail in chapter 10, and the social cost of reducing emissions through the use of diesel-engined vehicles in the LDV market is discussed in chapter 11.

CHAPTER 5 ALCOHOL FUELS: ETHANOL AND METHANOL

BACKGROUND

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

Proposals for using ethanol and methanol as transport fuels have ranged from using pure alcohol (E100 or M100[1]) to using blends of between 3 and 95 per cent alcohol with gasoline or diesel, often with co-solvents or emulsifiers to assist the blending process. Vehicle trials using pure alcohol or various blends are in progress in many countries, and use of alcohol fuels in fleets is also being tested in a number of countries.

Gasoline fuels containing alcohol are already in use in North America, Brazil and South Africa. 'Gasohol' blends accounted for 8 per cent of US gasoline sales in 1991 (IEA 1993).

Two-thirds of the spark ignition engines in South Africa are run on gasoline containing 8 per cent ethanol and 2 per cent higher alcohols. The South African ethanol and higher alcohols are derived from the South African coal-to-oil process (Clark & Dutkiewicz 1991). Pure ethanol has also been used as the fuel for a single engine light aircraft flight across the Atlantic (Shauck & Zanin 1991).

In Australia, both the use and trial of ethanol as a component of gasoline transport fuel have, until recently, occurred primarily in Queensland. All gasoline sold in Queensland from 1929 to 1957 contained 10 per cent ethanol (NSW Department of Minerals and Energy [NSWDME] 1990). It would appear that all the major Queensland trials since then have been conducted in the Mackay district and have used ethanol derived from sugarcane. Gasoline containing 10 per cent ethanol has recently begun to be distributed through a small number of

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[1] Ex (Mx) indicates a blended ethanol (methanol) fuel with x per cent ethanol (methanol).

independent fuel retailers in NSW and Victoria. This ethanol is produced from wheat starch at Nowra on the south coast of NSW.

In contrast to the use of ethanol and methanol as gasoline substitutes, substitution of these fuels for diesel is at an early stage of development (NSWDME 1990). Alcohols can be used in diesel engines by either modifying the fuel or by extensive engine adaptations (IEA 1990). Demonstration fleets of buses and trucks are being field tested in Canada, Germany, Japan, Sweden, New Zealand and the USA (IEA 1990).

Recent work in Australia by APACE Research Ltd has produced an ethanol and diesel emulsion called 'diesohol'. APACE claims that a diesohol emulsion containing up to 30 per cent ethanol will run in a diesel engine, with the engine requiring little or no modification. An unmodified heavy-duty diesel truck running on diesohol containing 15 per cent ethanol attained the lowest 'greenhouse gas index' in the Australian 1992 Energy Challenge sponsored by the New South Wales Office of Energy. The ACTION bus fleet in Canberra has recently commenced a trial with three new buses running on diesohol.

The use of ethanol and methanol in ETBE and MTBE as fuel additives is addressed in chapter 2 on reformulated gasoline.

CHARACTERISTICS OF ALCOHOL FUELS

Ethanol and methanol are alcohols. They are hydrocarbon compounds where a hydrogen atom has been replaced by a hydroxyl (OH) radical. Ethanol (C_2H_5OH) is the intoxicating component of alcoholic beverages, and is also used as a solvent in methylated spirits. Methanol (CH_3OH), sometimes called wood alcohol, is used as a component (5 to 10 per cent) of methylated spirits.

In contrast, gasoline and diesel are mixtures of a range of hydrocarbon compounds, none of which contains oxygen. Methanol contains 50 per cent oxygen by weight and ethanol 35 per cent. In blended fuels, the addition of the oxygen contained in the alcohol to gasoline or diesel changes a number of important fuel characteristics. These include changes in combustion properties, energy content and vaporisation potential.

The energy contained in one litre of methanol (about 16 megajoules) is less than that in ethanol (23 megajoules), which in turn contains less than gasoline (34 megajoules). Ethanol and methanol have similar research octane numbers, in the range 105 to 120, higher than that for premium unleaded gasoline (95 RON). This characteristic allows an engine designed for alcohol fuels to use a higher compression ratio for higher potential energy efficiency.

Problems can arise in the use of blended fuels and in fuel distribution systems due to the different solubility properties of alcohol fuels and gasoline. Both ethanol and methanol are completely soluble in water while gasoline is almost entirely insoluble. Ethanol and methanol are soluble in gasoline, but once the water content of the ethanol or methanol increases to more than a few per cent, phase separation will occur in the alcohol–gasoline blend.

PRODUCTION AND DISTRIBUTION

Ethanol production

Ethanol (C_2H_5OH) can be manufactured from:

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

Research in progress aims to produce ethylene from methane (CH_4) via a catalytic oxidative process (EPA 1990).

Ethanol from sugar and starch fractions

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

Ethanol has traditionally been produced in Australia from molasses, a by-product of the sugarcane industry. There are now three distilleries operating at Sarina (CSR), Rocky Point and Bundaberg in Queensland with an approximate annual output of 58 000 kilolitres from 200 000 tonnes of molasses (CSR, pers. comm. 1993). (Formerly around 100 000 kilolitres per annum had been produced from 350 000 tonnes of molasses [CSR 1980]). Ethanol production from wheat has recently commenced at Manildra's gluten and starch plant at Nowra. The major products of the mill are gluten and starch. The ethanol produced from the waste starch stream with further supplementations of starch is essentially a by-product of the gluten manufacturing process.

Ethanol from lignocellulose fractions

Lignocellulose is the structural component of plant biomass and can be derived from trees, grasses, and from cereal and paper wastes (EPA 1990; Wyman 1991). Lignocellulose is also a large component of municipal waste. Both the cellulose and hemicellulose portions of the material (which in the case of plants may comprise 65 to 80 per cent of the non-sugar and starch components) can be converted into ethanol. The proportion of cellulose and hemicellulose from various lignocellulose sources is dependent upon the specific biomass crop.

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

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

Supply of biomass feedstock in Australia

Stewart (1990) considered the major potential sources of biomass from the lignocellulosic fraction of crops (cereal straw, sugarcane bagasse, sugarcane field trash, forest residues and energy plantations) to be capable of supplying 235 PJ per year. This is equivalent to almost 30 per cent of 1991–92 Australian road transport energy usage. Stewart's estimate takes account of the effects on sustainability of cropping should the total available above ground biomass be collected, and also the feasibility and costs of harvesting crop and forest residues.

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

Recent studies discussed by the IEA (1993) suggest that, because of competing land use, no more than 15 per cent of US transport fuel demand could be met by wood-based methanol. Crop residues, for example corn stover, are not included in deriving this estimate, as it is suggested these would be better used for fertiliser. Estimates of biomass availability in the European Community lead to comparable results for Europe.

Ethanol production which relies on crops with short cropping seasons and subject to the vagaries of weather could fluctuate on a seasonal and annual basis. Where alternative biomass supplies are not available, storage capacity for either the crop or the produced ethanol may be necessary to ensure continuity of supply. Some crops, such as artichokes, may be stored in the field with a small loss of yield (Lowe et al. 1991). However, such storage mechanisms would not permit the planting of follow-on crops.

Appendix III contains details of ethanol and methanol production technology and supply constraints, and of the environmental consequences of both crop and fuel production processes.

Methanol production

Australia has no methanol plants at present.

Methanol (CH_3OH) can be produced from methane (CH_4) by an initial conversion to synthesis gas (a mixture of hydrogen and carbon monoxide). The ratio of hydrogen to carbon monoxide in the synthesis gas is adjusted, with methanol then formed from a reaction of the resultant mixture aided by a co-precipitated copper – zinc oxide catalyst (Bharucha 1991).

Natural gas is composed of 88 to 95 per cent methane (Dixon 1990). Current conversion technology achieves approximately a 70 per cent conversion efficiency of methane to methanol (Anker-Johnson & Schwochert 1990). New gas reforming technologies are claimed to have the potential to improve this conversion efficiency to 85 to 95 per cent (White 1990). Another potential source of methane suitable for conversion into methanol is coal seam gas (NSWDME 1990).

Methanol can also be produced by gasification of coal to produce synthesis gas (NSWDME 1990), and several procedures can be used to obtain methanol from wood or lignocellulose. These include destructive distillation, conventional steam-oxygen gasification, and high temperature pyrolysis. Another possibility involves coprocessing biomass with fossil fuel using the prospective *Hydrocarb* process (Steinberg 1990).

In the absence of any direct policy initiative to encourage production by other means for emission reduction purposes, any major production of methanol in Australia is most likely to be sourced from natural gas. This method has the lowest *demonstrated* production costs. The Broken Hill Proprietary Company Ltd (BHP) plans to construct a pilot methanol production plant using natural gas as the feedstock and utilising the ICI *Leading Concept Methanol process.* Should the pilot plant meet the company's expectations, a world scale methanol plant may be constructed.

World scale plants produce 2500 tonnes of methanol per day, about 0.83 megatonnes per year. Australia's current gasoline usage (approximately 17 gigalitres per annum) is equivalent to 28.5 megatonnes per annum of methanol. One such plant would therefore permit a replacement of just under 3 per cent of current gasoline usage. If optimised methanol engines were used in vehicles, 15 per cent less methanol would be required to replace any given level of gasoline use.

While reserves of natural gas in Australia are abundant, their use for methanol production would need to compete with demands for use of the gas directly as a transport fuel or for other energy or chemical production. Gas availability for production of methanol is therefore somewhat uncertain. With current demand, and pooling of resources in the Gippsland, Cooper and Amadeus Basins, depletion of these sources would occur by the year 2010 (Dixon 1990). New reserves may be discovered in these areas; however, without them, widespread use of natural gas would mean that the major supply would, before 2010, either have to come from the North-West Shelf field at higher cost, or from coal bed methane should that prove to be more economic.

Ethanol distribution

Difficulties with the distribution of neat ethanol or ethanol blends arise primarily from the solvency effects of ethanol and from ethanol's affinity for water. Ethanol is capable of dissolving substances accumulated in pipelines, storage tanks and other components of the distribution system, thus introducing impurities into the fuel (NSWDME 1990). These substances are insoluble in gasoline. Ethanol's affinity for water can result in phase separation of blended alcohol/gasoline fuels, resulting in engine damage or poor vehicle performance (NSWDME 1990). Phase separation is a function of water content, ethanol content, temperature and properties of the gasoline (NSWDME 1990).

As discussed in chapter 2, the Australian gasoline production and supply system is a relatively 'wet' system; and use of the existing distribution system for alcohol fuels could result in contamination by water throughout the entire process (NSWDME 1990). BP (pers. comm. 1992) claimed that it would be necessary to change to a more 'dry' system, at some considerable and as yet unspecified cost, before fuels containing oxygen (oxygenated fuels) could be used in Australia.

In contrast, most US distribution is inland, with greater use of 'dry' pipelines and systems facilitating the handling of oxygenated fuels. In the USA, ethanol is mostly produced in mid-west farm states, by around 50 commercial scale plants. It is shipped by rail car or truck, rather than by pipeline (the least expensive mode), because of the solvency effect problems identified above (EPA 1990). Blending occurs in the tanker truck at the distribution terminal prior to distribution to service stations (NSWDME 1990).

Since the energy content of ethanol is only two-thirds of that of gasoline, relatively more ethanol would need to be transported for the same energy supply (EPA 1990). How much extra transport infrastructure, in the form of storage and tanker trucks, and how many extra personnel this would entail would depend on the blends used, and on whether vehicles optimised to use the higher octane rating of ethanol were available and in general use.

Methanol distribution

Problems with the distribution of methanol are similar to those with ethanol because methanol is also water soluble and corrosive to some materials currently used in distribution systems (OTA 1990). According to OTA (1990), the current infrastructure of pipelines, storage tanks and road tankers in the USA may be incompatible with use of methanol and require extensive duplication or modification of existing equipment.

With half the energy content of gasoline, even more infrastructure than that required for ethanol would be needed to move an amount of methanol equivalent in energy terms to a given amount of gasoline.

COSTS TO USERS OF ALCOHOL FUEL AND VEHICLES

Fuel production costs

Ethanol

Ethanol from sugar and starch crops
The NSWDME (1990) study refers to estimated production costs of ethanol from sugarcane in the range 60 to 75 cents per litre (88 to 110 cents for the energy equivalent of a litre of gasoline [LGE]), and ethanol from sorghum in the range 55 to 70 cents per litre (80 to 102 cents per LGE). The actual costs in that study were influenced by feedstock cost, process technology, finance costs, plant location and configuration. Ethanol production costs based on the conversion of existing sugar mills quoted from a 1986 Energy Authority of NSW study amount to $1.08 per litre (NSWDME 1990) or $1.58 per LGE.

The cost of ethanol production from cassava in 1985 was considered too high to justify further development (Nguyen and Prince 1991). Estimates given by Nguyen and Prince (1991) of ex-factory production of ethanol from sweet sorghum range from 41 to 55 cents per litre with large scale production (60 to 80 cents per LGE); while technological improvements were estimated to offer a potential production cost as low as 28 cents per litre (41 cents per LGE). The production cost of ethanol from starch at Manildra's Nowra plant has been estimated at around 63 cents per litre (92 cents per LGE).

Recent estimates for the cost of ethanol produced from corn, based on IEA (1993, 99) are 36 to 56 (1987) Australian cents per litre (1987 US$ converted at 70 US cents per A$). This equates to 53 to 82 cents per LGE. Sinor Consultants (1993b) estimate the cost of corn ethanol at 47 (1992) Australian cents per litre, (at 70 US cents per A$), or 69 cents per LGE.

Ethanol from lignocellulose
As technology to convert cellulosic feedstocks to ethanol matures, a far wider range of materials — including cereal crop residues, sugarcane bagasse, and forest and sawmill residues — will become feasible feedstocks for ethanol production. The viability of using residues will be influenced by the amount of

residue produced and the costs of collection of the residue and transport to the ethanol production plant. Cost estimates for ethanol from lignocellulose depend on the method of production.

For the lignocellulose processes, the returns obtained from selling by-products arising from the production process can also be incorporated in the production cost estimates. Using a lignocellulose process still only at the laboratory stage, and assuming full by-product credits, Rogers (1990) estimated that ethanol could be produced for between 35 and 40 cents per litre (51 to 58 cents per LGE). US researchers have quoted potential ethanol prices as low as 16 US cents per litre (Australian LGE price of 33 cents per litre at 70 US cents per A$) from yet to be commercialised lignocellulose technologies (Lynd et al.1991).

APACE considers that the potential exists for production of ethanol in the range of 14 to 24 cents per litre (20 to 35 cents per LGE) using acid or enzymatic hydrolysis of lignocellulose (APACE 1992). Further reductions in the cost of ethanol production in the enzymatic hydrolysis procedure may arise from the genetic manipulation of organisms which may increase enzyme output and activity (APACE 1992). Wyman (1991) considers that further reductions in the cost of ethanol production will come from improving ethanol yield with lower enzyme costs, reducing the fermentation time and improving the pre-treatment step and yields.

Estimates based on IEA (1993, 99) for the cost of ethanol from wood lie in the range A$0.27 to A$1.29 (1987 $) per litre, (1987 US$ at 70 US cents per A$). This would be 39 cents to $1.88 per LGE.

Methanol

The cost of producing methanol will vary with a range of factors, particularly plant location, plant technology and feedstock costs. The raw materials available will influence the type of plant constructed, which in turn influences capital and operating costs. Raw material, transport, and capital and operating costs will all vary with location. Some indication of the extent to which plant location can influence investment and operating costs of a methanol plant can be gained from a Bechtel study cited in Fahy (1990). A methanol plant consisting of four 2500-tonne-per-day plant trains using natural gas at Port Arthur in Texas was estimated to have an investment cost of US$883 million (1988) and an operating cost (excluding gas costs) of 1.5 US cents per litre, compared with an identical plant located at Dampier (North-West Australia) where the investment cost was estimated at US$1537 million and the operating cost at 2.4 US cents per litre.

Methanol from natural gas

The NSWDME (1990) report contains estimates of costs for methanol produced from pipeline gas. The estimates range from $144 to $245 per tonne, and are based on production in a 2500-tonne-per-day (world scale) plant located at either Sydney, Wollongong or Newcastle. Methanol imported from Dampier using North-West Shelf gas is costed at $187 to $248 per tonne delivered to Port Botany. The range in costs given in the NSWDME study is influenced by the likely price range for gas and whether the plant incorporates new technologies, such as the ICI *Leading Concept Methanol process.* The range in methanol production prices ($144 to $248) equates to 12 to 20 cents per litre, or 25 to 42 cents per LGE.

Estimates for the cost of methanol from natural gas, based on IEA (1993, 99), fall in the range 13 to 27 (1987) Australian cents per litre (1987 US$ at 70 Australian cents per US$), or 27 to 56 cents per LGE.

Methanol from coal-seam gas or coal

The NSWDME (1990) report also identified methane resources of 5400 PJ in the southern NSW coal field. These resources were estimated to be adequate to supply a 2500-tonne-per-day methanol plant for 15 years. The methanol was estimated to cost $144 to $200 per tonne at 1990 prices. The technology for extracting gas from the coal requires further development and demonstration but would seem to be a competitive option for the future (NSWDME 1990). There is currently only one commercial coal-seam gas plant operating and this is in the USA. BHP has a pilot plant in Queensland based on the US technology. Coal seam gas reserves in other NSW coal fields and in Queensland are considered extensive.

The production of methanol from coal using current technology is severely greenhouse-detrimental, and involves higher costs than conversion of either natural or coal-seam gas. Manufacture of methanol at a Newcastle (NSW) location capable of producing 2500 tonnes per day using low ash steaming coal was estimated to cost $433 per tonne (NSWDME 1990). Coal-based methanol production plants have higher capital costs than plants using natural gas, and can cost from two to two and a half times as much (Fahy 1990).

Methanol from biomass

Research into producing methanol from biomass appears to be primarily confined to work sponsored by the US Department of Energy and implemented by the US National Renewable Energy Laboratory (NREL) and the Pacific Centre for High Technology Research. This program has a methanol production cost goal of 12.2 cents (47 US cents per gallon: 1990 $) per litre for a 10 000-tonne-per-day plant (Overend 1991). Methanol from biomass would currently cost 20 cents (75 US cents per gallon: 1991 $) per litre to produce (SERI 1991).

The IEA (1993, 99) estimates of the cost of methanol from wood indicate a range of 26 to 52 (1987) Australian cents per litre (1987 US$ at 70 Australian cents per US$), or 53 to 109 cents per LGE.

Imported methanol

Australian production costs would have to be lower than world market CIF prices for production in Australia to be an attractive economic proposition. Methanol imported from overseas has been assessed at costing from $180 to $220 per tonne (NSWDME 1990).

World methanol prices can vary considerably. In July 1992 the CIF methanol price into Europe was US$95 per tonne, but ranged from US$95 to $260 over the two years July 1990 to July 1992. Vidalin (1991), in Sinor Consultants (1992a, 96–8), suggests that the shortfall in methanol production in the USA could be 4.7 million tonnes by 1995. Methanol in the USA will be used mainly to meet projected production of MTBE, possibly accounting for 55 per cent of all methanol produced. This projected shortage of methanol is based upon the assumption that there will be no major market for methanol itself (M85 or M100) as a fuel. If the projected increase in methanol consumption in the USA is matched in Europe, international prices for methanol could end up at the high end of the price range quoted above until further methanol production capacity comes on line. The time taken to construct a functioning world scale methanol plant ranges from two and a half to three years (Fahy 1990).

Fuel distribution costs

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

The ex-refinery cost of gasoline is around 23 cents per litre, while the retail prices net of tax range from 32 to 40 cents per litre, indicating distribution, storage and retailer's costs within the range of 9 to 17 cents per litre. On the basis of a proportionate increase per unit volume, the distribution and storage cost element for methanol, for an equivalent amount of energy supplied, would be double that for gasoline; while ethanol distribution and storage costs would increase by around 50 per cent.

Vehicle costs

Additional costs to the consumer arising from the changes to vehicle design necessitated by the adoption of alcohol fuels will be determined in part by the fuel to be used and the volume of vehicle production and sales. With a gasoline blend containing 10 per cent ethanol, most new vehicles should not experience any problems. Any problems which do arise are likely to be make and model specific and will probably relate to an incompatibility of fuel system components with the blended fuel. Most consumers driving new vehicles with an E10 blend should not therefore incur any additional costs. For drivers of older vehicles, possible fuel system clogging, corrosion and other fuel incompatibility problems may result in additional costs.

The likelihood of additional costs arising from the incorporation of ethanol into diesel as diesohol can probably be considered to be similar to that from using E10 in gasoline vehicles. Methanol is not likely to be used as a low-level blending component, except as MTBE. If it were, more severe compatibility problems would arise than in the case of ethanol, with associated cost increases.

Magasanik et al. (1990) estimated increased production costs for methanol-fuelled vehicles of between A$500 and A$2000. In Brazil, ethanol vehicles were estimated to cost $500 more than equivalent gasoline vehicles (Homewood 1993). In the USA, Singh (1989) suggested the price increment required for mass-produced flexible fuel vehicles (FFVs) would be from US$210 to US$340, excluding the costs of improved catalysts that may be required for aldehyde reductions.

Current US production line FFVs from Ford and Chrysler are being retailed for the same price as the conventional vehicle equivalents (Sinor Consultants, 1992d, 87–8). However, Sinor Consultants (1992c, 81) report that American vehicle manufacturers have asked for financial assistance to introduce methanol vehicles, at least during low volume sales periods. General Motors has recently received support of up to US$2000 per vehicle (Chevrolet *Lumina*) from the California Energy Commission and two local air quality management districts.

EMISSIONS AND SAFETY

Greenhouse gas emissions

The ability of either methanol or ethanol to contribute to a reduction in greenhouse gas emissions on a FFC basis is very much influenced by the nature of the feedstock (tables 5.1 and 5.2) and by the source of power used for the production process. CO_2 emissions from the combustion process alone are fairly similar for alcohol fuels and gasoline on an energy equivalent basis, assuming complete combustion.[2]

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[2] Emissions of CO_2 from methanol are 61.2 grams per MJ, from ethanol 64.4 grams per MJ, and from gasoline 66 grams per MJ. Emissions of CO_2 from the combustion of one litre of fuel are 1.1 kilograms for methanol, 1.5 kilograms for ethanol, and 2.3 kilograms for gasoline.

TABLE 5.1 GREENHOUSE GAS EMISSIONS FOR LDVS AND HDVS USING ETHANOL AND METHANOL RELATIVE TO RFG AND DIESEL FUELS

(Percentage change in life cycle emissions[a])

	Present[b]		*Future*[c]	
Fuel type and source	*LDV*	*HDV*	*LDV*	*HDV*
Ethanol, wood[d]	–72.6	–71.3	–73.1	–71.6
Ethanol, corn with coal for processing	31.8	68.0	19.9	53.5
Methanol, natural gas	–2.8	15.5	–11.4	11.0
Methanol, coal	58.7	96.3	na	na
Methanol, wood[d]	–18.4	2.1	–60.0	–54.2

LDV	Light duty vehicle, gasoline (RFG) fuel
HDV	Heavy duty vehicle, diesel fuel
RFG	Reformulated gasoline (see chapter 2)
na	Data not given

a. FFC emissions plus emissions from vehicle manufacture, measured in grams per kilometre CO_2 equivalent, time horizon of 100 years.
b. Present refers to current technology vehicles.
c. Future refers to high efficiency vehicles optimised for alcohol fuel.
d. The assumptions underlying the use of 'wood', in terms of nature of vegetation replaced are not stated.

Source OECD (1991).

Ethanol

With ethanol derived from biomass, carbon dioxide emitted during combustion of the fuel is offset by that absorbed by the plant from the atmosphere during growth. However, greenhouse debits arise in the path from crop to ethanol consumption in vehicles. The use of agricultural chemicals, fuelling of farm machinery, transport of the crop, processing of the crop, drying of liquid wastes and transport of ethanol may all involve the use of fossil fuels and hence emissions of CO_2 (Colley et al. 1991). Denitrification of fertilisers applied to the crop is also a major problem (OECD 1991).

These greenhouse debits appear difficult to quantify and depend on the crop grown, the source of fuel used to process the crop and any additional release of greenhouse gases from the soil above natural levels. More importantly, perhaps, land proposed for special energy crops is unlikely to be entirely devoid of vegetation. Thus any new crop could replace existing plant biomass with a positive net CO_2 absorptive capacity, resulting in lower net greenhouse gas emission benefits.

Watson (1991) adopts a figure of 50 per cent for the greenhouse debits for ethanol from biomass (presumably the lignocellulosic fraction) and quotes a range of 41 to 79 per cent used by the US EPA and the oil industry. On this basis, he argues that if all new vehicles introduced into the Australian market from the year 1995 used E15, the greenhouse gas reductions from the total fleet in the year 2015 would be 2.5 per cent.

With ethanol produced from 'wood', the IEA estimate is that FFC greenhouse gas emissions will be 68 per cent (North America) to 78 per cent (Europe) less than from gasoline (IEA 1993).

As regards ethanol from corn, however, the IEA (1992a) has estimated that 32 per cent of the FFC greenhouse gas emissions arise from energy used in fertilizer manufacture and use. A further 45 per cent is attributed to the fuel production stage. IEA (1993) states that 84 per cent of life cycle greenhouse emissions from corn ethanol is due to fuel supply, 10 per cent to vehicle manufacture and 6 per cent to vehicle operation. This estimate relates to North American vehicles and fuel conversion systems, and assumes that CO_2

TABLE 5.2 FULL FUEL CYCLE GREENHOUSE GAS EMISSIONS, BY INDIVIDUAL GASES, FOR A 100-YEAR TIME SPAN

(Emissions from each fuel in grams per kilometre in CO_2 equivalents)

Fuel cycle, and gas emitted	*Reformulated gasoline*	*Methanol from:*		*Ethanol from:*	
		Natural gas	*Wood*	*Corn*	*Wood*
LDV					
CH_4	0.6	0.3	0.3	0.3	0.3
N_2O	10.8	10.8	10.8	10.8	10.8
NMOC	5.2	2.0	2.1	1.9	1.9
CO	11.4	13.4	13.4	13.4	13.4
NO_x	11.2	11.2	11.2	11.2	11.2
CO_2	168.1	134.6	–5.9	–5.9	–5.9
Total	207.3	172.3	31.9	31.7	31.7
Fuel processing					
CH_4	3.3	5.4	2.9	11.4	0.6
N_2O	1.9	1.2	4.4	60.4	5.2
NMOC	0.8	0.5	0.8	1.2	1.1
CO	0.4	0.3	1.3	–0.5	2.0
NO_x	8.6	18.1	16.3	36.3	16.0
CO_2	83.0	103.4	69.6	225.0	24.8
Total	98.0	128.9	95.3	333.8	49.7
Overall total	305.3	301.2	127.2	365.5	81.4

NMOC Non-methane organic compound

Note The assumptions underlying the use of 'wood', in terms of the nature of the vegetation replaced, are not stated.

Source M. DeLuchi, in Sinor Consultants (1992c, 13).

emissions from use of the ethanol itself are zero, being balanced by absorption during the growth phase. This assumption is unlikely to be sustainable for significant amounts of ethanol production, when displacement of other crops could be expected.

The IEA estimates of FFC greenhouse gas emissions from ethanol from corn range from 12 per cent above those from gasoline (for new, year 2005 North American vehicles) (IEA 1992a), to the equivalent of gasoline emissions (for new, year 2000 North American vehicles)(IEA 1993). For the OECD Europe vehicle market, the IEA (1993) estimates that greenhouse advantages of the order of 10 per cent relative to gasoline are possible from corn ethanol by the year 2000.

Studies by Taschner (1991) and Colley et al. (1991) have shown that use of ethanol produced from crops such as cereals, sugar-beet, artichokes or potatoes grown in Europe results in an increase in FFC greenhouse emissions compared with those from gasoline.

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

The lignocellulose process under development by the UNSW and APACE, and other teams overseas has the potential to improve the efficiency of ethanol production and therefore reduce costs and greenhouse gas emissions. APACE has suggested that lignin by-products could be used as a solid fuel substitute for coal — this would also contribute to lower greenhouse gas emissions from fossil fuel. The calorific value of the lignin is around 63 per cent of that of coal (APACE 1992).

The production of ethanol from the lignocellulose fractions of solid municipal waste, as planned in Florida (Sinor Consultants 1992c, 91), is likely to have substantial greenhouse gas emission benefits. These wastes would otherwise be decomposed over time by microbial action into carbon dioxide and methane and ultimately returned to the atmosphere.

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

Appendix IV contains information on the technological aspects of the use of ethanol in vehicles.

Methanol

Methanol produced from coal results in an increase in greenhouse gas emissions compared with gasoline, and will not be considered further in this chapter.

The proposed *Hydrocarb* process for producing methanol from biomass (with solid carbon as a by-product), using natural gas or other fossil fuels, may either be CO_2-neutral or liberate less CO_2 than is actually fixed by the biomass during its growth (Steinberg 1990). Smith and Kelly (1990) suggest such a process may be expensive, inefficient in its use of fossil fuel and currently far from practical realisation, but nevertheless may warrant technical and economic evaluation.

Methanol produced from lignocellulose via conventional steam-oxygen gasification of wood is currently the only available methanol production process which would lead to significant full fuel cycle greenhouse gas reductions when replacing gasoline or diesel.

Methanol derived from natural gas is likely to be the most economic of production options, but estimates of the greenhouse emission reduction benefits vary from around 1 to 11 per cent compared with gasoline (tables 5.1 and 5.2). Mandatory use of say, M85, from natural gas in all new cars might therefore be expected to yield greenhouse emission reductions of this order after some 15 years, depending upon the rate of introduction of vehicles optimised to take advantage of the higher octane rating of methanol and the turnover of the vehicle fleet. More substantial emission reductions would require the methanol to be produced from lignocellulose. Watson appears to suggest a 7 per cent reduction from cars by the year 2015, after mandating M85 in all new cars from the year 2000 (Watson 1991).

The IEA (1993) in its most recent analysis has only considered neat (M100) alcohols used in spark ignition engines. The IEA assumed methanol to be produced from wood and natural gas, and results have been expressed as the per cent difference from gasoline emissions from new cars for the year 2000. The IEA estimates that life cycle greenhouse gas emissions from methanol produced from wood would be 68 per cent lower than those from new gasoline cars. Methanol produced from natural gas is claimed to have life cycle greenhouse gas emissions between 4 and 7 per cent lower than those from new gasoline cars.

The introduction of methanol as a truck fuel awaits the vehicle developments undergoing trials in North America, Japan and Europe (Watson 1991). Some information on these is presented in appendix IV. However, with any methanol produced in Australia likely to be sourced from natural gas, the substitution of methanol for diesel would have adverse net greenhouse gas emission results.

Noxious emissions: ethanol and methanol

Motor vehicle emissions which give cause for concern in the urban environment arise both from the vehicle's tailpipe (exhaust) and from the fuel system (evaporative).

No clear picture emerges from the available material on tailpipe and evaporative emissions from ethanol and methanol. Some noxious emissions are lower and some are higher. Also, the results appear to vary with the vehicle model and the presence or absence of catalytic converters or other emission control devices, as well as the fuel characteristics and ambient temperature.[3] On balance the results are not unfavourable compared with those for gasoline or diesel. (Test results are not available for alcohol fuels in light duty diesel vehicles.)

Emission tests are typically performed on vehicles once the vehicle engine and catalysts have warmed to optimum operating temperatures. Very limited comparative test data for cold alcohol and gasoline or diesel vehicles are available. With an average trip length in Australia of around 8 kilometres (Adena & Montesin 1988), cold vehicle emissions are potentially an important source of noxious emissions (Watson 1993).

Vehicle test results

Most of the available data on emissions from alcohol-fuelled vehicles are derived from vehicles running on blends of gasoline and methanol. Often only one — or at most a few — vehicles are tested, and many of these are prototypes. Vehicle emissions data sourced from Brazil (for example Murgel 1990, Szwarc et al. 1991) are not comparable with data from Europe or North America because of either non-existent or very primitive emissions control equipment fitted to Brazilian ethanol and gasohol vehicles.

The most thorough alcohol-fuelled LDV emission testing program which has thus far reported results is the first phase of the American Auto/Oil Air Quality Improvement Research Program study (AQIRP). Its results have been reported in Colucci and Wise (1992), AQIRP (1993a, 1993b) and Automotive Engineering (1992a, 1992b). One series of tests involved twenty 1989 model gasoline vehicles (two each of ten models). Emissions from these vehicles were compared when run on gasoline, E10, gasoline containing 15 per cent MTBE and gasoline containing 17 per cent ETBE. Another test studied the influence of reducing the vapour pressure of the test fuels by 6.9 kilopascals (1 psi). The results of the comparison between gasoline and E10 and the outcome of reducing the vapour pressure of the E10 blend are presented in table 5.3.

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[3] *Vehicle exhaust emissions of CO, total HCs and aldehydes at cold starts have been shown to increase as ambient air temperature decreases, at least over a range of minus 10 to plus 10 degrees centigrade for unblended gasoline, gasoline containing 11 per cent MTBE and gasoline with 10 per cent ethanol; although the magnitude of the change is influenced by the vehicle type. No change in NO_x was found to occur (Prakash 1991).*

TABLE 5.3 RESULTS FROM AQIRP EMISSION STUDY FOR VEHICLES FUELLED WITH E10

(Percentage change in evaporative and exhaust emissions as compared with gasoline vehicles)

Type of emmission	*E10 vehicles*	*E10 vehicles with fuel vapour pressure reduced by 6.9 kPa*
CO	–13*	–15
NO$_x$	5*	1
NMHC^a	–6*	–11
•		
Diurnal^b	31•	–54
*		
Hot soak^c	51*	–16
Benzene	–13*	na
1, 3-butadiene	–6*	na
Formaldehyde	19	na
Acetaldehyde	159*	na

• Change significant at the 95 per cent confidence level
na Emission not tested

a. NMHC refers to non-methane hydrocarbons.
b. Diurnal emissions consist of evaporative VOCs emitted from the fuel tank of the vehicle during daily ambient temperature fluctuations.
c. Hot soak emissions are evaporative losses of VOCs that occur immediately after the engine has been turned off.

Source Colucci & Wise (1992).

In conjunction with ongoing AQIRP tests of gasoline vehicles, 19 pre-1990 prototype methanol FFVs and VFVs were tested for a range of noxious emissions. The vehicles had performed between 14 500 and 53 000 kilometres and were supplied by Chrysler, Ford, and General Motors. The prototype vehicles were fuelled with industry average gasoline (M0, and not reformulated), M10 and M85. Exhaust and evaporative emissions data from the tests are presented in tables 5.4 and 5.5 respectively. Tropospheric ozone effects from using methanol in the prototype vehicles in three US cities are given in the section on ozone effects.

There have been numerous other vehicle emission tests, particularly for methanol vehicles. With many of the tests it is often difficult to draw firm conclusions, or to extrapolate any further than the immediate test, while comparisons between tests require considerable caution.

For example:

- environmental conditions differ between test sites;
- different countries or vehicle manufacturers adopt different test procedures;

TABLE 5.4 RESULTS FROM AQIRP NOXIOUS EMISSION STUDY OF EXHAUST EMISSIONS FROM METHANOL-FUELLED PROTOTYPE FFV/VFV VEHICLES

(Emissions for each vehicle and fuel type in grams per kilometre)

Exhaust component	*Gasoline vehicles*[a]	*FFV/VFV*[b] *vehicles*		
		M0[c]	*M10*[c]	*M85*[c]
CO	1.73	1.75	1.61	1.20
NO_x	0.37	0.25	0.25	0.30
NMOG[d]	0.11	0.15	0.15	0.18
OMHCE[e]	0.14	0.18	0.17	0.11
Methanol	0.000	0.000	0.006	0.124
Benzene	0.0067	0.0091	0.0073	0.0015
1,3-butadiene	0.0005	0.0007	0.0006	0.0001
Formaldehyde	0.0012	0.0016	0.0016	0.0092
Acetaldehyde	0.0007	0.0005	0.0004	0.0001

Note The Reid vapour pressure of the gasoline was 60 kPa, the M85 was adjusted up to 60 kPa by the addition of butane and the M10 was 83 kPa.

a. 1989 gasoline vehicle average obtained from using industry average gasoline.
b. Flexible fuel or variable fuel vehicles.
c. Mx denotes a blend of x per cent methanol and (100 – x) per cent gasoline. MO refers to pure gasoline.
d. NMOG is defined as non-methane organic gases.
e. OMHCE is defined as the organic material hydrocarbon equivalent and excludes the non-reactive oxygen portion of the organic compounds.

Source AQIRP (1992).

- only one vehicle may have been tested (for example Anker-Jonhson & Schwoert 1990, Ohta et al. 1991, Namba et al. 1991);
- when multi-vehicle tests are performed, vehicles differing from each other in some way (fuel system, emission control and use) are often used, for example Iwai et al. (1991);
- many of the vehicles are prototypes and may not be representative of final production vehicles.

The specific components of noxious emissions from alcohol fuels, including CO, SO_2, NO_x, VOCs, aldehydes, other emissions and ozone effects, are considered separately below.

Carbon monoxide emissions

Carbon monoxide (CO), produced from the incomplete combustion of carbon in the fuel, is probably the least important of the noxious vehicle emissions in Australian cities, in that levels of carbon monoxide are generally below accepted levels (Munro 1990).

TABLE 5.5 RESULTS FROM AQIRP NOXIOUS EMISSION STUDY OF EVAPORATIVE EMISSIONS FROM METHANOL-FUELLED PROTOTYPE FFV/VFV VEHICLES

(Emissions for each vehicle and fuel type in grams per test)

Test and component	*Gasoline vehicles* [a]	*FFV/VFV* [b] *vehicles*		
		M0 [c]	*M10* [c]	*M85* [c]
Diurnal [d]				
NMOG	0.44	0.82	1.28	0.55
OMHCE	0.44	0.82	1.13	0.37
Hot soak [e]				
NMOG	0.50	0.59	1.56	1.15
OMHCE	0.50	0.59	1.22	0.69
Running loss [f]				
NMOG	8.24	0.28	nm	0.64
OMHCE	8.24	0.32	nm	0.54

nm Not measured

a. 1989 gasoline vehicle average obtained from using industry average gasoline.
b. Flexible fuel or variable fuel vehicles.
c. Mx denotes a blend of x per cent methanol and (100 – x) per cent gasoline.
d. Diurnal losses consist of evaporative VOCs emitted from the fuel tank of the vehicle during daily ambient temperature fluctuations.
e. Hot soak emissions are evaporative losses of VOCs that occur immediately after the engine has been turned off.
f. Running losses are evaporative emissions released during engine operation.

Note The Reid vapour pressure of the gasoline was 60 kPa, the M85 was adjusted up to 60 kPa by the addition of butane and the M10 was 83 kPa.

Source AQIRP (1992).

Reductions of 10 to 30 per cent in CO emissions have been achieved in the USA using 10 per cent ethanol–gasoline blends (NSWDME 1990, table 5.3). Reductions of up to 30 per cent have been achieved with methanol–gasoline blends (table 5.4).

Reduced CO emissions have also been observed when alcohol has replaced diesel. Compression ignition engined buses in Sweden running on 95 per cent ethanol, 3 per cent AVOCET ignition improver and 2 per cent MTBE, with increased compression ratios of 24:1 and catalytic converters,[4] emitted CO at a rate of 0.1 grams per kilowatt hour compared with the typical diesel bus (without a converter) at 1.5 grams per kilowatt hour (Ryden & Berg 1991).

Vehicles in which methanol replaces diesel appear to require exhaust catalytic converters to achieve lower CO emissions than from diesel. For example an M.A.N. bus converted to spark ignition and running on methanol (without

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[4] Catalytic converters are more easily adapted to alcohol-fuelled compressed ignition vehicles than to diesel-fuelled vehicles as absence of sulphur eliminates the need for particulate traps.

catalytic converter) emitted 17.5 grams of CO per kilometre compared with a diesel bus (also without catalytic converter) which produced 3.9 grams of CO per kilometre. However, when fitted with a catalytic converter to control CO emissions, the methanol bus produced only 0.81 grams per kilometre (Eberhard et al. 1989 cited in Black 1991).

It appears that a catalytic converter may not always give methanol a significant advantage over diesel. Unnasch et al. (1991) refer to two retrofitted Detroit Diesel Corporation (DDC) engined buses fitted with exhaust catalysts and running on methanol containing 3 to 5 per cent AVOCET. They produced CO emissions equivalent to, or only slightly lower than, those from a bus without a catalytic converter operated on diesel.

Sulphur dioxide emissions

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

This property of alcohol fuels may become more important in Australia as reserves of low sulphur oil dwindle and greater reliance is placed on imported motor fuel with a higher sulphur content (Munro 1990).

Oxides of nitrogen

Nitrogen oxides (NO_x) formed during the high temperature combustion of nitrogen and oxygen are involved in a complex series of reactions in the atmosphere leading to photochemical smog. Compounds in smog include respiratory and eye irritants and particulates that reduce visibility (Munro 1990). The indirect effects of NO_x through its contribution to ozone formation are discussed in a later section.

When alcohol is used to replace gasoline the NO_x emission results are mixed. In the AQIRP study involving E10 fuel, NO_x emissions were 5 per cent higher from vehicles when running on E10 as opposed to E0 (table 5.3). In the AQIRP study of FFV/VFV methanol vehicles using M85 as compared with M0, NO_x emissions from three of the vehicle models were lower by up to 41 per cent, and higher by up to 159 per cent from four other vehicle models (*Automotive Engineering* 1992b).

NO_x emissions from ethanol appear to be lower than from diesel, even without a catalytic converter. For example, the Swedish ethanol buses mentioned above emitted 2 grams of NO_x per kilowatt hour when equipped with a catalyst, and 4.5 grams without a catalyst. This is still markedly lower than the 16 grams of NO_x per kilowatt hour emitted by a typical in-service diesel bus (Ryden & Berg 1991).

With methanol and diesel, NO_x emission levels appear to be similar unless a catalytic converter is fitted. NO_x emissions from M.A.N. buses with diesel engines converted to spark ignition and running on methanol, at 7.5 grams per kilometre, were reported to be similar to those from the diesel vehicles, at 8.1 grams per kilometre (Eberhard et al. 1989 cited Black 1991). However, NO_x emissions from the two retrofitted DDC engined buses mentioned above (that is, with catalytic converters) were reported to be only half those of equivalent buses operating on diesel (Unnasch et al. 1991).

The use of ignition improvers in diesel engines running on alcohols may contribute to a portion of the NO_x emissions from those engines because the ignition improvers are often based upon organic nitrates[5] (Alternative Fuels Committee of the Engine Manufacturers Association 1982, cited in Black 1991). An increase in the concentration of AVOCET ignition improver has been shown to lead to a corresponding increase in NO_x emissions (Unnasch et al. 1991). This increase was ascribed to the improvement in combustion and reduction in ignition delay, which leads to higher peak pressures and temperatures.

Volatile organic compounds (VOCs)

VOCs play a role in the formation of photochemical smog. Some VOCs produce a detectable odour; others are carcinogenic (Munro 1990).

Exhaust VOC emissions

Exhaust emissions of VOCs from alcohol vehicles consist mainly of unburnt ethanol (73 per cent by mass from an E85 vehicle [Black 1991]) and unburnt methanol (OTA 1990).

Exhaust emissions of VOCs from vehicles using E10 have been reported to decrease by from 1 to 9 per cent compared with those from gasoline vehicles (NSWDME 1990 and table 5.3). Total exhaust VOC emissions[6] from the Swedish ethanol buses are at a level of 0.2 grams per kilowatt hour, compared with emissions from a typical in-service bus of 1 gram per kilowatt hour (Ryden & Berg 1991).

Alcohol-fuelled vehicles would have lower emissions of some carcinogenic pollutants, including benzene, polycyclic organics, and the alkene 1,3-butadiene (Gray and Alson 1989 and table 5.4).

However, because of the differences in *chemical composition* of the VOCs in exhaust emissions of alcohol-and gasoline-fuelled vehicles, comparisons of the effects of VOC emissions based simply on total mass of all compounds (NMHC, NMOG and OMHCE in tables 5.3 and 5.4) are difficult to make. The

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[5] Amyl nitrate, hexyl nitrate and cyclohexyl nitrate.

[6] Evaporative emissions are not considered to be a problem in Sweden.

photochemical potency of the exhaust gases from methanol vehicles has, however, been judged to be lower than from gasoline cars (Brandberg 1991).

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

Evaporative VOC emissions

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

The addition of alcohol to gasoline results in increasing vapour pressure and hence evaporative emissions (table 5.5), up to the point where the alcohol content exceeds about 75 per cent of the fuel (Furey 1985 cited in Furey & Perry 1991). It is unclear whether the use of alcohol–gasoline blends in unmodified modern cars would cause excessive evaporative emissions, but this is likely to be the case with older cars without evaporative emission control measures.

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

To contain evaporative emissions from vehicles using alcohol fuel, measures may need to be implemented to control fuel vapour pressure, increase the effectiveness of in-vehicle emission control equipment in gasoline vehicles and control evaporative emissions from diesel fuel vehicles.

The net effect of both the lower exhaust emissions and increased evaporative emissions of ethanol–gasoline blends, such as the 10 per cent blend currently available in the USA, is an increase in VOCs. This is a direct result of the increased fuel vapour pressure and the splash[7] blending process (NSWDME 1990).

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[7] Splash blending refers to the practice of adding the ethanol directly into the gasoline in a road tanker. Volatile components of the gasoline are emitted during this process.

Aldehyde emissions

Most aldehydes are emitted from alcohol-fuelled vehicles before the engine and catalytic converter have reached their efficient operating temperatures. Once an efficient temperature has been reached, aldehyde emissions are similar to those from an equivalent gasoline engined vehicle (EPA 1991b). Table 5.4 suggests that this is the case at least for blends containing low levels of alcohol. When an increase in exhaust emissions of aldehydes is apparent, such as in table 5.3, the increase can often reflect a low base.

In gasoline vehicles, one-third of vehicle-related emissions of formaldehyde is derived directly from the tailpipe, with the remaining formaldehyde being formed in the atmosphere by photochemical conversion of hydrocarbons from the tailpipe (Gray and Alson 1989). Since photochemical reactivity of methanol emissions is lower than that of gasoline emissions, methanol blends may have lower derived formaldehyde emissions, despite higher exhaust emissions. Other reactive aldehydes emitted from gasoline (such as acetaldehyde and acrolein) are also emitted from alcohol fuels (Taschner 1991; Brandberg 1991).

Some studies have investigated the effect of increasing vehicle mileage on aldehyde emission levels. For example a Mitsubishi FFV operating on M85 produced 125 milligrams per kilometre of formaldehyde before a catalytic converter was fitted, and 6.9 milligrams per kilometre after the exhaust gases had been passed through a converter. This was before the vehicle had travelled 8000 kilometres. By the time a further 75 000 kilometres had been travelled, formaldehyde emissions had only increased to 7.5 milligrams per kilometre (Namba et al. 1991). In contrast, a Nissan FFV with a catalyst, run on M85 and M0 at 8000 and again at 80 000 kilometres, showed aldehyde emissions increasing from 17 to 25 milligrams per kilometre for M85, and from 5 to 12 milligrams per kilometre for M0 (Ohta et al. 1991). Both of these vehicles are under development, and research continues into catalyst deterioration. Improvements in catalyst durability may result in reductions in aldehyde emissions.

In diesel vehicles also, the use of alcohol fuels increases aldehyde emissions (Brandberg 1991, table 4).

On balance, with low level blends, and once a vehicle that is fitted with a catalytic converter is warm, there does not appear to be very much difference between gasoline and gasoline–alcohol blends in terms of aldehyde emissions. However, there remains some uncertainty about emissions from cold vehicles. Emissions of aldehydes are considerably higher with high alcohol blends (table 5.4).

Other emissions from alcohol fuels

Particulates from the incomplete combustion of fuel and from the combustion of lubricating oil contribute to the discharge of particles into the atmosphere, reducing visibility (Munro 1990). With diesel vehicles, emissions of SO_2 form very fine droplets of sulphuric acid that become visible as particles in the atmosphere.

The utilisation of high alcohol content ignition-improved fuels in heavy duty engines can lead to a reduction in particulate emissions. For example Ryden and Berg (1991) provide particulate emissions data for a number of different buses running in Sweden. The typical diesel bus emits 0.6 grams of particulates per kilowatt hour. A diesel bus with sulphur-free fuel and a catalytic converter emits 0.1 grams of particulates; and a bus running on E95 and AVOCET emits only 0.05 grams of particulates per kilowatt hour.

US studies of M.A.N. methanol-fuelled diesels with spark-assisted ignition also reported reductions in particulates from 690 to 75 milligrams per kilometre (Eberhard et al. 1989 cited in Black 1991). Particulate emissions from two retrofitted DDC engined buses were reported to fall by at least 75 per cent relative to emissions from similar vehicles operating on diesel (Unnasch et al. 1991).

PAH emissions from ethanol-fuelled vehicles are lower than from gasoline and considerably lower than from diesel-fuelled vehicles. However, toxic alkyl nitrite emissions are increased by alcohol fuel use (Brandberg 1991).

The introduction of alcohol fuels in low level blends with leaded fuel could have some small influence on atmospheric lead concentrations. However, the potential for substitution could be limited by the advantage lead has — apart from its octane enhancing effect — in preventing 'valve seat recession' in older motor vehicles (Noel Trompp, NSW EPA, pers. comm.), and thus reducing engine wear.

The introduction of high alcohol content fuels would not influence atmospheric lead concentrations. Only new vehicles would be capable of accepting high alcohol content blends, and these would otherwise already be using unleaded gasoline. All vehicles manufactured for use in Australia since early 1986 are required to operate exclusively on unleaded gasoline.

Ozone effects of alcohol fuels

Ozone is not produced directly by vehicles. It is formed in a process of complex chemical reactions in the atmosphere involving oxides of nitrogen, VOCs and sunlight (Alson et al. 1989).

Low level blends of alcohol and gasoline, such as E10 or M10, will raise ozone levels, as these low level blends have a greater vapour pressure than gasoline and result in an increase in net evaporative emissions of VOCs (OTA 1990, table 5.5).

Ethanol blends with gasoline

In the USA, an 'Urban Airshed Model' has been used to predict changes in peak ozone levels (in Los Angeles in the year 2010, Dallas-Fort Worth in 2005 and New York in 2005) arising from the use of splash blended ethanol (E10). This model has shown that the LDV contribution to peak ozone from use of this fuel increased by 11 to 21 per cent, depending on the city and the amount of the increase in vapour pressure (results of AQIRP study in Sinor Consultants 1992c, 85–7).

By contrast, the National Alternative Fuels Laboratory preliminary study (cited in Sinor Consultants 1992c, 89–90) found that ethanol-blended gasoline had a lower vapour pressure than gasoline. This appears to have been the result of a reduced butane content. The study reported that a component analysis at the fuel pump revealed that the gasoline in the E10 blend and the non-blended gasoline tested were the same, and that the butane was thought to have been lost in transport or storage of the fuel.

Removal of butane from gasoline could possibly be used to reduce the vapour pressure of low level alcohol fuel blends. However, oil companies would probably find alternative uses of the butane less profitable. Butane is produced as a refinery by-product.

The National Alternative Fuels Laboratory study also showed that while the components of the blended gasoline evaporated at a faster rate than in the case of the pure gasoline, the individual components evaporated in the same proportion. This means that there would be no difference in the composition of evaporative emissions apart from the alcohol itself.

In the USA, the Environmental Protection Agency (USEPA) has proposed regulations to prohibit the use of ethanol in order to meet the Clean Air Act standards because of the increased vapour pressure of the fuel compared with gasoline (Sinor Consultants 1992c, 89). However, E10 blends with a vapour pressure 6.9 kilopascals (1 psi) above that of normal gasoline have been permitted.

Methanol blends with gasoline

The Urban Airshed Model was also used to predict changes in peak ozone levels from the use of M85 in Dallas-Fort Worth, Los Angeles and New York. Use of low level methanol blends are not currently envisaged in the USA, and their ozone effects have not been modelled. Based on emissions data generated by the AQIRP study, the airshed model showed that for M85 ozone levels could be reduced by as much as 86 per cent or increased by up to 26 per cent, with large variations within cities, depending on the assumptions of the model and the location of the city (Colucci & Wise 1991).

For methanol vehicles to be effective in reducing urban ozone levels, the sum of the effects of reactive compounds must be less than that from gasoline-only vehicles. Methanol in vehicle emissions is not especially reactive, while formaldehyde is highly reactive (OTA 1990). However, most tests of vehicle emissions provide only a limited breakdown of the chemical speciation of the organic compounds and are of limited use in establishing a vehicle's ozone reduction potential.

Existing dedicated M85 and M100 vehicles are prototypes, and extrapolation of results from emission tests for these to production vehicles requires caution (OTA 1990). Further, emissions data based on test cycles may not adequately represent emissions from vehicles under traffic conditions.

In summary, tests on the ozone effects of alcohol fuels have shown that, with low level ethanol blends ozone formation increases; and with high level methanol blends no conclusion can be drawn as results are highly variable. The BTCE is unaware of any test results for high level ethanol blends, or low level methanol blends.

Emissions from ethanol and diesel blends

Much of the work relating to emissions from vehicles using alcohol fuels has been performed on spark ignition engines or on compression ignition engines operating on alcohol–gasoline blends with a high alcohol content, for example M85. There appears to have been no independent test of vehicle exhaust gas emissions using diesel and alcohol mixtures as fuel.

However, APACE (1992) has claimed reductions of up to 10 per cent in NO_x emissions, 40 per cent in CO emissions and more than 50 per cent in particulate emissions from diesel engines using its diesohol fuel. Exhaust emission tests of buses running on diesohol in Canberra's ACTION bus fleet commenced early in 1993, and emissions tests of vehicles using diesohol were to begin in Sweden in 1993.

Emissions summary: alcohol fuels

Both methanol and ethanol have the potential to reduce greenhouse gas emissions from the transport sector, but would need to be produced from biomass (and for the most part from the lignocellulose) to make a significant contribution to reduction in these emissions. Methanol derived from natural gas using current technology offers at best only a small greenhouse gas emission improvement over gasoline. However, whether reductions in greenhouse gas emissions will in fact be available from use of ethanol or methanol will depend on the circumstances of the particular case.

Where the non-lignocellulosic fraction of crops is used, the source of energy for processing and the use made of the lignocellulosic fraction will be important in determining the net emissions. For example use of crop residue such as bagasse to replace a fossil fuel when it would otherwise be left to decompose (liberating CO_2), would assist in achieving an overall saving in emissions. Use of non-fossil fuel for energy would only be an advantage if it were not drawn from use elsewhere. Even where lignocellulose is utilised, the potential contribution will vary with the type of feedstock (municipal waste, trees, crops), and the extent to which it displaces other biomass. Land availability, the economics of production, use of fertilisers and transport needs will also influence the outcome.

In the urban environment the situation is uncertain. The introduction of alcohol fuels would probably result in lower emissions of CO from spark ignition engines, but catalytic converters would most likely be necessary to achieve lower emissions from diesel engines. Emissions of SO_2 and particulates, including lead, would be lower from alcohol fuels. For NO_x, test results are variable, but it appears that spark ignition engines have similar emissions levels whether running on gasoline or alcohol (Brandberg 1991). Emissions of NO_x from compressed ignition vehicles appear no worse, and possibly better. Aldehyde emissions will be higher from high-level alcohol blends, but with low level blends, emissions will be worse with cold vehicles, but much the same as for gasoline with warm vehicles. Exhaust emissions of VOCs tend to be lower with alcohol blends, and evaporative emissions higher, but the different composition of exhaust gases makes comparisons difficult. The effect on tropospheric ozone levels of alcohol-fuelled vehicles is not known for high-level blends, but low-level blends lead to an increase in ozone.

Health and safety issues with alcohol fuels

While use of alcohol fuels can generate a range of health and safety effects, this section focuses on those stemming from aldehyde emissions, alcohol vapours, direct contact with alcohol fuels and fires. The complex health and safety aspects of alcohol fuels are considered in more detail in appendix V.

The use of alcohol as a transport fuel would considerably increase the amount of neat alcohol and blended alcohol transported and used throughout the country. This would increase the potential for human contact with alcohol from spillage, fuel vapour and ingestion of ethanol. There would be increased contact with aldehydes — in particular in the changed chemical exhaust composition. There would be increased risk of environmental contamination from spills and leaks, and there would be a higher potential for alcohol fires.

The major health issues are the acute and chronic toxicities of the fuels and the products of their combustion.

Toxicity of fuels

Ingestion of under 70 milligrams of methanol per kilogram of body mass, in a single dose, can produce toxic effects (Machiele 1990). Single doses of over 300 milligrams per kilogram of body mass can be lethal (Costantini 1991) or lead to permanent visual impairment. There are currently no data available to address any chronic effects of methanol.

Ethanol concentrations of 50 to 150 milligrams per 100 millilitres of blood result in delayed reaction times, reduced co-ordination and blurred vision. Coma and death can occur at concentrations of 500 milligrams per 100 millilitres of blood (Rumack & Lovejoy 1986), equivalent to some 4000 milligrams of pure ethanol per kilogram of body mass. Lethal intakes of gasoline and diesel are similar, varying between 500 and 5000 milligrams per kilogram body mass (Gosselin et al. 1976). The chronic effects of ethanol are well documented from many case studies of alcoholics.

It is unlikely that exposure to alcohol vapours or dermal uptake of alcohol would cause acute toxicological problems. Nevertheless, antisiphoning devices and other physical deterrents, denaturants and public education may be necessary to reduce accidental and deliberate ingestion of alcohol fuels. Nadis and MacKenzie (1993) express the view that methanol is sufficiently hazardous to render self-service methanol pumps at service stations inappropriate. Ethanol at self-service stations would present fewer problems because of its lower toxicity.

Health effects of combustion products

Of the alcohol combustion products, only the aldehydes have attracted attention. However, the BTCE is not aware of any epidemiological evidence to support concerns about the acute toxicity or potential carcinogenic properties of acetaldehyde and formaldehyde, particularly at the levels likely to be encountered from alcohol vehicles fitted with catalytic converters (appendix V).

No data are available to permit assessment of the chronic effects of exposure to methanol, formaldehyde and other components in exhaust emissions either separately or in synergy (Costantini 1991).

Fire

In open or well ventilated areas, pure ethanol and methanol have a lower ignitability and produce less heat than does gasoline. Depending on the amount of alcohol in the fuel, blends of gasoline and alcohol may have a similar ignitability to gasoline.

Fires of pure alcohol are poorly visible but the addition of a small amount of gasoline (15 per cent) improves flame visibility. In enclosed containers partly filled with pure ethanol and methanol, the flammability range differs from that of gasoline. For example ethanol is flammable between –18.4 degrees Celsius and 7.7 degrees Celsius, whereas gasoline is flammable between –43 and –9 degrees Celsius. At ambient temperatures encountered in winter, a container of ethanol or methanol is therefore more likely to contain an explosive fuel and vapour mix than a container of gasoline.

The high solubility of ethanol and methanol in water reduces the value of water as a fire extinguishing medium. Water may in fact cause the fire to spread until the alcohol and water mix is sufficiently diluted to ensure extinction of the fire.

Appropriate methods for extinguishing alcohol fires include dry chemicals, CO_2 or alcohol resistant foam.

Health and safety assessment

The use of alcohol as a transport fuel would considerably increase the amount of neat alcohol transported and the potential for spills and human contact. Nevertheless, these fuels could be made at least as acceptable as gasoline. This would require a public education program, appropriate training for people regularly handling alcohol fuels, some modification of current fuel handling and safety techniques, the incorporation of denaturants and substances to make alcohol flames more visible and training for people in fighting fires where an alcohol fuel is involved.

CONCLUSION

To be able to achieve any significant reductions in emissions of greenhouse gases by using alcohol fuels, the ethanol or methanol will need to be produced from the lignocellulose fractions of biomass. However, it has yet to be demonstrated that large-scale production of alcohol from lignocellulose can be technically feasible and economically viable.

