TRANSPORT ENERGY AND EMISSIONS
IN AUSTRALIAN CITIES
- Technological and Land Use Options

A Thesis presented for the Honours Degree of Bachelor of Science in Environmental Science

By Jeffrey Raymond Kenworthy

The work described in this thesis was conducted over 1979 and is the independent work of the author, except where specifically acknowledged in the text. Neither the present thesis nor any part thereof has previously been submitted to any other University.

School of Environmental & Life Sciences, Murdoch University, November, 1979.
And the streets of the city shall be full of boys and girls playing in the streets thereof.

Zechariah 8:5
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Now therefore perform the doing of it; that as there was a readiness to will, so there may be a performance also out of that which ye have.

For if there be first a willing mind, it is accepted according to that a man hath, and not according to that he hath not.

2 CORINTHIANS 8, 11-12

... let patience have her perfect work, that ye may be perfect and entire, wanting nothing.

JAMES 1, 4
ABSTRACT

The problems of transport energy use and emissions have been examined using an overview approach involving basic and multi-disciplinary research, consistent with the emerging discipline of environmental science. Facets of both problems and the inextricable link between them have been explained.

An extensive literature review of the technological and land use options available for making contributions to the solution of both problems is presented. A wide range of criteria have been used in assessing the technological possibilities which reveal the complexity of planning for technological change. The potential for easy technological solutions when viewed in this total perspective is not apparent.

The easy solutions tend to have the least potential for providing energy and emissions benefits; for example electronic ignitions were tested and the results were consistent with this hypothesis. The harder solutions tend to have other more fundamental implications which tend to mitigate against their use.

Land use options were reviewed and they suggested considerable potential for improving energy and emissions through density, centrality and traffic restraint. To test this potential and to provide an overview of the problems a study of Australian cities was made to cover
their transport energy use, motor vehicle emissions and land use.

The study showed that:

1) The cities with highest train usage have the highest per capita public transport usage and electric rail systems are the most energy efficient mode in Australian cities.

2) There is a significant difference between Australian cities. Perth and Adelaide are at one extreme with high energy (and emissions) per capita, Brisbane and Sydney are at the other extreme and Melbourne is intermediate.

3) These variations were explained by land use characteristics which correlated significantly with the transport patterns and hence suggested a potential to pursue energy conservation and air pollution abatement through land use.

4) The differences between Perth, Adelaide, Melbourne and Sydney were accounted for by density, centralisation and traffic restraint factors, whilst the anomalous patterns in Brisbane appeared to correlate most with traffic restraint factors.

5) Because traffic restraint seems so important in lowering private vehicle use and giving a competitive edge to public transport it appears that traffic engineering approaches designed to save energy and lower emissions by freeing traffic would be self-defeating.
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1.1 RATIONALE FOR THE STUDY APPROACH

It is well recognised that many of the problems confronting societies today are too complex and too profound to be tackled using narrow criteria. Cities, countries and the world all face formidable obstacles for which no one person, group or even Government claims to have formulated any satisfactory, let alone complete answers. Many of the problems can no longer be viewed as confined to what are essentially arbitrary political boundaries between nations. This urgency to step back and gain a wider field and depth of vision is being felt with particular force as institutions try to assess and resolve some of the global issues such as energy production and expenditure, population growth, food production and the depletion of non-renewable resources.

Fundamental to an understanding of these problems is the growing realisation that rarely, if ever, can any of these problems be isolated and attacked on one front. For example the problem of finding further fossil fuels to meet expected energy demand throughout the world is being reassessed for a number of reasons. First, the basic rationale behind extrapolating energy demand growth curves into the future is being questioned. Daly, (1978) argues that such energy planning methods become "self-fulfilling prophesies" and as such are unnecessary. He states: "We can make a collective social decision regarding energy use and attempt to plan or shape the future under the guidance of moral will; or we can treat it as a problem in predicting
other peoples' aggregate behaviour and seek to outguess a mechanistically determined future. As the art of foretelling the future has shifted from the prophet to the statistician, the visionary goal oriented element and the accompanying moral exhortation have atrophied, while the analytical number crunching has hypertrophied".

Herman E Daly, (1978)
"On Thinking about Energy in the Future"

Second, the observation that per capita G.N.P. growth has historically followed the growth in per capita energy use and therefore increasing energy must be used to maintain G.N.P. growth and prevent recession, is also being questioned. Watt (1979) argues that in the U.S.A. growing energy use is now counter-productive and is in fact leading to a reduced G.N.P., due to complex economic relationships involving inflation and balance of payments problems. He also suggests that growing energy use in the U.S.A. can no longer be seen as synonymous with increasing standards of living because of the unaccounted for social costs of increasing energy use. Similarly, Bullard and Foster, (1976) have investigated ways of decoupling energy and G.N.P. growth by considering the impacts of changes in four classes of variables: population, per capita G.N.P., lifestyle and technology.

Third, the global environmental consequences of continuing to burn more fossil fuels has received much attention. Hayes (1977), Hrycak (1978) and Hafele and Sassin (1976) have all investigated the possible effects of accumulating CO₂ in the atmosphere. They agree that this factor alone may preclude the realisation
of predicted energy demand, even if it is technologically possible to continue exploiting greater quantities of fossil fuels.

There is evidence to suggest however, that the growing awareness of problem complexity is having some negative effects. For example Irving Kristol, Henry R. Luce Professor of Urban Values at New York University is resigning his Luce chair because:

'I don't have anything to say anymore. I don't think anybody does. When a problem becomes too difficult, you lose interest."

Similarly, in the same article by Nossiter, (1979), Daniel Bell a Harvard sociologist is quoted as saying:

'Nobody has any answers he is confident of. If he does he's a fool.'

For these reasons, Kristol claims, there has been a substantial retreat from research in areas which might give a new lead to public policy formation. In this regard McElroy (1977) has emphasised the need for a continuation and support of basic research into facets of the fundamental problems with which society is faced. This he asserts, is particularly important to major world problems. However he also points out the great need for what he terms multi-disciplinary, problem-oriented research. He states:
Of course, problem-oriented research involves basic research, but it also involves engineering and applied work (and there is a) ... need to accept, support, and reward members of the science community whose contribution is in this less traditional vein.

W D McElroy, (1977)
"The Global Age: Roles of Basic and Applied Research"

Environmental science has evolved largely from a recognition of the need for basic research into matters specifically concerning the environment, but also from a realisation that such basic research has its place in a multi-disciplinary, problem-oriented framework. This thesis, in addressing itself to the problems of diminishing world oil supplies and motor vehicle derived air pollution in cities has tried to highlight the merits of both approaches - basic and multi-disciplinary research.

First, it has drawn upon the results of a vast amount of basic research into the problems of present motor vehicles, their use of oil, the problems which the air pollution from vehicles creates, and possible methods for solving both the energy and emissions problem simultaneously. This effort has spanned the broad field of technological endeavour in the automotive, fuel and communications industries. It has also generated some basic research results in the field of add-on devices to motor vehicles in an effort to shed some light in an area often characterised by qualitative assessments and sometimes large claims of energy conservation and emissions abatement.
Second, there was a need to bring all this together in a multi-disciplinary framework to assess the various technologies according to a range of criteria. In addition to this, the multi-disciplinary approach included an examination of some fundamental aspects of the design and structure of cities which required consideration of material from a wide variety of research in the fields of urban planning and transportation planning. This was done in an effort to better understand some of the causal relationships in the energy and emissions problem. The ideas from these fields were then applied in some further basic research to examine differences between Australian capital cities: their transport energy use, emissions production and land use characteristics.

This study has not attempted to examine all aspects of the transport energy and emissions problems in detail. It has concentrated on the technological and land use aspects and pointed to the human, economic and political interactions where possible. Clearly there are many more aspects to the problem when the factors of social, economic and political forces are considered in depth. This study has thus only served to highlight the inextricable links between energy usage in road transport and the production of vehicular emissions and to point to possible directions which could be taken to help solve them through technological and land use planning means.
The need to further establish environmental science as an integrated discipline was expressed recently at the UNESCO Regional Workshop on the Teaching of Environmental Education at Tertiary and Postgraduate Levels 29 August - 2 September 1979. A major aim of the workshop was to follow up a previous recommendation by the Regional Meeting of Experts on Environmental Education in Bangkok in 1976 that environmental scientists be trained in problem solving on an integrated multi-disciplinary team basis and they be "described as integrationists as distinct from generalists or specialists" It is hoped that this study may contribute something to the development of this integrated science and that in the process options for solving some of the large and intractable global problems may be provided.

1.2 STRUCTURE OF THE THESIS

In Chapter 2 transport energy and emissions problems are reviewed. This is followed in Chapter 3, by a literature review of all the technological and land use options available to help solve these problems. Chapter 4 details all the methodologies used in this study to obtain basic data. Chapter 5 gives the results of the investigations made in the study, followed by a discussion of the implications of the findings. Chapter 6 draws some overall conclusions concerning the potential of technological
and land use options to mitigate the impact of dwindling oil supplies and motor vehicle air pollution problems.
CHAPTER 2
TRANSPORT ENERGY AND EMISSIONS PROBLEMS

2.1 INTRODUCTION

This chapter examines the broad issues surrounding the use of energy in transport; namely the oil supply problem and some of the ways of increasing conventional oil supplies. It then looks at the vehicular emissions problem which is a direct outcome of transport energy consumption. Finally, it considers the specific issue of leaded fuels as an illustrative example of the inextricable link between policies to conserve energy and reduce emissions.
2.2. ENERGY

2.2.1 Introduction - The oil supply problem

There is no shortage of energy but a real shortage of oil supply - this, in a few words, is the energy problem which forms a backdrop for this study.

During the 1960's and early 1970's there was some recognition of the potential seriousness of diminishing oil reserves particularly in the transport sector, but it was the Arab oil embargoes of 1973-4 which caused the oil crisis, as it is now known, to become so prominent in discussions around the world. The realisation that the biggest reserves of oil are in the Middle East (57.3% of the world total in 1978 (Australian Institute of Petroleum, 1979) and an even greater proportion (68.2%) is subject to the control of countries collectively known as O,P,E,C.\(^1\), led to dramatic reassessments of oil consumption patterns. The transport sector, which is virtually totally dependent upon oil in most Western countries became a centre of attention. Transport authorities became resource managers as they came to realise the extent of their responsibilities.

The oil crisis however did not occur overnight, but was the result of a situation portended as early as 1956 by a U.S. geologist, Dr. M.K. Hubbert.

\(^{(1)}\) Organisation of Petroleum Exporting Countries.
The basis of Hubbert's analysis is that an exhaustible resource like oil has a defined lifespan during which the most important point is peak production. A lack of awareness about this fundamental point lies at the root of the present oil crisis. Hubbert pointed out that supply problems would start after production had peaked, not when oil was nearly exhausted. In other words half the known oil could be intact, but because oil production would be in a state of decline rather than increase, normal economic and industrial practises would no longer apply, and oil supply would become a problem (Hubbert, 1973). U.S. oil production peaked in 1970, as Hubbert predicted in 1956, and the U.S.A. has become progressively more dependent upon imported oil ever since. In 1972 the U.S. were importing 25% of their needs and in 1979 this had risen to 50%. By 1984 it is predicted to be 75% (Joint Committee on Foreign Affairs and Defence, 1977).

Hubbert also applied this analysis to world oil production and arrived at the conclusion that oil production on a global basis will peak around 1990 or optimistically around 2000, (Hubbert, 1973). This fundamental point, which is shown graphically in figure 2.1, and the distribution of known oil are the basis of the present world oil situation characterised by unpredictable price hikes and the possibility of politically contrived supply cuts.
There is considerable debate about the reality of such physical limits despite the clear case of Hubbert's analysis as it applied to the U.S. (production has continued to fall since 1970 despite the opening of the Alaskan fields). However such arguments are largely academic because the reality is that oil supply is now a problem and no possibility of an easing in this situation is envisaged. The reason is that oil supply is not just a physical supply problem but has become a highly political matter and not without reason.

The prospect of world oil production peaking has led many countries to husband oil reserves in an effort to lower oil production and thus delay the year of peak production, whilst maximising their short and long term financial returns.
This is supported by the example of Saudi Arabia, the biggest O.P.E.C. oil producer, which plans to limit oil production to 12 million barrels a day from its fields, when world requirements for Arab oil are expected to rise to between 16 and 20 million barrels a day (The Guardian Weekly April 22, 1979).

This situation of demand exceeding supply, can be seen even more clearly by considering O.P.E.C. collectively. The Institute of Engineers Taskforce on Energy (1977) compiled a graph, shown in figure 2.2., of the likely consequences of the present world oil situation.

Figure 2.2. Projected supply and demand scenario for O.P.E.C. oil.
This prediction was pre-empted by the 1979 Iranian revolution which caused a break in supply and huge price rises. The spot price of oil went from around $30/barrel to over $50/barrel during 1979 (Australian Institute of Petroleum, Sept. 1979). The present oil supply situation is thus characterised by potential political intervention so that large scale dependence on foreign oil makes any nation extremely vulnerable and its security highly questionable (Joint Committee on Foreign Affairs and Defence, 1977). Oil suppliers are not consciously seeking such intervention. For example Saudi Arabian oil production was temporarily increased to fill the gap left by Iran's lowered production but Sheikh Yamani, the Saudi oil minister has warned the Western world many times that they must not continue to demand oil at present levels. Many O.P.E.C. nations are at saturation point in their ability to absorb the huge capital gained from their oil supplies; in fact, the rapid and dramatic influx of petrodollars has caused considerable social impact and political instability in O.P.E.C. nations. (e.g. Iran). They generally have little to gain by continuing to raise production and prices in the short term.

The importance of this problem should not be underestimated on a global scale; each new price rise pushes the international economy further into recession, each new threat to supplies makes the possibility of
international conflicts more possible. As is explained in the ensuing section Australia and the world have little option but to reduce the total amount of oil consumed.

Australia is not sheltered from this problem. Its oil reserves are going through a similar situation to that which occurred in the U.S.A. ten years ago. Figure 2.3 shows past, present and predicted future Australian production and consumption patterns for crude oil.
FIG. 2.3 AUSTRALIAN CRUDE OIL AND CONDENSATE PRODUCTION AND IMPORTS TO MEET DEMAND FOR PETROLEUM PRODUCTS

From 5th Report of Royal Commission on Petroleum
As can be seen from the graph the peak in Australian oil production is beginning to occur. The peak is blurred a little by the response to Iran's change in Government which forced Australia to increase its production in 1979 beyond anticipated levels. Australia is thus shifting from a position of about two-thirds oil self-sufficiency to two-thirds import dependence in less than a decade.

Australia is also very dependent upon Middle East oil because of the particular light oil which comes from this region. In 1977-8 the Middle East supplied 91% of Australia's imported refinery feedstock and 80% of total petroleum products, (Joint Committee on Foreign Affairs and Defence, 1977). Important financial and security implications will accompany a period of increasing dependence upon imported oil and thus much attention is now being paid in Australia and other oil-dependent countries to the oil problem.

This thesis will attempt to review the many options that are available in response to the oil problem. It will begin by examining ways of augmenting supplies of conventional oil, i.e. what are the possibilities of increasing supplies of conventional oil which may provide additional time for alternative sources of transport energy to be found and alleviate the economic and political impact of increasing foreign oil dependence.
2.2.2. Augmenting Supplies of Conventional Oil

[a] **Introduction**

Much attention has been drawn to the huge capital investments and long lead times involved in getting any alternative fuels onto the market, (Dutton, 1978, Hendry, 1974, Endersbee, 1979, Environmental Science and Technology, 1979), irrespective of their origin. This is examined in some depth in Chapter 3. The whole problem is summarised succinctly by L.A. Endersbee, Chairman of the Institute of Engineers Task Force on Energy. He states:

> Ultimately liquid fuels produced from coal, tar sands and oil shales, alcohols and other organic fuels will provide a greater proportion of the world's liquid fuel needs. Because of the time lags involved however, they are not likely to be significant contributors to meeting energy requirements until the next century. The high costs of synthetic-fuel plant inhibit early investment decisions and the environmental aspects may impose further restraints. (Endersbee, 1979).

It is therefore necessary to ensure that existing conventional supplies of oil are ample to bridge the gap during a period of transition. Apart from conservation efforts, there are a number of other ways of extending the economic life span of oil reserves. These are concerned primarily with improving exploration, drilling and extraction techniques.

There is evidence to suggest however that a danger exists in overstating or over-relying on the potential oil gains from such methods.
Equally there is a danger in perceiving that they offer an indefinitely long reprieve in the oil supply problem. It is therefore necessary to see in perspective the potential for new supplies of conventional oil especially those from new discoveries.

(b) **Methods**

The amount of natural oil available for use may be enlarged in two ways. First completely new oil discoveries may be found which add to known reserves, and second, advanced extraction technique for exploiting known oil resources can be developed and used if the price of oil is commensurate with the additional cost of extraction.

(i) **New Discoveries**

A distinction between resource and reserve is required before continuing this discussion. Reserves are those deposits in known locations which can be recovered profitably with current technology and in present economic conditions. Resources include all reserves plus deposits that are known to exist but which cannot be recovered at current prices and with current technology. Resources also include estimates of deposits as yet undiscovered. Such estimates are usually based on comparisons of geologic phenomena between exploratory areas and
known reserves and in the case of oil and gas usually differ greatly from what is finally discovered (Kerr, 1979).

Augmenting oil supplies involves a process of converting resources into reserves by confirming predictions of undiscovered oil or by developing new technologies to exploit confirmed deposits (Hayes, 1977). Changing resources to reserves also depends upon the changing price of oil.

A review of the literature strongly suggests that the potential for new discoveries of oil to close the growing gap between oil supply and demand outlined in the previous section is very limited. The following discussion summarises some evidence about world oil exploration which has led to the growing realisation.

Exploring and drilling for oil involves huge capital expenditure and high risks. Bringing discovered oil on stream is characterised by long lead times. Most of the world's easy-to-find and readily accessible oil has been discovered and is currently being used. The search for new oil has necessarily moved into more problematic environments such as deep offshore areas, the Arctic, Alaska and the North Sea.
Ecological problems related to oil spills add further constraints to where oil may be extracted e.g. opposition to oil drilling on the Great Barrier Reef and Santa Barbara Channel off the coast of California.

The difficulties encountered in problematic environments such as deep offshore areas escalate costs of production, stretch manpower endurance and make it economically essential that large reserves be found to justify the capital expenditure. In other words finding oil is part of the problem but other considerations such as the price of the final product, the time necessary to get the production on-stream, the investments required and the size of the find also influence whether oil is ultimately used (Hutchinson, 1978).

For example in the Gulf of Mexico where oil companies are spending over US $5 million per exploratory hole with no success, it is estimated that at US $17 per barrel of oil a 40 million barrel discovery in 300m of water will result only in break-even economics for the oil company. From 1965-1974 in the U.S.A. 1 in 153 discoveries was as large as 50 million barrels and 1 in 63 was greater than 25 million barrels. It was concluded that only in the event of very large discoveries in the Gulf of Mexico could oil be exploited profitably from this area (Hutchinson, 1978).
The Atlantic Coast situation is similar but more severe. It is estimated that at $U.S. 15 per barrel a US $90 million barrel discovery will just break even in 300m of water (Hutchinson, 1978). To put this in perspective it is useful to consider that in 1977, non-Communist world demand for oil was 50 million barrels per day. The U.S.A. alone consumes about 16 million barrels of oil per day (Australian Institute of Petroleum, 1979). It is also important to note that the Atlantic outer continental shelf (O.C.S.) was considered to offer the U.S.A. its brightest potential for finding new oil. In the 1970's oil potential of the Atlantic O.C.S. was thought to be about 30 to 40 billion barrels. In 1974 the U.S. Geological Survey announced officially that the potential would be between 10-20 billion barrels. However, in the same year Mobil Oil announced that the potential would only be 6 billion barrels. One year later the U.S.G.S. lowered its previous figure of 10-20 billion barrels to between 2 and 4 billion barrels (Kerr, 1979). The Baltimore Canyon Trough, which is thought to be the best prospect in this area has turned up 13 dry wells out of 15 with the other 2 striking natural gas but no oil (Kerr, 1979). The most widespread opinions amongst oil experts concerning the Atlantic O.C.S. oil potential are described as "dismal" or "very grim" (Kerr, 1979).
It is also important to consider the costs and time delays in offshore oil drilling. The costs of deepwater platforms rise rapidly as water depth increases. In 183m (600ft) of water one platform costs about US$30 million with a delay in fabrication and installation of 2 years. However in 366m (1200ft) the cost is ten times this amount ($300 million) with a delay of 4 years. A four year delay also raises costs such that to be profitable 40-50 percent more oil needs to be discovered at the site (Hutchinson, 1978).

