Alternative Transport Fuels

Beryl Cuthbertson
Project Leader
Bureau of Transport and
Communications Economics

Neil Kelso
Senior Research Officer
Bureau of Transport and
Communications Economics

Ken Thomas
Research Officer
Bureau of Transport and
Communications Economics

Abstract:

Alternative fuels have the potential to reduce greenhouse gas emissions from transport, and to reduce urban air pollution and noise. This paper reviews recent research findings on emissions from these fuels, as well as safety, costs and other aspects relating to both vehicles and fuels, which influence market acceptance. New motor vehicle technology optimised to account for the characteristics of each fuel would need to be implemented to achieve maximum benefit. The effects of taxes and charges on fuel price are noted. The paper emphasises that any decision about whether to promote or encourage the take-up of alternative fuels is rendered extremely difficult in the environment of changing technology, changing vehicle emission standards, developments in gasoline vehicle fuel efficiency, and the effect of these on new vehicle costs.

The views expressed in this paper are those of the authors, and do not necessarily represent those of the Bureau of Transport and Communications Economics.

Contact Author:

Beryl Cuthbertson
Bureau of Transport and Communications Economics
GPO Box 501
CANBERRA ACT 2601

Telephone: (06) 274 7453 Fax: (06) 274 6816

Introduction

This paper reviews the potential for the introduction of 'new' fuels in road transport, and the effects this would have on greenhouse gas emissions and local air pollution.

If alternative fuels (A/Fs) are to be widely used, they must be technically feasible, cost competitive (taking taxes and charges into account), and be accepted by the market. Cost competitiveness will be influenced, in part, by the extent to which the environmental costs of burning various fuels are incorporated into their respective market prices. Failure to charge fully for environmental and other costs resulting from fuel use will result in the 'wrong' fuels being bought. It is also likely that lack of knowledge about A/F options may preclude optimum market outcomes.

Use of A/Fs has implications beyond the environmental effects: reduced reliance on petroleum-based fuels would improve Australia's energy security, and there would be balance of payments effects given that domestically sourced A/Fs could replace imported oil and petroleum products, and perhaps generate exports of fuels and A/F technology. However, wider use of A/Fs would need to overcome the barrier presented by the existing infrastructure for petroleum based fuels, and would not be easy.

Reformulated gasoline

Reformulated petrol is being developed for the North American market because of legislation aimed at improving urban air quality. This unleaded 95 octane fuel will have reduced aromatics and sulphur, and contain 15% by volume of methyl tertiary butyl ether (MTBE) derived from methanol. Emissions of carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx) will be lower than for current petrol. Noxious emissions could be about 10% less than those from current Australian blends (based on Sinor *et al* 1992). Full fuel cycle greenhouse emissions per kilometre from reformulated petrol could be about 5 per cent lower (tailpipe emissions 9% lower) than from current petrol, even though slightly more fuel would be used. CO_2 emissions would be unchanged: other greenhouse gases would be reduced (IEA 1992).

Estimates of the price of reformulated petrol range between 1.4 and 6 cents per litre more than the current gasoline price, after accounting for lower energy content per litre (based on Sinor *et al* 1992). Replacing conventional by reformulated gasoline could be expected to result in a reduction of roughly 7% in the level of noxious emissions from urban transport and about 2.5% in transport sourced greenhouse emissions. Were reformulated petrol to be introduced in Australian cities, the relative emissions advantages of alternatives to petrol would of course be reduced.

Liquified petroleum gas (LPG)

LPG has been used as a transport fuel in Australia since the 1970s, particularly in taxis, and in vehicles which operate indoors (such as fork-lift trucks), and there is already an extensive distribution network. LPG has a price advantage over petrol, currently around 40 cents per litre, being free of excise charges. At representative fuel efficiencies for converted vehicles (Caldwell 1989), this price differential gives a

saving of about 3 cents per kilometre, and would mean a payback period of only 3 years on a conversion cost of $2000 at average car utilisation rates (Haley 1990).

The rate of growth in LPG use in road transport has been high over the past decade (18% pa), but LPG currently accounts for only 2.5% of road transport energy use, and it is expected to account for only 3% in 2005 (ABARE 1991). Since engine technology and refuelling infrastructure already exist for LPG, and given a short pay-back period, why is there not greater use of this alternative?

Though there is a large number of auto LPG outlets in Australia, there is poor availability in remote areas. Also, gas conversion of vehicles results in reduced range (with a similar size tank), power (about 3-4% for a *Commodore* or *Falcon* [(Caldwell 1989]) and boot space (a particular problem for small cars). The average time to recover conversion costs would be more than three years for vehicles with a low rate of fuel consumption or low annual VKT. Perhaps more importantly, the price advantage of LPG over petrol is not guaranteed: it relies on the Federal Government's not imposing sales tax or excise on LPG, or removing excise from petrol or diesel. At current oil prices, if LPG incurred an excise charge equivalent to that of petrol (in cents per litre), its operating cost advantage would be negated. A price advantage would remain, however, if externalities were costed and included in fuel prices.

The IEA (1992) estimates that the full fuel cycle greenhouse emissions from automotive LPG (a propane/butane blend) are 15% below those of petrol: Wilkenfeld (1991) estimates 18%. Urban emissions of CO are around half those from gasoline. HC and NO_x emissions are similar to those from gasoline. Sergeant (1991) advocates an increased role for LPG, perhaps more than doubling current LPG vehicle use. He suggests that affordable original equipment manufacture vehicles are needed to increase the viability of LPG (yet an LPG car introduced into Australia some years ago was not a commercial success). Doubling the penetration of LPG vehicles would lower current total transport greenhouse emissions by around 0.3%, and urban noxious emissions by roughly 1%.

Supply factors are important. About two-thirds of Australia's LPG supply is recovered during oil and natural gas production, the rest from oil refining. Australian production of naturally occurring LPG is forecast to decline over the years (reserves are 45 years at current annual production rates) and to meet domestic demand for all uses, LPG imports are projected to increase substantially (ABARE 1991). The scope for saving emissions by switching LPG from other uses to cars needs to be explored, but is likely to be limited. Importing LPG could be a possibility, but the transport costs would add around 20% to the fob price (about 7% to the retail price).

Diesel

Wilkenfeld (1991) has estimated total greenhouse gas emissions from cars in grams of CO_2 equivalents per km as 201 for diesel and 241 for petrol, on a full fuel cycle basis (emissions from oil well to tailpipe). For light duty vehicles (LDVs), the IEA (1992) estimates that diesel vehicles will have a greenhouse emissions advantage of 18.7% in North America and 20.2% in Europe in 2005, compared to a vehicle using *reformulated* petrol (full-fuel-cycle basis, including a factor accounting for the longer average lifetime of a diesel engine). This is similar to Wilkenfeld's results.