At present the pilot-scale production of ethanol and methanol from lignocellulose is at least two to three times more expensive than gasoline production. Reductions in production costs of alcohol fuels from biomass await the maturation of technologies currently in laboratory and pilot plant stages.

Alcohol fuels in some instances can lead to urban air quality benefits; but it is difficult to generalise. Some emissions increase and others decrease. Evaporative emission controls for vehicles would be important if low percentage alcohol blends were to be used — especially with gasoline, but probably also with diesel. Ethanol in high percentage blends (or neat) replacing diesel in urban buses appears to offer significant air pollution reductions especially where catalytic converters are fitted. Emissions from ethanol in low percentage blends replacing diesel (diesohol) have yet to be tested. While some increase in aldehydes could be expected, health concerns about the levels of aldehydes emitted from catalysed vehicle exhausts seem largely unwarranted.

CHAPTER 6 FUELS FROM VEGETABLE OILS

There has recently been renewed interest in the potential for using oilseed crops as a renewable fuel source. Vegetable oils are seen as providing a suitable alternative to diesel fuel, as they do not lend themselves to use in spark ignition engines. They are therefore of more relevance in countries which rely more heavily on diesel vehicles.

BACKGROUND

The first results of experiments with soybean oil as a fuel were published in 1928 by a Frenchman named Gautier (Seymour 1981). Since then fuels made from oilseeds have been used for short periods in various countries around the world. Tests on vehicles fuelled with a range of oils were conducted during World War II but subsequently abandoned when diesel fuel became cheaper and more readily available (Seymour 1981).

Revived interest has been influenced by the escalation of OPEC oil prices in 1973, and by increasing environmental concerns over diesel emissions. Research has been undertaken with rapeseed, soybean, linseed and sunflower oils as pure fuels in compression ignition engines, and as blends with diesel. This research has revealed the potential of vegetable oils as a diesel extender.

European interest

European countries including Italy, Germany, Austria and the UK, have been leading world research on vegetable oil fuels. Attention has focused on rapeseed, due, at least in part, to its current overproduction in Europe. The biodiesel derived from rapeseed, rape methyl ester (RME), results in lower emissions of CO, HCs and particulates than pure vegetable oils (Francese et al. 1991). It is being tested in the USA and in Australia as well as in Europe.

Interest in Europe has been boosted by changes to the European Common Agricultural Policy limiting food production and increasing the acreage of land approved for industrial crops, including vegetable oils for fuel. Farmers in France and Germany have already sown 60 000 hectares of rapeseed for fuel and France plans to use 700 000 hectares for fuel crops (Patel 1993).

This development has not been without criticism. The cost and emissions effectiveness of the plan has been challenged, in particular, by Germany's Federal Environment Office. Patel (1993) acknowledges that RME could be an economically and environmentally viable alternative fuel, but maintains that its promotion is motivated by agricultural rather than energy policy considerations.

The production of RME is relatively expensive compared with the production of fossil fuels (McDiarmid 1992). To make the new fuels more competitive, the European Commission has recommended that taxes on biodiesel should be limited to a maximum of 10 per cent of the level applied to fossil fuels (Meyer 1993). There is no diesel fuel tax applied to RME at present in Germany, Austria, Switzerland or France (Francese et al. 1991).

Australian involvement

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been one of the major players in exploring the use of vegetable oils in Australia, along with REPCO, and several universities. During the early 1980s CSIRO conducted a detailed appraisal of oilseeds as feedstock for a possible substitute for diesel fuel (Seymour 1981). Sunflower, linseed and rape seeds were examined, as these are rich in oil and the crops can be grown widely in Australia. These tests found that diesel engines performed to much the same standard with pure vegetable oil as with diesel.

The Department of Business Industry and Regional Development (DBIRD) in Queensland is currently involved in assessing the viability of establishing an RME plant. Novamont, a company producing the fuel in Italy, is keen to establish a plant in Australia, and has supplied two one-litre samples to Queensland Railways and the Brisbane City Council for laboratory tests. On completion of these tests larger quantities of the fuel are to be supplied for field tests in Queensland buses and trains. Novamont is only interested in establishing a plant if a tax-break — sufficient to allow RME to compete with gasoline and diesel — can be provided (DBIRD, pers. comm. 1993).

Use in vehicles

In the past pure vegetable oils have been used mainly in tractors on farms. With the renewed interest in these fuels, laboratory tests have been conducted to determine their suitability in a range of diesel engines. They have been found to generate problems in turbocharged direct injection engines with charge air coolers, used mainly in heavy duty trucks (Hemmerlein et al. 1991) and also in LDVs. Different engines have exhibited different emissions characteristics, and it appears that more research is required on engine modifications which might avoid adverse results.

Fuel derived from vegetable oils, called biodiesel, appears to offer more promise. Biodiesel is a chemical modification of pure vegetable oils with properties similar to diesel. Many European countries are testing biodiesel, particularly in their public transport systems (mainly buses), taxis and tractors. Water transport also seems to offer scope. A ferry on Lake Como in Northern Italy is being tested; and on 4 July 1992 the Sunrider Expedition commenced its voyage around the world in a boat powered by SoyDiesel (Sinor Consultants 1992g).

FUEL CHARACTERISTICS

The density, energy content and viscosity[1] of sunflower, rapeseed and linseed oils, and diesel, are compared in table 6.1. The physical and chemical characteristics of the oils are similar. All three vegetable oils have slightly higher density and slightly lower energy content (gross calorific value) than diesel. Vegetable oils have a lower carbon content than diesel, which means lower CO_2 emissions per litre at the tailpipe. CO_2 emissions per kilometre travelled may not be lower, however, due to the lower energy content of the vegetable oils. The major difference in physical characteristics between the vegetable oils and diesel is in the viscosity levels, which are much higher for the vegetable oils. Sunflower oil, for example, is more than 12 times as viscous as diesel at 20 degrees Celsius, and remains more than six times as viscous even after heating to 80 degrees Celsius.

TABLE 6.1 COMPARISON OF DIESEL AND 100 PER CENT VEGETABLE OIL

	Diesel	*Sunflower oil*	*Rapeseed oil*	*Linseed oil*
Density (kg/L)	0.835	0.925	0.922	0.932
Gross calorific value (MJ/L)	38.3	36.4	36.9	37
Viscosity (mm^2/s @ 37.8°C)	3.86	35	37	29
Composition:% of carbon, hydrogen and oxygen: C:H:O	86:14:0	78:12:10	78:10:12	na
Sulphur (%)	0.2	0.5	0.0012	na

na Not available

Sources Hemmerlein et al. (1991); Ziejewski et al. (1991); Stewart et al. (1981).

These high viscosity levels create problems for the use of vegetable oils as a pure fuel. The flow of the fuel from tank to engine is impeded, which can result in decreased engine power. Fuel filter blockages may also occur (Stewart et al. 1981). Engines can suffer coking of the combustion chamber and injector nozzles, and gumming — and hence sticking — of the piston rings (Seymour 1981). A progressive decline in power results. If left unchecked, dilution of the crankcase oil can lead to lubrication breakdown (Stewart et al. 1981). Long-term

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[1] Viscosity refers to the resistance to movement during flow.

engine tests have verified the build-up of carbon deposits in the injection nozzles and cylinder heads (Stewart et al. 1981).

The viscosity problem can be mitigated by blending diesel and vegetable oils or by chemical modification. Vegetable oils are completely miscible with diesel (Stewart et al. 1981). A 1:1 blend of sunflower oil and distillate will have a viscosity level less than three times that of pure distillate at 40 degrees Celsius (Stewart et al. 1981).

Chemical modification reduces viscosity by separating out the glycerine in the oils. The process, *transesterification,* involves the addition of methanol or ethanol to the oil to produce methyl or ethyl esters. The derived fuel is known as biodiesel (and in the case of rapeseed, as RME) (Francese et al. 1991). This has been the preferred method used in Europe for reducing pure vegetable oil viscosity.

Another alternative is to preheat the oils and use larger fuel lines to rectify the problem of impaired fuel supply to the engine (Seymour 1981).

The calorific value of all the oils is approximately 5 per cent lower by volume than that of diesel. This should reduce the torque and power output of engines, and would imply greater fuel consumption per kilometre. A German study on rapeseed oil (Hemmerlein et al. 1991), concluded that the reduction in power output would be only small (2 per cent) due to the higher injected fuel quantity pertaining to the rapeseed oil. This higher injected fuel quantity was argued to result from the higher viscosity of the rapeseed oil, and to be pronounced with distributor type injection systems (Hemmerlein et al. 1991).

Another major difference between diesel and oilseed fuels is the presence of oxygen in the oils, including RME. A higher oxygen content normally acts to improve combustion and therefore to reduce emissions of carbonaceous particulate matter. However, the high viscosity of the pure vegetable oils produces a fuel spray with a large range of droplet sizes, resulting in poor fuel atomisation. This causes a tendency toward incomplete combustion, which more than balances the oxygenate effect. The result is higher levels of CO, HC and particulate emissions.

Compared with the diesel fuel available overseas, rapeseed oil has a very low sulphur content, and would therefore have advantages where sulphate particulate emissions are a problem. Sunflower oil has a relatively high sulphur content. This advantage of rapeseed oil would be of less importance in Australia as long as low sulphur crudes remain available.

Apart from viscosity problems, vegetable oils may result in starting difficulties due to the high flash point of the oil.[2] This could be overcome by starting the

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[2] Flash point refers to the lowest temperature at which the oil will give off ignitable vapours.

vehicle on diesel and switching to the vegetable oil when the motor is warm, though a dual-fuel system would then be required (Seymour 1981).

Vegetable oils have a relatively slow burn rate due to their fairly low cetane rating. In the crude state therefore, they are probably unsuitable for high speed engines, such as in LDVs, where ignition delays are not acceptable (Hemmerlein et al. 1991).

Vegetable oils are easy to store as they are not volatile and do not absorb water vapour from the air (Australian Oilseeds Federation, pers. comm.).

Biodiesel

Biodiesel can be obtained from any of the oilseeds through reaction with methyl alcohol. This produces a fuel with very similar properties to pure diesel, but with an improved emissions performance.

Biodiesel can be used in a diesel engine without modification. Engine tests carried out in Italy revealed no problems in the injection system or other parts of the engine, and no uncommon wear effects (Francese et al. 1991). However, Meyer (1993) points out that glycerine in RME causes problems, as charred glycerine forms carbon deposits on the injection nozzles of the engine which eventually causes the vehicle to stop running. This problem is not necessarily serious, for as Meyer also points out, the production process of RME is such that the glycerine content varies considerably.

The fuel consumption of biodiesel per kilometre travelled is very similar to that for diesel (Francese et al. 1991).

The Scientific Services section of the Queensland Railways conducted a chemical analysis on biodiesel to determine whether it met the Australian standard for diesel fuel (AS 3570). The fuel did meet the specifications, except for its marginally higher density and oxidation stability (Queensland Railways 1992). It was reported that while a high density could lead to increased deposits in the combustion chamber, and a consequent increase in cylinder liner wear, there would probably not be a problem as the density was only slightly above that of diesel. The accelerated oxidation characteristic, however, could lead to storage problems in the medium to long term through the formation of sediments and gums (Queensland Railways 1992).

The properties of biodiesel and diesel are compared in table 6.2.

Results of tests using vegetable oil fuels

The problems attributed to viscosity were not apparent in the results of the CSIRO tests in the early 1980s. As indicated above, the tests found that diesel engines performed to much the same standard on pure vegetable oil as on diesel, revealing similar engine power, torque and efficiency. They were,

TABLE 6.2 PROPERTIES OF BIODIESEL COMPARED WITH DIESEL AND RAPESEED OIL

Property	*AS 3570* [a]	*Diesel*	*Biodiesel*	*Rapeseed oil*
Density (kg/L @ 15°C)	0.82–0.87	0.835	0.88	0.92
Viscosity (mm^2/s @ 37.8°C)	1.9–5.5 (@ 40°C)	3.26	4.7	37
Flash point (°C)	56 min.	64.0	118	200
Oxidation stability	25 max.	6.0	30–70	na
Sulphur (%)	0.5 max.	0.2	<0.01	0.0012

na Not available

a. Australian Standard 3570 (diesel fuel).

Source Queensland Railways (1992); Novamont (1991); Hemmerlein et al. (1991).

however, short-term engine tests, and longer term tests were deemed necessary to establish credibility of the results (Seymour 1981). The tests also found that due to the lower energy content of the oil, 10 per cent more fuel (by volume) was consumed.

Results from studies on pure and blended vegetable oil use conducted in the USA and South Africa have been in line with the CSIRO findings (Seymour 1981).

PRODUCTION AND COSTS

Oilseed crops in Australia in 1991–92 occupied 603 600 hectares of land with actual oil production of 1124 kilotonnes (table 6.3) (ABARE 1992). Of this, rapeseed is the largest specialised oilseed crop, occupying 140 000 hectares. Currently none of Australia's oilseed crops are grown for fuel purposes (Australian Oilseeds Federation, pers. comm.).

Oil extraction

Vegetable oils can be extracted mechanically, or by using the solvent hexane, which is generally more efficient. There are five solvent extraction plants in Australia, which account for 90 per cent of current production, and five small expeller plants which account for the remaining 10 per cent (Australian Oilseeds Federation, pers. comm.). Large extraction plants are more efficient, as they can run continuously.

While crude vegetable oil can be used directly in diesel engines, degummed or semi-refined oil has the potential to reduce fuel blockages. Currently soybean oil is the only degummed oil. Cottonseed is semi-refined, but all other oils are sold as crude. Biodiesel production, however, can use crude oils.

TABLE 6.3 OILSEED CROPS IN AUSTRALIA 1991–92

	Area ('000 ha)	*Oil production (kt)*
Sunflower	88	90.5
Rapeseed	140	161.0
Linseed	7	9.0
Safflower	37	24.0
Soybean	30	50.5
Cottonseed	282	749.0
Peanut	20	40.0

Source ABARE (1992).

The by-product of vegetable oil extraction — high protein livestock meal — is marketed domestically and internationally. Australia currently exports approximately 6500 tonnes with a value of $4.3 million annually (ABARE 1992). More than 1 tonne of meal is produced for each tonne of oil (Stewart et al. 1981). The hulls can also be used to provide heat and steam in the oil extraction process; 40 per cent (by weight) of the hulls would satisfy the requirements for this purpose (Stewart et al. 1981).

Production of biodiesel

Austria is the main user of biodiesel, with more than 100 gasoline stations selling the fuel, and one-fifth of the country's total rapeseed acreage of 50 000 hectares devoted to RME (McDiarmid 1992).

In late 1992 Novamont in Italy opened a plant capable of producing 60 000 tonnes of biodiesel a year (Meyer 1993). Meyer states that other plants which are in the planning stage or under construction in Europe will increase the total capacity to over 300 000 tonnes per year by the end of 1994. Novamont has supplied fuel to bus companies in Italy, the Berlin Taxi Association, all taxis in Bologna, buses in Zurich and a ferry in northern Italy (Francese et al. 1991).

Biodiesel production yields a number of commercial by-products including glycerine, meal and straw.

Potential Australian production capacity

Australia's output of rapeseed oil in 1991–92 was 161 kilotonnes (table 6.3). As an example, if the entire output were used in diesel cars the annual fuel needs of approximately 125 000 cars (about 1.6 per cent of the current total car fleet) could be met. Australia had 101 580 diesel cars in 1991–92. More could be fuelled of course if other vegetable oils were used for fuel. Experience in Europe has been to use vegetable oils in heavier vehicles rather than cars.

If Novamont were to establish a biodiesel plant in Australia it would have to compete with other uses for local supplies of feedstock. According to the Australian Oilseeds Federation, Australia's oilseed crops are not likely to be used for fuel purposes for at least another five years. Australia is a major importer of vegetable oil, and the Federation has recently finalised a five-year plan for self-sufficiency in meeting non-fuel needs (Australian Oilseeds Federation, pers. comm.).

A number of options for increasing Australia's oilseed production have been suggested by Stewart et al. (1981). Undeveloped land could be brought into cultivation, and there is also scope for raising production by improved farming practices.

Costs of production

Australia is a net importer of vegetable oils, and domestically produced oils are sold at import parity prices (Robert Green, Cargill Oilseeds Australia, pers. comm. 1993).

Estimated production costs for vegetable oils suggest the need for a subsidy if vegetable oil is to be offered at prices similar to that of diesel. The cost of pure vegetable oil includes the growing, transportation and processing costs of the feedstock, less the value of the meal and glycerol by-products. These costs were estimated in 1981 by CSIRO, on the basis that the seed is dehulled and the hulls burnt to provide the energy needed for processing. This improves oil and meal quality and the efficiency of the oil extraction plant. Linseed was valued at 44 cents per litre, rapeseed at 47 cents and dehulled sunflower at 59 cents per litre (Stewart et al. 1981). The 1981 wholesale cost of diesel, excluding excise, was 27 cents per litre.

The current cost of importing crude vegetable oils is stated to be in the range A$700–900 per tonne, roughly 55–70 cents per litre of oil (Robert Green, Cargill Oilseeds Australia, pers. comm. 1993).

Biodiesel

Biodiesel costs include also the net effect of the transesterification process costs and the profits from glycerine. A range of studies in different countries has estimated that production of biodiesel requires substantial assistance to enable it to compete with diesel.

The results of a UK Department of Trade and Industry (DTI) study were that a subsidy of 15 pence per litre (33 Australian cents at A$1 = 0.45 English £) would be required, and that such a subsidy may not be justified by the environmental benefits. The UK Minister for Agriculture has stated that biodiesel is unlikely to be able to compete with diesel on an equal basis unless there is a significant increase in the price of mineral oils (McDiarmid 1992).

In Germany, Federal Environment Office studies have led to the conclusion that growing crops purely to produce biofuels of any sort is neither economically nor environmentally justifiable (Patel 1993; Meyer 1993). Meyer states that making biodiesel competitive with diesel in Germany would cost taxpayers DM1 billion annually. Austrian producers are reported to be more optimistic, claiming that they can produce the biodiesel for the same price as diesel (McDiarmid 1992). However, it is possible that the comparison is of the excise free price of biodiesel and the diesel price inclusive of the excise.

Nevertheless, European agricultural reforms encouraging oilseed production are in place and the farm lobby is vigorously pushing biodiesel. As indicated above, biodiesel is exempt from the diesel fuel tax in some European countries and receives concessional tax treatment in others.

Australia currently applies the same level of excise to diesel for on-road use and gasoline — 29.6 cents per litre as from August 1993. Converting the UK cost estimates (A$1 = 0.45 £), the cost of untaxed biodiesel (including credit for the by-products) would be A$0.57 per litre, whereas the cost of untaxed post-refinery mineral diesel converts to approximately A$0.24 per litre. This would involve a subsidy for biodiesel of 33 cents per litre for equal costs before distribution and marketing, 3.4 cents per litre more than the existing excise. The question is whether the environmental benefits justify this subsidy.

The cost of producing biodiesel could be reduced if there were a technological breakthrough permitting the use of cheaper oils, such as palm or waste oils (Francese et al. 1991). Novamont is currently experimenting with these alternatives.

EMISSIONS AND SAFETY

Greenhouse emissions

Fuels derived from vegetable oils confer a net greenhouse benefit when replacing diesel.

While pure vegetable oils and biodiesel are considered 'CO_2 neutral' in that they release no more CO_2 when combusted than was earlier absorbed by the oilseed plants, some fossil fuel inputs are likely to be needed at the agricultural and processing stages (DTI 1993). The energy required for production of biodiesel, through the various phases of farming, crushing, refining and transesterification of the oil is less than the energy produced. The energy input–output ratio is currently between 1:1.5 and 1:2 according to (Novamont 1991). However, the UK DTI (1993) states this ratio to be between 1:1.3 and 1:3.8 depending on the use of the by-products. The energy balance can be improved (at least for biodiesel production) by using hulls or meal by-products for fuel in the production process. However, it may be more lucrative to sell the meal for animal food.

Initial removal of the hulls for energy purposes allows for more efficient production of oil and meal.

The DTI study for the UK concluded that the FFC amount of CO_2 saved for each litre of biodiesel used would be 1.5 kilograms (DTI 1993). The FFC emissions of CO_2 from petroleum based diesel fuel are approximately 2.8 kilograms per litre (BTCE 1991). Biodiesel CO_2 emissions would therefore be around 1.3 kilograms per litre — a reduction of 54 per cent on diesel emissions. Meyer (1993) estimates RME CO_2 emissions of 1.26 kilograms per litre, but points out that if other greenhouse gases (nitrogen oxides and methane) are included, then biodiesel's advantage slips to 35 per cent. If the meal and straw by-products were used as fuel, the advantage would be greater.

The UK study estimates that if all 630 000 hectares of 'set aside' land (land taken out of food production as a result of the European Common Agricultural Policy) were used for biodiesel production, approximately 6 per cent of the diesel market would be replaced, resulting in a 3.5 per cent reduction in CO_2 emissions from diesel (DTI 1993). However, the impact might be less than if the land were used for other purposes, for example growing lower input and higher yielding energy crops, such as wood, to be used in direct combustion.

Noxious emissions

Concern over the emissions from diesel fuel use — particularly visible black smoke, SOx and PAHs — has been an important factor motivating research on vegetable oil substitutes. Vegetable oils (apart from sunflower oil) contain only very small amounts of sulphur. Evaporative PAH emissions would be low, as vegetable oils contain no significant amounts of PAHs (Hemmerlein et al. 1991); however, vegetable oils do appear to generate PAHs during combustion, and Hemmerlein et al. indicate they are higher than from diesel (table 6.4). Recent tests show that CO and HC are also higher from pure vegetable oil than diesel. CO, HC and particulate emissions are reduced with the use of biodiesel (Francese et al. 1991). NO_x emissions, which vary with combustion temperatures, are higher from biodiesel than from diesel, but lower from pure vegetable oils than from diesel.

Emissions from diesel and rapeseed oil

A detailed study for the Society of Automotive Engineers (SAE) in Germany, comparing engine performance and exhaust emissions from diesel and pure rapeseed oil, was completed in 1991 (Hemmerlein et al. 1991). A range of engines were tested, including those in tractors, underground vehicles, LDVs, HDVs, building machines, generators and pumps. All of the combustion systems used in modern diesel engines were covered. The discussion below concentrates on the on-road vehicles. However, the percentage changes in emissions quoted relate to the whole range of engines tested, as separate figures were not provided for each category of on-road vehicle. The figures are

TABLE 6.4 COMPARISON OF EMISSIONS FROM USE OF RAPESEED OIL AND DIESEL FUEL

Emissions	*LDV*[a]	*HDV*[b]
CO	d	d
HC	dd	d
NOx	r	=
Particulates	r	dd
Aldehydes and ketones	dd	dd
Aromatic hydrocarbons	dd	dd
PAH	d	d
Exhaust-gas smell	d	d

r	Rapeseed oil better than diesel fuel
=	Rapeseed oil equal to diesel fuel
d	Diesel fuel better than rapeseed oil
dd	Diesel fuel clearly better than rapeseed oil

Combustion system:

a. Swirl chamber (light-duty cars) — indirect injection.

b. Direct injection, turbocharged, charge-air cooler (heavy duty trucks).

Source Adapted from Hemmerlein et al. (1991).

clearly influenced by the combustion system, power output and capacity of the various engines, which varied from 40 to 274 kilowatts, and 1.6 to 12 litres respectively.

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

Exhaust emissions were higher from use of rapeseed oil, despite its higher oxygen content. CO emissions were up to 100 per cent higher (this was not dependent on engine size nor the combustion system) and HC emissions up to 290 per cent higher for all engine types, depending on the operating range of the engine. These higher emissions are due to the incomplete combustion resulting from the high viscosity of rapeseed oil, and the consequent large range of fuel droplet sizes (Earl et al. 1991).

The slower combustion and lower maximum temperature in the combustion chamber from using rapeseed oil reduced NO_x emissions by up to 25 per cent.

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

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

Emissions from blends

Earl et al. (1991) claim that a 50–50 blend of rapeseed oil and diesel gives emissions of HCs and CO very similar to those from pure diesel, and that smoke levels (which in this case appear to be equivalent to particulate emission levels) increase with increasing concentrations of oil.

However, the apparent dearth of evidence on emissions from blends of vegetable oils and diesel suggests that more tests will be required before substantive conclusions can be drawn.

Biodiesel emissions

With biodiesel also there has been only limited testing of emissions and results are varied. However, the presence of oxygen in this fuel, and its lower viscosity relative to pure vegetable oil, would assure better combustion in the engine (Francese et al. 1991). Available evidence is that, compared with pure vegetable oils, emissions of CO, HCs and particulates are lower (Francese et al. 1991). Novamont (1991) claims that compared with diesel, biodiesel reduces emissions of CO by 67 per cent, HCs by 36 per cent and particulates by 50 per cent. NO_x emissions are increased by 42 per cent. IEA (1993) data on RME emissions, compared with those from diesel, show CO reductions of 13 per cent, VOC reductions of 20 per cent and particulate reductions of 16 per cent. NO_x emissions increase by 20 per cent. These emissions from biodiesel are under the 1993 EEC limits, whereas diesel emissions of CO, HCs and particulates are well over the limit.

Soydiesel emissions

Research at the University of Missouri in Columbia looked into the emissions from a diesel pickup fuelled with soydiesel, a biodiesel fuel similar to RME. Compared with diesel, there was a reduction of 1 per cent in CO emissions and 48 per cent in HC emissions, and a 20 per cent fall in particulate matter. NO_x increased by 13 per cent (Sinor Consultants 1992f). This result provides further support for the use of biodiesel rather than pure vegetable oils as a diesel substitiute.

Oilseed crushing: impact on the environment

The effect of the crushing of oilseeds on the environment is minimal. Because of strict controls, there is only a small amount of air pollution from the dust and hexane vapour. Odorous materials are not produced. Technology is available to control smoke emissions from furnaces which burn the hulls or crop residues, and the small solid wastes from the expellers and other machines are disposed of by incineration or land-fill. Water is used almost exclusively for cooling, hence water pollution is not a problem (Stewart et al. 1981).

Safety

Vegetable oils are not hazardous. Crude vegetable oil can be used for human consumption and there are no adverse health effects.

Biodiesel is less flammable than diesel and it does not produce a flammable air–fuel mixture (Novamont, 1991). Handling requirements are the same as for diesel (Novamont, 1991). Biodiesel is also biodegradable.

CONCLUSION

Interest in fuels from vegetable oils has been generated by their ability to provide a renewable source of energy, by the scope they provide for agricultural support, and because of concern over noxious gas emissions from diesel.

Pure vegetable oils, blends, and derived fuels such as biodiesel are all able to effect a reduction in greenhouse gas emissions. This reduction has been estimated at 35 per cent for biodiesel.

Biodiesel appears to offer scope for large reductions in emissions of CO, HCs and particulates, as well as CO_2. Overseas evidence is that these emission benefits would be gained at a considerable cost. A subsidy of around 33 Australian cents per litre (slightly more than the current fuel excise) would probably be needed if biodiesel prices were to match those of diesel.

The most likely potential use for biodiesel is where the advantages of the fuel (its biodegradability after spillages and its emission levels) can be exploited for specific niche markets. These could include inland water transport or inner city vehicles, which would allow any additional distribution costs to be minimised.

The use of pure vegetable oils as a diesel substitute is not likely to result in a significant improvement in noxious emission levels. Emissions of NO_x and probably SO_x are reduced, but CO, HCs and particulates increase.

Biodiesel is more expensive to produce than pure vegetable oils because of additional processing, but costs of the pure oils would still be higher than the cost of diesel. Pure vegetable oils also have the advantage of a ready market should demand for their use as fuel decline.

The short 92term opportunity for vegetable oil fuels in Australia is limited as there are few diesel cars. Use in buses, taxis, trucks, trains and tractors could be encouraged but would require subsidisation at current fuel prices.

Increased demand for vegetable oil fuels would entail further imports of oilseed feedstock. Australia is currently a net importer of oilseeds.

CHAPTER 7 NATURAL GAS

BACKGROUND

Natural gas is comprised of a mixture of gases, almost exclusively hydrocarbons, found in petroliferous geological formations. Methane (CH_4) is the principal component, generally comprising from 87 per cent to 97 per cent by volume depending on the source of the gas. Natural gas also contains small percentages of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), pentane (C_5H_{12}), nitrogen, oxygen and naturally occurring carbon dioxide (Gafcor 1986).

Natural gas may be used as a transport fuel in either compressed (CNG) or liquefied form (LNG). In Australia CNG is compressed to around 20 megapascals for on board storage. LNG is refrigerated to –162 degrees Celsius for liquefaction, and requires vacuum-insulated cryogenic tanks to maintain it in liquid form for storage. LNG is vaporised before combustion. Levels of gases other than methane can be reduced to low levels in LNG by the liquefaction process (IANGV 1990).

Natural gas technology in transport has been applied mainly to road vehicles. However, the technical viability of marine use of natural gas has been demonstrated in ferries, and on a short-voyage coastal ship using CNG in Australia, as well as in international shipping using LNG. In the former Soviet Union, a testbed Tupolev *154* passenger aircraft has had one engine converted to operate on either liquid methane (LNG), liquid hydrogen or jet fuel. The technology for railway applications is relatively undeveloped.

Proven and probable reserves of natural gas in Australia at 30 June 1990 had almost four times the energy content of Australian oil reserves, and at almost 81 000 PJ (AGA 1992a), represented 96 years' production at 1990–91 levels. This does not include coal-bed methane, estimated to amount to a similar level (AGA, pers. comm. 1993). Australia's major natural gas reserves are located in Bass Strait (10 per cent), the Cooper–Eromanga Basin (6 per cent) and the basins of Western Australia (83 per cent), and are owned and operated by the private sector. A trans-Australia pipeline to connect the basins of Western Australia with the major consuming areas of the south-east is expected to be required by around the years 2009 to 2015 (DPIE 1991a; AGA 1992a).

Most trunk pipelines are owned and operated by essentially state-based government instrumentalities. The single interstate pipeline (from the Cooper–Eromanga field to NSW), currently owned by the Commonwealth Pipeline Authority is in the process of being privatised. State-based utilities, both private sector and government-owned, reticulate gas to residential, commercial and industrial users. Appendix VII discusses gas market structures and gas prices.

Use of natural gas in Australian transport in 1992 was only around 1 PJ (AGL, pers. comm. 1992), while for the Transport and Storage sector as a whole, usage was about 6 PJ (ABARE 1993). In the short and medium term, from a supply perspective, there is considerable scope for expanded use of natural gas in transport.

Natural gas vehicle numbers

Natural gas vehicle (NGV) programs designed to encourage the replacement of gasoline cars with dual-fuelled[1] natural gas/gasoline vehicles have been introduced in a number of countries. Initially they were driven by economic or resource security reasons, but more recently, concerns over urban air quality have been a contributing factor. By 1988 large scale NGV programs were in place in Italy (250 000 vehicles), New Zealand (100 000 vehicles), Canada (19 000 vehicles) and Argentina (10 000 vehicles). The USA had about 30 000 NGVs at this time, and the Commonwealth of Independent States (then the USSR) 70 000. The latter were primarily dual-fuelled NGV/gasoline trucks used to replace gasoline-fuelled vehicles. Australia had 500 NGVs in 1988 (IANGV 1990).

In 1992 NGV numbers in Italy were 235 000, in Canada 26 000, and in New Zealand 60 000 (IANGV 1993). The CIS had around 80 000 vehicles in 1990, and plans to have 1 million NGVs by 1995. Numbers in Argentina in 1993 are understood to be of the order of 140 000 (AGA, pers. comm. 1993). In New Zealand, which had the highest level of market penetration of any country in 1986, numbers have picked up after falling to about 50 000 in 1990 (Pinnington 1992). The decline in numbers followed withdrawal of government support and stabilisation of oil prices. The number of NGVs in the USA was still around 30 000 in 1992. Australia now has over 600 NGVs (IANGV 1993).

In Australia initial interest in NGVs has been directed towards replacing diesel powered, depot-based buses and trucks, and more recently, using natural gas in line-haul heavy trucks. Replacement of diesel trucks appears to be driven by the fuel cost advantage of natural gas, which currently carries no Commonwealth

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[1] For definition see footnote 3 to chapter 3.

excise or state tax. Replacement of urban diesel buses has been prompted by both fuel cost and urban air quality reasons.

The Australian Gas Association (AGA), a national gas industry association, has established a goal for NGVs, which was presented as its '*10/10* plan' in December 1992. This goal envisages penetration of road vehicle fuel sales by natural gas to 10 per cent in 10 years. The target number of NGVs is 340 000, including 6600 buses, 225 000 cars, 41 000 LCVs, 8800 taxis, 41 000 urban trucks and 4700 interstate trucks. The AGA estimated vehicle costs of $400 million (presumably influenced by economies of scale in conversion) and refuelling infrastructure costs of $700 million. The gas industry 'is confident' of a pump price for natural gas of 35 cents per cubic metre (AGA 1992b,9). An important aspect of the 'plan' is the increased involvement of OEM vehicle manufacture for both light and heavy duty vehicles to ensure the availability of OEM vehicles and engines.

FUEL CHARACTERISTICS

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

The energy content of CNG varies from 37.7 megajoules per cubic metre at atmospheric pressure in New South Wales and South Australia to 38.8 in Victoria, 38.9 in Western Australia and 41.5 in the Northern Territory (Gafcor 1986). The average energy content is similar to that of one litre of automotive diesel oil (38.6 megajoules), and about 12 per cent above that of one litre of gasoline (34.2 megajoules) (ABARE 1991). Pressurised storage of a cubic metre of CNG, however, requires a volume of 4 to 5 litres.

The energy content of LNG from the North-West Shelf is 25.0 megajoules per litre — about 65 per cent of that of automotive diesel oil and about 73 per cent of that of automotive gasoline (ABARE 1991). This low energy content, together with the special low temperature storage requirements, results in particularly high storage costs for LNG.

The RON for methane is 130 — higher than for leaded gasoline (97), premium unleaded gasoline (95), unleaded gasoline (91–93), ethanol (104) and methanol (105). This high octane number permits high compression ratios to be used in spark ignition engines running on natural gas, allowing potentially higher engine efficiency.

Ignition temperatures are about 150 degrees Celsius higher than for gasoline, necessitating higher ignition voltages and shortening sparkplug life (Merz 1991). Lower flame speeds of natural gas compared with gasoline (in part due to the high ignition temperatures) mean that dual-fuel cars require ignition systems that can adjust timing to suit either fuel, while dedicated NGVs would have purpose-designed ignition systems.

Natural gas has a higher gross heat content than gasoline, about 55.7 megajoules per kilogram compared with 44.8 to 46.9 megajoules per kilogram for typical gasolines (Sergeant 1991). This does not necessarily result in higher temperatures in the engine. Raine and Jones (1990) compared engine temperatures for car engines running on gasoline and on natural gas, and found that at full throttle and stoichiometric (chemically correct) air–fuel ratios, use of natural gas yielded slightly lower combustion chamber temperatures than gasoline and significantly lower exhaust temperatures. With a lean fuel–air mix (a higher ratio of air to fuel than stoichiometric), natural gas use gave slightly higher combustion chamber temperatures than gasoline. Raine and Jones concluded that for both natural gas and gasoline, temperatures were very sensitive to ignition timing and air–fuel ratio. Significantly higher engine temperatures could have required modification of some engine components and upgrading of cooling systems to maintain engine life.

Combustion of natural gas, in general, creates higher temperatures than combustion of diesel fuel (Merz 1991). However, a lean-burn spark ignition natural gas engine developed by Gafcor (Victorian Gas and Fuel Corporation) and Bosch has lower exhaust temperatures than the diesel version of this engine. As natural gas burns well in lean mixtures (IEA 1992a), this development augurs well for future NGV fuel efficiency improvements. A lean mixture can improve fuel efficiency by 5 to 10 per cent.

Gaseous fuels displace more air from the engine cylinders than do liquid fuels, which tends to reduce engine power. A fall in maximum power output results, typically of 15 to 20 per cent for a converted NGV, but an engine optimised for CNG would have only 5 to 10 per cent less full throttle output than a gasoline or diesel engine (IEA 1993). These power reductions apply also to LNG conversions, where the fuel is vaporised before introduction to the engine. In the future, liquid-phase injection — as is currently being developed for LPG — may be a possibility.

An Australian bakery company operating dual-fuel LCVs (CNG/gasoline) reported power losses of 10 per cent (NSWDME 1991a). The NRMA, testing a dual-fuel Holden VN *Commodore,* on the other hand found only a marginal loss in performance (NRMA 1992). While about 25 per cent of NGV owners in New Zealand expressed dissatisfaction with the power output of their vehicles (IANGV 1990), much of the problem appears to have been due to poor quality conversions. Of a sample of 65 vehicles, almost 30 per cent had an average power deficit of over 20 per cent after conversion. After remedial action, 5 per cent of vehicles had an average power deficit of over 20 per cent. The IANGV (1990) warned of the problem of ensuring quality control when large numbers of vehicles were being converted on a retrofit basis by a large number of small workshops.

The variability in composition of natural gas from different sources may be a cause of power losses. In New Zealand it was found that cars tuned for CNG from one region did not run well on gas from an adjacent region (IANGV 1990). In Australia different engine settings for vehicles operating in different states might be required, and this could conceivably cause some difficulties for vehicles operating interstate.

Power can decrease when a CNG tank approaches empty. For example an Australian 28 seat dual-fuel bus with a CNG tank capacity of 145 litres experiences a loss in power when it has used about 130 litres (*Australasian Bus and Coach* 1990). On the other hand, the NRMA found that a dual-fuel Holden VN *Commodore* suffered only a 'very minor hiccup' when changing from one fuel to the other while driving, using the changeover switch fitted to the dashboard of the car (NRMA 1992).

Starting, although a concern with early gasoline/NGV conversions, should not now be a problem for properly installed and maintained conversions, although drivers may require initial training in starting techniques (IANGV 1990). The NRMA (1992) experienced a problem with stalling just after starting in cold weather, a problem ascribed to the entry of water to old gas reticulation pipelines and cured by the use of a water trap in the vehicle refuelling appliance (VRA).

Implications for engine conversions

Because of its characteristics, natural gas can be used in spark ignition engines, but in compression ignition engines a proportion of diesel fuel is usually required to trigger ignition.[2] Alternatively, diesel engines can be converted to spark ignition for natural gas use.

In the case of gasoline LDVs converted to dual-fuel configurations, required modifications consist of the addition of a gas fuel system — including a cylinder — a device to mix the natural gas with air, and a mechanism to allow switching from one fuel to the other. Modifications to the ignition sytem may also be needed to cater for the different ignition timing optimal for natural gas. Dedicated 'original equipment' natural gas engines for LDVs would probably be given a higher compression ratio by manufacturers than the gasoline equivalent. The vehicle would probably also be modified to provide space for more cylinder capacity.

For diesel engines (primarily HDVs in Australia), the conversion to a compression ignition dual (mixed) fuel configuration involves use of a pilot supply of diesel to ignite the natural gas. This requires the addition of a gas fuel system alongside the existing diesel fuel system, together with a mechanism for regulating the proportion of diesel and gas for the engine speed and load conditions. According to the IEA (1993) engine efficiency for this configuration is

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[2] The cetane number of natural gas is low, indicating a high auto-ignition temperature (IEA 1992a).

about the same as that for a diesel engine. Ly (pers. comm. 1993) states that efficiency of dual (mixed) fuel systems can be equal to or higher than for diesel at high loads, but lower at part loads. For this reason, the overall efficiency in service is lower than for diesel.

Conversion of diesel engines to spark ignition engines running solely on natural gas requires more extensive modification, in that the diesel fuel injectors in the cylinder head will be replaced by spark plugs, and an ignition system added to the engine. A compression ratio lower than that of the diesel is likely to be required. Also, a greater volume of gas cylinder capacity than that viable for a dual (mixed) fuel system may be needed, as there is no possibility of reverting to pure diesel use after the gas is used up.

CURRENT STATE OF NGV TECHNOLOGY

Technological aspects affecting the potential for use of NGVs relate to conversions, engine efficiency, vehicle range, cylinders, space and carrying capacity, power output and refuelling time. Increasing reliance on OEM vehicles is expected to reduce technological problems associated with early NGV technology and so increase the potential for NGV use. Appendix VI contains additional material on the current state of NGV technology and applications and of possible developments.

Conversions and engine efficiency

The technology of NGV conversions is developing rapidly and the involvement of vehicle and engine manufacturers, though it has been small (Merz 1991), is increasing. Cars converted to run on natural gas with gasoline dual-fuel capability are intrinsically less efficient than a purpose-designed natural gas engined vehicle would be (AGA, pers. comm. 1991). AGL (pers. comm. 1992) considers that when an adequate refuelling infrastructure is in place, the NGV car will be a single-fuel vehicle optimised for gas. As well as increasing efficiency, this would allow the cost differential between an NGV car and a gasoline car to be minimised. Higgs et al. (1989) state that the potential fuel efficiency of the dedicated NGV car would be from 10 to 30 per cent higher than that of an existing gasoline car or NGV conversion.

The state of development of NGV conversions of truck engines is considered to be two to three years behind that for buses, in part because of the greater complexity of truck engines (Yorke 1991).

Heavy vehicle spark ignition natural gas engines are currently some 3 to 5 per cent less efficient than diesels and somewhat heavier than necessary, but fully developed engines should match comparable diesel engine efficiency (Yorke 1991). The lean-burn spark ignition natural gas engine developed by Gafcor and Bosch reportedly has a thermal efficiency of 37 per cent at full load, close to that of the same engine in diesel form and some 5 per cent better than overseas natural gas engines (Clifford 1991).

However, the most efficient diesel engines now available have thermal efficiencies considerably higher than this. Diesel engines with turbocharging and intercooling have thermal efficiencies as high as 44 per cent while a thermal efficiency of 46 per cent is claimed for the recently introduced Scania Turbo compounded diesel (*Truck Australia* 1992).

In the future, gas injection direct to the cylinder could yield significant fuel savings and emission reductions (Gafcor 1988).

Range

Perhaps the greatest operational drawback of NGVs is the restricted range imposed by space, weight and cylinder costs. These factors preclude the fitting of the large volume of tanks required to match the range of gasoline or diesel vehicles. Dual-fuel capability would need to be retained for vehicles which may at times need to travel long distances.

In the future, engines optimised for gas will allow some increase in range for given cylinder volume. Progress in reducing cylinder weight and bulk can also be expected.

Range with CNG

As indicated above, the energy content of 1 cubic metre of natural gas is similar to that of 1 litre of diesel oil, 38.6 megajoules, and about 10 per cent above that of gasoline, 34.2 megajoules (ABARE 1991). One cubic metre of natural gas at atmospheric pressure compresses to a volume of about 4 litres at a pressure of 20 megapascals.[3] Thus about four times the volume of diesel storage would be required for natural gas to have equal range, given equal engine efficiencies. This gives rise to problems of space, weight and cylinder costs.

CNG light vehicles

The range on natural gas of a 1.6 litre car would be about 160 kilometres with a 60 litre cylinder (dual-fuel) or about 380 kilometres with two 60 litre cylinders (dedicated NGV) — about three-quarters of its range on gasoline (IANGV 1990). The NRMA (1992) found that the range for a Holden VN *Commodore* with a 75 litre tank was about 130 kilometres in the city, and up to 200 kilometres elsewhere.

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[3] In steel cylinders natural gas is stored at between 16 and 25 megapascals.

Operators of Ford *Falcon* NGV taxis in Goulburn found range to be a major problem. With one cylinder, maximum operating range was about 100 kilometres and refuelling needed to be considered after only 60 kilometres, while two cylinders occupied most of the boot space (Goulburn Taxis, pers. comm. 1992). However, the Ford *Falcon* taxi currently being developed by Ford Australia (appendix VI) will have two CNG cylinders fitted in a modified boot for a target range of 400 to 450 kilometres. It will have no gasoline tank.

Range for CNG trucks

Range is heavily influenced by cylinder weight. For example, a diesel tank holding 725 litres (2.4 metres long by 0.4 metres diameter), would weigh 51 kilograms empty and give a typical heavy truck a range of almost 1500 kilometres. To store the same energy, the necessary CNG cylinders would weigh some 2900 kilograms and occupy about 6.5 times the space. When filled, the diesel tank would weigh around 660 kilograms, and the CNG cylinders over 3400 kilograms (BTCE estimates based on data in IANGV 1990 sourced to Armour 1988).

NELA (1991a) assumed a 500 kilometre range for its investigation of the potential of NGVs in line-haul trucking, although this was stated to be a conservative assumption given the ongoing development of NGV technology. Merz (1991) considers the maximum practicable range of a CNG heavy truck to be about 500 kilometres considering the weight, cost and space required for gas storage; while Yorke (1991) regards 600 kilometres as feasible for a dedicated CNG truck, and about 700 kilometres for a dual (mixed) fuel truck. The weight penalty involved would then be about 1 tonne. A maximum practicable range of 500 kilometres may not be such an important factor as may at first appear, provided adequate refuelling facilities are available. Maximum driving hours between rest breaks for heavy vehicle drivers are 5 or 5.5 hours in various mainland States (NELA 1991a). In addition, weight may not always be a consideration, depending on the nature of the freight task.

Range for CNG buses

In Victoria, a M.A.N. spark ignition gas bus on trial with the Public Transport Corporation of Victoria (PTCV) has a range of only 300 kilometres, although Mercedes Benz spark ignition natural gas buses achieve 400 kilometres or more. (Fifteen per cent of route distances per shift from the Doncaster depot are more than 300 kilometres, but only 5 per cent from other depots.) The PTCV has found that the extra half-tonne weight of NGVs is not a problem, as its buses do not run to 16 tonne axle load limits. There is an agreement with the unions that the buses will carry only 63 passengers, instead of the 80 to 90 possible (PTCV, pers. comm. 1992).

The Scania spark ignition buses on trial with State Transit in NSW have a range above 300 kilometres from 800 litres of gas storage in eight fibre-wrapped cylinders, with a net weight penalty of three-quarters of a tonne. There is the capability to carry another 200 litres. Some daily runs will be in excess of 300 kilometres. State Transit has made a submission to the Roads and Traffic Authority of NSW (RTA) for a dispensation to run at the design weight of 18 tonnes, arguing that the air suspension of the Scanias is less harsh on the road and on the grounds of the environmental benefits from NGVs (State Transit 1992). Australian axle load weight limits (6:10 tonnes front:back) are lower than European (7:11 tonnes). Aluminium tanks were not regarded as a lower weight alternative. The National Road Transport Commission is currently undertaking studies in this area.

ACTION buses in the ACT operate on route distances per shift less than 300 kilometres for the NGV bus trial. Refuelling is then needed only once per shift — the same as with the diesel buses, which have a range of about 450 kilometres. Axle load limits are approached with ACTION's Renault buses, so that weight-saving modifications such as replacing the high level exhaust with an under-bus exhaust could be required (ACTION, pers. comm. 1992).

Range with LNG

While the use of LNG imposes a storage weight and space penalty compared with diesel, the penalty is much smaller than would be imposed by the use of CNG for the same operating range. To store the same energy as the 725 litre, 51 kilogram diesel tank in the example of the CNG truck above, the necessary LNG tanks would weigh around 785 kilograms and occupy about 2.5 times the space (BTCE estimates based on data in IANGV 1990 sourced to Armour 1988). When the weight of the fuel is taken into account, the diesel tank would weigh 660 kilograms full, while the LNG tanks would weigh around 1100 kilograms (BTCE estimates). One LNG tank gives a range of more than 500 kilometres in normal service (NGV Newsletter, June 1993).

The two Australian-made 500 litre LNG tanks fitted to the International *Transtar* truck operating between Alice Springs and Yulara have a reflective mylar film as well as the vacuum between the stainless steel inner and mild steel outer casings of the cryogenic tanks. The tanks each weigh (when full) about one-half tonne (*Truck Australia* 1990), less than half of which is the weight of the fuel. An operating range of 1000 kilometres is claimed. The tanks are filled to about 90 per cent of capacity to allow space for vapour from boil-off (Hatfield 1990).

CNG cylinders

Heavy articulated vehicles experience a weight penalty of about 1 tonne at the maximum practicable range of around 500 kilometres (Merz 1991), which would reduce payload where vehicles are operated close to axle load legal limits.

Gafcor points out that where a much shorter range is acceptable, there would be no significant overall difference in fully-fuelled vehicle weights for the same volume of fuel storage, natural gas being lighter than diesel for the same volume tank. Weight difference between full and empty would be smaller than with diesel, giving suspension and handling advantages (Skjellerup 1991).

Research and development on cylinder design is proceeding towards lighter weight cylinders, shapes other than cylindrical and higher cylinder pressures to permit greater fuel capacity. Current aircraft technology allows for gas pressures up to 10 times current NGV cylinder pressures. In Australia fibre reinforced, hoop-wrapped welded steel cylinders are being developed (AGA 1992c). Aluminium cylinders have been used in Transperth's CNG buses (*Bus Ride* 1990), but use has now been discontinued. According to the IEA (1992a), aluminium cylinders encased in composite fibre material are capable of operating at pressures of up to 20 megapascals.

Cylinders made of fibre-reinforced composites promise the lightest — although most expensive — storage and would be more progressive in their mode of failure, leaking rather than failing suddenly (Gafcor 1988). The IEA (1992a) expects cylinders of lightweight ceramic materials to be available in 10 years.

CNG storage by activated carbon adsorption

The use of activated carbon adsorption has the potential to allow increased gas storage for a given cylinder pressure. Joint British and Canadian research has shown that, using materials already commercially available, it is possible to store (at a pressure of 3.5 megapascals) an amount of natural gas equivalent to that stored in a conventional cylinder at 10 megapascals (*Automotive Engineer* 1991b). With future developments in adsorbent materials, the equivalent pressure could rise to between 15 and 17 megapascals. Even at these storage capabilities, storage will be less than is already available with simple high pressure cylinders at 20 megapascals.

Low pressures would facilitate the use of tank shapes other than cylindrical, allowing greater volumes or less obtrusive storage positions. The CSIRO is involved in research on cylinder problems (CSIRO 1989).

Space for components

As with LPG conversions, the limited under-bonnet space in some front-wheel drive cars may prevent the necessary components from being fitted to the engine. However, they have fitted easily into a two-seater Honda 800cc micro car, albeit with a very compact engine. With OEM vehicles this would not be a problem.

A CNG cylinder would have a substantial effect on available boot space, especially in small cars. AGL (pers. comm. 1992) regards forward control vans as the most difficult vehicles to convert satisfactorily, as the cylinder impinges significantly on the cargo space.

It has been argued that the bulk and weight of CNG required precludes most depot-based trucks from carrying a full day's fuel supply (Merz 1991). Large articulated trucks can easily accommodate sufficient CNG to give a range of 400 to 500 kilometres by using large diameter cylinders attached to the rear of the prime mover (Skjellerup 1991).

Buses have the underfloor space to accommodate storage for a range of 400 kilometres, using long, narrow cylinders. However, the PTCV points out that the trend is for buses to have a low floor with gas bottles on the roof. Mercedes Benz and M.A.N. now make more low-floor than high-floor buses.

Performance

The power disadvantage compared with a gasoline engine (discussed above) can be alleviated in a dedicated NGV engine by using a higher compression ratio to take advantage of the higher octane number of natural gas (*Automotive Engineer* 1991a). The better fuel–air mixing possible with gaseous fuels may also assist. Stephenson (1991), however, considers that after optimising the engine for gas, the power loss would still be 5 to 10 per cent. Rate of acceleration losses of up to 20 per cent are common with dual-fuel conversions (IEA 1993).

This power loss needs to be considered in the light of the overall service potential of the vehicle. In optimised vehicles, for example, the higher compression ratio possible can also result in improved fuel efficiency.

For spark ignition conversions from diesel, an increase in power or torque — or both — is possible. Dynamometer tests of a lean-burn spark ignition dedicated natural gas truck engine developed by Gafcor and Bosch have shown readings of up to 400 horsepower, although the diesel engine from which it is derived is rated at 320 horsepower (Clifford 1991). A dedicated CNG spark ignition engine used in Transperth's CNG buses gave 15 per cent better maximum torque at a lower engine speed, providing better acceleration from bus stops (*Bus Ride* 1990). Improved 'bottom end' torque was also reported by ACTION (pers. comm. 1992) for its buses in the Australian Capital Territory. PTCV drivers found that the performance of NGV and diesel buses was the same (PTCV, pers. comm. 1992).

Refuelling times

If retail refuelling stations are to become widely used for NGVs, refuelling times comparable with those for liquid fuels would be required.

Refuelling may be fast fill or trickle fill. Trickle fill is used for home refuelling, and could suit some depot applications. The minimum VRA flow capacity is 2 cubic metres per hour, although rates of over 3 LGEs per hour appear common (NSWDME 1991b; AGL, pers. comm. 1992).

For depot refuelling, Gafcor's modular refuelling stations for trucks and buses have compressor capacity rates of up to 400 cubic metres per hour and on-site storage of up to 2500 cubic metres of natural gas. This would be sufficient to fill over 15 000 litres of cylinders at 16.5 megapascals. The refuelling time would probably be limited by the size of the refuelling connectors.

Benders Busways Pty Ltd of Geelong, which operates a fleet of CNG dual (mixed) fuel buses, has depot refuelling facilities which can refuel its buses more quickly than equivalent diesel vehicles can be refuelled (*Australian* 1992). The PTCV (pers. comm. 1992) achieved refuelling times of 120 seconds for an average bus fill of around 270 litres. Similarly, the *Louisville* heavy truck operated by Ford Australia which carries 800 litres of CNG, can be refuelled in about four minutes (Clifford 1991), compared with about three minutes to fill a heavy diesel truck (*Australian Energy Research* 1989).

Some depot applications may remain suited to slow overnight trickle filling. Five to 10 per cent more gas can be stored for a given final pressure using slow refilling, as quick filling leads to a rise in temperature (IANGV 1990). As no on-site storage tanks are required, trickle filling is cheaper, and it also requires less energy for compression (Merz 1991).

Refuelling with LNG is described as quick and simple, although requiring caution and the use of heavy gloves (Yorke 1991).

NGV COSTS

The costs of NGV use include the reticulated fuel cost, the cost of refuelling infrastructure, vehicle conversion costs or, alternatively, the additional costs incurred in producing new, dedicated vehicles, non-fuel operating costs and any costs associated with the shorter range, reduced boot space, carrying capacity or other factors affecting the utility of NGVs.

For the potential NGV user, the financial viability will depend on whether the private costs of conversion (including the cost of gas cylinders) and any refuelling infrastructure (as well as costs imposed by shorter range, more frequent and perhaps slower refuelling and reduced payload) can be recovered in an acceptable time through lower operating costs. This will depend critically on the price of gas relative to that of other fuels, on the amount of fuel used by the vehicle per year and on the price of conversion.

DPIE warns that technological breakthroughs in gas conversion to other fuels or chemicals, such as methanol, could quickly alter the economics of NGV use (DPIE 1991a).

Conversion costs

AGL (pers. comm. 1992) put the cost of converting a small gasoline vehicle to NGV at $2000 to $2500, including cylinder costs. IANGV (1993) gives a range of US$1350–4000 for conversion, depending on the size, weight and number of cylinders. The NRMA quotes the cost of conversion of a dual-fuel Holden VN *Commodore* at about $2000 (NRMA 1992). Gafcor has put the cost of converting to NGV using its 'production' 400 horsepower engine at $15 000 to $20 000 (Clifford 1992). State Transit in NSW stated (pers. comm. 1992) that a spark ignition NGV bus costs about $20 000 more than the diesel version.

Cylinder costs

The cost of a CNG cylinder suitable for an LDV is about $600 to $1000 (AGL, pers. comm. 1992). The IANGV (1993) gives a cost of US$450. For a full gas heavy truck, Yorke (1991) quoted an installed cost of $A20 000 for 1600 litres water capacity of gas cylinders, providing a range of about 600 kilometres.

IEA (1993) assumed cylinder costs for dedicated NGVs of between US$30 and US$60 per kilogram, which equates to US$24 to US$45 per cubic metre, or US$480 to US$900 for 120 litres of CNG.

The cost of LNG cylinders in 1988 was approaching that of CNG cylinders for the same energy storage (Gafcor 1988).

AGA considers that cylinder rental, with the rental cost included in the gas price, could be a viable approach to cylinder supply (AGA, pers. comm. 1991). NGV Australia[4] (pers. comm. 1992) is to hire cylinders rather than sell them, at $25 per month for a 120 litre cylinder, including retest at five-year intervals. This would amount to about 2 cents per kilometre, assuming the annual average distance travelled by LDVs. The PTCV (pers. comm. 1992) indicated that Gafcor had offered leased cylinders which would store 1 cubic metre of natural gas for $8 per year.

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[4] NGV Australia is the business unit of the Gas and Fuel Corporation of Victoria, which trades as Gafcor. NGV Australia is involved in the development of NGV technology.

Dedicated CNG LDV costs

The IEA (1993) forecasts that dedicated CNG vehicles in the US car market in year 2000, capable of two-thirds the range of otherwise equivalent gasoline vehicles, will cost between US$677 and US$1403 more than the gasoline vehicles, and CNG vehicles capable of the same range, between US$1080 and US$2210 more.

Fuel costs

The AGA's *10/10* plan aims for a price of 35 cents per cubic metre of natural gas. In energy content this is equivalent to about 1.1 litres of gasoline or 1 litre of diesel. The 35 cent price (about $9.20 per gigajoule) is the estimate which would cover all costs and normal profit up to the retail pump, irrespective of whether the costs were borne by the gas utilities or other firms — for example, oil companies — if natural gas were sold at existing service stations.

IEA (1993) has made estimates of prices for retail CNG in the year 2000 in the USA. These are, in 1992 dollars, US$4.0 to 6.2 per gigajoule (about A$5.7 to 8.9), where the lower figure relates to CNG facilities installed in existing gasoline stations. The break-up of these IEA estimates is shown in table 7.1.

An NRMA (1992) test of a CNG vehicle using home refuelling found that gas supplied cost around 39 cents per cubic metre. The lease of the home refuelling appliance ($208 per year) and the electricity used to compress the gas ($93.75) added 36 per cent to the gas cost, for a total cost of around 53 cents per cubic metre. Based on the 17 000 kilometres driven in the year on gas, the overall fuel cost per kilometre at 6.7 cents was 30 per cent below the gasoline cost of 9.6 cents.

For firms operating their own refuelling facilities, natural gas costs may be lower than 35 cents per cubic metre, depending on the cost of gas to the firm and on compression costs. Gas costs vary among states, among residential, commercial and industrial market categories, and according to an enterprise's

TABLE 7.1 ESTIMATED US CNG RETAIL PRICE COMPONENTS

Cost category	*Lower estimate ($US4.0 per GJ) (per cent)*	*Upper estimate (US$6.2 per GJ) (per cent)*
Delivered gas price	66.0	42.0
Facility energy use	12.5	8.0
Non-energy operating costs	15.0	35.0
Construction costs (over 20 year life)	6.5	15.0

Source IEA (1993).

overall gas consumption. The Industry Commission has estimated that 'free and fair' interstate trade in gas could reduce gas prices by around 10 per cent (TPC 1992).

For depot based refuelling, gas costs may vary with the level of natural gas usage by a firm for other purposes. For example, an Australian company operating NGV/gasoline dual-fuel trucks and LCVs and an NGV/diesel dual (mixed) fuel truck, faced fuel costs equivalent to 26 cents per litre on average in summer, but only 19 cents per litre during winter (NSWDME 1991a).

In calculating rates of return on investment in NGVs, Yorke (1991) used 1991 Victorian prices for natural gas of 18.5 to 23 cents per kilogram, (13.9 to 17.3 cents per cubic metre). Operating costs for the compressors (excluding capital costs), estimated at 3.4 cents per cubic metre, added 20 to 25 per cent to the reticulated gas cost.