Due to some of the constraints already outlined, it has become extremely expensive to increase available oil by new discoveries. For example it has been calculated that for an investment of US$200 million in exploration alone about 2 4/3 days supply of oil for the U.S.A. may be discovered. Over US$30 billion dollars would be required to gain a year's supply assuming that oil remains to be discovered. At present an investment of US $100 million in oil exploration in the U.S.A. stands an 18 per cent chance of total loss (Capen, 1978).

The situation in the U.S.A. is more bleak than in other places. The U.S.A. has a drilling density about seven times higher than the world average so the probability of finding more oil is lower (Hayes, 1977). Worldwide however it is generally recognised
that oil is becoming more difficult to locate, and more
difficult to extract (Pole, 1973).

The conclusions from two assessments in the
U.S.A. summarise the problem of finding new oil:

Clearly petroleum resources are getting much
caller to find and those we do find tend to be
smaller and deeper accumulations... It will be
ecessary to expend prodigious sums of money to
find and produce oil and gas... Uncertainties
associated with the search for oil and gas are
enormous compared to the magnitude of uncertainty
aced by most business (Capen, 1978).

New technology and the engineering application of
his technology has enabled the petroleum industry
to move into increasingly hostile conditions en­
countered in the deeper offshore waters. We can
do it but do we want to pay the cost?... appli­
cation of the technology and expansion of this
capability to meet new challenges demands avail­
able capital and today there are restraints on
available capital in the form of price controls,
proposals to withdraw large areas of public lands
from multi-use purposes, and other moves which run
counter to permitting technology to work in concert
with economics and the environment. (Hutchinson,
1978).

Australia has had sufficient oil production
over recent years to maintain approximately 70 per cent
self-sufficiency in oil even though its total reserves
constitute only 0.2 per cent of world reserves
This situation is changing rapidly as resource depletion occurs. The Chairman of the Shell Oil Group estimated in 1975 that Australia would need to find more than 3000 million barrels of oil, the equivalent of another two Bass Strait oil provinces over the next few years, if it wanted to remain two thirds self-sufficient in oil by 1990, (The West Australian Nov. 14th, 1975). The likelihood of this occurring is slim. Barnett (1979) concluded that it is unlikely that the N.W. Shelf will offer an oil bonanza although it might be an important oil province for Australia if the costs can be met. King (1978) in a detailed study of energy use in transport in Australia concluded that Australia is not a likely oil province and even if large discoveries were made on the Exmouth Plateau they would be very expensive to produce, take many years to bring into production and be relatively short-lived.

This appraisal can be understood more clearly by considering some data concerning exploitation of possible oil reserves on the Exmouth Plateau. Average water depth on the Exmouth Plateau is between 800 and 2000 metres. In mid 1974 the maximum depth of water in which platforms had been installed was 150m and it is considered that 450m represents an upper limit for the types of platforms currently available. It has been estimated that to install a single platform on the N.W. Shelf in only 134m of water will cost hundreds of millions of dollars.
compared to $10 million dollars in the Gulf of Mexico (Barnett, 1979).

There are a number of reasons for this. The N.W. Shelf has been compared to the North Sea in terms of conditions to be encountered. The weather conditions, particularly wind speeds and wave heights are similar, resulting in an extremely harsh environment for oil production. The use of concrete platforms which are cheaper than steel platforms is precluded by the uneven and unstable nature of the sea floor on the N.W. Shelf (Barnett, 1979).

Finally in assessing the potential of new oil discoveries to meet demands for oil by all countries it is important to stress again the distribution of proven oil reserves which gives some indication of the likelihood of the location of significant new reserves. In 1978, 57.3 per cent of proven reserves were located in the Middle East, 14.4 per cent in the Soviet Bloc and China, and 16.3 per cent in Latin America, Caribbean and African nations (Australian Institute of Petroleum, 1979). As oil becomes scarcer it is inevitable that oil will come under increasingly tight political and strategic control which may affect not only the overall availability of oil but also the distribution of sales around the world.
In summary this brief review would suggest new discoveries of oil cannot play a major role in delaying or diminishing the gap between demand and supply. Those reserves which may be added in the future will require much higher levels of capital investment to exploit and, involve a higher degree of ecological risk, and the final product will be much more expensive and take longer to come on stream. 

A synopsis by the Australian Institute of Petroleum captures the circumstances, and an excerpt from an interview with Dr. Ulf Lantzke, Executive Director of the International Energy Agency where he warns of an oil shortage in the 1980's, shows quantitatively the magnitude of the problem:

Through this century the world has been in a fortunate situation where discoveries of new fields and upgrading of estimates of proved reserves in existing fields have risen faster than the increase in world demand for oil. This situation is changing rapidly. The rate of additions to proved reserves is declining. World demand for oil has been rising. There are technical and political limits to rates of production. (Australian Institute of Petroleum, 1979).

New sources will enable us to keep production and consumption in balance only temporarily. Any accident which disrupts the flow of new oil, or any adverse political development in the Middle East will upset this precarious equilibrium. The situation is particularly grave because this short-term balance is creating a climate of complacency.
We would have to discover at least the equivalent of one North Sea oil field per year to keep reserves and consumption in balance. I see no chance that this will happen. The sad fact is we are running out of oil. Any new discoveries can only give us breathing space. (Harriss, 1978)

(ii) Increased Recovery From Existing Reserves

The efficiency of recovery of oil from existing wells around the world is usually low. Less than 35 per cent of the oil present in a reserve is generally recovered (Sampson, 1978), though it may rise to 40% (ATAC, 1978). An average 25-30 per cent of oil from any field is presently recovered (Australian Institute of Petroleum, 1979). The percent recovery varies according to the specific well and the recovery technique employed, e.g. Barrow Island off the Coast of W.A. produced only 11 per cent by primary methods of recovery and it is estimated that to recover 34 per cent would require an expensive secondary technique (Barnett, 1979).

The nature of an oil reserve is such that only a relatively small proportion of total oil escapes under its own pressure. Extracting more oil requires sophisticated recovery techniques, the economics of which depends upon the price obtained for the crude product. Recovery techniques can be classified into two groups:
1. Conventional Recovery and
2. Enhanced Recovery. (Sampson, 1978)

Under the first grouping are primary and secondary recovery methods. Primary methods use natural reservoir energy to drive the oil through complex bore networks into the well. The most common secondary method is water flooding. Water is pumped into special injection wells to flush oil out from the rock bores. Enhanced recovery or tertiary technique consist of three types: (a) thermal (b) carbon dioxide miscible flooding and chemical flooding.

Thermal recovery involves steam injection and in-situ combustion. In steam injection a mixture of hot water and steam is injected to reduce the viscosity of the oil and allow freer movement of the oil.

In-situ combustion involves burning part of the crude oil in the reservoir by injecting air and igniting the mixture. The viscosity of the oil is reduced and it moves to the well by a combination of steam, hot water and gas drive (Sampson, 1978).

Carbon dioxide miscible flooding uses chemicals which when injected into the reservoir lower the interfacial tension between the injected fluid and the reservoir. Displacement efficiency is improved and
some of the hydrocarbons move more freely through the pores.

Enhanced recovery offers some potential for increasing oil supply however it is extremely expensive and oil-price sensitive, and is itself energy intensive (Hayes, 1977). By using enhanced recovery at Barrow Island in W.A. it may be possible to boost recovery to between 39 and 47 per cent. However this would require boosting the set price in 1977 of $3.7 per barrel to world parity and would result in little more than a year's supply for Australia (Barnett, 1979). Similarly at Moonie in Queensland, recoverable oil could be increased by 5-7 million barrels (a 25% increase on present recoverable oil) by using a tertiary technique such as polymer (chemical) flooding. Bass Strait could produce an additional 400 million barrels if world parity prices were adopted. However this is equivalent to only two years' total supply for Australia (Barnett, 1979).

Enhanced recovery can only be employed if prices are sufficiently high. For example in the U.S.A. it has been estimated that if oil prices were raised to $ U.S. 25 per barrel, production could reach 3.5 million barrels per day in 1995 compared to 1 million barrels per day in 1995 at current prices. In terms of converting resource potential into reserves it is estimated that at $25 per barrel, 25 billion barrels
are involved but at current prices, 10 billion barrels are involved (Sampson, 1978). It would appear unlikely that the cost of oil per barrel will present any obstacles to this being done.

In summary, enhanced recovery techniques do offer potential for expanding current reserves of petroleum. In Australia this is considered the most promising way of extending reserves (ATAC, 1978). It is likely that such techniques will play an important role in maintaining oil supplies during a transition period. The magnitude of this potential, and how soon it could become available remains largely speculative because it is highly dependent upon world oil prices. It is predicted that enhanced recovery will become comparatively more important in OPEC countries where unexplored areas are scarce and production costs are comparatively low (Australian Institute of Petroleum, 1979). There is however a physically defined limit to the amount of oil which can be recovered irrespective of oil prices. Enhanced recovery techniques as with new discoveries are not solutions to the oil supply problem, and will provide additional oil only at a relatively high price for a comparatively short period.
2.3. EMISSIONS

2.3.1. Introduction - Automotive emissions in context

The problem of air pollution in cities has commanded great attention around the world from as early as the 1950's. Much of this attention, particularly since the late 1960's and early 1970's has been directed towards the transportation sector which has been steadily growing in its contribution to urban air pollution. Concern over air pollution has been generated for three important reasons. First and possibly foremost, are the potential health threats from the range of pollutants found in urban airsheds e.g. lead and photochemical oxidants. Second are the economic implications of air pollution in terms of damage to materials and plants and the social costs of air pollution-related health problems. Third is the aesthetic impact of high levels of particular types of pollutants e.g. the haze associated with photochemical pollution. The visual or aesthetic effect of air pollution can be a strong force behind air pollution abatement legislation. For example, in Britain, a strong reaction against smoky odourous diesel exhausts resulted in stringent measures to control these sources (Sharp and Jennings, 1976), although they generally contain far lower concentrations of hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx) which are the main pollutants in invisible petrol engine exhausts. Diesel exhausts also contain no lead. The health economic and aesthetic impacts of various automotive pollutants
are examined in more detail later in the section. An outcome of the increasing incidence and severity of air pollution from both primary and secondary pollutants,\(^{(1)}\) and the desire to minimise the adverse effects just mentioned, has been the setting of motor vehicle emissions standards, generally in terms of grams of pollutant emitted per kilometre. The criteria for selling of motor vehicle emissions standards is a fervently debated topic (Grad, 1972, Marshall, 1978, Gage, 1979) the details of which are beyond the scope of this study. The fundamental criticism is that they are based on air quality goals which suggest certain maximum desirable ambient concentrations of specific pollutants over given periods (e.g. 9ppm CO, 8hr maximum). The air quality goals however have been questioned on the grounds that they are based upon inadequate, scientific and medical evidence concerning the effects on human beings which they seek to protect.

\(^{(1)}\) primary pollutants are those actually emitted such as CO, \(\text{NO}_x\) and HC and secondary pollutants such as photochemical oxidants form in the atmosphere as a result of complex chemical reactions.
The setting of air quality goals for primary pollutants is further complicated by the complex reactions and synergisms which some of these undergo to form secondary pollutants (e.g. HC and NO\textsubscript{x} in the formation of photochemical oxidants).

Despite the arguments surrounding motor vehicle emissions standards they have become much more stringent over the years. These trends are illustrated for Australia, the U.S.A. and California in table 2.1

**TABLE 2.1 Automobile exhaust emissions standards (g/km)**

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbons</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Federal</td>
<td>21.28</td>
<td>*</td>
<td>24.0</td>
<td>0.25</td>
<td>0.9</td>
<td>0.25</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>California</td>
<td>2.1</td>
<td>*</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
<td>0.25</td>
<td>*</td>
<td>-</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Federal</td>
<td>24.25</td>
<td>*</td>
<td>22.0</td>
<td>21</td>
<td>0.3</td>
<td>2.1</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>California</td>
<td>24.2</td>
<td>*</td>
<td>-</td>
<td>-</td>
<td>14.9</td>
<td>-</td>
<td>2.1</td>
<td>-</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Federal</td>
<td>-</td>
<td>2.8</td>
<td>1.9</td>
<td>*</td>
<td>30</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>California</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
<td>-</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**NOTE:** Asterisks (*) in the table indicate where legal requirements did not change from the last value given.

**SOURCE:** Crossland, 1974, Department of Transport, Australia, 1978, Grad, 1972, Ayres and McKenna, 1972.

Orig = Original      Int = Interim
It can be seen from this table that the most stringent requirements for Australia are much less severe than those in the U.S.A. In fact current Australian standards correspond to those introduced in 1973 in the U.S.A. The trend in emissions standards has not been consistently downwards. In some cases standards have been temporarily revised upwards where it has been demonstrated that meeting them with current technology would prove difficult or involve unacceptable increases in costs and fuel consumption. The attempted introduction of a new Australian standard (ADR 27A, third stage) in 1981 was accepted initially by only two States (N.S.W. and S.A.) the others having followed the Federal Governments' initiative in insisting that more stringent controls would result in large increases in fuel consumption (of the order of 5%) (Australian Academy of Technological Sciences, 1979), and other motoring costs. (This issue is pursued further in Chapter 3). Currently N.S.W. is the only State which is insisting on going ahead with the third stage of ADR 27A.

It is also worth noting from the table, that California which has severe photochemical smog problems, has a history of earlier and slightly more stringent controls.
In the U.K. and Europe there has been strong opposition to tougher emissions standards particularly for nitrogen oxides, on the grounds that there are less photochemical smog problems in this area and considerable doubts about the health effects of typical ambient concentrations of nitrogen oxides found in European cities. Since 1973 the fuel economy losses associated with controlling nitrogen oxides with current technology has added to the aversion against introducing tougher standards (Advisory Council on Energy Conservation, 1977).

The reasons for the overall trend towards more stringent control of vehicle emissions can be partly supported by considering the percentage contribution of various pollutants from transport sources in a city or a country as a whole. Table 2.2 shows some data which highlights the importance of transport as a source of air pollution.

### Table 2.2 Relative contribution of transport related air pollution for specified areas.

<table>
<thead>
<tr>
<th>PLACE</th>
<th>YEAR</th>
<th>SOURCE OF EMISSIONS</th>
<th>PERCENTAGE CONTRIBUTION TO TOTAL ANNUAL EMISSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERTH (1)</td>
<td>1976</td>
<td>Motor Vehicles</td>
<td>HC 57.4 CO 87.3 NOx 56.7 Lead 75.4</td>
</tr>
<tr>
<td>ADELAIDE (2)</td>
<td>1974</td>
<td>Motor Vehicles</td>
<td>HC 74.0 CO 89.0 NOx 35.0 Lead N/A</td>
</tr>
<tr>
<td>MELBOURNE (6)</td>
<td>1976</td>
<td>Motor Vehicles</td>
<td>HC 60.0 CO N/A NOx N/A Lead N/A</td>
</tr>
<tr>
<td>SYDNEY (6)</td>
<td>1976</td>
<td>Motor Vehicles</td>
<td>HC 60.0 CO N/A NOx N/A Lead N/A</td>
</tr>
<tr>
<td>U.S.A. (4)</td>
<td>1970</td>
<td>Transportation</td>
<td>HC 56.2 CO 75.4 NOx 51.5 Lead N/A</td>
</tr>
<tr>
<td>U.S.A. (5)</td>
<td>1974</td>
<td>Transportation</td>
<td>HC 42.1 CO 77.7 NOx 47.6 Lead N/A</td>
</tr>
<tr>
<td>AUSTRALIA (3)</td>
<td>1971</td>
<td>Motor Vehicles</td>
<td>HC 51.0 CO 63.0 NOx 27.0 Lead N/A</td>
</tr>
</tbody>
</table>

**SOURCES:** Over page
Note: transportation includes aircraft, railways, and shipping but these contribute extremely small fractions of the total. Motor vehicles are the main source.

It can be seen that in general, transportation and more specifically motor vehicles, are the single largest contributors of HC and CO and also make very significant contributions to NO\textsubscript{x} emissions. Sometimes they are the single largest contributors to NO\textsubscript{x} emissions. It is also important to note that data showing relative contributions of various sources to total air pollution are much less meaningful on a national basis because they give little indication of the intensity of the emissions, which is important in determining adverse effects. However in cities the relative contribution to total pollution of various sources is much more important.

The next section examines more closely the environmental health implications of a number of pollutants and shows more clearly the importance of
reducing emissions from transportation sources.
2.3.2 Environmental health impacts of transportation pollutants.

(a) Introduction

None of the pollutants examined in this section come solely from transportation sources but as has been shown, transportation sources contribute very significantly to the total load in most cities. The serious photochemical smog problem experienced in many cities, Los Angeles, Sydney and Tokyo, being the most often cited examples, is directly related to motor vehicles and is the subject of ever increasing concern in these cities (Los Angeles Times, July 22, 1979). Despite the generally held view that high levels of atmospheric pollution, particularly in automobile cities such as Los Angeles, constitutes a general threat to health (Ehrlich, Ehrlich and Holdren, 1977, Brown et al 1975), the details remain contentious for many specific pollutants. This section examines some of the environmental health issues surrounding the most important transportation pollutants.
(b) **Carbon monoxide**

The physiological effects of carbon monoxide are well documented and generally agreed upon (Grad, 1972, Berry *et al.*, 1974). CO has between a 200 and 300 times greater affinity for haemoglobin in the bloodstream than oxygen. It reacts to form carboxy-haemoglobin (COHb). In this way carbon monoxide causes a reduction in the oxygen carrying capacity of the blood and interferes with the oxygen releasing mechanism of haemoglobin in body tissues. Oxygen leaves vital tissues in the presence of COHb which may cause a variety of symptoms ranging from dizziness, headaches, lassitude, loss of visual acuity, impaired mental ability, decreased muscular coordination and eventually death, depending upon concentration and exposure. CO constitutes a greater threat to the developing foetus, children, elderly people and those suffering from impaired circulation, heart disease, anaemia, asthma or lung impairment (Berry *et al.*, 1974, Grad, 1972). While the physiological mechanisms and range of symptoms are generally agreed upon, there are arguments concerning the impacts on health of concentrations found in urban airsheds. For example a major concern has been the possibility that CO might be responsible for increases in accident rates due to a lowering of vigilance, visual discrimination and general performance of drivers (Grad, 1972, Berry *et al.*, 1974).
Central nervous system effects have been demonstrated at COHb levels as low as 2% (Bilger, 1972), but at the other extreme, heavy smokers have been recorded with COHb values as high as 16% with little or no effect, (Hartmann, 1973). The range in observable effects of differing concentrations of CO, and the added complication of isolating CO from other factors such as visibility, vehicle conditions and other driver conditions, makes firm correlations between ambient CO values and accidents very difficult (Grad, 1972). Despite the variations it is generally conceded that a COHb level of 5% is an upper-most acceptable value for a city population because in general, marked physiological effects can be demonstrated at this level (Hartmann, 1973). At levels of 5% COHb, cardiovascular changes impose greater burdens on the heart and circulatory systems of people with pulmonary emphysema and coronary heart disease (Grad, 1972). It has also been shown that exposure to ambient levels of 30ppm for 8 hours or 120ppm for 1 hour, may be a serious health risk to sensitive persons. Measurements inside vehicles in traffic in the U.S.A. showed averages of between 21 and 39ppm CO, (Berry et al, 1974). Health threats from automobile CO are generally considered to be a central-city problem and the World Health Organisation has set a CO ambient air goal of 9ppm (8hr. average) and 35ppm (1 hr average) in an effort to minimise risks to all persons (O.E.C.D, 1973).
At 15ppm the equilibrium level of COHb is 2.5-2.6% (Australia Academy of Technological Sciences, 1979). Results of monitoring in George St. Sydney from 1970-1973 show that on average the 8 hr. goal was exceeded 290 days per year and the 1 hr goal on 44 days per day (Iverach, 1976). U.S.E.P.A. standards are set so that COHb levels do not exceed 2.9% (Australian Academy of Technological Sciences, 1979). The effects particularly in monetary terms of exceeding such goals or standards (which vary around the world, O.E.C.D., 1973), remains largely undetermined. Clearly there is scope for more adequately assessing the problem and arriving at a more rational response to CO control based upon a fuller understanding of its effects in urban atmospheres. Amongst other factors these depend upon temperature, humidity and the condition of the individual. Ultimately it may prove simpler for administrative reasons to continue to assume certain adverse effects and work from the premise that the lowest levels possible are desirable.
(c) *Nitrogen oxides*

Nitrogen oxides include nitric oxide (NO) and nitrogen dioxide (NO₂). A significant portion of NO immediately oxidises to NO₂ but at most times in city streets the ratio of NO: NO₂ is about 2:1 (Sherwood and Bowers, 1970). Nitrogen dioxide is the only oxide of nitrogen believed to have an adverse effect on health at ambient concentrations; NO is not a health hazard (Grad, 1972).