The IEA (1992) notes that since a fair proportion of the greenhouse advantage of diesel arises from lower relative emissions of HC and CO, tighter emissions regulations for petrol-powered cars would reduce this advantage significantly. In terms of CO_2, the IEA estimates only an 8% advantage for diesel (Wilkenfeld derives 7%).

Considering urban emissions, a new diesel car would have over 60% lower CO and HC emissions than a comparable gasoline vehicle (IEA 1992), but particulate emissions are a growing health concern. The Advisory Committee on Vehicle Emissions and Noise (ACVEN) is currently investigating standards for particulates, CO, HC, and NO_x for diesel LDVs and trucks. Though these will not apply to diesel passenger cars, if use of these cars were to increase, their particulate emissions would have to be considered. Progressively tighter constraints on particulate emissions from diesels would eventually result in a more energy-intensive diesel fuel production process, with a consequent lowering of diesel's greenhouse advantage.

Stricter emission standards for vehicles could be expected to influence vehicle costs and total emissions from different fuels, taking into account the greenhouse impact of stricter standards on vehicle fuel efficiency. It is clearly difficult to predict the future emissions rankings, let alone the effects on vehicle costs.

Refinery configurations and feedstocks constrain the output of diesel (and LPG) in Australia, and therefore the substitution potential of diesel for gasoline (NSWDME 1990). Demand for diesel is projected to increase by some 70% in road transport from 1988 to 2005 (ABARE 1991), so that making diesel available for LDVs may require the substitution of CNG or alcohol fuels for diesel in heavy vehicles. Scope for this may be limited, unless actively supported by government policy. Using the natural gas directly in LDVs would seem a preferable option, especially as there are major health concerns over particulate emissions, which are primarily from diesels. For this reason, importing diesel may not be warranted, even if the economics were favourable.

Alcohol fuels: ethanol and methanol

Ethanol or methanol can replace petrol as pure ethanol (E100) or methanol (M100), can be used in blends of 3 to 90% alcohol with gasoline, or can be combined with isobutylene to form MTBE or ethyl tertiary butyl ether (ETBE). These act as octane enhancers and as oxygenates reducing CO emissions in vehicle exhausts (OTA 1990).

Use of ethanol as a diesel substitute is at an early stage of development (NSWDME 1990). Alcohols can be used as diesel fuel extenders or, with extensive engine adaptations, in larger proportions (IEA 1990). Demonstrations of alcohol fuels in buses and/or trucks are being conducted in Canada, Germany, Japan, Sweden, NZ and the US (IEA 1990). In Australia, APACE Research Ltd has developed an ethanol and diesel emulsion (diesohol) which, if the emulsion contains less than 25% ethanol, can be used in unmodified diesel engines. An unmodified Mack truck using diesohol (15% ethanol) had the lowest 'greenhouse gas index' in the 1992 Energy Challenge.

Ethanol is currently manufactured from biomass, via fermentation of sugars. In laboratories it has been made from lignocellulosic fractions of crops. Ethanol can also be made from petroleum and natural gas. Methanol can be produced from biomass, natural gas or coal, but with widely varying full fuel cycle greenhouse gas emissions.

Vehicle technology

In current technology gasoline engines, alcohol blends of up to 10% seem to be a feasible option, though even these will cause some drivability problems -vapour lock, and in older vehicles, deterioration of fuel system components, including clogging of

the fuel filter (NSWDME 1990). High alcohol content fuels are not suited to retrofitted vehicle programs. Higher cost new technology vehicles will be required if fuels with higher alcohol content or pure alcohol are to be used. These vehicles could be optimised to the fuels' combustion characteristics to provide greater efficiency and emission benefits. High alcohol content fuels can contaminate engine oils causing corrosion of engine components, especially on cold starts and short trips. Starting difficulties in cold conditions may also be experienced. A blend with 15% gasoline would help, although further work on cold starting is still required. Control of aldehyde emissions is also needed.

Flexible or variable fuelled vehicles (VFVs) have been developed to assist the transition from gasoline to alcohol fuels. VFVs sense the fuel blend in use and automatically adjust the engine to run on any combination of fuel. VFVs share some of the problems of single-fuel vehicles, as well as having some of their own. Formulation of suitable lubricating oils may be more complex. Emission certification would be required for the full range of fuels used and catalysts would need to be effective over a wide range of exhaust compositions (Magasanik *et al* 1990). VFVs are more complex and costly, and VFV engines cannot be optimised for alcohol fuels.

Emission of greenhouse gases

The potential of methanol or ethanol fuels to reduce greenhouse gas emissions is dependent on the source of the feedstock (Table 1), as well as vehicle technology. With biomass feedstock, CO_2 produced during combustion is re-absorbed from the atmosphere during plant growth, although some additional CO_2 emissions arise from farming and processing the crop (Watson 1991). Emissions depend on the crop grown, the process fuel and release of greenhouse gases from the soil above natural levels. Also, special energy crops may simply replace existing CO_2 absorbing plant biomass. Production of ethanol from lignocellulose via technologies currently under development will be needed if significant greenhouse gas emission improvements are to be achieved relative to gasoline fuel. Ethanol from corn fields (as in the US) using coal generated electricity for processing will not improve emissions. Denitrification of fertilisers applied to the crop can also contribute to emissions (Sperling and De Luchi 1991).

Methanol from natural gas (the most cost effective source) provides at most a 3% reduction in greenhouse gas emissions over gasoline in present technology vehicles. In Australia, Watson (1991) has suggested that mandatory implementation of M85 fuel (from gas) in the year 2000, could by the year 2015 achieve a 5% reduction in greenhouse gas emissions from the vehicle fleet assuming some of the vehicles would be optimised to the combustion characteristics of the fuel.

Noxious emissions

In urban areas the principal pollutants from motor vehicles include CO, sulphur dioxide, NOx, HC, particulates and lead. The effect of alcohol fuels on exhaust emissions of non-greenhouse gases relative to gasoline is mixed, often situation specific and influenced by the state of prototype development. Increasing the alcohol content of the fuel, under most circumstances, will result in reductions of CO, aromatic compounds, SO_2, and in diesel vehicles, particulates, while aldehyde and alcohol emissions increase. Any change in atmospheric effects from the use of VFVs

Table 1 Greenhouse gas emissions for light and heavy duty vehicles using M100 or E100 relative to reformulated gasoline and diesel fuels.