The PTCV (pers. comm. 1992) stated that fuel cost savings by its buses were difficult to quantify because the price of diesel to the PTCV varied considerably. It was usually 10 cents per litre below service station retail prices. Diesel bus costs were estimated at about $30 per 100 kilometres, with spark ignition natural gas at about $17 per 100 kilometres at a gas price of 35 cents per cubic metre. However, the PTCV estimated cost savings varying between $100 and $1000 per bus per year for older dual (mixed) fuel buses where the amount of diesel used preempted the benefits which might have been gained from lower natural gas prices. The PTCV considered that gas supplied at 35 cents per cubic metre from a Gafcor owned station was a good price for gas, electricity and interest on capital (PTCV, pers. comm. 1992).

Fuel costs as a proportion of total truck operating costs vary with truck size and type of use. Thoresen (1992) estimated diesel fuel and oil costs on average at 21 per cent of vehicle operating costs per kilometre (including wage costs) for articulated trucks, 17 per cent for rigid trucks with trailers, and for rigid trucks between 13 per cent (four-axle) and 10 per cent (two-axle). For large combinations, fuel was about 25 per cent of operating costs (Thoresen 1992). Data in Milthorpe (1992) showed fuel costs for NSW State Transit buses in 1990–91 were only 6 per cent of unit costs per kilometre.

Excise treatment

The AGA (1992b, 13) has stressed that the possibility of achieving its *10/10* goal hinges on a continuing excise-free status for natural gas for road vehicles, for at least the planning horizon of 10 years. The goal was predicated on the current price differential between different fuels continuing for the 10 years. The AGA argues that certainty on the excise free status would be required to permit successful marketing of NGVs to potential users, and for the gas utilities to undertake the infrastructure investments that would be required.

The AGA did not foresee a net return to the gas utilities from the *10/10* strategy for the first eight years. After the 10-year period, the AGA (1992b, 14) held that 'preferential taxation treatment would no longer be required'.

A number of other countries provide preferential tax treatment for NGVs. For example, Nela (1991a) notes the exemption of NGVs from the Canadian Federal Sales and Excise Taxes (about 11 cents per litre in 1991).

While an excise or road user charge levied on natural gas may render a 35 cent per cubic metre price unattainable at retail refuelling facilities, gas supplied to large depots (at lower prices) may be able to carry a degree of such taxes before its cost reached the 35 cent level. The effect of a reduction in the price advantage of natural gas on rates of return on NGV conversions is examined in Holmes and Naughten (1993).

Refuelling costs[5]

To achieve widespread adoption of NGVs, there would be a requirement for normal retail refuelling facilities for light and heavy vehicles, as well as private depot facilities for fleet vehicles.

Retail refuelling facilities

Widespread availability of public NGV refuelling facilities will depend on significant penetration of NGVs into the car, taxi and LCV market (Merz 1991), or at least on the expectation that this penetration will occur. It has been argued that this presents a 'chicken and egg' situation as, given the limited range of NGVs and the cost and refuelling times of VRAs, there may not be significant penetration of the light vehicle market until a network of retail refuelling facilities is available. The Gas and Fuel Corporation of Victoria (VGFC) considers that a significant penetration of the car market would require 400 NGV stations in Victoria (VGFC, pers. comm. 1991). Governments in several countries, including New Zealand (Merz 1991), Argentina and Canada, have provided assistance for the establishment of retail outlets. The Canadian government contributed $50 000 to the cost of each retail refuelling facility (NELA 1991a).

The AGA's *10/10* goal for NGVs involves an estimated expenditure of $700 million for refuelling stations to reach the target of 340 000 NGVs in 10 years. The AGA figure for refuelling expenditure represents an annualised amount of about $100 million at 7 per cent over 10 years. Given the projected numbers of vehicles and penetration of the fuel market, recovering this amount would

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[5] Amendments to the Sales Tax (Exemptions and Classifications) Act have exempted NGV refuelling equipment (Schedule 1, item 57A) from sales tax.

appear to account for around 8 to 10 cents of the estimated total cost of 35 cents per cubic metre.

Home refuelling

The AGA (pers. comm. 1991) regarded VRAs for home refuelling as only an interim measure until a network of refuelling stations is in place. NGV Australia (pers. comm. 1992) considered that VRAs are not viable in Melbourne, as compression costs make NGV more expensive than LPG (often available at around 20 cents per litre).

AGL has an interest in VRAs as a potential way of permitting better use of reticulation infrastructure. The average natural gas car would use 90 gigajoules per year (assuming higher than average mileage for natural gas cars), while average household use is 20 gigajoules per year. AGL has a NSW State Energy Research & Development Fund grant to test VRAs. About 50 units are now in service in NSW, six with AGL staff, the rest with private motorists and businesses.

The cost of the 150 Sulzer VRAs purchased from Canada was A$5000 per unit. However, AGA (pers. comm. 1991) suggested that production costs could be about A$2000 in larger numbers, and in mass production could be about A$1000 to A$1500. The VRAs are to be offered for a quarterly charge of $52 (billed with the gas account) to cover supply, installation and maintenance of the equipment.

VRAs require a gas supply uncontaminated by water. The NRMA found that a VRA installed in an area in which the gas mains had not been upgraded was affected by water leakages into the mains. The consequent corrosion in the cylinder's burst disc led to its activation at a lower than designed pressure until a water trap was installed. The water content of the gas supplied to the vehicle also caused some driving problems. These were overcome by fitting a filter to the vehicle. AGL will not now supply VRAs to 'wet' areas (NRMA 1992).

VRAs must be located in the open air, which could be a disincentive to vehicle owners whose cars are garaged for various reasons. These units also consume electricity for compressing the gas.

Widespread use of VRAs could raise problems in relation to the collection of any excise or road user charges which might be levied on natural gas. AGL (pers. comm. 1992) pointed out that a sub-meter could be fitted to the VRA, or possibly the number of hours run could be used.

Depot refuelling

For depots the VGFC has introduced a series of fully self-contained modular NGV fuelling stations in three sizes:

- package 1, designed to replace 1.5 million litres of liquid fuel per year — suitable for 40 buses or 20 trucks;
- package 2, to replace 560 000 litres of liquid fuels — suitable for a fleet of 10 trucks;
- package 3, to replace 150 000 litres of liquid fuel (Gafcor nd).

Table 7.2 gives capital costs for stations that are comparable in size.

The National Institute of Economic and Industry Research (NIEIR 1988) estimated fuelling station operating and capital costs in 1987 dollars. Though outdated, these costs indicate the effects on costs of different scale operations. These costs were amortised at 15 per cent per year, and excluded land costs and profit margins. The costs were:

- $2.12 per gigajoule for a station of 12 000 gigajoules per year — around 7 to 8 cents per litre;
- $0.64 per gigajoule for a 54 000 gigajoules per year capacity — around 2.4 cents per litre;
- $0.39 per gigajoule for a 300 000 gigajoules per year station — around 1.3 to 1.5 cents per litre.

As a proportion of the total fuel cost, the cost of the refuelling infrastructure fell from 35 per cent for the 12 000-gigajoule station (which would replace about 310 000 litres of diesel) to 9 per cent for the 300 000-gigajoule facility (which would replace about 7.8 million litres of diesel).

Merz (1991) estimated compression costs, over and above the reticulated gas price, of $2.30 per gigajoule. Operating costs of refuelling equipment have been estimated at 3 cents per cubic metre of natural gas (NSWDME 1991a). However, as in the case of the PTCV (pers. comm. 1992), there may be a substantial peak electricity demand for compressors, which would affect

TABLE 7.2 CAPITAL COSTS OF NGV REFUELLING STATIONS

Vehicle type	*Costs*
Cars	400 public stations @ $500 000 — $200m to serve 100 000 NGVs
Route buses	$350 000 to $450 000 per 50 bus depot metropolitan area
Heavy urban trucks	$350 000 to $450 000 per 35 truck unit metropolitan area
Line-haul trucks	$15 000 per truck served

Source VGFC (pers. comm. 1991).

operating costs. This could be countered by the use of gas powered compressors.

The Canadian government also provides a 25 per cent subsidy for private depot developments (NELA 1991a, 77).

Truck stop refuelling

The VGFC and AGL are investigating the economics of introducing natural gas into line-haul trucking in all Australian intercity corridors. The gas utilities have considered establishing refuelling facilities in the early stages of development, possibly handing these over to outside interests in the longer term (AGA, pers. comm. 1991).

NELA (1991a), reporting on the most cost-effective method of introducing CNG into intercapital line-haul trucking, recommended a four-stage approach to the provision of refuelling infrastructure:

- Sydney–Melbourne corridor — by 1994;
- Melbourne–Adelaide and Sydney–Adelaide — by 1996;
- Brisbane corridor — by 1998;
- Perth corridor — by 1999.

Apart from refuelling stations in the respective capitals, there would be intermediate stations at: Gundagai (stage 1); Horsham, Mildura and Narrandera (stage 2); and Dubbo, Armidale, Grafton, Newcastle and Goondiwindi (stage 3). These stations would be modular facilities, to cope with increasing market penetration over time. NELA recommended that CNG, rather than LNG, tanker trucks be used to supply intermediate refuelling stations not supplied by pipeline. These tanker trucks could supply direct into-vehicle refuelling (Hutton and Pedersen 1992).

Total costs

It appears that fuel cost savings could allow a reasonable rate of return on private investment in NGV conversion, depending on fuel prices, excise treatment, fuel consumption and mileage travelled. The Australian bakery company which began operating NGV delivery trucks and LCVs in 1985 expected a pay-back period at that time of six years. Oil price increases reduced this to three years, and it is claimed that at 1991 oil prices the position has improved further.

The IEA (1993) estimates that for cars in the USA in the year 2000, the cost of switching from gasoline to CNG would be between –1.2 and 0.4 1992 US cents per kilometre for reduced range vehicles, and between –0.7 and 1.4 1992 US cents per kilometre for a full range CNG vehicle. These costs are based on assumptions of a 5 per cent discount rate and the same tax treatment for CNG (per LGE) as for gasoline.

Typical scenarios for private investment are addressed in chapter 10.

EMISSIONS AND SAFETY

NGVs have the potential to reduce greenhouse gas emissions when replacing gasoline, and to reduce emissions of certain air pollutants. For natural gas to have a significant effect on greenhouse emissions, it would have to penetrate the passenger car market (VGFC, pers. comm. 1991).

Greenhouse gas emissions

Carbon dioxide

Tailpipe emissions of CO_2 from natural gas would be lower than from gasoline due to the lower ratio of carbon to hydrogen in methane (about 75 per cent by weight compared with 83 to 89 per cent for typical gasolines). Sergeant (1991) estimates the combustion product as 49 grams of CO_2 per megajoule from natural gas and 67 grams of CO_2 per megajoule from gasoline. Tailpipe CO_2 emissions from a sample of 1986–1989 Australian natural gas cars were found to be between 16.5 and 34.9 per cent lower than from gasoline versions by the Victorian EPA (1991a). Gafcor (nd) has claimed a 15 per cent reduction in tailpipe CO_2 emissions from an NGV as compared with a diesel.

Estimates of FFC emissions are not quite as favourable for NGVs, the estimated reduction compared with gasoline being 16 per cent. The FFC emission coefficient for average Australian natural gas is around 61 grams of CO_2 per megajoule, compared with the gasoline coefficient of 73 grams of CO_2 per megajoule, and a diesel coefficient of 76 grams of CO_2 per megajoule (BTCE estimates based on DASET 1991). Varying carbon content of crude oil inputs to refineries could cause variations of some 5 per cent in the emission rates of gasoline and diesel over time. Also, Wilkenfield (1991) has calculated that FFC emissions from natural gas (before compression/liquefaction) on a state by state basis can vary from 57 grams per megajoule in Western Australia, to 70 grams per megajoule in South Australia, depending on the source of the natural gas.

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

Wilkenfeld (1991) estimates a national average FFC figure for natural gas (uncompressed) of 61.3 grams of CO_2 per megajoule, consisting of 52.7 from combustion, 4.6 from energy overheads, and 4.0 from CO_2 vented at the well-head. Wilkenfeld estimated that, for Victoria, FFC CO_2 emission rates per unit of transport task were 170 grams per kilometre for CNG, compared with 200 for diesel and 214 for gasoline.

Methane emissions from vehicles

Methane, the principal component of natural gas, has a greenhouse radiative forcing effect greater than that of the same weight of CO_2 (BTCE 1991), depending on the time horizon over which comparisons are made. Estimates range from 71 times over 20 years to 11 times over 500 years, methane having a much shorter atmospheric lifetime than CO_2 (IEA 1993). It is therefore important that tailpipe losses of unburnt fuel and fugitive/evaporative losses are minimised.

As methane is a non-reactive hydrocarbon, it has been argued that tailpipe emissions of methane are not as well controlled by catalytic converters as are more reactive hydrocarbons. Amann (1992) considered methane 'remarkably resistant' to oxidation in a catalytic converter. Natural gas may not therefore be a suitable fuel for high-performance engines having significant overlap between the opening periods of their inlet and exhaust valves, and hence an increased risk of unburnt fuel passing through the exhaust valves. Stephenson et al. (1992) report test results for an NGV car fitted with engine management systems developed for natural gas fuel. These show methane emissions some 10 to 13 times higher than those from the gasoline version, though all other emissions measured were lower. However, Ly (pers. comm. 1993) argues that correct catalyst formulation and accurate engine controls can give excellent emissions results.

The automotive NGV installation standard AS 2739 requires that the ignition be switched on and the engine cranking before gas can be supplied to the engine (Salmon 1992). Nevertheless, to minimise tailpipe emissions of unburnt methane fuel, it may be important for an NGV to be kept in a good state of tune and the battery in good condition to minimise engine cranking during starting.

Different views are held on evaporative emissions. One is that CNG vehicles do not have any, due to their sealed pressurised fuel system (ABARE, pers. comm. 1992). The IEA (1992a), on the other hand, refers to 'frequent leaks' as a technical problem to be solved for NGVs. According to the IEA (1993), existing CNG cars have methane emissions of around 1 gram per kilometre (over six times that typical for gasoline cars), adding around 10 per cent to life cycle greenhouse gas emissions (in CO_2 equivalents).

Experience with the LNG road train built to operate between Alice Springs and Yulara suggests that fugitive losses from LNG boil-off in intermittent use may not be a major problem. The LNG tanks, filled to 90 per cent of their volume

(Hatfield 1990), stood without use for 10 days before the pressure opened a relief valve (Yorke 1991).

Methane fugitive losses in distribution

Fugitive losses would have the potential to reduce substantially any advantages which natural gas may have in terms of emissions. Wilkenfeld (1991) gave gas losses as 9.55 PJ in 1986–87, in which year total consumption was 588.4 PJ (ABARE 1991) — a loss rate of 1.6 per cent. The VGFC considered that fugitive losses would be less than 2 per cent, and concentrated entirely in the old town-gas reticulation systems (VGFC, pers. comm. 1991). Refuelling depots or retail refuelling facilities would be serviced by new medium or high pressure lines, and fugitive losses from this form of distribution might be expected to be very low. A recent Swedish study estimated methane leakages from new supply lines at only 0.05 per cent (Sinor Consultants 1992b). Ly (pers. comm. 1993) points out that fugitive losses may be exaggerated through a lack of understanding of the term 'unaccounted for gas'—which is the overall accounting error including metering over a vast distribution network.

If home refuelling using VRAs were to become common, there would be a lot more gas flowing through suburban reticulation networks. AGL does not see this as a problem as VRAs cannot be used in old reticulation areas due to the presence of water in the mains; and the older, low pressure reticulation lines are gradually being replaced with leak-proof nylon pipes (AGL, pers. comm. 1992). Ly (pers. comm. 1993) points out that increased amounts of gas in the reticulation network do not necessarily mean increased leakages, depending on the time the gas is drawn off.

DeLuchi (Sinor Consultants 1992c) estimated that methane losses from supplying NGVs via the natural gas distribution system would be lower than the methane vented from coal mines providing fuel for electricity to fuel electric vehicles. Wilkenfeld (1991) implies the average methane loss from Australian natural gas distribution is around 0.4 grams of CH_4 per megajoule delivered, while the average emission from electricity is around 0.26 grams of CH_4 per megajoule delivered. The electricity figure is as high as 0.5 for NSW.

Overall greenhouse emissions from light duty vehicles

Wilkenfeld (1991), using Unnasch et al. (1989) data on fuel-optimised gasoline, diesel and NGV variants of the same car model, estimated total CO_2 equivalent emission rates (for Victoria) of 200 grams per kilometre for CNG, 201 for diesel and 241 for gasoline on an FFC basis. Wilkenfeld concluded: 'there is little greenhouse emissions advantage to be gained by substituting CNG for diesel'.

Wilkenfeld's estimates are consistent with those of the IEA (1991b; 1992a) for North American light duty vehicles (LDVs). However, the Victorian EPA (1991a) reported USEPA tests for gasoline and CNG versions of three US cars, which show that the relative greenhouse impact is dependent on the global warming factor (GWF) attributed to methane. At a value of 16 (time horizon about 150 years), the CNG cars showed lower greenhouse impacts than the gasoline versions by between 13 per cent and 20.5 per cent. If, however, a GWF of 65 were used for methane (time horizon around 20 years), while two of the cars still had lower greenhouse impacts (by 3 per cent), the other was higher (by 8 per cent). When a factor of 116 was used (instantaneous effect), all three NGVs had a greenhouse impact between 15 per cent and 34 per cent higher. The Victorian EPA noted that while a value of 16 is frequently quoted by respected researchers (Pearman 1989), there is no general consensus and values up to 116 have been suggested (EPA 1991a, 24).

The IEA (1993) estimates that CNG could, by the year 2005, have a life cycle emission advantage over gasoline of 11 per cent in the North American market and 13 per cent in the European market. The advantages of diesel over gasoline were 19 and 23 per cent respectively. The IEA emphasises that this result is very sensitive to the assumptions made. A range of estimates is provided in which the worst case for NGVs has emissions 40 per cent higher than in the diesel worst case, and the best NGV case has emissions 17 per cent less than those from diesel.

These IEA figures are influenced by the relatively high emissions from the fuel supply process; these are estimated at 21 per cent of the life cycle greenhouse gas emissions from NGVs using CNG. Ecogen (1990) also estimated that the extraction, refining and distribution of natural gas accounted for 23 per cent of total greenhouse emissions from supply and use of CNG in a motor vehicle (using a GWF of 16 for methane). This compares with its estimate of 14.2 per cent for the proportion of emissions from gasoline vehicles due to fuel supply.

In contrast, data from the NZ Liquid Fuels Trust Board indicate that NGVs had net greenhouse advantages of 15 per cent over diesel and 10 per cent over gasoline vehicles (ABARE, pers. comm. 1992).

Sperling and DeLuchi (OECD 1992) estimated life cycle emissions from CNG and RFG from various classes of LDV. For the 'base case' LDVs, emissions from CNG were 1.4 and 15.3 per cent below those from RFG, for a 20 year and 500 year time horizon respectively. For high efficiency LDVs, the 100 year time horizon estimate was for emissions 17.2 per cent below those from RFG (OECD 1992).

Sperling and DeLuchi also illustrate the level of uncertainty about the greenhouse effects of such fuel substitution (Sinor et al. 1992c). They provide a span of estimates for LDVs on CNG or LNG compared with RFG, from a 35 per cent increase to a 35 per cent decrease in CO_2 equivalent emissions, depending on a number of factors including a time horizon of 20 to 500 years.

The emission effects of NGVs will be influenced by the emissions equipment of the vehicle converted. According to Shell (1992), vehicles with catalytic converters will show much smaller reductions in CO emissions when converted to NGV than will those without catalytic converters, while NO_x and methane emissions will probably be higher. Shell's view is that FFC emissions from CNG vehicles will range from a 10 per cent decrease to a slight increase, depending on the concentration of CO_2 in the raw gas, the fuel used to provide the energy used in compression, and on fugitive methane losses.

Overall, while there is significant variation in estimates for greenhouse emissions from LDVs, natural gas generally shows a clear advantage over gasoline, except in the case of a short time horizon.

Overall greenhouse emissions from heavy vehicles

The situation is different for heavy vehicle emissions, regarding which there is a diversity of opinion.

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

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

Similarly, Wilkenfeld (1991, 142–3) concluded:

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

Milkins (1989) estimated a 16 per cent reduction in CO_2 emissions from replacing a future 'clean' diesel vehicle with an optimised lean-burn CNG vehicle. Walker (1990) had considered that natural gas might substitute for almost 10 per cent of ADO in road transport by 2005, and that this could reduce CO_2 emissions from all trucking by about 2.5 per cent, implying reductions in CO_2 emissions of around 25 per cent from converting a diesel heavy vehicle to CNG in 2005. However, methane emissions from NGVs would reduce the overall greenhouse advantage. In dual (mixed) fuel natural gas vehicles, high methane emissions could negate or reverse the CO_2 advantage (Milkins 1989, 15).

The estimate of Oppenheimer and Zingarelli (1991) of a 12 per cent greenhouse advantage for CNG heavy vehicles supplied from high pressure reticulation (in Victoria) used a GWP for methane of around 15 (100 years). Their sensitivity analysis using a GWP of around 29 (20 years) had this advantage declining to 4 per cent. Also, nitrogen oxide emissions (which have some greenhouse impact) were not included in this analysis. Though NO_x emissions are likely to be higher from an NGV than from a diesel powered vehicle (unless lean mixtures are used), this would probably not affect their results greatly.

Sperling and DeLuchi (OECD 1992) estimated life cycle emissions from base case CNG HDVs ranging from 13.1 per cent above those from diesel with a 20 year time horizon to 4.9 per cent above with a 500 year horizon. For high efficiency CNG HDVs, Sperling and DeLuchi's estimate was for emissions 2.3 per cent below those from diesel HDVs (100 year time horizon).

DeLuchi (Sinor Consultants 1992c) gave a span of estimates for CNG or LNG compared with low sulphur diesel in HDVs, ranging from a 45 per cent increase to a 15 per cent decrease in CO_2 equivalent emissions, depending on a number of factors, including the time horizon.

Some recent information on the use of CNG buses in Australia is that reductions in tailpipe CO_2 emissions can be significant. Tests of South Australian State Transit Authority buses indicate a saving of 15 per cent (*Public Transport International*, April 1993). In Canada also, recent tests on comparable diesel and natural gas buses on city cycles have shown CO_2 emissions to be 15 per cent lower from the natural gas buses (Milkins, pers. comm. 1993).

Assessment

There would appear to be a significant greenhouse advantage in replacing gasoline vehicles with NGVs, but as the diversity of views on HDV emissions indicates, it is not clear that there would be a greenhouse advantage from replacing diesel with natural gas. AGL regards the Wilkenfeld and IEA estimates of little or no greenhouse reduction from substituting natural gas for diesel in HDVs as conservative because they are based on old NGV technology (AGL, pers. comm. 1992).

The optimised lean-burn NGV engine, with higher fuel efficiency than existing NGVs, could in future offer some greenhouse emissions advantage over diesels, depending on the relative rates of improvement in fuel efficiency of diesels and NGVs, and on rates of methane emissions during the full natural gas fuel cycle.

Local air pollution and noise

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

NGVs have the potential to effect a significant reduction in local air pollutants such as CO, NMHCs, SO_x, particulates, smoke and odour. The situation with regard to NO_x is less clear cut, and the effects of traces of formaldehyde in NGV exhausts (though less than from alcohol fuels) have yet to be determined (Merz 1991).

The level of emissions from NGVs is strongly affected by the state of tune of the engine (IANGV 1990); also, purpose-designed OEM NGVs can have different emission levels from conversions. For example a Chrysler OEM NGV van has been officially certified as an ultra-low emission vehicle (ULEV) by the California Air Resources Board (AGL, pers. comm. 1992).

Carbon monoxide

Carbon monoxide emissions are very low under lean mixture conditions (IANGV 1993), but operating at mixtures richer than stoichiometric for maximum power leads to higher CO emissions. The Victorian EPA (1991a) found that tailpipe CO emissions from its sample of 1986–1989 cars were between 49 per cent and 99 per cent lower than from the gasoline versions, albeit at leaner fuel-air mixtures than applied in the gasoline cars. Australian fleet average CO emissions are of the order of 20 grams per kilometre, and new vehicles emit less than 5 grams per kilometre (Carnovale et al 1991). ABARE (pers. comm. 1992) has referred to data supplied by the NZ Liquid Fuels Management Group showing that NGVs produced CO at a rate of 4.8 grams per kilometre, much lower than from New Zealand gasoline cars.

Carter et al. (1992) reported comparative CO emission rates for three gasoline and three NGV versions of cars and light trucks in the USA. Two out of the three NGV cars showed higher emissions than those from the comparable gasoline versions, but two of the three still met the Californian 'low emission vehicle' (LEV) standard (3.4 grams per mile). All three NGV light trucks met the LEV standard for CO, and one the 'ultra-low emission vehicle' (ULEV) standard. However, two of the trucks, including the one meeting the ULEV standard, had CO emissions higher than from their comparable gasoline versions.

Reductions in CO emissions of 60 to 75 per cent for gasoline to dual-fuel NGV conversions — of around 55 per cent for diesel to dual (mixed) fuel conversions, and of 100 per cent for diesel to spark ignition conversions — have been claimed by the IANGV (1990).

Oxides of sulphur

Most Australian natural gas is designated as 'sweet', with low concentrations of sulphur compounds helping to minimise SO_x emissions. While odorants required to be added to natural gas as a safety measure may add to total sulphur content, sulphur content of gas remains relatively very low at 0.005 per cent by weight. While Australian crude oils are also low in sulphur, the prospects are for increased imports of crude oil with a significant sulphur content.

Oxides of nitrogen

NO_x emissions increase with engine operating temperature (Gafcor 1986), and natural gas burns with a hot, rapidly propagating flame (IEA 1992a). For gasoline to dual-fuel NGV conversions, the IANGV found a wide range of emissions results for engines prior to fitting of emissions equipment (IANGV

1990). The Victorian EPA (1991a) found that with the exception of one car with a 1.6 per cent reduction, tailpipe NO_x emissions from its sample of 1986–1989 Australian cars increased, in one case by as much as 208 per cent. In contrast, AGL's experience, using the same official cycle tests as used by the EPA, has been that its own vehicles tested over the past five or six years have not emitted higher tailpipe emissions of NO_x (AGL, pers. comm. 1992).

US tests of dual-fuel gasoline/CNG cars, by the US EPA and CARB, found that three out of five vehicles tested suffered increases in NO_x when using CNG, two of them to the extent that the passenger car standard of 1 gram per mile was exceeded (Sinor Consultants 1990). The more recent tests of Carter et al. (1992) on three NGV cars yielded results for two cars which were 20 and 26 per cent below those from the comparable gasoline versions, and which met the Californian transitional low emision (TLEV) standard (0.4 gram per mile). The third car produced NO_x emissions 19 per cent above those from the comparable gasoline version, but still met the TLEV standard for NO_x. All three NGV light trucks met the TLEV standard, with NO_x emissions between 47 and 77 per cent of those of the gasoline version, with one of the vehicles meeting the LEV standard (Carter et al. 1992).

Narushima (1992) reported NO_x emissions of 0.02 gram per kilometre from a Nissan AD Van equipped with a special catalytic converter developed for natural gas fuel, and considered that the vehicle could meet the ULEV standards on the US test cycle for NO_x and other emissions.

The IANGV (1990) stated that for a diesel to spark ignition conversion, NO_x emissions were reduced when operating under lean mixture conditions to match the power of a diesel, but operating the NGV engine at mixtures richer than the stoichiometric (or chemically correct) mixture for maximum power led to higher NO_x emissions. NGV Australia (pers. comm. 1992) stated that significant NO_x reductions were possible provided that the air-fuel ratio was greater (leaner) than 1.4 times the stoichiometric ratio. Gafcor (nd) claimed a 25 per cent reduction in NO_x emissions compared with diesel for an NGV using its *Lambda 2* engine management system. The Cummins engine developed by NGV Australia operated at ratios between 1.4 and 1.8 (Clifford 1992). Gafcor claimed up to 80 per cent less NO_x for this lean-burn spark ignition engine (Skjellerup 1991).

Yorke (1991), reviewing the experience of International Trucks Australia Limited with the development of four natural gas trucks, concluded that while NO_x emissions could be a concern, they could be controlled using catalyst technology, as for other low NO_x engines. For dual (mixed) fuel buses on trial in Melbourne, Gafcor claimed 7 per cent less NO_x than from diesel buses (Gafcor nd).

Hydrocarbons

The Victorian EPA (1991a) found that tailpipe HC emissions for a sample of 1986–1989 Australian cars increased by between 141 per cent and 430 per cent when using natural gas, with three of four failing the ADR 37 limit of 0.93 grams per kilometre. This was attributed to factors that included the basic nature of the fuel–air mixer used, catalytic converters being designed for gasoline fuel, non-optimised ignition settings and the use of open-loop NGV systems, rather than to the chemical nature of the fuel.

However, 90 per cent or more of the HC emissions were methane, which is relatively stable and non-reactive (although a greenhouse gas), and only 10 per cent or less were reactive non-methane hydrocarbons. The Victorian EPA cited CARB and US EPA tests which showed that reactive hydrocarbon emissions were lower from NGVs than from gasoline vehicles (EPA 1991a). ABARE (pers. comm. 1992) concluded, on the basis of data supplied by the New Zealand Liquid Fuels Trust Board, that typical gasoline engines produced HC emissions at a rate of 12 grams per kilometre and NGVs at only 1.6 grams per kilometre. However, AGL (pers. comm. 1992) noted that NZ data need to be used with care in an Australian context, and may not be comparable with emissions results for post-1986 Australian cars complying with ADR 37, which typically emit less than 0.6 grams of HC per kilometre (Carnovale et al. 1991).

IEA (1993) figures indicate non-methane HC emissions from CNG vehicles are around one-quarter of those from comparable gasoline cars. Carter et al. (1992) have also compared non-methane organic gas (NMOG) emissions for US gasoline and natural gas versions of cars and light trucks. All three NGV cars met the Californian TLEV standard (0.04 grams per mile), while one met the ULEV standard for NMOG. Two of the three NGV light trucks met their ULEV standard, but the other exceeded the Californian standard (Carter et al. 1992).

Particulates

Emissions of particulates, some of which are carcinogenic, are almost eliminated with natural gas use. The IANGV (1990) noted that the NGV engine's lubricating oil appeared to be the source of remaining particulate emissions. The IANGV cited test results of 0.02 gram per brake horsepower-hour for a CNG engine, compared with the 1994 US HD Diesel Standard of 0.1 gram per brake horsepower-hour (IANGV 1990). Gafcor (nd) claimed an 80 per cent reduction in exhaust smoke from NGVs. The PTCV experience (pers. comm. 1992) was that smoke levels from its dual (mixed) fuel CNG buses were lower than from its diesel buses.

Noise

Gafcor tests indicate a reduction in the noise levels of 3 decibels at peak load, and 6 decibels at idle and light load, from a heavy truck engine converted to spark ignition natural gas (Clifford 1991; Skjellerup 1991). As a 3 decibel increase in noise level indicates a doubling of noise intensity, these reductions might indicate a significant lowering of noise intensity, especially in urban areas, where light load and idling would be common.

Van Akkeren (1992) reported a 2.7 decibel reduction in outside noise levels for an NGV city bus at 30 kilometres per hour, but only an 0.8 decibel reduction at 49 kilometres per hour. The PTCV (1992) pointed out that the noise level difference from its dual (mixed) fuel buses was almost undetectable, and was not an issue. Ford Australia (pers. comm. 1992) also considered that the noise level from its CNG Ford Louisville was almost indistinguishable from that from a diesel.

Noise of refuelling installations

Gafcor modular refuelling stations are acoustically lined, and emit noise measured at 55 decibels at a distance of one metre (Gafcor nd). By comparison, conversational speech would register 60 decibels or more at the same distance (Holman 1971). An Email Westinghouse Fuel Maker VRA registered 45 decibels at five metres distance (NSWDME 1991b), similar to the background noise level within an average residence (Holman 1971). The NRMA has described a VRA installed at an employee's home as 'very quiet in operation' (NRMA 1992, 2).

Safety

The safety concerns with NGVs chiefly relate to the risk of fire and explosion in collisions, while refuelling or in vehicle repairs. The IEA (1992a) describes the safety record of natural gas as a fuel as 'very good'. This view is supported by Merz (1991) and Svendsen and Andersen (1992).

In Italy during the period 1974 to 1980, there were about three-quarters of a million cylinders in circulation. The average rate of explosions was 0.0049 per 1000 cylinders in this period; no explosions were reported between 1981 and 1983. In New Zealand, following a cylinder explosion in 1989 during refuelling, a recall of the particular brand of cylinder concerned found that some 10 per cent had the manufacturing fault which had caused the explosion (IANGV 1990). This cylinder make and model has never been approved for use in Australia (AGL, pers. comm. 1992).

Explosion and fire hazard

Yorke (1991) notes that natural gas, being lighter than air, diffuses readily if released, and this is likely to bring the mixture below the lower flammability (or explosive) limit. Burst discs and fusible plugs permit the release of gas when fire causes cylinder pressure to rise to the rupture point of the burst disc (Ly, pers. comm. 1993). Fusible plugs melt at 100 degrees Celsius (Salmon 1992).

State Transit in NSW regards NGVs as very safe. State Transit referred to a 1990 bus depot fire in Utrecht as a result of which 35 buses, including two NGVs, were destroyed. Diesel tanks exploded, but the NGVs' burst discs operated, releasing gas in two streams of flame without exploding. The escape velocity of the gas was such that there was no chance of the flame entering the cylinder, which in any case contained no oxygen (State Transit 1992). In extinguishing an NGV fire, it is advisable to allow the gas to burn off first via the disc valve or fusible plug.

Safety in collisions

Yorke (1991) states that CNG cylinders are stronger and better protected than liquid fuel tanks, and generally have better mountings. Safety release valves further reduce the risk of explosion. IANGV (1990) provides details of a crash fire simulation in which gasoline was ignited underneath and in the boot of a natural gas car. When the temperature in the boot reached 850 degrees Celsius, the cylinder burst disc ruptured, allowing the contents to be vented and burned off. CNG tanks are considered by Merz (1991) to be much safer than those used for liquid fuels.

Safety during distribution and re-fuelling

The AGA maintains that natural gas refuelling stations would be safer than LPG refuelling points, as bulk fuel tends not to be stored on site. Gas is taken from the mains and compressed just before being put into the vehicle (AGA, pers. comm. 1991). However, Gafcor's modular refuelling stations for trucks and buses have on-site storage of up to 2500 cubic metres.

NG refuelling systems are designed to eliminate spillage while refuelling (Yorke 1991), and safety devices are fitted to prevent overfilling of the cylinder, and to prevent the vehicle's engine from being started during refuelling (Salmon 1992). With the current standard refuelling coupling, disconnection by operators is not possible while the line is pressurised.

Safety in vehicle servicing/repairs

Leaks during servicing are probably not a problem since natural gas can be detected at very low concentrations by the addition of an odorant. Frost or ice will form at the site of small leaks (Yorke 1991).

Toxicity and carcinogeneity

Tests in California found that natural gas in concentrations of 25 per cent was without demonstrable effect on humans, and animals kept in an atmosphere of 25 per cent natural gas remained normal (Gafcor 1986). French tests on animals corroborated the US tests. Natural gas is, however, an asphyxiant (Gafcor

1986). Salmon (1992) points out that the cylinder vapour seal is designed to direct any leakage away from the passenger compartment.

Regulation and standards

Vehicle installations are covered by Australian Standard AS 2739. A new international standard is being developed to cover cylinders, covering new designs and materials. This new standard will be adopted as the basis for an Australian standard. Refuelling stations are constructed to an industry code of practice (AG 504). Design, construction and operation are subject to approval by the gas utility concerned (AGL, pers. comm. 1992). While Merz (1991) pointed to the need for certification and registration of approved converters and installers, AGL has indicated that installers have to be licensed motor mechanics, have an LPG 'ticket', and a natural gas 'ticket' (AGL, pers. comm. 1992).

In Victoria each natural gas cylinder must be registered with the Department of Labour and Industry (DLI), which could cause problems for an interstate registered NGV. There is a five year retest program for cylinders, and an out-of-date cylinder may not officially be refuelled. The Victorian Government has recently set up — under its Road Safety Act — an industry self-regulation body, the Automotive Alternative Fuels Registration Board (AAFRB), to police compliance with Australian Standards and other regulations for all transport fuels other than gasoline and diesel. Although initial emphasis is on LPG, discussions have been held with Gafcor regarding future action with regard to NGVs.

CONCLUSION

NGVs offer vehicle operators the potential for lower fuel costs, but at the expense of vehicle range and refuelling convenience. Substantial initial costs to the vehicle operator are involved for vehicle conversion and, if depot refuelling or home refuelling is required, in the provision of private refuelling facilities.

Although substantial developments in NGV technology have been made in recent years, further improvements can be expected with development of OEM engines and vehicles. The long-term thrust in the NGV industry is towards OEMs. Expected improvements include lean-burn technology, direct injection systems, adaptation of the latest diesel engine technology (such as turbocompounding) to NGV engines, reductions in loss of useable space, further development of LNG vehicles (including perhaps liquid phase injection) and the development and production of dedicated NGVs optimised for natural gas fuel, once the demand has been established. These developments could be expected to consolidate the fuel cost advantages of NGVs over gasoline or diesel, at least at current fuel price relativities, and to alleviate the drawbacks (range, reduction of payload or bootspace and refuelling availability) currently associated with NGV use.

The market potential for NGVs in Australia, which will depend to a large extent on the payback periods which vehicle operators can achieve by converting to natural gas, is discussed in chapter 10.

In the local environment, it appears that NGVs would reduce particulate emissions, SO_x, CO, and NMHCs as compared with gasoline vehicles. It is not clear whether NO_x emissions would generally be higher or lower; test results differ. In comparison with diesel, NO_x emissions would be lower if NGVs were operated under lean-burn conditions, rather than with richer mixtures to increase power output. Particulate, SO_x and NMHC emissions would be lower than from diesels. CO emissions are low from both diesel and natural gas.

Natural gas replacing gasoline in vehicles is likely to reduce greenhouse gas emissions per unit of transport task. Where NGVs replace diesel the greenhouse emissions could be much the same, depending on relative technical progress in NGVs and diesel vehicles.

The effect of NGVs on total Australian greenhouse emissions needs to be considered in the light of demands for natural gas in other sectors. If increased demand for natural gas from large numbers of NGVs were to bid up the price for natural gas, this could inhibit its substitution for higher emission fuels in other sectors, such as for coal in electricity generation. However, it is suggested in chapter 11 that this is unlikely, given estimated natural gas reserves.

CHAPTER 8 ELECTRIC VEHICLES

BACKGROUND

Electric vehicles (EVs) have no tailpipe emissions and are quiet. They have therefore been of increasing interest to policymakers concerned to improve the urban environment, particularly in Europe and the USA.

Recent initiatives in the USA include the 1990 California Air Resources Board (CARB) regulations and the 1988 Los Angeles Electric Vehicle Initiative. The CARB regulations will provide an American market for EVs from 1998, although carmakers can earn credits by selling EVs before then. The CARB regulations require that by the year 1998, 2 per cent of new cars and light trucks sold, and by 2003, 10 per cent of those vehicles sold, must be zero-emission vehicles (ZEVs). The Los Angeles Initiative has the goal of introducing 10 000 EVs to the city by 1995.

The Californian moves should provide a market, in 2003, for about 200 000 EVs. Some 12 other US states have announced an intention to adopt the Californian ZEV program, and these states — and California — contain about one-third of the US car market (Nadis & MacKenzie 1993). The AEVA (1992b) cites estimates of a US demand for 850 000 EVs per year — or 5 per cent of total US vehicle sales — in 2001. Manufacturers in the USA, Japan and Europe have responded to these changes by developing electric vehicles for the market, as well as new prototypes, including cars, buses, vans and motor-cycles. Some of the models being developed are listed in appendix VIII.

There is, however, a problem with buyer acceptance of EVs, arising in particular from short range and relatively high costs. At present EVs are expensive, being prototypes or having short production runs. This suggests that continuing subsidisation of EV programs will be needed until such time as these shortcomings are resolved. A recent survey in the USA suggested that reservations on the part of consumers were such that 75 per cent were not likely to consider purchase of an electric car (JD Power & Associates, quoted in the *Australian Financial Review*, 12 May 1993).

EVs may be pure or hybrid. Pure EVs rely on electricity from on-board batteries usually recharged using the electricity grid. Some supplementary electric power could be derived from solar cells mounted on the vehicle or at the vehicle's home base. Hybrid powerplants, such as a constant speed internal combustion engine, could be used to recharge a vehicle's batteries while driving or to supply power directly during extended running.

Current EV research effort is focused upon increasing vehicle range by improving battery storage capacity, by increasing motor and drive train efficiencies, and by reducing vehicle drag, rolling resistance and vehicle mass. Any resulting improvements in the latter areas will of course benefit other cars besides EVs.

BATTERIES

Battery performance improvements will be critical in overcoming the current performance shortcomings of EVs, especially their limited range. Battery life will be an important determinant of EV operating costs, and battery reliability will be important for EV acceptance. Battery problems are the single most common cause of calls to motorists' organisations for road service for present-day gasoline vehicles (40 per cent in Victoria) (Bill Tuckey, motoring journalist, pers. comm. 1992).

Many countries are involved in research and development to improve lead–acid batteries and to develop and commercialise other battery types. Appendix IX discusses various batteries with potential for use in electric vehicles.

An international consortium, the Advanced Lead-Acid Battery Consortium (ALABC) — which includes three Australian companies (Pasminco, MIM and GNB) — has recently been established to develop an advanced lead-acid battery for the EV market (Deshpande 1992). The US Advanced Battery Consortium (USABC), funded jointly by the US Department of the Environment, carmakers, electricity companies and battery-makers, is to investigate a number of battery types for EV use. These will probably include sodium-sulphur, lithium–aluminium/iron sulphide, zinc–air and lithium polymer (AEVA 1992d). Funding has been provided for the development of a nickel–metal hydride battery (Ovshinsky et al. 1992).

Assessment of batteries

Table 8.1 shows energy densities, power densities and indicative cost estimates for various types of batteries. Energy density influences vehicle range, while power density influences acceleration and hill-climbing. Table 8.1 also shows mid-term and long-term energy density and power density targets for the ALABC and the USABC.

Rand (1992) is of the opinion that no battery type will be able to meet the performance targets set for advanced EV batteries by the US Advanced Battery Consortium (table 8.1), before the turn of the century. In his survey of battery

TABLE 8.1 BATTERY ENERGY AND POWER DENSITIES

	Energy density (watt-hrs/kg battery weight)	*Power density (watt-hrs/kg battery weight)*	*Source*	*Cost* US$/kWh*
Lead–acid	4–40	33–176	1	70–130
Aluminium–air[b]	220–300	160	2	na
Iron–air[a]	100	90	2	50
Nickel–zinc[a]	33–90	66–220	1	200–500
Nickel–cadmium[a]	53	180	3	na
Nickel–hydrogen[a]	60–70	300	2	700–2000
Nickel–iron[a]	40–60	80–150	2	200–1400
Lithium–chlorine[b]	330–440	200–400	1	na
Lithium–polymer[b]	85–130	na	2	100
Lithium–sulphur[b]	245–350	550–800	1	110
Sodium–sulphur[b]	175–330	200–350	1	na
Sodium–sulphur[a]	100–140	130–180	2	110
Vanadium–redox[a]	30		4	72–206
	20–25		5	
Zinc–air[a]	44–165	44–77	1	na
Zinc–air[a]	120–200	30–80	2	110
Zinc–bromine[a]	70–80	35–100	2	150–300
ALABC[c]	50	200	6	
USABC[d]	>80	>150	2	<150
USABC[e]	200	400	2	<100

na Not available

a. Current development status.

b. Projected energy and power densities.

c. Goals of Advanced Lead Acid Battery Consortium.

d. Mid-term performance target of the US Advanced Battery Consortium.

e. Long-term performance target of the US Advanced Battery Consortium.

Sources *Rand (1992), except for Vanadium redox cost which is source 4; 1: SEC (1991);
2: Rand (1992); 3: Ishitani 1992; 4: Skyllas-Kazacos (1991); 5: Schodde (1991);
6: Deshpande 1992.

development for EVs, Rand concluded that it would be expedient to use an advanced lead-acid battery in the EVs being produced for the market created by the CARB regulations.

Schodde (1991) considers that only three new battery types have the potential to become commercially available within a 10 year timeframe: the sodium–sulphur, the vanadium–redox and the zinc–bromide batteries. The State Electricity Commission of Victoria (SEC 1991) considers the sodium–sulphur, zinc–air batteries and an additional type, the zinc–chlorine, to have the most promise.

Tests on availability of power for hill climbing in EVs showed that at 80 per cent discharge, batteries were only able to supply power at 45 watts per kilogram

TABLE 8.2 PERFORMANCE AND AVAILABILITY OF BATTERIES FOR THE CHRYSLER *TE VAN*[a] (816 KILOGRAM BATTERY PACK)

	Range (km)	*Lifespan (km)*	*Available by year*
Advanced lead–acid	90	27 000	1993
Woven lead–acid	150	68 000	1995
Nickel–hydride	240	120 000	1995
Sodium–sulphur	250	38 000	1996
Nickel–cadmium	170	68 000	1996
Lithium polymer	450	158 000	2001
AFS flywheel	450	450 000	1995

a. An electric mini-van of around 500 kg carrying capacity.

Source EPRI (quoted in *Economist,* 19 September 1992, 105).

battery weight. This was only sufficient for hill climbing at 50 kilometres per hour over periods ranging from two minutes for a valve regulated lead–acid battery, to 14 minutes for an ABB sodium–sulphur. These tests were conducted by Argonne National Laboratories in the USA as part of an evaluation of eight advanced batteries (AEVA 1992c).

A projection of performance and likely availability of various battery types has been provided by the US-based Electric Power Research Institute (EPRI) *(Australian,* 22 September 1992, 26 *et seq.*). These are reproduced in table 8.2.

In the medium term, the sodium–sulphur battery appears to be regarded as the most promising candidate, in terms of performance, for EV use. The nickel–cadmium battery has the advantage of a rapid recharge capability, but supplies of cadmium may limit the number of vehicles which can be powered by these batteries. One estimate is that world cadmium supplies would be sufficient for only about 100 000 vehicles per year (Nadis & MacKenzie 1993).

Regenerative braking

Regenerative braking is the process by which much of the kinetic energy of the moving vehicle is returned to the battery during braking, rather than being dissipated as heat as in mechanical braking. For EV conversions of conventional internal combustion (IC) cars, regenerative braking can add about 15 per cent to the vehicle's range. For high efficiency EVs such as the GM *Impact,* the range is extended by 30 to 40 per cent by regenerative braking (Wilson 1992).

HYBRID POWERPLANTS

EV hybrids may be battery/IC engine powered, battery/flywheel powered or battery/roadway powered. The hybrid allows zero emissions in polluted city centres, while retaining the performance and flexibility of the IC engine for use in suburban or interurban areas. In the absence of a breakthrough in battery technology (and perhaps even with such a breakthrough), the hybrid may be the form of EV most acceptable to the market.

Hybrids cannot qualify as ZEVs under the CARB regulations (Boyd 1992). However, the company responsible for the design of the *LA301* hybrid car intended for the Californian market considers that the CARB regulations will have to be modified to allow ultra-low emission hybrids to qualify as ZEVs, as pure EVs 'fall short of official expectations' due to battery limitations (*Australian*, 19 November 1992, 19).

Internal combustion engine/battery hybrids

A hybrid powerplant, having both an IC engine and an electrical drive, would provide the operational flexibilty which pure EVs lack. It may also offer greater savings in CO_2 emissions. *Automotive Engineering* cites potential fuel savings of 20 per cent, to be compared with the emissions reduction of 5 to 6 per cent from purely electric drives (*Automotive Engineering* 1991a).

There are two major types of IC/battery hybrid configuration: series and parallel. In the series hybrid an IC engine, probably running at a constant speed, drives a generator which may supply power directly to the electric motor or to recharge the batteries while driving. By contrast, the parallel hybrid may use its IC engine to supply power directly to the drive axle during acceleration, hill-climbing or extended running.

General Motors is developing the *HX3* gasoline/electric series hybrid van, with a 900 cm^3, three cylinder constant speed engine (developing 40 kilowatts at 2500 revs per minute) to recharge a bank of 32 batteries. General Motors also has the Lotus hybrid *M300* sports car under development in the UK, for availability by the turn of the century. This has a gasoline engine to recharge the batteries during extended non-urban running.

Volvo's Environmental Concept Car is a series hybrid using a diesel-fuelled gas turbine to drive a generator which revolves at the same speed as the turbine (up to 90 000 revs per minute). The generator recharges Ni-Cad batteries, or supplies power directly to the electric motor which drives the front wheels (*SAE-Australasia* 1992). The driver can choose to operate the vehicle in any one of three modes: electric, hybrid or gas turbine. In hybrid mode, a vehicle management unit automatically activates the gas turbine when battery charge is low. In city traffic, battery-only range is about 85 kilometres (*Automotive Engineering* 1993). Peugot is also considering a series hybrid car, possibly using a turbine engine as a generator.

Volkswagen has a *Golf* parallel hybrid diesel/electric vehicle under test. While this car can be operated using the IC engine, the electric drive or both (selected either by the driver or by a central control unit) the 60-volt battery is not recharged during running. The four seater *LA301* parallel hybrid car has been developed by International Automotive Design in response to the CARB regulations. Lead–acid batteries give a range of almost 100 kilometres. The IC engine is a very small four cylinder unit, running on gasoline, which comes into operation automatically when required provided the vehicle speed is in excess of 50 kilometres per hour (unless the driver prevents it from doing so by activating a 'short journey' switch). The IC engine can be used when parked to recharge flat batteries. The next phase of this program is to engineer this vehicle for production (by an Anglo-Swedish firm, Clean Air Transport AB) and certification to meet US standards (Harding 1992).

According to Automotive Engineering (July 1991a), the parallel hybrid is the more efficient configuration. Despite the advantages of running the IC engine at a constant speed in a series hybrid, the losses inherent in the design were argued to result in low overall efficiency. Losses resulted from conversion of mechanical to electrical energy in the generator and then electrical to mechanical energy in the electric motor.

Interchangeable EV/IC vehicles

General Motors German subsidiary Opel is developing the concept of 'snap-on' interchangeable gasoline and electric drive modules, each comprising gasoline or electric motor, gasoline tank or battery pack, transmission and wheels. An Opel *Twin* concept car has been developed. A mechanic would remove the electric drive module and replace it with the gasoline module when highway travel was to be undertaken. Target gasoline consumption of the three cylinder four-stroke engine is 3.5 litres per 100 kilometres (AEVA 1992f).

Battery/flywheel hybrids

Battery/flywheel hybrids are also a possibility for the future. The flywheel can be regarded as an electromechanical battery, recharged by plugging into the electricity mains.

A recent project conducted for the US Department of the Environment by the Lawrence Livermore National Laboratory showed that although flywheels were a more expensive energy storage medium than batteries, they could deliver greater power and their efficiency was higher (96 per cent compared with about 75 per cent for a lead-acid battery). The Livermore flywheel consisted of concentric tubes of high strength carbon composite around an electric motor rotating at up to 145 000 revs per minute in electro-magnetic bearings (which are used to speed up or 'charge' the flywheel) and enclosed in a vacuum containment vessel (Hamer 1992).

The flywheel would provide power for acceleration while the battery provided power for steady running. Regenerative braking would return power to the flywheel rather than the batteries. Recharging of the flywheel could be performed in 15 minutes.

A commercial company, American Flywheel Systems (AFS), has been formed to produce a prototype suitable for EVs. An energy density of 130 to 200 watt hours per kg is claimed (Sinor Consultants 1992e), three to four times that of the ALABC target for lead–acid batteries. Current estimates are that an AFS flywheel large enough for a range of about 480 kilometres would cost about US$5500, but would have a life of some 400 000 kilometres — probably outlasting the vehicle — in contrast to lead–acid batteries with a life of a couple of years in EV use (Sinor Consultants 1992e).

Battery/roadway powered electric vehicle hybrids

Another potential power source for EVs is an electric cable, buried just below the surface of the roadway, which transfers propulsion power to the EV motor by inductance. The power from the roadway cable can also be transferred to the vehicle's batteries, either when the vehicle is in motion and the available power exceeds that required to propel the vehicle at the time, or if the vehicle were stationary above a cable, including in parking areas. This allows the vehicle to be used off the electrified roadway network. A demonstration roadway powered electric vehicle (RPEV) project was underway in California in 1990 (Nesbitt et al. 1990). Static inductive battery charging is already in use, mainly in large automated factories in the USA, Canada and Europe.

The cost of a pickup inductor with suspension system has been estimated at US$1500 to $4000 per car. The on-board controller, including a rectifier to convert AC power to DC power for battery charging, has been estimated to cost US$350 to $650. Cabling costs could be US$1 million to $2 million per mile per lane. Under optimistic assumptions (including about the numbers of RPEVs which share the cable installation and maintenance costs), the cost of owning and operating an RPEV, estimated at 27 to 49 US cents per mile, could be comparable with those of a gasoline car with costs of 30 to 37 US cents per mile (Nesbitt et al. 1990). The wide range in the Nesbitt et al. estimates for RPEVs is due to the uncertainty surrounding the likely costs. For billing purposes, RPEVs can be equipped with meters that record the amount and time (peak and off-peak) of roadway powered travel (Nesbitt et al. 1990).

The estimated range for the energy efficiency of an EV using power from roadway cable is 14 to 22 per cent, compared with that for an EV using battery power of 12 to 18 per cent (Nesbitt et al. 1990). CO_2 emissions from RPEVs could be slightly lower in consequence. High volume urban roads would be prime candidates for RPEVs, although moderate length intercity routes might also feasibly be electrified. A disadvantage of RPEVs could be the increased demand for electricity at times of high load from other uses, whereas EVs might more often be recharged during off-peak hours (Nesbitt et al. 1990).

Photovoltaic boosting for EVs

Photovoltaic solar panels mounted on a vehicle (such as on Ford's *Ghia Connecta*, planned for production in the UK) could partially recharge the vehicle's batteries during the day, as the sun could provide up to 1.1 kilowatts per square metre according to Gosden (pers. comm. 1993). Zillman (1990) estimates a higher figure of 1.4 kilowatts per square metre. After allowing for efficiency losses in conversion, Gosden (1990) estimates that power for 3500 kilometres per year might be expected from a roof-mounted solar array on an Australian EV.

Photovoltaic boosting could not only extend EV operating range and reduce emissions, but also extend battery life by reducing the depth of discharge, especially where the vehicle is often driven distances close to its range limits. A US study suggests that solar voltaic cells could perhaps even double battery life, and that this aspect could be more important than extending EV range (Nadis & MacKenzie 1993).

However, many cities have multi-storey car parking or tall buildings, and there may not be adequate access to sunlight to justify the additional cost of incorporating solar cells. According to Nadis and MacKenzie, it is preferable to fit solar panels to the roofs of parking stations, rather than to the EVs, to supply power to recharging points or to the electricty grid when demand from EVs is low. Solar photovoltaic panels at a vehicle's base might also be used to recharge exchange batteries or spent battery electrolytes (for example for vanadium redox, if these batteries were used in vehicles). A prototype solar photovoltaic EV recharging station was built in Sacramento California, in 1992, and a further 70 are planned by the end of 1993 (Sinor Consultants 1992e).

Rippel (1990) estimated payback periods for photovoltaic arrays ranging from six months to 166 years, depending on design and use. Reasonable payback periods (defined as less than 10 years) occurred with high vehicle use, high electricity costs, high battery cost and battery sensitivity to depth of discharge, low cost[1] and high efficiency of the photovoltaic array, high solar insolation, and a low efficiency vehicle.

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[1] Ford Australia provided details of costs for various grades of solar cells. Martin Green at the University of NSW has silicon solar cells with up to 20 to 21 per cent efficiency, but at a cost of $75 000 to $90 000 per square metre, and crystalline silicon cells (16 to 17 per cent efficiency) at $5000 to $6000 per square metre. Satellite-type (high grade photovoltaic) cells cost $25 000 to $40 000 per square metre (also 16 to 17 per cent efficency). Polycrystalline cells (11 to 12 per cent efficiency) cost $1000 to $1200 per square metre, while amorphous silicon cells (5 or 6 per cent efficiency) cost $500 per square metre. Photovoltaic paint (using amorphous silicon) should be available in the future, but with very low efficiency (Ford Australia 1992). Costs for high efficiency cells could be much lower in large scale production.

Payback periods less than two years occurred when the pattern of use was such that photovoltaic boosting was able to prevent an excessive depth of discharge in the battery (which would result in short battery life).

Solar vehicles

With an on-vehicle array of practical size, the maximum rate of collection of solar energy is about 1 kilowatt using current technology. This small amount of power directly available from the solar-voltaic cells would not be sufficient to give acceptable in-city passenger vehicle performance. Thus any practical solar vehicle must carry a bank of batteries, even for use in strong sunlight, and according to Allen (1989), should be considered as an EV with solar battery charging.[2]

EV DRIVE SYSTEMS: MOTORS AND CONTROLLERS

Motors capable of high effiencies for both propulsion and regeneration are essential if maximum range is to be obtained. Thione (1992) considers that drive systems are the EV components closest to being optimised at present.

Electric vehicle motors can use either direct current (DC) or alternating current (AC) electricity. A number of different design types are available in either DC or AC motors. Until recently DC motors were more commonly used in EVs. What is claimed to be the first production EV drive unit — by the French company Leroy Somer for the Peugot *106* EV car scheduled for volume production in 1995 — uses a DC motor. However, the state-of-the-art GM *Impact* uses an AC motor (Narraway 1993).

Developments in inverters, such as MOSFETs (metal oxide silicon field effect transistors), allow the efficient conversion of DC power from batteries to AC. Together with digital microcontrollers, this has allowed the use in EVs of highly efficient permanent-magnet AC motors. Permanent-magnet motors are more suited to high torque, low speed usage, while induction motors are suited more to low torque, high speed applications (Gosden 1990). Rare earth magnets, using materials such as samarium cobalt or neodymium iron boron, although very expensive at present, have the potential to provide more compact and efficient electric motors in the future (Narraway 1993).

Compared with DC motors, the AC motor is lighter and lower cost, with higher speed capabilities and reduced maintenance requirements, though controllers for AC motors are more complex and expensive. Together, AC motors and their controllers are similar in efficiency to high performance advanced technology DC

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[2] The *Impact* has a battery capacity of 14.3 kilowatt hours. One kilowatt could drive the *Impact* 11.6 kilometres at its consumption rate of 86 watt-hours per kilometre, or at 11.6 kilometres per hour given a continuous supply of strong sunlight and ignoring start-up.

motors (Bullock 1989). The Australian Electric Vehicle Association (AEVA) considered the AC type to be the motor of the future (AEVA, pers. comm. 1992).

ELECTRIC VEHICLE COSTS

The initial purchase price of EVs tends to be high, due largely to low production volumes. For example, the Fiat *Panda Elettra*, with a production target of 1000 in 1992, is priced in Italy at between 73 per cent and 225 per cent above *Panda* gasoline models (Rogers 1991). The *LA 301* hybrid is expected to sell for approximately US$25 000 (Nadis & MacKenzie 1993). The BMW *E1*, a smallish four seater car, could go into series production in the mid-1990s, at a cost in the region of DM100 000 (about A$100 000 in late 1992). The Australian Huntington *Mira* conversion has a quoted price of $16 000 plus sales tax — about twice the price of the gasoline *Mira*. Bartezzaghi et al. (1992) consider that production costs for EVs could equal those for gasoline cars at production volumes of 50 000 per year (cars) and 10 000 per year (vans).

The use of lightweight materials such as magnesium and aluminium in advanced, purpose-designed EVs also adds significantly to costs. Yaguchi (pers. comm. 1992), after describing the development of the Nissan *FEV* concept car, thought that EVs would be 20 per cent to 50 per cent more expensive in mass production than comparable IC cars. However, it is the target of Japanese EV developers to reach an EV cost of only 20 per cent above the price of a gasoline equivalent by the year 2000.