The basic pathological response to NO₂ is an inflammation of the lungs but at higher concentrations, (e.g. 13ppm) not usually found in urban air, eye and nose irritation can occur; NO₂ is also injurious to plants in high concentrations (Berry et al, 1974). Nitrogen dioxide can be smelled at concentrations as low as 3ppm.

NO₂ has two primary effects on the respiratory system. First it has been correlated with a greater incidence of chronic lung disease and second it leads to a greater susceptibility to infection in the respiratory tract (Grad, 1972). Much of the evidence concerning short and long term exposure effects of NO₂ is based upon laboratory animal studies (Grad, 1972), with very much less being known about the effects of concentration of 1-3ppm common in polluted urban air (Berry 1974).
In Australia, available evidence suggests that ambient levels of NO₂ do not pose any significant direct health threats. Values generally fall below recommended W.H.O. and U.S. standards (Galbally, 1975, Bottomley and Cattell, 1975). It is generally conceded that the most significant effect of NOₓ is its role in the formation of photochemical smog (Australian Academy of Technological Sciences, 1979). This is particularly true of automotive NOₓ emissions which tend not to build up to significant concentrations except in highly polluted city areas where adverse meteorological conditions may prevail. A different situation however can occur where human settlements are located close to a number of high emitting sources (Grad, 1972).

In Australia NOₓ emissions from cars are controlled primarily to guard against photochemical smog formation, rather than for direct health reasons (Australian Academy of Technological Sciences, 1979).
As with NO$_x$ emissions, HC emissions are controlled almost solely to reduce or protect against photochemical smog, (Australian Academy of Technological Sciences, 1977). Some polynuclear aromatic hydrocarbons (P.N.A.) or cyclic hydrocarbons, however are known to have carcinogenic effects. The most common example is benzo(a)-pyrene one of the main combustion products in smoking. Diesel engines, especially when starting from cold emit high levels of benzopyrenes. One study suggested that breathing city air can give intakes of benzo(a)-pyrene equivalent to smoking between 7 and 36 cigarettes a day (Berry et al., 1974).

An epidemiological study in Switzerland strongly suggested a link between a greater incidence of cancer and people living near main roads. (Environmental Science and Technology, 1977). The reason, it was suggested, was the high levels of polynuclear aromatic hydrocarbons detected in the study area. A further study in the U.S.A. has suggested that directly active nitro derivative mutagens are formed on exposure of benzo(a)pyrene to gaseous pollutants in photochemical smog (Pitts 1978). The importance of this possibility is seen in the section on photochemical oxidants.
Automobiles generally contribute less than 5% of the P.N.A. in urban atmospheres and P.N.A. levels in emissions depend primarily on the P.N.A. content of the fuel. Commercially available motor spirit for the spark ignited internal combustion engine normally contains a maximum of 3ppm benzo(a)-pyrene, (Hakala et al, 1975). At present the direct health threats of hydrocarbons from conventional fuel appear to be of less concern than their role in the formation of photochemical smog. Some concern has been expressed however over the higher aromatic content of synthetic petroleum from coal, oil shale and tar sands currently being investigated in many parts of the world (Kant et al, 1974). (See Chapter 3).
(c) **Photochemical oxidants**

(i) **Background**

Photochemical smog is a mixture of various strong oxidising substances of which ozone ($O_3$) is the most important contributor. Ozone generally accounts for about 90 per cent of the oxidising capacity of photochemical smog (Ferrari and Johnson, 1976) and as it can be measured successfully, its concentration in the atmosphere is commonly used to indicate the degree of smog formation, (Australian Academy of Tech. Sciences, 1972). Other significant constituents include peroxyacyl nitrates (PANS), nitrogen oxides, aldehydes, hydrocarbons, acrolein and other aerosols. The haze or atmospheric discolouration which usually accompanies significant oxidant levels is caused by the absorption and scattering of light by aerosols (Australian Academy of Technological Sciences, 1979). The atmospheric chemistry of photochemical smog is very complex and not yet fully understood. A wide range of hydrocarbons with different photochemical reactivities take part in smog formation and there is a need to examine smog in each location to fully account for the mechanisms which may be operating.
For example a study of the potential for photochemical smog formation in Sydney in 1967 based on a Los Angeles model concluded there would be no problem until 1998 (C.S.I.R.O., 1974). The first recorded photochemical smog occurred in Sydney in 1971 and Sydney now has a major photochemical smog problem. Despite the lack of detailed knowledge the formation of photochemical smog is generally represented by the following reactions:

\[ \text{NO}_2 + \text{hv} \rightarrow \text{NO} + \text{O} \] (1)
\[ \text{O}_2 + \text{O} \rightarrow \text{O}_3 \] (2)
\[ \text{O}_3 + \text{NO} \rightarrow \text{O}_2 + \text{NO}_2 \] (3) (Ferrari and Johnson, 1976)

Reaction (3) tends to deplete ozone so high levels of oxidant do not generally exist in the presence of high levels of NO. City centres have relatively low oxidant levels due to higher concentrations of NO than in most other locations in the urban areas. If these were the only reactions involved ozone would not tend to build up. However NO is converted to NO\(_2\) by two processes: natural oxidation and reaction of hydrocarbons such as oxygenated hydrocarbon radicals, which react further with NO to form NO\(_2\). The conversion of NO to NO\(_2\) is further accelerated in sunlight by hydrocarbons, carbon monoxide, water, oxygen and other substances acting as intermediaries which produce a number of by-products some of which are organic compounds containing nitrogen (Australian Academy of Technological Sciences, 1979).
Apart from ozone, PANS are probably the next most important constituent in photochemical smog. PANS, acrolein and aldehydes are responsible for the eye, nose and lung irritation characteristic of smog days in cities such as Los Angeles; ozone is not an eye or nose irritant. (Australian Academy of Technological Sciences, 1979). The formation of PANS and NO$_2$ can be represented by a combination of equations (1), (2) and (3) and of three equations which are a simple summary of over 200 individual reactions.

\[
\begin{align*}
HC + O & \rightarrow \text{Products including} \\
HC + O_3 & \rightarrow \text{PANS ((HC)$_x$ OONO) and NO$_2$.} \\
HC + OH &
\end{align*}
\]

(Daly, 1977).

Overall, the formation of oxidants depends largely on the intensity of irradiation and the ratio of HC: NO$_x$, but because a large number of reactions are involved, the relationship is extremely non-linear, i.e. halving concentrations of either NO$_x$ or HC does not lead to a halving of oxidants formed (Daly, 1977).

The complexity of photochemical smog formation causes uncertainty in deciding which precursor is the most important to control: HC or NO$_x$. It is generally held that controlling HC emissions offers the most effective means of combatting smog (Bilger, 1978), although some control of NO$_x$ is essential, particularly over a number of consecutive days with meteorological conditions favourable for O$_3$ accumulation,
e.g. stable air masses, clear skies and subsidence inversions (Australian Academy of Technological Sciences, 1979, C.S.I.R.O., 1978). Considerable work has been done in Sydney to better understand ozone precursor relationships (Kewley and Post 1978, Post and Bilger, 1978). The complex nature of smog also causes considerable uncertainty as to which components are of the most importance to environmental health (Marshall, 1978).

(ii) Health effects

A number of health effects are attributed to ozone. These are:

(a) increased frequency of asthma attacks,
(b) aggravation of existing respiratory diseases,
(c) general impairment of lung functions especially during exercising and in children,
(d) chest pains, headaches, fatigue, and loss of visual acuity at high levels (e.g. during smog episodes in Los Angeles), (Berry et al 1974, Australian Academy of Technological Sciences, 1979).

(1) A smog episode occurs when an hourly concentration of ozone of 0.10ppm has been equalled or exceeded on three or more consecutive days (Ferrari and Johnson, 1976).
There is also some evidence to suggest that ozone reduces the body's resistance to respiratory infections (Ferrari and Johnson, 1976, Australian Academy of Technological Sciences). Research so far suggests that the effects of ozone are acute not chronic for healthy adults. This is apparently true for cities such as Tokyo and Los Angeles where ozone levels are, or have been, higher than Australian levels. High ozone exposure (e.g. 0.15ppm to 0.21ppm) however may permanently damage asthmatics and children, or persons with cardio-pulmonary problems (Australian Academy of Technological Sciences, 1979).

The effects of pure ozone above about 0.37ppm are generally accepted (Marshall, 1978). However, specific dose-response relationships below this level in a smog are more difficult to define because of the variation in susceptibility in a population, possible synergistic effects and the effects of other oxidants. For example the effect of ozone may be enhanced in the presence of sulphur dioxide (Australian Academy of Technological Sciences, 1979). In other words the response to pure ozone levels less than 0.37ppm may be different to the same ozone levels measured in a smog. As mentioned previously, it is the PANS, acrolein and aldehydes which are responsible for the frequent nasal, throat and eye irritation reported during photochemical smog activity overseas, not ozone (Grad, 1972). In Australia, photo-
chemical smog has not yet been reported to cause these responses, although oxidant concentrations in Sydney have reached 0.38ppm (1hr average) which are in excess of those required to produce irritation in other cities. For example in Los Angeles the threshold for eye irritation is about 0.10ppm (Grad, 1972, C.S.I.R.O. 1978, Australian Academy of Technological Sciences, 1979).

The only severe incidence of photochemical smog effects on humans in Australia occurred in Sydney in March, 1976, when three schoolboys were taken to hospital with chest pains and breathing difficulties (C.S.I.R.O. 1978). Ozone readings on the day near the site may have been between 0.02 and 0.29ppm (Academy of Technological Sciences, 1979).

In an effort to clarify the situation, W.H.O., (1972) studied data on oxidant effects and suggested the following dose-response relationships:

<table>
<thead>
<tr>
<th>Increased asthma attacks</th>
<th>Pulmonary dysfunction</th>
<th>Annoyance and eye irritation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125ppm</td>
<td>0.100ppm</td>
<td>0.100 ppm</td>
</tr>
</tbody>
</table>

These oxidant concentrations measured as ozone they concluded, would produce the stated effects in vulnerable members of the population. This study led to the setting of extremely stringent recommendations: a long term
8 hr goal of 0.03 ppm and a 1 hr goal of 0.06 ppm for photochemical oxidants. In the U.S.A. the standard for photochemical oxidants (measured as ozone) has been 0.08 ppm until recently when it was raised to 0.12 ppm (1 hr. maximum), (New York Times, 27th January, 1979). Not only has this standard been raised but it is for ozone only thus rejecting other photochemical oxidants as specific legislated pollutants (Marshall, 1978). Australia has not set goals for photochemical oxidants (Australian Academy of Technological Sciences, 1979).

The fundamental problem in setting any standard for smog is that it is still largely speculative as to what substance or substances are actually causing the symptoms which have been reported. Ozone levels are used as indicators of smog intensity and certain effects have been correlated with specific ozone levels, (e.g. increased asthma attacks in U.S. cities when ozone levels exceeded 0.25ppm (Australian Academy of Technological Sciences, 1979), yet unexplained differences between various locations still remain. Concern has been expressed that the new U.S. standard which is only for ozone, is assuming too much with regard to the health threats from ozone alone (Marshall, 1978). It is maintained, that although the level of ozone is a general indication of the level of other photochemical oxidants, it is desirable to continue the option of regulating all photochemical oxidants as new evidence on health effects appear (Marshall, 1978).
Considering the highly complex nature of photochemistry, and the comparatively small understanding of it, especially in specific locations, it would seem prudent not to assume that the potential danger of photochemical smog increases linearly with ozone levels. At present it can be concluded that for health reasons, it is important to minimize photochemical oxidants in urban airsheds. Clearly more needs to be known of the health effects of smog and particularly the reasons for the observable differences in response to similar levels of ozone in various cities. The epidemiology of photochemical smog responses also needs to be improved.

(iii) Materials, Plants and Visual Effects

Ozone damages textiles, discolours dyes and accelerates the cracking of rubber. Paints and synthetic fibres are also attacked by ozone (Berry 1974). In the U.S.A. in 1970 it was estimated that ozone caused damage to materials of $1.2 billion annually (Australian Academy of Technological Sciences, 1979). Other oxidants in smog may cause damage to materials (Grad, 1972).

Oxone, PANS and nitrogen dioxide damage plants according to their concentration and the duration of exposure. Effects of ozone may be (a) acute, characterized by leaf lesions and a drop in yield and reproduction or
(b) chronic, characterised by colour changes and necrotic patterns (Grad, 1972). Plant responses vary widely but tend to be more dramatic in citrus trees, ornamental plants and leafy vegetable crops. Effects may be noticed at ozone levels as low as 0.05ppm. (Australian Academy of Technological Sciences, 1979). Ozone also damages forest trees particularly conifers (Berry et al 1974). Estimates of crop losses in the U.S.A. are variable ranging from $100 million to several $100 million. In Australia estimates of plant damage are usually less than $100,000 per episode (Australian Academy of Technological Sciences, 1979). The effects of single episodes can however be severe. For example in 1959, in the U.S.A., $US5 million damage was done to tobacco crops in Connecticut in 2 days (Daly, 1977). PANS damage plants in a similar way to ozone but leave recognisably different lesions and may attack a wider variety of plants (Grad, 1972, Berry 1974).

There is some evidence that the haze which generally accompanies smog in Australian cities, increases with higher oxidant levels. However, the exact composition of summer haze in Australia is not known.
Melbourne and Sydney haze may be due to carbonaceous polymers whereas in the U.S.A. and Europe it is attributed to fine particles of ammonium sulphate (Australian Academy of Technological Science, 1979). Regardless of their specific cause, visual effects tend to engender more concerted remedial action (Sharp and Jennings, 1976), and it is likely that if a definite causal link between motor vehicle emissions and haze is established, then this may become a significant force in controlling vehicle emissions. The control of photochemical smog will remain a difficult problem while there continues to be a lack of fundamental knowledge about its mechanisms of formation and impact on humans, plants and materials. Photochemical reactions are invariably non linear, i.e. they occur when certain thresholds are reached; at present legislation tends to assume a linear situation and until more is known relevant to each Australian city little else can be expected. Meanwhile there is enough evidence to suggest photochemical smog should be avoided or reduced if at all possible.
The addition of lead to petrol was discussed earlier in this chapter. Lead is emitted to the atmosphere from motor vehicle exhausts as volatile lead compounds such as lead halides, unburnt tetra-ethyl lead and as particulates such as lead oxide (Bini, 1973). Automotive exhausts are the major contributors to lead emissions in most cities (Berry et al. 1974, Bini, 1973, Solomon and Hartford, 1976, Bryce-Smith, 1976), although other sources include plant and factory emissions. In the U.S.A. it is estimated that 90 per cent of total lead emissions are from car exhausts (U.S.E.P.A., 1978). The estimation of total lead emissions from motor vehicle exhausts remains a difficult task however due to complicating factors such as deposition or "hang-up" in vehicle engines and exhaust pipes in low speed driving, which may be emitted later during acceleration (Watson, 1978). Emission factors for lead may lie somewhere between 50 and 90 per cent of added lead (Bini, 1973).

Innumerable investigations into the pathological effects of lead have been carried out. The toxicity of lead in large quantities is generally accepted, the symptoms of which may include (1) severe malfunctioning of the alimentary tract (loss of appetite, constipation and colic), (2) general weakness and malaise, (3) impaired functioning of the nervous system (weakness, atrophy and paralysis of extensor muscles)
(4) permanent brain damage, (5) anaemia and death, (Berry et al., 1974, USEPA, 1978). However the health threats from ambient levels of lead in urban air are still rigorously debated.

The neurotoxic effects attributed to lead levels in urban air can be listed as follows:

(a) increased hostility and depression accompanied by a general sense of a loss of well-being (Bryce-Smith, 1976).

(b) hyperactivity in children resulting from a small degree of brain damage or dysfunction. Hyperactivity is characterised by a variety of symptoms. These include, restlessness, difficulty in concentrating, excessive talking, poor tolerance of frustration and poor control of impulses. Educational difficulties may ensue. (Bryce-Smith, 1976).

(c) hyperactivity predisposes individuals to delinquency and a link between high blood-lead levels and delinquency has been proposed (Bryce-Smith, 1976). A correlation between high blood lead levels and behaviour in children ranging from aggressive to violent has also been suggested (James, 1977).

(d) a general level of central nervous system dysfunction as evidenced by lowered scores in performance tests (1) on lead industry workers and others in lead contaminated environments. (Valciukas et al., 1978).

(1) neuro-behavioural clinical tests.
(e) The probability of abnormal red blood cell formation in subjects with blood lead levels above 20mg/100g of lead has been suggested (Bilger, 1972).

Two recent comprehensive studies claim to have further substantiated some of these links. An American report from Harvard Medical Centre and the childrens' Hospital Medical Centre in Boston Massachusetts (The Guardian April 15, 1979), has eliminated some of the social and environmental differences between test subjects and controls, which have overshadowed previous studies. The study claims that as a result of extensive psychological and mental investigation, children with a history of high lead exposure performed significantly worse than children with low exposure in all aspects of mental abilities (word processing ability, reaction times and intelligence tests). A systematic fall-off in the childrens' ability to concentrate and behave well was noticed with increasing lead exposure. The study was based on lead dentine levels in milk teeth.

In Australia a study which analysed lead content of Sydney air and the blood and hair lead levels of Sydney school children, arrived at similar conclusions concerning the effects of lead. These may be summarised as follows:

- raises the level of lead in air;
- raises the level of lead in blood;
- lowers the activity of the enzyme ALAD;
- lowers the erythrocyte level or haematocrit in blood;
- has an adverse effect on haematology;
- raises the body lead burden;
- raises the level of lead in hair;
- has some adverse effects on health;
- has a wide range of adverse effects on behaviour;
- raises the level of other undesirable metallic contaminants;

(Garnys, Freeman and Smythe, 1979)

As a result of their investigation they recommended that a number of important actions be taken to overcome the problem. These have been taken directly from their report:

1. Immediately lower the levels of lead in urban petrol to 0.30 gram per litre.

2. Implement legislation to progressively reduce the Pb-Air levels in urban areas from levels above 1.0 μg/cubic meter to 0.5 microgram lead per cubic metre of air, averaged over a calendar quarter and based on current high volume methods.

3. Implement legislation to encourage the progressive elimination of lead from petrol in the near future.

4. Aim to prevent individual schoolchildren in Australia from exceeding a blood lead level of 25 microgram per 100 millilitre of blood. On a population basis this represents a population arithmetic mean of 13μg Pb 100ml⁻¹ and a median of 12μg Pb 100ml⁻¹.

5. Establish a national "lead burden in children" monitoring program.

6. Establish and encourage public and private clinical facilities available to medical practitioners in the capital cities, for the determination of Pb-B, (1) ALAD, free erythrocyte protoporphyrin (FEP) and zinc protoporphyrin (Zn PP) in blood samples.

7. Establish studies to determine the effects on health and behaviour of lead burden in Australian children.

(1) Pb-B indicates blood lead level.
8. Establish studies to determine the cycle of lead from petrol in typical Australian urban areas. These studies should include forms of lead in air, surface run-off and automotive sump oil disposal.

9. Establish studies to quantify other metallic pollutants in urban air.

10. Establish studies to determine the origin of lead in hair of school-children, including studies to determine the relative levels of lead in the blood of scalp and brain tissues and correlations with venous and capillary blood to determine if lead in hair is a better index of brain damage than lead in venous or capillary blood.

(Garnys, Freeman and Smythe, 1979).

Concern over the effects of lead from automotive emissions has not been confined to urban air. Considerable investigation has occurred in a number of other important areas where the likelihood of lead entering food chains involving man has been considered high.

Ward and Brooks (1978) investigated lead levels in sheep grazed close to highways and expressed concern that high lead levels were found in kidneys, livers, lungs and bones. They recommended that the parts of sheep from lead contaminated areas be discarded to minimise the likelihood of lead ingestion by humans.

Soloman and Hartford (1976) analysed lead and cadmium dusts in a small U.S. urban community. Interior and exterior levels of lead in dust and soil were significantly higher than in non-urban communities. They concluded that the danger of direct lead ingestion by children from household dusts, could add seriously to body lead burdens.
The issue of lead accumulation in food chains has been raised by a number of authors in relation to automotive emissions (Bini, 1973, Bottomley and Boujos, 1975). Undesirably high lead levels have been correlated with traffic patterns.

The issue of lead in the urban environment, particularly the air, remains a subject requiring much more attention. For example, as recently as December 1977, the U.S.E.P.A. set an ambient standard for airborne lead of 1.5μg per cubic metre (Three month average). This was designed to protect children from exceeding 30μg lead per decilitre of blood, above which value, impairment of cell function is believed to occur (U.S.E.P.A., 1978). However, the latest recommendation from Australia is for no more than 25μg per decilitre (Garnys, Freeman and Smythe, 1979). In Australia the need to consider a number of important factors has been stressed:

(1) the effects of climate on lead build-up.
(2) the need to continuously monitor lead in a variety of locations.
(3) the need to know the precise nature of lead emissions and their movement through the environment. Lead in Australian fuel contains significantly different mixtures and derivatives of the basic lead forms,
(TML and TEL) as well as associated additives such as dibromoethane and dichloroethane which affect lead emissions (Personal communication Dr. O'Connor, W.A.I.T.).