Fuel type and source	*Percentage change in life-cycle emissions (grams per kilometre CO2 equivalent)*[a]			
	Present[b]		*Future*[c]	
	LDV[d]	*HDV*[e]	*LDV*[d]	*HDV*[e]
Ethanol, lignocellulose[f]	-72.6	-71.3	-73.1	-71.6
Ethanol, corn with coal	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, lignocellulose[f]	-18.4	2.1	-60.0	54.2

Notes a. Time horizon of 100 years
b. Present refers to current technology vehicle.
c. Future refers to high efficiency vehicles optimised for alcohol fuel.
d. LDV, light duty vehicle, gasoline fuel.
e. HDV, heavy duty vehicle, diesel fuel.
f. Lignocellulose from plantation forest or plant residue
na data not given.

Source Sperling and De Luchi (1991)

depends on the composition of organic compounds in the exhaust and how each reacts in the atmosphere to form smog (Anker-Jonhson and Schwochert 1990). Because of differences in chemical composition of volatile organic compounds (VOCs) in exhaust emissions of alcohol and gasoline fuels, comparisons of VOC and organic material hydrocarbon equivalent (OMHCE) emissions (Table 2), based simply on total mass of all compounds, do not allow meaningful comparison of relative atmospheric effects.

In regard to evaporative emissions blends of alcohol and gasoline have a greater volatility than straight gasoline (OTA 1990). The effect of this increase in VOC on ozone production is thought to be counterbalanced by the reduction in CO exhaust emissions associated with using alcohol blends (OTA 1990). The net effect of a 10% ethanol blend is a HC emission increase due to increased fuel volatility. Increased emissions of NOx (5-6%) and aldehydes have been reported from US vehicles using alcohol blends (NSWDME 1990). Extrapolations from emission test performances to production vehicles also require caution (OTA 1990). For diesel engines using diesohol fuel, APACE (1992) claim reductions of up to 10% in NOx emissions, 40% in CO emissions and over 50% in particulate emissions.

Costs

Vehicle costs: Magasanik *et al* (1990) estimated increased production costs of between $500 to $2000 for VFVs. Because ethanol is less corrosive then methanol the increment to vehicle production costs would be less than for methanol.

Fuel production costs: To be cost competitive, large-scale production from lignocellulose from the technologies currently under development will be necessary.

Table 2 Exhaust emissions of noxious gasses

Fuel[a]	*Vehicle*	*Emission components (grams per km)*						
		VOC	*OMHCE*[b]	*CO*	*NOx*	*Formal-dehyde*	*Benzene*	*1,3-Butadiene*
M0	Gasoline[c]	na	0.137	1.73	0.37	0.0011	0.0067	0.0005
	FFV/VFV[d]	na	0.18	1.75	0.29	0.0017	0.0091	0.00075
	Corsica[e]	0.74	na	1.43	0.124	0.0025	na	na
M10	FFV/VFV[d]	na	0.17	1.61	0.25	0.0016	0.0073	0.00062
M25	Corsica[e]	0.174	na	1.68	0.124	0.0037	na	na
M50	Corsica[e]	0.137	na	1.24	0.124	0.0075	na	na
M85	FFV/VFV[d]	na	0.11	1.20	0.31	0.0092	0.0015	0.00006
	Corsica[e]	0.162	na	1.49	0.124	0.0155	na	na

Notes a. Mx denotes a blend of x% methanol and (100-x)% gasoline.
b. OMHCE excludes the nonreactive oxygen portion of the organic compounds.
c. US 1989 gasoline vehicle industry average.
d. average from a fleet of pre 1990 prototype flexible/variable fuel vehicles
e. General Motors Corsica methanol variable fuelled vehicle.
na. data not available.

Sources Anker-Jonhson and Schwochert 1990, Sinor *et al.* 1992.

In Australia, scenarios are confined to using biomass feedstocks. Watson (1991 using Stewart *et al* 1979) estimated that agriculture would not be able to support more than anE15 petrol/ethanol mix (from the non-lignocellulosic fraction), based on cultivation of new land for a range of energy crops, taking into account soil and climatic constraints. Use of the lignocellulosic fraction, which would increase the quantity of ethanol available, was not considered in the analysis. Potential crops for ethanol production include sugar cane, sugar beet, cassava, artichokes, sweet sorghum and other cereal grains.

When lignocellulose conversion technology is fully developed a far wider range of materials including crop, forest and sawmill residues may be usable. APACE (1992) has suggested that growing crops for ethanol production be ultimately integrated into revegetation programs. Growing tree crops for ethanol production in a medium term rotation on degraded farm land could help stabilise land degradation and may provide farmers with an economic rationale for looking after presently unproductive land.

A consultant's report to the NSW Dept of Minerals and Energy (NSWDME 1990) estimated production costs of ethanol from sugar cane and sorghum to lie in the range of 92 to 115 cents per litre of gasoline equivalent [LGE] for sugar cane, and from 84 to 107 cents per LGE for sorghum. Costs in that study were influenced by feed stock prices, process technology, finance, and 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 $1.66 LGE (NSWDME 1990).

Using a lignocellulose process still at the laboratory stage and assuming full by-product credits, Rogers (1990) estimated ethanol could be produced for 54 to 61 cents per LGE. US researchers have cited costs as low as A$0.32 per LGE from yet-to-be commercialised lignocellulose technologies (Lynd *et al* 1991 in Sperling and De Luchi 1991). Australian researchers hope to be able to use acid or enzymatic hydrolysis of lignocellulose for a factory-gate price of 14 to 24 cents per litre, (APACE 1992).

In Australia, natural gas would be the most economically feasible option for methanol production. A NSWDME (1990) consultancy study estimated costs of methanol produced from pipeline gas at 33 to 44 cents per LGE at Sydney, Wollongong or Newcastle (a world scale plant producing 2500 tonnes per day). Methanol imported to the Sydney region from Dampier using NW Shelf gas was costed at 33 to 44 cents per LGE (4 world scale conventional plants producing 10,000 tonnes per day in total). Costs given in the study are influenced by projected natural gas and technology costs, and it is not known at this stage whether larger scale production would lower costs. Methanol imported by tanker from overseas was assessed at costing 33 to 39 cents per LGE.

Costs of distribution: Difficulties with the distribution of neat ethanol or ethanol blends, arising primarily from the solvency effects of ethanol and ethanol's affinity for water, may mean additional distribution costs. If ethanol were distributed via the existing gasoline system there would be the potential for water contamination throughout the entire process (NSWDME 1990). Ethanol can dissolve accumulated substances in pipelines, storage tanks and other components of the distribution system that are insoluble in petrol (NSWDME 1990), leading to impurities in the fuel.