There is also the cost of replacing batteries every two to four years. For example, replacement of the Delco-Remy lead-acid battery pack for the *Impact* has been stated to cost about US$1500 every 32 000 kilometres (*International Business Week* 1990) or every three years. On these figures, the battery cost per kilometre for the *Impact* would be more than 6 Australian cents. It would exceed the gasoline cost of 4.2 cents per kilometre for a Daihatsu *Charade* at a gasoline price of 70 cents per litre and 6 litres per 100 kilometres (urban cycle). Interest on battery costs, and electricity costs, would be additional for the EV, while the gasoline vehicle would have engine maintenance costs not applicable to an EV. Clearly the difference in running costs between the vehicles will be very sensitive to the battery and engine maintenance costs.[3] For example at engine maintenance costs of 2 cents per kilometre and battery costs of 6 cents per kilometre, the EV has no advantage over the gasoline vehicle. If, however, battery costs were somewhat lower, and/or engine maintenance costs higher, the EV would yield some return on the higher initial cost of the car. Some schemes have proposed battery leasing arrangements, spreading the cost over the life of the batteries.

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[3] EV calculations do not take heating costs into account. Some EVs are heated by heat-pumps, and some by gasoline burners.

The high initial cost of EVs may to some extent be offset by a longer vehicle life relative to IC engined vehicles, if not by lower maintenance costs. Nesbitt et al. (1990) consider the lifespan of an EV could be from 25 to 100 per cent longer than that of a gasoline vehicle because of the relatively long life of an electric motor. A fleet of electric vans in the UK is reported to have lasted three times longer than diesel vans under the same operating conditions (Nesbitt et al. 1990).

Even assuming the running costs of EVs are less than for gasoline cars, it appears doubtful that the likely savings would be sufficient to yield satisfactory returns on the additional initial capital outlay. A rough comparison of costs of the Diahatsu *Mira* and the Huntington *Mira* EV suggests that the simple payback period for the EV would range from 21 years (100 per cent extra cost and 15 000 kilometres per year) to 31 years (100 per cent extra cost and 10 000 kilometres per year).

Seurat and Seurat (1992) have made discounted cash flow analyses of EVs and gasoline vehicles. They have concluded that while EVs are at present 34 per cent more expensive on average to own and operate, a favourable scenario for 1996 could see EVs 7 per cent less expensive on average. This scenario involved cooperation between carmakers and electricity suppliers. If it did not eventuate EVs could be 29 per cent more expensive than gasoline vehicles to own and operate.

Recent reports indicate that General Motors has put on hold plans to put the *Impact* EV into volume production, due to high costs and limited practicality (AEVA 1993). It appears that about 50 will be made for field trial purposes. Ford is adopting a similar approach with its *Ecostar* van.

EMISSIONS AND SAFETY

Emissions of greenhouse gases

Whether EVs can make a contribution to reducing greenhouse gas emissions will depend on the source of power for, and efficiency of, electricity generation, the timing of demand for power, the numbers and efficiency of EVs, and the way in which the EVs are used.

The higher the proportion of electric power derived from non-fossil fuel sources, the greater the probability of CO_2 reductions from the replacement of gasoline or diesel vehicles with EVs. Electric vehicles could effect a large reduction in greenhouse emissions per vehicle kilometre in countries using a large proportion of hydro or nuclear electricity.

In Australia electric power generation is mostly fossil fuel powered. In 1989–90 the power generation mix was: black coal 55 per cent, brown coal 25 per cent, hydro 11 per cent, natural gas 8 per cent and oil 1 per cent (DPIE 1991). The

Electricity Supply Association of Australia gives the thermal efficiency of a typical Australian black coal-fired generating plant at 38 per cent (ESAA 1991), while conventional brown coal-fired stations achieve only about 29 per cent. On the basis of the OECD (1993) comparison of life cycle emissions from EVs (using various power sources) and gasoline cars in North America and the OECD in year 2000, EVs in Australia would be expected to yield only moderate reductions in life cycle emissions (around 6 to 13 per cent) compared with gasoline vehicles (BTCE estimate based on OECD 1993).

However, there is scope for greater reductions in emissions if power station efficiency increases. Advanced black coal stations may be capable of 40 to 45 per cent thermal efficiency, and combined cycle plants using natural gas may be capable of 50 per cent (Diesendorf 1992). New technology for brown coal generation is claimed to increase its efficiency by 50 per cent by removal of water content before burning (SECV, pers. comm. 1992). However these efficiency improvements would be from new technologies, not yet fully commercial; and given the rate of introduction of new technology, any such increased efficiencies would only be available in the very long term.

Sporckmann (1992) estimates that EVs in Europe would generate CO_2 emissions of 45 and 48 per cent of those from diesel and gasoline cars respectively. These estimates are based on the average European power generation mix, which is 53 per cent nuclear, hydro, or renewable and only 33 per cent coal-fired. However where European EVs are powered by coal-based electricity, emissions will be comparable with those from gasoline cars (IEA 1993).

Use of natural gas rather than coal for generating electricity can in some circumstances make a large difference to EV emissions (DeLuchi 1993). However, DeLuchi's estimates of the potential improvement vary. Compared with emissions from a gasoline vehicle, gas-fired electricity gave a 75 per cent reduction in FFC CO_2 equivalent emissions for the most favourable scenario, and a 15 per cent increase for the least favourable. Coal-fired electricity gave an increase of 100 per cent to a decrease of 60 per cent. The IEA (1993) estimates that for urban driving (OECD Europe, year 2000), EVs powered by gas-based electricity would have half the life cycle emissions of gasoline vehicles.

Comparisons of emission rates between electric and gasoline powered vehicles are often difficult because these vehicles are not equal in terms of utility. Range and carrying capacities differ, and may affect emissions per passenger-kilometre, and distance travelled to satisfy a particular need. Commercial vans on a general urban delivery service are the class of vehicle most comparable, as vehicle range is less of a concern.

In the USA, EPRI (1989) compared one medium and one small electric van (*G-van* and *TEVan*) with two gasoline vans with freight capacity equal to that of the EVs. For the gasoline vans, greenhouse gas emissions included refinery operations and fuel distribution. EV emissions included those from power generation, electricity transmission and distribution, and mining and transport of the fuel. The gasoline vans emitted 684 and 553 grams of CO_2 per kilometre, while emissions attributable to the comparable EVs using electricity derived from current US-coal fired power stations were 677 (*G-Van*) and 389 (*TEVan*) grams per kilometre (EPRI 1989).

Comparisons between electric and gasoline vehicles using energy consumed per tonne-kilometre of freight, or per passenger-kilometre, may be more appropriate. Unfortunately these data are usually not available for EVs. Gosden (1991) averaged the specific energy consumption of five EVs (four vans and one passenger car) to arrive at a specific energy consumption of 132 watt-hours per tonne-kilometre. Electricity was assumed to produce 915 grams of CO_2 per kilowatt-hour, supplied to the consumer. These data indicate that an EV would produce around 121 grams of CO_2 per tonne-kilometre (though of course this figure will vary according to state power sources). A 1 tonne gasoline vehicle travelling one kilometre and generating at the tailpipe 2.4 kilograms of CO_2 per litre of fuel consumed would need to consume less than 5.2 litres per 100 kilometres to have lower greenhouse emissions than Gosden's (1991) average EV.

The General Motors *Impact* EV is a current state-of-the-art vehicle design, powered by sealed lead–acid batteries, and incorporating advanced aerodynamic and structural design features and low rolling resistance tyres. Gosden (1990) estimated that the *Impact* had a specific energy consumption of 81 watt-hours per tonne-kilometre at a constant 96 kilometres per hour highway speed. This gives a CO_2 emission of 87 grams per tonne-kilometre using Australia's power supply mix, equivalent to that from a gasoline vehicle with an average fuel economy of 3.6 litres per 100 kilometres.

However, General Motors has produced a gasoline-engined concept car, the *Ultralite*, which has a claimed highway cycle consumption of only 2.9 litres per 100 kilometres. No vehicles on the Australian market currently incorporate the advanced body and tyre design features of the *Impact* or the *Ultralite*. Nevertheless, the Daihatsu *Charade* and Suzuki *Swift* can average 4.6 litres per 100 kilometres for the highway cycle (DPIE 1991c). The *Charade* and *Swift* have twice the range of the *Impact*, which seats only two adults.

In urban areas, which are the areas most suited to EVs, advanced purpose-designed EVs like the *Impact* may produce less emissions per vehicle-kilometre (VKM) than advanced gasoline powered cars. While the *Impact* is only a two seater, and its emissions per seat-kilometre are somewhat higher than those of the *Ultralite*, the average occupancy of a car on the journey-to-work is only 1.2 persons (BTCE 1991), and so the emissions per actual passenger-kilometre performed might still be lower than those of the *Ultralite* during peak periods. Table 8.3 shows BTCE estimates of FFC CO_2 emissions per vehicle-kilometre, and per seat-kilometre, for current and future internal combustion engine vehicles (ICEVs), and for converted and advanced EVs in urban use.

TABLE 8.3 COMPARISON OF FFC CO_2 EMISSIONS FROM EVS AND ICEVS IN URBAN USE

Car	*Type*	*g CO_2/VKM*	*g CO_2/seat-km*
Charade	Current gasoline (6L/100 km)	136.8	34.2
Ultralite	Concept gasoline (5.2L/100 km)	118.5	29.6
Huntington *Mira*	Converted EV (160 Wh/km)[a]	146.4	73.2
BMW 3 Series	Converted EV (107 Wh/km)[a]	98.5	19.7
Impact	Advanced EV (85.8 Wh/km)[b]	78.5	39.3

a. Based on maximum urban range and total battery capacity.

b. Based on 100 km range to 60 per cent discharge.

Source BTCE estimates based on stated energy consumption rates.

Gosden (1990) compared CO_2 emissions from EVs and NGVs, concluding that if electricity were generated using natural gas, an EV would result in emissions 27 per cent lower than if the gas were burned in an NGV. A similar result is given in DeLuchi (1993), and IEA (1993) estimates (North America, year 2000) show a 37 per cent decrease.

Cost-effectiveness of EVs in reducing CO_2 emissions

While EVs in large-scale production may become competitive on a cost basis with gasoline vehicles, this in unlikely to occur until EVs are able to offer a better range. If a price premium of 25 per cent over comparable gasoline powered models is assumed for EVs in mass production, and if the emissions per vehicle kilometre for the *Charade* (137 grams per vehicle kilometre) and the Impact (79 grams per vehicle kilometre) are used as indicative (table 8.3), then a 40 per cent reduction in the rate of CO_2 emissions from the replacement vehicles might be expected for an extra initial cost of $5000 per vehicle. The capital cost would be in the vicinity of $5 billion to achieve a 1 megatonne reduction in emissions each year over the life of the vehicles. The total cost would include any differences in operating costs, and would be reduced according to the valuation of reductions in urban emissions.

This cost estimate is indicative only, being very dependent on the nature of the vehicles replaced, the mileage travelled, the area of travel, the emissions estimates and the assumed vehicle price.

The effect of EVs on electricity generation

The SECV regards EVs as having some commercial potential for power system load levelling through off-peak recharging. Special low rates for electricity can be offered for overnight recharging. Victoria's brown coal stations are difficult to shut down, and hence tend to be kept running at base load. Another reason for cheaper off-peak recharging suggested by Tassicker (1992) is that only the more efficient generating units would operate at these times. 'Smart' battery chargers would be desirable to position the night-time load from slow charging EVs to mesh with the existing pattern of load. Tassicker estimates that modern residential electricity grids could support overnight EV recharging at 20 per cent of residences, while in older suburbs with overhead wiring the grid could support overnight EV recharging at only 10 per cent of residences.

Tassicker noted that fast charging would draw very high currents (1000 amps for the Nissan *FEV*) which could not be supported by residential wiring systems, and which would require transformer upgrades in the vicinity of charging stations. Daytime fast charging by large numbers of EVs would be extremely undesirable from a load pattern point of view. However, differential pricing for peak and off-peak recharging would assist in this regard.

Gosden (1991) has emphasised the influence of battery recharging on EV energy use and emissions. More efficient battery rechargers can avoid energy losses through overcharging and consequently reduce emissions from EVs. Charging efficiency also varies with battery type and state of charge, and may decrease as the battery approaches full charge.[4] However, energy losses can be minimised with modern charging systems where the power being carried by the charger as full charge is approached is very much less than in the earlier part of the charge (Gosden, pers. comm. 1993).

Noxious emissions

EVs could have a very beneficial effect on the urban environment, as local pollution and noise are virtually eliminated.

Nearly all emissions attributable to EVs arise from electric power generation. The impact of these emissions would be mostly in the area near the power station and areas down wind of the smoke stack. Shifting pollution away from many moving motor vehicles in an urban area to a single power station may in fact facilitate implementation of pollution controls.

Emissions would also arise from the manufacture of several of the battery types available, for example, lead and nickel cadmium.

Safety of electric vehicles

Rajan et al. (1989) list four possible safety concerns relating to the operation of EVs. These are: release of poisonous gases, hydrogen explosions, sulphuric acid burns and electric shock. The severity of each of these factors depends on the type and design of battery and the electrical safety measures employed.

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[4] According to Schodde (1991), charging efficiencies for lead–acid batteries fall from over 97 per cent when less than half-charged to less than 50 per cent when the battery is more than 80 to 90 per cent charged.

Gaseous emissions and their effects are reduced by correct battery charging procedures and adequate ventilation (Rajan et al. 1989).

The behaviour of heavy battery-packs (that for the *Impact* weighs about 400 kilograms) in collisions or rollover situations is a concern, especially in vehicles which are designed so as to save weight in other areas (the *Impact* weighs about 1040 kilograms). Disengagement of EVs from crashes could be hazardous for rescue personnel (electric shock and acid spills), and EVs may have to carry an identifying mark, as in the case of LPG vehicles.

Safety in an accident, or under abnormal battery operation, is a particular concern with certain battery types. With sodium–sulphur batteries, major concerns are sodium fires, sodium–water explosions and a runaway sodium–sulphur reaction (Rajan et al. 1989). Each of these can produce toxic gases and other by-products (Stodolsky 1989). Other high temperature batteries, such as lithium–sulphur and lithium–chloride, also give rise to safety concerns. Leakage of bromine fumes from a zinc–bromide battery has resulted in the hospitalisation of 14 people in the USA (AEVA 1992c). A small car using zinc–bromide batteries needs to carry approximately 140 litres of aqueous bromide and organic bromide complex on board the vehicle (AEVA 1992c). The danger arising from a spill of bromine in an accident would seem potentially very high.

Production, use and disposal of the vehicle's batteries raise environmental and health issues. Lead from lead–acid batteries is likely to be salvaged; additional lead production with the introduction of EVs will mostly be for the initial batteries used in the vehicles. There may be some increase in emissions of lead and associated metals such as cadmium from mining and manufacturing (Rajan et al. 1989).

Electromagnetic radiation arising from EVs could be an issue because of its effect on electronic equipment in close proximity to the EVs. Disturbance to pacemakers, radio equipment and acoustic aids has been identified as an area of concern (Benini 1992 cited in Casalgrandi & Redolfi 1992).

The wide range of safety concerns (high voltages, high temperature, explosive and toxic batteries and possible electromagnetic interferences) compared with the typical IC-engined vehicle, may mean that a new series of design and safety standards will need to be developed and implemented to control all aspects of EV operation on Australian roads.

ELECTRIC URBAN PUBLIC TRANSPORT

While the emphasis in this chapter has been on the electric car and van, it is appropriate to consider the greenhouse implications of electric urban public transport compared with diesel-fuelled buses. However, emissions per passenger-kilometre from trams, trains and buses are difficult to assess. There are inadequate data on distances travelled by passengers as well as on passenger numbers; and emissions vary with vehicle size, terrain, time of day and source of power for electric traction. Estimates are therefore very approximate.

Table 8.4 shows emission results from a recent study (Armour & Jordan 1992) conducted for the Victorian Public Transport Corporation (VPTC). The average emissions figures might be expected to be higher than for other States, for the same load factor, because of Victoria's use of brown coal for electricity

TABLE 8.4 CO_2 INTENSIVENESS: VICTORIAN PUBLIC TRANSPORT CORPORATION

Vehicle and period	*Grams CO_2/ per pass.-km (FFC)*
Electric rail[a]	
Average	
Peak (3 carriage or 6 carriage)[b]	30
Day offpeak (3 carriage–6 carriage)[c]	162–319
Weekend (3 carriage–6 carriage)[c]	265–522
Marginal	
Peak (3 carriage or 6 carriage)[b]	20
Electric light rail (tram)	
Averages for different tram types	
Peak[b]	40–57
Day offpeak	77[d]–375[e]
Weekend	126[d]–615[e]
Marginal	
Peak[b]	27–39
Diesel bus	
Government bus	91[f]–171[g]
Private bus: urban average	75
Private bus: urban + rural average	103

a. No metromiser on-board computer (figures with metromiser are approximately 25 per cent lower). Two engines are required for 6 carriage trains.

b. Average of morning and evening peak: 96 per cent load factor.

c. Offpeak average load factor 8 per cent.

d. Average occupancy 58 per cent.

e. Average occupancy 10 per cent.

f. Assumes an average ride length of 10 km per passenger.

g. Assumes an average ride length of 5 km per passenger.

Source Derived from Armour & Jordan (1992).

generation.[5] However, brown coal use for electric traction is in fact limited, and is likely to be used for any increase in demand up to the year 2005 only at weekends. Electric traction makes up less than one per cent of total Victorian electricity demand, and is classified as 'intermediate demand' (met primarily by gas and black coal fired stations), rather than as 'base load' (met by brown coal stations).

Electric rail

Much of Australia's urban rail network is already electrified. Urban heavy rail performed approximately 7 billion passenger-kilometres in 1990–91, compared with around 4.9 billion passenger-kilometres performed by urban buses (Cosgrove & Gargett 1992).

For 1988, the BTCE (1991) estimated that FFC emissions from Australian urban rail, averaged over the states, were 150 grams of CO_2 per passenger-kilometre. This figure relates to the full rail system, and includes power used both for traction and for ancillary services such as signalling and workshops. A figure for rail traction alone would be about 120 grams of CO_2 per passenger-kilometre. These aggregate emission estimates were biased by the high average CO_2 emission rate assumed for Victorian power generation, and did not make allowance for the specific source of power for rail as in the VPTC study. NSW urban rail would have a full system average emission rate of around 120 grams of CO_2 per passenger-kilometre, and around 90 grams per passenger-kilometre for traction alone.

These figures may be compared with the BTCE (1991) estimate for average FFC emissions from urban buses of 120 grams of CO_2 per passenger-kilometre.

The BTCE estimates are at average load factors. With high load factors, it appears rail might achieve lower emissions per unit task than buses (table 8.4), though the data available do not permit precise comparison. The overall *average* emissions rate for PTCV buses was 33 grams CO_2 per *seat*-kilometre in 1990–91, while the estimate for private buses was 28 grams per *seat*-kilometre (Armour & Jordan 1992). Emissions during peak hours, when load factors are high, would be likely to generate somewhat higher emissions than 33 grams per seat kilometre due to congestion. On the other hand, average loadings may be higher than indicated by seat numbers at peak hours.

Electric light rail

A comparison of electric light rail and diesel buses based on Armour and Jordan (1992) suggests that there may not be much difference in emissions from light

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[5] Armour and Jordan (1992) give figures of 1160 to 1400 grams of CO_2 per kilowatt-hour for brown coal stations, compared with 970 grams of CO_2 per kilowatt-hour for a Victorian black coal unit, and 480 to 690 grams of CO_2 per kilowatt hour for gas-fired stations.

rail and buses, except perhaps at weekends, when buses may be better. The Armour and Jordan results are, however, for Melbourne; light rail systems in other states may compare more favourably.

For example an average PTCV bus, at 10 per cent load factor, would have an emissions intensity of 333 grams of CO_2 per passenger-kilometre, compared with 375 grams of CO_2 per passenger-kilometre for the average day off-peak tram at 10 per cent load factor. Light rail appears to be more emissions-intensive than heavy rail at comparable load factors (table 8.4).

Wilkenfeld (1991) has overall averages for Melbourne of 140 grams of CO_2 per passenger-kilometre for trams and 120 and 130 for government and private buses respectively.

Newman (pers. comm. 1993) emphasises that modal comparisons of emissions are not necessarily indicative of what would happen if one mode were preferred over another. He points out that although in engineering terms electric rail and diesel buses have similar greenhouse emissions, studies have shown electric rail to be a stronger attracter of housing and employment within walking distance of the service. There is therefore a stronger impact on overall emissions through a reduction in the number of car trips needed.

CONCLUSION

As a result of recent environmental legislation in the USA and domestic pollution in many other countries, trial programs for EVs have been launched by national authorities on a significant scale. It is appreciated by these authorities, however, that any real breakthrough will depend on achieving a number of measures in combination to create the infrastructure for recharging, the incentive for consumers and the vehicles.

EVs at present production volumes have high capital costs, which are unlikely to be recouped by low running costs except in the long-term. Purchase costs comparable with those of gasoline vehicles will require comparable production volumes or subsidisation.

To overcome the problem of limited range, there will need to be either a significant breakthrough in battery technology or in the development of hybrid vehicles. Hybrid EVs may prove to be the most practical form.

While EVs may allow some reduction in greenhouse gas emissions, at present high vehicle costs they do not appear to offer a cost-effective option for reducing these emissions alone — at least in Australia where coal-fired electricity generation predominates. If electricity were produced by power stations fuelled with natural gas the greenhouse emissions effect from EVs would be more favourable.

However, EVs could contribute substantially to reductions in noise and urban air pollution, as power stations tend to be located away from urban areas. Depending on the value attributed to improvements in the urban environment, and on the cost of EVs when produced on a larger scale, they could prove to be cost-effective overall.

CHAPTER 9 HYDROGEN

BACKGROUND

Hydrogen may become a viable transport fuel in internal combustion engines or in fuel cells, but this is not expected to happen in the near future. The IEA (1992a) regards hydrogen fuel as a possibility only in the long term, and hydrogen fuel cells in the very long term. Fuel cells produce electricity by chemical action, as in a battery, but use a continuing input of hydrogen to fuel the electrochemical reaction. The IEA (1993) states that hydrogen is not likely to be used widely in new vehicles before the year 2010. It would be a lot later before these vehicles could form a major part of the vehicle fleet.

Hydrogen was first used as a transport fuel in airships. In the 1920s modified Maybach gasoline aero-engines were used to power Zeppelin airships, and in the 1930s Daimler Benz converted diesel engines to run on hydrogen for airship use (Garrett 1991). Prospects for hydrogen were damaged following the *Hindenburg* disaster in 1937. Although the mishap was not due to the use of hydrogen in the engine, the event appears to have curtailed research and development up until the 1950s. Since then the potential for use in aircraft has been explored and demonstrated in flight, and in the mid-1980s Daimler Benz conducted successful hydrogen road vehicle trials (Gray 1991). Mazda displayed a hydrogen car which used a rotary engine at a recent Tokyo motor show.

In the USA, the Department of Energy is providing a small amount of funding for hydrogen programs (particularly relating to fuel cells), and has developed the Hydrogen Multi-year Program Plan to guide government support for hydrogen research and development (Sinor Consultants 1992c). Pilot projects involving non-fossil fuel hydrogen systems are being investigated globally, particularly in Germany and Canada.

FUEL CHARACTERISTICS

Hydrogen (H_2) could be used in various forms to fuel vehicles directly, or could be used indirectly to fuel electric vehicles from hydrogen fuel cells. It can also be used as *hythane,* a blend of hydrogen and natural gas, which has been tested in the USA as a means of reducing noxious emissions. Hydrogen has an octane rating of 106 RON (Edsell 1993), somewhat higher than that of leaded gasoline.

Hydrogen storage in vehicles

Hydrogen fuel could be stored on board vehicles in gaseous, liquefied or metal hydride forms, making use of substances which absorb hydrogen. An alternative would be storage in the form of liquid ammonia (NH_3). Nadis and MacKenzie (1993) consider that this latter option is probably ruled out for everyday use on the grounds of toxicity and smell. Ammonia is a liquid at room temperature whereas hydrogen must be cooled to –253 degrees Celsius to be liquefied and requires storage in thermally insulated containers.

Gaseous hydrogen

The low energy density of gaseous hydrogen may preclude its use in some types of vehicles. Unless cylinder pressures five or six times as high as the current Australian standards for natural gas were to be used, weight, cost, and storage capacity problems would arise.

Liquid hydrogen

The fuel tank for a liquid hydrogen powered vehicle would need to hold about four times the volume of a gasoline tank to give the same range, and would be up to six times as bulky. The weight would not be significantly greater.

Refuelling times would be slightly longer than for gasoline (DeLuchi 1989). Boil-off of fuel from unused vehicles would be a safety concern, and would waste fuel. Losses of up to 3 per cent per day can escape from fuel stored in the tank, and between 10 and 25 per cent is boiled off during refuelling (IEA 1993).

Hydride storage

Hydrogen can be stored in the form of solid metal hydride granules, or in liquid form — for example as methylcyclohexane for heavy vehicles.

Granular metal hydrides

Metal hydride storage allows for higher energy densities than can be achieved by either liquid or gaseous hydrogen, and does not need the low temperature or very high pressure storage. Waste heat from the exhaust is used to liberate the hydrogen gas from the hydride storage medium, although a separate heater would be required for starting (Garrett 1991).

Hydride systems can be refilled to 80 per cent capacity in about 10 minutes, although the final 20 per cent can take much longer (DeLuchi 1989). Weight considerations could limit the amount of fuel storage, as at present the hydrogen fuel comprises only 1 or 2 per cent of the total weight of the storage medium (Gray 1991). DeLuchi (1989) estimated that storage weight would limit cars to a range of about 150 to 300 kilometres — a 160 litre hydride system weighing 265 kilograms would give a range of about 250 kilometres for a small car (using 6.7 litres per 100 kilometres on gasoline). Other estimates indicate less of a problem. Garrett (1991), for example, claims that a tank containing magnesium hydride granules would weigh only twice as much as an equivalent tank of gasoline, with a 310 litre hydride tank weighing 316 kilograms. Garrett (1991) considers that magnesium hydride granules may be the cheapest option.

Nadis and MacKenzie (1993) report the recent development of an amorphous nickel hydride by the US Ovonic Battery Company. This hydride can store up to 7 per cent hydrogen by weight and would thus have the potential to extend the practical operating range of hydrogen cars significantly.

Liquid hydrides

The *MTH* (methylcyclohexane, toluene and hydrogen) process, developed by DERECO in Switzerland, releases hydrogen from a liquid hydride by catalytic dehydrogenation. The residue — toluene — is stored in a separate tank. The system is too bulky and heavy for cars (an experimental dehydrogenation unit weighed 750 kilograms), but may be suitable for buses and trucks (Garrett 1991).

The methylcyclohexane liquid hydride has an energy density of 9.6 to 12.0 megajoules per kilogram, only one-fifth to one-quarter of the energy density of diesel fuel (about 45.5 megajoules per kilogram). In DERECO tests, 500 kilograms of hydride was used for a 300 kilometre journey by a 20 to 25 tonne truck (Garrett 1991). A possible more efficient alternative to methylcyclohexane could be n-heptane, which could produce four times as much hydrogen.

Hydrogen fuel cells

The hydrogen fuel cell is a potential power source for electric vehicles in the long term. Fuel cells are highly efficient and would overcome the problem of large volume storage of fuel, as only very little fuel would be needed on-board the vehicle (IEA 1992a). The hydrogen fuel cell might be used in combination with batteries to provide the power for extended range. Batteries can provide the necessary power density for acceleration and hill-climbing more cheaply.

A fuel cell is similar to a battery in that it produces electricity electrochemically. However, it does not rely solely on its contents to generate power, as there is a continuing input of the power generating elements. In the hydrogen fuel cell electricity is produced from inputs of hydrogen and oxygen.

One US developer claims to have developed a reversible cell, the *Lasercell*, wherein electricity from the mains can be used to recharge the vehicle's hydrogen stock overnight by converting water into hydrogen and oxygen, without erosion of the cell's electrodes. The developer claims an output of 10 kilowatts from a 45 kilogram cell measuring 0.25 metres in diameter and length — much smaller and lighter than other comparable fuel cells. The *Lasercell* has been demonstrated in the *Lasercell–1*, a fuel cell–battery hybrid in a Ford *Fiesta* car. A range of 500 kilometres has been claimed, using iron–titanium hydride storage rather than compressed gas storage (Webb 1991).

PRODUCTION METHODS AND COSTS

Hydrogen may be produced on a large scale from water, oil, coal (using steam) or natural gas by the application of energy (Gray 1991). The source of the energy used will be the main determinant of the level of greenhouse emissions from the full hydrogen fuel cycle.

Water

Hydrogen is produced from water by splitting the hydrogen oxygen bond. This process requires large amounts of energy.

Methods include:

- photolysis — using energy from light
- thermolysis — using heat energy, either solely or with a catalyst. Both methods are still at the laboratory stage.
- electrolysis — using electrical energy, for which a mature technology exists (Gray 1991). Electrical energy may be from solar, hydro or fossil sources.

Natural gas

The most common source of hydrogen is natural gas. A steam reforming process mixes methane and steam at 800 degrees Celsius to produce hydrogen and carbon monoxide.

Oil

Production from heavy oil is by partial oxidation using oxygen at 1200 degrees Celsius.

Coal

Gasification of pulverised coal uses steam and oxygen to produce hydrogen, CO and then CO_2. Alternatively the *Hydrocarb* process converts coal to methane at 1100 degrees Celsius by hydropyrolysis. The methane is further pyrolised to solid carbon plus hydrogen, avoiding the production of CO_2 (Gray 1991).

Costs of production

Hydrogen electrolysis plants powered by hydro-electricity have existed for some time to supply the chemical industry. Efficiencies are typically 75 to 80 per cent. Improvements up to 90 per cent are at an advanced stage of development, while efficiencies of close to 100 per cent may be possible (Gray 1991). However, more significant reductions in the cost of electrolytic hydrogen would have to come from a reduction in electricity costs.

Price (1991) gives the cost of hydrogen produced by cheap hydro-electric power at about 4.2 times that of jet fuel on an energy equivalent basis. (Spot-market jet fuel prices varied between US$0.63 and US$1.40 per US gallon in 1990 due to the Gulf War — roughly 20 to 50 Australian cents per litre. Normally prices are similar to gasoline prices net of excise tax). IEA (1993) estimates of the fuel cost of liquid hydrogen from existing electricity generation are 2.8 to 5.6 US cents per kilometre (1987 prices).

Nadis and MacKenzie (1993) cite estimates of hydrogen from natural gas at 4.4 times the cost of gasoline at 1990 US prices.

Hydrogen produced by gasifying coal or biomass would have a cost lower than that of methanol produced from the same source (IEA 1993).

In Germany an experimental solar photovoltaic powered plant has been built to produce electrolytic hydrogen. Forster (1990) states that the cost of this hydrogen is now very high, but could be halved during the 1990s. Even so, Siemens estimates that it would cost DM2 (about A$2) per kilometre to fuel a vehicle with liquid hydrogen from this source.

Nadis and MacKenzie (1993) consider that amorphous silicon solar photovoltaic cells offer a long-term prospect of low-cost electricity for hydrogen production. They refer to Ogden and Williams' 1989 US estimates for solar-generated hydrogen costs, of US$1.68 to $2.35 per gallon of gasoline equivalent by the year 2000. These costs equate to 44 to 62 Australian cents per LGE (A$1 = US$0.70). Nadis and MacKenzie (1993) also note that there is scepticism about such low costs for hydrogen.

DeLuchi's (1989) opinion is that given a strong research effort, hydrogen may become competitive with gasoline in perhaps 30 years or less, taking account of the social costs of pollution, greenhouse effects and resource security. The IEA considers that if the most optimistic projections of the cost of solar-voltaic electricity are realised (2 US cents per kilowatt-hour), then, on a life cycle basis, hydrogen could compete with gasoline priced at 50 US cents per litre. If the electricity cost were 5 cents per kilowatt-hour, the price of gasoline would need to be 80 cents per litre for hydrogen to compete (OECD 1991).

Life cycle costs would need to include the extra cylinder and storage costs, and increased hydrogen vehicle costs.

DISTRIBUTION AND STORAGE

Hydrogen can be distributed or stored as a gas, liquid or solid.

Mass-produced hydrogen would be most efficiently transported by pipeline, possibly in the long run utilising natural gas pipelines. Embrittlement of the steel pipes could be controlled by adding a proportion of CO_2 to the hydrogen. Nadis and MacKenzie (1993) state that transmitting hydrogen by pipeline is more economical than transmitting electricity through cables. Depending on the production site, it may be possible, as Gray (1991) has suggested, to use exhausted oil and gas wells for bulk storage of hydrogen fuel. As storage costs would be high, it would be expected that production and consumption would be matched as closely as possible.

POTENTIAL FOR USE IN TRANSPORT VEHICLES

Hydrogen-fuelled cars

Carmakers have been experimenting with prototype hydrogen-fuelled internal combustion-engined vehicles for some time. Mercedes Benz operated a fleet of hydrogen powered vehicles in the mid 1980s (Gray 1991). Mazda is developing a hydrogen rotary engine as the company's primary alternative energy powerplant, but sees it as an option for the 21st century, with the electric car as the more feasible short-term option (AEVA 1992d). Mazda, in conjunction with Nippon Steel, hopes to have a prototype for road testing in about three years. Mazda views the rotary engine as particularly suited to hydrogen fuel, as the fuel injection and compression phases are relatively long compared with those in a reciprocating engine (*Australian,* 14 October 1992).

In Australia, the Ford Motor Company has been developing a hydrogen powered vehicle in conjunction with the University of Melbourne. The initial vehicle used was a Ford *Cortina,* and the results have been adapted for a Ford *Capri.* De Fraga, motoring journalist for the Australian, assessed the finished product as running better than the BMW or Mercedes cars converted in Germany (Moll, pers. comm. 1992). In particular, there was less backfiring.

Because of its low ignition energy, hydrogen tends to ignite before it gets into the cylinder, and needs special valve arrangements. Ford used a double-sleeved inlet valve, which allowed air into the cylinder to cool the hot spots on the piston and other components which caused the backfiring, before the sleeve opened to allow hydrogen to enter (Ford Australia, pers. comm. 1992).

According to Milkins (1992), the Melbourne University hydrogen *Capri* uses not much more than half of the amount of energy used by the gasoline version. An extremely wide range of air–fuel mixtures can be ignited, so that engine power output can be controlled by varying the mixture strength (rather than by using a throttle valve) thus obviating the pumping losses which a gasoline engine experiences under part load. Milkins notes that water injection may be needed at high engine loads to avoid premature ignition of the hydrogen fuel by hot surfaces in the combustion chamber.

BMW is participating in a German pilot project to examine the potential of solar–hydrogen technology (using solar-voltaic electricity to produce hydrogen by electrolysis). BMW has converted a *735iL* car to use hydrogen fuel. For maximum power, cryogenic liquid hydrogen (stored at –253 degrees Celsius) is injected directly into the combustion chambers. A cruising range of 300 kilometres has been achieved with a tank of 93 litres (BMW 1991b). This engine is very complex, and presents problems with engine materials.

BMW is also experimenting with a lean-burn hydrogen engine. This engine requires a mechanical supercharger to achieve a power output 30 per cent below that of the gasoline version (BMW 1991b).

As a possibility for the medium-term, BMW has investigated gasoline/hydrogen dual-fuel vehicles, and estimates the total ownership and operating costs — when vehicles operate 50 per cent of the time on each fuel — at 60 per cent above those of a conventional gasoline vehicle (Sinor Consultants 1992e).

Hydrogen-fuelled engines for heavy vehicles

Edsell (1993) states that very little development work has been done on hydrogen in heavy duty vehicles, but that both spark ignition and dual-fuel compression ignition hydrogen/diesel engines have been tested. The technical viability of a dual (mixed) fuel hydrogen/diesel engine, with diesel used as a pilot fuel, has been demonstrated by trials at the University of Melbourne (Milkins 1990).

M.A.N. in Germany is developing a bus to use liquid hydrogen fuel, which is expected to be available for demonstration in 1994 (Sinor Consultants 1992e).

Potential for hydrogen fuel use in aircraft

Liquid hydrogen may become an alternative to jet fuel, again in the long-term. Price (1991) states that there appear to be no insurmountable technical problems, although tank size, safety and price are issues. Fuel tank capacity would need to be almost four times as large as for the jet fuel currently used, for although hydrogen has almost three times the energy content of the same weight of aviation turbine fuel (avtur), its density in liquid form is only about one-eleventh of that of avtur.

A Canberra bomber with one engine converted for liquid hydrogen fuel flew in 1956 (Gray 1991). In the former Soviet Union, a testbed *Tupolev 154* passenger aircraft, redesignated as a *TU 155*, had one engine converted to operate on either liquid methane (LNG) or liquid hydrogen, as well as on jet fuel.

The operational advantages of liquid hydrogen as an aircraft fuel include a greatly reduced fuel load and the consequent higher cruising altitude, which reduces fuel consumption at a given speed (Price 1991). Fuel load for a Boeing *747* is given as 41 000 kilograms of liquid hydrogen — compared with 121 600 kilograms of jet fuel — while cruising altitude increases from 31 000 to 36 000 feet. Wing loadings and length of runway required for take-off would be reduced.

Price considers that, with hydrogen, engine life would be longer, maintenance requirements lower, and engine noise levels lower. Price (1991) notes engine manufacturers' estimates of a 5 to 10 per cent gain in specific fuel consumption, in terms of the energy content of the fuel burned. In the example of the Boeing *747* above, the energy content of the 41 000 kilograms of hydrogen is 7 per cent less than that of the 121 600 kilograms of jet fuel.

EMISSIONS AND SAFETY

Greenhouse gas emissions

Although combustion of hydrogen would produce virtually no tailpipe CO_2 emissions, some NO_x could be produced by the high combustion temperatures (IEA 1992a). The chief tailpipe emission — water — is a greenhouse gas, but the likely amount from vehicles would be so small in comparison to global evaporation that it could be ignored (Gray 1991).

FFC emissions, on the other hand, could be greater than from gasoline or diesel fuel use, depending on the method of producing the hydrogen fuel. Hydrogen could assist in reducing greenhouse gas emissions only if electricity used in production were derived from sources other than fossil fuels. The IEA (1992a) estimates that hydrogen produced using electicity from nuclear power could have FFC emissions 71 per cent below those of a gasoline LDV in the North American market. DeLuchi (1993) estimated that hydrides produced using nuclear power would produce FFC CO_2 equivalent emissions equal to 40 per cent of those from RFG.

DeLuchi et al. (1988) are of the opinion that fossil fuels would not be used to generate electricity to produce hydrogen by electrolysis, as it would be cheaper to produce directly by gasification of coal or steam-reforming of natural gas. However, DeLuchi et al. estimate that hydrogen produced from coal gasification would result in 100 per cent more emissions than from petroleum fuels when used in the form of hydride, and 143 per cent more when used in the form of liquid hydrogen. DeLuchi et al. regard hydrogen as the least promising of the alternative fuels in the short term.

Noxious emissions

Debate over noxious emissions from hydrogen relates only to the size of the reduction in emissions of NO_x. Gray (1991) states that tailpipe NO_x emissions from hydrogen fuel are about one-tenth of those from gasoline, while only traces of HC, CO and CO_2 arise from burning lubricating oil on the cylinder walls. DeLuchi (1989) argues that an optimised hydrogen car would have lower average lifetime NO_x emissions than 1989 gasoline cars with catalytic converters.

Test results for the Ford *Cortina* hydrogen vehicle discussed above show CO emissions only 2.5 per cent of those from the gasoline version, and six per cent of the current ADR 37 standard. HC emissions were 0.01 grams per kilometre, much lower than the 1.41 grams per kilometre from the gasoline version[1] and the ADR 37 requirement of 0.93 grams per kilometre. NO_x emissions were 0.96 grams per kilometre compared with 1.42 grams per kilometre for the gasoline version, and the ADR 37 requirement of 1.93 grams per kilometre (Edsell 1993). The NO_x emissions from the hydrogen fuelled *Cortina* are only marginally lower than average values for the post-1986 car fleet, as estimated by Watson (1993).

For a 4 tonne bus, data in Edsell (1993) show that HC and CO emissions for the hydrogen version were small fractions of the US 1981 Federal Test Procedure (FTP) standard requirements, while NO_x emissions were 70 per cent of the standard level.

Edsell (1993) claims that NO_x emissions from hydrogen vehicles could be controlled by emissions control measures, and gives data for a US hydrogen car, developed by UCLA, which achieves NO_x emissions of 0.2 grams per mile, equal to the level required by the California Ultra Low Emission Vehicle (ULEV) standard.

Daimler-Benz has experimented with hydrogen in converted gasoline engines, and by using a very lean air–fuel mixture has obtained virtually zero NO_x emissions (IEA 1993).

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1. The tests on the Ford vehicle were conducted prior to the introduction of ADR 37, and tested against ADR 27A.

Emissions from use of hythane

The IEA (1992a) points out that by adding 5 per cent hydrogen to natural gas to produce *hythane*, the level of methane, NO_x and CO tailpipe emissions from NGVs could be reduced to levels low enough to meet the CARB ULEV standards.

Edsell (1993) provides US test results for a US *S–10* light vehicle at low altitude. NO_x was 0.2 grams per mile, equal to the ULEV Standard, CO was 0.7 to 0.9 grams per mile compared with the standard of 1.7 grams per mile, and NMHCs were 0.01 grams per mile compared with the standard of 0.04 grams per mile. In high altitude tests, it appears that the ULEV NO_x standard is exceeded (Edsell 1993).

The cost of adding hydrogen to natural gas would increase its price by approximately 7 per cent, based on a recent US price estimate for hydrogen from hydro-electric power.

Noxious emissions from aircraft

In aircraft use there would be no CO emissions from hydrogen fuel and NO_x emissions would be reduced. However, the amount of water vapour produced would be more than doubled. This water vapour has a greenhouse effect as, above about 9000 metres, it may form ice-crystal clouds which, while allowing sunlight to pass through, reflect heat back to the earth. The ice crystals can also act as sites for chemical reactions which attack ozone (Barrett 1991).

Safety

The legacy of the *Hindenburg* airship disaster may have created apprehension about hydrogen as a fuel for everyday use. Nadis and MacKenzie (1993) point out that over 70 per cent of those on board the airship *Hindenburg* survived the disaster and that most of the deaths were the result of people jumping from the burning airship. Gray (1991) adds that those who rode the gondola to the ground were unharmed by the low-luminosity flames.

The US Office of Technology Assessment has concluded that hydrogen is not a particularly dangerous fuel (in *Replacing Gasoline* quoted in Nadis & Mackenzie 1993). DeLuchi (1989, 88) considers that hydrogen ‘is not necessarily more dangerous than gasoline and may be safer’, and Gray (1991) also considers that hydrogen’s reputation as dangerous and difficult to handle is unwarranted, arguing that it is less dangerous than liquid fossil fuels. Gray points out that a hydrogen fire radiates relatively little heat due to the low luminosity of the hydrogen flame, and liquid hydrogen evaporates quickly if spilled. It is claimed to be non-toxic and non-carcinogenic (Nadis & MacKenzie 1993).

Metal hydride is a very safe method of storing hydrogen. In US Army tests, a metal hydride tank pierced by bullets resulted in a very small stable flame, whereas a gasoline tank similarly treated exploded in a fireball.

However, there may be dangers with liquid hydrogen, due to the large increase in volume (some 900 times) which occurs between hydrogen's boiling point (–253 degrees Celsius) and atmospheric temperature and pressure. Training in the handling of cryogenic liquids would be required — especially for vehicle service personnel — if excessive pressures and consequent risks of storage vessel explosion are to be avoided. Hydrogen in fuel tanks would need venting via a safety release valve to avoid the pressure increase from any rise in temperature.

Boil-off could create a safety hazard for vehicles parked in confined spaces. Boil-off is about 2 per cent per day according to Nadis and MacKenzie (1993), and between 0.1 and 0.5 per cent per day according to Gray (1991), depending on the surface to volume ratio of the container. A spark could cause an explosion if the ambient concentration of hydrogen were above 18.3 per cent.

BMW considers that the risk with a hydrogen vehicle should be no greater than with a gasoline-fuelled vehicle, assuming the vehicle and its fuel system are properly designed and handled. Although hydrogen requires very little ignition energy, BMW has found that hydrogen/air mixtures in open spaces have required artificial turbulence or an igniting jet to cause a detonation. The lower detonation limit is a high 18.3 per cent concentration of hydrogen in air, a figure BMW considers unlikely to be reached in accidents.

However, design measures have been taken to let hydrogen escape freely from the tank and vehicle after any severe damage to the fuel system. This allows the hydrogen to evaporate rapidly and dilute. Sensors in the vehicle are designed to open windows, sunroof and boot to prevent an ignitable mixture accumulating within the vehicle. Hydrogen is non-toxic, although contact of cryogenic hydrogen with the skin can cause a short-lived shock effect (BMW 1991b).

CONCLUSION

Hydrogen offers the promise of a transport fuel which could greatly reduce emissions of local air pollutants from internal combustion engines. In fuel cell form, it would produce virtually no local air pollution. Greenhouse gas emissions would only be reduced if the hydrogen were produced without using fossil fuel.

The current consensus is that hydrogen technology will not be practical for another decade or two (Nadis & MacKenzie 1993, 90). In the interim, a range of technical, economic and perceived safety factors militate against use of hydrogen as a transport fuel. These include limited production capacity, limited non-fossil sources of electricity, high costs until cheap solar electricity is realised, vehicle technology problems, cost and volume of in-vehicle storage, and doubts about safety in the minds of potential users.

For hydrogen to become an economically viable transport fuel in the long-term, the costs of production will need to be reduced in line with optimistic projections, or there will need to be large increases in the prices of other fuels, relative to hydrogen.

The hydrogen fuel cell is expected to be an important element in electric vehicles in the long term.

PART II: DEMAND CONSIDERATIONS

CHAPTER 10 MARKET ACCEPTANCE OF ALTERNATIVE FUELS

INTRODUCTION

Gasoline and diesel fuels have achieved almost total dominance, within their respective transport market sectors, by offering cheap and convenient transport energy. This market position is supported by large in-service stocks of vehicles. New vehicles are designed and produced for use with gasoline and diesel. Petroleum based fuels are supplied by large firms operating world-wide systems of production, distribution and marketing.

Alternative fuels have been able to penetrate this market to only a very limited extent to date, despite the 'implicit subsidy' most of them receive through exemption from the Commonwealth excise and state taxes applying to gasoline and diesel. Previous chapters have identified technical deficiencies which could influence market demand, as well as relatively high vehicle costs, or in some cases, high fuel costs. Unless current lack of consumer interest can be attributed to a lack of knowledge, then it must be assumed that the additional costs to users of alternative fuels are not being offset by the current 'subsidy' that they receive.

Lack of knowledge about alternative fuels, and uncertainty about government policy in relation to alternative fuel pricing (for example, continuation of excise exemption), will influence demand directly. If consumers are risk-averse, they may require very high rates of return on additional capital outlays to offset the uncertainty. Consumers may also lack confidence that they will be able to recoup the value of investments in alternative fuel vehicles when sold.

If alternative fuels are to achieve a wider market, technological improvements reducing vehicle and equipment costs, as well as the implicit costs of alternative fuel use, will be important, as will expectations about the price of these fuels relative to gasoline. Prices will depend on policy on the fuel excise, road user charges and possible adjustment of prices to reflect environmental effects. Availability of refuelling infrastructure, of OEM vehicles offering better performance and of maintenance services, and full warranties for vehicles and equipment will also be major factors. On the positive side, promotion of alternative fuels as environmentally beneficial could influence some consumer choices.

Market acceptance surveys

A report for the OECD on alternative fuels offers eight major findings on consumer choice (OECD 1991, 63), albeit with a warning that there is 'little history or past experience with alternative fuels'. The findings are:

- the posted fuel price is used as an indicator of economic attractiveness, with much less attention to energy density or energy efficiency;
- fuel availability is critical, with at least 10 to 15 per cent of fuel stations offering the fuel before dedicated vehicles are introduced;
- additional power is important to consumers;
- consumers are willing to pay for a cleaner fuel, to a similar extent to which they are willing to pay extra for a fuel which would deliver more power;
- image and market positioning are critical, that is whether the fuel is seen as a premium fuel or an inferior fuel;
- commitment of multifuel car owners to using the alternative fuel is required;
- exceptionally high levels of quality must be maintained with all aspects of the new fuel: vehicles, distribution and fuel quality;
- the role of government in reducing uncertainty [about the future for alternative fuels] is crucial.

The OECD claims that while 'consumer purchase behaviour is fundamentally conservative', it can be 'greatly influenced by messages transmitted by government and industry'. These might concern the environment, fuel availability and cost and vehicle resale values.

Reporting on Australia, Gafcor (1988, 15) found:

> generally a poor perception of alternative fuels such as NGV, particularly in terms of the convenience of use and refuelling, driving distance limitations, fuel availability, longer-term reliability of gas engine technology and longer-term economics (both in terms of economics of operation and resale value of the vehicle).

A survey of potential NSW users of natural gas in transport conducted by Merz (1991) emphasised limited range, lack of involvement by engine manufacturers (except manufacturers of OEM NGV bus engines), and lack of hard evidence as to viability as major barriers to growth in NGV usage.

The Merz survey found that fuel costs were only of medium priority for most transport organisations. Time and labour costs of longer refuelling or possible breakdowns from poor equipment were of more concern. This could inhibit widespread use of alternative fuels in transport firms until evidence accumulates to show that these costs would be outweighed by fuel savings.

MARKET POTENTIAL

Private sector vehicle owners appear to require fairly short payback periods, (or use high discount rates) on the capital costs of adopting alternative fuels.[1] Gafcor (1988) has stated that a payback period of about one year is required on light-duty passenger NGVs, and two years on heavy-duty NGVs. Merz (1991) concluded that a three-year payback period was required on average, on the basis of surveys and interviews with potential private and business NGV users. Hensher and Young (1991, 38), in a study of fuel demand elasticities, considered that 'very large price relativities' would have to occur before there would be 'any significant substitution' of alternative fuels for gasoline or diesel.

Vehicle costs are higher for alternatives to gasoline vehicles with the exception of those running on low-alcohol fuels. In the longer term, larger scale production of vehicles and equipment may reduce the cost disadvantage, both in terms of the direct costs of manufacture and in terms of amortisation of research and development costs.

For short payback periods on the extra investment, alternative fuel prices need to be substantially lower than the gasoline price, and high annual mileages need to be travelled. The effect of changes in relative prices on fuel cost savings and achievable payback periods for heavy-duty NGVs is shown in tables 10.4 and 10.5.

Governments may base decisions on alternative fuel use for their own fleets on differences in the social cost of fuels, rather than on market price differences, by taking account of tax effects and externalities such as the costs of greenhouse gas emissions, air pollution, noise and safety. For example, environmental considerations have been important in decisions on the type of urban buses to be operated by government transit authorities in a number of states. Governments may also adopt a lower discount rate for investments than would be applied by potential private sector users of alternative fuels.

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[1] Simple payback periods will significantly overstate the financial viability of conversion unless payback periods are quite short. If payback periods are not short, a discounted cash flow analysis should be used.

Liquefied petroleum gas

Engine technology and reasonable refuelling infrastructure have existed for some decades for LPG. Given a payback period of around two to three years for a large car which travels about 20 000 kilometres per year (Haley 1990), it is perhaps surprising that LPG is not used more widely.

Many private car owners could achieve these payback periods. Indications are that around 35 per cent of private cars and over 60 per cent of commercial vehicle cars and station-wagons are driven more than 20 000 kilometres annually (West 1986). Also, the fuel economy of cars (litres per 100 kilometres) is skewed towards the higher fuel consumption categories where fuel cost savings would be more important. There is a high proportion of private motorists among Australia's LPG vehicle users compared with some overseas countries (Borgas 1993). Borgas (1993) states that of 250 000 LPG vehicles, 72 per cent are private cars, 20 per cent commercial vehicles and 8 per cent are taxis.

West (1986) refers to a Society of Automotive Engineers estimate that on technical and economic grounds, LPG had the potential to substitute for around 40 per cent of total motor spirit demand. Institutional and non-technical factors affecting conversion decisions reduced this to what was considered a more likely estimate of 10 to 15 per cent.

The General Manager of the ALPGA believes that, in general, private vehicle owners are discouraged from converting to LPG by the slight performance loss, slightly higher fuel consumption and a fear of explosions (*BRW* 1992b).

Availability of OEM vehicles is particularly important. South Australian market surveys supporting a study of institutional and marketing factors in LPG automotive use found that 'the potential for LPG would be greatly enhanced by the availability of OEM LPG vehicles' (West 1986,1). Of survey respondents, 46 per cent of those classified as 'rejectors' of LPG in converted vehicles indicated that they would consider the purchase of a readily available OEM LPG vehicle.

An OEM Datsun *200B* LPG car introduced in Australia in the early 1980s was not a success. However, the refuelling network available for LPG vehicles was then much less extensive than it is now. Recent rapid growth has taken the number of outlets from about 1100 in 1988 to about 2200 in early 1993. The Holden *Commodore* has now been made available from dealers with a fully warranted ex-factory LPG/gasoline capability. The cost, as at November 1992, was $1499 for the equipment plus $300 installation (Gerald Slaven Holden, pers. comm. 1992). An LPG/gasoline Ford *GL Falcon* was released in early 1993 at a cost of approximately $1900 above the cost of the gasoline-only version (Ford Australia, pers. comm. 1993).

The trend to replace gasoline LCVs with diesels could limit the role of LPG in the LCV market sector. Almost half of the respondents in West's (1986) LPG commercial vehicle survey had replaced gasoline vehicles with diesels in recent years. Three-quarters of this group had not considered LPG. Of the other quarter which decided against LPG, convenience, and a more assured fuel supply, were major reasons for choosing diesel.

Safety

Perceptions about safety are an inhibiting factor in market acceptance of LPG. The South Australian survey (West 1986) found that safety is a concern with 46 per cent of potential LPG users, and with 56 per cent of those classified as 'rejectors' of LPG. Only 35 per cent of potential LPG users and 27 per cent of LPG 'rejectors' disagreed that there were safety concerns (West 1986).

Range

Conversion of vehicles to run only on LPG results in reduced range. LPG taxi operators using only LPG have installed tank sizes in the range 60 to 90 litres, depending on availability. With preferred larger-size tanks — typically 84 to 88 litres (usable capacity around 68 litres) — these taxis would have a range of 590 to 680 kilometres, about 70 to 80 per cent of the range of the gasoline equivalent (based on DPIE fuel consumption guide highway cycle at 77 kilometres per hour). A recent test driver of the OEM *Commodore* reported a range of 400 kilometres city driving and 600 kilometres country driving (at 100 to 110 kilometres per hour), and indicated this was much the same as could be expected from gasoline (Lee 1993).

Reduction in boot capacity due to the space taken up by the cylinder can be a problem, particularly for small cars and for conversions. Tanks in vans, when fitted underfloor, may give a range of only about 250 kilometres because of space limitations (Wild 1990).

Refuelling facilities

Although there is a large number of auto LPG outlets in Australia, many are located in major cities. There may be poor availability in remote areas away from major highways. However, with the exception of taxis, the majority of LPG vehicles are dual-fuel, and can switch to gasoline when LPG is not available. It is possible to drive around Australia on Highway 1 using only LPG (Gogas, pers. comm. 1992).

Performance loss

Caldwell (1989) gives a figure of about 3 to 4 per cent for power loss from using LPG in a *Commodore* or *Falcon.*

Almost half of the LPG vehicles in the South Australian survey experienced a noticeable power loss (West 1986). Perceived power losses are apparently enough to induce many operators to have their LPG vehicles running too rich a mixture, with adverse emissions consequences, in order to minimise any loss in performance.

While small front-wheel-drive cars may have problems accommodating the necessary components for LPG under the bonnet, only 8.4 per cent of LPG vehicles in South Australia in 1986 had engine capacities under 2 litres (West 1986).

Capital cost

Conversion costs or ex-factory dual-fuel capability costs are currently $1600 to $2000. Losses may occur on resale of used vehicles, depending on vehicle type, and relative gasoline and LPG prices, but there are exceptions.

A Sydney fleet management company considered that second-hand LPG cars sold for about $1000 less than their gasoline equivalents (BRW 1992b). Wild (pers. comm. 1994) of TNT Fleet Management also claims that LPG vehicles currently have a resale value $1000 lower than that of comparable vehicles using standard fuels. Second-hand ex-Government LPG cars are devalued by about $1500 in current markets, according to the Department of Finance (cited in EPA 1991a). The Victorian EPA (1991a, 40) also considers that the second-hand car market 'devalues cars fitted with LPG'. However, Gafcor has been receiving a premium on LCVs converted to LPG, presumably influenced by Melbourne's significantly lower LPG prices (Energy Victoria, pers. comm. 1992). Also Melbourne based transport operator Linfox assumed no resale penalty for LPG cars in calculating its payback period for recent LPG conversions (pers. comm. 1992).

Payback period

The NRMA estimated a saving of around 3 cents per kilometre for a Holden VL dual-fuel *Commodore* operating on LPG rather than gasoline, based on Sydney prices (Caldwell 1989). Other estimates indicate savings of 2.2 cents for a VN *Commodore*, 2.3 cents for an EA *Falcon*, 3.5 cents for a *Falcon* van, 1.8 cents for a *HiAce* van, and 2.6 cents for an *Express* van, using fuel consumption rates up to 25 per cent lower for the gasoline vehicles (*Fleet Systems* estimates reported in *BRW* 1992b).

NRMA estimates of payback periods were 2.2 years for a Ford EA *Falcon*, 2.6 years for a Holden VN *Commodore*, and 3.7 years for a Toyota *Corolla*, allowing for interest at 15 per cent per year, an LPG conversion cost of $2000, and car utilisation of 20 000 kilometres per year (Haley 1990).

In 1990, Wild of TNT Fleet Management calculated that a Mitsubishi *Magna* which performed 40 700 kilometres per year repaid the entire $1750 original installation cost in one year with LPG at 31 cents per litre. When a $500 end-of-life value of the conversion kit was assumed, the *Magna* repaid its net conversion cost after 29 000 kilometres. For a Ford *Falcon* the figures were 34 200 kilometres to recover the full installation cost, and 24 400 kilometres to recover net conversion cost (Wild 1990). Wild used the Nissan *Urvan* to compare the costs of light vans using diesel or LPG as opposed to gasoline. The LPG conversion was cheaper than the diesel option, and had a breakeven point of 29 000 kilometres compared with 40 000 kilometres for the diesel option. Wild recommended that LPG be used for cars travelling more than 15 000 kilometres per year, and for light commercial vehicles where the fuel is available (Wild 1989).

However, Wild (pers. comm. 1994) has recently stated that TNT is no longer using LPG vehicles. Since his earlier calculations, installation costs have increased somewhat, resale values have proved to be lower than estimated, serious problems have been experienced with maintenance, and users did not use the dual-fuel LPG option as often as anticipated. While the recent availability of factory conversions with warranties would remove some of the problems, the lower resale value resulting from buyer resistance to LPG use remained a problem, unless really high mileages were being performed. TNT cars are sold after four years.

The average time to recover conversion costs would be substantially longer than three years for vehicles with a low rate of fuel consumption or low annual mileage. Where the period required to recoup investment is relatively long, uncertainty as to whether the Federal Government will maintain the excise tax differential favouring LPG in the long term will be important. According to BP, there is a perception that the Federal Government will decide to impose a tax when market penetration of LPG reaches 12 to 15 per cent (BP, pers. comm. 1992).

Removal of excise exemption from LPG would remove much of the incentive for conversion. For example a scenario with the current tax regime, $2000 conversion costs, 25 000 kilometres per year travelled, 10 litres per 100 kilometres gasoline consumption, gasoline at 70 cents per litre and LPG at 25 cents per litre, and 15 per cent more LPG used gives a simple payback period of two years. With the excise exemption removed, the payback period would be 4.6 years. A discount rate as high as 20 per cent would increase the simple payback periods to 2.7 and 14.2 years respectively (BTCE estimates).