2.3.3. Quantifying transportation air pollution damage

As has been shown it is a difficult epidemiological task to trace a specific adverse health effect back to one particular pollutant and many of the asserted links between pollutant and effect are still hotly debated. The lead issue is a particularly important example. The detailed reasons for this situation, related to isolating various interfering factors and identifying synergisms, is beyond the scope of this overview. It is thus an even more difficult and hazardous exercise to quantify, in monetary terms, the impacts of air pollution. The uncertainties are magnified even further when attempts are made to apportion these impacts to the various source sectors (e.g. transportation). Despite these inherent problems monetary impacts of air pollution remain important considerations in setting air quality standards (Grad, 1972). A number of important works have been carried out to quantify air pollution damage, some of which have been briefly discussed here.

(1) Walther (1972) attempted to rank the various pollutants from each source in the U.S.A. in 1969 according to their effects. Table 2.3 and table 2.4 show a summary of their work for the transportation sector.
### TABLE 2.3 Emissions from the U.S. transportation sector 1969, ranked by mass emitted

<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>ANNUAL QUANTITY</th>
<th>% OF TOTAL OF ALL SOURCES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^6$ tons</td>
<td>%</td>
</tr>
<tr>
<td>CO</td>
<td>111.5</td>
<td>77.2</td>
</tr>
<tr>
<td>HC</td>
<td>19.8</td>
<td>13.6</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>11.2</td>
<td>7.7</td>
</tr>
<tr>
<td>Aerosol</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>SO$_x$</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>144.4</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**SOURCE:** After Walther, (1972)

### TABLE 2.4 Emissions from the U.S. transportation sector 1969, ranked by effect

<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>ANNUAL QUANTITY</th>
<th>EFFECT FACTOR</th>
<th>EFFECT</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>19.8</td>
<td>125.0</td>
<td>2480</td>
<td>86.3</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>11.2</td>
<td>22.4</td>
<td>251</td>
<td>8.7</td>
</tr>
<tr>
<td>CO</td>
<td>111.5</td>
<td>1.0</td>
<td>111.5</td>
<td>3.8</td>
</tr>
<tr>
<td>Aerosol</td>
<td>0.8</td>
<td>21.5</td>
<td>17.2</td>
<td>0.6</td>
</tr>
<tr>
<td>SO$_x$</td>
<td>1.1</td>
<td>15.3</td>
<td>16.8</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>144.4</td>
<td>-</td>
<td>-</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**SOURCE:** Walther, (1972)
Table 2.3 shows that in terms of mass emitted, CO was the most important followed by HC and NO\textsubscript{X}.

Transportation overall accounted for 51.4\% of the total air pollution load in the U.S.A. in 1969. However, table 2.4 shows that when the actual effects were taken into account (the effect factors are based upon national primary ambient air quality standards in the U.S.A.), CO accounted for only 3.8\% compared to 77.2\% by mass. On the other hand hydrocarbons which accounted for 13.6\% of the total mass of pollutants from the transportation sector, accounted for 86.3\% of the effect from this sector.

The effect factor for HC which caused such a high ranking was based upon the importance of HC in forming ozone. (Berry \textit{et al.}, 1974). Despite the ranking changes, the transportation sector was still estimated to have accounted for 43.3\% (not shown in the tables) of the total air pollution effects in the U.S.A. in 1969 (Walther, 1972).

Obviously the validity of this analysis is highly dependent on the correctness of the effect factors. If the analysis is valid then it points to priorities in the spending of money to reduce air pollution both within the transportation sector and in the U.S.A. overall.

(2) Barrett and Waddell (1971) and later Waddell (1974) produced a lengthy and complex series of calculations to estimate the economic costs of air pollution damages which were based on:
(a) a survey of the literature on environmental economics.
(b) an extrapolation of other studies that attempted to estimate air pollution costs and which passed a critical review stage, and
(c) on prevailing air quality levels in 1970.

They concluded that valid methods to estimate air pollution damages in monetary terms must be based upon a broad combination of economic and social techniques such as:
(a) technical co-efficients of production and consumption.
(b) market studies.
(c) opinion surveys of air pollution sufferers.
(d) litigation surveys, and
(e) political expressions of social choice.

The results of their calculations for the U.S.A. in 1970 suggest that the total cost of air pollution damages might lie somewhere between US$ 6.1 billion and US$ 18.5 billion with a best estimate around US$ 12.3 billion. Of this it was estimated that only US$ 1.1 billion could be attributed to transportation (9%). Of this $1.1 billion 18.2% could be attributed to reduced aesthetics and soiling, 9.1% to human health damage, 54.6% to materials damage and 18.1% to vegetation damage.
It is significant to note however that the early 1970's saw the commencement of tight motor vehicle emissions standards (as already discussed) at considerable expense and opposition. The authors of the estimates admit that many of the costs of air pollution are not yet amenable to quantification in dollars and cents. It would thus appear that the movement to control automotive emissions was not at that stage based firmly in quantifiable effects, but rather in less tangible effects which were given a subjectively high ranking e.g. aesthetics.

(3) Small, (1977) performed a detailed analysis of the air pollution costs per km of various transport modes and produced estimates of total costs of air pollution in the U.S.A. in 1974. Of the $20.74 billion total cost estimate, $2.19 billion was calculated to arise from road transport (10.6%). Automobiles accounted for 75% of this $2.19 billion. It was concluded on the basis of known effects in terms of damage to health and materials and the resulting costs per kilometre of vehicle travel, that a reduction in automobile use is not justified, i.e. the social costs per kilometre of air pollution are low compared to the cost of motoring. However the relatively high air pollution costs per kilometre of automobile travel compared to the relatively low costs per kilometre of emissions reduction do, it was concluded, justify significant expenditure on air pollution control systems. The conclusions to this study stressed though, that such reasoning is only based on quantifiable environmental damage.
Small (1977) states:

The transport planner will have to use his or her own judgement as to the weight to be given to toxic lead accumulation, asbestos particles from brakes, aesthetics of smog, oil spills or water pollution from gasoline production, visual aesthetics of transport facilities, possible long term ecological damage and many other factors.

The vagaries of an economic analysis, which is so dependent upon quantifying what are often intangible effects, may not be as important as the continuing growth in awareness that photochemical smog, airborne lead and a steady haze are unacceptable to a large number of people. Surveys in U.S.A. and Australia continue to show that people place a high priority on the need to clean-up urban air. For example, the results of a 1978 survey in the U.S.A. show that air pollution was ranked high in seriousness. Table 2.5 summarises these results.
TABLE 2.5 "How serious do you feel (inflation, etc.) is in this country? Is it very serious, serious or not serious?"

<table>
<thead>
<tr>
<th></th>
<th>Very Serious</th>
<th>Serious</th>
<th>Not Serious</th>
<th>Don't Know</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation</td>
<td>64%</td>
<td>30%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Air Pollution</td>
<td>32</td>
<td>46</td>
<td>18</td>
<td>4</td>
</tr>
<tr>
<td>Energy shortage</td>
<td>29</td>
<td>48</td>
<td>19</td>
<td>5</td>
</tr>
<tr>
<td>Water Pollution</td>
<td>29</td>
<td>46</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Unemployment</td>
<td>26</td>
<td>41</td>
<td>27</td>
<td>6</td>
</tr>
</tbody>
</table>


Similarly a national U.S. survey in January 1977 to determine attitudes toward pollution cost trade-off alternatives, showed that in 1978, 53% indicated that environment standards could not be too high and continuing improvements must be made regardless of cost. In contrast only 10% in 1978 stated that standards had gone too far and were not worth the cost, compared to 19% in 1977. (Resources for the future, 1978).

The growing scientific and medical literature on the often subtle and unpredictable effects of urban air pollutants, will probably continue to sensitise people to this priority.
2.3.4. Leaded petrol - An energy-emissions issue

(a) Introduction

It has been shown so far that it is important for countries around the world to consider very closely their level of oil consumption. It has been shown that additional evidence on the health effects of lead in urban air is pointing strongly to the desirability of limiting lead emissions. The debate about leaded versus unleaded fuels is important because it embraces both these important issues and cannot be meaningfully considered without reference to both its energy and emissions implications.

It is the purpose of this section to review the leaded fuel debate with particular reference to Australia, in order to show the way energy and emissions have the potential to be either traded-off against one another, in which case an amenable solution is only found to one of the problems, or to be treated as two inextricably linked problems to be solved simultaneously.

(b) The debate

The most important petrol additives are tetra-methyl and tetra-ethyl lead. Lowering or removing lead from petrol invokes an energy penalty at the refinery and makes engine "knocking" a problem. On the other hand maintaining or increasing lead levels poses a potential health threat as described earlier in this chapter.
Lead additives have become a controversial issue in Australia where impending oil shortages and price rises are forcing consideration of ways to conserve petroleum. One suggestion is that present lead levels be maintained or increased rather than progressively lowered as is being done in N.S.W. (N.E.A.C., 1978). In N.S.W. legislation enacted on January 1 1975 is currently in force to limit the lead content of petrol sold in Sydney, Newcastle and Woollongong, to 0.45 grams per litre, and by the 1 of January 1980, to 0.40 grams per litre (S.P.C.C. undated). These actions are designed to minimise the lead exposure risk of people living in areas of high vehicle use. In comparison the current lead level in Perth for super-grade petrol is 0.83 grams per litre (Department of Conservation and Environment, 1979).

The reduction or removal of lead in petrol has numerous financial implications, including impacts on the present suppliers of lead additives, but the issue of current concern is the fuel loss at the refinery, associated with raising the octane number of petrol without lead. More feedstock must be used to produce a low lead petrol of equivalent octane number. If on the other hand, lower octane unleaded fuel with lower "anti-knock" quality, is accepted, then lower compression ratio engines are required to prevent knocking. This also involves a fuel loss because low compression engines have lower thermal efficiencies than high compression engines.
A study by Bettony and Cantwell, (1978) revealed some data which clarifies this situation:

1) Calculations by Exxon, Texaco and Phillips in the U.S.A. show that on average, an extra 5 per cent more energy would be consumed at the refinery to raise the R.O.N.\(^{(1)}\) of unleaded gasoline from 87.5 to 95. An R.O.N. of 95 can be obtained by adding 0.6 g per litre of lead without any fuel penalty.

2) When considering energy losses due to unleaded fuel, the factor of in-vehicle efficiency must also be considered. In doing this it is useful to examine the energy use factors step-by-step starting from a basic reference point. This data applies to the U.S.A., where unleaded fuel was introduced primarily to protect catalytic converters.

a) If unleaded fuel of R.O.N. 87.5 (base-case) is to be raised to an R.O.N. of 95, two alternatives are available: addition of 0.6 grams per litre of lead or extra refining without lead.

b) If the first alternative is chosen, no refinery energy penalty is involved, and a 10 per cent saving of fuel in the vehicle is possible over the base case.

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(1) Research Octane Number.
(c) If the second alternative is chosen, as low as a 3% loss in energy at the refinery may occur, but a 10% saving of fuel in the vehicle still occurs, maintaining the net energy loss at 3%. Similar analyses apply to raising the unleaded R.O.N. even further, e.g. 4% for R.O.N. 96.

(d) If on the other hand a lower octane unleaded fuel is accepted, and lower compression engines are used, the loss at the refinery may be less than 3% but the overall fuel penalty can be greater. For example in the U.S.A. R.O.N. 91 unleaded fuel is used in a fleet of vehicles with low compression engines (Shinnar, 1975) and the overall fuel penalty is estimated to be about 6.5% (DePalma et al. 1974). The major source of loss in this case is the vehicle inefficiencies introduced by lowering compression ratios.

(e) Shinnar, (1975) expanded this point even further by claiming that increasing the unleaded octane rating of all petrol in the U.S.A. above present values, and using higher compression engines, could improve in-vehicle efficiencies in excess of refinery losses.

(3) In Australia it was suggested that for optimum octane quality, the potential fuel loss from replacing leaded fuels with unleaded fuels would be 9%. This estimate however was based upon a maximum lead content of 0.84 grams per litre, a 0.29 grams per litre increase over the Australian average for 1977, and in this sense represents a maximum opportunity cost rather than a present real cost.
In response to these relationships the National Energy Advisory Council of Australia recommended that restrictions on the upper limit of lead in petrol be raised from 0.55 grams per litre to at least 0.65 grams per litre as high as 0.84 grams per litre by 1984-5. (NEAC, 1978). It also recommended that the use of lead filters be adopted to cope with the extra lead burden.

The issue of lead additives in fuel however is not a simple one, and it is certain that future policies on lead levels need to consider more than the energy problem just outlined. This is suggested by A.T.A.C. (1978) when it stated:

"The issues associated with the lead content of petrol require further examination in the Australian situation before an authoritative view can be stated."

It did not however elucidate what these issues might be.

Clearly, a number of important issues surround the question of leaded versus unleaded fuels. These can be summarised by the following points.
(1) Firstly, the "anti-knock" quality of lead is an important consideration in the design of engines. It has been found that unleaded fuel of the same octane rating as leaded fuel still cannot match the "anti-knock" performance of the latter. When unleaded fuel is introduced, closer attention to design is required to minimise the tendency of the engine to "knock" (Addicott and Barker, 1971).

(2) The Prime Minister's energy policy statement (Prime Minister, 1979), which alludes strongly to the likelihood that the Government will support the N.E.A.C. recommendation, must be seen in context with trends in other countries. The U.S.A. has introduced unleaded fuel, although a choice is still available. West Germany is aiming to produce unleaded fuel by 1980. At present the average level is only 0.15 grams per litre. In the U.K. and U.S.A. the average lead level is 0.45 grams per litre (Hothersall and Salter, 1977). Legislation to reduce this to 0.13 grams per litre by January 1, 1979 was successfully challenged by the Ethyl Corporation, but an appeal by the U.S.E.P.A. is in progress. The highest value of lead in U.S. petrol was 0.69 grams per litre in 1970 (Ehrlich, Ehrlich and Holdren, 1977).

(3) The general environmental effects of lead in food chains, and more specifically the human health issues of urban air lead levels are of major concern in the debate.
It is therefore necessary to attempt to incorporate, preferably in a quantitative manner, these social costs of lead additives in any assessment of future policy. In terms of the Australian situation, this would involve weighing up the social costs of lead additives against the 3% increase in petrol supply, predicted by the Federal Government, if lead levels were raised. This assessment would also need to consider the Federal Government's contention that it:

... recognises that health considerations have to be taken into account but this measure (raising lead levels.) is one which can be implemented quickly and reversed quickly. (Prime Minister, 1979).

(4) The lead emissions problem is inseparable from the issue of other motor vehicle air pollution. It has been pointed out that the use of unleaded fuel has the potential for lowering HC, CO and NOx emissions by allowing the use of catalytic converters in motor vehicles (S.P.C.C., 1979, De Palma et al., 1974). The use of catalytic converters in the U.S.A. has allowed motor vehicle manufacturers to revamp the fuel economy penalties engendered by other forms of emissions control over the past ten years (ATAC, 1978). In this sense unleaded fuels may offer some balancing mechanism to offset the more immediately obvious refinery losses associated with their manufacture. The use of catalytic converters does however present numerous other problems such as susceptibility to tampering, sensitivity to the use of incorrect fuels and the possibility that they might hinder more fundamental engine design changes to prevent pollutant production (Australian Academy of Technological Sciences, 1979).
(5) Thought should also be given to the potential of alternative additives to raise octane ratings and yield good "anti-knock" performance. In the U.S.A. methyl-cyclopentadienyl manganese tricarbonyl (CH₃C₅H₄Mn(CO)₃) has been used and shown to be about twice as effective as tetra-ethyl lead in raising petrol octane numbers (Surgeon General, 1962). Its use however seems to have been restricted to improving the "anti-knock" quality of fuel in conjunction with lead. There are also some doubts about the toxicity of the resulting emissions of manganese. For example the threshold limit value (1) in air for emissions resulting from this additive, is 0.1 micrograms per cubic metre as manganese (U.S. Dept. of Health Educ. and Welfare, 1976). By contrast the USEPA states a National Ambient Air Quality Standard for lead of 1.5 micrograms per cubic metre (three month average). The T.L.V. may exceed this amount (U.S.E.P.A., 1978). Although these data are not directly comparable it does suggest that substituting manganese for lead in petrol may not be advantageous from an emissions standpoint. Concern has been expressed over ambient levels of manganese in some urban areas (W.H.O, 1972).

(1) TLV represents upper limits in ceilings on human exposure to a substance before adverse effects occur.
Similarly, any alternative to lead would need to be thoroughly investigated from a toxicity and economic standpoint.

Alcohols raise octane ratings when mixed with petrol in ratios of 10-20 per cent or more. Lead free fuel can be produced in this way (ATAC, 1978). This is discussed in Chapter 3.

Other possibilities for raising octane numbers are high-benzene or high-toluene petrol, although these may raise polynuclear aromatic emissions (Bini, 1973). The effects of these on health are discussed earlier in this chapter. Cycloparaffins can also be used without producing objectionable emissions (Bini, 1973).

(c) Summary

In summary, close attention is needed to the issue of petrol additives and fuel quality from both an energy and environmental standpoint. Such changes as the current proposal to increase the octane rating of standard petrol in Australia from 87 to 92, so that 30% of the vehicle fleet may use standard fuel, instead of the present 10%, needs to be evaluated using both these criteria.
Currently it is usual to assess such proposals only from the energy efficiency viewpoint (ATAC, 1978). A more comprehensive assessment of the energy-emissions trade-off might yield a markedly different picture. This example shows in one important way, the fundamental need to consider the many energy-emissions links in road transport and urban planning, which are developed in detail in this thesis. It also leads onto the next section of the study which is a literature review of the many options which are being presented in an attempt to simultaneously solve the problem of urban transport energy and emissions.
CHAPTER 3

OPTIONS FOR SOLVING TRANSPORT ENERGY/EMISSIONS PROBLEMS - A LITERATURE REVIEW.

3.1 A CONCEPTUAL MODEL FOR EXAMINING ENERGY/EMISSIONS PROBLEMS.

The problems of transport energy and emissions have been shown in Chapter 2 to be serious in the short and long term for Australian cities. It is also not difficult to see that the two problems are highly related. There is a large body of literature which has developed to show that there is a close relationship between energy use and environmental impact (Ehrlich & Holdren, 1971; Newman, 1975). The thermodynamic relationship between energy use through combustion and the generation of emissions is a fundamental chemical phenomenon. It is important therefore just considering this physical relationship, to approach the solving of energy and emissions problems in a unified way.

It is also important to generate a systematic and unified approach to the two problems from a number of other perspectives. First, it may seem easier in the short term to trade-off gains in one problem with losses in the other, e.g. emissions controls that mean greater energy consumption or energy conservation that leads to worse emissions. However, such an approach can only be temporary, and if encouraged could misdirect a lot of technological innovation and waste valuable investments by failing to
consider a more permanent solution to both problems. Second, enduring solutions will not be found unless all possible options are seen together, their individual advantages and disadvantages weighed up, and the various implications and trade-offs examined. These options cover all aspects of society from individual lifestyle choices to collective economic/political choices, and from purely technological choices to fundamental ethical choices.

It is not possible to make an assessment of all these options available. However, it is the aim of this study to review the options in terms of 3 factors – technological, land use and human factors. These have been placed in a conceptual model which enables some perspective to be gained on how they relate together.

Fig. 3.1 A conceptual model for examining energy/emissions problems.

The model shows how energy and emissions are closely inter-related, how they are mutually affected by each of the other factors and hence should be solved as...
part of the one problem.

Each of the three factors have a direct impact on the problems, but they are also related to each other; they are rarely separate isolated factors.

**Technological** factors include the type of vehicles, their engine characteristics and capacity to be adjusted to meet higher standards of fuel and emissions; it also includes alternative fuels and electronic alternatives to travel. However, it is not hard to see how the type of vehicle in a city can alter land use patterns and vice versa, or how human values and social goals can affect the priority to be placed on new cleaner and efficient but more expensive vehicles.

**Land Use** factors include the design of the city, its density, centrality and amount of roads and parking; all of these factors again having technological and human components.

**Human** factors include individual lifestyles, human values related to mobility and access in a city, questions of priority in regard to technological change and the social economic and political framework which obviously gives so much direction to land use and technology.

This study cannot hope to make an exhaustive list of the options for solving energy/emissions problems in all these areas. The aim has been to concentrate on the technological options primarily, the land use options where
possible, and the human factors where they arise from the other two. Several reasons for this approach are offered.