Methanol is water soluble and corrosive to some materials currently used in present distribution systems (OTA 1990), and has only half the energy content of gasoline thus requiring more transport infrastructure to move an equivalent (on an energy basis) amount of fuel. It is possible that the current infrastructure of pipelines, storage tanks and road tankers may not be compatible with methanol, and that extensive duplication or modification of existing equipment would therefore be required (OTA 1990).

Safety

The safe use of alcohol fuels will require the incorporation of denaturants to deter deliberate human ingestion, and substances to make the flames from alcohol fires more visible, as well as a public education programme and training for people who regularly handle alcohol fuels. Accidental ingestion could be reduced by fitting anti-siphoning devices to fuel tanks.

Natural gas

Natural gas may be used as a transport fuel in either compressed or liquified form (CNG or LNG). Natural gas vehicle (NGV) technology is fairly well developed, and development is proceeding on a wide front in Australia and elsewhere. Natural gas is already available in large quantities in Australia, and the backbone of a distribution system is in place. Australia's known gas reserves contained almost 4 times the energy content of its oil reserves in 1988. DPIE (1991) estimated that natural gas reserves exceeded 50 years at 1991 production levels.

The Australian Gas Association (AGA) has developed its '*10/10/35*' plan for NGVs. This strategy involves reaching a target of 10% penetration of fuel sales for road vehicles (or about 340 000 NGVs) in 10 years, at a 'pump' price of 35 cents per cubic metre. In energy content, a cubic metre is equivalent to 1.09 litres of petrol or 0.98 litres of diesel. In Australia, initial interest in NGVs has been directed to replacing diesel-powered depot-based buses and trucks with dedicated NGVs. NIEIR (1988) estimated that use of NGVs could replace about 2500 ML of oil in 2003 valued at some $700m (in

1987 dollars), under a scenario involving about one-sixth more vehicles than the AGA *10/10/35* plan. By comparison, in 1987-88 Australia imported about 13 000 ML of crude oil, other refinery feedstocks and petroleum products, and exported about 9000 ML.

Emissions

Widespread use of NGVs could have significant environmental implications: globally in terms of greenhouse gas emissions; and locally, in terms of air pollution and vehicle noise in urban areas. Wilkenfeld (1991) estimated full fuel cycle greenhouse emissions for cars, in grams of CO_2 equivalents per km, of 200 for CNG, 201 for diesel and 241 for petrol. For LDVs, the IEA (1991) estimated that, while CNG had lower tailpipe emissions than either petrol (by 18%) or diesel (by 10%), greenhouse emissions from fuel production, distribution, compression and vehicle manufacture negated the greenhouse advantage over diesel. An advantage of about 15% over petrol remained. In heavy vehicles, Wilkenfeld (1991,142,143) 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....'. The AGA (1990, p1882) stated that there appeared to be no significant greenhouse advantage in replacing diesel with natural gas.

The Victorian Gas and Fuel Corporation (VGFC) considers that for NGVs to have a significant effect on greenhouse emissions, they would have to penetrate the car fuel market (VGFC 1991 personal communication). Otherwise, the main environmental effects would be on local air quality and noise from use in trucks and buses. NGVs have the potential to reduce certain noxious emissions significantly, such as oxides of sulphur (from imported crudes), HCs (hence photochemical ozone and smog) and particulates. NOx emissions may be similar to those from petrol.

Methane, the principal component of natural gas, has a radiative forcing greenhouse effect about 16.5 times that of CO_2, by weight (Pearman 1989). If there were to be significant fugitive losses, this would greatly reduce (or negate) the advantage which NGVs could yield in terms of tailpipe emissions. The VGFC considers that fugitive losses are concentrated in the old town-gas reticulation systems, with effectively no fugitive losses from new lines to natural gas refuelling stations.

Practicality of NGVs

Major concerns about the practicality of NGVs are their limited range and the availability of refuelling facilities. Space, weight and cylinder/tank cost limitations preclude fitting the gas capacity required to match the range of petrol or diesel vehicles. Loss of power and carrying capacity, as well as refuelling times and availability of service facilities are also factors to be considered. With suitable design and installation standards, safety should not be a major concern. Safety devices are available to prevent cylinders from exploding. Merz (1991) considers that, although there are only limited data, natural gas has a good safety record.

The car of today, if converted to natural gas/petrol dual fuel use would be less efficient than a purpose-designed natural gas engined vehicle. A future car would be designed primarily as an NGV, but with a secondary ability to use petrol in a 'limp home' mode. If for greenhouse reasons it were decided to encourage the widespread use of NG cars, then it would seem desirable to encourage their manufacture, vehicle conversions being less efficient than purpose-designed NGV engines. The International Association for Natural Gas Vehicles (IANGV 1990) suggests that the range of a 1.6 litre car will be about 160 km with a 60 litre cylinder, (dual fuel), or about 380 km, (dedicated NGVs), with two 60 litre cylinders, about three-quarters of the range on petrol. One operator of NGV taxis undergoing trial in Goulburn found range a problem and has since reverted to LPG fuel (1992 personal communication).

Engines in NGV trucks and buses may be either dual-fuelled diesel engines using a pilot supply of diesel to initiate ignition of the natural gas, or diesel engines converted to spark ignition and running solely on natural gas. Dual fuel engines in buses have achieved 90 to 95% gas substitution for diesel at high loads; in trucks, about 80 to 85%. Gas substitution at idle is zero, and increases with load, the overall average for trucks being about 60% (Yorke 1991). Yorke (1991) considers that the state of development of conversions of truck engines for natural gas is two to three years behind that for buses, in part because of the greater complexity of truck engines, with turbochargers and aftercooling now normal. Merz (1991) points out that microprocessor engine management systems, now common on cars, are only beginning to be considered for trucks. Spark ignition natural gas engines are currently 3 to 5% less efficient than diesel engines, but the efficiency of fully developed engines should match diesel engines (Yorke 1991). The lean-burn spark ignition natural gas engine developed by Gafcor and Bosch reportedly has a thermal efficiency of 37%, close to that of the same engine in diesel form, and some 5% better than overseas natural gas engines (Clifford 1991). Lean-burn engines will emit less NOx, HCs and soot, and should be available by 1993.