Prior to the announcement in late 1992 that the excise exemption for alternative fuels would continue for another five years, Linfox was holding off further conversions (Linfox, pers. comm. 1992). BP stated that the current automotive LPG market would 'die' without the exemption (BP, pers. comm. 1992).

Assessment

There is economic and technical scope for a larger market share for LPG. LPG prices and the availability of OEM LPG vehicles are expected to be the principal influences on LPG's market share. The excise treatment of LPG will therefore be crucial. Under the present tax regime, there are short payback periods for vehicles travelling over 20 000 kilometres per year. Around 35 per cent of private car owners travel this distance or more. Resale values would appear to be of significance in determining the value of LPG use in cases where cars are turned over after two to three years.

Diesel

Cars and LCVs

Australia has few diesel cars. In Europe there has been considerable growth in diesel numbers over the past decade or so, when the proportion of diesel cars in the fleet is currently estimated at 11 per cent (IEA 1993, 146). Important factors in the market acceptance of diesel cars are, according to the IEA (1992a):

- a significant difference between the prices of gasoline and diesel fuel — in parts of Europe this difference can be around 40 per cent;
- diesel fuel efficiency advantages;
- vehicle price and taxation treatment;
- a favourable public perception of the performance, reliability and maintenance costs of diesel cars.

Shell (1992, 5) refers to 'the poor image from which diesel cars have traditionally suffered', although better engine designs and fuel technology are challenging this. Turbocharged diesels would minimise the performance losses compared with gasoline-engined cars, but would cost even more than naturally-aspirated diesels.

In West Germany, diesel numbers increased from 11 per cent of new car sales in mid-1983, to 27 per cent in mid-1986. This share fell back to 11 per cent by mid-1989 after tax incentives for diesels were removed and publicity was given to concerns about the carcinogeneity of diesel particulates (*Automotive Engineer* 1990). In late 1991 diesel fuel prices in Germany were 61 per cent of those of unleaded gasoline per unit of energy (IEA 1992b).

There was a similar situation in Italy, where the sales share of diesel vehicles fell from about 25 per cent in mid-1987 to 15 per cent in mid-1989, after a change to the car tax regime (*Automotive Engineer* 1990). Nevertheless, in late 1991, diesel fuel prices in Italy were still only 57 per cent of those of leaded gasoline per unit of energy (IEA 1992b). Diesel cars in 1989 comprised 13.8 per cent of the Italian car fleet, after an average growth of about 30 per cent per year from 1970 to 1985 (IEA 1992a, chapter 12).

According to the IEA (1993), promotion of diesel vehicles has been strongest in France. The price of diesel fuel has typically been about 40 per cent below that of gasoline during the 1980s, and the purchase tax on diesel cars is lower than on gasoline cars. The share of diesels in new car sales has grown steadily, to over 30 per cent in 1990. Diesel cars comprised 13 per cent of the French fleet in 1989 (IEA 1992a, 183).

In the USA, the share of diesels in the car market rose from 1 per cent in 1976 to 6 per cent in 1981, falling back to 1 per cent in 1986. US experience has shown the critical influences on consumers to be the relative per gallon prices of diesel and gasoline (rather than the cost per mile or life cycle cost of gasoline and diesel vehicles), and the perceived quality of diesel vehicles and engines. In 1982 the price per gallon of diesel rose above that of gasoline in the USA, and by 1983 diesel cars generally cost more than gasoline cars to own and operate. The fuel cost advantage of diesel cars was also eroded by the improving fuel economy of gasoline cars. Quality and performance problems with GM's 7.7 litre diesel engine adversely influenced consumer perceptions of reliability and engine life (Kurani & Sperling 1988).

Payback periods

In 1992 in Australia, diesel versions of LCVs and 4WDs sold for more than their gasoline equivalents. The percentage margin typically varied between 2.6 per cent (Holden *Jackaroo* four cylinder turbo diesel compared with six cylinder gasoline) and 18.4 per cent (Toyota *HiLux* 4 cylinder cab-chassis). For a random sample of nine common models, the average price difference between diesel and gasoline versions was about 10 per cent, or about $2200 retail (*Glass's Guide*).

However, the Mercedes Benz *300D* diesel sold for between 13 and 21 per cent less than the gasoline *300E* between 1986 and 1992. It was $30 000 cheaper in 1990 (*Glass's Guide*). This price differential could have been the result of a marketing strategy for Australian consumers rather than of production costs.

The Holden *Gemini* diesel car sold for 7 to 8 per cent more than the gasoline version when sold in Australia between 1982 and 1984 (*Glass's Guide*). This amounts to about $1000 for a $15 000 car. If diesel cars were required to fit catalytic converters and particulate traps to conform to emissions standards, costs could increase by several thousand dollars (Kulkarn 1992).

The returns on the additional outlays are not high. A diesel travelling 15 000 kilometres per year using 7 litres per 100 kilometres[2] would have a fuel cost of $682 with diesel at 65 cents per litre. The comparable gasoline model would use 9.6 litres per 100 kilometres, and the annual fuel cost would be $1008 with

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[2] The Mercedes Benz *190D* 2.5 litre automatic has a rated fuel consumption of 7.8 litres per 100 kilometre urban, and 6 litres per 100 kilometre highway; the Mercedes Benz *190E* 1.8 litre automatic has a rating of 10.5 litres per 100 kilometre urban, and 8.5 litres per 100 kilometre highway (DPIE 1991c).

gasoline at 70 cents per litre. The undiscounted payback period, for a vehicle price differential of $1000 would be just over three years. With a discount rate of 20 per cent, the payback period would be greater than five years. If the price differential were $4000, allowing for a catalytic converter and particulate trap, the undiscounted payback period would exceed 12 years at the current price differential between gasoline and diesel. The discounted payback period would be very long, exceeding 100 years at rates just over 8 per cent.

For a larger diesel travelling 25 000 kilometres per year and using 8.1 litres per 100 kilometres,[3] the fuel cost would be $1316 with diesel at 65 cents per litre. The comparable gasoline model would use 10.7 litres per 100 kilometres and the annual fuel cost would be $1872 with gasoline at 70 cents per litre. The undiscounted payback period would be about 3.6 years, based on a vehicle price differential of $2000. With a discount rate of 20 per cent, the payback period would be seven years. If the price difference were $5000, including the cost of a catalytic converter and particulate trap, the undiscounted payback period would be about nine years. At a discount rate of just over 11 per cent, the payback period would exceed 100 years.

Assessment

In Australia the current retail price difference between gasoline and diesel per litre does not provide a large incentive to use diesel cars. The extra range offered by diesels may be more important in niche markets, such as that for large passenger 4WDs.

The extra cost of a catalytic converter and particulate trap, which could be required to make widespread use of diesel cars acceptable in terms of urban air pollution, would detract from the market acceptance of diesel cars.

Alcohol fuels

Costs associated with alcohol fuels

Ethanol is produced only in small quantities in Australia. It costs as much as or more than gasoline or diesel inclusive of excise, per LGE. Methanol is not as yet produced in Australia, although the proposed BHP pilot plant, if successful, may lead to production on a larger scale. Cost estimates for methanol production in Australia from natural gas, or for imports, place methanol into the market at the same price as gasoline per LGE, or at 70 per cent above the cost of gasoline

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[3] The Mercedes Benz *300D* 3 litre automatic has a rating of 9 litres per 100 kilometre urban, and 7 litres per 100 kilometre highway; the Mercedes Benz *300E* 2.6 litre automatic is rated at 12 litres per 100 kilometre urban and 9 litres per 100 kilometre highway (DPIE 1991c).

per LGE, before excise. In general the more alcohol in the fuel the higher the cost to the consumer.

While there is potential for reduction in the cost of alcohol fuels, these reductions would need to be very substantial before the fuels could compete with gasoline or diesel, before excise. Vehicles designed to run on any fuel with a major alcohol component are expected to be more expensive (appendix III), and distribution costs for alcohol fuels will also be higher (chapter 5).

Alcohol-fuelled vehicles

Anker-Johnson and Schwochert (1990) claim that General Motors methanol VFVs will have slightly better performance when operating on M85 than on gasoline, though most drivers will be unaware of any performance changes. Drivers of compression or spark ignition vehicles running on E10 to E15 are also unlikely to notice any reduction in vehicle performance. New vehicles should be compatible with low-level ethanol blends (≤E15), though with some specific models, fuel system problems are possible owing to material incompatibility. Vehicles already in the fleet may experience fuel system problems using blends of ≤E15 depending on vehicle model, age, and amount of deposit build up and corrosion already in the fuel system (appendix III).

Discussions with ACT retailers of Holden, Mitsubishi and Hyundai vehicles indicate that any damage caused by an alternative fuel (for example E10) would not be covered under new vehicle warranties. These retailers were not, however, aware of any problems being caused by low level ethanol blends. Ford knew of problems resulting from the use of E10 in two of its models. In these cases E10 caused the fuel gauge sender unit to malfunction, and this failure would not be covered under new vehicle warranty. The malfunction could be corrected by returning to normal unleaded gasoline.

Alcohol fuels can be dispensed in the same manner as gasoline, though the lower energy content would involve more frequent fuel stops or larger tanks taking longer to fill. General Motors experimental VFVs operating on M85 have a driving range of only 60 per cent of that of the equivalent gasoline vehicle. Ford and Chrysler have had to increase the capacity of their VFV fuel tanks to provide an acceptable range. Vehicle range constraints would also apply to dedicated alcohol vehicles.

Safety concerns with using alcohol

In the event of a collision leading to a fuel fire, the high alcohol content fuels burn more slowly and with less heat than gasoline. While the toxicity of methanol may cause community concern, if procedures outlined in appendix V were to be implemented, methanol vehicles would present no greater health problem than gasoline or diesel.

Overseas encouragement for alcohol fuels

Overseas programs promoting alcohol fuels are in place in, for example, Brazil, USA, Canada and Sweden. Examples of assistance are subsidies for feedstocks, lower fuel tax on alcohol fuels, government distribution of alcohol fuels, encouragement for (or mandated government fleet purchases of) alternative-fuelled vehicles, credits towards meeting fuel consumption targets, producer tax incentives, and government-sponsored in-service trials of alcohol-fuelled vehicles.

Assessment

Only low level blends of ethanol (≤E15) are likely to gain any consumer acceptance in the Australian market for some time. Even this limited acceptance is likely to require the continued excise moratorium on the alcohol component of the fuel. Use of high level alcohol fuels (M85 or E85) would depend on the availability of production vehicles, a fuel distribution system and a reliable supply of the fuel. At present only imported alcohol would be available to satisfy demands for M85 or E85. The cost of imported fuel, with excise added, would be higher than the cost of gasoline or diesel.

Natural gas

For market penetration of natural gas, high returns on the initial capital outlays, generated by fuel cost savings, would appear to be crucial until such time as perceived problems with use of the fuel are overcome. In a recent US survey of fleet managers on barriers to NGV use (Sinor Consultants 1992b, quoted in IANGV 1993), high initial cost of NGVs was shown to be the principal concern. Fuel cost savings for vehicle operators are listed as the main driving force in the AGA plan for NGVs in Australia. IANGV (1993) states that the incentive that will motivate the vehicle, transport and gas industries to commit the investment necessary to achieve its goal of 10 per cent market penetration will be the continuing difference between natural gas and gasoline or diesel prices.

Gafcor (1988) has stressed the importance of providing for 'total system' requirements if alternative fuels are to be successfully introduced. These include the technology, vehicle conversion and servicing programs, refuelling infrastructure, institutional and regulatory support, and marketing and promotion.

Acceptable payback periods

As mentioned earlier, Gafcor (1988) holds that payback periods should be no more than one year for small passenger vehicles and two years for diesel trucks and buses, while Merz (1991) concluded that a three-year payback period was the average requirement. The Gafcor and Merz payback periods suggest required rates of return considerably in excess of average estimates of consumer discount rates, or 'hurdle' rates of return for commercial investments.[4] These required short payback periods[5] would have reflected such factors as:

- short intended ownership periods of the various types of vehicles;
- pessimistic views of the resale market for converted vehicles (or the costs of restoring the vehicle to gasoline or diesel);
- the risk of a change in the fuel tax regime adverse to alternative fuels;
- non-fuel costs of using NGVs.

Business cars may be kept for only two to three years, and while heavy vehicles can have a long working life, their patterns of use may become less intensive over time. For example new articulated trucks may be used on interstate routes while older units may be used on shorter haul work. City buses have a life of around 14 years, but only a proportion — say one quarter or so — will actually travel large mileages (Gafcor, pers. comm. 1992).

Changes in the fuel tax regime would severely affect the payback periods for NGV conversions. The 1992 announcement of an excise moratorium for alternative fuels for at least five years has removed some of the uncertainty surrounding this issue.

For private vehicle owners, the non-monetary costs of converting to NGV would mostly relate to loss of convenience and time. Extra refuelling stops would be required. There would be a limited network of refuelling facilities possibly involving extra travel to refuel, and there would be less luggage space because of the size of the gas cylinders. For heavy vehicle operators also there would be costs associated with reduced range and hence extra refuelling stops, a more limited refuelling network, and possibly a reduced payload because of the size of the gas cylinders. There could be extra costs associated with obtaining vehicle maintenance.

If NGV use were to become common, some of these costs would be eliminated.

Estimates of payback periods

Recent estimates of the costs and benefits of NGVs include those of Yorke (1991), NELA (1991a), NRMA (1992) and Holmes and Naughten (1993).

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[4] Greene (1983), in a study of consumer valuation of car fuel economy in the USA, found implicit discount rates ranging from 39 per cent for low income earners down to 4 per cent for high income earners. Most estimates for required real rates of return for marginal private investment in Australia over the decade from 1976 range from around 7 per cent (AGSM 1986) to around 12 per cent (DOF 1987).

[5] Discounted payback periods will be considerably longer when the undiscounted payback period is itself longer than a couple of years or when the discount rate is significant.

Holmes and Naughten (1993) have calculated internal rates of return on NGVs for various classes of vehicle at different fuel price differentials as well as payback periods for specific scenarios. The payback periods are shown in table 10.1.

Rigid trucks have the least attractive rates of return due to their relatively low annual distance travelled and relatively high conversion costs. In addition, stop-start use results in low percentage substitution of natural gas for diesel in dual (mixed) fuel engines. However, Yorke (1991) notes that smaller truck conversions could be economic if these formed part of a fleet of larger vehicles. Depot refuelling infrastructure costs for these trucks might then be marginal.

For cars, the payback periods may be adequate for some users, and with higher annual distances will show shorter payback periods. However, the 8 per cent discount rate is lower than would be adopted by many potential users. Higher discount rates would lengthen the payback period to what would be unacceptable levels in terms of both the Gafcor and Merz criteria (one and three years respectively). In addition, the conversion cost adopted ($1500) is lower than AGL's (pers. comm. 1992) estimate of $2000 to $2500. At this cost, cars would need to travel 20 000 to 25 000 kilometres per year to achieve a three-year payback period.

The internal rate of return calculated for the Holmes and Naughten scenario for cars is 32 per cent, assuming a vehicle life of seven years (Holmes and Naughten 1993).

The NRMA (1992) estimated an undiscounted payback period of over three years for a dual-fuel Holden VN *Commodore* with a conversion cost of $2000, travelling 85 per cent of its 25 000 kilometres per year on gas. Natural gas supplied from a VRA at domestic rates was costed at 39 cents per cubic metre. VRA leasing and compresssion costs raised the effective price to about 53 cents per cubic metre. The NRMA pointed out that while 25 000 kilometres per year is typical for new vehicles, the overall average distance per year is only about

TABLE 10.1 PAYBACK PERIODS FOR NGVS

	Payback period at 8% interest (years)	*Annual distance (km)*	*Price difference between NG and diesel/gasoline (cents)*
Cars	Just over 3	16 000	35
LCVs	2.5	20 000	35
Rigid trucks	Over 8	20 000	30
Articulated trucks	1.4	80 000	30
Urban bus	3 to 4	50 000	30

Source Holmes & Naughten (1993).

16 000 kilometres, at which level of usage the payback period would be 'unrealistically long'. The NRMA (1992, 4) recommended 'a very careful financial analysis' for specific applications.

High mileage heavy trucks converted to natural gas clearly show favourable returns at current fuel price differentials.

Table 10.2 shows undiscounted payback periods estimated by NELA (1991a) for the operators of line-haul heavy trucks. The NELA calculations are based on natural gas prices of $9.06 and $10.50 per gigajoule (35 and 41 cents per cubic metre) and a diesel price of 60 cents per litre. Payback periods could be shorter to the extent that cheaper depot refuelling is used for some part of fuel supply. Table 10.3 contains estimates of rates of return for investments in NGV conversions and refuelling facilities, calculated by International Trucks Australia Ltd (Yorke 1991). Yorke used the 1991 Victorian price of 14 to 17 cents per cubic metre, depending on the user, and a diesel price of 71 cents per litre.

The capital cost of refuelling facilities is included in Yorke's calculations. Rates of return therefore vary with fleet size. For example the fleet of 20 full gas B-doubles is assumed to have two refuelling units each costing $350 000. If truck numbers were to fall to 10, the rate of return would fall to 79 per cent, and to 62 per cent with a fleet of five. A single B-double with one $350 000 refuelling unit would show a rate of return of 44 per cent (Yorke 1991).

TABLE 10.2 PAYBACK PERIODS ON CONVERSION OF LINE-HAUL HEAVY TRUCKS TO CNG

(years)

	Spark ignition at gas price:		*Dual-fuel at gas price:*	
Vehicle class	*$9.06/GJ*	*$10.50/GJ*	*$9.06/GJ*	*$10.50/GJ*
Rigid trucks				
100 000 km/yr	1.9	2.5	2.3	3.0
150 000 km/yr	1.3	1.6	1.5	2.0
Articulated trucks				
150 000 km/yr	0.9	1.1	1.1	1.4
200 000 km/yr	0.7	0.8	0.8	1.1
300 000 km/yr	0.4	0.6	0.5	0.7
Conversion costs				
Rigid trucks	$14 400		$13 200	
Articulated trucks	$16 900		$15 600	

Note Diesel price of 60 cents per litre.

Source NELA (1991a).

TABLE 10.3 INTERNAL RATES OF RETURN ON CONVERSION OF TRUCKS TO CNG

		Rate of return (per cent)	
Type	*Application*	*Dual-fuel*	*Full gas*
ACCO 1850/180 (medium duty 16 tonne)	City	–16.9	9.8
	Suburban	1.8	17.0
	Highway	21.2	23.5
SF 2670 L10 300 (43 tonne)	Intrastate	26.4	26.6
SF2670 fleet 360 (43 tonne)	Interstate	53.7	81.7
Transtar N444 (60 tonne)	B-double	60.2	87.8

Note Rates calculated for fleets of 20 vehicles.
Diesel price of 71 cents per litre; gas price of 14 to 17 cents per cubic metre.

Source Yorke (1991).

Governments concerned with the air pollution and noise effects of fuel use may accept payback periods longer than those required by private users. Dual (mixed) fuel natural gas urban buses undergoing trial by the NSW STA cost $9000 more than diesel buses. At a discount rate of 11 per cent, the benefit–cost ratio is greater than one (STA, pers. comm. 1991). The STA's spark ignition Scania NGV buses cost about $20 000 more than diesel buses. A payback period of six to 10 years is expected on these, given usage of 40 000 to 50 000 kilometres per year.

In the future the additional costs of NGVs could be offset to some extent by the cost of catalytic converters, particulate traps or more sound proofing required for diesel vehicles.

Effect of higher gasoline or diesel prices on NGV payback periods

Levels of penetration of natural gas will be influenced by changes in gasoline and diesel prices relative to the price of natural gas. The effects of a diesel fuel price increase from 60 cents to $1 per litre on the payback periods estimated by NELA (1991a) for the operators of line-haul heavy trucks are shown in table 10.4. All rigid and articulated trucks become very attractive conversion propositions with diesel at $1 per litre. Table 10.5 shows how the rate of return calculated by Yorke (1991) for a dual (mixed) fuel *SF2670 fleet 360* on interstate runs varies with the price of diesel fuel. The payback period is approximately one year at a diesel price of around 82 cents per litre. The Gafcor(1988) two-year maximum payback period criterion corresponds to a price of diesel of around 54 cents per litre.

TABLE 10.4 PAYBACK PERIODS ON CONVERSION OF LINE-HAUL HEAVY TRUCKS TO CNG: EFFECT OF HIGHER DIESEL PRICES

(years)

	Spark ignition at diesel price:		*Dual-fuel at diesel price:*	
Vehicle class	*$0.60/L*	*$1.00/L*	*$0.60/L*	*$1.00/L*
Rigid trucks				
100 000 km/yr	2.2	0.8	2.6	0.9
150 000 km/yr	1.4	0.5	1.8	0.6
Articulated trucks				
150 000 km/yr	1.0	0.4	1.2	0.4
200 000 km/yr	0.8	0.3	0.9	0.3
300 000 km/yr	0.5	0.2	0.6	0.2
Conversion costs				
Rigid trucks	$14 400		$13 200	
Articulated trucks	$16 900		$15 600	

Note Gas price of $9.78/GJ, based on average of prices used by NELA (1991a).

Source BTCE estimates based on case studies in NELA (1991a).

TABLE 10.5 RATES OF RETURN ON CONVERSION OF HEAVY DUTY INTERSTATE VEHICLES TO CNG: EFFECT OF CHANGES IN DIESEL FUEL PRICES

Diesel fuel price (cents per litre)	*Internal rate of return (per cent)*
55	52.7
60	61.9
65	70.9
70	79.8
71	81.7
75	88.7
80	97.5
85	106.4

Note International *SF2670 fleet 360* on interstate routes. Gas price of 14 to 17 cents per cubic metre.

Source BTCE estimates based on data and methodology in Yorke (1991).

Conclusions on payback periods

High rates of return (short payback periods) appear to be required for investment in NGVs, given doubts about resale values and non-monetary costs associated with vehicle use. With 1992–93 relative fuel prices, vehicle operators can achieve satisfactory payback periods for articulated trucks and large, high-mileage rigid trucks. Returns on buses would appear to be adequate for government transport operators. Cars travelling over 25 000 kilometres per year could provide sufficiently short payback periods to encourage operators to convert. For smaller cars with low annual mileages, reduced inconvenience costs (actual and perceived) or lower vehicle costs appear necessary to render the payback period acceptable for most vehicle owners. The economics will be influenced significantly by changes in relative fuel prices.

Potential market penetration by NGVs

The AGA has indicated that its goal for 10 per cent penetration of the Australian transport fuel market in 10 years is achievable provided natural gas remains free of excise (AGA 1992b). Overseas NGV programs have relied heavily on government involvement. Heavy duty NGVs may receive indirect government assistance if the cost of diesel vehicles increases in order to comply with the new Australian standards for diesel exhaust emissions announced in September 1993 (chapter 11).

Given the current difference between gasoline and natural gas prices, there is scope for a very large penetration of the LDV market by CNG, provided payback periods of three years are acceptable. However, payback periods of less than two years would require annual distances of around 30 000 kilometres (assuming a conversion cost of $2 000), compared with the annual average distance travelled of only 16 000 kilometres. Thirteen per cent of cars travelled over 25 000 kilometres in 1991, and 7.7 per cent over 30 000 kilometres (ABS, pers. comm. 1993). While the scope for penetration in this high distance category is limited to some extent by current use of LPG in taxis, taxis are only a very small proportion of total car numbers in this category.

On the assumption that 8 per cent out of the 13 per cent of vehicles travelling over 25 000 kilometres (with an estimated 28 per cent of car fuel consumption) were to convert to natural gas, 15 per cent out of the 25 per cent in the high mileage LCV market, and 50 per cent of the articulated truck market, natural gas could substitute for almost 20 per cent of gasoline and diesel fuel. This scenario, however, ignores the non-monetary costs associated with alternative fuel use, and the likelihood that shorter payback periods (such as estimated by Gafcor) would be required.

Merz (1991) argued that in NSW, the infrastructure costs[6] needed for market development would be lowest for the heavy truck market segment, which also

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[6] Infrastructure bonds, which companies may issue to fund projects operating for a minimum of 30 years, could reduce the interest costs of providing an NGV refuelling network. Interest paid to bond-holders is tax-free. Interest expense is not tax deductible to the issuing companies which, however, would be likely to have other expenses to offset against income earned in the early stages of an infrastructure project.

appears to gain most from conversion. A spur pipeline to Yass from the Moomba to Sydney pipeline would be the only major development required to cater for the Sydney–Melbourne corridor.

Holmes and Naughten (1993) conclude that while rates of return and payback periods for natural gas conversion suggest that a significant impact on the overall market for vehicle fuels may be possible, 'other influences on individual incentives to switch fuels are such that prospects may be limited to niches within the vehicle market accounting for only a small share of road fuel consumption'.

As with LPG, removal of the excise exemption or imposition of road user charges on natural gas would have a severe impact on returns on conversion. (A charge of 18 cents per cubic metre on natural gas, for example, would result in an approximate doubling of simple payback periods, assuming natural gas is purchased at 35 cents per cubic metre.)

NGV applications

Market penetration of natural gas in different market sectors may be influenced by the relative ease of developing technologies, infrastructure and regulation. Gafcor (1988) ranked natural gas market sectors in order of priority for ease of market penetration as follows:

- urban buses;
- heavy duty urban trucks;
- line haul trucks;
- mining, rail and marine applications;
- passenger cars and light duty spark ignition vehicles.

Urban buses and trucks

Both urban buses and trucks can utilise depot refuelling facilities. The payback periods for rigid trucks, however, are such that only high mileage vehicles are likely to be converted.

Depot based articulated trucks may be a potential market. Articulated trucks performed some 16 per cent more tonne-kilometres than rigid trucks in urban areas in 1987–88 (BTCE 1991), although an unknown amount of this task would have been by trucks running along intercity transport corridors.

In the bus market, NGVs are increasing, with most Australian transit authorities and some private companies now operating trial natural gas buses. The NSW STA has ordered 250 new Scania natural gas buses, with deliveries to commence in 1994 provided its trial buses prove satisfactory.

Line-haul trucking

The economics of introducing natural gas into line-haul trucking in all Australian intercity corridors has been under consideration by the VGFC, AGL and the AGA. It is expected that corridors in south-eastern Australia would be supplied with natural gas by spur lines from the existing pipelines, while others would be supplied by road tankers (NELA 1991a).

The NELA (1991a) study for the AGA found that introduction of CNG into interstate corridors would be financially viable for the gas utilities provided that market penetration exceeded 15 per cent. For truckowners, payback periods were found to vary from five months to under three years, with gas at 35 cents per cubic metre. Introduction of road user charges for NGVs, however, could reduce these payback periods substantially. Also, technical credibility would need to be established before truckowners would be prepared to take the risk of converting. This could be achieved through demonstration of successful interstate operations (NELA 1991a).

Ford Australia (pers. comm. 1992) does not see natural gas winning a large share of the heavy truck market, but considers that the involvement of OEM manufacturers would be expedient to mitigate the problem of high truck costs.

The market penetration of LNG, especially in trucks, will be affected by the scarcity and expense of liquefaction plants. NGV Australia (pers. comm. 1992) has indicated that the Alice Springs liquefaction plant would have cost in the region of $10 million to $15 million. There is a natural gas liquefaction plant in Melbourne, which produces a gas reserve in case of a break in supplies from Bass Strait.

Cars

If natural gas is to make a significant inroad into the transport fuel market in Australia, then it must penetrate the LDV market. Cars use over 60 per cent of road transport fuel and over half of total transport fuel. The AGA goal aims at 225 000 cars and 8800 taxis at the end of its 10 year plan period (AGA 1992b).

The AGA sees most potential for NGVs in Australia in the six and eight cylinder car market, eventually in OEM vehicles. NGVs are not expected to compete with EVs, at least for some time. EVs are more suited to the market for smaller cars (AGA, pers. comm. 1991). Small cars running on natural gas are said to require extensive redesign to enable adequate range while maintaining sufficient carrying capacity (Sinor Consultants 1992a). However, in the recent 886 kilometre Sydney to Melbourne trial of the Honda *Today*, no refuelling was required (AGA 1993).

Reduced resale values could be a problem where dedicated NGVs are bought for car fleets. One option to overcome this, and still ensure that the full benefits of the cheaper fuel are exploited, would be to manufacture cars with dual-fuel capability, with the gasoline capability disabled for the fleet purchaser, but available to the second-hand car buyer (VGFC, pers. comm. 1991).

It has been pointed out that LPG has made only a limited impact on the transport fuel market despite its availability and fuel cost advantage over gasoline. Natural gas and LPG share some disadvantages for the consumer, compared with gasoline. However, natural gas, at least outside Melbourne, has a greater price advantage per unit of energy content. Gasoline at 70 cents per litre costs two cents per megajoule. At 35 cents per cubic metre, natural gas costs 0.9 cents per megajoule. The cost of LPG at 32 cents per litre (a mid-range Sydney price) would be about 1.2 cents per megajoule. LPG in Melbourne is often available for around 21 cents per litre or about 0.85 cents per megajoule. Imposition of excise or road user charges on NGVs would reduce the present price advantage of natural gas over gasoline and diesel, and hence the attractiveness of the payback periods now available.

The natural gas industry emphasises that plans for natural gas use in cars are directed towards development of OEM vehicles, which is expected to lead to increased market penetration.

Future NGV numbers in the USA and Canada have been projected by the Delphi VI study conducted by the US Office for the Study of Automotive Transportation (OSAT). The forecasts were made by automotive industry experts. The median response was that 3 per cent of North American passenger vehicles produced in the year 2005 would be NGVs (2 per cent in 2000, 0.5 per cent in 1995). The NGVs were estimated to represent about 20 per cent of expected 2005 production of alternative fuel vehicles, produced largely in response to stricter emissions and fuel economy regulations (Sinor Consultants 1992a). A Canadian Gas Association survey in 1989 found that 51 per cent of those surveyed would be willing to convert to natural gas if their cars could be refuelled at home (Sinor Consultants 1990).

Taxis

Taxis converted to natural gas could have payback periods of well under one year, given their high annual distances travelled. Engine wear could be less than with LPG cabs. A recent change in Queensland Department of Transport regulations allowing station-wagons to be used as taxis has caused increased interest in conversion to NGVs in Brisbane, as two or more cylinders can be fitted for a useful range (AGA 1991b). An Adelaide taxi has a similar configuration.

Trials in Goulburn have not been particularly favourable for natural gas taxis, with all of the 14 cabs originally fuelled by natural gas reverting to LPG. Range was the major problem (chapter 7). The fuel savings were outweighed, according to one operator, by the cost of fares lost while travelling back to the AGL facility to refuel, and by the cost of this extra travel. The quarterly billing practice was a further factor influencing natural gas acceptance in Goulburn (Goulburn Taxis, pers. comm. 1992), though presumably a problem which could easily be overcome.

Future use of natural gas in taxis will be facilitated by the involvement of car manufacturers in developing vehicles optimised for natural gas, such as the Ford *Falcon* station-wagon taxi (chapter 7). Five of these models are to be built to assess the vehicle specification, after which 50 more are to be produced.

Marine applications

CNG appears to have the potential to replace some proportion of diesel fuel in lightly loaded small and medium sized ships, especially those operating within harbour limits. Natural gas is distributed to most major Australian ports (*Australian Energy Research* 1989).

Ferries comprise one market and harbour tugs another potential dual (mixed) fuel application. Tugs spend a considerable proportion of time alongside wharves, allowing ample opportunity for refuelling. They rarely have more than three jobs per day, and a typical job lasts between one and one and one-half hours in most Australian ports (BTCE 1989).

LNG would need to be used to give the range necessary for coastal or international shipping operations (Merz 1991), though limited availability of LNG in some overseas ports would inhibit international use. However, the price of LNG relative to fuel oil would appear to be too high for effective competition (Merz 1991).

Rail

With no commercially available gas locomotive engines or conversions, widespread natural gas use in railways is seen as a longer term prospect only. A payback period of about nine years has been estimated for 3000 horsepower locomotives, with other types not being economic to convert (Merz 1991).

The feasibility of natural gas in locomotives is affected by operating range, power loss, ease of operation, refuelling times and the need for a separate tender to carry the fuel.

Light diesel vehicles

While light duty diesels tend to be home based, they are often unsuited to home refuelling. For example, a typical *HiAce* van would use two cylinders of natural gas per day. Home refuelling alone would not be a viable option. NGV Australia (pers. comm. 1992) points out that small trucks are often gasoline-fuelled overseas and could be easily converted to spark ignition natural gas (SING) if imported. Research at NGV Australia is concentrated on the bus and forklift market, and on B-doubles. The M14 engine (rated at 320 HP on diesel) can produce up to 400 horsepower on gas.

Market acceptance of NGVs overseas

Use of natural gas for transport overseas is usually backed by government support programs, some quite vigorous. The initiatives adopted are varied and include: government and industry planning and promotion of NGVs; development of standards; financial assistance for gas utilities, car and VRA buyers and for fuel retailers; licensing of dual stations to sell both liquid fuels and natural gas; favourable tax treatment for natural gas and NGVs (sales tax, road tax, fuel excise, tax credits and rebates); and legislated use of NGVs, such as requiring that all newly registered buses and taxis in Buenos Aires be NGVs.

However, IANGV (1993) states that the responsibility for promoting natural gas is being increasingly assumed by industry coalitions or associations of utilities and pipeline companies. These include the NGV Coalition in the USA, and the European Natural Gas Vehicle Association. With more emphasis on OEM vehicles, these associations and coalitions are becoming more involved in the necessary inter-industry negotiations with, for example, vehicle operators and equipment suppliers.

The IANGV (1993) warns that in measuring the advantages of NGVs and setting strategies, the industry should not lose sight of advances being made in the reformulation of liquid fuels. Upgrading of liquid fuels to meet vehicle equipment needs is changing the competitive position in relation to natural gas.

While a considerable increase in NGV numbers, and progress with NGV technology and NGV marketing has occurred in several countries (IANGV 1993), some support programs appear to have had limited success. In Italy natural gas has been used as a transport fuel since the 1930s (IANGV 1990). The natural gas price has been less than one-third that of gasoline, and less than half that of diesel or LPG. But while NGV numbers are large relative to those in other countries, NGVs account for only about 1 per cent of the total number of cars and trucks, and for only about 0.7 per cent of road sector energy consumption (IEA 1992a).

Electric vehicles

The short operating range and high cost of electric cars constitute a major barrier to their market acceptance in Australia in the short and medium term. The current lack of OEM EVs is a major consideration, given the time that it takes to develop such vehicles and to bring them to the production line stage.

Japanese EV developers have a target to reduce the price of an EV to 20 per cent above that of a similar sized gasoline car by the year 2000. At present, however, an EV may be twice the price of the gasoline model from which it is converted (chapter 8). The production cost of state-of-the-art EVs, such as the *Impact*, is comparable with prestige vehicles rather than with ordinary small cars. Retail prices are more likely to reflect company policy on amortising development costs rather than actual production costs, at least until large scale production begins. The prospective high cost of the *Impact* EV is perhaps the main reason for the reported revision of General Motors' production plans for this vehicle.

However, it has been argued that production volumes of 50 000 per year for cars and 10 000 per year for vans may allow EV prices to equal those of gasoline cars (chapter 8). Hybrid vehicles are likely to be significantly more expensive than EVs embodying a similar level of technology.

EVs could benefit from increases in energy prices, in so far as the cost of electricity is a very minor component in the cost of an EV, and much lower than fuel costs of gasoline cars.

Potential applications

For inner-city delivery or for short daily mileages from a depot where vehicles can be refuelled overnight, an EV's performance could be acceptable and the extra initial costs could be amortised over a longer vehicle life. A considerable part of EV development by car manufacturers is directed towards this market, especially in California and other states following the Californian lead. Examples include Ford's *Ecostar* van, General Motors' *G-Van*, Chrysler's *TE Van* and Peugot's *J5* light truck.

Ford is planning to introduce an electric car to the USA market in 1998. Dr Nichols, the manager of Ford's US EV planning office, reportedly considers that should Ford decide on a small car, it could possibly be produced in Australia for the local market. In Dr Nichols opinion, EVs will eventually account for 5 to 10 per cent of total world car sales, as 'second cars' used for commuting rather than as family cars (AEVA 1992).

Potential market penetration

Households with more than one vehicle may be in a position to choose an EV, especially where the second car is mainly used for short distance trips. However, various studies have attributed very high values to the disutility of limited range. Turrentine and Sperling (1992) cite stated preference studies which estimate the disutility of a range of 80 kilometres compared with a range of 320 kilometres at US$10 000 (1991$) (Morton et al. 1978), US$16 250 (Beggs et al. 1981), and US$15 000 (Bunch et al. 1992).

Turrentine and Sperling (1992) point out that these values imply that the probability of purchase would be very low. However, they consider that stated-preference studies are subject to large errors when new products, rather than familiar products, are involved. These authors preferred an approach which purports to account for dynamic factors in the market, such as the diffusion of innovations and changes in consumer tastes. They concluded that 20 to 60 per cent of all households in the USA could substitute an EV with a range of 160 kilometres for one of its existing vehicles.

Graves (BTCE 1978) conducted a survey of 679 Melbourne households to determine the suitability of EVs for household use. An EV, with an assumed 80 kilometre range, was deemed suitable if it satisfied the criteria of:

- belonging to a multi-car household (25 per cent of households in 1977);
- travelling 40 kilometres or less on a typical weekday (69 per cent of vehicles in 1977);
- travelling 10 000 kilometres or less per year (32 per cent of cars in 1977);
- travelling more than 80 kilometres per day less than 12 times per year (40 per cent of cars in 1977).

Graves concluded that 13 per cent of vehicles in the surveyed households could have been replaced by an EV. If only one car per household could be an EV, the percentage fell to 11. These percentages may have changed somewhat with changes in travel patterns since the survey.

The household cars which met Graves' criteria were generally older and less valuable than the average private car. It might not be financially attractive or feasible for many households to replace these cars with EVs, at least until there is a market for lower cost second-hand EVs.

Assessment

EVs are not viable alternatives to gasoline or diesel vehicles, given present relative vehicle and fuel prices. They do not offer comparable convenience or performance, and initial costs are higher, though in the longer term commercial production of advanced batteries may bring the range for EVs closer to that of gasoline vehicles.

Apart from urban delivery vans and the use of EVs in government fleets, increased use of EVs will be difficult to achieve without support, for some time, either from regulations directed to the improvement of urban air quality, such as those of the CARB, or from some other substantial incentive. Hence the level of market penetration will be influenced by how keen authorities are in pursuing reductions in air and noise pollution in urban areas. EVs in large numbers could have a dramatic effect on urban air and noise pollution.

In the future, EV technology may mature as a result of overseas — particularly US — pressure for ULEVs and ZEVs. It might then be appropriate to limit access to some areas of major Australian cities by private cars other than EVs or other ULEVs, depending on air and noise pollution levels. Planning for such a policy would, however, need to begin well before the intended restrictions were imposed. EVs would not assist in alleviating urban congestion problems.

Hydrogen

Hydrogen is generally expected to be primarily of experimental or demonstration interest in the period to the year 2005 at least. In the longer term, as non-renewable fuel reserves are depleted and population pressure encourages food rather than energy crops, hydrogen may become a major source of transport energy. Developments in metal hydride storage or in hydrogen fuel cells could assist in overcoming any market resistance stemming from perceived safety problems with hydrogen.

CONCLUSION

Widespread use of alternative-fuelled vehicles in the period to the year 2005 will not occur without substantial government encouragement. Government support will be needed for even modest levels of alternative fuel use up to 2005, given present levels of production costs for these fuels and their operational drawbacks, the state of technology and lack of OEM vehicles.

Available research results suggest that strong advertising — particularly of the energy content available for the fuel price — and of payback periods, along with availability of fully warranted OEM vehicles, could be important factors in securing market penetration of alternative fuels.

To make a substantial market impact it will be necessary for alternative fuels to make inroads into the car market, which is responsible for around 54 per cent of transport fuel use in Australia. However, fuel costs are not usually a high enough proportion of total costs in this market to give the required payback periods and so offset other drawbacks.

Government policies in relation to road user charges, fuel excise, the inclusion of the social costs of air pollution and noise in fuel costs, and specific assistance to alternative fuels will have a major impact on the results.

There is scope to increase the market penetration of LPG above the rate of growth in consumption projected by ABARE, though imports might be needed to cater for increased growth beyond 2005. There is probably only limited scope to increase diesel use in cars while the price differential between diesel and gasoline remains small.

There is potential for ethanol use in Australia in the short term, in low percentage blends with diesel or gasoline in essentially unmodified engines. One very important proviso is that manufacturers accept the use of these fuels for warranty purposes, and fuels would have to be made available at acceptable prices. Production costs are as yet relatively high. The market penetration of high percentage alcohol blends with either gasoline or diesel in dedicated or VFV engines seems much further off, and is likely to depend on overseas developments of these vehicles.

While EVs in large numbers could reduce urban air and noise pollution substantially, increased use of EVs will be difficult to achieve without strong government regulation or other support. The level of market penetration is therefore likely to depend on the level of support for air and noise pollution reduction in urban areas.

Market penetration of hydrogen as a vehicle fuel in the period to 2005 is not expected to occur, but in the long term this fuel could play an important role in transport.

PART III: POLICY ISSUES

CHAPTER 11 POLICY ISSUES

INTRODUCTION

Governments could have a role to play in establishing standards for alternative fuels, vehicles and equipment, and for vehicle emissions. Governments could also provide information to improve consumer knowledge and to protect consumers from product defects or adverse safety and health consequences. The need for this form of government intervention arises because the market for alternative fuels is relatively new. There are as yet no emissions standards for vehicles converted to run on alternative fuels; Australian standards relate only to emissions from new vehicles.

Many governments go beyond this role and provide financial and regulatory assistance for alternative fuels. The main policy issue is whether such assistance is warranted. Some level of support could be justified if alternative fuel use generates benefits for society over and above the benefits which accrue to the industry or consumer. It is therefore important to assess the extent of any such benefits, or 'externalities', from using particular alternative fuels.

Another issue is, if externalities are significant, what form of assistance might maximise the benefits to society from encouraging the use of alternative fuels. Options include adjustments to relative fuel or vehicle prices, industry assistance through favourable taxation treatment or research and development grants, regulations and standards which favour alternative fuel vehicles or alternative fuels, and governnment purchasing practices.

Not all of these issues are addressed here. The arguments for supporting alternative fuels are considered, including the resource security, macroeconomic, balance of payments, and industry specific arguments which are often mooted, as well as the environmental arguments. The emphasis is on the extent to which government intervention is warranted by benefits arising from environmental externalities.

ENVIRONMENTAL EFFECTS

Many alternative fuels generate lower greenhouse or noxious emissions than gasoline. Noise levels from some alternative fuel vehicles are also lower. Ideally these environmental effects should be included in the factors taken into account by consumers when they make decisions on fuel use. This might be achieved most efficiently by levying charges on emissions at their source.[1] Use of less polluting fuels would incur lower charges.

Unfortunately, techniques are not yet available to permit a system of direct charges on emissions. Proxy measures for these charges are required to approximate the effect that a direct tax on emissions would have on fuel consumption patterns. Those most often proposed include variations to market prices of fuels and, in the transport sector, subsidisation of vehicle prices, or regulation of vehicle emissions or fuel standards which favour the more environmentally friendly fuels. With variations to market prices of fuels, the intention should be to have the prices of alternative fuels and gasoline reflect their respective environmental impacts.

Fuel prices

Alternative transport fuels (other than diesel) already have a price advantage in that they are not subject to the Commonwealth excise and state taxes applying to liquid petroleum based fuels. In effect, they receive a 'subsidy' — currently around 29 to 39 cents per litre. In 1992 the Prime Minister extended the excise exemption for a further five years with one year's notice of termination (*Statement on the Environment,* 21 December 1992).

It is therefore of interest to consider whether the difference between the pollution costs of gasoline and any alternative fuel is likely to be as large as the current 'subsidy'.

If it is considered efficient to adjust transport fuel prices to include an allowance for road track, accident and congestion costs, as well as environmental costs of vehicle use (noise, air, and possibly visual pollution), the price differences among fuels (over and above resource cost differences) should reflect only the difference in environmental effects.[2] Vehicles powered by alternative fuels would be expected to pay the same road track, accident and congestion charges as

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[1] A charge equal to the cost of the emission would reduce output to the point where the marginal benefit to the consumer would equal the marginal social cost of production inclusive of the pollution cost. Consumers not prepared to pay the social cost of pollution would leave the market.

[2] The Inter-State Commission recommended road use charges in 1990 of 24.1 cents per litre for diesel and 20.5 cents for gasoline. These included an externality charge of 8.5 cents per litre for diesel and 5.1 cents for gasoline (Butcher 1990, 53).

similar vehicles using gasoline or diesel, as they would impose similar costs (see, for example Butcher 1990, 117).

It may not, however, be efficient to adjust prices of transport fuels to reflect externalities if fuel prices are not adjusted in other sectors too. This could result in misallocation problems which would offset the gains to be made in the transport sector. For example internalising costs in transport alone could mean that natural gas is used in transport rather than in electricity generation where it might be economically more valuable. Naughten et al. (1992), modelling total energy sector emissions, found that road transport emissions were reduced by 5.1 per cent in 2005 by growth in the number of NGVs, given continuing excise exemption to 2005. However, total emissions from the energy sector (including transport) rose by 0.6 per cent, as the price of gas was bid up, reducing its substitution for coal in electricity generation.

Industry position

It is argued by the LPG and natural gas industries (for example AGA 1990b)[3] that a lower subsidy (for example a small excise as opposed to an exemption) would be inadequate to maintain LPG and natural gas as alternative fuels. The scope for alcohol fuels or EVs[4] to obtain a market share would be made even more difficult. The industry case for continued assistance has received a certain amount of support (Special Premiers' Conference Communique [July 1991], Senate Standing Committee on Industry, Science and Technology Report [Senate 1991, 85], Interim ESD strategy report and National Greenhouse Response Stategy [Commonwealth of Australia 1992, 27]).

Certainly only very high mileage vehicles would maintain payback periods on conversion costs of under two years if there were a substantial reduction in the current level of assistance. Such a reduction might occur if, for example, a road user charge were imposed on NGVs to match the notional portion of the excise assumed to represent road user charges on diesel and gasoline.[5] The impact of a lower price advantage for natural gas compared with gasoline and diesel on rates of return on NGV conversion is illustrated in Naughten and Holmes (1993, 12 *et seq.*).

The alternative fuels industry would appear to require some form of market intervention to maintain or increase its role, particularly in the private car market.

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[3] The AGA (1990) has indicated that a ten year moratorium on the imposition of an excise would be required to provide the necessary stimulus to investment in the NGV industry.

[4] Applying the equivalent of the fuel excise to EVs would involve charging according to distance travelled.

[5] The National Road Transport Commission has recommended road user charges for heavy vehicles of 18 cents per litre of diesel used, as well as fixed registration charges, to cover road damage costs.

Alternative fuels are probably not financially viable at present in any country without some form of assistance. Additional costs incurred in using these fuels may include additional capital costs, additional fuel costs and costs to users associated with inconvenience or uncertainty.

In the future, if the costs of alternative fuel use are reduced to match the costs of gasoline car use — or diesel use in HDVs — there may *still* be no incentive for consumers to adopt alternative fuels. The question arises as to whether in this situation some form of 'one-off' assistance should be provided. This could enable alternative fuels to overcome the barrier resulting from the entrenched market position of existing fuels, in the event that environmental or other benefits justifying ongoing support were inadequate. There would seem to be no economic reason to encourage the switch to alternative fuels in this case, unless some additional unpriced benefits existed. These benefits might arise from introducing wider choice, a more diversified fuel supply or a 'one-off' effect on employment levels (for example, from the provision of alternative fuel infrastructure).

Environmental benefits

The value of the environmental benefits from using alternative fuels rather than gasoline is extremely difficult to assess. Estimates of achievable reductions in greenhouse and noxious emissions vary widely, and there are significant difficulties in assigning monetary values to any reduction in emissions.

Emissions from alternative fuels

Emissions from transport fuels are usually expressed in grams per kilometre travelled, and hence based on the amount of fuel used per kilometre for a particular vehicle type. Alternatively they may be expressed in grams per megajoule or grams per litre. There are some problems with these measures even in the case of greenhouse gas emissions.

Greenhouse gas emission reductions

Estimates of reductions in emissions of direct greenhouse gases (CO_2, CH_4, N_2O and CFCs) from using different fuels vary with the carbon content of the fuel, the nature of the full fuel cycle, the efficiency of combustion, emissions control technology, and vehicle fuel efficiency. Full fuel cycle emissions vary with different production, distribution and refining processes. For example emissions attributed to ethanol, EVs and hydrogen can be very different depending on the way these fuels are produced. Other differences in emission estimates occur where test vehicles, engines, and vehicle condition vary, or where test conditions — such as temperature and the way the vehicle is driven — differ.

TABLE 11.1 LIFE CYCLE GREENHOUSE GAS EMISSIONS FROM LIGHT DUTY VEHICLES
(grams CO_2 equivalent per km)

	North America year 2000	*Per cent below gasoline*
Gasoline	260	
Reformulated gasoline	263	–1
Diesel	210	19
LPG	201	23
CNG	231	11
Methanol, from natural gas	250	4
Ethanol, from biomass	82	68
Liquid hydrogen produced by electricity from non-fossil fuel	77	70
Electricity from hydro power	35[a]	86

a. BTCE estimate based on IEA (1993) emissions data for urban driving cycle only.

Source IEA (1993).

While emissions of indirect greenhouse gases are not as important in terms of quantity (chapter 1), they still have an influence on the accuracy of emission reduction estimates. Estimates of emissions of these gases from different fuels are subject to considerable variation.

Choice of conversion factors used to express the various greenhouse gases in terms of a common denominator (CO_2 equivalents), can also lead to variations in estimates. For example if a short time horizon effect is chosen, the advantages of natural gas will not be as large as with a longer time horizon, as the impact of methane emissions is much stronger in the short term. The IPCC admits to uncertainty in the conversion factors recommended for calculating CO_2 equivalent emissions from the range of different direct and indirect greenhouse gases emitted.

Table 11.1 shows IEA (1993) estimates of life cycle[6] greenhouse gas emissions from alternative fuels compared with gasoline, based on year 2000 technology vehicles. Tables 11.2 and 11.3 show the wide range of possible outcomes estimated by DeLuchi. The wide range results from different assumptions about fuel production and vehicle use (Sinor Consultants 1992c; DeLuchi 1993).

IEA estimates of reductions in greenhouse gas emissions from use of alternative fuels are 23 per cent or less, except for ethanol from biomass, (liquid) hydrogen

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[6] Life cycle emissions include full fuel cycle emissions and emissions from vehicle manufacture.

TABLE 11.2 RANGE OF GREENHOUSE GAS EMISSION ESTIMATES FROM USE OF ALTERNATIVE FUELS IN LIGHT DUTY VEHICLES COMPARED WITH RFG[a]

(Per cent change)

Fuel	*Worst*	*Best*
Reformulated gasoline (RFG)	+6	–4
Standard US gasoline	+3	–6
Diesel fuel	–6	–25
Methanol from coal	+75	+10
Methanol from natural gas	+12	–25
Methanol from wood	–5	–100
CNG or LNG	+35	–35
LPG	–6	–37
Ethanol from corn/coal	+80	–66
Ethanol from corn/corn stover	0	–72
Ethanol from wood	+12	–100
Hydrogen: hydride/nuclear electrolysis	–41	–80
Liquid hydrogen/nuclear hydrolysis	+10	–80
EV/coal fired	+100	–61
EV/marginal US power generation mix	+67	–43
EV/natural gas fired	+15	–73
EV/nuclear electricity generation	–81	–88
EV/wood fired electricity generation	–10	–100
EV/solar	–89	–92
Methanol from coal: fuel cell	+10	–25
Methanol from natural gas: fuel cell	–33	–50
Methanol from wood: fuel cell	–45	–100
Hydrogen from solar: fuel cell	–81	–89

a. Results show a comparison of each fuel with RFG for a number of test scenarios over which RFG results also vary. Emissions are on a life cycle basis.

Source DeLuchi (1993).

TABLE 11.3 RANGE OF GREENHOUSE GAS EMISSION ESTIMATES FROM USE OF ALTERNATIVE FUELS IN HDVS COMPARED WITH DIESEL

(Per cent change)

Fuel	*Worst*	*Best*
LPG	+15	–11
CNG or LNG	+45	–13
Methanol from natural gas	+35	–6
Methanol from coal	>+100	+40
Ethanol from corn/coal	+100	–56
Ethanol from wood	+35	–100
Hydrogen: hydride/ nuclear electrolysis	–26	–85
Hydrogen: hydride all-solar fuel cell	–84	–92

Note Emissions are on a life cycle basis.

Source Sinor Consultants (1992c).

and electricity from non-fossil sources. These emissions effects vary considerably according to the particular circumstances. DeLuchi (Sinor Consultants 1992c, 12) argues that 'the use of any fossil fuel feedstock will not significantly reduce emissions of greenhouse gases as long as the fuel is used in an internal combustion engine'. This would apply to fuels such as LPG, diesel, natural gas, methanol from coal or natural gas, electric vehicles powered from coal-fired or gas-fired power stations, and hydrogen produced using power generated from fossil fuels.

Noxious emission reductions

There is also a lot of variation in estimates of the potential reduction in noxious emissions available from use of alternative fuels. Test results vary with a range of factors including fuel use, pollution control equipment, engine management systems, the efficiency of the combustion process, the test cycle conditions, driving patterns and the number of cold starts.

Pollution control devices can make a big difference. It has been calculated for Sweden, for example, that the social cost of air pollution per litre for a car consuming 10 litres per 100 kilometres is 14 cents with a catalytic converter, and 44 cents without (Hansson 1991). Comparisons of vehicles with pollution control equipment are therefore likely to indicate lower achievable reductions in noxious emissions from use of alternative fuels than comparisons of vehicles without such equipment.

The amount of fuel used can be a poor indicator of noxious emissions. Newer vehicles with stricter emission control devices can in fact use more fuel than they would without these devices.

Another problem is that emission reductions available from alternative fuels are likely to change as emission standards for all vehicles tighten. Similarly, technological developments, particularly in the relative fuel efficiency of gasoline vehicles, may reduce the potential for achieving emission reductions from alternative fuels.

The value of emission reductions

Even if reliable estimates of physical emissions from transport fuels could be found, there are no reliable estimates of emission costs. Estimates are few, vary greatly, and no pretence is made about their accuracy.

Also, while the value of greenhouse gas emission reductions is the same irrespective of where the emissions occur, the value of reductions in noxious emissions differs between urban and non-urban areas. The populations likely to benefit from noxious emission reductions in non-urban areas are relatively limited; consequently, the value of noxious emission reductions in these areas is limited. It would not therefore be efficient to subsidise the use of any high-cost fuels in non-urban zones, on the grounds of low noxious emissions. However, it may be difficult to distinguish fuel used for urban and non-urban travel. High mileage fixed route articulated trucks converted to natural gas would be major beneficiaries of either a lower excise or a continuing excise holiday. However, 90 per cent of freight tonne-kilometres performed by articulated trucks are in non-urban areas (BTCE 1991).

Noxious emission costs

Estimates of the costs of noxious emissions also vary over a wide range. The ISC (1990) attributed costs of 0.8 cents per kilometre to gasoline cars for urban air pollution and noise emissions. This would amount to about 6.8 cents per litre of gasoline at recent Australian fleet average fuel consumption rates. BTCE (1993) provides an estimate of one cent per kilometre for noise and air pollution, using ISC data averaged over all vehicle types. These costs are of the same order as those estimated by Ottinger et al. (quoted in CRCNPT 1992, 1118). The Ottinger et al. estimates (in US$ per kilogram) would translate to around 2 to 6 Australian cents per litre of gasoline for NO_x, SO_2 and particulate emissions from average Australian fleet cars. The range is due to the level of pollution control equipment installed in vehicles.

The ISC estimates have been regarded as too low. Other US estimates (Moffet 1991)[7] for air pollution from cars (for the whole of the USA) are 2.6 to 3.7 Australian cents per kilometre, or around 22 to 31 cents per litre. Estimates of damage costs for Norway are also high. Hansen (1992) quotes NO_x emission costs about six times higher, and particulate emissions about three times higher, than those estimated by Ottinger et al. Hansson (1991) quotes 14 to 44 cents per litre for the external effects of pollution for Sweden, determined on a control cost basis.

Recent estimates for Melbourne, for health costs attributable to ozone formation and cancers due to toxic motor vehicle emissions, suggest these costs would amount to 0.08 to 0.2 cents per vehicle kilometre (BTCE estimate based on RCG/Hagler, Bailly, Inc., 1993). Such costs would mean that benefits from reducing ozone and toxic emissions through use of alternative fuels would be very low, even if the proportionate reduction in emissions were high. The highest estimate made of health costs from ozone in Melbourne was in 1988–89, when the estimated range was $0.8 million to $10.8 million. For 1992–93 the estimated range was $0.3 million to $4.4 million. Health costs from cancers attributed to toxic motor vehicle emissions were estimated at $26 million to $45 million in 1990 (RCG/Hagler, Bailly, Inc. 1993). The health costs from these two sources indicate a range of $14 to $31 per vehicle in Melbourne. If these

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[7] The Moffet estimates were derived from data on emissions from power stations, did not purport to reflect transport emission costs accurately, and depend on US populations affected, US climatic conditions and the US vehicle fleet.

estimates for Melbourne are indicative, they suggest that many emission control policies (such as controls on vehicles or conversion to alternative fuels) may not be economic.

The Canadian Royal Commission on National Passenger Transportation (CRCNPT 1992) assigned some 'extremely speculative' values to particular pollutants on the assumption that 'the charges necessary to achieve nationally declared goals for these emissions reflect the social value placed on preventing the damage'. On a per litre basis, the Canadian estimates would amount to about 15 Canadian cents per litre for NO_x and VOCs in summer in the ozone prone areas.

Apart from EVs, NGVs and diesel cars are likely to provide the largest reductions in noxious emissions. Potential reductions from RFG are more limited. Alcohol additives may be promising, and though use in low level blends may not yield large reductions per litre, the reductions attributed to the alcohol component could be high. For example if ethanol is used as a 10 per cent blend with gasoline (E10), a greenhouse emission reduction of about 4 to 5 per cent could be expected per LGE, based on a 60 per cent lower emission rate than from gasoline. In a 15 per cent blend with diesel and an assumed 50 per cent lower emission rate the greenhouse saving per LGE would be around 5 per cent. It is uncertain whether LPG use will yield emission reductions from current vehicle conversions. These conversions have sometimes been poorly performed, and the vehicles inadequately maintained. There is potential for improvement should vehicle emission standards become effective.

The particular scenario in appendix X suggests that converting cars to NGVs could result in a reduction of about 34 per cent in the cost of urban pollution and noise, based on ISC (1990) emission cost estimates and emission reductions assumed by the BTCE on the basis of various test results. The 34 per cent reduction amounts to about 0.27 cents per kilometre (2 to 3 cents per LGE). If the higher Moffet (1991) cost estimates for the USA are used, the reduction in pollution cost from using NGVs is of the order of 1.5 Australian cents per kilometre (around 14 cents per LGE). The estimated benefits may be compared with the current Commonwealth excise of around 3 cents per kilometre (29 cents per litre since late 1993), depending on fuel consumption. However, the physical emission reductions assumed by the BTCE are subject to a possible wide margin of error, given widely varying results from domestic and overseas tests.

For noxious urban emissions from diesel trucks, a 1.6 to 2 cent per kilometre reduction in emission costs from NGV heavy vehicles might be expected on the basis of both the ISC and Moffet cost estimates and the emission reductions assumed in appendix X. The present Commonwealth excise is around 14 cents per kilometre for a large truck using 50 litres per 100 kilometres.