(1) A major reason for making this approach was gained after examining the literature on energy/emissions: there is an enormous amount of literature in the technological area, less so on land use and very little on human questions. However the quantity of literature does not mean it has been systematically examined and it soon became apparent that overviews of the problems were very rare as discussed in Chapter 1.

(2) Many of the authors and not necessarily just those in the popular press, have presented their findings in a way which shows where they consider the most hopeful solutions to be. Invariably this has been in a technological direction with land use factors and human factors being considered less hopeful or at least very long term. It was therefore an aim of this review to try to examine the validity of this hope through an assessment of the technological option primarily and the land use options where possible. The human factors will be referred to only as they come out of these two approaches.

The nature of the technological hope and the virtual dismissal of the other factors is found in both attempts to solve the energy and the emissions problems.

Energy

Some writers see the elimination of technological inefficiencies as a virtual solution to at least the energy
supply problem (Shinnar 1975, Carrier 1974, Karagheuzoff, 1974). Others see technological change as the most cost effective and efficient way of saving energy in the short term (Hirst, 1976). Still others at least recognise the other factors (Fels and Munson 1974, McGillivray 1976) but all however tend to view the technological factors as the "soft" or easy options and the other factors as more difficult to change, i.e. the "hard" options.

The appeal of all these technological solutions to energy supply is easily appreciated, by considering some facts about cities. Use of the private motor vehicle has become a dominant feature of lifestyle in most Western cities whereby because of their low density, dispersed land use, access to a car has become almost essential. The Executive Director of the Australian Road Research Board states:

I must point out that there is at present, virtually no community acceptable solution other than the private car, to the provision of reasonable transport services to the low density suburban areas that comprise most of our cities (Lay, 1979).

Pierce further elaborates this situation by describing the inertia in the present system of transport in the United States, he states:

One does not have to be a partisan of the automobile to recognise that virtually every aspect of American life - industrial, commercial, cultural and recreational - is now organised around the existence of motor vehicles. Whether or not they provide the most rational means of transportation in an advanced technological society is, of course, a matter of debate (and) ...no dramatic change in transportation methods or habits can be expected or effectuated in the short run, say before 1990 (Pierce, 1975).
These statements suggest that such automobile based cities have evolved to a point where commitment to technological improvements in the transport systems which serve them appears essential to their survival.

Two further studies elaborate upon this conclusion and introduce the idea that technological improvements are a means of circumventing lifestyle and locational changes which may be undesirable or too difficult to foster. In this capacity, technology is perceived as affording a "path of least resistance" or "soft" option for Governments attempting to formulate policies to overcome energy supply problems.

A recent study in the U.K. estimated that the highest energy savings are possible through changes in the technology of private vehicles;

...changes in private vehicle technology appeared an attractive target area, particularly as it would not require the significant locational change which would be necessary to achieve a high level of transfer to public transport services of journeys to work by private vehicle, or the locational change and the likely social costs involved in a substantial reduction in other personal and social travel by private vehicles (Maltby et al, 1978).

The qualification was made that this prediction assumed no extra travel would result from improved fuel economy of private vehicles.

A comparable study in the U.S.A. arrived at similar conclusions;

During the last 3 years, there has been a significant shift to high mile per gallon autos, but they still constitute less than half of new
car sales. Thus, there is much to be accomplished through improvements in the mile-per-gallon efficiency and mix of new cars sold each year, but this is a long term effort. The trend toward improvement must be promptly accelerated. This will save the most fuel and minimize disruptions of lifestyles. Since smaller cars cost less and increased fuel efficiency results in reduced operating costs, costs to operators are reduced (French, 1976).

Distinct from the perceived benefits of maintaining the present economic structure and lifestyle, the desire to eliminate obvious technical inefficiency in the present transport system, is a normal rational response to the limitations imposed by scarcity and high price of an essential resource. Most economic and personal activities initially respond to circumstances involving high price or scarcity by encouraging improved efficiency.
Emissions

The assessment of the emissions problem has many similar features to the energy problem. The majority of approaches tend to see it as essentially a technological problem. Other approaches which have been suggested in the literature (Krzyczkowski et al., 1974), for example increasing public transport patronage, car and van pooling (which would also tend to lower energy consumption) and monetary methods such as emissions taxing, are generally viewed as more indirect, longer term options. They are also considered politically less attractive. The idea of staggering working hours has also received some consideration as a means of both reducing emissions through lower congestion, and spreading the emissions load more evenly throughout the day to avoid the sudden concentration build up which occurs in morning and peak periods. This too is considered as a somewhat indirect way of tackling the problem and possibly ineffectual approach.

It is important therefore, to examine the whole range of technological options available to assist in reducing emissions and to see how compatible they are with the energy conservation goal. These options embrace a wide field of research from minor changes in present technology (i.e. efforts to clean up present vehicles), to entirely new engines and alternative fuels.

There is however one important difference between reducing emissions and conserving fuel. The
Academy of Technological Sciences, 1979). Thus there will be a discussion in this chapter of some of these trade-offs that are being experienced by the individual vehicle owner.

It is not hard to recognise that behind many of the technological changes designed to control emissions are difficult human questions: does a government have a right to assign a level of environmental quality which can increase costs to the individual, and should individuals have the right to remove emissions control devices if they consider increased fuel consumption to be a bigger problem? This thesis will not try to answer such questions but it will try to review the potential for technological change to make significant emissions reductions (with and without extra fuel consumption); it will also examine some of the lesser known land use options with potential to reduce both emissions and energy consumption.
The aim of the literature review is to systematically review the range of technological and land use options available in the search for solutions to energy supply and emissions problems in urban land transport systems. It has attempted to place each option into perspective with respect to its potential energy and environmental benefit particularly which options may assist both energy and environment, and which might be helpful to one but antagonistic to the other. However, it was also necessary to make some technological assessment using criteria other than just fuel and emissions. If other reasons will preclude the technology or make it very attractive, then fuel and emissions criteria may be superfluous. Thus other criteria are used such as engineering feasibility, (how complex it is, and how far off the drawing board it is) economic costs, (both capital and recurrent), the infrastructure changes required and safety. Such detailed considerations are also essential to gain a clear understanding of how technological changes might take place, and how technology must be considered in relation to the other factors shown in the model.

In the light of the evidence presented, some overall conclusions have been drawn regarding what might be a sensible level of reliance on the potential of technological options and land use options to forge sound and lasting contributions to energy conservation and emissions abatement.
3.2 TECHNOLOGICAL OPTIONS

3.2.1 ALTERNATIVE FUELS

3.2.1(a) Introduction - The need for alternative fuels

Much of the discussion of energy conservation and emissions control in ensuing sections will be centred upon efforts to improve the way in which fuel is used, which presupposes a continuation of supplies in one form or another. At present, transport systems around the world are locked into a reliance on liquid hydrocarbons as an energy source. Most analysts would agree that this situation will eventually give way to some other system. In the interim however, concerted efforts must be made to progressively mitigate this dependence which has many undesirable security and environmental ramifications. These have been fully described in Chapter 2. The process ahead thus seems to be one of trying to use more efficiently hydrocarbon fuel supplies in one form or another, while portending some more fundamental changes in transport energy supply.

In this section alternative fuels will be reviewed as part of the overall effort to find lasting solutions to energy and emissions problems.

Alternative fuels may be defined as non-petroleum based substitutes for naturally occurring oil suitable for the automotive transportation sector (Gonnermann, Moore and McCallum, 1975).
A major impetus behind the development of alternative liquid and gaseous fuels is a general awareness of the need to diversify transport energy sources. Unlike the commercial, residential and industrial sectors which may draw energy from a variety of sources (e.g. coal, oil, natural gas, nuclear, solar or wood) transport is almost totally dependent upon dwindling oil supplies. Developing alternative fuels is one way of mitigating this vulnerability and preparing for what must ultimately be a post-petroleum world (Hayes, 1977).

The oil supply problem is thus a very important reason for the upsurge of interest in new transport fuels. However, a number of other factors have featured, though perhaps less dramatically, in this growing field of research. Firstly, the health threats from leaded petrol are causing a general movement away from fuels which require lead additives. This in turn has led to concern over how to avoid excessive oil consumption in the refining of unleaded fuels and how to match the superior "anti-knock" performance of leaded fuels in present vehicles. Secondly, the problem of automotive emissions has highlighted the desirability of using fuels with inherently cleaner combustion properties such as L.P.G. Using cleaner burning fuels could greatly simplify emission control procedures in present vehicles, and in alternative combustion systems (see section 3.2.2) could eliminate them entirely.
The development of alternative fuels is thus very closely linked to changes which will be necessary in the technology of motor vehicle propulsion systems. Substantial research efforts are therefore being put into producing alternative fuels which will be compatible with present internal combustion engines, (e.g. syncrudes) or will require relatively minor changes (e.g. methanol blends, L.P.G.). This approach is seen by some as the only way alternative fuels may have any impact on energy supply or emissions in this century (Carlson and Goss, 1975, King, 1978).

Before a new fuel could be seriously considered as a potential replacement for conventional petroleum in urban areas, a range of other important criteria would have to be met. Many of these relate to the broader issues of overall compatibility with present urban systems. These may be listed as follows;

(1) It must have a sufficiently high energy density to supply ample power in short bursts or as required.

(2) It must be in a form which is conveniently carried in the vehicle and easily renewed.

(3) It must be capable of being stored and transported safely, preferably using existing infrastructure.

(4) Its combustion properties should be such that air pollutant formation is minimised and no potentially toxic substances are emitted.
(5) It should not be in limited supply.

(6) It must not be prohibitively expensive and its use in motor vehicles should allow comparatively simply, mass produced systems to be adopted.

(7) Its provision in large quantities should not jeopardise the environment from which it is taken or derived.

(8) Its use should have a minimal adverse effect on the engine.

(9) Its adoption should not place its users in a position of vulnerability with respect to supply disruptions, and,

(10) Its provision, distribution and use should be as compatible as possible with the present economic order and structure or at least be conducive to a gradual phasing-in process involving minimal disruption.

These criteria limit the choice of substances and sources amenable to supplying energy for transportation in the future. In particular these conditions place severe constraints on short-term alternatives (0-10 years).

A wide range of fuel types have been investigated in an effort to find a fuel or number of fuels which are both capable of propelling a vehicle and meeting some of the broader requirements listed above. From the literature review, the fuels investigated can be grouped into two
distinct categories: (a) Fuels with some proven technological potential, (b) Fuels with more serious technological problems.

Fuels in the first category include;

(i) Methanol
(ii) Ethanol
(iii) Liquid Petroleum Gas (LPG)
(iv) Petroleum fuels from coal, oil shales and tar sands.

Fuels in the second category include;

(i) Methane
(ii) Hydrogen
(iii) Ammonia
(iv) Hydrazine.

Each of these fuels has been investigated in some depth to assess its potential as an oil substitute and its ability to reduce the automotive emissions problem. This section summarises the results of these investigations.
3.2.1(b) Fuels with some proven technological potential.

(i) Methanol (CH$_3$OH).

The use of blended methanol-petrol mixtures and pure methanol in internal combustion is not new. During time of oil shortages such as in war, and at other times of oil shortage fears, renewed interest in methanol has been shown, but this interest has generally receded as oil supply security returned. Since the Second World War until about 1972, most methanol fuel development has been directed towards racing, but since 1972 there has been a greatly renewed interest in methanol as an ordinary motor fuel. This has been brought about both by the introduction of stringent motor vehicle emissions standards and the growing oil supply problem (Gonnermann, Moore and McCallum, 1975).

Production

The following discussion examines methanol for automotive purposes by considering four main headings: Production, Advantages and Disadvantages - U.S.A. Experience, Engine Design Modifications and Emissions and Fuel Economy.

Methanol may be thought of either as a renewable resource or a non-renewable resource depending upon how it is derived. Methanol may be synthesised from vegetable matter such as crops, crop residues, municipal wastes, wood, natural gas, petroleum, oil shale and coal (Carlson and Goss, 1975). Methanol was produced from wood by pyrolysis
and distillation at Wundowie in W.A. until 1977. Large quantities of methane are flared to waste in the Middle East, and it may even be possible to economically synthesise methanol from this waste and transport it as liquid methanol (Advisory Council on Energy Conservation, 1977). Using nuclear or solar power it may also be possible to synthesise methanol from water derived hydrogen plus carbon dioxide (Tillman, Spillman and Beach, 1975).

In as far as there are sufficient biomass resources (e.g. land, water, fertilizer) to provide raw materials for methanol production at the level required, methanol is a renewable resource. Synthesis of methanol from other hydrocarbon sources however has a finite life span and pre-empts these non-renewable resources from other uses.

Methanol may be used as a complete substitute for petrol or it may be blended with conventional petrol as a fuel supplement. There are technical and economic difficulties associated with both its method of use and with the various methanol production methods.

Methanol is most readily synthesised from natural gas or methane, but there is an energy loss of about 50% associated with this method. The latest production processes claim about 68% thermal efficiency (Energy Advisory Council, 1979). In the U.K. the use of natural gas for methanol production is considered too costly in
energy and economic terms because natural gas has other important uses (Advisory Council on Energy Conservation, 1977). This situation also applies to the U.S.A. where natural gas is only sufficient to meet existing demands and growth (Tillman, Spillman and Beach, 1975).

In Australia, N.W. Shelf gas could be used for methanol production, but at the present time on a per barrel basis this is much more costly than world oil prices and even more costly in terms of energy equivalence (Endersbee, 1979). This is because the energy content of a barrel of methanol is about half that of a barrel of oil (Hughes et al, 1975). The calorific value of methanol is 19.6 MJ/kg compared to 43.9 MJ/kg for gasoline (Energy Advisory Council, 1979). An assessment by the Energy Advisory Council, (1979) in W.A. concluded that natural gas is better used as a straight fuel than converted to methanol, even though by 1986 up to one-third of North West Shelf gas could be used in fuelling Australian cars with a 15 percent methanol-petrol blend (A.T.A.C., 1978). No estimate of how long this could continue was given.

Methanol may also be produced from hydrogenation or gasification of coal, by coal liquefaction and from processing of oil shales. These methods are however more complex and costly. Coal must be converted into liquid refinery feedstock which can then be used to produce methanol. There are also significant environmental problems associated with water availability, land rehabilitation and waste disposal (King, 1978, Carlson and Goss, 1975). In the
U.K., hydrogenation of coal is viewed as being better suited to producing conventional hydrocarbon fuels which are safer to manufacture and store (Advisory Council on Energy Conservation, 1977).

The potential of methanol production in Australia from biomass and coal has been studied in some detail. In a major report to the Commonwealth Bureau of Roads in 1975 it was suggested that in-situ coal gasification will provide the basis for methanol production in Australia (Economic Research Unit Pty. Ltd., 1975). However, the capital costs of methanol production from coal in Australia need to be examined. Table 3.1 shows the capital costs and annual operating costs of a number of coal-to-methanol plants compared to similar data for a natural gas to methanol conversion plant.

Table 3.1  Capital cost of methanol plants (5000 tonnes/day)

<table>
<thead>
<tr>
<th>Feedstock and Location</th>
<th>Feedstock costs</th>
<th>Total Capital Investment ($Amillion)</th>
<th>Annual Operating Costs ($Amillion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas, Dampier</td>
<td>$1/10^6$ BTU</td>
<td>235</td>
<td>93.0</td>
</tr>
<tr>
<td>N.S.W. black coal,</td>
<td>$10/tonne</td>
<td>396</td>
<td>80.4</td>
</tr>
<tr>
<td>near Newcastle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Queensland black</td>
<td>$13/tonne</td>
<td>396</td>
<td>92.2</td>
</tr>
<tr>
<td>coal Gladstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Victorian brown coal</td>
<td>$2.50/tonne</td>
<td>451</td>
<td>86.3</td>
</tr>
<tr>
<td>Latrobe Valley</td>
<td>$2.50/tonne</td>
<td>453</td>
<td>80.1</td>
</tr>
</tbody>
</table>

The table demonstrates that substantial amounts of capital are required to establish a single coal-to-methanol plant. The 5000 tonnes per day example considered in Table 3.1 would provide enough methanol to supply a 15 percent blend for the 1977 Australian motor vehicle fleet (ATAC, 1978).

In a study of South Australia's energy for transport it was concluded that coal liquefaction for the production of any type of synthetic fuel would not be viable for Australia as a whole until 1990, due to economic, environmental and technical problems (King, 1978). It is estimated that the production cost of methanol from coal would be twice the cost of oil from coal (ATAC, 1978). A study by the C.S.I.R.O. differs from this assessment however, stating that the cost of methanol from coal would be 10-14 cents per one litre equivalent of motor spirit while the cost of motor spirit via oil from coal using the Sasol process would be 19 cents per litre. This data applies to 1975-1976 dollars (Stewart et al., 1979). Similarly a U.S. assessment estimated that gasoline from coal would cost $2.24 per $10^9 J to manufacture, whereas methanol from coal would cost $1.90 per $10^9 J to produce. Both estimates are in 1973 U.S. dollars (Billings, 1975).

In the same C.S.I.R.O. study the potential of producing methanol from various biomass sources was reviewed. It was estimated that by using all available crop and forest residues and planting all available arable
land not presently used for food and fibre production to suitable energy crops and fuel plantations, about 287 PJ (287\times10^{15} \text{J}) of methanol could be produced. The total amount of liquid fuels used in Australia for transport in 1977-78 was approximately 700 PJ. Thus the potential liquid fuel production in the form of biomass-derived methanol would equal about 41% of Australia's 1977-78 transport energy needs. About 22% of this production would come from existing residues and 19% would come from energy crops (Stewart et al, 1979).

This assumes that all the estimated potential could actually be realised. Such an achievement would involve considerable time lags and would not be a straightforward exercise because of the large area from which residues and crops would have to be collected and transported. On the basis of capital costs per GJ (1\times10^9 \text{J}) of gross annual output for the various methanol sources, a conservative estimate of the capital costs necessary to meet the production potential outlined above is A$8,520 million. Such capital requirements would need to be met over a number of years. It is also difficult to stimulate early investment in such projects when the price of the final fuel is higher than that of oil (Endersbee, 1979). It is estimated that methanol (one litre equivalent of motor spirit) would cost about 3 to 4 times as much as motor spirit (Stewart et al, 1979).
Advantages and Disadvantages - U.S.A. Experience

In addition to the economic problems associated with producing methanol, there are numerous other considerations which must be taken into account including the technological problems associated with methanol production. In other countries, particularly the U.S.A. which has vast coal and oil shale reserves, very substantial and detailed feasibility studies of methanol for automotive purposes have been made. It is necessary to present some of the findings of these studies to gain a complete picture of the problems and advantages of using methanol.

Methanol is suitable as an automotive fuel for a number of reasons. These can be listed as follows;

(1) Pure methanol has a research octane number of 106 which allows the compression ratios of conventional engines to be increased which in turn results in higher thermal efficiency (Farmer, 1975, Carlson and Goss, 1975).

(2) Blended methanol-petrol burns cooler and more efficiently and yields better fuel economy in terms of kilometres per MJ. Up to 20% methanol-petrol blends can be used in conventional engines with no major modifications (Farmer, 1975, Carlson and Goss, 1975). Methanol has good octane blending characteristics although it does reduce the effectiveness of the butane and pentane components of petrol which assist in motor vehicle starting efficiency (ATAC, 1978).
(3) Methanol has the potential to substantially lower vehicle emissions, especially NO\textsubscript{x} due to its cooler burning characteristics (Farmer, 1975, Carlson and Goss, 1975). This is discussed in more detail later.

There are however a number of problems associated with the use of methanol. The most important ones can be listed as follows;

(1) Methanol is sensitive to water: methanol-petrol blends are susceptible to phase separation when in contact with small amounts of water, i.e. two layers will form in the fuel tank - one of water-methanol, the other of petrol-methanol. Water absorption by methanol makes distribution by the existing petrol system problematic. This can possibly be overcome by the use of emulsifiers (Economic Research Unit Pty. Ltd., 1975) or by distributing the methanol in a dry form and blending at the pump to avoid phase instability.

(2) A 5-10 percent blend of methanol in petrol has a high vapour pressure which gives a non-ideal solution.

(3) Some driveability problems can arise due to change in air-fuel ratio necessary to burn methanol-petrol blends.

(4) Methanol has higher distribution costs on a per MJ basis due to its 50 percent lower energy content (by volume). In effect a complete changeover to methanol using the existing distribution system would result in a halving of its energy carrying capacity.
Storage of methanol requires effective sealing against water, although this should not be a major problem.


Methanol production problems and potentials have been exhaustively analysed in the U.S.A. Some of the results of these studies can be summarised as follows:

(1) The technology of producing methanol-from-coal is similar to that of producing crude oil from oil shale and is ready for first generation commercial production (Hughes et al, 1975).

(2) Methanol-from-coal technology is more advanced than that of crude oil-from-coal mainly because greater attention has been paid to substitute natural gas (SNG) than coal liquefaction over the past 10 years (Hughes et al, 1975). In Australia it is estimated that coal-to-methanol technology is about 5 years ahead of coal-to-oil technology (ATAC, 1978).