Merz (1991) considers that the maximum practicable range of a CNG heavy truck is about 500 kilometres, considering the weight, cost and space required for gas storage. Yorke (1991) gives a cost of A$20,000 for the cost of cylinders (including mounting brackets) with a CNG capacity of 1600 litres (equivalent to about 300 litres of diesel), for a (full gas) heavy truck with a range of 600km. NELA (1991) estimate a weight penalty of almost 1.3 tonnes for an articulated NGV truck with a range of 775km, which would reduce payload if trucks are customarily operated close to axle load limits.

NGV costs

Investment in CNG refuelling facilities for the general public would require assurance of significant penetration of the car, taxi and light commercial vehicle market. Cars, on average, perform low annual kilometres compared to commercial vehicles, and acceptable payback periods on conversion expenses for most light vehicles may rely on continued exemption from excise or other taxes.

A 'chicken and egg' or 'VHS/Beta' problem arises: given the limited range of NGVs, and the cost and refuelling times of home refuelling appliances, there may not be significant penetration of the light vehicle market until a network of public refuelling facilities exists. The VGFC considers that to make a significant penetration of the car market, there would need to be 400 NGV refuelling stations in Victoria alone (VGFC 1991 personal communication). The AGL sees home refuelling as making better use of reticulation infrastructure. The average vehicle would use around 90GJ per year: average NSW household use is about 20GJ per year.

The VGFC has introduced a series of fully self-contained modular NGV fuelling stations for depots. The VGFC and AGL are investigating introducing NGVs into line-haul trucking in Australian inter-city corridors. Acceptable payback periods on conversion costs (less than 2 years, according to Gafcor (1988), or 3 years on average according to

Merz 1991) are available for buses using gas supplied at industrial rates from depots (NIEIR 1988) and for articulated trucks using gas supplied at the *10/10/35* price and travelling typical distances per year (NELA 1991). For rigid trucks only large high-mileage units might be converted.

Electric vehicles (EVs)

Recent development of EVs has been spurred on by the 1990 California Air Resources Board regulations, developed in response to the deterioration in urban air quality due to internal combustion engined motor vehicles. These regulations require that 2% of new cars and light trucks sold in 1998 must be zero-emission vehicles (ZEVs), growing to 10% in 2003. This would provide a market for over 120 000 EVs in 2003. Some other US states have announced that they will adopt the Californian ZEV program (Purcell 1992). Current EV research is aimed at increasing the electric vehicle's limited range by improving battery storage capacity, battery life, motor and drive train efficiencies, and reducing vehicle drag, rolling resistance and weight.

Batteries

Table 3 shows battery energy densities (of which vehicle range is a function) and power densities (of which acceleration and hill-climbing are functions). Rand (1992) in surveying battery types for EVs concluded that the lead-acid battery was 'the obvious, if not the only' battery for medium-term, large-scale production. An international consortium has recently been established to develop an advanced lead-acid battery for the EV market, with a target energy density of 50 watt-hr/kg (Deshpande 1992).

The nickel-iron 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 1992). Nickel-cadmium (Ni-Cad) batteries are used by Nissan in its *FEV* car, fully rechargeable in 15 minutes, and in the Japanese *IZA*, for which is claimed a range of 548km at a steady 40kph (Ishitani 1992). Fiat's *Panda Elettra* gives 30% better range in city use with NI-Cad batteries than with lead-acid batteries (Rand 1992), although at a significantly higher cost. However Rand (1992) considers that cadmium-based systems should not be considered on environmental grounds due to disposal problems of highly toxic cadmium. Matsushita has developed a nickel-hydride battery vehicle for which it claims 2.8 times the range given by lead-acid batteries. BMW's *E2* car, planned for sale in California by 2003, uses sodium-sulphur batteries, as does Ford's *Ghia Connecta*.

An international consortium (ALABC, the Advanced Lead-Acid Battery Consortium) has recently been established to develop an advanced lead-acid battery for the EV market (Deshpande 1992). In the US, the Advanced Battery Consortium (funded jointly by the US Dept of the Environment, carmakers, electricity companies and battery makers) is to investigate three or four battery types. These may include sodium-sulphur, lithium-aluminium/iron-sulphide, zinc-air and lithium polymer (AEVA 1992).

Hybrid powerplants, such as a constant speed internal combustion engine (perhaps running on an A/F) could be used to recharge the vehicle's batteries while driving or to supply power directly during extended running. GM has developed the *HX3* petrol/electric concept car, while Volkswagen have a hybrid diesel/electric vehicle under test. Solar panels mounted on a vehicle (such as on Ford's *Ghia Connecta*, planned for production in the UK this year) could partially recharge the batteries during the day.

Table 3 Battery energy and power densities

	Energy density (Wh/kg)	Power density (W/kg)	Cost[4] (US$/kwhr)	Source
Lead-acid[1]	4 to 40	33 to 176	70 - 130	SEC (1991)
Nickel-zinc[1]	33 to 90	66 to 220	200 - 500	SEC (1991)
Zinc-air[1]	44 to 165	44 to 77	110	SEC (1991)
Nickel-iron[2]	40 to 60	80 to 150	200 -1400	Rand (1992)
Nickel-cadium[2]	53	180	na	Ishitani (1992)
Nickel-hydrogen[2]	60 to 70	300	700 -2000	Rand (1992)
Lithium-chlorine[3]	330 to 440	200 to 400	na	SEC (1991)
Lithium-sulphur[3]	245 to 350	550 to 800	110	SEC (1991)
Sodium-sulphur[3]	175 to 330	200 to 350	110	SEC (1991)

na not available
1. Practical, rather than theoretical, energy and power densities.
2. Current development status.
3. Projected energy and power densities.
4. Source Rand (1992)

Gosden (1990) considered that power for 3,500 km per year might be expected from a roof-mounted solar array in Australia. However, many cities have multistorey car parking or tall buildings: there may not be adequate access to sunlight to justify the additional cost of incorporating solar cells. Gosden (1990) considers that more efficient battery rechargers will be needed to avoid energy losses through overcharging.

Electric vehicle motor technology

Motors capable of high efficiencies for both propulsion and regeneration are essential for maximum range to be obtained. Current research is centred on alternating current (AC) as opposed to direct current (DC) motors, both permanent magnet and induction types. The AC motor has lower costs, higher speed capabilities and reduced maintenance requirements, though AC motors require controllers which are more complex and currently more expensive than those for DC motors. Together, AC motors and their controllers are similar in efficiency to high performance advanced technology DC motors (Bullock 1989), and the controllers are becoming more efficient and cheaper.