It is emphasised that these comparisons are illustrative only. The BTCE does not consider that estimates of achievable reductions in noxious emissions or of the costs of noxious emissions are sufficiently precise to permit noxious emission externalities from different fuels to be priced with any accuracy. Any conclusions about desirable price differences among alternative fuels and gasoline to reflect noxious emissions would therefore be tenuous.

If noxious emission costs *were* to be internalised through adjustment to fuel prices, the emission costs would have to be at the high end of the above range of estimates to make a substantial difference to relative fuel prices. EVs, with no noxious emissions, would benefit most from such a price adjustment. Prices for other alternative fuels, which would not generate such large reductions in noxious emissions, would be unlikely to differ greatly from the gasoline price. It is possible, therefore, that most alternative fuels may not warrant assistance to any great extent on the grounds of lower noxious emissions.

Vehicle emission standards

The level of noxious emissions from various fuels depends in part on emissions standards imposed by governments. If the same emissions standards were to apply to all new vehicles, and in due course, common standards were to be applied to all in-service vehicles, market prices of vehicles and fuels would reflect the cost of meeting standards. If alternative-fuelled vehicles were able to meet standards more easily, they would have a price advantage in this respect, and the case for support for fuels with lower emissions would not be as strong.

Some fuels would always be likely to have advantages in respect of some emissions — particulates in the case of NGVs. Overall, however, the benefits from the lower emissions from alternatives to gasoline, when all fuels are required to meet the same standards, may not be very high.

It may be some time before such standards are in place, particularly for in-service vehicles. In the interim, alternative fuels could contribute to an improved environment. However, there may be a risk in encouraging fuel systems with high infrastructure costs, which might not prove warranted in the long run.

New standards for diesel vehicles, announced in September 1993, will take effect from 1995 to 1996. A review of diesel standards is proposed for 1995, with the intention of moving to a tighter standard in the late 1990s. Proposed new standards for gasoline vehicles will take effect during 1998 and 1999. It is likely that the coverage of the new gasoline standards will be extended to cover LPG and natural gas vehicles also. Current research into in-service emissions and factors causing deterioration of vehicles may lead to introduction of in-service standards by the late 1990s.

The current and proposed standards for gasoline and diesel passenger cars are shown in table 11.4. The data suggest that the scope for emission reduction from use of alternative fuels rather than gasoline will be reduced significantly when gasoline vehicles meet the new standards. However, the comparison may

TABLE 11.4 CURRENT AND PROPOSED NEW PASSENGER CAR EMISSION LIMITS FOR AUSTRALIA

	Limits on emissions (grams per vehicle km)			
Vehicle type and standard	*CO*	*HCS*	*NO_X*	*Particulates*
Gasoline cars				
Current ADR 37/00	9.30	0.90	1.93	
Proposed standard (1998–99)	2.10	0.26	0.63	
Diesel cars				
Current standard	nil	nil	nil	Relates to smoke only
Standards from 1995–96				
US, or	2.1	0.26	0.63	0.12
EC, or	4.5 g/kWh	1.1 g/kWh	8.0 g/kWh	0.63 g/kWh
Japan	2.7	0.62	0.72	0.34

Source FORS (1993a, 1993b).

be misleading, as many new vehicles already achieve much lower emissions than required by the existing standard (FORS 1993a).

Greenhouse gas emission costs

The damage costs of greenhouse gas emissions are not known. Estimates of 'control costs' may sometimes be used as a proxy. These are intended to provide a surrogate estimate of the cost of emissions, or of the value of a reduction in emissions, by reference to the cost of reducing them in the cheapest way. There is insufficient information available as yet on these control costs; estimates of the costs of achieving the 'Toronto target' in Australia vary from net benefits to very large costs, and many strategies have not been costed. There is therefore no particularly reliable basis for valuing the contribution of any particular policy instrument, such as alternative fuel use, in reducing emissions. Some estimates given below may nevertheless assist in providing an order of magnitude of the likely benefits from use of alternative fuels to reduce CO_2 emissions.

Moffet's estimate for the control cost of CO_2 emissions is 3.5 to 7.5 US cents per mile. This translates to about 30 to 67 Australian cents per litre of gasoline (70 US cents = A$1), and the value of the reduction in emissions from using natural gas, for example, would be around 4 to 13 cents per litre. These estimates are based on tree planting costs to absorb CO_2. Ottinger et al. on the other hand, estimate the cost of sequestration of CO_2 by tree planting at only 6 to 7 Australian cents per litre (BTCE estimate based on Ottinger et al. 1990, quoted in CRCNPT 1992, 1118).

The Canadian Royal Commission on National Passenger Transportation assigned a value of about 8 Canadian cents per litre for CO_2 emission control costs for Canada (CRCNPT 1992). Hansson (1991) quotes CO_2 charges of 10 US cents per litre proposed for controlling emissions from transport in Sweden.

For Australia, Naughten et al. (1991) calculated control costs for CO_2 emissions based largely on the cost of substituting natural gas for coal in electricity generation. The carbon tax required to achieve the required level of substitution would result in a levy on transport fuel of around 10 cents per litre of motor spirit in the year 2000, and 23 cents per litre in 2005.[9] (These taxes would overestimate the social cost to consumers of reducing emissions.)[10]

As most alternative fuels are not likely to reduce greenhouse gas emissions by more than about 20 per cent, the maximum greenhouse benefit would be around 13 cents per litre of gasoline replaced, and could be less than one cent, based on the above range of costs of 6 to 67 cents per litre.

Total emissions costs

The estimates for noxious emission costs and greenhouse gas control costs together indicate a range of costs of around 8 to 111 cents per litre. Clearly it is difficult to generalise about the benefits of substituting alternative fuels for gasoline from this range. However, the majority of estimates are towards the lower end of the range. Given the estimated percentage emission reductions available from each alternative fuel, it is probably fair to say that the potential benefits are not likely to be as great as the existing level of assistance currently being provided for alternative fuels in Australia.

Cost-effectiveness of using alternative fuels to reduce greenhouse gas emissions

Table 11.5 contains some rudimentary calculations of the social cost-effectiveness of using alternative fuels to reduce greenhouse gas emissions.[11] The estimates relate to specific scenarios. Social cost-effectiveness is estimated as the average cost per megatonne of emissions reduced, where the average cost per megatonne is the net present value (NPV) of additional capital

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[9] Naughton et al. (1991) calculated the costs of achieving the 'Toronto target' in the energy sector and maintaining emissions at the 2005 target level through to 2020. The total cost was estimated at $18.9 billion, discounted to 1990. The target was to be achieved by imposing a carbon tax of $143 per tonne from 2000 and $337 per tonne from 2005.

[10] Those consumers deterred from buying the taxed fuel would value it at less than the tax. Their loss would therefore be less than the tax.

[11] Social costs include all costs to society. In the case of using alternative fuels rather than gasoline, a full social cost analysis would include the additional costs of capital, fuel and other resources valued at opportunity cost, the unpriced costs to users (such as inconvenience costs) and externalities such as noise or air pollution.

expenditures and fuel cost savings, over 10 years, divided by the emissions savings over 10 years. (Ten years is assumed to be the life of a vehicle.) Fuels are priced at resource cost net of all taxes to reflect opportunity costs.

Social costs would be lower to the extent that urban emissions are reduced by alternative fuels. It is considered that it would be misleading to include monetary values for noxious emission reductions at this stage, given the uncertainty. The costs of inconvenience to consumers are also excluded, and these are expected to be significant for some fuels. The discount rate adopted is 5 per cent. Most of the scenarios refer to the replacement of gasoline in light vehicles.

The results in table 11.5 serve to indicate, very approximately, the relative cost-effectiveness of the various alternative fuels in reducing emissions of greenhouse gases, and to provide a starting point for comparing the costs of using these fuels in preference to other strategies for emission reduction. Care needs to be exercised in comparing the results with other estimates of emission reduction costs where underlying assumptions may be very different. The results in table 11.5 are based on IEA (1993) estimates of life cycle emissions and fuel consumption for new vehicles in the year 2000 and are therefore dependent on the validity of the IEA forecasts.

For comparison, the Moffet estimate of 27 to 60 cents per litre for reducing emissions with tree planting (Moffet 1991) would be equal to $107 million to $239 million per megatonne of emissions reduced (undiscounted).

The cost of reducing greenhouse gas emissions with the least-cost alternative option would indicate the maximum level of any 'subsidy' which would be warranted for alternative fuels on greenhouse grounds. If there were no lower cost ways than using alternative fuels, then the level of subsidy warranted for all alternative fuels (on greenhouse grounds) would depend on the cost of the marginal fuel introduced to achieve the required reduction in emissions.

Increasing the use of diesel in cars and other LDVs emerges as possibly the most socially cost-effective option for reducing greenhouse gas emissions. Under some price assumptions it could be a 'no regrets' option,[12] ignoring any effects of lower diesel car performance on driver utility and any costs associated with increased noxious emissions. Diesel is still comparable with other options when a more expensive car is used to eliminate particulate emissions.

However, at typical current prices of gasoline and diesel, it is not an attractive option in terms of private costs, given the apparent higher discount rates adopted by private consumers. Diesel's greenhouse gas emissions advantage when used in cars would suggest some favourable treatment to reflect its

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[12] A 'no regrets' option for reducing greenhouse gas emissions is one which does not impose net costs on the community, or which has net benefits.

TABLE 11.5 COST-EFFECTIVENESS OF ALTERNATIVE FUELS IN REDUCING GREENHOUSE GAS EMISSIONS

Fuel	*Social cost of greenhouse gas gas emission reduction* [a] *$ million per megatonne (NPV)*[b]	*Possible range*	*Noxious emission reduction benefits*
RFG	742[c]	495 to 1485	Modest to good
LPG	104[d]	68 to 443	Uncertain; modest with new vehicles
Diesel			
No part. trap	15[e]	–32 to 141	Good and bad
Part. trap	132[f]	73 to 253	Good
Ethanol (wood)			
Diesohol	134[g]	111 to 224	Uncertain, possibly an improvement
Gasohol	68[h]	52 to 134	Uncertain, possibly an improvement
NGV	65[i]	14 to 115	Modest to good
EV	1217[j]	553 to 3476	Very good

a. Excise and state taxes excluded from fuel prices. Costs include additional vehicle costs and net change in fuel costs. Vehicle life of 10 years assumed.

b. Calculated over 10 years, discount rate of 5 per cent. Values reflect prices of the early 1990s.

c. RFG @ 5 cents per litre above gasoline price, and 2 per cent greenhouse advantage over gasoline. Fuel consumption 10 litres per 100 kilometres. Range variation due to different fuel cost and greenhouse advantage assumptions.

d. LPG @ 30 cents per litre; gasoline @ 35 cents per litre; conversions $1750 per car; 23 per cent greenhouse advantage; gasoline 10 litres per 100 kilometres, LPG 12.3 litres per 100 kilometres; 25 000 kilometres per year. Range variation due to LPG fuel consumption in the range 15 per cent to 45 per cent above that for gasoline.

e. Diesel @ 33 cents per litre; gasoline 35 cents per litre, 19 per cent greenhouse advantage; gasoline car 10 litres per 100 kilometres, diesel car 7.9 litres per 100 kilometres; 25 000 kilometres per year; $2000 extra per car. Range relates to additional vehicle cost of $1200 with greenhouse advantage of 19 per cent, and vehicle cost of $3000 with 10 per cent greenhouse advantage.

f. Same as (e) but $4000 extra per car (catalytic converter plus particulate trap). Range variation due to extra vehicle costs of $3000 with 19 per cent greenhouse advantage, and $4000 with 10 per cent advantage.

g. 15 per cent blend in diesohol; ethanol @ 44 cents per litre (production cost 35 cents per litre plus 9 cents per litre for profit, distribution and blending costs, and retailer's margin); gasoline 35 cents per litre; unmodified vehicles; 61 per cent greenhouse advantage for the proportion of ethanol compared with diesel; 5.9 per cent saving per kilometre for the blend. Range variation due to ethanol prices of 40 to 60 cents per litre.

h. 10 per cent blend with gasoline, 68 per cent greenhouse advantage for the ethanol portion compared with gasoline; 5.4 per cent saving per kilometre for the blend. Range varies with ethanol prices of 40 to 60 cents per litre.

i. NGV: $2000 per car conversion; 25 000 kilometres per year; gasoline car 10 litres per 100 kilometres, NGV 8.6 cubic metres per 100 kilometres; gas @ 35 cents per cubic metre; greenhouse advantage 11 per cent; gasoline @ 35 cents per litre. Range variation due to range of conversion costs from $1500 to $2500.

j EV: EV cars cost $5000 more than gasoline cars; 12 000 kilometre per year; gasoline car 6 litres per 100 kilometres; electricity @ 3 cents per kilowatt-hour; batteries @ $1500 every three years, greenhouse advantage 20 per cent. Range due to variation in emission reduction from 44 per cent (gas-fired power) to 7 per cent.

Note Emissions are based on IEA (1993) estimates of life cycle emissions and fuel consumption of new, year 2000 vehicles.

Source BTCE estimates based on emission and fuel consumption data in IEA (1993).

environmental benefits relative to gasoline, as diesel is currently subject to the full fuel excise, in contrast to other emission reducing fuels.

The use of natural gas in place of gasoline appears to be the next best option (table 11.5) in terms of social costs and benefits. Including the value of urban pollution reductions would reduce the net costs for natural gas and would tend to increase the advantage of natural gas in comparison with LPG and ethanol. However, no inconvenience costs to users of NGVs have been included in the cost estimates.

While ethanol in blends has costs of a similar order to those for natural gas, the assumptions underlying the ethanol result are more questionable. The cost of ethanol in large-scale use is uncertain. Also, the assumed reductions in emissions are considerable and may not be achievable. If the APACE projected cost reduction for ethanol production (to 14 to 24 cents per litre from lignocellulose, similar to the ex-refinery price of diesel fuel) can be realised, then ethanol replacing a proportion of diesel or gasoline could be a ‘no regrets’ option for emission reduction. Because there are few initial costs, it would also impose minimal private costs on users. The claims for more than proportional air pollution emission reductions from the ethanol portion of ethanol blends remain to be confirmed.

LPG could be relatively high cost when greenhouse reductions are at the lower end of the assumed range, as when new LPG cars are compared with the latest gasoline models. Costs appear less likely to be offset by urban air pollution benefits than in the case of natural gas. Introduction of RFG would be a high cost strategy, and greenhouse advantages are doubtful. While urban air pollution benefits would be substantial in the case of EVs, they remain a high cost option in Australia for reducing greenhouse gas emissions.

Methanol has not been considered, as methanol produced from natural gas (likely to be the major Australian production route in the forseeable future) appears to offer little greenhouse advantage.

TABLE 11.6 ESTIMATES OF COSTS OF GREENHOUSE GAS EMISSION REDUCTION FROM ALTERNATIVE FUEL USE: USA AND FRANCE

(1992 US $m per megatonne saved from switching from gasoline to diesel or CNG

Annual distance	*Diesel*	*CNG low range*	*CNG full range*
USA			
16 400 km	180 to 600	–320 to 100	–300 to 600
25 000 km	–321 to 7[a]	–356 to 27[a]	–390 to 404[a]
France			
13 800 km	–100 to 540	–120 to 200	8 to 600
20 000 km	–441 to 110[a]	–169 to 117[a]	–84 to 441[a]

Note Range of estimates results from assumptions about vehicle price. Costs have been discounted at a rate of 5 per cent. Negative figures denote benefits.

a. BTCE estimates based on data in IEA (1993).

Source IEA (1993).

IEA greenhouse gas emission reduction cost estimates

The cost-effectiveness of switching cars from gasoline to diesel and CNG as a means of greenhouse gas abatement has been investigated by the IEA (1993). The IEA has calculated costs for two sets of car market assumptions, one relating to the USA and one to France. Costs are for CO_2 equivalent emissions avoided over the vehicle life cycle. The analysis relates to all costs associated with the whole of the vehicle and fuel life cycle. Costs include purchase costs, insurance, maintenance and fuel costs, and take account of vehicle life and resale values. Pre-tax fuel prices for diesel and CNG on an LGE basis were considerably lower than gasoline prices (16 per cent lower for diesel, 16 to 45 per cent lower for CNG in the USA; 9 per cent lower for diesel in France and 12.5 to 33 per cent lower for CNG). Results are shown in table 11.6. Allowing for the relatively lower pre-tax prices in the IEA analysis, the results are consistent with the BTCE results in table 11.5.

MACROECONOMIC, INDUSTRY, AND RESOURCE SECURITY IMPLICATIONS

Resource security and macro-economic benefits are often cited in support of an expanded alternative fuels program.

With respect to macro-economic issues, the usual arguments are that an alternative fuel expansion program could increase output and employment, and save on imports. If foreign exchange earnings are assumed to constrain growth, these import savings could allow growth to occur without causing balance of payments problems.

Proponents argue that an alternative fuels program could therefore offset the output and employment effects of any decline in Australian oil production and increase in oil imports. Australian production of crude oil and condensate is now expected to peak in 1997–98, then remain above current (1992–93) levels up to 2004–05 (ABARE 1993). Increasing domestic demand for petroleum based fuels will mean a rise in projected net crude oil imports, estimated by ABARE (1993) to rise from 6365 megalitres in 1992–93 to 15 653 megalitres in 2004–05, an increase of 140 per cent.

To support these arguments it would need to be established that the use of resources to increase the supply of alternative fuels would be a relatively efficient way of achieving macroeconomic objectives, and that there is some market imperfection preventing this from happening. It is unlikely that an industry which is relatively unprofitable, and which requires subsidisation to compete, would prove to be a cost-effective way of achieving macroeconomic or other objectives. It will not be efficient to use resources where their cost is greater than the value of their product to consumers, unless there are substantial social benefits which more than offset the difference.

Macroeconomic implications

The macroeconomic effects of increased alternative fuel use would include the effect of increased production of fuels, import substitution, changes in expenditure on vehicles and any expenditure on infrastructure for alternative fuels.

One estimate of the macroeconomic effects of an alternative fuels program has been provided by NIEIR (1988) in a study of increased natural gas use for the AGA. NIEIR modelled the economic impact of the displacement of gasoline and diesel by natural gas, including the consequent reduction in oil imports and increase in activity related to the introduction of NGV systems. The NIEIR results reflect growth from a base year in which large scale marketing efforts commence.

NIEIR (1988) estimated that, under a high market penetration scenario, with NGVs replacing 397 014 gasoline and diesel vehicles, GDP in the year 2003 could be increased by some 4 per cent, employment by about 210 000, and the current account balance improved by about 0.6 per cent of GDP. The potential reduction in oil imports in 2003 was 16 million barrels (2544 megalitres).

The degree of market penetration assumed by NIEIR is somewhat higher than that required by the AGA to meet its *10/10* goal of 338 400 vehicles (chapter 7). Also, as the number of trucks is higher in the NIEIR scenario, total fuel replacement would be much higher. A 1988 study of NGVs, involving a lesser degree of market penetration than the *10/10* plan, predicted 120 000 jobs in an NGV industry (AGA, pers. comm. 1991), which could be partly at the expense of jobs in other sectors.

NIEIR's low market penetration scenario, with 62 553 NGVs, predicted that GDP would increase by 1.3 per cent by 2003, employment by 69 000 and that the balance on current account would improve by 0.2 per cent of GDP (NIEIR 1988).

These NIEIR results depend specifically on the assumptions underlying the NIEIR model.

Estimates of system costs for NGVs

The macroeconomic effects will depend partly on the costs of establishing an NGV fuel and vehicle supply system. The total additional expenditure envisaged to achieve the AGA *10/10/35 goal* was $400 million for NGVs and almost $700 million for refuelling infrastructure, spread over 10 years (AGA 1992b).

Figures quoted in this paper for refuelling equipment and conversion costs would suggest that the AGA estimate is low. Clearly the total investment costs will be influenced by assumptions about economies of scale in conversion equipment, and about the numbers of vehicles that could make use of depot refuelling facilities.

The AGA argues that the NGV alternative could obviate the need for an estimated $7 billion investment in refineries required to upgrade capacity to cater for future increased demand for diesel. The cost for the NGV option would be about $2 billion for engine conversions, cylinders and refuelling infrastructure (AGA, pers. comm. 1991). However, unless the diesel investment cost were to be recouped via cross-subsidisation of diesel by other refinery sales, the difference in investment costs would not appear to justify interfering with market decisions between diesel and presumably, in this situation, lower-cost natural gas.

A trans-Australia natural gas pipeline costing around $6 billion could be required by about 2010, on current projections of demand and reserves (DPIE 1991a), to connect south-eastern Australia with the major sources of supply in north-western Australia. However, the AGA argues that this pipeline will be required for non-transport uses of gas, and that only a part of its costs would be attributable to natural gas use in transport.

Balance of payments effects

Domestically-sourced alternative fuels could replace some proportion of imported oil and petroleum products, and may generate exports of fuels and alternative fuel technology. In the short term at least there would be an offsetting effect from importation of considerable quantities of capital and vehicular equipment.

The net reduction in imports is not likely to constitute a social gain for the economy unless, again, alternative fuels can be produced relatively profitably. If subsidised, use of these fuels in transport is likely to be less cost-effective than other ways of earning foreign exchange. For example, more foreign exchange might be earned by exporting the natural gas and importing more oil for transport purposes. It would also be necessary to consider the net effect on Australian importers and exporters in general if reduced imports of oil resulted in an exchange rate appreciation.

In any case, the importation of conversion equipment and cylinders would entail considerable expenditure of foreign exchange for widespread adoption of NGVs, at least until domestic production becomes viable. A typical candidate car for conversion could use 3000 litres of gasoline per year, valued at $540 (at US$20 per barrel, A$0.18 per litre). Cylinders for a light vehicle can cost $600 to $1000 (retail), with a mid-range cylinder costing perhaps $650 CIF. The import cost of $650 would then be offset by reduced oil imports ($540) in 14 to 15 months, and in less than three years if all conversion equipment had to be imported, at a CIF cost of around $1500.

Given Australia's expertise in NGV technology, there could be potential to export OEM NGVs to New Zealand, which still has a large NGV fleet, and to other countries with substantial gas reserves. Countries in the Asia/Pacific region had combined natural gas reserves some three times as large as Australia's in 1988 (AGA 1990a). These included Indonesia with reserves of 64 years, and Malaysia with reserves of 176 years at current rates of use (Sinor Consultants 1992b). Indonesia, Thailand and China, after some NGV trials, have plans for major NGV projects (Allen 1992).

Export potential in itself is not a valid argument for subsidising alternative fuels. Again, it would need to be demonstrated that subsidisation of alternative fuels was the least-cost means of gaining foreign exchange out of all possible opportunities within the economy. This is an unlikely scenario.

Industry arguments

It is sometimes argued that the NGV industry needs assistance to overcome a 'chicken and egg' problem in getting started. Consumers will not buy alternative fuel vehicles without an assured fuel distribution and vehicle service network, and confidence in the resale values of their vehicles; the network will not be established without some assurance on future natural gas prices and confidence that vehicles will be available; OEM vehicles, because of the very high cost of low production runs, will not be manufactured unless the infrastructure is in place; and buyers may not convert vehicles if OEM vehicles are expected.

The argument appears to be exaggerated, as the situation with alternative fuels may not be very different from that applying to other large, high-risk investment projects. The problem of interdependent markets (vehicles, fuel production and fuel distribution) could be addressed by coordinated action by the major players. It does not appear relevant to argue that a fuel may be as good as or even better than existing fuels, but that it cannot compete because of the already existing network. The product to be marketed is not the fuel, but a coordinated system for fuel supply and use. If the product is likely to prove popular, and expected profitability for the system adequate, the necessary investments are likely to proceed. If profits are not seen as sufficient to cover risks and the necessary marketing and development costs, the investment will not and possibly should not proceed.

The question was raised earlier as to whether a 'one-off' level of assistance would be warranted to overcome consumer inertia, such as might prevent the uptake of a new fuel even when it could otherwise compete on an equal basis with an established system. However, there would be costs associated with overcoming consumer resistance. As indicated, these would have to be weighed against the potential benefits from introducing wider choice, a more diversified fuel supply or a one-off effect on employment.

Restrictions on movement of resources within the industry, and any obstructionist behaviour by entrenched interests with market power, would warrant intervention by governments if significant. Removing restrictions on interstate trade in natural gas has been recommended by the Industry Commission (TPC 1992) and is expected to have the effect of reducing gas prices by 10 per cent. Experience in New Zealand with natural gas indicates that vested interests may adopt marketing practices to influence consumer acceptance of new fuels.

It is arguable that sugar produced in Australia should be available for use in ethanol plants at the export price. This would better reflect the true opportunity cost of the sugar and remove an impediment to the cheaper production of ethanol. The issue does not arise with wheat currently being used for ethanol production at Nowra. There are no longer restrictions on purchase of wheat direct from growers, and consequently no significant difference in domestic and export prices.

External economies of scale resulting in benefits to other industries from expansion of alternative fuel use could provide a basis for assistance, but this possibility has not been addressed.

Resource security implications

At current world energy prices, Australia has large reserves of energy resources with the exception of the liquid petroleum supplies on which transport currently depends.[13] It is often argued that reduced dependence on petroleum based fuel would allow Australia more control over its transport energy supplies.

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[13] Reserves of shale oil are large, but would require a substantial increase in world oil prices to become economic. Similarly, higher world oil prices would encourage further exploration for petroleum.

The *net* benefits of achieving increased resource security, however, are open to debate. While there are costs associated with short-term disruptions to supplies, the costs of avoiding such disruptions could be even higher. For example, if alternative fuel use were to play a significant role in reducing the impact of potential future disruptions, a large proportion of vehicles would have to be using alternative fuels. The cost of converting and using the vehicles, including the costs to users if alternatives are not as convenient, could prove to be much higher than the benefits. Also, there are different ways of ensuring increased security, such as holding larger stockpiles of oil, and these could have lower costs than large scale switching to alternative fuels. Alternatively, it might be more cost-effective to rely on price increases or rationing to effect any adjustment to restricted supplies.

Where the concern is with depletion of oil reserves in the long-term, it is sometimes argued, paradoxically, that rather than convert to domestic supplies of alternative fuels, Australia should preserve its supplies of non-renewable energy sources, or that current exports of alternative fuels should be curtailed in the interests of long-term security. However, other alternatives, such as solar or hydrogen, may provide relatively cheap options in the long run. The opportunity cost of keeping fossil fuel reserves in the ground could then outweigh revenues from sales of these fuels in the future.

Concerns about fuel security in the event of war may be equally misplaced. Even in a major conflict, supplies are unlikely to be cut off completely, although their cost is likely to be higher. The trans-Atlantic supply of Britain in the 1940s is a good example. Recent history demonstrates that trade embargoes are similarly ineffectual in stopping completely (or even substantially) the supply of even strategic commodities to a country.

Any proposal to justify support for alternative fuels would need to assess fully the actual risks faced by Australia of losing access to current fuel supplies. The risk-weighted benefits from avoiding supply disruptions would need to exceed the costs of conversion to alternative fuels to support direct assistance.

Availability of petroleum fuels

Australian situation

Australia's net imports of crude oil and petroleum products are projected to increase from 15 per cent of final energy consumption of these products in 1991–92, to around 30 per cent in 2004–05 (ABARE 1993). Such estimates are uncertain, however, as instanced by the DPIE (1991) view that increased energy efficiency and switching to other fuels might be able to maintain the reliance on imported petroleum products to near present levels for the next 15 years.

World situation

There is not expected to be a problem with availability of petroleum fuels, at least until well into the next century (Shell 1993; BP, pers. comm. 1992). As at January 1992, world proven oil reserves were equivalent to 45 years' supply at current production rates of about 60 million barrels per day (Shell 1993). Shell (1993) presents a 'plausible scenario' where 'sufficient additional capacity will come on stream to keep crude oil prices fluctuating between US$15 and US$20 a barrel in real terms over the rest of the decade. BP sees gasoline and diesel as the major transport fuels for the next 30 years, with no serious availability problems in this period.

Improved oil recovery rates (Trim, pers. comm. 1992) above the current 50 per cent in the Middle East and 60 per cent in Australia are also possible, as is utilisation of coal and oil shales to produce synthetic gasoline and diesel. However, the likely cost of oil from shale may be no lower than that of other alternative fuels such as ethanol or methanol.

Availability of alternative fuels

At present, natural gas would be the only domestically sourced fuel with both the reserves sufficient to contribute significantly to replacing gasoline or diesel and the potential to compete on a commercial basis. Even so, there are limits on the extent to which substitution would be possible in the short term. In the longer term, lower production costs for EVs and alcohol fuels might also enable these fuels to make a sizeable contribution to domestic fuel supplies.

Expansion of the current fairly minor role of natural gas in electricity generation could affect the depletion rate of reserves and the price of gas in the future. Gas turbine combined cycle plants are now a viable alternative for baseload generation, while for peak load supply, open cycle gas turbines are now much more economic than was previously the case (ESAA 1991). Higher gas prices would reduce the financial incentive to substitute natural gas for gasoline or diesel in transport.

However, the estimated consumption of energy by the electricity industry in Australia in 2004–05 is 1400 PJ (ABARE 1993). This compares with the estimated 111 000 PJ of estimated proven, probable and prospective reserves of natural gas (AGA 1992a). Also, there are large quantities of methane gas associated with Australia's coal deposits, which may be suited to on-site electricity generation (ESAA 1991). These deposits are, for the most part, located reasonably close to east coast markets. Where the alternative is venting to the atmosphere, any combustion use of this gas will have significant greenhouse benefits.

CONCLUSION

Most alternative fuels do possess some environmental advantages over gasoline, and some level of price differential or government support may be desirable to reflect these social benefits. The difficulty lies in determining how much.

The extent of benefits varies among fuels, and among differently produced versions of the same fuel. There is uncertainty about achievable physical emission reductions, and there is no accurate method for valuing emission reduction benefits.

On the basis of the limited emissions costings available, it appears unlikely that the environmental benefits from most alternative fuels are as large as the existing 'subsidy' they now receive. Macroeconomic and resource security benefits are questionable, and would not seem to provide strong grounds for substantial additional support.

Of the various alternative fuels, use of diesel or CNG in passenger vehicles appears, at present, to offer the most socially cost-effective means of reducing emissions of greenhouse gases. Both fuels could also prove socially cost-effective in reducing noxious emissions, depending on the cost of particulate traps in diesel vehicles. However, a more comprehensive analysis of these and other options is required to identify the cheapest strategies overall.

Given the difficulty of determining price differentials to reflect environmental benefits, it could be preferable to opt for some other means of having environmental factors influence transport fuel choices. Rather than assist specific fuels, common emission standards could be set for all fuels and/or vehicles, tradeable rights to generate emissions could be established, or incentives could be provided for research. With regard to standards, a clearly specified target date would need to be set to allow manufacturers and consumers adequate time to plan responses and so minimise costs. Those fuels or vehicles able to meet the standards more easily would have a market advantage.

There also appears to be a role for government in establishing quality standards for alternative fuel vehicles and equipment, in providing information to improve consumer knowledge and to protect consumers from product defects or adverse safety and health consequences, and in ensuring that current standards for gasoline vehicle emissions are broadened to apply also to vehicles using alternative fuels.

APPENDIX I CONVERSION FACTORS FOR GREENHOUSE GASES

The *natural greenhouse effect* maintains the earth's temperature at a level suitable for sustaining life. A summary of this process is contained in NGAC (1992). Greenhouse gases, responsible for this natural effect, are essentially transparent to the incoming shortwave radiation from the sun, but almost opaque to the infrared radiation emitted upwards from the solar heated ground. Greenhouse gases absorb radiation (particularly the upward directed infrared), and re-emit it both upward and downward, and in this sense are said to be radiatively active. This process results in the heating of the earth's surface to a higher equilibrium temperature than would otherwise be the case.

Human activities cause substantial net emissions of greenhouse gases. Over the past decade, the evidence has become conclusive that the atmospheric concentrations of various greenhouse gases have been steadily increasing. These increases have been linked to increases in global temperatures, through the so called *enhanced* greenhouse effect.

The major contribution to the natural greenhouse effect is from atmospheric water vapour (H_2O). Water vapour is not normally considered in greenhouse gas emission inventories because human output is negligible compared with the day-to-day precipitation cycle. The next most significant radiative gas is carbon dioxide. CO_2 is the major contributor to the enhanced greenhouse effect.

Besides CO_2, the radiatively active gases (called direct greenhouse gases) emitted by transport include methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). Indirect greenhouse gases are those that do not have a radiative effect themselves, but have an impact on the concentrations of direct greenhouse gases. Such emissions from transport include nitrogen oxides (NO_x), carbon monoxide (CO) and non-methane hydrocarbons (NMHC). Ozone is a potent direct greenhouse gas, but is not emitted by transport vehicles. It is formed by photochemical reactions involving atmospheric oxygen and a variety of vehicle emissions. These gases, the most important of which are NO_x and volatile organic compounds (VOCs), are known as ozone precursors. Some direct greenhouse gases (such as methane) have both direct effects and indirect effects (through decomposing to produce CO_2 or aiding the formation of ozone).

Although CO_2 is the major greenhouse gas emission, the contributions of the other gases are important, even in the transport sector. The warming effect of a greenhouse gas depends on its atmospheric concentration and reactivity, infrared absorption capability, and average residency time in the atmosphere. These factors vary considerably among gases. To represent the total greenhouse effect of emissions of several different gases from an activity, or to compare the greenhouse (or *radiative forcing*) effect of emissions of different gases, their emissions are stated in terms of CO_2 equivalents. This is done on the basis of the *global warming potential* (GWP) for each gas. The GWP is an index, defined to be the warming effect over a given period (usually taken as 100 years) due to an emission of a particular gas, relative to that of an equal mass of carbon dioxide.

Representative GWP values have been calculated for the main greenhouse gases by the Intergovernmental Panel on Climate Change (IPCC). Due to the varying lifetime of greenhouse gases, GWP figures depend on the assumed time period over which the effects of emissions are considered. The IPCC (1990, 1992) has estimated global warming potential factors which range over various time horizons, including 20 years, 100 years and 500 years. Many analyses dealing with greenhouse gas emissions (including IEA 1993) use 100 year values derived by the IPCC. Estimated values for the direct GWP components given in IPCC 1992 are presented in table I.1. Indirect GWP values were reported in IPCC 1990, and these are also presented in table I.1.

However, due to the present incomplete understanding of the complex chemical processes involved in the indirect effects, numerical values for indirect GWPs were not given in IPCC 1992. Since there is considerable uncertainty in the indirect values (their refinement being a topic of current research), the IPCC (1992) has stated that 'care must be exercised in applying GWPs in the policy arena'. Concerning the current knowledge of indirect GWPs, the IPCC (1992) states that the scientific community is only confident that:

- the indirect GWP for methane is a positive number, possibly comparable in magnitude to its direct value;
- CO, VOCs and NO_x 'will affect the radiative balance of the atmosphere through changes in tropospheric ozone'.

The set of GWPs given in table I.1 does not therefore explicitly represent the current IPCC position, but is an indicative scenario for global warming based on various IPCC results. Though the IPCC is reasonably confident that the GWP values for direct effects are of the right order, the current uncertainty surrounding the indirect effects hampers quantitative analysis on comparisons of alternative fuels. Rather than forgo such analysis, the BTCE has used the GWP scenario given in table I.1, on the understanding that the results derived need to be suitably qualified.

In an attempt to assess the dependence of the study findings on any future GWP revisions, the BTCE performed some simple sensitivity analysis using IEA emissions data. The IEA (1992) has estimated the life cycle greenhouse emissions (in-vehicle emissions and those from vehicle manufacture and fuel supply) for a range of alternative fuels. These calculations were based on the GWP values given in table I.1.

Table I.2 presents the percentage change in grams of CO_2 equivalent emissions per kilometre relative to (reformulated) gasoline, resulting from the use of various alternative fuels (derived from IEA 1992a results), using different assumptions about GWP values. The indirect effects which are varied in each scenario (to test the sensitivity of results) are those in table I.1 relating to the formation of ozone and water vapour. The table provides a comparison of emissions results for North American light duty vehicles at the year 2005 vehicle efficiency (forecast by IEA 1992a).

As a further comparison, table I.2 also includes more recent IEA (1993) results for North American light duty vehicles (forecast for the year 2000), estimated using slightly different assumptions concerning vehicle efficiencies and fuel conversion processes, and with the NO_x GWP (which is the most uncertain) set to zero.

Across the scenarios presented in the table, the assumed variation in possible GWP conversion factors does not greatly affect the estimates of *relative* greenhouse advantage for the various alternatives. Within all the tabulated values the ranking of the fuels was affected by GWP changes in only one case. CNG moved from slightly better (in the greenhouse sense) than methanol (made from natural gas) in the baseline scenario (IEA 1992a), to slightly worse than methanol in the doubled indirect effects scenario.

Assumptions about fuel conversion and vehicle efficiency had more effect, halving the advantage of methanol (from natural gas) and negating the disadvantage of ethanol (from corn) with respect to reformulated gasoline between the two IEA analyses (IEA 1992a and IEA 1993).

Any data or conversion factors relating to energy consumption are in terms of Gross Calorific Values (also called Higher Heating Values [HHV]), rather than the OECD standard of Net Calorific Values (also called Lower Heating Values [LLV]), since Australian energy statistics are typically reported in gross terms. When energy conversion factors from the literature have been given in net terms, they have been reduced by 5 per cent for solid and liquid fuels, and 10 per cent for gaseous fuels before use in this report.

TABLE I.1 GLOBAL WARMING POTENTIALS OF ATMOSPHERIC GASES RELATIVE TO CO_2, WITH RESPECT TO A 100-YEAR TIME HORIZON

Type of gas	*Estimated atmospheric lifetime (years)*	*Direct greenhouse gas affected*	*Global warming potential*
Direct effects			
Carbon dioxide	120		1
Methane	10.5		11
Nitrous oxide	132		270
CFCs	55–116		3400–7100
Indirect effects			
Methane		Ozone	8
Methane		CO_2	3
Methane		Water	4
Carbon monoxide		Ozone	1
Carbon monoxide		CO_2	2
Nitrogen oxides		Ozone	8
NMHC		Ozone	8
NMHC		CO_2	3

CFCs Chlorofluorocarbons (used in transport for vehicle air conditioners and refrigerated freight)

NMHC Non methane hydrocarbons

Note The ozone referred to is tropospheric, that is, occurring within the lower atmosphere, as opposed to stratospheric ozone which is depleted by emissions of CFCs. Since ozone is formed from other emissions, it is not normally assigned a GWP. Its contribution is attributed to the indirect effects of ozone precursors (such as CO, VOCs and NOx).

Sources IPCC (1990); IPCC (1992); IEA (1992).

TABLE I.2 SENSITIVITY OF ALTERNATIVE FUEL EMISSION ESTIMATES TO CHANGES IN THE GLOBAL WARMING POTENTIAL CONVERSION INDEX

(Per cent change in CO_2 equivalent life cycle emissions from forecast North American light duty vehicles, relative to reformulated gasoline)

	Fuel type							
Scenario for GWP values	*Ethanol from corn*	*Methanol from NG*	*CNG*	*Diesel*	*LPG*	*Electric vehicles*[a]	*Ethanol from wood*	*Hydrogen*[b]
IEA 1992[c]	11.8	–11.9	–14.5	–18.7	–24.6	–27.1	–67.7	–71.0
IEA 1992 excluding indirect effects[d]	14.2	–11.4	–16.4	–18.4	–24.6	–25.1	–67.5	–70.2
IEA 1992 with indirect effects doubled[e]	11.6	–13.3	–10.1	–19.8	–24.6	–30.1	–63.8	–71.0
IEA 1993[f]	–1.2	–4.9	–12.2	–20.1	–23.6	–24.7	–68.8	–70.7

NG	Natural gas
CNG	Compressed natural gas
LPG	Liquefied petroleum gas

a. Electricity generated by average North American power mix.

b. Liquid hydrogen, derived from non-fossil electrolysis of water.

c. Using IEA 1992 emission data and all the GWP values given in table I.1 (for direct and indirect effects).

d. Using IEA 1992 emission data and the direct GWP values in table I.1, and setting GWPs for the indirect effects (relating to the formation of ozone and water vapour) to zero.

e. Using IEA 1992 emission data and the direct GWP values in table I.1, and doubling the GWPs for indirect effects (relating to the formation of ozone and water vapour).

f. Using IEA 1993 emission data (which is based on slightly different technical assumptions from IEA 1992) and the GWP values in table I.1, with the exception of the NO_x GWP which is set to zero.

Sources IEA (1992, 1993); BTCE estimates.

APPENDIX II BTCE ESTIMATES OF POTENTIAL EMISSIONS SAVINGS FROM USE OF RFG IN AUSTRALIA

In order to estimate the possible impact of the introduction of current US reformulated gasolines into the Australian fuel market, calculations based on various US studies were performed.

Noxious emissions

Sinor Consultants (1992b) report AQIRP test results for the effects of fuel sulphur removal on emission levels. For a reduction in fuel sulphur content from 450 parts per million to 50 parts per million, emission reductions in hydrocarbons (HCs), carbon monoxide (CO) and nitrogen oxides (NO_x) were obtained of 18, 19, and 8 per cent respectively. The response was found to be effectively linear over this range. The Australian fuel refiners' Code of Practice maintains Australian sulphur levels at below 0.05 per cent by weight, wherever possible. Sulphur levels of 50 parts per million are equivalent to a content of around 0.015 per cent by weight, allowing the above figures to be scaled for Australian conditions. This gives:

for HC, $(-18 \times (0.05/0.015) \times (50/450))\% = -6.7\%$
CO, $(-19 \times (0.05/0.015) \times (50/450))\% = -7.0\%$
NOx, $(-8 \times (0.05/0.015) \times (50/450))\% = -3.0\%$.

AQIRP fleet studies (reported in EPA 1991b) on the use of various reformulated fuels found average respective emission changes in HCs, CO and NO_x of –21, –26 and +3 per cent for new cars and +7, –6 and –14 per cent for older cars (pre-1986). IEA (1992a) figures for the CO emission benefits of RFG use in new cars are also of this order, at around a 22 per cent reduction. Weighting these values by the proportion of Australian car emissions from post-1985 cars — specifically, around 11 per cent for HCs, 12 per cent for CO and 28 per cent for NO_x (based on emission rates given in Carnovale et al. 1991) — gives:

for HCs, $(-21 \times 0.11) + (7 \times 0.89)\% = +6.2\%$
CO, $(-26 \times 0.12) + (-6 \times 0.88)\% = -8.4\%$
NOx, $(3 \times 0.28) + (-14 \times -0.72)\% = -9.2\%$.

ARCO results for the use of EC-X (reported in Nadis & MacKenzie 1993) give emission reductions of 28, 25 and 26 per cent for HCs, CO and NO_x. Again, the reference (unreformulated) fuel had a higher sulphur content than would be expected of any Australian gasoline. Assuming that the bulk of the EC-X emission reductions are due to the reduction in fuel sulphur content (from 350 ppm to 40 parts per million) — which is supported by AQIRP analysis on the separate effects of different reformulation strategies (Colucci & Wise 1992) — these results may be scaled in the same manner as previously. This gives emission reduction estimates for possible Australian gasoline replacement by EC-X of 10.8, 8.9 and 9.3 per cent in HCs, CO and NOx.

Hoekman (1992) reports fleet tests for an RFG having a similar sulphur content to existing Australian gasolines. Emission reductions obtained were 11 to 21 per cent for CO, zero for NO_x, and between 7 per cent for non-catalyst cars and 22 per cent for three-way catalyst cars for total volatile organic compounds (VOCs). Taking the midpoint for CO and apportioning the HC emissions between old and new cars (as previously) gives:

for HCs, $(-22 \times 0.11) + (-7 \times 0.89)\% = -8.7\%$
CO, $(11 + 21)/2\ \% = -16\%$
NO_x, 0%.

Averaging over these values results in the following estimates for RFG emission benefits:

- for HCs, $(-6.7 + 6.2 + -10.8 + -8.7)/4 = -5.0\%$, with a typical range of +5 to −10 per cent;
- for CO, $(-7 + -8.4 + -8.9 + -16)/4 = -10.1\%$, with a typical range of −5 to −20 per cent;
- for NO_x, $(-3 + -9.2 + -9.3 + 0)/4 = -5.4\%$, with a typical range of 0 to −10 per cent.

In summary, though these calculations are very approximate, it appears that typical RFGs offer emission benefits for noxious gases of around 5 to 10 per cent over current Australian gasoline.

Greenhouse gas emissions

The tailpipe emission of full combustion CO_2 (in grams of carbon emitted per kilometre, gC/km) from gasoline can be expressed as a function of the fuel's volume carbon content (grams of carbon per litre, gC/L) and its efficiency of use in the vehicle (litres of fuel used per kilometre travelled, L/km). That is:

$$gC/km = gC/L \times L/km.$$

The carbon content by volume can be influenced by changes to the fuel's specific gravity (grams of fuel per litre, gF/L), carbon content by weight (gC/gF), energy density (MJ/L), and carbon content per unit energy (gC/MJ). That is:

$$gC/L = gF/L \times gC/gF = gC/MJ \times MJ/L.$$

Differences in these fuel characteristics between RFG and standard gasoline in the literature (IEA 1992a; Hoekman 1992; EPA 1991b; Unzelman 1991a) imply that grams of carbon per litre would be between 2 and 4 per cent lower (with a mean value of 3.4 per cent) when using RFG.

Vehicle efficiency estimates in the literature (IEA 1992a; EPA 1991b; *Oil and Gas Journal,* 1991; Sinor Consultants 1992b) imply litres per kilometre increase by between 1 and 3 per cent when using RFG, with an average of 1.3 per cent. The typical range of grams of carbon per kilometre for RFG therefore appears to be between 1 per cent higher (–2 + 3) and 3 per cent lower (–4 + 1) than for conventional gasoline, with an average value of 2.1 per cent lower (–3.4 + 1.3).

The IEA (1992a) estimates that total greenhouse gas emissions (in CO_2 equivalents — using IPCC Gross Warming Potential [GWP] values given in Appendix I) — from the exhaust are 5.9 per cent lower with RFG use. The IEA estimates the fuel supply process for RFG contributes 9.6 per cent more greenhouse gas output than for conventional gasoline. IEA figures have exhaust emissions accounting for 80 per cent of full fuel cycle (FFC) greenhouse emissions from cars, with the fuel supply accounting for the other 20 per cent. The FFC emissions advantage of RFG is thus estimated to be around 3 per cent (the greenhouse gas emissions difference being –5.9% x 0.8 + 9.6% x 0.2 = 2.8%).

Based on the above analyses, typical values (and ranges) for the various components of total greenhouse gas emissions from motor vehicles are (in terms of differences between RFG and conventional gasoline):

- CO_2 exhaust emissions, –2 per cent (+1 to –3 per cent);
- emissions from fuel supply, +10 per cent (+5 to +10 per cent);
- CO exhaust emissions, –10 per cent (–5 to –20 per cent);
- other emissions from the vehicle, –5% (0 to –10 per cent).

The proportions that these components contribute to FFC emissions are approximately 75, 10, 5 and 10 per cent respectively (based on BTCE 1991; Cosgrove 1992; DASET 1991). Summing the differences by these weights (which would depend somewhat on the GWP values used, see appendix 1) gives:

$$(-2\% \times 0.75) + (10\% \times 0.1) + (-10\% \times 0.05) + (-5\% \times 0.1) = -1.5\%.$$

FFC greenhouse gas emissions from current RFGs are therefore of the same order as conventional gasolines, typically between 1 and 2 per cent below (and would probably fall in the range of 2 per cent above to 4 per cent below). IEA (1993) estimates that 'reformulating gasoline to current US Clean Air Act standards produces virtually the same life cycle greenhouse gas emissions as the use of premium unleaded gasoline'.

APPENDIX III PRODUCTION OF ETHANOL AND METHANOL

The uncertainty over the cost of producing alcohol fuels in the Australian market, discussed in chapter 5, stems from doubts about the feasibility of the production processes, the availability of raw materials, and about environmental factors affecting the supply or processing of raw materials.

This appendix provides an overview of current and potential alcohol fuel production processes, and of related environmental issues. The discussion focuses on the state of technical development and the problems that still need to be overcome.

METHANOL

World methanol consumption in 1989 was around 18.2 million tonnes, most of which was used by the chemical industry particularly to produce formaldehyde (Fahy 1990). The fastest growing area of the methanol market is fuel oxygenates, such as MTBE.

The raw materials required for methanol (CH_3OH) production are the fossil carbon sources (natural gas, coal and petroleum) and/or biomass. Currently most of the world's methanol is produced from natural gas, with a small quantity being derived from coal. Reductions in greenhouse gas emissions from substitution of methanol for other transport fuels are relatively minor (chapter 5).

Methanol from natural gas

Methanol from natural gas is at present the cheapest means of production, and the various production processes are described below. Emerging new technologies offer the potential to improve the efficiency of the production process, reducing both the costs of production and the level of full fuel cycle greenhouse gas emissions from use of methanol.

Conventional steam reforming

In this process methane (CH_4) is decomposed in the presence of steam (H_2O) to produce a synthesis gas mix. These synthesis gases (syngas) are produced at temperatures of around 800 degrees Celsius and pressures of 1.5 to 5 megapascals over a nickel based catalyst (Bharucha 1991). The syngas is cooled and compressed before undergoing a range of reactions over a copper and zinc based catalyst at 250 degrees Celsius and at a pressure of 5 to 10 megapascals (methanol synthesis). The chemical reactions which occur are:

Steam reforming produces	$CH_4 + H_2O = CO + 3H_2$ and
	$CO + H_2O = CO_2 + H_2$
Methanol synthesis then occurs	$CO + 2H_2 = CH_3OH$ and
	$CO_2 + 3H_2 = CH_3OH + H_2O$
The overall equation is	$CH_4 + H_2O \rightarrow CH_3OH + H_2$

The excess hydrogen produced in the reaction can be burnt to produce heat, or CO_2 can be injected into the process and combined with the hydrogen as part of the overall methanol synthesis. However, this can lead to the formation of carbon deposits which impair action of the catalyst (Trimm & Wainwright 1990).

The high temperatures associated with steam reforming are responsible for approximately 75 per cent of the cost of the methanol produced (Trimm & Wainwright 1990). The cost of compression between the reforming and synthesis stages is also high. Only about 25 per cent of the synthesis gas is converted to methanol after each pass over the catalyst, and recycling and recompression of the synthesis gas must occur.

Desulphurisation of the natural gas and removal of other impurities which can poison the catalysts may be necessary before the reforming occurs. After the synthesis stage the methanol must be distilled to remove the water and any impurities produced.

Some of the ongoing research work associated with this conventional method of methanol production involves a search for better catalysts. Improved catalysts would increase the conversion efficiency of the synthesis gas and enable this to occur at lower pressures and temperatures. A further procedure in what is known as a gas-solid-solid trickle flow reactor, is to remove the methanol from the reactant stream (unconverted syngas) as it is produced, thereby removing the chemical equilibrium point of the reaction and enabling conversion of the remaining syngas (Wainwright 1988). Small reductions in methanol costs can be expected from such work.

The steam reforming stage is expected to remain a major focus of research. One of the approaches suggested is to separate the production of synthesis gas into two stages involving firstly, steam reforming and, secondly, catalytic partial oxidation (combined reforming). An alternative process is to produce the syngas directly via partial oxidation without the steam reforming phase. Another is direct partial oxidation of methane to methanol without an initial steam reforming stage.

Partial oxidation in the combined reforming process

In partial oxidation the production of synthesis gas occurs at a temperature range of 1100 to 1500 degrees Celsius and a pressure of 1 to 4 megapascals and the gasifying media are oxygen and steam. The basic reaction involving the oxygen is:

$$CH_4 + {}^1\!/_2O_2 \rightarrow CO + 2H_2$$

One advantage of partial oxidation is the production of significant quantities of energy which can be used for heat in the initial steam reforming stage (Trimm & Wainwright 1990). The combined reforming process also allows a reduction in plant size. It is understood that the pilot plant to be constructed by BHP is of this type. Should this pilot plant prove successful, BHP apparently plans to construct a larger plant on a floating platform (*Australian Financial Review,* 8 April 1993, 20).

Problems include the high temperature generated and needs for a thermally stable catalyst and a supply of oxygen.

Direct partial oxidation process

A direct partial oxidation process still at the laboratory stage involves a reaction of methane and oxygen over a catalyst (porous alumina impregnated with platinum or rhodium salts) at a temperature of 850 to 1150 degrees Celsius to give syngas at a yield of 90 per cent (Hickman & Schmidt 1993). Hickman and Schmidt suggest that 'this process has great promise for the conversion of abundant natural gas into liquid products such as methanol'. Such promise arises from the ability to do away with expensive and emission-intensive steam reforming as a means of producing syngas.

Direct oxidation of methane to methanol

Work on the direct oxidation of methane to methanol is still at the laboratory stage and involves interrupting the oxidation of methane almost at its inception. It is based upon the equation $CH_4 + {}^1\!/_2O_2 \rightarrow CH_3OH$.

Such a process should be more energy efficient and would yield the methanol in one step. It is likely that far reaching economic consequences would result should a technologically feasible large scale method for direct conversion be found.

Methanol from coal

To produce methanol from coal, the coal is ground and mixed with water in the form of a slurry. This slurry is fed into a gasifier, mixed with oxygen and heated to produce a synthesis gas mix with a range of impurities and a slag waste material. Water is added in a 'shift conversion' process to adjust the hydrogen and carbon monoxide ratio. This produces CO_2 which must be removed.

Impurities such as hydrogen sulphide, tars and oils must also be removed to avoid interfering in the methanol synthesis stage. Methanol synthesis and distillation follow as in the methanol from gas pocess.

Production of methanol from coal is not as economic as from natural gas and it seems unlikely that technological developments will match those using natural gas. Currently there are a few small plants producing methanol from coal in South Africa (less than 20 000 tonnes per year). One large plant in the USA produces 195 000 tonnes per year, and another plant may be constructed to generate electricity and make methanol using new technology. The co-production of electricity and methanol may reduce methanol production costs by 25 per cent but would still be 50 to 100 per cent more expensive than methanol from natural gas (NSWDME 1990).

Methanol from biomass

Use of methanol from biomass as a transport fuel has the greatest potential to reduce emissions of greenhouse gases. The CO_2 liberated by burning the methanol is offset to some extent by absorption of CO_2 in the growth phase of the biomass.

Before methanol was commercially produced from natural gas the traditional method of production involved the destructive distillation of wood. Only about 6 per cent of the carbon contained in the wood was converted to methanol (Steinberg 1990). Techniques currently envisaged for the production of methanol from biomass are conventional steam–oxygen gasification of wood, and high temperature pyrolysis of wood. These require initial conversion to syngas, and then methanol synthesis, as for methanol currently produced from natural gas and coal. The conversion of the carbon in the wood to methanol occurs at an efficiency of 55 per cent for the steam–oxygen gasification of wood and at an efficiency of 29 to 41 per cent for high temperature pyrolysis (29 per cent at 800 degrees Celsius and 5 megapascals pressure, and 41 per cent at 1000 degrees Celsius and 101 kilopascals pressure) (Steinberg 1990).

As with the raw syngas produced from coal gasification, the output from biomass gasifiers produces a range of impurities which include particulate matter, methane, tar and light hydrocarbons, but no sulphur. These impurities must be removed before the methanol synthesis stage. The syngas from biomass gasification, like that from coal, also has ratios of hydrogen to CO which are not ideal for methanol production. A 'shift conversion' is necessary to improve the balance of gases. Developments in the laboratory are likely to lead to improvements in the syngas conditioning for the production of alcohols through new steam-reforming and tar cracking catalysts.

Before the impurity-free and adjusted syngas mixture is fed into the methanol synthesis stage, the CO_2 produced during the shift conversion must be removed. The removal of the CO_2 by emission to the atmosphere may account for 40 to 60 per cent of the carbon contained in the biomass (Overend 1991), which means that about 0.4 kilograms of methanol can be produced from one kilogram of dry wood (Reimert 1984 cited in White 1990). Some of the thermochemical laboratory work into biofuels at the US National Renewable Energy Laboratory is aimed at utilising the waste CO_2 by using electrochemical catalysts to reduce the CO_2 to CO and then reinject the CO into the thermochemical production unit. This would increase the efficiency of methanol production and reduce the level of CO_2 vented to the atmosphere in the production phase (Overend 1991).

Methanol from co-processing biomass with fossil fuels

In the co-processing of biomass with fossil fuels using the *Hydrocarb* process as proposed by Steinberg (1990), fossil fuels and biomass are combined to form solid carbon and methanol. The overall stoichiometry when using methane as the fossil fuel is:

$$CH_{1.44}O_{0.66} + 0.3CH_4 \rightarrow 0.64C + 0.66CH_3OH$$

wood + natural gas → carbon + methanol

The stoichiometric formula for the wood ($CH_{1.44}O_{0.66}$) is derived from the elemental weight analysis of the major components of the wood (~50% C, ~44% O and ~6% H) (Steinberg 1990).

This gives an overall carbon efficiency of 46 per cent when based upon the biomass and methane consumed to produce methanol, or a 198 per cent carbon efficiency when taking into account only the methane proportion. Coal and oil can also be used, but with lower efficiencies. The major benefit of the *Hydrocarb* process is that much of the waste product is pure carbon rather than CO_2.

It appears that the *Hydrocarb* process is still at a theoretical stage of development. Smith and Kelly (1990) have suggested that such a procedure may warrant a critical technical and economic evaluation, but they also note that the process may be expensive and inefficient in its use of fossil fuels.

ETHANOL

Ethanol can be manufactured from:

- biomass via the fermentation of sugar derived from grain starches or sugar crops;
- biomass via the utilisation of the non-sugar lignocellulosic fractions of crops;
- petroleum and natural gas (reduction or steam cracking of ethane or propane fractions) via an ethylene intermediate step.

Research in progress aims to produce ethylene from methane via a catalytic oxidation process (EPA 1990).

Production of ethanol from sugar and starch fractions

Starch and sugar crops in Australia which have received attention as a potential source of ethanol include cassava, sugarcane, sweet sorghum, Jerusalem artichokes, sugar beet, potatoes and cereals. Potential yields from these energy crops are listed in table III.1. Research in progress is seeking to improve starch yields from grain crops through the application of genetic engineering principles.

In Australia ethanol is produced from molasses, a by-product of sugarcane, at three distilleries—Bundaberg, Sarina and Rocky Point. Ethanol production from these distilleries is approximately 58 000 kilolitres per annum from about 200 000 tonnes of molasses (CSR, pers. comm.1993).

Recently ethanol production from wheat has commenced at the Manildra gluten and starch plant at Nowra in NSW. The major products of the mill are gluten and starch. Among the co-products is ethanol, which is produced from the waste starch stream, with supplementations of starch.

Production processes

Ethanol production from sugar and starch sources involves extracting the sugar or starch fraction of the crop using wet or dry milling. When starch (a linear or branched chain of sugar sub-units) is the feedstock for ethanol, it must first

TABLE III.1 ETHANOL YIELDS FROM SUGAR AND STARCH BASED ENERGY CROPS GROWN IN EASTERN AUSTRALIA

Crop	*Dry mass yield (tonnes per hectare)*	*Ethanol yield litres per hectare)*	*Agricultural practice*
Barley	1.3	513	Rain-fed
Cassava	10	2 000	Rain-fed
	14–35	3 000	Irrigated
Jerusalem artichoke	20–40	6 400–12 800	Irrigated
Maize	3.2	1 264	Rain-fed
	12	4 740	Irrigated
Potatoes	2.2	990	Rain-fed
Sugar beet	16–20	5 700–6 400	Irrigated
Sugar-cane	No data	6 000–7 000	Rain-fed
Sweet sorghum	7–18	2 700–8 000	Irrigated
Wheat	1.7	670	Rain-fed
	8	3160	Irrigated

Note Yields are approximate and depend upon climate, plant variety and variability of fermentable content of crop.