(3) Methanol-from-coal has been identified as a possible fuel source for the 1975-1985 or 1985-2000 time periods. However, market uncertainties surround methanol for large scale commercial use. In the U.S.A. it has been estimated that by 1985 methanol production will still be restrained and before 1985 its principal use may be limited to fuel for electric utilities (e.g. gas turbine generators) (Gillis, Pangborn and Vyas, 1975, Hughes et al, 1975).
Despite its relatively advanced state of technological development, methanol in the U.S.A. is estimated to cost more than any of the petroleum type fuels (Farmer, 1975).

A study to determine the 'maximum credible implementation scenario' for synthetic fuels in the U.S.A. estimated that by 1990 a total of 1 million barrels per day (oil equivalent) of methanol could be produced and by 2000, 4 million barrels per day (1460 million barrels per year) might be possible (Hughes et al., 1975). It is estimated that in 2000 the automotive energy demand for the U.S.A. will be $30.3 \times 10^{15}$ Btu (31950 PJ) or 5387 million barrels of oil. \(^{(1)}\)

Automotive energy demand currently accounts for about 55% of U.S. crude oil consumption (Gillis, Pangborn and Vyas, 1975). If current automotive oil demand trends continue in the U.S.A. and are able to reach 5387 million barrels per year, then the maximum percentage of that demand which can be met by methanol from coal is 27.1 percent. In 1985, demand for automotive energy is expected to be $20.2 \times 10^{15}$ Btu (21,300 PJ) or 3592 million barrels, and at this time maximum methanol production is expected to be only 109.5 million barrels per year oil equivalent or 3.1 percent of demand (Hughes et al., 1975, Gillis, 1975).

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\(^{(1)}\) Assumptions used in conversion:

Crude oil = 160,800 Btu (average) per Imperial Gallon
Imperial Gallon = 0.02859 Barrels of oil (White et al., 1978).
Pangborn and Vyas, 1975). Such scenarios show methanol in a much more favourable light if the transport energy demand were to be reduced. Options which show the feasibility of such reduced demand will be examined in later sections.

**Engine Design Modifications**

Methanol-petrol blends up to about 20 percent can be used in conventional engines without major modifications, although 15 percent is usually considered an upper limit (Energy Advisory Council, 1979). However, considerable vehicle and engine design modification is necessary before pure methanol can be used as an automotive fuel. These modifications must take account of (i) the different materials necessary to cope with methanol's corrosive properties, (ii) methanol's high heat of vapourisation and (iii) its low heat of combustion. Most of the engineering expertise necessary to overcome these problems has already been developed by motor racing and other car enthusiasts, but there has been little "cross-fertilisation" between these groups and ordinary automotive engineers (Gonnermann, Moore and McCallum, 1975).

The major technical obstacles to methanol use in motor vehicles can be discussed under three main headings;

(1) Induction systems.

(2) Ignition systems.
(3) Engine design

(Gonnermann, Moore and McCallum, 1975).

(1) Induction systems.

Methanol has a high heat of vapourisation, is harder to atomise and must be supplied at about twice the rate of petrol. Cold starting difficulties are experienced because of its vapourisation difficulties. A number of techniques have been applied to overcome these problems. These are:

(a) Different means of fuel preparation. Methods such as constant flow fuel injection, electronic multiple carburettion, and sonic or vibratory disruption have been successfully developed.

(b) Improved intake manifold design - systems have been developed which give improved fuel distribution uniformity and exhaust heating. Some of these are made of aluminium and employ much higher mixture velocities than in conventional engines.

(c) Exhaust gas heating of intake manifold - most new conventional engines employ this system, but it is possible to improve designs for higher efficiency. The induction problems of methanol cannot be entirely solved by this method.

(d) Combustion air preheat - this allows improved distribution through better vapourisation, use of leaner mixtures and lower fuel condensation during warm
up. As with the previous method, this alone is unable to permit methanol use in conventional vehicles.

(e) New carburettion methods - these usually involve some form of multi-carburettion using either single carburettors with multiple jets (e.g. Quadrajet by E.M.) or a number of separate carburettors.

The aim of these systems is to enhance the uniformity of fuel distribution by producing high mixture flow rates, high venturi velocities, short flow path lengths and fair symmetry. Carburettion changes alone do not permit methanol use in vehicles.

(2) Ignition systems.

To ensure efficient burning of methanol and other fuels it is desirable to have some form of improved ignition system, such as an electronic ignition. In general, electronic ignitions offer, high arc energy, high available voltage, short voltage rise times and longer arc duration. These characteristics improve the probability of ignition occurring and allow spark plug gaps to be widened which can improve flame front strength.

(3) Engine design.

Existing conventional engines can be and have been converted to operate optimally on 100 percent methanol. Depending upon the particular purpose, standard engines can be modified to perform various types of tasks by
introducing a variety of part combinations and operational changes within the engine. These include: (i) valve timings, durations and overlaps according to the camshaft employed and (ii) compression ratios and combustion characteristics according to the choice of piston head and crankshaft.

Methanol's adaptation problems, particularly those associated with its low vapourisation, can also be overcome by using a system which vapourises the methanol before its entry into the carburettor. This system employs normal petrol and methanol from separate tanks. The engine is warmed up on petrol and the exhaust heat is conducted through a short, jacketed stainless steel section where liquid methanol is vapourised. When sufficient methanol has been vapourised the engine automatically switches from petrol to methanol. Only minor changes to the fuel system and carburettor are necessary because methanol is not vapourised in the carburettor. This system offers a more efficient fuel distribution, overcomes liquid fuel collection in the intake manifold and avoids the need for precision controlled fuel injection. It could feasibly be used as a transitional technology employing both petrol and methanol. There is scope for further improving the warm up period to a few seconds which would result in the use of small amounts of petrol (Lindsley, 1977).

Most of the changes in vehicle engineering which have been discussed can be achieved as after-market or
post-production changes to present motor vehicles. In the event that sufficient methanol could be supplied to warrant the mass production of new vehicles designed to run on methanol, a wide field of technological experience could be drawn on to ensure minimal problems.

Alternatively, methanol from coal can also be used as an intermediate compound in the synthesis of high octane petrol. This process is being worked on jointly by Mobil and the U.S. Department of Energy. The process converts 100 parts by weight of methanol to 44 parts hydrocarbons and 56 parts water. In energy efficiency terms, 95 percent of the energy content of the methanol is transformed to petroleum, with an unleaded research octane rating of approximately 96. The method employs a special zeolite⁴ catalyst termed ZSM-5 consisting of silicon, oxygen and aluminium which produces approximately 85 percent high octane petrol, 13.6 percent L.P.G. and 1.4 percent light fuel gases. Considerable scope exists for reducing the cost of this type of fuel because approximately 90 percent of the cost is incurred in the coal to methanol stage which is being intensively researched (Smay, 1978). Converting methanol to conventional petroleum products overcomes the engine design modifications problem, but adds complexity to the fuel production process.

(1) Zeolites are porous, crystalline, alumino silicates (Collocott and Dobson, 1974).
Emissions and fuel economy.

It is widely agreed that methanol has the potential to reduce vehicle emissions of CO, HC, and NO\textsubscript{X} compared to current engines running on petrol, but there is disagreement on the magnitude of this reduction (Farmer, 1975, Carlson and Goss, 1975). It is possible that HC and CO in alcohol fueled engines may be reduced as much as 75 and 80 percent respectively with no change in NO\textsubscript{X} (Deslandes, 1974). Other studies report the potential to reduce NO\textsubscript{X} because methanol has cooler burning characteristics, and it has a lean limit much lower than petrol (Farmer, 1975, Gillis, Pangborn and Vyas, 1975).

In a U.S. study, the potential of methanol to reduce NO\textsubscript{X} exhaust emissions was investigated. The results indicate that the 1972 petrol vehicle average for NO\textsubscript{X} was 1.4 g/km whereas the methanol fueled vehicle results indicate 0.2 g/km NO\textsubscript{X} (Billings, 1975). However, no details are given of how many vehicles were tested with either fuel and so no firm conclusions can be drawn from this data. It suggests that NO\textsubscript{X} emissions are substantially reduced by the use of pure methanol.

A more comprehensive study compared the use of a 15 percent methanol-petrol blend in a variety of vehicles with pure gasoline in the same vehicles (Kant \textit{et al}, 1974). Fuel economy measurements were also taken during the emissions tests. These test results are summarised in Table 3.2.
Table 3.2 Comparative Emissions and Fuel Economy of vehicles with pure petrol and a 15% methanol blend.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Emissions g/km</th>
<th>Fuel Economy</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
<td>CO</td>
<td>NO\textsubscript{x}</td>
<td>Formaldehyde</td>
</tr>
<tr>
<td>1967 Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/O Methanol</td>
<td>3.2</td>
<td>51.6</td>
<td>4.0</td>
<td>0.08</td>
</tr>
<tr>
<td>+ 15% Methanol</td>
<td>2.4</td>
<td>25.5</td>
<td>5.0</td>
<td>0.12</td>
</tr>
<tr>
<td>1973 Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/O Methanol</td>
<td>0.7</td>
<td>13.0</td>
<td>1.6</td>
<td>0.05</td>
</tr>
<tr>
<td>+ 15% Methanol</td>
<td>0.7</td>
<td>5.0</td>
<td>1.1</td>
<td>6.21</td>
</tr>
<tr>
<td>Advanced Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/O Methanol</td>
<td>0.06</td>
<td>0.19</td>
<td>1.6</td>
<td>0.001</td>
</tr>
<tr>
<td>+ 15% Methanol</td>
<td>0.06</td>
<td>0.25</td>
<td>1.4</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Source: After Kant \textit{et al.}, (1974).

Notes:

(i) All testing was by the U.S. Federal Test Procedure.

(ii) 1967 model = 4737cc V8 engine.

1973 model = 5753cc V8 engine.

Advanced model = 5753cc V8 engine.

All models were automatics and no carburettion changes were made for methanol use.
A range of results were observed:

(a) Firstly, in the 1967 model, lower CO and HC were observed with an increased NO\textsubscript{x} value using the methanol blend. Fuel economy on a volume basis remained unchanged but an improvement of 8% in terms of actual energy used was observed with the methanol fueled vehicle.

(b) In the 1973 vehicle with methanol, CO was decreased with no change in HC and a decrease in NO\textsubscript{x}. Fuel economy on a volumetric basis was slightly decreased and slightly improved on an equivalent energy basis using methanol.

(c) In the case of the advanced model using methanol, CO and HC were too low to conclude any effect from fuel, while NO\textsubscript{x} was slightly reduced and fuel economy on a volume basis was reduced but on an energy basis was improved.

A further study in the U.S.A. involving fourteen cars using a 10% methanol blend tested by the Federal Test Procedure indicated a mixture of results similar to those in the previous study. It concluded that HC and NO\textsubscript{x} emissions changes were not significant while CO reductions of between 7.1 and 12.5 g/km were realised. The volume based fuel economy was reduced by between 0.05 and 0.24 km/l (i.e. between 1 and 5 percent less than with pure gasoline) (Brinkman, Gallopolle and Jackson, 1975).
Although it appears that the emissions of CO, HC and NO\textsubscript{x} might be reduced in varying amounts using pure methanol and methanol-petrol blends, question arise concerning the emission of formaldehyde, (Deslandes, 1974) which gives exhausts a strong odour. It has been pointed out that formaldehyde and other aldehydes could be more harmful to health than present emissions.

Conclusions to Methanol

The potential of methanol as an alternative fuel for the medium term seems to lie in its ability to be used as a petrol blend, although difficulties relating to methanol's water affinity and starting impairment would have to be overcome. The costs of doing this could be high (NEAC, 1979). Using methanol as a blending agent in petrol would have a number of advantages:

(1) Methanol's high octane quality means that lead could be eliminated from fuel. Emissions of lead could be stopped in this way though the question of formaldehyde emissions would need to be closely assessed.

(2) Engine adaptation problems with methanol-petrol blends are minimal compared to using pure methanol. This is especially attractive from an economic point of view.

(3) Producing significant quantities of methanol would require large amounts of capital and long lead times. The possibility of procuring sufficient capital to produce enough methanol for blending with petrol
(e.g. a 15% methanol blend) is thus much more achievable than considering running vehicles on pure methanol.

(4) Pure methanol is an irritant and central nervous centre depressant. The chance of toxicity effects of methanol (blindness and death in sufficient quantities) would be less in methanol-petrol blends than with pure methanol where the risk would be high.

Methanol also has advantages in having a variety of sources from which it can be derived (i.e. coal, natural gas and biomass). This will be a very important advantage in the future as it will enable some flexibility in production methods and resource availability. It has also been indicated that the potential exists for converting methanol into high octane petrol. At present the capital costs and long time lags associated with producing methanol seem to be the major drawbacks, particularly the very high capital costs of methanol-from-biomass which is perhaps the most desirable of all the sources of methanol; methanol from biomass is a renewable resource. The likelihood however, of pure methanol being used in vehicles at any where near the level of petrol usage would seem at present to be very remote.

Methanol could become an important fuel in reducing oil dependence particularly in Australia where potential has been shown for producing methanol from coal, natural gas and biomass. U.S.A. experience suggests that
some emissions benefits could be expected from the use of methanol-petrol blends though in Australian vehicles, the magnitude of these benefits would have to be determined by the testing. The most important emissions advantage would be the elimination of lead.
(ii) \textbf{Ethanol} \((C_2H_5OH)\)

The use of ethanol as a blending substance for petrol and as a pure fuel has been known for many years. During the 1950's Germany operated an ethanol from wood plant on a commercial basis (C.S.I.R.O., 1976). In Queensland during the Second World War, a 10 percent blend of ethanol was used (Endersbee, 1979). Over the past five years the world oil supply and price situation has stimulated vigorous new research into the production of ethanol from biomass sources.

Brazil is perhaps the best known example of the use of ethanol as a substitute for conventional oil. The massive programme undertaken in this country is planned to completely replace imported oil with ethanol produced from cane and cassava by 1990 (C.S.I.R.O., 1979). The original aim was for complete liquid fuel independence by 1985 (C.S.I.R.O., 1977). In some Brazilian cities, many cars already operate on 20% alcohol/petrol mixtures (gasohol). It is significant to note however that most of the vehicles are small and use a manual shift transmission (e.g. Volkswagens) (Energy Advisory Council, 1979). Brazil's plans to 1981 are aimed at having about 17 percent of new cars running on pure ethanol, (C.S.I.R.O., 1979) and at present in some areas up to 30 percent of petrol usage has been substituted by ethanol (ATAC, 1978).

However, special conditions have both forced and allowed Brazil to contemplate such a programme. Firstly,
Brazil has been forced to seek other sources of transport energy because 80 percent of its petroleum is currently imported at a cost of about $4,000 million per year. Secondly, Brazil has been able to meet with some success in its programme because vast areas of arable, well-watered land are available in climates capable of supporting large energy crops. Brazil has a large number of poor unemployed labourers to provide most of the work needed to operate the scheme which is very labour intensive. This improves the energy efficiency of the production process which is a problem in Australia where energy intensive means would be used (C.S.I.R.O., 1977). The Brazilian Government has created an economic environment conducive to the use of ethanol by advancing the necessary capital investment at low interest rates and by taxing motor spirit to a level which makes ethanol attractive (Energy Advisory Council, 1979). In terms of per-capita energy requirements, Brazil has a modest demand compared to Australia and the U.S.A. which makes the production of ethanol much more significant for Brazil.

To produce ethanol on a large scale a number of important criteria must be met, some of which are suggested by the Brazil analysis. Consideration of these criteria is necessary to gain perspective on the potential of ethanol as a fuel in Australia, where conditions are greatly different to those in Brazil.
Production

Ethanol is produced from agricultural products and wood by a fermentation process which varies in conversion efficiency according to the type of raw material used. Generally the process is much less efficient than the corresponding conversion of crude oil to petrol. Table 3.3 shows the general efficiency(1) of a number of ethanol conversion processes compared to methanol and conventional petrol production.

Table 3.3  Efficiency of energy use in making liquid fuels.

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Product</th>
<th>General efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>Petrol and Distillate</td>
<td>87</td>
</tr>
<tr>
<td>Cereal Grains</td>
<td>Ethanol</td>
<td>33</td>
</tr>
<tr>
<td>Sugar-cane juices</td>
<td>Ethanol</td>
<td>41</td>
</tr>
<tr>
<td>Molasses</td>
<td>Ethanol</td>
<td>36</td>
</tr>
<tr>
<td>Wheat Straw</td>
<td>Methanol</td>
<td>40</td>
</tr>
<tr>
<td>Bagasse and Cane-Field wastes</td>
<td>Methanol</td>
<td>35</td>
</tr>
<tr>
<td>Wood</td>
<td>Methanol</td>
<td>33</td>
</tr>
<tr>
<td>Wood</td>
<td>Ethanol</td>
<td>14</td>
</tr>
</tbody>
</table>


(1) general efficiency = 100 x energy value of liquid fuel output ÷ total energy inputs.
Figure 3.2  Ethanol production processes.

Source: After Gillis, Pangborn and Vyas, (1975).

Figure 3.2 shows the range of options available to produce ethanol. Details of the individual processes are not considered here. The most important factors in considering the potential of ethanol as an automotive fuel are the scale at which raw materials can be produced, the economics of production and processing and the environmental constraints.

Calculations have been made in Australia of the raw materials and land areas required to produce sufficient feedstock for a large scale ethanol industry (Stewart et al, 1979). Some agricultural crops considered so far are sugar cane, cassava, sugar beet, and sweet sorghum.
Investigation of tree crops has been limited to Eucalypts. Crop residues and urban wastes have also been investigated. The major physical constraint confronting energy crop production in Australia is climate.

It has been estimated that 26 million ha of undeveloped land is available in Australia for growing energy crops, 17 million ha of which is in N.S.W. and Queensland west of the Great Dividing Range (C.S.I.R.O., 1979). Much of this total area is marginal land with low, erratic rainfall, but is suitable for a variety of crops as shown in Table 3.4.

Table 3.4  Estimates of arable land available in Australia for energy crops.

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Land area (million ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat, barley, rye</td>
<td>4</td>
</tr>
<tr>
<td>Pearl millet and grain sorghum</td>
<td>17</td>
</tr>
<tr>
<td>Sugar cane and cassava</td>
<td>0.6 - 0.7</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>1.0</td>
</tr>
<tr>
<td>Tree crops</td>
<td>1.1</td>
</tr>
<tr>
<td>Other</td>
<td>2.2 - 2.3</td>
</tr>
<tr>
<td></td>
<td>26</td>
</tr>
</tbody>
</table>

On the basis of these land area estimates, Stewart et al. (1979) have estimated the total, maximum energy yield possible from energy crops. Crop and forestry residues were considered better suited to methanol production. They calculated that if the full potential of energy crops was exploited, $132.5 \times 10^{15}$ J (132.5 PJ) in the form of ethanol could be produced per year. This is equivalent to about 19.0 percent of Australia's 1977-8 transport liquid fuels demand, 9.6 percent of total oil use (energy equivalence) and 4.4 percent of total Australian energy use.

This estimated energy potential assumes no loss of present land under cultivation for food or fibre and is based upon realistic crop yields given the physical constraints of the environments under consideration. Crop yields may be boosted by the use of intensive farming involving fertilisers and irrigation, although such inputs would reduce net energy yields. New plant strains suitable for energy production rather than food production, will also increase yields though how much is uncertain.

A number of important logistics problems are also encountered when considering ethanol production. An ethanol production plant would require feedstock all year round which would necessitate it being located centrally in a region with high plant yields. The yield of marginal areas which could not produce a crop all year round would have to be transported to the processing plants. The problem of high energy inputs necessary to harvest and

The final and perhaps most important constraint on ethanol production is cost, both in terms of capital and price of the final product. Stewart et al (1979) estimate that the capital cost of ethanol production including costs of new irrigation dams range from $35 to $45 per G.J. of gross annual output of ethanol. On this basis a conservative estimate of the cost of ethanol production at the maximum level suggested by this study would be $5,300 million. The previous section suggested $8,520 million for maximum methanol production. However these are based on net annual output and Stewart et al (1979) indicate that the total capital cost of producing the maximum amounts of methanol and ethanol in Australia (630 PJ gross, c.f. 419 PJ net) would be about $20,000 million. The final cost of ethanol would be little different to methanol, i.e. about 3 to 4 times as expensive as motor spirit ex. refinery. However if about 10 cents per litre excise distribution and retail costs were applied the estimated cost for the equivalent of one litre of motor spirit in 1975-6 would be 37 to 54 cents, i.e. more than twice the comparable retail price of motor spirit at that time (Stewart et al, 1979).