Emissions of greenhouse gases

Comparing emissions from electric and gasoline powered vehicles can be difficult. Usage patterns and carrying capacities differ. Commercial vans in urban delivery service, where vehicle range is less of a concern, may provide a valid comparison. The EPRI (1989) compared one medium and one small electric van (G-van and TEVan) with two petrol vans of equal freight capacity to the EVs. For the petrol vans, greenhouse gas emissions included refinery operations and fuel distribution: EV emissions included those from power stations, mining and transport of fuel, and electricity distribution. The petrol vans emitted 684 and 553gCO_2/km: emissions for the comparable EVs using power from US coal-fired stations were 677g (G-Van) and 389g (TEVan) CO_2/km (EPRI 1989).

Comparisons between electric and petrol vehicles using energy consumed per tonne-kilometre of freight (tkm), or per passenger kilometre (pkm) may be more appropriate. Unfortunately these data are usually not available for EVs. Gosden (1990) averaged the specific energy consumption of five EVs (four vans and one passenger car) to arrive at a specific energy consumption of 131 Wh/tkm, using electricity producing 1080g CO_2/kWh as supplied to the consumer. From these data, based on currently available technology, an EV would produce 141g CO_2/tkm. A 1,000kg petrol vehicle generating at the tail pipe 2.4 kg CO_2 per litre (L) of fuel consumed would need to consume under 5.9 L/100 km to have lower greenhouse emissions than Gosden's (1990) average EV.

The GM *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 the *Impact* to have a specific energy consumption of 81 Wh/tkm at a constant 96 kph, giving a CO_2 emission of 87 gm/tkm using Australia's power supply mix, equivalent to a petrol car with an average fuel economy of 3.6 L/100 km. However, GM has produced a petrol-engined concept car, the *Ultralite*, which has a claimed highway cycle consumption of only 2.9 L/100km. No vehicles now on the Australian market 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 L/100 km for the highway cycle (DPIE 1990). The *Charade* and *Swift* have twice the range of the *Impact*, which seats only two adults.

In urban areas, the natural areas of operations for EVs, advanced purpose-designed EVs like the Impact may produce less CO_2 emissions (93g/km) than advanced petrol-powered cars (*Ultralite* is 119g/km). While the Impact is only a 2-seater, and its emissions per seat-km are higher than those of the 4-seat *Ultralite*, the average occupancy of a car on the journey to work is only 1.2 persons (BTCE 1991), and the emissions per actual passenger-km might still be lower than those of the *Ultralite*.

Gosden (1990) compared CO_2 emissions from EVs and NGVs, concluding that if natural gas were to be used to generate electricity, CO_2 emissions would be 27% lower from an EV than from an NGV. However using electricity from the Australian power station mix to supply EVs, it appears that CO_2 emissions would be considerably higher from current EV conversions than from NGVs, but for 'state of the art' EVs (eg *Impact*), they could be 20% lower.

Emissions of noxious gases and safety of electric vehicles

Noxious emissions due 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. Emissions also arise from battery manufacture. Shifting pollution from a diffuse source (many moving motor vehicles) to a point source (power station) may facilitate implementation of pollution controls.

Rajan *et al* (1989) list four safety concerns relating to the operation of EVs which will need to be addressed. 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. Gaseous emissions and their effects are reduced by correct battery charging procedures and adequate ventilation (Rajan *et al* 1989). Safety in an accident or under abnormal battery operation is a particular concern with sodium/sulphur batteries. Major concerns are sodium fires, sodium/water explosions and a runaway sodium/sulphur reaction (Rajan *et al* 1989), each of which can produce toxic gases and other byproducts (Stodolsky 1989).

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).

Electric vehicle costs.

The initial purchase price of EVs may 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% and 225% above *Panda* petrol models (Rogers 1991). The Australian Huntington *Mira* conversion has a quoted price of $16,000 plus sales tax, about twice the price of the petrol *Mira*. There is also the cost of replacing batteries every two to four years. For example, replacement of the battery pack for the *Impact* has been stated to cost about US$1500 every three years. Some schemes have proposed battery leasing arrangements, spreading the cost over the life of the batteries.

The high initial cost of EVs, which in mass production may be 25-50% above the cost of petrol versions, may to some extent be offset by a longer vehicle life and lower maintenance relative to internal combustion engined vehicles. However while the running costs (including battery costs) of EVs are likely to be substantially less than for petrol cars, a very rough comparison of the Diahatsu *Mira* and the Huntington *Mira* EV suggests that the simple pay-back period on the additional capital outlay for the EV would range from 16 years (100% extra cost and 15,000 km pa) to 27 years (100% add-on and 10,000 km pa).

Hydrogen

In the longer-term, hydrogen may become a viable transport fuel, either as a fuel for internal combustion engines, or in fuel cells. The IEA (1992) regards hydrogen only as a long term possibility, and hydrogen fuel cells as a very long term possibility. However, the IEA (1992) points out that, by adding 5% hydrogen to natural gas ('*hythane*'), the level of methane, NOx and CO tailpipe emissions from NGVs could be reduced to levels low enough to meet the California Air Resources Board Ultra-Low Emission Vehicle standards. Were this standard to be adopted in Australia, an approximate calculation suggests that such a reduction in urban emissions could be achieved at a cost of an extra 7% on the natural gas price, based on a recent US price estimate for hydrogen produced by hydrolysis using hydro-electricity.

Carmakers have been experimenting with hydrogen-fuelled internal combustion engined vehicles for some time. Recent demonstration projects include a BMW hydrogen powered car as part of a German project to examine the potential for hydrogen produced by solar-voltaic electricity. 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 1992). The fuel tank of a liquid-hydrogen powered vehicle would, for the same range, need to have about 4 times the volume of a petrol tank, due to hydrogen's low energy storage density.

The energy needed to produce hydrogen fuel in Australia at present, would result in more greenhouse emissions than petrol or diesel fuel use, although the vehicle itself would be 'clean', with no tailpipe CO_2 emissions, although some NOx and N_2O are

produced by the high combustion temperatures (IEA 1992). Only if hydrogen were produced using electricity derived from other than fossil fuels could it contribute to reducing greenhouse emissions, although pressure for low emission cars for urban use, especially in the USA, could encourage production of hydrogen cars. The IEA (1992) estimates that hydrogen produced using nuclear electricity could have full fuel cycle emissions 71% below those of a petrol light duty vehicle in the North American market.