Source Mendelsohn & Hinkley (1985); Nguyen & Prince (1991).

undergo hydrolysis to turn the starch solution to one containing sugars. These sugars are then fermented by micro-organisms such as yeasts to produce CO_2 and a dilute ethanol solution:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

When the sugars have been consumed, the resultant broth is heated and fed to a distillation unit, where the ethanol and some of the water evaporate leaving behind large volumes of liquid waste. The solution of 95 per cent ethanol and 5 per cent water from the evaporated mix undergoes a further distillation to remove the water and produce ethanol suitable for blending with gasoline (CSR 1980). An azeotropic distillation process is used which requires the addition of cyclohexane or benzene to the mix.

The ethanol production processes described above are energy-intensive and produce a large volume of effluent. This effluent has a high organic solids content (hence a high biological oxygen demand), an inorganic material content high in potassium, and a high level of plant colorants with low biodegradability.

One innovation that improves the economics of traditional ethanol production has been the development of the *Biostil* process, which has a higher efficiency and produces a high value concentrated waste. The *Biostil* process is used at the CSR distillery at Sarina and at a wheat based ethanol plant in France, where 100 000 litres of ethanol per day are produced.

The French *Biostil* plant process begins with starch liquefaction and addition of an enzyme to the slurry, followed by a temperature increase to 90 degrees Celsius. Saccharification follows, involving cooling the liquefied slurry to 60 degrees Celsius, after which the slurry is acidified and an enzyme added. The resulting liquid, which contains sugar, is then cooled to 30 degrees Celsius and fed continuously into a single tank fermenter. Nitrogen is added to promote yeast growth, with the yeasts being continuously recycled (Danielsson 1991).

The ethanol concentration in the mixture from the fermentation process is around 8 per cent. This mixture is separated into fibre, a protein suspension (yeast) and the dilute ethanol solution (Danielsson 1991). At the French plant the dilute ethanol solution is fed into a distillation unit and becomes a 96 per cent ethanol solution, which is further concentrated by pervaporation.

The *Biostil* process has distinct advantages over the normal azeotropic distillation process in being a more energy efficient and simpler operation, and one which can produce pharmaceutical grade ethanol (Danielsson 1991). Le Bouar and Missaglia (1991) have claimed that ethanol dehydration using pervaporation technology is achieved at one-quarter of the cost of using azeotropic distillation and half the cost of molecular sieve technology.

The technology for production of ethanol from starch and sugar crops is relatively mature. Future improvements may come from developing microbial strains that are more tolerant of higher concentrations of ethanol, and from developing alternative, less energy-intensive procedures for separating the ethanol from the water after fermentation. These technological improvements will also be applicable to ethanol production from lignocellulose.

Production of ethanol from lignocellulose fractions

Lignocellulose can be derived from trees and grasses, and from cereal and paper wastes (EPA 1990; Wyman 1991). Production of ethanol from lignocellulose is still largely in the research and development stage, with most plants operating at laboratory or pilot scale. Production by the Swedish Ethanol Development Foundation, as a by-product of paper-pulp operations, is an exception.

The two major research efforts aimed at extracting ethanol from lignocellulose involve technologies using either acid, or enzymatic hydrolysis, with the enzymes used being derived from micro-organisms.

Lignocellulose

Lignocellulose is the main structural component of plant biomass and is composed of lignin, cellulose and hemicellulose. Both the cellulose and hemicellulose fractions of the material (which may comprise 65 to 80 per cent of the non-sugar and non-starch fractions of the plant) can be converted to ethanol. Proportions of cellulose and hemicellulose from various lignocellulose sources are listed in table III.2. Lignin is particularly resistant to biological degradation. It does not provide sufficient energy to support the lignin degrading micro organisms, which therefore need another carbohydrate energy source (Kirk 1987).

Cellulose is made up of unbranched chains of glucose molecules (a six-carbon monosaccharide), two of which combine to make the disaccharide-repeating unit of cellulose called cellobiose (Coombs 1987). The distribution of cellulose in the plant cell wall is such that the cellulose molecules form structural units (termed micro fibrils) which are generally arranged in a crystalline lattice, with regions of amorphous cellulose also present (Coombs 1987).

The degree of crystallinity is variable and depends on the cellulose source (Henrissat et al. 1985 cited in Knowles et al. 1987), with some of the resistance shown by cellulose to hydrolysis only partly influenced by the degree of crystallinity (Everleigh 1987). Resistance of cellulose to enzymatic hydrolysis is decreased by increasing pore structure of the cellulose (Everleigh 1987).

Hemicellulose differs from cellulose in terms of both chemical composition and structural form. On the basis of its chemical composition, hemicellulose can be considered to consist of three main polysaccharide groups; xylans, mannans and galactans (Coombs 1987). The main hemicellulose in hardwoods and agricultural residues consists of xylans which primarily yield xylose (a five-carbon monosaccharide) upon hydrolysis. In softwoods, mannans are the main

TABLE III.2 COMPOSITION OF POTENTIAL LIGNOCELLULOSE FEEDSTOCKS

Per cent

Lignocellulose sources	*Cellulose*	*Hemicellulose*	*Lignin*
Agricultural residue[1]	38	32	na
Solid municipal waste[1]	50[a]	5[a]	na
Hardwood[1]	50	23	na
Hardwood[2]	45–50	20–25	20–25
Herbaceous energy crop[1]	45	30	na
Softwood[2]	35–40	25–30	27–30
Wheat straw[2]	33	25	15
Waste newspaper[2]	61	20	16

na Data not available

a. Estimate based on paper, wood, food, garden and backyard refuse content of municipal waste.

Sources 1: Wyman (1991); 2: Coombs (1987).

hemicellulose, which upon hydrolysis yield mannose, glucose and galactose (all six-carbon monosaccharides) in a 3:1:1 ratio respectively. When the hemicellulose group galactans are present, they hydrolyse, mainly to yield galactose and arabinose (a five-carbon monosaccharide).

Production processes

Before microbial conversion of plant products into ethanol can occur, pre-treatment is necessary to make the cellulosic components in the plant tissues available for hydrolysis and conversion to ethanol. Pre-treatment essentially opens up the structure of the lignocellulose material.

The first stage of pre-treatment — fractionation — reduces the dimensions of the feedstocks, for example wood chipping. A number of options are available for the second stage. Of these, Fox et al. (1989) cited in Fox et al. (1990), suggest that high-pressure steam treatment is the most cost-effective method of increasing the enzymatic susceptibility of sugarcane bagasse; while Wright (1988) cited in Wyman (1991), suggests that the dilute acid process offers the best near-term economic potential. Chemical pre-treatment processes may present a problem with disposal of the resulting effluent. Choice of pre-treatment process and the degree of fine tuning is likely to be influenced by the type and range of biomass resources to be processed.

This pre-treatment phase separates the hemicellulose fraction from the remaining biomass and converts it into its component sugars. These are then fermented to produce ethanol. The bacterium *Zymononas mobilis* is being manipulated genetically to convert xylose to ethanol, while other researchers have transferred a gene from *Z. mobilis* into *Escherichia coli* to enable it to convert xylose also to ethanol. Further research has opened up the potential to use *Z. mobilis* in place of yeasts for the glucose fermentation, as well as xylose fermentation, which should increase yields and reduce costs (NSWDME 1990).

The separated cellulose fraction undergoes additional processing. There are several competing technologies for the conversion of this remaining fraction into ethanol.

Technologies for conversion of cellulose to ethanol

The hydrolysis of cellulose is achieved via either acid or enzymatic treatment, although neither of these processes has been technically and economically proved in large-scale demonstration or commercial facilities. The sugar solution resulting from the hydrolysis is fermented to yield ethanol and CO_2.

Problems with acid hydrolysis include corrosion, high cost of acid recovery, fouling of equipment because of mineral scale deposits and resin formation, and low yields (Katzen 1991).

The techniques of enzymatic conversion of cellulose to ethanol also involve hydrolysis and fermentation. In two of the procedures both hydrolysis and fermentation occur in the one vessel. The hydrolysis of cellulose is achieved by a multi-component enzyme system known as cellulase, which is derived from micro-organisms. The cellulase is generally considered to be composed of three main components: endo-1,4-glucanase, cellobiohydrase and cellobiase, with a further component glucohydrolyse sometimes present (Everleigh 1987). These components of cellulase also consist of more than one distinct chemical entity with their exact formula and activity dependent upon the species or even strain of micro-organism from which they are derived. During the hydrolysis procedure the activity of the cellulase enzyme declines as the cellulase is adsorbed on to the surface of particles. Enzyme recycling systems offer the potential to recover and reuse a proportion of the enzymes.

The direct microbial conversion (DMC) process uses two types of bacteria to produce enzymes to break down the cellulose into ethanol. Katzen (1991) reports that ethanol yields from the DMC process are lower than from either the simultaneous saccharification and fermentation (SSF) process or the separate hydrolysis and fermentation process (SHF).

In the SSF procedure the presence of the yeast along with the cellulase enzymes in the one vessel minimises the accumulation of sugars which inhibit cellulase, while the presence of ethanol makes the process less vulnerable to invasion by unwanted micro-organisms (Katzen 1991). In the SHF process the separate steps involve enzyme production, hydrolysis of cellulose and sugar fermentation. In such a process, extra vessels are required, and some effort is required to reduce inhibition of cellulase enzymes (Katzen 1991).

Some current research priorities with microbial fermentation systems involve genetic manipulation of the microbes to increase the capabilities of the bacteria or fungi to tolerate higher levels of ethanol, utilise a wider range of sugars and increase the rate of fermentation.

Achieving a commercially feasible lignocellulose ethanol production process is likely to be protracted. Many of the individual processes have been shown to function in the laboratory, and some have been demonstrated at pilot plant scale. There is also the Swedish example. In general, however, scaling up pilot production to produce several tonnes of ethanol per plant per day will inevitably produce further challenges.

Supply of biomass feedstocks

The estimates in chapter 5 of Australia's capability to supply the transport sector with alcohol fuels derived from biomass sources revealed a high level of uncertainty.

The extent of agricultural and forest resources — including waste products — available for utilisation can change over time. The cost of harvesting, collecting and transporting these resources will also influence biomass supplies. Also, a lignocellulosic ethanol process optimised for a particular feedstock, for example bagasse, may not work well with another feedstock, such as a softwood. Wyman et al. (1991) found this to be the case in a laboratory study involving the SSF procedure. And the amount of alcohol fuel required for a given level of fuel substitution will be influenced by the fuel efficiency of vehicles running on alcohol, which may or may not be optimised to take advantage of the relatively higher octane levels of alcohol fuels.

Agriculture

Until the lignocellulose process is proven to be economically feasible, alcohol fuel feedstocks are likely to be sourced from agricultural sugar and starch output. A comprehensive assessment of the agricultural potential to provide these feedstocks would be necessary if alcohol fuels were to be seriously considered for substantial fossil fuel replacement.

Whether Australian agriculture will supply crops such as sugar and cereals for alcohol fuel production will depend on international prices for traditional export crops, and on whether the demand for crops for alcohol fuels will be sufficiently rewarding for farmers.

The extent to which new agricultural land could become available for growing energy crops would depend on the requirements of the particular variety of the crop to be grown, and the amount of environmental degradation which the community will tolerate. New varieties of crops are continually coming on to the market and these could allow previously unsuitable land to be viably cropped. Costs of harvesting and transport, however, will influence the viability of areas distant from processing or market zones.

Forestry

The likely availability of Australian forest products to supply lignocellulose for alcohol fuel production would be difficult to gauge, given controversy over woodchipping, the value of forests as wilderness and recreation, wildlife habitat and water catchment. The conflicting claims of Stewart (1990), Stewart et al. (1979) and APACE (1992) were presented in chapter 5. As in the case of agriculture, Australia's capacity to provide forest products for alcohol fuel production is an issue which will need resolution as the technology for producing fuels from lignocellulose develops and the potential for effective competition with fossil fuels increases.

When a forest is used for timber and pulp products there are large volumes of residues which may also be suitable for conversion to alcohol fuels. Most forest resources, however, are located in relatively remote areas, and transport costs are an important consideration. Processing plants need to be located fairly close to the timber resources.

It has been suggested by APACE that planting trees on degraded farmland could provide viable supplies of lignocellulose. The practicality of the 'trees on farms' suggestion will be influenced by location relative to the processor, costs of harvesting small areas, and the ability to convince a suitable number of farmers in a region to adopt such an idea and to plant similar tree species (for ease of harvesting) which would provide a sustainable harvest.

ENVIRONMENTAL CONCERNS WITH ALCOHOL FUELS

Growing energy crops

Large-scale production of energy crops on presently under-utilised land may have positive and negative aspects. APACE has suggested that lignocellulose energy crops may be suitable for vegetation programs in Australia (pers. comm. 1992). Revegetation of degraded farmland presently lacks an economic incentive. Growing tree crops for ethanol production on a medium-term rotation could help stabilise land degradation, and would provide farmers with an economic rationale for looking after presently unproductive land. Growing lignocellulose crops requires far less fertiliser and cultivation than food crops (Wyman 1991).

It is uncertain to what extent major new areas of irrigated land could be given over to energy crops without exacerbating water quality and land degradation problems already present in Australia. In Europe Taschner (1991), of the European Environmental Bureau, has warned of the possible problems associated with intensive growing of energy crops. These include impoverishment of soil, greater use of pesticides (since the produce will not be targeted for human consumption) and increased pollution of ground water by nitrogenous fertilisers. Marginal land taken over for energy crops could significantly reduce the habitat area and hence the viability of many species of fauna and flora.

Organic farming practices could perhaps reduce the problems associated with fertilisers and pesticides. Total energy inputs into growing such crops would be reduced, although crop yields could suffer. Tree crops grown for lignocellulose production may have a beneficial role in lowering or stabilising ground water levels.

In the USA, researchers are studying dedicated energy crops, including trees, which have been genetically altered to require minimum management and to produce high yields (SERI 1991). Environmental concerns about the need to apply pesticides may arise from the widespread introduction of crops with a narrow genetic basis, such as those designed for easy harvesting, fast growth and high yields. This could be important in Australia if native tree species, with pre-existing pests and pathogens, are genetically manipulated in a similar manner to crops in the USA.

Disposal of wastes

The production of ethanol from energy crops generates many co-products. New ways of using these co-products is an area of active research, as it can significantly alter the economics of ethanol production.

Disposal of liquid waste, or dunder, from conventional ethanol production processes has been reported to cause problems when sprayed on to land. These include odour, and adverse soil effects. If disposed of in waterways, reduced oxygen concentrations result. However, dunder from the CSR *Biostil* process is evaporated to dryness and sold as an animal feed supplement (Rogers, pers. comm. 1993).

Methanol produced from thermochemical conversion processes also presents potential waste disposal problems. Wastes include ash and incompletely reacted products.

APPENDIX IV VEHICLE TECHNOLOGY FOR ALCOHOL FUELS

Only blends of 15 per cent or less ethanol with gasoline or diesel can be used in new vehicles currently on the Australian market. Major engine modifications would otherwise be required. Minor adjustments may still be necessary in some vehicle models, as ethanol can attack plastic and rubber compounds in fuel systems, and can interfere with fuel metering devices.

With older vehicles, the use of low percentage blends or emulsions up to 15 per cent ethanol (E15) may cause some additional problems. In older vehicles, deposits in the fuel system derived from gasoline become unattached when fuel containing ethanol is used. These can clog fuel filters and may affect carburettors or fuel injectors until eventually scoured from the system, perhaps at the cost of several fuel filters. Corrosion already present in the fuel system of these older vehicles may be accelerated.

Vapour lock in vehicles fuelled with ethanol blends (E10) has been reported in summer in the USA (NSWDME 1990). Other problems experienced in the USA, particularly for older vehicles, include corrosion of the fuel tank, deterioration of other fuel system components and clogging of the fuel filter during the initial use (NSWDME 1990). Driveability problems have been confined to vehicles with carburettors and without an air–fuel ratio feedback system. Phase separation of the blend into gasoline and ethanol has only been a problem where vehicles have remained idle for several months (NSWDME 1990).

Australian trials of 10 to 15 per cent ethanol blends have reported problems similar to those in the USA in a few vehicles, as well as a small increase in fuel consumption and nitrogen oxide emissions (NSWDME 1990).

The major problems with using high level blends of alcohol fuels in currently available vehicle models arise from their corrosive nature, combustion properties which differ from those of gasoline or diesel, their lower energy density, and exhaust aldehyde emissions. Lower energy density means higher volumes for the same energy output, requiring an increase in fuel handling capacity compared with other fuels.

Avoiding these problems would involve either a substantial vehicle refit or use of purpose-built vehicles. Many of the problems associated with using alcohol fuels are common for blends of methanol and gasoline in gasoline vehicles, ethanol and gasoline in gasoline vehicles, and blends of either methanol or ethanol and gasoline in flexible fuel vehicles (FFVs).

Vehicles suitable for high level blends of alcohol fuel, and the technical problems associated with their use, are considered in what follows.

METHANOL IN SPARK IGNITION VEHICLES

Retrofitting vehicles for methanol use is not especially practicable because of corrosion of the components used in older vehicles (Alson et al. 1989). Also, fuel tank capacity would have to be doubled to provide the same range as from gasoline, due to methanol's lower energy content per litre.

Alson et al. (1989) make a distinction between current technology methanol vehicles and advanced technology methanol vehicles. Engines in current technology methanol vehicles are similar to engines in gasoline vehicles. They are not optimised to run on methanol fuel, and they have efficiency and emission characteristics similar to those of FFVs.

Engines in prototype advanced technology vehicles are optimised to take advantage of the combustion properties of methanol fuel (wider flammability limits and higher octane rating), and provide greater efficiency and emission improvements. All the potential improvements arising from advanced technology vehicles can be achieved with either M85 or M100 (Alson et al. 1989).

Problems with methanol vehicles

Cold starting

Use of M85 rather than M100 would reduce cold-start difficulties. In the US Federal Methanol Fleet of retrofitted M85 vehicles, no special cold-start systems were needed in mild climates (McGill et al. 1991). In Australia, cold starting of M85 (or E85) vehicles is unlikely to be a problem in most regions. Some difficulties may be experienced in southern highland areas.

Cold-start difficulties with M85 arise because of the low volatility of the fuel, and because of electrical shorting of the spark plugs caused by methanol from the fuel condensing around the spark plug electrodes (Suga et al. 1991). One strategy utilised by Honda to avoid cold-start problems has been to heat the centre of the spark plug and to enrich the air-fuel mixture (Suga et al. 1991). Starting the vehicle on gasoline when the ambient temperature falls below a certain level has also been tried (McGill et al. 1991). This requires a separate small gasoline tank and a starting system of greater complexity. Mitsubishi has incorporated a 'cold-start injector'.

Vapour lock

Vapour lock is the premature vaporisation of fuel in the fuel supply system. Vapour lock in hot climates should not arise with M100, but when using methanol–gasoline mixtures, low molecular weight components of the gasoline would need to be removed to prevent vapour lock in warm weather (Wainwright 1990).

Namba et al. (1991) report severe hot-start problems with fuel blends between M10 and M60, and conclude that fan-assisted cooling after engine shutoff could solve the problem. Wainwright (1990) has suggested that pure methanol would be more useful to avoid problems of vapour lock in Australia.

Oil contamination

High methanol content fuels can contaminate engine oils. Contamination can be particularly bad after cold starts and on trips of around five minutes duration (Schwartz et al. 1990). Methanol enters the engine oil during cold cranking, forming an emulsion in the oil which is then distributed through the lubrication system. Water enters the oil several minutes after ignition (Schwartz et al. 1990). These volatile contaminants reduce the oil's protective properties (McGill et al. 1991). Once the engine reaches a high enough temperature, the methanol, water and fuel additives used to enhance cold starting are removed from the oil via evaporation (Schwartz et al. 1990).

Engine wear

Ryan et al. (1990) identified performic acid as the likely corrosive agent responsible for the high cylinder, ring and bore wear rates encountered in methanol-fuelled engines. They suggested a viable approach to preventing this corrosion would be the development of a suitable lubricant to act as a surface barrier against the acid.

Suga et al. (1991) report that methanol engines have higher wear rates of intake and exhaust valves and valve seats than gasoline engines. This is caused by a lack of the lubrication supplied by tetra-ethyl lead in leaded gasoline, and by the corrosion created by methanol combustion.

Fuel tank corrosion

To avoid corrosion, methanol fuel tanks can be constructed of tin-plated low carbon steel. If formic acid is present in the fuel, the addition of 5 per cent chromium to the steel will prevent corrosion (Mizuguchi et al. 1991).

ETHANOL IN SPARK IGNITION VEHICLES

Many of the problems with high level blends of ethanol in spark ignition vehicles, are similar to, although less severe, than those with methanol.

Ethanol's lower energy density results in a vehicle range for E100 approximately two-thirds of that from gasoline. Cold-start problems occur with E100 (OTA 1990).

MODIFIED SPARK IGNITION VEHICLES — FFVS

Flexible (or variable) fuel vehicles (FFVs) have been developed to assist a transition from gasoline to alcohol fuels. In FFVs, the vehicle's engine systems have the ability to sense the fuel blend in use and to adjust the engine automatically to run on any combination. FFVs are more complex and costly than dedicated fuel vehicles, with extra hardware and more engineering input required. Engines in FFVs cannot be optimised to take advantage of the combustion characteristics of alcohol fuels.

FFVs share some of the problems of vehicles designed for a particular fuel, as well as having some of their own. In a 1990 report, Magasanik et al. identified a number of difficulties which required resolution before commercial production of methanol FFVs could occur. These included cold-start problems with high alcohol content fuels, due to the different vaporisation characteristics of methanol and gasoline. Fuel systems with low-cost production-ready materials, and engine lubricants compatible with methanol, were needed. Formulation of suitable lubricating oils could be complex. Emission certifications would be required over the full range of operating fuels, and catalysts would need to be effective over a wide range of exhaust compositions (Magasanik et al. 1990).

Chrysler, Ford and General Motors in the USA have recently begun production runs of methanol compatible FFVs. In June 1992 General Motors delivered the first of 50 production-line ethanol-fuelled (E85) Chevrolet *Lumina* FFVs. These were part of a US Department of Energy program to evaluate fuel economy, emissions performance and durability of ethanol vehicles. The *Lumina* uses a capacitive fuel sensor to measure the alcohol content of the fuel, which can range from 0 to 85 per cent (Sinor Consultants 1992d, 96). Capacitive fuel sensors have been reported to be better than optical sensors, which are sensitive to the aromatics in the gasoline (Suga et al. 1991; Ohta et al. 1991). Mitsubishi, however, has reported satisfactory operation of an optical fuel sensor (Namba et al. 1991).

Chrysler will initially make 2100 vehicles for the same price as the conventionally fuelled versions, with further expansion up to 100 000 units for 1994 and 1995 if demand warrants. Ford plans to produce 2800 units for the 1993 model year.

Both Chrysler and Ford have increased the fuel tank capacity of the FFVs to give the vehicles an adequate range when operating on M85.

The type of spark ignition alcohol vehicles finally in production are likely to be influenced by the fuel types available. If either neat alcohol fuel or high alcohol composition blends (70 to 90 per cent) were to be introduced, the vehicle fleet would best consist of vehicles dedicated to the particular fuel to take advantage of its combustion characteristics. If the availability or composition of alcohol blended fuel in the market were to be variable, FFVs would be necessary. If alcohol composition of the fuel were to amount to less than 10 per cent by volume, or if RFG containing alcohol/ether derivatives were introduced, current production technology vehicles would be suitable.

COMPRESSION IGNITION VEHICLES

In order to use alcohol fuels in a diesel engine it is necessary to modify the fuel, the engine, or possibly both. Research on the use of alcohol fuels in diesel engines is directed towards:

- development of alcohol and diesel fuel emulsions using an emulsifier (for example APACE research on diesohol);
- adding ignition improvers to alcohol fuels (for example AVOCET);
- using a pilot charge of diesel fuel, and either directly injecting alcohol into the cylinder or introducing vaporised fuel into the air intake;
- maintaining a high enough temperature to ignite the ethanol with either glow plugs or a hot surface;
- converting diesel engines to spark ignition.

Intermittent trials of diesohol, with between 10 and 30 per cent ethanol, have been conducted since 1980 in a number of countries. All these trials have reportedly 'demonstrated technically satisfactory results with regard to fuel consumption, power output and engine wear' (APACE, pers. comm. 1992). Heavy vehicle trials using 15 per cent diesohol are in progress in Australia; these trials include several vehicles in the ACTION bus fleet in Canberra.

The incorporation of 15 per cent ethanol into the diesel fuel generally does not require any major engine modifications, although the engines run best when maintained in the correct state of tune. In some circumstances fuel lines may need to be relocated because of the higher volatility associated with incorporating ethanol into diesel fuel, and some fuel system components may need to be replaced.

A more severe fuel volatility problem has become apparent during the diesohol bus trial in Canberra, when on very hot days severe difficulty has been experienced with hot starts. In these cases the fuel has boiled and vaporised in the fuel pump after the engine was switched off. This is presumed to have resulted from poor ventilation in the engine compartment. How often, and in what other vehicles this problem may arise, is uncertain. Technical solutions to the vapour lock problem are available, but might best be done as factory modifications.

No range penalty using 15 per cent ethanol is evident, and the vehicles can be switched back to straight diesel fuel if necessary. The use of higher level blends of ethanol could require vehicle modifications and substantial retuning, and could reduce range.

Ignition improvers

The addition of ignition improvers to methanol or ethanol enables these fuels to be used in diesel engines without the need for spark plug ignition (Short et al. 1991). Short et al. (1991) have reviewed the operation of alcohol fuels in heavy vehicle trials in a number of countries which have been using the ICI AVOCET ignition improver, as a 2 to 5 per cent component of the fuel. AVOCET also contains lubricity and anti-corrosion additives. In relation to AVOCET and methanol, they report that existing engines can be retrofitted, and minimum requirements include upgrading the fuel supply system to handle a larger volume of fuel, and replacing fuel system components liable to attack by alcohol. The ideal conversion is considered to include new pistons, fuel injectors, blower, fuel tank, fuel lines, fuel pump and fuel cooler. To avoid problems with deposits in the engine, low ash content engine lubricants are also necessary (Short et al. 1991).

In New Zealand two M.A.N. engine buses running on AVOCET and methanol showed an increase in thermal efficiency of up to 15 per cent. Performance, drivability and engine durability were judged to be equivalent to diesel engines. In California six diesel-engined (Detroit) buses were converted to AVOCET/methanol in 1990, and vehicle operators are reported to claim that the vehicles run better using methanol with the ignition improver than with diesel. There is apparently no change in cold-start performance or engine warm-up period, and the engine runs more smoothly with reduced noise and vibration. AVOCET/methanol fuel is also being tested in two garbage trucks in Vancouver, a shuttle bus in New York, a number of pile drivers in California, and in two Mercedes Benz buses in Basle (Short et al. 1991).

In France, four Renault engined buses have been fuelled with 91 per cent hydrous ethanol (which contains 5 per cent water) derived from sugar beet, 5 per cent AVOCET and 4 per cent butanol, and isopropanol co-solvents (NSWDME 1990). These buses have apparently been as reliable as the diesel vehicles, and have shown reduced engine noise and vibration. One engine stripped down after 81 000 kilometres showed no signs of wear (Short et al. 1991). In Stockholm, 32 buses using high compression (24:1) engines equipped with oxidising catalytic converters are being run on AVOCET/ethanol, with an AVOCET concentration of as low as 2 per cent (Short et al. 1991).

APPENDIX V HEALTH AND SAFETY ASPECTS OF ALCOHOL FUELS

Health and safety issues relating to alcohol fuels include toxicity to humans from ingestion or exposure to the fuels themselves or their combustion products (including exposure from fuel spills) and the risk and effects of alcohol fires.

Adverse effects of a chemical agent may occur as a direct effect of the chemical, or indirectly from the products of the chemical's bio-transformation. Important factors that influence the effect are the dosage, route of exposure (ingestion, inhalation or topical), duration and frequency of exposure, the presence of other chemicals with which an interaction may occur and tolerance owing to a previous exposure. Other factors may be specific to the individual. These include genetically determined abnormal reaction to a chemical, and adverse reaction resulting from previous sensitisation.

TOXICITY OF FUELS

Ethanol

Ethanol is one of the most widely used legal drugs of western societies, being the intoxicating component of beer, wine and spirits. It is also widely used as a solvent, in methylated spirits, and as a preservative for biological specimens. The health effects of ethanol are well documented. Andrews and Snyder (1986) claim that the literature on ethanol's biological and medical effects is the largest single literature in medical science. Adverse effects on most organs in the body have been reported.

Ethanol undergoes transformation in the body to acetaldehyde mainly by the alcohol dehydrogenase enzyme pathway. The acetaldehyde is then converted to acetate via the acetaldehyde dehydrogenase enzyme pathway. The conversion of ethanol to acetaldehyde and then acetaldehyde to acetate occurs in the liver. Oxidation of the acetate in the liver is inhibited because of a complex chain of events that commenced with the initial transformation of the ethanol; hence acetate is released from the liver and oxidised peripherally (Andrews & Snyder 1986).

At blood concentrations of 50 to 150 milligrams of ethanol per 100 millilitres of blood, ethanol begins to slow reaction time and leads to reduced co-ordination and blurred vision. Coma and death can occur at concentrations of 500 milligrams of ethanol per 100 millilitres of blood (Rumack & Lovejoy 1986). This level of blood alcohol translates approximately to an ingestion of 4 grams of absolute ethanol per kilogram of body mass. The actual lethal level, and the individual response to ethanol exposure, are very much influenced by the amount of alcohol generally consumed. Individuals who drink alcohol have a greater tolerance to ethanol than non-drinkers.

Mechanisms need to be developed and instituted to ensure that fuel ethanol is not readily accessible for human consumption. Such mechanisms include the use of denaturants, and physical and legislative barriers to easy access to the fuel. Denaturants with an unpleasant smell or taste could be developed and added to ethanol to deter deliberate consumption.

Patterns of accidental ingestion of alcohol fuels could be expected to be similar to those for gasoline. CONCAWE (1992, 21) considered ingestion of gasoline to be a 'very unlikely event with normal storage and use'. Ingestion of gasoline is usually the result, with adults, of siphoning attempts or, with children, of drinking from unlabelled or incorrectly labelled containers (CONCAWE 1992). Another source of severe exposure to gasoline can occur when an accident victim lies in a pool of spilt gasoline. In such a situation gasoline can be absorbed through the skin or inhaled.

Accidental ingestion of alcohol fuels could be reduced by fitting anti-siphoning devices to fuel tanks. A more elaborate approach would be to incorporate a mechanism into the nozzle of the fuel bowser and to the fuel tank inlet of vehicles, so that the bowser would only release fuel when the nozzle was placed into the vehicles fuel inlet. Current LPG fuelling systems operate under such a principle.

Methanol

Methanol occurs naturally in the human body at levels of approximately 0.5 milligrams per kilogram, with the average daily intake in food and drinks estimated to range from 0.3 to 1.1 milligrams per kilogram (Machiele 1990). Methanol becomes toxic when the intake exceeds the body's capacity to metabolise it safely, which is dependent upon the individual (Machiele 1990). Ingestion of under 70 milligrams per kilogram can produce toxic effects (Machiele 1990). The minimum lethal dose range would seem to be highly variable, and is generally between 300 to 1000 milligrams per kilogram body mass (Costantini 1991).

According to Anker-Johnson and Schwochert (1990), methanol is metabolised slowly in the human body. It can be absorbed into the body by ingestion, dermal uptake or inhalation of methanol vapours. Like ethanol, methanol is rapidly circulated through the body according to the distribution of water in the body (Andrews & Snyder 1986).

Commencement of bio-transformation of methanol in humans occurs mainly via the alcohol dehydrogenase pathway in the liver which rapidly converts methanol to formaldehyde, which in turn is rapidly converted via the aldehyde dehydrogenase pathway to formic acid (Andrews & Snyder 1986). At this stage elevated formic acid levels occur in the blood, as the transformation of formic acid to CO_2 mediated via the tetrahydrofolate-dependent pathway is slower than the transformation of the methanol and formaldehyde (Andrews & Snyder 1986).

The tetrahydrofolate is derived from folic acid in the diet, and it is possible that individuals with an inadequate dietary intake of folic acid may be more susceptible to methanol poisoning. Folic acid uptake from food can also be reduced by certain drugs such as some antibiotics and diuretics (Flint & Wahlqvist 1988). More severe affects could possibly arise from chronic exposure to methanol during pregnancy. If the mother is folate deficient, exposure to methanol may cause diversion of folate from the requirements of the developing child. Folic acid deficiency can produce malabsorption in the small intestine, and can affect bone marrow function and thus reduced production of red and white blood cells and platelets (Strauss 1988). Folic acid is also important for cell division and the pathway for DNA synthesis (Wahlqvist 1988).

Methanol poisoning is mainly a primate disease because of the way methanol is transformed in primates. It causes three separate diseases: organic solvent poisoning, systematic acidosis and central nervous system effects that include changes to the basal ganglia and eye (Potts 1986). Humans who recover from severe methanol poisoning suffer permanent visual impairment (Potts 1986). Methanol poisoning affects the retina, and the permanent blindness which can result 48 hours after ingestion appears to be due to the elevated formic acid levels in the blood (Andrews & Snyder 1986).

The preferred treatment for methanol poisoning is haemodialysis which removes the methanol from the body. Where dialysis is not available, or is delayed, treatment can be effected by administration of intravenous ethanol. The ethanol competes more successfully for alcohol dehydrogenase, allowing time for methanol to be excreted in the urine and breath (Potts 1986).

Similar procedures as are designed to deter consumption of fuel ethanol may also be used to deter consumption of fuel methanol. Additives of a few parts per million are available to produce colour, odour and a bitter taste (Machiele 1990).

TOXICITY OF EMISSIONS FROM ALCOHOL FUEL USE

In respect of methanol, public exposure would be most likely to result from inhalation of unburnt fuel in exhaust emissions, of fuel evaporating during refuelling, or of hot vehicle evaporative emissions (Costantini 1991). Service station attendants would appear to be most at risk from such methanol sources, and some exposure to vapours from accidental spills during refuelling may also occur. There are currently no data available on the chronic effects of methanol, nor on the combined effects of exposure to methanol, formaldehyde and other components in exhaust emissions (Costantini 1991).

The American Conference of Governmental Industrial Hygienists (ACGIH) has defined three categories of Threshold Limit Values (TLVs)[1] for solvent exposure (Andrews & Snyder 1986). The three categories are:

- the time-weighted average (TWA) — a value for an eight hour work day and 40 hour week;
- short-term exposure limit (STEL) — usually 15 minutes;
- a ceiling value that should not be exceeded (TLV-C).

The ACGIH recommends a TWA of 200 parts per million and a STEL of 250 parts per million for methanol vapours based on the irritancy of methanol (Andrews & Snyder 1986).

Exposure to methanol vapours under the ACGIH-recommended exposure limits would be unlikely to cause any ocular toxicity. Achieving a deleterious effect through dermal exposure is considered more unlikely (Andrews & Snyder 1986). This is because a TWA for an eight hour period of 200 parts per million would result in a methanol body burden of approximately 25 milligrams per kilogram — 2 to 8 per cent of lethal levels. Estimates for exposure to methanol based on a worst case scenario would produce a methanol body burden of less than 1 milligram per kilogram (Costantini 1991), of the same order of magnitude as the daily intake from food.

Aldehyde emissions from alcohol fuels

Critics of alcohol fuels claim that the presence of aldehydes in the exhausts of vehicles will cause cancer or have other health effects. The major aldehydes emitted from exhausts of vehicles running on fuels containing alcohol are formaldehyde (from methanol) and acetaldehyde (from ethanol). Some acrolein is also present.

Acetaldehyde

Acetaldehyde may be present in the human body as the initial breakdown product of the ethanol in alcoholic beverages. It is listed by Hayes and Campbell (1986) as a synthetic flavouring substance, and is used as a food additive.

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[1] TLVs are defined as airborne concentrations of substances which it is believed nearly all workers may be exposed to day after day without adverse effect.

Acetaldehyde has been reported to induce tumours in the nasal cavity of rats, but by standards of *in vitro* tests, acetaldehyde is not genotoxic[2] (Williams & Weisburger 1986). The lack of any human cases of nasal cancers attributable to acetaldehyde exposure suggests that inference from the animal model may be inappropriate in this instance. This fact, and the capability of humans to consume and metabolise ethanol (with acetaldehyde being formed in the initial phase of ethanol metabolism) would suggest that acetaldehyde levels emitted from vehicle exhausts are unlikely to cause serious, or even minor, health problems.

Acrolein

Acrolein may account for about 5 per cent of total aldehydes in polluted air, and is more of an irritant than formaldehyde. Concentrations of acrolein below 1 part per milion can irritate the eyes and the mucous membrane of the respiratory tract (Amdur 1986). Concentrations of 30 to 34 parts per billion are detectable by most people (Beauchamp et al. 1985 cited in Marnett 1988). Inhalation of acrolein, in concentrations as low as 2.1 parts per million for 40 hours, affects some rat liver enzymes. The suggested mechanism is the irritant action of acrolein on the pituitary–adrenal system (Amdur 1986).

Formaldehyde

Formaldehyde has been described as 'the major chemical intermediate manufactured in the industrial and developing countries'. World formaldehyde production amounts to around 15.5 million tonnes per year (Fahy 1990, 30). Human contact with formaldehyde in the environment may come from vehicle exhaust fumes, cigarette smoke, wood burning, upholstery, cosmetics, pharmaceuticals, air fresheners, glues, paints, plywood, dyes and embalming fluids (Chang & Gershwin 1992). The concentrations of aldehydes in cigarette smoke are several orders of magnitude greater than they are in ambient air (Marnett 1988).

Formaldehyde is estimated to account for approximately 50 per cent of the aldehydes in polluted air (Amdur 1986). Normal human tissue loadings of formaldehyde are in the range of 3 to 12 micrograms per kilogram (Hileman 1984 cited in Chang & Gershwin 1992). Concentrations of formaldehyde in the air of 0.5 to 1 part per million are detectable by odour. Concentrations of 2 to 3 parts per million will produce mild irritation, while above 5 parts per million, concentrations become intolerable (Amdur 1986). Worksafe Australia have adopted the ACGIH TWA limit of 1 part per million.

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[2] Reacting chemically with DNA.

Exposure to high amounts of formaldehyde can cause a range of dermatological and respiratory problems (Chang & Gershwin 1992). Formaldehyde irritates the eyes and mucous membranes of the nose and upper respiratory tract (Amdur 1986). It readily diffuses through these mucous membranes and combines with various substances in the body (Chang & Gershwin 1992). Formaldehyde, like acetaldehyde, has been shown to cause nasal cancers in rats chronically exposed to concentrations of 3.5 to 15 parts per million (Amdur 1986). *In vitro* tests have also shown formaldehyde to be genotoxic (Williams & Weisberger 1986), in that it causes strand breaks with DNA and inhibits RNA synthesis (Chang & Gershwin 1992).

Amdur (1986) suggests that if formaldehyde were a new chemical, results from the animal data would have led to a ban on its widespread use in industry and consumer products. Chang and Gershwin (1992) consider that most health related problems caused by formaldehyde are often the result of invalid conclusions, and based on poorly controlled anecdotal observations. They contend that there is no evidence of formaldehyde's causing immunological diseases, and concerns about its carcinogenity are not backed by epidemiological evidence. Chang and Gershwin (1992) state 'there is one anecdotal report in the literature of three cases of malignant melanoma of the nasal mucosa in a laboratory assistant, a house builder, and a chicken broiler, who were exposed to formaldehyde for several years'. They go on to point out that the level of exposure was not quantifiable.

It seems that study of formaldehyde effects on rats, and *in vitro* in cultured cells, are not appropriate for demonstrating the carcinogenity of formaldehyde in humans, particularly at the likely exposure levels arising from alcohol-fuelled vehicle exhaust emissions. Marnett (1988, 586) has pointed out that the test animals 'are obligate nose breathers whereas humans are not', which has implications for levels of aldehydes reaching various tissues by inhalation. The rapid metabolization of formaldehyde in the body has led Chang and Gershwin (1992) to suggest that any effects of formaldehyde should clear rapidly following removal of the formaldehyde source.

From the evidence above, a vehicle fitted with a properly functioning catalytic converter system capable of handling aldehydes should not present a health risk in terms of aldehyde emissions. However, aldehydes emitted on start-up from vehicles in enclosed car parks, before the emission controls are functioning efficiently, may build up to noticeable levels. The most likely health implication of aldehyde emissions, should a catalytic converter cease to become effective, would appear to arise from the irritant nature of the aldehydes.

HEALTH ISSUES ASSOCIATED WITH ALCOHOL SPILLS

The EPA (1990) considers the greatest difference between methanol and ethanol with regard to spills is that human consumption of water contaminated by ethanol would be relatively safe, while water contaminated by methanol could be quite hazardous, depending on the concentration.

Ethanol

The use of ethanol as a motor fuel would greatly increase the amount of ethanol stored and transported around the country, increasing the chances of a spill and of leaks from storage tanks into ground water.

Ethanol spills are a source of concern because of ethanol's toxicity in high concentrations (EPA 1990). Under a number of scenarios, however, the EPA (1990) regards an ethanol spill as less hazardous than a petroleum spill. Because of ethanol's high solubility, biodegradability and ease of complete evaporation (EPA 1990), it could quickly dilute to non-toxic concentrations in water. If spilt on land, it may evaporate or decompose.

Methanol

An M100 spill reaching the ground water is completely water soluble, biodegrading rapidly in the environment. M85 may cause a larger ground water problem then either M100 or gasoline (Machiele 1990), with the alcohol slowing down the process of chemical breakdown and transporting gasoline further and more rapidly into the soil. Little et al. (1992) have shown that the indoor air of buildings can be contaminated with volatile organic compounds (such as those from spilt fuel) from contaminated soil and ground water.

Enhanced solubility into ground water of the various components of gasoline, when the gasoline is blended with alcohol or other oxygenates, is influenced by the percentage of the fuel that is oxygenate or alcohol, and by the fuel to water ratio (Cline et al. 1991; Poulsen et al. 1992). The most water-soluble components of gasoline are the monoaromatic hydrocarbon fractions of the fuel, such as benzene, toluene, ethyl benzene and xylenes, collectively known as BTEX (Poulsen et al. 1992).

In a study examining the potential for ground water contamination by soluble BTEX gasoline fractions from methanol blended gasoline, Poulsen et al. (1992) concluded (i) that the addition of oxygenates (including methanol) to gasoline will reduce the amount of BTEX in the gasoline and hence reduce the amount of BTEX available to contaminate ground water; (ii) with high methanol content gasoline (M85), all of the BTEX in the gasoline phase may be come soluble; and (iii) releases of gasoline with high methanol content fuel may produce dissolved plumes with high aqueous methanol and elevated aqueous BTEX concentrations near the plume front. Poulsen et al. (1992, 2483) suggested that fuels with a high methanol content 'could have a more serious initial impact on ground water than would releases of methanol-free gasoline'.

It is likely that identical mechanisms would operate with respect to BTEX contamination of ground water when high ethanol content fuels are involved instead of methanol. However, the addition of 10 per cent ethanol to gasoline is not likely to enhance the solubility of BTEX from gasoline in ground water in any significant manner (Cline et al. 1991).

HEALTH ISSUES ASSOCIATED WITH ALCOHOL FUEL FIRES

Fire on board a ship containing a cargo of alcohol, or on a land transport vehicle, may have less severe environmental implications than fire with a cargo of oil or gasoline. The nature of the combustion products from burning of gasoline or oil (black smoke, CO, CO_2 and an assortment of aromatic and non-aromatic hydrocarbons) are likely to be different from those from burning alcohols. It would seem likely that burning alcohol would produce less black smoke and hydrocarbons than an oil or gasoline fire, although more aldehydes would presumably be produced from an alcohol fire.

Ethanol

Ethanol is much less likely to ignite in an open area than gasoline because of its lower vapour density and volatility, and higher 'lower flammability' limit (EPA 1990). Ethanol burns more slowly than gasoline, and releases heat at one-fifth the rate (EPA 1990). The flame visibility of ethanol is less than with gasoline but greater than with methanol.

Because of the factors that limit the danger of an ethanol flame in the open, ethanol can form a flammable vapour–air mixture in the fuel tank under normal ambient temperatures (EPA 1990). Precautions need to be adopted to prevent flammable air–vapour mixtures.

Similar procedures would be required to extinguish a neat ethanol or blended ethanol gasoline fire as are identified for methanol in the next section. Since the inclusion of ethanol in diesel as diesohol increases the volatility of the fuel, fire safety precautions identical to those for gasoline will need to be applied to diesohol.

Methanol

Methanol has a lower ignitability and burn rate in the open atmosphere than gasoline (Anker-Johnson & Schwochert 1990) because of its low vapour pressure (Wainwright 1990).

The US EPA has estimated that fatalities which occur with gasoline fuel fires could be reduced by 95 per cent with the use of methanol fuel (Black 1991).

However, an M100 fire presents an additional hazard, in that M100 spilt on a clean surface in an open area will burn with an almost invisible flame (Anker-Johnson & Schwochert 1990). The addition of high aromatic content gasoline to make M85 makes the flame more visible (Machiele 1990).

Ignition of methanol, or for that matter gasoline, in a fuel tank is influenced by temperature and the volume of the tank filled with fuel, as well as the composition of the fuel blend (Battista et al. 1991). The relatively low vapour pressure of methanol causes a container partially filled with methanol to be flammable over a wider range of temperatures compared with conventional fuels, but addition of gasoline to form M85 reduces the potential of a flammable mixture in a methanol fuel container (Anker-Johnson & Schwochert 1990), such that the flammability of M85 is similar to that of gasoline (Battista et al. 1991).

In modern vehicles, fuel tanks often contain fuel pumps driven by electric motors, which provide potential ignition sources within the fuel tank. Flame propagation within the tank can be reduced or prevented by fitting foam in the tank (Battista et al. 1991).

Methanol, unlike gasoline, is completely water-soluble. However, fires can be extinguished using the same recommended procedures as for gasoline and diesel, except that water based foams are not effective, while water is effective once the concentration of methanol becomes less than 21 per cent by volume (Machiele 1990). In situations where foam is considered necessary, alcohol tolerant foams will need to be used and made more widely available. M85, designed to burn with greater luminosity then M100, may burn off the 15 per cent gasoline component faster than the methanol, with the consequence that the remaining period of the burn is poorly visible (Machiele 1990). Application of water to an M85 fire may result in a separation of the M85 blend, leading to a gasoline fire on top of a water methanol mix (Machiele 1990).

APPENDIX VI NATURAL GAS VEHICLE TECHNOLOGY

Natural gas in cars

As noted in chapter 7, the future for NGVs is expected to lie in optimised vehicles, which will be better able to compete with gasoline cars on cost and efficiency grounds. In the interim, conversion technology is developing (Merz 1991), and cars can be designed as NGVs, with a fall-back gasoline facility.

Engine conversion involves the addition of a pressure regulator and a venturi mixer or gas carburettor to the engine, with an electronic ignition modifier as an additional refinement (Gafcor 1988). A fuel switch is required to bypass the existing carburettor or disenable the fuel injection system (IANGV 1990). Modern microprocessor engine management systems increase the difficulty of conversion (Gafcor 1988). While ABARE (1992) points out that the higher temperatures in spark ignition natural gas engines may require higher quality components and more maintenance, AGL (pers. comm. 1992) contends that this is not backed up by industry experience.

Natural gas cars available in the future, but before an adequate refuelling structure permits dedicated vehicles, are likely to be designed primarily as NGVs, with a secondary ability to use gasoline in a 'limp home' mode (AGA 1991). Modern engine management systems would be able to forestall detonation problems due to the higher compression ratio for a limited range of operating conditions, although emissions would be high for this small proportion of running time (AGA, pers. comm. 1991).

However, as indicated in the body of the paper, Ford Australia has received ERDC funding to develop an NGV *Falcon* station-wagon taxi, using an optimised NGV engine. Developing the engine will take 12 months, as the engine will be uniquely calibrated to natural gas and have a compression ratio of 15 or 16 to 1, necessitating special pistons and different spark plugs (though available from a current range of plugs). Limp home mode on gasoline is unlikely. Although the engine management system could retard the spark to avoid detonation, separate gasoline tank and other equipment would not be justified, given that two NGV tanks will be fitted for a target range of 400 to 450 kilometres. Five vehicles will be built initially to assess the specification, followed by 50 more. Ford has a joint venture arrangement with the UK based firm Tickfords to produce low volume special vehicles in Australia. A general use NGV *Falcon* derivative is a possibility in perhaps three or four years, depending on market acceptance (Ford Australia, pers. comm. 1992).

Natural gas trucks and buses

The greater complexity of truck engines, with turbochargers and aftercooling, is said to have added to the difficulties of conversion of trucks, as compared with buses (Yorke 1991). However, the State Transit Authority (STA) of NSW recently took delivery of two Scania NGV buses with turbocharged, intercooled engines. Merz (1991) points out that the microprocessor engine management systems, now common on cars, are only beginning to be considered for trucks, which could add to existing difficulties.

As discussed in chapter 7, natural gas engines for heavy vehicles may be either dual (mixed) fuel compression ignition (diesel) engines, or diesel engines converted to spark ignition engines. There is only one gasoline engine in production suitable for heavy trucks (Yorke 1991), and it would require a substantial increase in compression ratio to be optimised for natural gas.

Dual (mixed) fuel bus engines have achieved 90 to 95 per cent gas substitution for diesel at high loads, whereas the figures for trucks are about 80 to 85 per cent (Yorke 1991). Gas substitution at idle is zero and increases with load. The overall average for trucks is about 60 per cent. However, the dual (mixed) fuel engine cannot be optimised for natural gas, and is about 10 per cent less efficient in fuel use than a pure natural gas engine (Yorke 1991).

Spark ignition natural gas engines are currently some 3 to 5 per cent less efficient at maximum load than diesels, and are somewhat heavier than necessary, but fully developed engines should match the full-load efficiency of diesel engines (Yorke 1991). However, Fisher and Allen (1992) report the fuel consumption of a spark ignition NGV line-haul heavy truck as equivalent to 4.5 miles per gallon of diesel, a consumption rate about 15 per cent higher than the 5.3 miles per gallon of a comparable diesel truck.

Merz (1991) states that new generation lean-burn engines will emit less CO_2, NO_x, hydrocarbons and soot, and should be available by 1993. The lean-burn spark ignition natural gas engine developed by Gafcor and Bosch reportedly has a full-load thermal efficiency (37 per cent), close to that of the same engine in diesel form, and some 5 per cent better than overseas natural gas engines (Clifford 1991). However, the most efficient diesel engines now available have thermal efficiencies considerably higher than this. Diesel engines with turbocharging and intercooling have thermal efficiencies as high as 44 per cent, while the recently introduced Scania turbocompouded diesel, wherein a second exhaust turbine feeds power back to the crankshaft via a fluid coupling, claims a thermal efficiency of 46 per cent (*Truck Australia* 1992).

Current gas carburettors were not sufficiently accurate or reliable for use with turbocharged and aftercooled truck engines, according to Yorke (1991). Gas injection direct to the cylinder could yield significant fuel savings and emission reductions (Gafcor 1988).

International Trucks Australia Ltd, in association with engine manufacturers Cummins and Perkins have developed heavy dual-fuel NGV trucks, and is working on a spark ignition conversion (Yorke 1991). NGV Australia, Cummins, Ford and eight major transport operators are cooperating (depending on ERDC funding) in a project to take the prototype heavy truck engine through to commercial installation. Ford will do fundamental engine design to make the engine suitable for production. Volvo Australia Pty Ltd is the only other vehicle maker involved in NGV truck development in Australia (NELA 1991a). In the USA, diesel engine manufacturers Cummins and Detroit were developing natural gas engines in 1990 (Sinor Consultants 1990), while M.A.N. and Mercedes Benz have produced spark ignition NGV bus engines (Allen 1992).

In the longer term gas turbine engines fuelled by CNG may be available for heavy vehicles. Recently it has been reported that development is underway in the UK on a gas turbine/electric hybrid power plant for long distance trucks. An aircraft-derived turbine will provide the primary motive power source for the vehicle, and will also charge batteries that will provide supplementary power for hill-climbing etcetera. In the USA, a large (5.8 litre) rotary engine is being developed, capable of operating with very lean mixtures for low NO_x emissions (Sinor Consultants 1992b). This engine may have applications in heavy vehicles in the future.

Bus trials

In the 1970s in Victoria Gafcor requested support from the Tramways Board for an NGV bus trial. A Volvo engine was lent to Melbourne University for conversion to dual (mixed) fuel. After satisfactory engine bench tests a 10 month in-vehicle trial proved NGV was satisfactory as an alternative fuel. The Australian and New Zealand City Transit Authorities (ANZCTA) decided that NGVs would be included in the next purchase of new buses. The Public Transport Commission of Victoria (PTCV) opted for 10 dual (mixed) fuel buses, as these had effectively no range limit, while other authorities chose spark ignition engined buses, which had to refuel twice per day. The first M.A.N. natural gas buses were delivered in 1986, and were used on ordinary routes (PTCV, pers. comm. 1992).

Some problems were experienced with fitout and with engine seizures and piston melt-down, and the trial was eventually abandoned. No measurable engine wear was found, and the engines were cleaner inside than diesels, although the buses travelled only 30 000 kilometres. Only a 28 per cent substitution of gas for diesel was achieved, with little substitution at low power or high power, and none at idle. More energy was consumed by the natural gas buses than by the diesels. The PTCV is waiting on funding to convert the dual (mixed) fuel buses to spark ignition natural gas to continue the trial (PTCV, pers. comm. 1992).

One demonstration M.A.N. spark ignition natural gas bus was found to backfire flames and stall at lights. It was only 95 per cent as energy efficient as the diesel version.

The PTCV regards spark ignition natural gas as the better option in the longer term. The dual (mixed) fuel configuration would only be suitable for new buses.

The NSW STA has operated two Mercedes Benz spark ignition natural gas buses since 1988. The quality of the conversion was deficient, and teething problems were experienced—possibly from failure to use NGV trained mechanics. These buses have been used only during morning and evening peak periods. Their range is about 200 kilometres from 560 litres of storage (STA, pers. comm. 1992).

Recently the STA took delivery of two Scania natural gas buses for trials. These buses have turbocharged, intercooled engines, and cost around $20 000 more than a diesel bus. A pay back period of six to ten years is expected, given usage of 40 000 to 50 000 kilometres per year. In future the additional costs of NGVs could be partly offset by less demanding requirements for pollution control equipment and soundproofing compared with the diesel version.

Scania has a tender to supply 300 buses — including 250 natural gas buses — to the STA, subject to satisfactory performance by the trial buses. The production versions are to be delivered at a rate of 50 per year from 1994, and should comprise about 17 per cent of the fleet by 1999. The STA believes that although natural gas buses are at an early stage of development, it is important to to encourage that development.

In the Australian Capital Territory, ACTION Buses has carried out a short-term trial of a spark ignition M.A.N. bus on loan from the manufacturer. Although peak power has been found to be down a little, bottom-end torque has increased, enhancing driveability compared with the diesel bus. The natural gas bus is noticeably quieter on drive-by. Passengers, however, may not notice any difference, as the existing Renault diesel buses have good sound insulation around the engine compartment and wheel arches.

ACTION did not favour converting existing buses, considering OEM spark ignition the most viable option, despite the additional $20 000 cost. As the technology was still developing, longer term trials would be required before any decision was taken to adopt more NGVs. ACTION did not consider dual (mixed) fuel a good option due to its complexity (ACTION Buses, pers. comm. 1992).

NG in railway locomotives

The technology for using natural gas in railway applications is not well developed at this stage.

The potential application of CNG or LNG in diesel locomotives was the subject of a NERDD project: *Natural gas for locomotives — a feasibility study.* The study reported on factors such as operating range, power loss, ease of operation, refuelling times and the need for a separate tender to carry CNG fuel. A demonstration project on one of Australian National's South Australian rail operations was envisaged some years ago (Merz 1991; Australian Energy Research 1989) but has not been put into effect.

In the USA, Burlington Northern railway has been testing gas locomotives since 1982 with CNG (power did not match that of a diesel), and since 1986 with LNG. A range of 3000 kilometres was achievable with the use of a separate tender for the LNG. Union Pacific is to conduct trials of a range of LNG locomotives, including dual (mixed) fuel, an Electro-Motive dual-fuel unit, Dash 8–40C locomotives belonging to a consortium formed by General Electric, and a spark ignition LNG unit (*Railway Gazette International* November 1992, 759).

NG in ships

The technical viability of natural gas has been demonstrated in Australia by successful applications in ferries, in a short-voyage coastal ship using CNG and in international shipping using LNG.

In Queensland, a dual (mixed) fuel (CNG and diesel) powered passenger ferry formerly operated on the Brisbane River. Refuelling times of three to five minutes were aimed at. The Australian coastal ship *Accolade II* operates primarily on CNG, with diesel used as a pilot fuel to promote fuel ignition. The 8410 deadweight tonne limestone carrier operates on a short passage basis for nine to 10 hours per day. Consumption at the service speed of about 10 knots is about 6 tonnes per day of CNG and 1 tonne of diesel. For steady running, fuel use would be about double these amounts for 24 hours (Adelaide Brighton Cement Ltd, pers. comm. 1991).

The marine engine manufacturer, Wartsila, recently released a medium speed engine which can run on fuel oil, diesel or natural gas and diesel. The engine uses high pressure concentric injection of gas and pilot fuel, and claims NO_x emissions of only half those of an emissions-optimised diesel engine (*Motor Ship* 1992).

Tanker ships carrying exports of LNG from Australia's North-West Shelf fields are fuelled largely by boil-off from the cargoes they carry. For the class of ships including the *Northwest Sanderling*, the boil-off is 180 cubic metres per day or about 83 tonnes, which is sufficient for a speed of 16 knots fully loaded. To achieve the scheduled speed of 17 knots, this amount must be supplemented by either spraying the cargo to vaporise more of the LNG or by using about 10 tonnes per day of heavy fuel oil (HFO). To minimise thermal stressing, some cargo is retained in the tanks during the return voyage. Boil-off is then sufficient only for 14 knots, requiring supplementary spraying to increase vaporisation and permit a speed of 16 knots (Australian LNG Ship Operating Company (ALSOC), pers. comm. 1991).

According to ALSOC, no problems have been experienced with LNG as a fuel. LNG burns more cleanly and without soot, and contains no vanadium. There has been no need for the use of HFO as a pilot fuel. Previously, regulations had required the use of pilot fuel oil. HFO is used as a dual-fuel during manoeuvring, though there is no real need for this even at low engine speeds. Excess boil-off in port is dumped to the condenser (ALSOC, pers. comm. 1991).

NG in aircraft

In the former Soviet Union, a testbed *Tupolev 154* passenger aircraft (redesignated as a *TU 155*) has had one engine converted to operate on either liquid methane (LNG), liquid hydrogen or jet fuel. LNG has an energy density of 25 megajoules per litre, some three times that of liquid hydrogen (8.48 megajoules per litre), but less than that of jet fuel (36.8 megajoules per litre). About 50 per cent more storage volume would be required for LNG than for jet fuel.

LNG has a higher specific energy (54.4 gigajoules per tonne) than jet fuel (46.4 gigajoules per tonne) but has only about half the specific energy of liquid hydrogen (119.19 gigajoules per tonne) (*Automotive Engineering* 1991b). Compared with jet fuel, LNG would offer lower fuel load on takeoff for equal range, depending on the weight of the necessary vacuum-insulated double wall storage tanks.

Some of the research and development work on road transport NGVs could be applied to piston-engined light aircraft in the longer term.

APPENDIX VII GAS MARKET STRUCTURE AND GAS PRICES

There is considerable variation in production and transport costs of gas among States, and the margin between delivered price to the gas supplier/reticulator and the retail price also varies substantially. Costs of gas suppliers/reticulators in different states could also be expected to vary.

Market structure

DPIE (1991d) notes that domestic marketing of natural gas is not particularly flexible. Most gas producers are private firms, selling gas on long-term fixed-price or indexed contracts to one market, often a single gas utility.