As mentioned previously, the possibility of producing ethanol from tree crops has been investigated
in Australia. Stewart et al (1979) did not consider ethanol from tree crops because the general efficiency of production is low (14 percent). However a number of investigations have been made of the potential of native Eucalypts for ethanol production. Some of the findings can be summarised as follows:

1. To produce half of Australia's estimated liquid fuel requirements in 2000 as ethanol from fast growing Eucalypts would require 13 million hectares of plantation at a yield of 12.5 tonnes of stem wood per ha each year. This average yield rate is very high. Experiments with *Eucalyptus globulus* on selected sites with high rainfall yielded only 4 tonnes of dry stem wood per ha each year for the first four years (C.S.I.R.O., 1977).

2. If it is assumed that a yield of 10 tonnes per ha per year could be realised the land area required almost doubles (23 million ha) (C.S.I.R.O., 1977).

3. Even though it is possible to obtain extremely high yields from Eucalypts (e.g. *Eucalyptus regnans* or Mountain Ash) on the best sites, (up to 22.6 tonnes per ha per year) these are already in use for other commercial enterprises such as plantations for timber or woodchip production (C.S.I.R.O., 1976).

4. The question of yields is dwarfed by the problem of finding suitable land for such enormous plantations.
This can be seen in perspective by considering that the current Australia-wide pine planting programme plans to have established, with considerable difficulties, just over 1 million ha by 2010 (Personal Communication, Forestry Dept., W.A.), i.e. about 5% of that which might be required for energy production.

Adapting to Ethanol

The same basic problems apply to ethanol as a blend or pure fuel as those described for methanol. In engineering terms the problems are slightly less severe. Ethanol contains between 57 and 61 percent the energy content of petrol on a weight basis compared to 45 percent for methanol (Energy Advisory Council, 1979). It is also superior in its petrol blending qualities. The higher energy content of ethanol compared to methanol means that transport and storage are less problematic. For example a 15 percent blend of methanol is equivalent to an 11.5 percent blend of ethanol (Stewart et al., 1979) and to entirely replace a 91 litre petrol tank with an equivalent ethanol tank would require 136 litres compared to 186 litres for methanol (Kant et al., 1974). Ethanol also has a lower ignition temperature which makes it easier to burn. Cars can be run on up to 25 percent ethanol blends (C.S.I.R.O., 1976).
Emissions and Fuel Economy

Little data are available on the emissions characteristics or fuel economy of ethanol either as a blend or as a pure fuel. The small amount of testing so far suggests that emissions would be similar to methanol (Deslandes, 1974). With an ethanol blend, emissions of CO and HC are likely to be reduced slightly while NO\textsubscript{x} would remain either unchanged or slightly increased (Kant et al, 1974). The higher energy content of ethanol would probably result in better fuel economy performance than methanol on both a volume and equivalent energy basis. Perhaps the most important emissions advantage of both methanol and ethanol is their high octane quality which can be exploited to eliminate lead additives in fuel (Stewart et al, 1979).

Conclusions to Ethanol

The suitability of ethanol as a blending agent in petrol has been demonstrated by experience in Brazil and Queensland although it has some technical adaptation problems. The major problems confronting the use of ethanol in Australia are the high capital cost of establishing production facilities and the logistics and energy expenditure problems associated with continuously providing the biomass feedstock. Ethanol production does not offer the same resource flexibility as methanol although a wide range of
biomass sources can be exploited for ethanol production with various conversion efficiencies. As with methanol, ethanol cannot be viewed as having potential to substitute for petrol at anywhere near present petrol usage levels. If ethanol is to contribute to oil conservation it will almost certainly be as a blend with petrol. Its petrol blending qualities are superior to methanol and using ethanol as a blend would avoid the likely social problems associated with distributing it in a pure form. The significance in terms of emissions of using ethanol-petrol blends in Australian vehicles would have to be determined by experiment. The most important foreseeable advantage is in the elimination of lead. The relative importance of both methanol and ethanol in Australia in terms of providing energy for transport would appear much more significant if overall transport energy consumption could be reduced. Under present consumption patterns and economic constraints methanol and ethanol combined could not be considered as being able to offer total solutions to transport energy supply problems in Australia. The future use of either ethanol or methanol in Australian transport will hinge on a number of interacting technological, political and economic factors about which no firm predictions can be made.
(iii) **Liquid Petroleum Gas (L.P.G.)**

Considerable discussion in Australia has centred upon the prospects of utilising liquified petroleum gas as a major fuel for motor vehicles. This has been due mainly to the comparatively large natural deposits found in Bass Strait and the excitement over N.W. Shelf L.P.G. prospects. On a world basis L.P.G. has not stimulated wide interest as a potential alternative transport fuel because the resource and supply situation is similar to that of oil.

**Production**

L.P.G. is obtainable from two sources - oil and natural gas.

**From Oil.** Seventy three percent of L.P.G. production in Australia comes from oil refineries as a petroleum fraction in crude oil. In Australia the L.P.G. fraction is about 2 percent of a barrel of oil. The L.P.G. from this source consists of a mixture of propane, butane, propylene and butylene. For automotive use L.P.G. must contain at least 90 percent propane and less than 5 percent propylene and butylene (CHOICE, 1979).

**From Natural Gas.** L.P.G. can be obtained from natural gas by a special stripping process which yields only propane and butane.
Australia has considerable scope to expand the supply and distribution of L.P.G. from this source. The N.W. Shelf and Bass Strait could offer significant reserves for domestic use, particularly if current L.P.G. exports and export proposals are revised. Currently between 70 percent and 90 to 95 percent of Bass Strait L.P.G. production is exported mainly to Japan. There is some disagreement as to the precise percentage of Bass Strait L.P.G. which is exported (Energy Advisory Council, 1979, ATAC, 1978, CHOICE, 1979). However it has been estimated that if the total Bass Strait production was used entirely for transport only 6 percent of Australian motor vehicle fuel demand could be satisfied (ATAC, 1978). It is expected though, that unlike Bass Strait oil, L.P.G. production will continue at high levels until 2000 (ATAC, 1978).

It is thought that the N.W. Shelf might offer considerable potential for expanding domestic L.P.G. supplies (Endersbee, 1979). Actual estimates of propane production potential of the N.W. Shelf show that about 400,000 tonnes per annum could be obtained along with 300,000 tonnes of butane. Butane is however unsuitable for use in petrol fueled vehicles but is more suitable as a replacement for diesel fuel in buses, trucks and trains. If this quantity of propane was marketed exclusively as transport fuel it would be sufficient to reduce the projected 1985-6 W.A. petrol consumption by 30 percent (Energy Advisory Council, 1979). Based upon current vehicle design and usage patterns it would be
equivalent to converting 80,000-100,000 vehicles to L.P.G. (Energy Advisory Council, 1979).

This estimate however would not only require L.P.G. to be used exclusively in transport but would also require the level of vehicle conversion indicated above. It is unlikely that these two criteria could be met (Energy Advisory Council, 1979). It has also been pointed out that such a commitment of L.P.G. to transport could be detrimental to other sectors of the economy which in the future might benefit comparatively more from L.P.G. availability, e.g. petro-chemical industries. The Australian Transport Advisory Council concluded that Cooper's Basin and N.W. Shelf L.P.G. is unlikely to be available for transport use because of export and petro-chemical commitments (ATAC, 1978). King (1978) however concluded that L.P.G. offers the only short term (10 years) alternative to petrol which Australia has and he estimated that about a 20 percent reduction in Australian motor spirit demand can be achieved by 1990 by substitution of L.P.G.

Adapting to L.P.G.

The suitability of L.P.G. as an alternative fuel is attested to by the increase in conversions which are occurring around Australia particularly in Victoria. L.P.G. liquefies under a moderate pressure of 689.5 kNm$^{-2}$ (100 p.s.i.) (Deslandes, 1974). Storing L.P.G. in
existing motor vehicles is thus technically simple although important safety and insurance problems have been encountered. L.P.G. installations must conform to the Australian safety standards set out in AS 1428-1973 (CHOICE, 1979).

L.P.G. is particularly suited to urban buses and vehicle fleets such as taxis. In Melbourne a large number of taxis have been converted to L.P.G. operation (Endersbee, 1979). In Perth similar interest is being shown in L.P.G. usage (Page, 1979).

Up until recently the widespread use of L.P.G. in Australia has been discouraged by pricing decisions. In November 1978 the maximum price per tonne for L.P.G. in Victoria was $83 and earlier, $67 per tonne. However the export price for sale to Japan was $110 per tonne with the result that from the Gippsland fields alone 1.3 million tonnes have been exported annually for a number of years (Barnett, 1979). In June 1979 the Commonwealth Government revoked its 2.1 cents per litre tax on automotive L.P.G. and removed excise charges on L.P.G. conversion equipment in an effort to encourage greater use of L.P.G. (CHOICE, 1979).

Conventional engines are easily converted to L.P.G. operation. The major changes required consist of installing:
(1) a pressurised, steel storage tank and high pressure fuel line,
(2) a fuel-lock filter,
(3) a converter or fuel vapouriser including a pressure regulating device, and

After installation, engine timing and mixture adjustments are made to suit power requirements and the slower flame speed of L.P.G. In Australia conversions currently cost between $600 and $1,000 (CHOICE, 1979). Conversion to a duel-fuel system which is recommended in Australia because of supply and distribution point limitations involves some ignition timing problems when switching between fuels and a 10 to 15 percent sacrifice in L.P.G. fuel economy because of compromises in operating conditions between petrol and L.P.G. (Energy Advisory Council, 1979, CHOICE, 1979).

There are a number of technological advantages involved in using L.P.G. and a number of problems which tend to offset these benefits. Table 3.5 compiled from the literature summarises these advantages and disadvantages. The advantages listed can only be gained if the vehicle is well maintained according to recommended practices for L.P.G. fueled vehicles. It can be inferred from this table that switching to L.P.G. is not a simple matter of obtaining cheaper fuel but involves a whole series of factors which the individual must trade off according to perceived priorities. The
Table 3.5 The problems and benefits of L.P.G. usage in conventional engines.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prolonged engine oil life</td>
<td>High initial cost</td>
</tr>
<tr>
<td>Prolonged oil filter life</td>
<td>Limited availability and distribution problems</td>
</tr>
<tr>
<td>Less wear on battery due to easier starting</td>
<td>Storage dangers - explosion and fire</td>
</tr>
<tr>
<td>especially in cold weather</td>
<td>Equally vulnerable to fuel supply disruptions</td>
</tr>
<tr>
<td>Improved spark plug life</td>
<td>Loss of boot space due to fuel tank</td>
</tr>
<tr>
<td>Engine life extension</td>
<td>Reduced engine power</td>
</tr>
<tr>
<td>Smooth engine running</td>
<td>Engine damage under consistently heavy loads</td>
</tr>
<tr>
<td>Cheaper fuel</td>
<td>Engine retiming necessary for long trips with dual fuel systems</td>
</tr>
</tbody>
</table>

Sources: (CHOICE, 1979, Pace, 1979, Energy Advisory Council, 1979).

potential of L.P.G. as an alternative fuel is thus dependent not only on technological constraints but on a number of human choice factors.

Emissions and Fuel Economy

L.P.G. has better combustion characteristics than petrol. It burns cleaner, has a high octane number and "anti-knock" characteristics, produces fewer heavy hydrocarbons because of its lower molecular weight, ignites more rapidly and burns more nearly to completion (Revis, 1973). Higher compression ratio engines can be
used to improve thermal efficiency. It is considered that the use of L.P.G. in place of petrol on a sufficiently large scale might alleviate many urban air pollution problems. Particularly important is the absence of lead emissions with L.P.G. (Barnett, 1979, Revis, 1973).

A wide range of values for emissions reductions has been reported. The magnitude of benefits derived in this respect depends upon (i) whether a dual-fuel system or single-fuel system is used, (ii) the vehicle's weight, and engine size and (iii) the air-fuel ratio used. In general single fuel systems which involve specially designed carburettors give the best emissions and fuel economy results. Table 3.6 gives some emissions results for L.P.G. converted vehicles tested by the U.S.E.P.A. The data highlights the difference between the single fuel and dual fuel systems.

Table 3.6 Comparative emissions of dual and single fuel L.P.G. systems and petrol systems.

<table>
<thead>
<tr>
<th></th>
<th>Emissions Reduction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual Fuel Carb.</td>
<td>8</td>
</tr>
<tr>
<td>Single Fuel Carb.</td>
<td>20</td>
</tr>
</tbody>
</table>

Source: U.S.E.P.A., (1972)
The percent reductions in emissions represent changes over identical petrol fueled vehicles. As can be seen a wide range of emissions reductions was observed with the dual-fuel system and a much smaller range with the single fuel system.

Testing has also been carried out in Australia. Table 3.7 shows a summary of the results of these tests for a single passenger car fitted with two makes of L.P.G. conversion kits. Both are single fuel systems.

Table 3.7  Emissions characteristics of L.P.G. fueled vehicles in Australia compared to an equivalent petrol fueled vehicle.

<table>
<thead>
<tr>
<th></th>
<th>Emissions, gm/km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Standard Vehicle</td>
<td></td>
</tr>
<tr>
<td>(Petrol Century)</td>
<td></td>
</tr>
<tr>
<td>LPG Conversion</td>
<td>1.9</td>
</tr>
<tr>
<td>Impco LPG Conversion</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Source: Department of Shipping and Transport, (1971)

These results were obtained using the ADR27 driving cycle. A 10 percent loss in power was noted in both systems. The results of the tests show that in this case substantial reductions in emissions were gained. The L.P.G. fueled vehicle obtained emissions below the levels of current Australian standards (24.2g/km CO; 2.1g/km HC and 1.9g/km NOx). Neither vehicle types had emissions control equipment.
More recent data from the N.S.W. State Pollution Control Commission obtained in a similar way substantiate this general observation of emissions reduction.

Table 3.8 summarises the results for a typical vehicle with a single fuel system. Results are percent reductions over comparable petrol fueled vehicles.

Table 3.8 Pollutant reductions using L.P.G. in a single-fuel system.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>92</td>
</tr>
<tr>
<td>HC</td>
<td>38</td>
</tr>
<tr>
<td>NOx</td>
<td>22</td>
</tr>
<tr>
<td>CO at idle</td>
<td>95</td>
</tr>
</tbody>
</table>


These percent reductions vary from vehicle to vehicle.

Overall the use of L.P.G. offers reduced emissions of HC, CO and NO\textsubscript{x} in most cases and completely eliminates lead emissions. In general these reductions may range for a single fuel system with a power loss of 25 percent, from: (1) 42-88 percent with an average of about 80 percent for HC; (2) 51-97 percent with an average around 83 percent for CO, and (3) 39-92 percent with an average around 70 percent for NO\textsubscript{x}. For dual-fueled systems' reductions are not as high. For a 10 percent loss in power average reductions of about
40 percent for HC, 80 percent for CO and 25 percent for NO\textsubscript{x} seem likely (Deslandes, 1974). It is important to note that to reap the highest emission reductions, significant losses in power must be accepted.

Although the reductions are significant and involve little or no use of emissions controls, substitution for L.P.G. would have to be widespread to reap large benefits in terms of total pollutant output. An American study suggested that the use of L.P.G. would only offer large benefits in highly polluted city areas where a number of fleets of vehicles make a large contribution to total vehicle kilometres travelled within the area. This occurs in Manhattan in the case of Medallion Taxi Cabs (Revis, 1973). However the use of L.P.G., C.N.G.\textsuperscript{(1)} or L.N.G.\textsuperscript{(1)} is not considered a feasible widespread alternative to petrol in the U.S.A. because supplies are not sufficiently large to meet other demands. The effect on fuel economy of L.P.G. conversion varies according to the particular vehicle, its condition and the type of system it uses. It has already been mentioned that systems completely converted to L.P.G. (i.e. single-fuel systems) offer the best fuel economy performance because the engine is optimised for L.P.G. fuel. Such vehicles generally achieve almost identical fuel economy on a volume basis to that when the car was petrol fueled (CHOICE, 1979).

\textsuperscript{(1)} C.N.G. = Compressed natural gas \textsuperscript{(1)} These are forms of methane which are considered later.

L.N.G. = Liquefied natural gas
A survey of Melbourne taxi operators observed between a 5 percent increase and an 8 percent decrease in fuel economy (by volume) depending upon vehicle age and condition (Page, 1979). Given L.P.G.'s lower energy content (1) per litre it would be expected that for equal power, fuel economy on L.P.G. would be less.

Savings in operating costs can still be made with a 10 percent fuel economy penalty if the price of L.P.G. is sufficiently low (ATAC, 1978), although it has been calculated that on average a car in Australia would need to be used for in excess of 18,000km a year to reap real petrol cost savings with a minimum break-even period of 25 months to cover conversion costs (CHOICE, 1979). This data applies to dual-fuel systems, which are the most practical in Australia at the present time.

Conclusions to L.P.G.

Although L.P.G. is currently an underexploited resource for Australian transport systems, it is not in sufficient abundance to be viewed as a long term alternative to petrol. At best L.P.G. can be expected to reduce the pressure on Australia's diminishing oil supplies and thus to a small degree fulfill a transitional

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role. This assessment applies both to L.P.G. from oil and from natural gas. The Australian Transport Advisory Council concluded that L.P.G. does not provide a long term solution to the transport energy problem since it is a non-renewable resource of limited supply (ATAC, 1978). The degree to which L.P.G. is used will depend upon a range of decisions by individual car owners based upon the relative economics, performance, convenience, and safety of L.P.G. compared to petrol. The economic attractiveness of L.P.G. will in turn largely depend upon pricing decisions. The emissions from L.P.G. vehicles are generally much lower than from petrol-fueled vehicles but the significance of these reductions depends upon the overall level of substitution of L.P.G. As with other alternative fuels, significant time lags would be involved in substituting L.P.G. for petrol. These time lags would be related to the large infrastructure changes necessary to expand supply, distribution and conversion networks. Currently long time delays are involved in L.P.G. conversion due to a shortage of gas cylinders (CHOICE, 1979).
(iv) Petroleum Fuels from Coal, Oil Shales and Tar Sands

Coal, oil shales and tar sands can be treated by a number of different processes to produce what are collectively known as synthetic crudes or 'syncrudes'. In turn these can be refined to produce essentially the same petroleum products which are obtained from conventional crude oil. Synthetic crudes are obtained most 'easily' from tar sands due to the relatively simply extraction technology compared to shale and coal, high hydrogen to carbon ratios, and because tar sands are simplest to mine. Even with these advantages problems are formidable. Once oil is obtained the viscosity must be greatly reduced and high sulphur content must be removed. Tar sands contain up to 50 percent sulphur and a high metals content (Environmental Science and Technology, 1979). Coal is the most difficult source from which to obtain syncrudes (Barnett, 1979).

The fuels produced by these methods involve the least changes to existing automotive systems, infrastructure and fuel distribution networks. Worldwide coal, oil shale and tar sands deposits constitute massive sources of fossil fuel energy. Oil shale deposits in the U.S.A. alone contain more oil than is presently obtainable in Saudi Arabia (The Guardian, August 12, 1979). The C.S.I.R.O. (1975) suggests that by 2000 about 2 percent of world reserves of coal will have been used and in Australia by the same year 16 percent
of available brown coal and 2 percent of available black coal will have gone. It also suggests that known deposits of oil shale in North and South America, Europe and Asia could theoretically supply more fuel than the entire world's known oilfields. However these estimates must be viewed against a background of considerable technological, economic and environmental constraints.

This section deals primarily with syncrudes from coal which are of the greatest relevance to Australia. Black coal constitutes 93.9 percent of Australia's fossil fuel reserves and there are no tar sand deposits (C.S.I.R.O., 1975). Oil shale deposits of about 600 million barrels are found in Rundle in Queensland but these are low grade and it is estimated that commercial developments of these deposits would require a doubling of world oil prices (1978) before they could be considered (Barnett, 1979).

Production

The basic objective in all oil from coal processes is to raise the normal coal hydrogen:carbon ratio from 1 part hydrogen to 16 parts carbon to 1 part hydrogen to 7 parts carbon found in oil (Barnett, 1979).

The major processes for producing crude oil from coal are:
(a) Liquefaction

by (i) direct hydrogenation - this involves treating coal with hydrogen at high temperatures and pressures in the presence of a catalyst. Hydrogenation may yield between 1.5 and 3.3 barrels of oil per tonne of coal (Barnett, 1979).

(ii) donor solvents - or solvent extraction involves the use of hydrogen donor solvents which may be catalytically regenerated external to the liquefaction reactor.