DeLuchi *et al* (1988) considered that hydrogen would be produced by electrolysis only where the electricity was produced from non-fossil fuels. Fossil fuels would not be used to generate electricity to produce hydrogen by electrolysis: it would be cheaper and more efficient to produce hydrogen directly from the fossil fuel by gasification of coal or steam-reforming of natural gas. However, Deluchi *et al* estimated that hydrogen produced from coal gasification would result in 100% more greenhouse emissions than petroleum fuels when used in hydride form, and 143% when used as liquid hydrogen, and regard hydrogen as the least promising of the A/F in the short term (Deluchi *et al* 1988).

Market acceptance of alternative fuels

Market acceptance of alternative fuel vehicles (AFV) will be influenced by costs and vehicle performance, driving range, fuel availability, refuelling time and safety. The financial viability of an AFV will depend on whether costs of conversion (or additional purchase price), possible lower resale value, any additional maintenance or repair costs, and costs imposed by shorter range, more frequent refuelling and reduced payload, can be recovered in an acceptable time through lower fuel costs. Potential governmental actions in pursuit of cost recovery may also create uncertainty in the minds of potential AFV buyers.

Vehicle production costs are currently higher than for gasoline equivalents for NGVs, EVs, hydrogen, and for vehicles which run on a fuel with a major alcohol component. Operating range for these vehicles is much less than for a gasoline equivalent, unless a major sacrifice in carrying capacity is made. AFVs that can switch to gasoline still suffer loss of carrying capacity. AFVs with a low range require more frequent refuelling, which with natural gas or electricity may take significantly longer than with gasoline.

Although average trip length (day to day travel) is less then 8km (Adena and Montesin 1989), most drivers need to travel longer distances on occasions. Thus for many vehicle users the range limitation of AFVs is likely to be a major constraint on acceptance of A/Fs. Commercial production of batteries with much higher energy densities than current lead-acid batteries may result in a range for EVs closer to that for petrol vehicles. Delivery vehicles with trips of low cumulative daily distances, which can be refuelled overnight, have the greatest short-term potential for natural gas or electricity. Households with more than one vehicle may be able to choose an AFV, especially where the 'second car' is mainly used for short distance trips. However, the second car is often older than the fleet average, and has a low resale value. To replace this vehicle with an AFV may entail an unacceptable outlay for some consumers. Modern petrol vehicles provide a very flexible form of travel: use of an AFV requires far more forethought, particularly if vehicle range is low or fuel stations are infrequent. Uncertainity about the availability and adequate distribution of A/Fs, and about the plans of vehicle manufacturers to produce AFVs, will deter consumers from switching to AFVs.

The scope for recouping any costs associated with AFs through lower fuel prices depends, perhaps crucially, on policy on fuel taxation: currently only gasoline, aviation gasoline and diesel (automotive, industrial and marine) fuel oil carry excise. A review (Butcher 1990) of the Inter-State Commission report on road user charges (ISC 1990) recommended that vehicles powered by LPG or other A/Fs should pay the same road track charges per vehicle kilometre as vehicles using petrol or diesel, and pay essentially the same externality charges for noise (EVs were not considered, and CNG vehicles would also be quieter), although for air pollution, externality charges would vary with the fuel concerned. However, there appears to be a commitment from the July 1991 Special Premiers' Conference not to tax A/Fs *at this stage*. Were the existing system of fuel excises to be extended, in the future, to A/Fs these fuels may warrant a lesser rate of tax than diesel or petrol, because of environmental advantages. However, even a lower level of government charges would have a severe impact on the viability of NGVs. The AGA has stated that the imposition of taxes on NGVs would "effectively kill" the NGV industry, although it appears that high mileage heavy vehicles might still be financially viable. Taxes on ethanol and methanol fuels would have a similar effect unless the potential of new technologies is realised and production costs decrease considerably.

Uncertainty about the availability, distribution and long-term excise treatment of A/Fs, and about the plans of vehicle manufacturers to produce AFVs, will deter consumers from switching to these vehicles.

Conclusion

This paper has shown the potential for A/Fs to lessen the impact of transportation on the environment. Difficult questions need to be answered on whether the benefits of having more environmentally friendly fuels outweigh the costs involved in making them available (including infrastructure as well as fuel costs). One line of argument would be to let the market decide on the basis of administered fuel prices, set to reflect the social cost of the fuels sold. However fuel prices are never likely to reflect their social costs. Fuel pricing is a complex issue, and any solution would inevitably be a 'second best' one.

Without initial assistance, the most promising 'new' fuel appears to be natural gas, with the potential, in the short-term, to win substantial niche markets (such as depot-based buses and heavy trucks) through fuel cost savings. Given some assistance, ethanol is a possibility as a fuel extender (perhaps as 'diesohol') or in niche markets, such as heavy trucks in certain areas, in the medium-term. Electric vehicles appear, in the absence of California-style zero-emission vehicle legislation, to require commercial availability of battery types with higher energy density and faster recharging than the lead/acid battery for market acceptance. Hydrogen fuel may be a long-term possibility, depending on the composition of Australia's electricity generating facilities.

Widespread use of AFVs, which would probably only happen with Government encouragement, would be required for any of the A/Fs to have any significant impact on transport emissions. But without other policy actions, even with widespread introduction of these more environmentally-friendly fuels, emissions from transport seem likely to increase, given projected rates of fuel consumption (ABARE 1991), at least until (if ever) hydrogen from non-fossil sources becomes the major transport fuel or until electricity generation is based on renewable energy or both. It is a daunting task to attempt a conclusion about the way to go in regard to AFs. Not only is the technology not static, but there is the changing environment of regulated vehicle emission standards,

the effect of these on fuel consumption, developments in fuel efficiency of gasoline vehicles, and the unknown impact of these on new vehicle costs.

References

ABARE (1991) *Projections of Energy Demand and Supply Australia 1990-91 to 2004-05* Canberra: AGPS

Adena, M A & Montesin, H J, (1988) *Day-to-day Travel in Australia 1985-86* Report CR 69 Canberra: Federal Office of Road Saftey

AEVA (1992) *Electric Vehicle News* Melbourne: Australian Electric Vehicle Assoc. Inc.

AGA (1990) *Reducing the impact of the greenhouse effect* Canberra: submission by Aust. Gas Assoc. to the Senate Standing Committee on Industry, Science and Technology

Anker-Johnson, B & Schwochert, H (1990) *Is Electricity or Methanol the Next Automotive Fuel? Environmental, Technological and Economic Considerations* Melbourne: Paper presented to the 1990 Invitation Symposium of the Australian Academy of Technological Sciences and Engineering

APACE (1992), *New Technology for Ethanol Production - Its Use as a Transport Fuel* Canberra: Presentation to Dept. of Arts Sports Environment and Territories, 25 February

BTCE (1991) *Greenhouse Gas Emissions in Australian Transport* Canberra: BTCE

Bullock, K J (1989) 'The Technological Constraints of Mass, Volume, Dynamic Power Range and Energy Capacity on the Viability of Hybrid and Electric Vehicles', *Recent Advances in Electric Vehicle Technology*, Society of Automotive Engineers.