The gas utilities responsible for retailing natural gas are state based organisations. Only one trunk pipeline transports gas across state borders. This is the line bringing Cooper Basin gas from South Australia to New South Wales, operated by The Pipeline Authority, a Commonwealth instrumentality (DPIE 1991a).

Despite Section 92 of the Constitution, providing for free trade and commerce among the States, States have acted to restrict the sale of gas interstate or to preserve portions of gas reserves for their own use (DPIE 1991a). Estimates of the Industry Commission are that 'free and fair' interstate trade in gas could reduce gas prices by around 10 per cent (TPC 1992).

The AGA (1992a) has called for a freeing up of interstate trade, estimating that if current restrictions remain, gas prices in 2030 would be higher by between 24 per cent (Melbourne) and 32 per cent (Sydney) than if trade were unrestricted. The cost to consumers of these restrictions could be between $1.5 billion and $4 billion, depending on the level of gas use at that time (AGA 1992a).

The Chairman of the Trade Practices Commission has foreshadowed the removal of legislative barriers to interstate trade in gas and the extension of Trade Practices and Prices Surveillance legislation to cover the gas industry uniformly, as recommended by the Industry Commission (TPC 1992).

Gas prices

The IEA has characterised Australian gas prices as low relative to oil prices, though the Victorian Government move towards pricing gas at opportunity cost in 1982 reduced what would otherwise have been a larger gap (IEA 1991a).

Table VII.1 shows 1988–89 average values in various states for natural gas producer prices, transport charges, retail prices, and margins between retail prices and costs to gas suppliers/reticulators (IES 1990). In 1989 average retail gas prices in Australia varied from $3.65 per gigajoule in Western Australia to $5.56 per gigajoule in NSW. The disparity in prices among the States gives point to the Industry Commission estimates of scope for a 10 per cent reduction in gas prices from 'free and fair' interstate competition (TPC 1992). The IEA cites estimates of the production costs of gas from the NW Shelf equivalent to about $0.66 per gigajoule, stating that onshore production costs are lower than this (IEA 1991a).

Average city-gate prices (production plus transport to gas supplier/reticulator) per gigajoule for gas in 1991 were: Sydney $2.85, Melbourne $2.40, Brisbane $3.70 and Adelaide $2.40 (AGA 1992a). The AGA (1992a) projections for gas prices in 2029–30 in 1992 dollars per gigajoule, under an enhanced demand scenario, with free interstate trade in gas, are: Sydney $4.49, Melbourne $4.11, Brisbane $4.68 and Adelaide $4.25.

Retail gas prices

Gas price to the consumer is determined on the basis of customer category, quantity consumed, load profile and location with respect to the distribution system (Merz 1991). Gas customers are categorised by the utilities as domestic, commercial light industrial or contract customers, the last being users of over 10 000 gigajoules per year. The industrial average gas prices include supplies to

TABLE VII.1 1988–89 STATE AVERAGE NATURAL GAS PRICES AND CHARGES

($ per GJ)

	NSW	*Victoria*	*WA*	*SA*
Producer price	1.73	0.50	2.00	1.73
Government impost[a]		1.40		
Transport charge	0.77	0.15	1.00	0.32
Retail price	5.56	4.63	3.65	4.56
Balance for supplier/reticulator	3.06	2.58	0.65	2.51

a. The Victorian Government impost refers to the Statutory Authority Contribution levied on the Gas and Fuel Corporation by the Victorian Government.

Source IES (1990); NIEIR (1988).

large contract customers at lower than gazetted prices (IES 1990). Table VII.2 shows average 1989–90 gas revenues from the different market sectors.

Gas costs

The AGA's *10/10* goal for NGVs aims at a gas price of 35 cents per cubic metre, equivalent in energy terms to 1.09 litres of gasoline or 0.98 litres of diesel. The 35 cent price (about $9.20 per gigajoule, depending on gas source) is the estimate which would cover all costs and normal profit up to the retail pump, whether borne by the gas utilities or some other company (such as an oil company) if natural gas were to be sold through existing service stations.

Table VII.3 shows a comparison between the cost breakdowns of a litre of gasoline and diesel and a cubic metre of natural gas in NSW. The portion of the pump price available for refining and distribution, marketing and retailing is larger for natural gas than for the two petroleum fuels, if natural gas is free of excise and taxes.

TABLE VII.2 AVERAGE REVENUE PER UNIT OF NATURAL GAS SALES:1989–90

($ per GJ)

	NSW	*Vic.*	*Qld*	*WA*	*SA*	*Total*
Residential	11.35	7.03	15.55	13.15	10.38	8.23
Commercial	8.66	5.68	11.58	12.67	5.71	7.12
Industrial	4.66	3.19	6.12	3.63	3.02	3.77
Total	5.88	4.99	7.93	4.12	4.67	4.99

Source AGA 1991.

TABLE VII.3 FUEL COST COMPONENTS

Component	Gasoline (cents/litre)	Diesel (cents/litre)	NG (cents/m^3 in NSW
Producer share	16.1 [a]	16.1 [a]	6.6
Pipeline charge			2.9
Excise	26.2	26.2	0.0
State fuel tax	6.7 [b]	6.7 [b]	c
Margin for refiner/ Marketer and retailer	19.5	16.0	25.5
Pump price	68.5	65.0	35.0

a. Includes royalties (0.2) and Resource Rent tax (4.8).

b. Estimated average for states.
Gasoline: NSW 6.53, Vic. 7.2 (11 per cent wholesale), Qld nil, SA 2.98 to 5.5 depending on zone, WA 5.67, Tas. 6.48, NT 6.0, ACT 6.53 cpl.
Diesel: NSW 6.57, Vic. 7.1 (11 per cent wholesale), Qld nil, SA 4.17 to 6.69 depending on zone, WA 7.45, Tas. 6.11, NT 6.0, ACT 6.57 cpl.

c. The NSW Government announced in December 1992 that alternative fuels would be exempted from the state fuel franchise fee.

Sources IES (1990); BRW (1992b); BRW (1992c); BTCE estimates.

APPENDIX VIII SOME ELECTRIC VEHICLES FROM CAR MANUFACTURERS

The GM *Impact* car was designed for 60 miles (100 kilometres) per day use. The maximum urban range is 110 miles (176 kilometres) to full discharge, which would shorten battery life considerably. The lead–acid batteries are capable of being fully charged in three hours, or 50 per cent in half-an-hour. Battery replacement would cost about US$1500. Regenerative braking provides 35 to 40 per cent of the *Impact*'s range, compared with the 15 to 20 per cent normally provided to EVs. This improvement is due to the car's propulsive efficiency and to the efficiency of its braking system. The vehicle was to go into production in 1994 (Wilson 1992), but it appears that more recent plans are for a lower output than originally intended.

PSA Peugeot Citroen has developed a multi-stage approach for entering the electric vehicle market. Three electric vans are available (Peugeot *J5*, Citroen *C15 & C25*), and as at 1992 around 500 vans had been built or were on order.

The second stage involves the introduction of two compact vehicles in 1995. The vehicles are to be fitted with Ni-Cad batteries and will be conversions of the gasoline models Peugeot *106* and Citroen *AX*. Trials of these vehicles will commence in the French city of La Rochelle in 1993. Fifty vehicles will be made available for use by La Rochelle residents. These trials will focus on driver behaviour, vehicle and battery recharging system operation, maintenance requirements, impact on the city's air quality, noise levels and traffic safety. Additional vehicles may be added to the trial fleet depending upon the early results. The city of La Rochelle has agreed to set aside parking places for the EVs throughout the city. These parking places will be equipped with recharging stations. Rapid recharging stations are to be placed at selected service stations (PSA Peugeot Citroen publicity brochure 1992).

The third stage of the program will be to optimise the design of an EV car, and put it into large scale production. A (series) hybrid car is also being considered, possibly using a turbine engine as a generator (Bertrand 1992). In the first phase of the hybrid development a Peugeot *405* station wagon has been fitted with an electric motor, batteries and an optimised diesel generator. This experimental vehicle uses Ni-Cad batteries for driving in the city. A six-minute battery recharge is adequate for 20 kilometres of travel. On the open road the diesel generator operates with additional power from the batteries if necessary. Highway range is reputed to be 750 kilometres (PSA Peugeot Citroen publicity brochure 1992).

In addition, PSA Peugeot Citroen is developing the subcompact *Citela,* a concept car which is claimed to have a motor life of 1 million kilometres. The *Citela* has a unique design which enables the detachable passenger cabin to be removed and replaced with another option in under five minutes, so that the *Citela* can be used as a goods vehicle. The *Citela* will have Ni–Cad batteries reputed to last 10 years. The batteries allow for a range of 110 kilometres on an urban driving cycle. Two battery recharging circuits are available. One circuit charges the batteries in eight hours. The other circuit will provide enough of a charge to give the vehicle a range of 2 kilometres for every minute of charge (PSA Peugeot Citroen publicity brochure 1992).

Fiat has had a commercially available electric car (the *Panda Elettra*) in Italy since 1990. The electric *Panda* is derived from the gasoline version. It is capable of carrying two adults and 100 kilograms of luggage. The *Elettra* is fitted with regenerative braking and lead–acid batteries are standard. Recharging time with an on-board battery charger takes eight hours. Ni–Cad batteries are available as an option. Vehicle range on the ECE urban cycle is 70 kilometres with lead acid batteries or 100 kilometres with Ni–Cad batteries. Fiat is also investigating new batteries with an emphasis on Zn–Br and lithium battery types. Over 200 *Elettras* had been sold by mid 1991. The *Elettra* cost £12 000 in 1991 compared with the gasoline version cost of £3600 to £6800 (Rogers 1991).

The *Elcat* van produced in Finland retails for US$19 000. Approximately 100 *Elcats* have been sold. It is capable of carrying a 250 kilogram load including the driver. The 440 kilograms of lead–acid batteries can be fully recharged by the on-board charger in 12 hours or charged to 80 per cent capacity in eight hours. Correct battery temperature is maintained by an automatic heating and ventilation system. When the state of battery charge drops to a low level, a battery care system renders normal driving impossible and excessive discharge of the batteries is avoided. The batteries can be replaced in 15 minutes. Range is claimed to be 60 to 70 kilometres on the urban cycle (*Elcat* publicity brochure 1992).

The *Elcat* is fitted with automatic and manual safety systems in the event of an accident. If the vehicle is involved in a rear-end collision the safety system disconnects the power circuit in the battery pack. If the battery cables short, internal fuses disconnect the battery circuit. A main switch is fitted in the cabin for the driver to disconnect the battery circuit should disconnection be required (*Elcat* publicity brochure 1992).

Nissan's concept car the *Future Electric Vehicle (FEV)* is the outcome of an EV research program that commenced in the 1960s. The *FEV* features an aerodynamic body design, low rolling resistance tires and a multiple battery recharging arrangement. The Ni–Cad batteries can be recharged by the on-board battery charger in eight hours, or a rapid recharging system can charge the batteries to 40 per cent capacity in six minutes. Another quick recharging system has been developed for rapidly recharging sealed lead–acid batteries to 40 per cent capacity in 12 minutes. The *FEV's* regenerative braking system can recharge the batteries during deceleration. Solar cells with a 16 per cent efficiency, embedded in the vehicles roof, also charge the batteries. These cells would need five weeks of continuously fine weather to fully recharge the batteries (Irie 1992).

The *FEV* is claimed to have a range of 100 kilometres at a constant speed of 72 kilometres per hour, or 250 kilometres at a constant speed of 40 kilometres per hour. Maximum speed is 130 kilometres per hour. The *FEV* is fitted with a separate motor to drive an airconditioner, and a heatpump is used to provide heating. The vehicle's windows are made of thermally insulated glass to reduce airconditioner load. The *FEV* also has power-assisted brakes. The vehicle's seating capacity is limited to two adults and two small children (Irie 1992).

BMW has developed a number of EVs based upon their series three gasoline vehicle range. These electric vehicles provided the experience necessary for BMW to design a concept EV, the *E1*. Another vehicle, the *E2*, is being developed for the Los Angeles market.

The *E1's* body is made of an aluminium supporting structure and a plastic skin. Seating capacity is adequate for two adults and two children. The *E1* is fitted with a Na–S battery system which can be recharged in 12 hours. If a rapid charging system is available, recharging can occur in two hours. Data derived from the Na–S battery fitted in the Series 3 vehicles show that when the average daily distance travelled is 10 kilometres, the vehicle uses 25 per cent of its energy for propulsion, 65 per cent to maintain the battery at its operating temperature and the remaining 10 per cent to heat the passenger compartment. When the distance travelled is 100 kilometres a day, 80 per cent of the vehicle's energy is used for propulsion. The battery is reputed to remain warm for four days after a full charge. The *E1's* range is about 142 kilometres, based upon an FTP-75 test cycle and an extended ECE test cycle. Maximum speed is 120 kilometres per hour, and total payload is 300 kilograms.

Table VIII.1 lists some EVs under development or currently available.

TABLE VIII.I EXAMPLES OF ELECTRIC CARS

Car	*Maker*	*Battery type*	*Range (km)*	*No. pass.*	*Cost/status*
Series 3	BMW	Na–S	150–260	5	Prototype
E1		Na–S	150–260	4	Concept
E2		Na–S	260		Prototype
TEVan	Chrysler	Ni–Fe	195		Production engineering
LA301	Clean Air Transport	Lead–acid (hybrid)	100–240	4	Prototype
Citela	Citroen	Ni–Cd	200	4	Prototype
C15 van		Ni–Fe	112		Production
Hijet van	Daihatsu	Sealed lead–acid	140 @ 40 kph		Production
Panda Elettra	Fiat	Lead–acid Na–S	69(ECE) 100	2	~A$29 000 (in Italy)
Mira	Huntington/ Daihatsu	Lead–acid	60–90	2	$18 400
Impact	GM	Lead–acid	177	2	Production engineering
HX3		Lead–acid (hybrid)	40–480		Prototype
323EV	Mazda	Lead–acid	105		Prototype
MX-5		Ni–Cd	190		
190E	Mercedes Benz	Na–S Na–NiCl$_2$	150		Prototype
FEV	Nissan	Ni–Cd	100 250 @ 40 kph	2–4	Prototype
205E	Peugot	Ni–Fe	112		Prototype
106					Pre-production
Elecktro-Clio	Renault	Lead–acid	80		Prototype
Every Multiroof	Suzuki	Ni–Zn	230 @ 40 kph		Production
IZA	Tokyo Electric Power Co.	Ni–Cd	548 @ 40 kph 270 @ 100 kph	4	Prototype
Elin Bus	VW	Zb–Br	200		Prototype
Citystromer		Lead–acid	80		
Golf		Na–S	120		
		Ni–Cd (hybrid)	20		Fleet test
ETV1	Sydney University/ Suzuki	Lead–acid	80	2	Prototype
ETV2	Sydney University/ GMH	Lead–acid	100	2	Prototype

Sources AEVA (various issues); Barber & Arbarcar (1992).

APPENDIX IX BATTERIES FOR ELECTRIC VEHICLES

Many types of battery are under development for electric vehicle use. Some others, while intended primarily for stationary use, may also have potential for use in electric vehicles.

Lead–acid

In surveying battery types for EVs, Rand (1992) concluded that the lead–acid battery was 'the obvious, if not the only' battery for medium-term, large-scale production. Schodde (1991) noted its characteristics of low cost with reasonable performance and life (although mediocre under heavy discharge), with the ability to supply high power for short periods. Recent lead–acid batteries are valve-regulated designs with an immobilised electrolyte (either gelled with silica or absorbed in a glass-microfibre mat) which obviates water loss and the need for topping-up in service.

Research and development, including that by CSIRO and ALABC, is proceeding on advanced lead–acid batteries with potential energy densities of 50 watt-hours per kilogram. Another ALABC objective is to increase the number of cycles in battery life. After about 1500 cycles to 80 per cent discharge, the storage capacity of present lead–acid batteries is appreciably reduced: a target is to increase this figure to over 2000 charge–discharge cycles (Schodde 1991).

A US company, *Electrosource,* has developed a design which uses woven lead wire screens rather than solid lead plates, and claims an energy density of 52 watt-hours per kilogram, as well as recharge times of only 30 minutes for 99 per cent recharge, and eight minutes for 50 per cent recharge (AEVA Electric Vehicle News 1992). Twice the cycle-life is claimed for the ELSI battery, and the US Electric Power Research Institute (EPRI) expects availability by 1995 (*Australian,* 22 September 1992, 26).

Tubular plate batteries, generally used in large stationary lead–acid units (Schodde 1991), give higher energy densities than flat plate batteries (Rand 1992), and may be an alternative to multiple flat plate units now used in EVs powered by lead–acid batteries. The General Motors *G-Van,* in small scale production, uses tubular lead–acid batteries (Barber & Abarcar 1992).

Nickel–iron

The nickel–iron (Ni–Fe) battery is seen by some as the viable next step beyond the lead–acid battery, and is to be used by Chrysler in its *EPIC* commuter and *TEVan* (AEVA 1992a). The Ni–Fe battery has an energy density about one-third greater than the lead–acid battery but, with expensive nickel electrodes is likely to be three to ten times more expensive than the same capacity of lead–acid batteries. Cycle-life of 2000 discharges is about one-third greater than the maximum to be expected from current lead–acid batteries (Rand 1992).

The energy efficiency of the Ni–Fe battery is only about 60 per cent, that is, it returns only 60 per cent of the energy with which it is charged from the electricity grid. This is over 20 per cent less than the efficiency of the lead–acid battery. Regular addition of de-ionised water is required, and the Ni–Fe battery produces considerable amounts of hydrogen gas during recharging, which may present a safety hazard.

Nickel–zinc

Although nickel–zinc batteries have higher energy and power densities than lead–acid batteries, their cycle-life is much lower at present, at about 500 cycles or about one-third that of lead–acid batteries. New designs show promise of greater life and obviate the need to top-up with water. Small units are in commercial production in Japan, and were used in a vehicle which completed the 1990 Solar Challenge. Cost is estimated at three to four times that of comparable lead–acid battery capacity (Rand 1992).

Nickel–cadmium

Nickel–cadmium (Ni–Cad) batteries are used — by Nissan in its *FEV* car; fully rechargeable in 15 minutes, or 40 per cent in six minutes — and in the Japanese *IZA*, for which is claimed a range of 548 kilometres at a steady 40 kilometres per hour (Ishitani 1992). Peugot production EVs will have Ni–Cad batteries produced by Saft-Nife, currently the largest producer of Ni–Cad batteries. Fiat's *Panda Elettra* gives 30 per cent better range in city use with Ni–Cad batteries than with lead–acid batteries (Rand 1992), although at a significantly higher cost.

The AEVA (1992a) cites estimates of a battery cost of three times the ex-factory vehicle cost for a 50 kilowatt-hour battery giving a 160 kilometre range. However, a representative of Saft-Nife predicted dramatic price reductions for Ni–Cad batteries in high-volume production (*BRW* 1992d). Ishitani (pers. comm. 1992) predicted that in the future Ni–Cad battery costs would fall to be similar to those of lead–acid batteries.

While disposal problems of highly toxic cadmium may be considered to rule out cadmium based systems on environmental grounds (Rand 1992), Saft-Nife points out that recycling facilities operate in Japan, Korea, the USA and Sweden, with the Swedish plant providing a large proportion of the materials for new Saft-Nife batteries (*BRW* 1992d).

Nickel–hydrogen

Nickel–hydrogen (Ni–H_2) batteries have electrodes of nickel and of gaseous hydrogen, with the hydrogen stored either as a gas under pressure (the form used in satellites) or in the form of a hydride (currently under development for use in small portable power sources) (Rand 1992). Although the cost will be high (about 5 to 10 times that of equivalent lead–acid battery capacity), the Common Pressure Vessel form of the gaseous hydrogen type may be competitive with lead–acid batteries. It has a long life (over 2000 cycles) and low maintenance costs. Its energy density is only slightly higher than that of lead–acid batteries (Rand 1992).

In nickel–metal hydride (NiMH) form, the Ovonic battery prototype in the USA has shown an energy density somewhat higher again. The makers claim an energy density of 80 watt-hours per kilogram in a size suitable for units in an EV power pack, with a power density of over 200 watts per kilogram and a demonstrated battery life of over 900 cycles to complete discharge. At 30 per cent depth of discharge, a life of over 10 000 cycles has been achieved in tests. The makers project a cost of US$200 per kilowatt-hour (based on mass production of metal hydride alloys), much less than Rand's estimate in table 6.1 (Ovshinsky et al. 1992).

The USABC is funding the development of a mass-produced version (Charles 1992) through the only medium-term contract it has awarded (*Australian,* 22 September 1992, 26). EPRI expects availability by 1995 (*Australian,* 22 September 1992, 26), and Hyundai plan to use these cells in cars by 1995 (Rand 1992). Matsushita has developed a nickel–hydride battery vehicle for which it claims 2.8 times the range given by lead–acid batteries.

Sodium–sulphur

Sodium–sulphur (Na–S) batteries are being developed by the Swedish firm ASEA Brown Boveri (ABB) and Britain's Chloride Silent Power Ltd (CSPL) (Charles 1992). This battery type uses low-cost materials, and costs in mass-production may be similar to those of lead–acid batteries. A disadvantage is the high operating temperature, and several fires have been experienced with Na–S batteries (AEVA 1992c).

BMW has developed an experimental EV version of its Series 3 car, which uses two 180-volt ABB Na–S batteries — one of 19 kilowatt-hours in the engine compartment and one of 9 kilowatt-hours in the boot — for a stated range of between 150 and 260 kilometres in urban use. BMW claims three times the energy density of lead–acid batteries, and a battery life of 150 000 kilometres in urban use (BMW 1991a). BMW's *E2* car, planned for sale in California by the year 2003, also will use sodium–sulphur (Na–S) batteries. The head of Ford's EV program in 1990 considered that it could be 1995 before it is clear that the Na–S battery is a viable option (*International Business Week* 1990). However, plans are for Ford's *Ghia Connecta* and *Ecostar* van demonstration fleets to use Na–S batteries.

Experiments by BMW found that when a vehicle with Na–S batteries had an average daily use of only 10 kilometres, propulsion of the vehicle accounted for 25 per cent of the total energy used, with 65 per cent being used to maintain the battery temperature and 10 per cent for heating the passenger compartment. From a greenhouse perspective, the Na–S battery may not therefore be a desirable power source for short distance commuter cars, as emissions per passenger-kilometre would be relatively high. When the distance rose to 100 kilometres per day, propulsion accounted for 80 per cent of the energy used, heating the battery 10 per cent, and heating the passenger compartment 10 per cent, giving a somewhat better emissions performance on a passenger-kilometre basis (BMW 1991a).

Ford's *Ecostar* electric van program involves a demonstration fleet of 82 vans, including some hybrids, to be made available to selected customers in 1993. These vehicles will have Na–S batteries, which operate at temperatures of up to 350 degrees Celsius, and give a range of up to 160 kilometres (Nichols 1992).

The ABB Na–S battery achieved the highest simulated driving range and highest specific energy of any battery type in recent tests conducted by the US Argonne National Laboratory. At the end of the test—589 cycles—the ABB battery had lost 19 per cent of its initial ampere-hours capacity. ABB currently warrants its Na–S battery for 600 cycles or one year. A production plant will be in operation in Germany in 1994. The cost is around that of the Ni–Cad battery, which is felt to be too high for market acceptance, but a target for the late 1990s is for US$150 to $200 per kilowatt-hour in high-volume production. The CSPL battery, which had higher internal resistance and hence lower peak power output, failed after 795 cycles (Sinor Consultants 1992e).

Schodde (1991) considers the Na–S battery to be three to four years from commercialisation, with work to be done on problems such as corrosion of the electrolyte and steel container, and seal failures, in order to extend battery life beyond the current 2000 cycles.

Metal–air

Metal–air batteries (aluminium–air, iron–air and zinc–air) have high theoretical energy densities (2815 watt-hours per kilogram for the aluminium–air battery, and correspondingly lower for the heavier metals) but have, at present, low energy efficiencies, returning only about half the energy consumed during charging. All three battery types may be recharged mechanically (by refilling with electrolyte containing finely ground metal), and the iron–air and zinc–air batteries may also be recharged electrically.

The aluminium–air battery is in a comparatively early stage of development, but according to Rand (1992), is the only EV system with the potential to provide range and refuelling times comparable with those of gasoline vehicles.

Zinc–bromine

The zinc–bromine (Zn–Br) battery is under development in the USA, Australia and Japan, and is close to commercialisation (Schodde 1991). This battery is fairly complex, requiring separate storage tanks and pumps for two electrolytes, and any escape of fumes from the battery could be hazardous. Although it has been demonstrated in a vehicle, stationary battery storage systems may be the most appropriate use.

The minimum economic size is likely to be about 20 000 watt-hours (equivalent to at least 500 kilogram of lead–acid batteries), indicating the battery could be suitable for larger EVs. A Volkswagon bus with a 48 000 watt-hour unit has achieved a range of 150 kilometres (Schodde 1991).

Reliability remains a problem at this stage. The Zn–Br battery loses about 40 per cent of its charge in 48 hours (Rand 1992), making it unsuited to vehicles with intermittent use. Recent tests by the Argonne National Laboratory found a life of only 334 cycles (Sinor Consultants 1992e).

Vanadium–redox

Vanadium–redox batteries are being developed in Australia. These can be recharged conventionally in about one-tenth of the time required for a lead–acid battery. The alternative of refilling with fresh electrolyte is potentially as quick as refilling with gasoline, though much more frequently required. The energy density of this battery will be similar to that of the lead–acid battery (Allen 1989) because of the high density of the electrolyte. However, the claimed energy efficiency is higher, being 87 per cent compared with a maximum 65 to 75 per cent for lead–acid batteries (Kasherman et al. 1990). This means that more of the energy taken from the electricity grid is recoverable from the battery, which should result in lower greenhouse gas emissions. An indefinite life is claimed for a vanadium–redox battery (Kasherman et al. 1990).

Schodde (1991) considers that the vanadium–redox battery will require several pumps, storage tanks, complex plumbing and a sophisticated control system, and that there would therefore be concerns about reliability. It is also thought that it may be too large and complex for automotive use. Kasherman et al. (1990) consider it a possible vehicle power source for the future.

Skyllas-Kozacos (1991) claims that the cost of electricity from a large scale vanadium–redox battery would be about 60 per cent of that of electricity from a lead–acid battery system. Skyllas-Kozacos (1991) also points out that its relatively low energy density may limit its vehicle use to niche areas such as industrial trucks and delivery vans.

Lithium–sulphur

The Li–S battery, like the Na–S battery, is a high temperature (400 to 500 degrees Celsius) molten-salt electrolyte battery, with the advantage (for compactness and stackability) of being a flat-plate design, rather than a tubular design as is the Na–S. The operating temperature is somewhat higher than the Na–S type, and the safety concern with the Na–S battery would also be a concern with the Li–S battery (Rand 1992). A Li–S EV battery is currently under test in a van in the USA, and a range of 200 kilometres is expected (Rand 1992).

Lithium–chlorine

The Li–Cl battery operates at a still higher temperature, up to 650 degrees Celsius (SEC 1991), which suggests that safety concerns may be even more important than with Li–S or Na–S batteries.

Lithium–polymer

This is a solid-state battery with a solid polymer electrolyte. The individual cells can be produced in thin films, which may be laminated into various shapes and sizes. Research is under way to scale up the small units now available for electronic devices to make them suitable for EV use. Heat dissipation during recharging is a major problem to be solved before an acceptable cycle-life can be achieved. At the current early stage of development, performance is inferior to that of batteries with liquid electrolytes. Major advances are, however, expected (Rand 1992) and EPRI anticipates the batteries will be available by 2001 (*Australian,* 22 September 1992, 26)

Whereas the usual approach is to dissolve lithium salts in the polymer, a recent development at Arizona State University has been to dissolve the polymer in the lithium salts. This results in a rubbery electrolyte which overcomes problems of brittleness with previous solid lithium polymer electrolytes. The rubbery electrolyte is said to be a good conductor at air temperature, whereas earlier models of liquid electrolyte lithium batteries operate at high temperatures (*Daily Commercial News,* 16 March 1993, 5).

Fuel cells

A possible power source for vehicles in the very long term is the fuel cell, which uses fuel to produce electrical energy directly from a chemical reaction in the cell. Fuel cells were used in Apollo space missions (*Webb* 1991). Recent advances in material technology have the potential to make fuel cells commercially viable (*AEVA* 1992e).

The IEA (1992a, chapter 11, 23, draft of 8 April) classifies fuel cells into five categories, four of which (phosphoric, polymer electrolyte, molten carbonate and solid oxide) use methanol as a fuel and the other (the alkaline fuel cell or AFC) using hydrogen. Operating temperatures range from 80 to 1000 degrees Celsius. The IEA regards the polymer electrolyte cell as the most promising because of its low operating temperature and high specific power. The phosphoric cell is at present the closest to commercialisation.

Swan and Appleby (1992) consider the fuel cell to be impractical for transport use at present, as the cost is very high and the power density is low.

An Australian consortium comprising BHP, Pacific Power, CSIRO, ERDC and the SECV has recently established a company (Ceramic Fuels Ltd.) to develop fuel cells (SECV, pers. comm. 1992). The modular cells will use hydrocarbon fuels such as natural gas or coal gas as a fuel and air as the oxidant. A power density of 1 kilowatt per litre is aimed for, and a life of six to 10 years is hoped for (*AEVA* 1992e).

APPENDIX X VALUE OF URBAN POLLUTION BENEFITS FROM NATURAL GAS VEHICLES: HYPOTHETICAL SCENARIO

For illustrative purposes, the value of reduction in pollution from use of NGVs has been calculated, using:

- pollution costs per kilometre estimated by the Inter-State Commission (ISC 1990), and by Moffet (1991) for the USA. The ISC estimates have been regarded as too low, but no more recent authoritative estimates have yet been published for Australia. US estimates could overstate urban air pollution costs in Australia. The estimates might therefore be useful as upper and lower bounds.
- a particular scenario for percentage reductions in emissions and noise from use of NGVs, based on a number of sources. Estimates of reductions in emissions vary a lot, and the values used would not be representative of all situations where NGVs are substituted for gasoline or diesel vehicles.

TABLE X.1 VALUE OF REDUCTION IN URBAN POLLUTION FROM USE OF NGVS: HYPOTHETICAL SCENARIO

Emission	*Urban pollution costs (cents per km) ISC estimates*	*Pollution costs (US cents per mile) Moffet estimates*	*Assumed per cent reduction from NGVs (100% gas)*	*Reduction in costs from NGVs ISC costs (cents/km)*	*Reduction in costs from NGVs (100% gas) Moffet costs (US cents/ mile)*
Cars					
CO	0.105	2.04	50	0.05	1.02
HC	0.195	0.73	80	0.16	0.58
NO_x	0.318	0.1–1.4	0	0.00	0.0
SO_x	0.013	0.01–0.06	100	0.01	0.01–0.06
Particulates	0.045	0.01	100	0.05	0.01
Noise	0.13	ni	5	0.01	ni
Total cost	0.807	2.9–4.2		0.27	1.62–1.67
Per cent reduction				34	40–56
Heavy-duty vehicles					
CO	0.057	1.2	50	0.03	0.6
HC	0.116	0.7	80	0.09	0.56
NO_x	1.766	1.2–16	0	0.00	0.0
SO_x	0.292	0.06–0.27[a]	100	0.29	0.06–0.27[a]
Particulates	0.124	0.6	100	0.12	0.6
Noise	7.06	ni	20	1.41	ni
Total cost	9.41	3.76–18.77		1.94	1.82–2.03
Per cent reduction				21	11–48

ni Not included

Note CO = carbon monoxide, HC = hydrocarbons, NO_x = oxides of nitrogen, SO_x = oxides of sulphur, NGV = natural gas vehicle.

a. BTCE estimate based on Moffet (1991) data.

Sources BTCE estimates based on ISC (1990); Moffet (1991).

GLOSSARY

Acetaldehyde CH_3CHO, the major aldehyde emission produced in the combustion of ethanol.

Acrolein CH_2CHCHO, an aldehyde and a minor component of vehicle exhaust emissions.

AGA 10/10 goal Penetration of the road transport fuel market by natural gas to 10 per cent in 10 years.

Alcohol General term for a hydrocarbon compound with a hydrogen atom replaced by a hydroxyl (OH) group.

Aldehydes Organic compounds containing the CHO radical.

Alkanes Hydrocarbons which are arranged such that all the carbon atoms are bonded either to other carbons by single bonds or to hydrogen atoms, and of which methane is the simplest member.

Alkenes Hydrocarbons containing one or more carbon to carbon double bonds, of which ethylene is the simplest member of the series.

Amines Compounds formed by replacing hydrogen atoms of ammonia (NH_3) by organic radicals.

Amorphous Pertaining to a solid which is non-crystalline, having neither definite form nor structure.

Anthropogenic greenhouse effect Defined in chapter 1.

Antiknock index *See* **octane number**.

Antioxidant An inhibitor effective in preventing oxidation by molecular oxygen.

Arabinose A monosaccharide (sugar) with each molecule containing five carbon atoms.

Aromatic hydrocarbon Hydrocarbons containing hexagonal rings of carbon joined by alternating single and double bonds.

Articulated truck Truck consisting of two or more usually separable wheeled units, and consisting of a towing vehicle and a towed unit.

Asphalt Brown to black hard brittle or plastic bituminous material, composed principally of hydrocarbons.

Azeotropic distillation Traditional distillation process used to separate ethanol from water once the ethanol concentration is greater than 95 per cent.

Benzene C_6H_6, a colourless, flammable liquid, the simplest aromatic hydrocarbon, a scheduled poison and a suspected human carcinogen.

Bioethanol production Ethanol produced from biomass.

Biomass Usually measured as the dry mass of living matter, but in general usage refers to any material of biological origin.

Biostil process A process for producing ethanol from starch and sugar crops which gives a higher value more concentrated waste than does conventional ethanol production processes.

Brown coal Coal of relatively recent origin, intermediate between peat and bituminous coal.

Butadiene $CH_2CHCHCH_2$, a gas which is a suspected human carcinogen.

Butane C_4H_{10}, an alkane. It occurs in natural gas, and is produced by cracking petroleum. A constituent of LPG.

Calorific value The quantity of heat produced by a given mass of fuel on complete combustion.

Carbon dioxide CO_2, a colourless, odourless, tasteless gas about 1.5 times as dense as air. A major anthropogenic greenhouse gas.

Carbonyls Group of organic compounds comprised of aldehydes and ketones.

Carbon monoxide CO, a colourless, odourless gas resulting from incomplete oxidation of carbon.

Carcinogen An agent initiating the development of a carcinoma or any other sort of malignancy.

Catalyst Substance that alters the velocity of a chemical reaction and may be recovered essentially unaltered in form and amount at the end of the reaction.

Catalytic oxidation Oxidation which occurs in the presence of a catalyst.

Catalytic converter An emission control device fitted in the exhaust system of spark ignition engines to reduce the pollutant potential of combustion products.

Catalytic cracking A process where feedstocks are heated to high temperatures in the presence of catalysts to break down the longer chain molecules into lighter products.

Catalytic reforming This process supplements isomerisation in order to convert low octane hydrocarbons into high octane components.

Cellobiose A disaccharide repeating unit of cellulose which upon hydrolysis decomposes into two molecules of glucose.

Cellulase An enzyme aiding the conversion of cellulose into sugars.

Cellulose The main polysaccharide in living plants forming the skeletal structure of the plant cell wall.

Cetane number Rating for diesel fuels as a measure of the time required for a fuel to ignite after injection into a compression ignition engine. The higher the number the shorter the time to ignite. The cetane number is measured by comparison with a number of mixtures of cetane ($C_{16}H_{34}$) with alpha methyl napthalene, where the cetane is given a value of 100, and the alpha methyl napthalene is given a value of zero.

Charge cooling Removal of heat from the induction charge of an engine to increase its density and consequently the total charge mass and engine ouput per firing stroke.

Closed loop fuel system Electronically controlled carburettor or fuel injection system in which the mixture strength is adjusted by feedback signal from the monitoring of exhaust gas composition.

Coal seam gas Gases trapped within coal formations, main component methane.

Combustion chamber The part of an engine in which combustion takes place.

Compression ratio In an internal combustion engine, the ratio of the volume in the cylinder and cylinder head above the piston at bottom dead centre (at the bottom of the intake stroke) to the volume above the piston at top dead centre (the top of the compression stroke).

CO_2 equivalent emissions Defined in chapter 1.

Crankcase Part of the structure of an engine that contains the crankshaft and main bearings.

Cryogenic A liquid which boils at temperatures of less than about 110 degrees Kelvin at atmospheric pressure, such as hydrogen, nitrogen, oxygen , air and methane.

Cycloalkane A cyclic hydrocarbon compound containing only single bonds bonds between carbon atoms.

Cyclohexane A colourless liquid that is a cyclic hydrocarbon synthesized by hydrogenation of benzene.

Cylinder head Part of an engine that seals or closes the upper ends of the cylinders.

Denaturant An inert, bad-tasting or poisonous chemical substance added to a product to make it unfit for human consumption.

Diesohol An emulsion containing ethanol and diesel.

Direct greenhouse gases Defined in chapter 1.

Direct injection Engine injection system in which the fuel is injected directly into the engine cyclinder.

Distillates, middle *See* **distillation.**

Distillation The separation of individual liquids from a mixture by collecting separately fractions boiling at different temperatures. Distillation is the fundamental process in refining petroleum, where a fraction taken from around the centre of the petroleum boiling point range (such as kerosene) is known as a middle distillate. Similarly, fractions taken from the top of the boiling point range (such as fuel oil) are known as heavy distillate.

Dual-fuel vehicle A vehicle which is designed to run on either of two fuels, utilising separate fuel systems.

Dual (mixed) fuel vehicle Vehicles operating on a variable combination of gas and diesel fuel but which often retain the capability to operate solely on diesel when the gas supply has been exhausted.

Dunder Liquid waste from conventional ethanol production process.

Dynamometer A special type of electric rotating machine used to measure the output torque or driving torque of rotating machinery.

EC-X A reformulated gasoline produced by ARCO.

Energy crop An agricultural crop or forest plantation grown for the purpose of providing energy.

Engine knock *See* **knock.**

Enhanced greenhouse effect Defined in chapter 1.

Enzyme A single or chain of protein molecules which catalyse biochemical reactions.

Enzymatic hydrolysis Hydrolysis mediated by an enzyme.

Ester Esters are derivatives of acids obtained by the exchange of the replaceable hydrogen for organic radicals.

ETBE $C_2H_5OC(CH_3)_3$, ethyl tertiary butyl ether, an oxygenate produced from ethanol and isobutylene.

Ethane C_2H_6, a colourless odourless gas.

Ethanol C_2H_5OH, an alcohol, component of alcoholic beverages, a colourless liquid used as a reagent and solvent or as a fuel. Miscible with water.

Evaporative emissions Emission of fuel vapours to the atmosphere by evaporation of fuel.

Ex A fuel blend comprising x per cent ethanol and (100 – x) per cent gasoline.

Exothermic Indicating liberation of heat.

Fermentation An enzymatic transformation of organic substrates, especially carbohydrates, generally accompanied by an evolution of gas.

Flash point The temperature to which a fuel must be heated before vapours will ignite by a free flame in the presence of air.

Flexible fuel vehicle A vehicle capable of using fuels with a variable composition. In this document synonymous with variable fuel vehicle.

Flywheel Heavy wheel or disc attached, for example, to the crankshaft of an engine, to store kinetic energy of rotation and smooth the output from the irregular firing of the engine.

Formaldehyde HCHO, the simplest aldehyde, a gas with a pungent odour at room temperature and poisonous. In water it forms a clear, colourless liquid solution.

Formulate A term used in the petroleum industry for the process of blending distillation products.

Fugitive emission A loss of gas to the atmosphere from any part of the storage and supply system.

Full fuel cycle emissions Defined in chapter 1.

Galactan Any of a number of polysaccharides composed of galactose subunits.

Galactose A six-carbon monosaccharide.

Gallon US measure of volume, equal to approximately 3.785 litres.

Gasoline A complex mixture of hydrocarbons, refined from petroleum and used as fuel in internal combustion engines. Commonly called petrol.

Genotoxic Chemicals that react with DNA.

Global warming potential (GWP) The warming effect from emission of a particular gas relative to that of an equal mass of CO_2, over a given period (usually taken as 100 years).

Glycerin A colourless, odourless, viscous liquid with a sweet taste. It is completely soluble in water and alcohol, but only partially soluble in common solvents (such as ether and ethyl acetate).

Greenhouse gas Defined in chapter 1.

Greenhouse effect Defined in chapter 1.

Gross calorific value The quantity of heat released by a unit quantity of fuel when it is burned completely with oxygen and the products of combustion are returned to ambient temperature. *See also* **net calorific value**.

Hemicellulose A type of polysaccharide found in plant cell walls in association with cellulose and lignin.

Hemodialysis A process to separate soluble substances from blood.

Heptane A hydrocarbon which is a water insoluble, flammable, colourless liquid.

Hybrid vehicle Vehicle employing two distinct but interdependent forms of propulsion, such as an electric motor and an internal combustion engine.

Hydrocarb process A process for utilizing fossil fuels and biomass to produce energy with reduced CO_2 emissions.

Hydrocarbon A chemical compound that contains only carbon and hydrogen. It is the principal constituent of liquid fossil fuels.

Hydrocracking A catalytic, high pressure petroleum refinery process that can produce either high octane gasoline or aviation jet fuel.

Hydrolysis Decomposition or alteration of a chemical substance by water.

Hydrolytic enzymes Enzymes that will catalyse the hydrolysis of a wide range of organic substrates (for example proteins, nucleic acids, starch and fats).

Import parity prices Domestic prices on a par with the landed price of imports.

Indirect greenhouse gases Defined in chapter 1.

Injector nozzle Fine sprayer or atomizer through which fuel is injected into an engine.

Isomerisation A process which uses catalysts to convert the straight chain compounds in straight-run gasoline into branched chain molecules. This will allow the fuel to burn more smoothly and slowly.

Ketone An organic compound containing a carbonyl group (a carbon atom double bonded to an oxygen atom, C=O).

Knock Violent explosions in the cylinder of an internal combustion engine due to over-compression of the mixture of air and fuel vapour before sparking.

Larch The common name for members of the genus *Larix*, of the pine family, having short, spurlike branches which annually bear a crown of deciduous needles.

Life cycle emissions All greenhouse gas emissions associated with fuel use including exhaust and evaporative vehicle emissions, emissions from extracting, transporting and refining or producing fuels, and from vehicle manufacture and disposal.

Lignin A complex substance that together with cellulose and hemicellulose forms the woody cell walls of plants and cements them together.

Lignocellulose Any of a group of substances in woody plant cells consisting of cellulose, hemicellulose and lignin.

Liquefied petroleum gas LPG, a light hydrocarbon fraction derived from refinery processes and consisting primarily of propane and butane.

Liquid-phase injection Injection to the cylinder or inlet tract of a liquefied fuel (LPG or LNG) as liquid droplets rather than, after vaporisation, as a gas.

Litre of gasoline equivalent The amount of a particular fuel which contains an amount of energy equivalent to that contained in one litre of gasoline.

Mannan Any of a group of polysaccharides composed chiefly or entirely of D-mannose units.

Mannose A six-carbon monosaccharide.

Methane A colourless, odourless and tasteless gas, lighter than air (CH_4).

Methanol CH_3OH, an alcohol, a colourless, toxic, flammable liquid.

Microbial process A process involving the action of microbial organisms (for example bacteria and fungi).

Microfibril The sub-microscopic unit of a microscopic cellular fibre.

Monosaccharide A carbohydrate that cannot be hydrolyzed to a simpler carbohydrate.

MTBE $CH_3OC(CH_3)_3$, methyl tertiary butyl ether, an oxygenate produced from methanol and isobutylene.

Mutagen An agent that raises the frequency of mutation above the spontaneous rate.

Mx A fuel blend comprising x per cent ethanol and (100 – x) per cent gasoline.

Naphtha A general term for mixtures of hydrocarbons obtained from the distillation of petroleum, with boiling points between 20 and 200 degrees Celsius. A naptha would generally contain a mixture of C_4 to C_{10} alkanes and aromatic hydrocarbons.

Natural gas A combustible gaseous mixture of low molecular weight alkanes (mostly methane), generated below the surface of the earth, with varying amounts of carbon dioxide present.

Naturally aspirated Air is not compressed before being taken into the cylinder.

Net calorific value The gross calorific value of a fuel less the heat of vaporisation of the water present in the fuel and that formed during combustion. Net calorific values are typically 5 per cent lower than gross calorific values for oil and coal, and 10 per cent lower for natural gas.

Nitrous oxide N_2O.

Noxious emissions Term used for emissions that contribute to air pollution in the local environment where they are emitted.

Octane enhancer An additive that will increase the octane number of the fuel.

Octane number A measure of the anti-knock properties of a fuel. Octane number is equal to the percentage by volume of iso-octane (2,2,4-trimethylpentane) in a mixture of iso-octane and normal heptane (C_7H_{16}) which has the same knocking characteristics as the fuel under test.

Olefin A family of chemicals containing carbon to carbon double bonds. Old term for an alkene.

Open loop system Carburettor or fuel injection system in which there is no feedback to mixture strength from monitoring of exhaust gas composition.

Opportunity cost The opportunity cost of a particular use of resources is the value lost by not using the resource in the most profitable alternative use.

Oxidant A substance which supplies the oxygen in a reaction that combines oxygen with other substances.

Oxygenate A compound containing oxygen. Typically, a substance such as MTBE, which is mixed with fuels to raise their oxygen content.

Paraffin A solid crystalline hydrocarbon mixture.

Particulates The solid particle content of exhaust products, mainly in the form of carbon and partially burned hydrocarbons.

Pathogen A disease-producing agent.

Pentane C_5H_{12}, a colourless, flammable, water-insoluble hydrocarbon liquid.

Performic acid A very reactive acid formed by the reaction of hydrogen peroxide and formic acid.

Pervaporation A method of dehydrating ethanol using membrane technology.

Petajoules A measure of energy content, 10^{15} joules. A litre of gasoline contains about 34.2 million joules of energy.

Photochemical Caused by the action of light, particularly sunlight.

Photochemical smog Chemical pollutants in the atmosphere resulting from chemical reactions involving hydrocarbons and nitrogen oxides in the presence of sunlight.

Photosynthesis The process by which plants use light energy to convert carbon dioxide and water into carbohydrate, with the liberation of oxygen.

Piston Reciprocating component, usually in the form of a cylinder closed at one end, that operates under fluid pressure within a smooth walled engine cylinder.

Piston ring Ring, generally of hard, springy material, set in a groove beneath the piston crown or piston skirt.

Polycyclic aromatic hydrocarbon (PAH) A hydrocarbon composed of three or more benzene rings also called polynuclear aromatic hydrocarbons.

Polymer A material built up of smaller units (monomers).

Polymerisation The chemical union of two or more smaller molecules which react to form larger molecules (polymers) that contain many repeating units.

Polysaccharide A carbohydrate composed of many monosaccharides.

Prechamber Small chamber in which combustion is initiated prior to delivery into the main combustion chamber of an engine.

Propane C_3H_8, a hydrocarbon gas (at atmospheric pressure) stored in liquid state under pressure. A constituent of LPG.

Propylene C_3H_6, a colourless, unsaturated hydrocarbon gas.

Pyrolysis The breaking apart of complex molecules into simpler units by the use of heat.

Reformulation The control of refinery inputs and conversion processes to obtain fuels meeting certain specifications.

Reformulated gasoline A variety of improved (unleaded) petrol blends which are being developed to improve air quality. Typically RFGs have oxygenates added and reductions in volatile compounds — see chapter 2.

Regenerative braking Braking in which the loss of kinetic energy from braking is stored and subsequently fed back to provide tractive effort.

Research octane number *See* **octane number**.

Rigid truck A non-articulated truck.

Saccharification Conversion of complex polysaccharides into simple sugar molecules.

Slurry A free-flowing suspension of fine solid material in a liquid.

Splash blended A procedure used for blending ethanol and gasoline in the tanker truck.

Steam cracking High-temperature cracking of petroleum hydrocarbons in the presence of steam.

Straight-run gasoline This is the simplest grade of petrol, derived from naphtha, consisting of hydrocarbons having a straight carbon chain structure.

Surfactants A surface active agent that reduces the surface tension of liquids, or reduces interfacial tension between two liquids or a liquid and solid.

Swirl chamber Small chamber or cavity formed in cylinder head of an engine to promote swirl (which improves mixing and heat transfer).

Synthesis gas A mixture of gases prepared as feedstock for a chemical reaction.

T90 Temperature at which 90 per cent of a fuel evaporates.

TAME Tertiary amyl methyl ether, an oxygenate.

Toluene Colourless, aromatic liquid derived from coal tar or from the catalytic reforming of petroleum.

Torque The product of a force and the perpendicular distance from its line of action to the axis of rotation. A measure of the turning power of an engine shaft.

Transesterification Conversion of an organic acid ester into another ester of that same acid.

Triglyceride A naturally occurring ester of normal fatty acids and glycerol. It is used in the manufacture of edible oils and fats.

Turbocharger Induction pressure charger normally comprising an exhaust gas driven air turbine driving an air compressor.

Turbocompounding A system employing a second turbine in a vehicle's exhaust, downstream of the turbine used to compress the intake mixture, which captures residual energy from the exhaust and feeds it, via a fluid coupling, to the crankshaft, thus increasing the energy efficiency of the engine.

Valve seat recession A form of wear to the valve seats in internal combustion motors.

Vapour lock The premature vapourisation of fuel in the fuel supply system.

Variable fuel vehicle *See* **flexible fuel vehicle**.

Viscosity Property of a fluid by which it resists movements or change in shape; opposition to flow.

Xylans One of the major polysaccharide components of hemicellulose which upon hydrolysis yields xylose.

Xylose A pentose sugar found in many woody materials.

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Abbreviations

ABARE	Australian Bureau of Agricultural and Resource Economics
ABS	Australian Bureau of Statistics
AEVA	Australian Electric Vehicle Association
AFR	*Australian Financial Review*
AGA	Australian Gas Association
AGL	Australian Gas Limited
AGPS	Australian Government Publishing Service
AGSM	Australian Graduate School of Management
AIA	Automotive Industry Authority (Australia)
AIP	Australian Institute of Petroleum
ALPGA	Australian Liquefied Petroleum Gas Association
ALPGI	Australian Liquefied Petroleum Gas Industry
AQIRP	Auto/Oil Air Quality Improvement Research Program
ARRB	Australian Road Research Board
BP	British Petroleum Pty Ltd
BRW	*Business Review Weekly* (Australia)
BTCE	Bureau of Transport and Communications Economics (Australia)
BTE	Bureau of Transport Economics (Australia)
CFR	*Clean Fuels Report,* Colorado, USA
CNI	Confederacao Nacional das Industrias (Brazil)
CRCNPT	Canadian Royal Commission on National Passenger Transport
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CSR	CSR Limited
DASET	Department of Arts, Sport, Environment, Tourism and Territories (Australia)
DOF	Department of Finance (Australia)
DPIE	Department of Primary Industries and Energy (Australia)
DTC	Department of Transport and Communications (Australia)
DTI	Department of Trade and Industry, (UK)
EPA	Environmental Protection Authority

EPRI	Electric Power Research Institute (USA)
ERDIC	Energy Research, Development and Information Centre (Australia)
ESAA	Electricity Supply Association of Australia
ESCAP	Economic and Social Commission for Asia and the Pacific
ESD	Ecologically Sustainable Development (Australia, Committee on)
FORS	Federal Office of Road Safety (Australia)
Gafcor	Gas and Fuel Corporation of Victoria, Australia (trading name)
IANGV	International Association for Natural Gas Vehicles
IC	Industry Commission (Australia)
IEA	International Energy Agency
IES	Intelligent Energy Systems Pty Limited
IPCC	Intergovernmental Panel on Climate Change
ISC	Inter-State Commission (Australia)
nd	Not dated
NELA	Nelson English, Loxton & Andrews, Pty Ltd
NERDP	National Energy Research and Demonstration Program (Australia)
NGAC	National Greenhouse Advisory Committee (Australia)
NGV	Natural gas vehicle
NIEIR	National Institute of Economic and Industry Research (Australia)
NRC	National Research Council (USA)
NRMA	National Roads and Motorists' Association (Australia)
NRTC	National Road Transport Commission (Australia)
NSW	New South Wales
NSWDME	New South Wales Department of Minerals and Energy
OECD	Organisation for Economic Cooperation and Development
OTA	Office of Technology Assessment (USA)
PSA	Prices Surveillance Authority (Australia)
RACV	Royal Automobile Club of Victoria, Australia
SAE	Society of Automotive Engineers
SEC	State Electricity Commission of Victoria, Australia
SERI	Solar Energy Research Institute (USA)
STA	State Transit Authority of NSW
TPC	Trade Practices Commission (Australia)
USEPA	United States Environment Protection Agency
VGFC	Victorian Gas and Fuel Corporation (Australia)

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ABBREVIATIONS

$	Australian dollars unless otherwise stated
4WD	Four wheel drive
ABARE	Australian Bureau of Agricultural and Resource Economics
AC	Alternating current
ACT	Australian Capital Territory
ACTION	Australian Capital Territory Internal Omnibus Network
ADO	Automotive diesel oil
ADR	Australian Design Rule
AEVA	Australian Electric Vehicle Association
AFV	Alternative fuel vehicle
AFR	Australian Financial Review
AGA	Australian Gas Association
AGL	Australian Gas Light Company
AGSM	Australian Graduate School of Management
AIA	Automobile Industry Authority
ALABC	Advanced Lead-Acid Battery Consortium
ALSOC	Australian LNG Ship Operating Company
ALPGA	Australian LPG Association
ALPGI	Australian Liquefied Petroleum Gas Industry
AN	Australian National (railways)
AQIRP	Auto/Oil Air Quality Improvement Research Program (USA)
ARCO	Atlantic Richfield Company
AS	Australian Standard
ATAC	Australian Transport Advisory Council
avgas	Aviation gasoline
avtur	Aviation turbine fuel
bhp	Brake horsepower
BHP	Broken Hill Proprietary Company
BP	British Petroleum Pty Ltd
BTE	Bureau of Transport Economics
BTCE	Bureau of Transport and Communications Economics
BTEX	Benzene, Toluene, Ethylbenzene & Xylenes
CARB	California Air Resources Board
CEPA	Commonwealth Environmental Protection Authority
CFC	Chlorofluorocarbon
CH_4	Methane
CIF	Cost including insurance and freight

CIS	Commonwealth of Independent States (parts of the former Soviet Union)
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO	Carbon monoxide
CRTC	Chevron Research and Technology Company
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSR	CSR Limited
dB	Decibel
DC	Direct current
DDC	Detroit Diesel Corporation
DM	Deutschemark
DMC	Direct microbial conversion
DOF	Department of Finance
DPIE	Australian Department of Primary Industry and Energy
DTI	Department of Trade and Industry (United Kingdom)
EFI	Electronic fuel injection
ERDC	Energy Research and Development Corporation
ESD	Ecologically Sustainable Development
EPA	Environment Protection Authority
EPRI	Electric Power Research Institute (USA)
ESAA	Electricity Supply Association of Australia
ETBE	Ethyl tertiary butyl ether
EV	Electric vehicle
Ex	Fuel with x per cent ethanol
FCAI	Federal Chamber of Automotive Industries
FEV	Future electric vehicles
FFC	Full fuel cycle
FFV	Flexible fuel vehicle
fob	Free on board
g	Gram
g/km	Grams per kilometre
Gafcor	Victorian Gas and Fuel Corporation (trading name)
GDP	Gross Domestic Product
GJ	Gigajoule (10^9 joule)
GM	General Motors
GWP	Global warming potential
GWF	Global warming factor
ha	Hectare
HC	Hydrocarbon
HDV	Heavy duty vehicle
HFO	Heavy fuel oil
hp	Horsepower
IANGV	International Association for Natural Gas Vehicles
IC	Industry Commission (Australia)
IC	Internal combustion

ICEV	Internal combustion engined vehicle
ICI	Imperial Chemical Industries Pty Ltd
IDF	Industrial diesel fuel
IEA	International Energy Agency
IES	Intelligent Energy Systems Pty Limited
IPCC	Intergovernmental Panel on Climate Change
ISC	Inter-State Commission
kg	Kilogram
km	Kilometre
km/yr	Kilometres per year
kPa	Kilopascal
kph	Kilometres per hour
kt	Kilotonne
kW	Kilowatt
kWh	Kilowatt hour
L	Litre
LCV	Light commercial vehicle
LDV	Light duty vehicle
LEV	Low emission vehicle
LGE	Litre of gasoline equivalent
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
m	Metre
mg	Milligram
MJ	Megajoule (10^6 joules)
mL	Millilitre (10^{-3} litres)
ML	Megalitre (10^6 litres)
mm^2/s	Square millimetres per second
MPa	Megapascal
MTBE	Methyl tertiary butyl ether
Mx	Fuel with x per cent methanol
nd	Not dated
NELA	Nelson English, Loxton and Andrews
NERD&D	National Energy Research, Development and Demonstration Program
NG	Natural gas
NGV	Natural gas vehicle
NGAC	National Greenhouse Advisory Committee
NGRS	National Greenhouse Response Strategy
NIEIR	National Institute of Economic and Industry Research (Australia)
NMHC	Non-methane hydrocarbons
NMOG	Non-methane organic gases
NO_x	Oxides of nitrogen
NRMA	National Roads and Motorists' Association (NSW)
NRTC	National Road Transport Commission
NSW	New South Wales

NSWDME	New South Wales Department of Minerals and Energy
NZ	New Zealand
N_2O	Nitrous oxide
°C	Degrees Celsius
O_3	Ozone
OECD	Organisation for Economic Cooperation and Development
OEM	Original equipment manufacture(r)
OMHCE	Organic material hydrocarbon equivalent
OPEC	Organisation of petroleum exporting countries
OSAT	Office for the Study of Automotive Transportation
PAH	Polycyclic aromatic hydrocarbons
PSA	Prices Surveillance Authority
PJ	Petajoule (10^{15} joules)
psi	Pounds per square inch
PTCV	Public Transport Corporation of Victoria
RACV	Royal Automobile Club of Victoria
R&D	Research and development
RFG	Reformulated gasoline
RME	Rape methyl ester
RON	Research octane number
RPEV	Roadway powered electric vehicle
rpm	Revolutions per minute
RTA	Roads and Traffic Authority of NSW
RUC	Road user charges
RUEC	Road user and externality charges
SAE	Society of Automotive Engineers
SECV	State Electricity Commission of Victoria
SHF	Separate hydrolysis and fermentation
SI	Spark ignition
SING	Spark ignition natural gas
SO_x	Oxides of sulphur
SO_2	Sulphur dioxide
SPCC	State Pollution Control Commission (New South Wales)
SRI	SRI, formerly Stanford Research Institute
SSF	Simultaneous saccharification and fermentation
STA	State Transit Authority of NSW
STEL	Short-term exposure limit
TAME	Tertiary amyl methyl ether
TEL	Tetraethyl lead, $C_8H_{20}Pb$
TLEV	Transitional low emission vehicle
TLV	Threshold limit value
TPC	Trade Practices Commission
TWA	Time weighted average
UCLA	University of California, Los Angeles
ULEV	Ultra low emission vehicle
UNCED	United Nations Committee for Economic Development

UNSW	University of New South Wales
ULP	Unleaded petrol
UPT	Urban public transport
UK	United Kingdom
US	United States
USA	United States of America
USABC	United States Advanced Battery Consortium
USEPA	United States Environmental Protection Agency
V	Volt
VFV	Variable fuel vehicle
VGFC	Victorian Gas and Fuel Corporation
VKM	Vehicle kilometre
VOC	Volatile organic compound
VRA	Vehicle refuelling appliance
Wh	Watt-hour
W/kg	Watts per kilogram
ZEV	Zero emission vehicle