Butcher, E W A (1990) *Inter-state Commission Proposed National Road Pricing and Funding Scheme: A Review* Canberra: AGPS

Caldwell, P (1989) 'The Latest On L.P.G.' *The Open Road* June, pp 71-74.

Clifford, M (1991) 'Gas Sparks Interest in lean burn Louisville', *Truck Australia* September.

DeLuchi, M A, Johnston, R A & Sperling, D (1988) 'Transportation Fuels and the Greenhouse Effect', *Transportation Research Record*, 1175, pp. 33-44.

Deshpande, S L (1992) *Advanced Lead-Acid Batteries for Near Term Electric Vehicles* Melbourne: paper presented at the Electromotive Electric Vehicle Seminar, June 1 - 3

DPIE (1991) *A National Strategy fo the Natural Gas Industry: A Discussion Paper* Canberra: AGPS

EPA (1990) *Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel* Ann Arbor: US Environmental Protection Agency

EPRI (1989) *Electric Van and Gasoline Van Emissions: A Comparison*, EPRI Technical Brief, TBCU.177.10.89.

GAFCOR (1988) *Natural Gas For Transport in Australia*, Canberra: Consultancy Report Number 33 for the National Energy Research, Development and Demonstration Program

Gosden D F (1990) *Electric Vehicles and the Greenhouse Effect* Technical Note, Electric Vehicle Research Facility School of Electrical Engineering University of Sydney.

Haley, J (1990) 'The Gas Option', *The Open Road*, December, pp 34-35.

IANGV (1990) *A Position Paper on Natural Gas Vehicles 1990*, Auckland: International Association for natural gas Vehicles

IEA (1990) *Substitute fuels for road transport* Paris: International Energy Agency OECD

- (1991) *natural Gas, Prospects and Policies* Paris: International Energy Agency

- (1992) *Energy and the Environment: Transport System Responses in the OECD* Paris: International Energy Agency OECD

ISC (1990) *Road Use Charges and Vehicle Registration: a National Scheme* Canberra: AGPS

Ishitani, H (1992) *Overview - EV's in Asia/Pacific* Melbourne Proceedings of 'Electromotive' Seminar, June 1 - 3, 1992

Magasanik, D, Hamilton, R and Watson, H C (1990), *Commissioned Study on Alternative Fuels: Methanol for Transport in Australia*, National Energy Research, Development and Demonstration Program, Consultancy Study Report number 32

Merz (1991) *Natural Gas in Transport: Potential for Natural Gas Within the NSW Transport System* Sydney: NSW Department of Minerals and Energy

NELA (1991) *Final Report for the Study of Natural Gas for the Line Haul Trucking Industry*, Melbourne: Nelson English Loxton & Andrews Pty Ltd

- (1992) *Study on Potential to Improve Fuel Economy of Passenger Motor Vehicles* Melbourne: Nelson English Loxton & Andrews Pty Ltd

NIEIR (1988) *The Macroeconomic Impact of Increased Market Penetration of Natural Gas Vehicles (NGVs) in the Transport Sector 1988-2003, a Report Prepared for the Australian Gas Association* Melbourne: NIEIR

NRC (1992) *Automobile Fuel Economy: How Far Should We Go?* Washington: National Research Council

NSWDME (1990) *Investigation into Ethanol and Alternative Transport Fuels in New South Wales*, Sydney: Report to the Minister for Minerals and Energy
NSWDME (1990) *Greenhouse Effect Program Project* Sydney: Report to NSW Dept of Minerals & Energy on a Study of Greenhouse Gas Emissions From Motor Vehicles.

OTA (1991) *Improving Automobile Fuel Economy: New standards, New Approaches* Washington, DC. US Congress, Office of Technology Assessment

Pearman, G (1989) The Greenhouse Effect, Global & Australian Perspectives, *Energy and the Greenhouse Effect* Melbourne: Australian Institute of Energy

Purcell, G (1992) *Electric Vehicle Legislation in the United States* Melbourne: Proceedings of 'Electromotive' Seminar, June 1 - 3

Rajan, J B, Saricks, C L, Singh, M K & Walsh, W J (1989), *Environmental, Health and Saftey Concerns Associated With Nonpetroleum Fuel Use in U.S. Transportation,* Argonne National Laboratory, U.S. Department of Energy.

Rand, D (1992) *Candidate Batteries for Road Electric Vehicles* Melbopurne: Proceedings of 'Electromotive' Seminar, June 1 - 3

Rogers 1990) *Ethanol as a Transport Fuel*, paper presented at the Vehicles: Energy and Environmental Impact, seminar sponsored by the NSW Department of Minerals and Energy and AGL

Rogers, K (1991) 'Fiat on a Charge', *Autocar & Motor*, August pp 38 - 39.

Sergeant, G (1991) *Alternative Fuels in Practice. What is Needed to Make Them Work?* Melbourne: paper presented to the Energy Management Forum DPIE

SEC (1991) *Battery Electric Vehicles*, Inf. Sheet 18, State Electricity Comm. of Victoria.

Sinor, J E Consultants Inc (1992), *The Clean Fuels Report* Vol. 4:2.

Sperling, D and De Luchi, M (1991) *Alternative Transportation Fuels and Air Pollution Impacts* Paris: Consultants report to the OECD, Environment Directorate

Stewart, G A, Gartside, G, Gifford, R M, Nix, H A, Rawlins, W H M & Siemon, J R (1979) 'Liquid Fuel Production From Agriculture and Forestry', *Search* v10, pp382-87

Stodolsky, F (1989) 'Safety Considerations for Sodium-Sulfur Batteries for Electric Vehicles', *Recent Advances in Electric Vehicle Technology*, Soc. of Automotive Engineers.

Watson, H C (1991) *Future Fuels: Market Penetration and Environmental Impact* Sydney: paper presented to conference on Transport and the environment 22 & 23 April.

Wilkenfeld, G (1991) *Greenhouse gas emissions from the Australian energy system, the impact of energy efficiency and substitution* Canberra: ERDC 22 Energy Research and Development Corporation

Yorke, P L (1991) *Natural Gas - an Alternative or Not*, paper presented at the October 1991 Conference on Automotive Manufacturing, Congress of the SAE - Australia.