(b) Pyrolysis

In pyrolysis coal is decomposed by heating in the absence of air to produce varying proportions of liquids, gas and carbon (char or coke) depending on the process. Flash pyrolysis under study in Australia is aimed initially at producing heavy oils. It involves pulverising coal to a particle size of 0.1mm or less and heating to temperatures of 700°C in about 0.5s. This is an economically attractive process due to its simplicity (no high pressures or catalysts are involved). However the liquid product does require upgrading and desulphurising by treating with hydrogen (Gillis, Pangborn and Vyas, 1975). Another significant advantage of coal processing by pyrolysis is that it produces energy products which may be used in electricity generation. It may thus be possible to integrate liquid fuels production with electricity generation. Pyrolysis yields about 50-60 percent char, 0.5-1.0 barrel of oil per tonne of coal and 50-250 cubic metres of combustible gas (Barnett, 1979).
(c) Fischer-Tropsch Process

In this process coal is gasified by reaction with steam and oxygen to produce CO and H₂ which is then catalytically converted at high temperatures and pressures to produce liquid hydrocarbons (Kant et al, 1974, C.S.I.R.O., 1975). South Africa's Sasol plant operates by this method. In the Sasol process 12 percent of the carbon used is made into saleable products and the energy conversion efficiency is 30 percent (Kant et al, 1974, C.S.I.R.O., 1975). South Africa expects to be producing 40 percent of its petroleum requirements by 1981 using this method (C.S.I.R.O., 1979). In Yugoslavia another commercial oil from brown coal plant uses the Lurgi process which is a variation on pyrolysis. These are the only two commercial oil from coal plants in operation and they operate at a level well below that which would be required of commercial plants in the U.S.A. (Barnett, 1979).

None of these three processes are fully evolved technologically and none have been proven capable of producing competitively priced crude oil. The Sasol plant although reported as operating at a profit of $A77 million after tax in 1978 (The Australian, June 27th, 1979) probably produces oil at a price close to $30 per barrel (Time, June 11, 1979). Cost figures are not released by the South African Government.
The major problems confronting syncrudes are economic and environmental, which are further related to the present state of production technology. A great amount of research is still required to develop commercially viable oil from coal, shale or tar sands. Some of the problems include:

(1) spent shale and coal washer refuse must be disposed of in an environmentally acceptable way. A 100,000 barrel per day oil from shale plant would generate 150,000 tonnes of solid waste including toxic materials (The Guardian, August 12, 1979).

(2) surface mined shale and coal deposits must be permanently reclaimed on a large scale.

(3) large amounts of water are needed all year round; oil shale deposits in the U.S.A. are in areas of extreme water shortage.

(4) in the U.S.A. planning and sociological problems are envisaged as a result of the large scale influx of people into new, sparsely populated mining areas.

(5) there is a need to develop more efficient methods of generating hydrogen from coal for use in hydrogenation processes.

(6) liquefaction processes must be improved to give more selective molecular weight reduction with minimum hydrogen consumption; this may involve developing better catalysts.
(7) refining of coal syncrude must be capable of producing acceptable sulphur, nitrogen and oxygen content fuels from a wide range of feedstock derived from a variety of coals.

(8) the Fischer-Tropsch process needs to be improved in its resource and energy conversion efficiency.

(Kant et al, 1974; Farmer, 1975; C.S.I.R.O., 1975).

In the long term if coal, oil shale, or tar sands are to produce significant quantities of oil, extraction of oil must be achieved in-situ. A number of methods are being investigated all involving extracting oil underground. In the case of coal there is a need for an underground liquefaction process. In-situ extraction from oil shales and tar sands is being attempted by
(a) underground fires and pumping
(b) radiowaves conducted by electrodes in bore holes to "cook" the oil out, and
(c) injecting steam into the ground and then pumping
(Kant et al, 1974, Time, June 11, 1979).

Technological and environmental constraints make syncrudes uneconomical at present. Massive capital investments are needed to commence production and investors are generally reluctant to commit themselves when the final product costs much more than a barrel of conventional oil. The capital cost problem is exemplified by considering that between $50 and $250
per barrel per day investment is needed to produce Middle Eastern oil. (1) Amortized over the oil field's lifetime this reduces to a few cents per barrel. By contrast synthetic fuels from coal currently demand a capital investment of between $20,000 and $50,000 per daily barrel (Hayes, 1977). Translated into costs per barrel a 1979 report quoted an estimate that coal liquids in 1978 dollars will cost somewhere between U.S.$25 and U.S.$33. The same report quoted an average price per barrel for oil from oil shale of U.S.$18-$25 (Environmental Science and Technology, 1979). Thus the final price of the syncrude is fast approaching present oil prices but the capital to establish the plant is the key problem.

The enormous capital requirements of any syncrude developments can be further highlighted by considering some specific examples of fields that are being developed.

Tar Sands.

Production of oil from these sources in Canada has accumulated a loss of U.S.$85 million. Capital commitment by private firms for expanding activities has been withdrawn. The capital costs of a proposed 125,000 barrel per day plant has escalated from U.S.$744 million in May 1973 to U.S.$2,000 million in February 1975. In 1976 the cost of a proposed

(1) Wells and pipelines.
100,000 barrel per day plant had grown to U.S.$3,000 million from U.S.$960 million in 1973 (Barnett, 1979). It presently stands at U.S.$4,000 million (The Guardian, August 12, 1979).

Coal Oil.

Australian studies suggest a very constrained future for crude oil from coal. A recent study estimated that the capital cost of a liquefaction plant producing 100,000 barrels per day (current petroleum consumption in Australia is about 650,000 barrels per day) would be A$2,000 million, and would consume 40,000 tonnes of coal per day (current Australian coal consumption is 80,000 tonnes per day) (ATAC, 1978). A combined oil/gas process would yield a product which would cost about $26.10 per barrel (Barnett, 1979). With a pyrolysis process integrated with industry or a power station to burn the waste char, syncrude may cost as little as $10-15 per barrel. However the oil from such plants would only be of strategic significance, e.g. to provide lubricants and fuel oil which are currently obtainable only from heavy crude oil imports (ATAC, 1978).

Important physical and economic limitations confront coal-oil production in Australia. They may be summarised as follows:

(1) Technological gaps exist in the feasibility of utilising Australian coal in the already established SASOL process. Even greater unknowns surround the use
of Australian coal in other higher yield processes. At the earliest Australia might commence production of synthetic oil from coal in the late 1980s (Barnett, 1979) and the Department of National Development has estimated that oil derived from coal is unlikely to provide more than 10 percent of Australia's oil demand by 2000 (ATAC, 1978).

(2) Water availability is an important constraint in Australia. A 100,000 barrel per day plant would consume about one-third of the average water flow of the Hunter River.

(3) To the capital cost of plant establishment must be added the cost of new mine developments, ancillary infrastructure costs, and training of a large workforce of skilled miners (Barnett, 1979).

(4) Despite Australia's large coal deposits it has been estimated that known reserves, suitable for low cost mining and oil production would only be sufficient to provide half domestic liquid fuel requirements for twenty-five years (ATAC, 1978).

Assessments of the potential of coal oil in the U.S.A. have run up against similar limitations. These may be summarised as follows:

(1) an exhaustive study of the potential of coal oil determined the absolute maximum production by 2000 to
be 4 million barrels per day which represents 27.1 percent of the expected U.S. automotive energy demand (Gillis, Pangborn and Vyas, 1975, Hughes et al, 1975).

(2) In 1990 the maximum expected contribution of oil from coal in the U.S.A. to the total expected automotive energy demand would be less than 1 percent (Gillis, Pangborn and Vyas, 1975, Hughes et al, 1975).

(3) The Carter administration has set a target of 2.5 million barrels per day which would reportedly require an investment in fifteen U.S.$3,000 million plants in addition to a U.S.$20,000 million investment in coal mining infrastructure to produce annually an additional 35 percent of present coal production (The Guardian, August 12, 1979). In all a total of U.S.$65 billion would have to be invested to reach the proposed target.

Adapting to Syncrudes

As was suggested earlier syncrudes offer the most amenable solution to oil shortages in terms of the changes required in the present system of transport. The physical properties of syncrudes will probably not differ significantly from present fuels and thus give the same problems in terms of distribution, storage and use in present vehicles (ATAC, 1978). The only significant difference of pure coal fuels may be their higher
aromatic content. Special attention may need to be paid to gaskets, diaphragms and hose materials to resist high aromatic concentrations though this is a minor problem (Kant et al., 1974).

Emissions and Fuel Economy

Fuel economy and emissions characteristics of syncrudes will probably be similar to conventional petrol when used as syncrude-petrol blends. Generally however there is a dearth of information on product quality and performance of coal and shale derived fuels (Kant et al., 1974). Only three emissions problems have been identified so far:

(1) Coal gasolines may contain trace elements such as heavy metals which may be at odds with current trends to limit lead additions in petrol (Gillis, Pangborn and Vyas, 1975).

(2) Higher nitrogen content could exacerbate the problem of NOx emissions control (Gillis, Pangborn and Vyas, 1975).

(3) The higher aromatic content of syncrude gasoline may require special combustor design in diesel and external combustion engine vehicles to limit smoke and particulate emissions (Kant et al., 1974). Blending of coal fuel with conventional petrol may ease these problems.
It is also possible that the higher aromatic content of syncrudes could result in hydrocarbon emissions which differ significantly from the present range in their photochemical reactivity. In general aromatics are undesirable compounds to emit in large quantities into urban air sheds, e.g. the carcinogenic effect of benzpyrene found in diesel exhausts and cigarettes.

Conclusions to Petroleum Fuels from Coal, Oil Shales and Tar Sands

It can be concluded overall that synthetic crude oils from any source must not be considered to possess a significant potential to alleviate reliance on conventional crude oil in Australia or the world before 2000. Certainly they do not appear to be a panacea, even after the turn of the century. In Australia Barnett (1979) concluded that there is little prospect, if any, of significant syncrude production before 2000. Most production technologies including the SASOL system are not yet fully developed and most work has only been done on a pilot-plant scale. There is no firm evidence as yet to suggest that any of these pilot-scale experiments can be translated into commercial scale plants (ATAC, 1978). Although syn-crudes are the most compatible alternative fuels for present transportation systems, by the time they become available on a large scale (if at all), transport
technology or other developments may have moved in a direction which would undermine their importance (e.g. electric vehicles or land use changes). Syncrudes appear to offer nothing in terms of actual energy conservation or in the reduction of vehicular emissions. Profound environmental problems, as yet unsolved, are associated with the production of coal, oil shale and tar sand syncrudes.
3.2.1.(c) Fuels with more Serious Technological Problems

(i) Methane \((CH_4)\)

Compressed natural gas, liquefied natural gas, substitute natural gas and biogas\(^1\) have all been considered as potential automotive fuels. The major component in all these fuels is methane. Normal car engines run well and slightly cooler on methane. Like hydrogen however methane is a gaseous fuel and it encounters serious problems in adapting to widespread use as a transport fuel.

Production

Methane can be obtained from natural gas, coal and various organic wastes. The limitations of the first source are similar if not worse than for oil on a global scale. In Australia the N.W. Shelf is the largest reserve and any consideration of methane as an alternative fuel must take into account that natural gas, like oil, is non-renewable and already has other important uses especially in industry and for residential uses (ATAC, 1978). The production of methane from coal for automotive uses is even more remote than producing coal syncrudes, particularly considering

\(^1\) Natural gas is almost pure methane (92-99 percent), whereas biogas is about 70 percent methane and 30 percent \(CO_2\) with a trace of \(H_2S\).
methane's poor compatibility with present systems.

The potential for producing methane from organic wastes on a scale large enough for widespread automotive use is very small. It has been estimated that the energy content of sewage, garbage, farm and forest wastes in Australia contain about 15 percent of the total energy consumption in Australia in 1974. However it would not be possible to convert all this to useful energy (C.S.I.R.O., 1977). Any effort to obtain significant energy for transport from organic waste would be confronted with similar logistics problems to those described for ethanol. Methane from organic waste appears to offer significant potential for use in farming and in industry where waste processing on-site for on-site use can replace some of the exogenous energy inputs in these activities. The high cost of waste disposal is making waste processing in a methane digester more attractive than conventional methods (C.S.I.R.O., 1977).

Adapting to Methane

As already stated methane has serious drawbacks due to its poor compatibility with present transport systems. Its major problems can be summarised as follows:

(1) Fuel storage in the vehicle. Methane compresses but will not liquefy under pressures normally available.
In a compressed form it is known as C.N.G. (compressed natural gas). Depending upon whether a one, two or three stage compressor is used methane can be stored at 1,000, 3,000 or 21,000 kPa respectively (150, 500 or 3,000 p.s.i.). With the highest pressure container 55 litres (12 gallons) of methane can be stored but this is equivalent to only 12.5 litres of high octane petrol. As biogas the same container could store the equivalent of only 9 litres of petrol. High pressure containers are very heavy but are essential if methane is used as a gaseous fuel. To store the equivalent of 12.5 litres of petrol at atmospheric pressure would require a 15 cubic metre tank (540 cubic feet) (C.S.I.R.O., 1977, Deslandes, 1974).

Methane may be stored as a cryogenic liquid (L.N.G.) which reduces the energy-volume-weight problem. For example the equivalent of 91 litres of petrol can be stored as 204 litres of cryogenic liquid compared to 400 litres of compressed methane. As petrol the total weight would be about 66kg (145 lb.) and as cryogenic methane it would be 75kg (165 lb.). Cryogenic equipment is however sophisticated and very expensive (Gillis, Pangborn and Vyas, 1975).

(2) Conversion Costs. Fuel delivery systems must be modified to cope with the problems of a gaseous fuel and safety standards must be more stringent. This is not an insurmountable problem but involves considerable expense to both the private motorist and car manufacturers.
Cryogenic systems overall involve substantially higher costs (Deslandes, 1974). In general conversion to gaseous fuels requires some basic changes in the vehicle. These can be listed as follows:

(a) fitting of a gas storage system with a shield between it and the passenger compartment together with a positive ventilation system.

(b) fitting of a dual or single fuel carburettor to permit liquid and gaseous or gaseous fuel operation.

(c) fitting of a high pressure line (with a relief valve) from the fuel tank to the carburettor.

(d) a solenoid operated shut-off valve operated from the ignition.

(e) a two-stage water-heated regulator to convert liquid fuel (in the case of cryogenic storage) to a gaseous form and to reduce gas pressure for carburettion.

(f) an additional fuel contents gauge.

(Deslandes, 1974).

(3) Power Output. Gaseous fuels usually involve a power loss of the order of 10-25 percent due mainly to a loss in volumetric efficiency and slower flame speed with lean gaseous fuel-air mixtures (Deslandes, 1974).

(4) Engine Wear. Gaseous fuels may increase engine wear because:
(a) Piston ring/liner scuffing may increase due to fuel "dryness".

(b) The absence of lead can cause excessive valve wear but this can be minimised, for an additional cost, by induction hardening of the valve seat or use of hard alloy inserts (Deslandes, 1974).

Fire and Explosion Risks. These risks tend to be higher with gaseous fuels and require more stringent safety measures.

Fuel Economy and Emissions

The fuel economy on a volume basis of vehicles fueled with methane will be much lower than comparable petrol fueled vehicles. This is due to methane's lower energy density and is reflected by the large size fuel tanks required to store sufficient methane for long range travel. It has been estimated that two 55 litre tanks at 170 atmospheres would be required by a six cylinder vehicle to travel 150-200km (i.e. a fuel economy of between 1.4 and 2.0 kilometres per litre) (Energy Advisory Council, 1979).

Methane however offers substantial emissions advantages, particularly as it would eliminate lead from exhaust emissions. Table 3.9 summarises the results of tests on six vehicles in the U.S.A.
Table 3.9 Comparative emissions of methane and petrol vehicles.

<table>
<thead>
<tr>
<th>FUEL</th>
<th>AVERAGE EMISSIONS g/km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC*</td>
</tr>
<tr>
<td>Petrol</td>
<td>3.4</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.2</td>
</tr>
<tr>
<td>% Reduction</td>
<td>94</td>
</tr>
</tbody>
</table>

* excluding methane.

Source: (After: Deslandes, 1974).

Hydrocarbon emissions from natural gas powered vehicles consist mainly of unburned methane which has no photochemical reactivity so for comparative purposes is excluded from data in table 3.9. These emissions results were achieved with a 30 percent reduction in power due to timing specifically to minimise emissions.

In general it has been shown that exhaust emissions from vehicles or stationary car engines fueled with methane can be substantially reduced. However the magnitude of these reductions is dependent upon engine design, timing and vehicle weight. Evaporative emissions are eliminated because of the sealed fuel tanks and special carburettors which must be used. Where a sacrifice in engine power is unimportant g/km emissions reductions of between 52-95 percent for HC, 69-89 percent for CO and 14-84 percent for NO_x can be achieved through methane's lean fuel operation and good fuel distribution characteristics. Methane will burn at fuel to air equivalence ratios which cause misfire in petrol powered
cars but only power losses in methane fueled cars. Where close to equivalent performance is desired with methane, average reductions of 50 percent for HC and 25 percent for \( \text{NO}_x \) may be obtained with CO remaining about the same (Deslandes, 1974).

Conclusions to Methane

Methane or biogas does not offer great potential as a transport fuel substitute or supplement because supplies are limited and natural gas is already in great demand for industrial, residential and commercial purposes. Storage and transport of methane as C.N.G. is a serious drawback due to the great weight, bulk and expense of storage containers. L.N.G. is not practical for normal vehicles because of safety problems and the difficulties of maintaining and transporting a fuel tank at \(-160^\circ\text{C}\) (N.E.A.C., 1979). ATAC (1978) concluded that the only significant transport use methane might fulfill in Australia is in indoor vehicles which could benefit from methane's low emissions characteristics. Methane, despite its high octane number, is not suitable for diesel engines because of its low cetane number\(^{(1)}\) (Kant et al., 1974). The potential of methane as a substitute for conventional oil products appears to lie more in stationary operations.

\(^{(1)}\) Cetane number provides a similar quality rating method for diesel fuel as that of octane number in petrol.
Hydrogen is being investigated as an automotive fuel for a number of reasons. The factors in favour of hydrogen can be listed as follows:

1. The wide range of sources and methods available for generating hydrogen make it an attractive fuel in terms of supply flexibility.

2. It is possible to run conventional ICE's on hydrogen fuel without extensive design changes. This protects the massive capital and research resources vested in I.C.E. technology.

3. Reports vary on the economics of hydrogen production but the possibility remains of producing hydrogen in the future on a scale sufficiently large for the final cost to be comparable to conventional petrol and other alternatives.


This discussion summarises the results of a number of reports on the feasibility of hydrogen as an automotive fuel, including its advantages, disadvantages and the major technological and economic problems associated with introducing it on a large scale.
Production

Hydrogen can be produced by a number of processes.

(1) Coal gasification. Coal or char is gasified and methane in the gasifier effluent is converted to CO and H₂ and the CO is shifted with H₂O to CO₂. CO₂, H₂S and CO are then removed. A number of gasification schemes exist and most can be adapted to yield H₂ as the major product (Kant et al., 1974).

(2) Electrolysis of Water. This process requires large amounts of electricity which may be supplied by coal, solar or nuclear energy. In the short term coal and nuclear energy offer the only options but in the long term solar energy might be used for this purpose (Kant et al., 1974). It has been estimated that to produce hydrogen via the electrolysis of water with solar energy would cost $33 per gigajoule compared to $2.10 per gigajoule for oil at $13 per barrel (Barnett, 1979).

(3) Thermochemical Conversion of Water. Numerous different thermodynamic cycles have been proposed and analysed theoretically and experimentally. The net effect of all methods is given by the equation:

\[
\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2
\]

(Kant et al., 1974).
(4) On-board Steam Reformation of Methanol. This method overcomes hydrogen storage problems by using the low temperature waste heat of the engine to convert a methanol-water gaseous mixture to hydrogen and carbon dioxide according to the reaction:

\[
\text{CH}_3\text{OH}(g) + \text{H}_2\text{O}(g) \xrightarrow{\text{Catalyst} \ 505\degree\text{K}(232\degree\text{C})} 3\text{H}_2 + \text{CO}_2(g)
\]

(Kester, Konupka and Comara, 1975).

The obvious disadvantage with this process is that methanol must first be produced.

None of these processes have been proven commercially and considerable technological development still remains to be done. Producing hydrogen from water using nuclear or solar energy appears to offer total independence from fossil fuels (Escher, 1975) and in these terms is worth pursuing. However adapting hydrogen to the present transport system involves some complex problems.

Adapting to Hydrogen

Hydrogen may be burned at extremely lean air-fuel ratios and give high thermal efficiencies (up to 80 percent in normal driving conditions) (Escher, 1975, Billings, 1975). However hydrogen is an ideal gas and thus has physical properties which complicate its use as an on-board motor vehicle fuel. Firstly it has
an extremely low viscosity and density both as a gas and as a liquid and requires very low temperatures to store it as a cryogenic liquid (temperatures below $-253^\circ$C) (Deslandes, 1974). Secondly, it has a flame speed which is about five times that of air-petrol mixtures which complicates control of the combustion process. Thirdly hydrogen is colourless and odourless and is highly flammable. Its use as a fuel would require extremely stringent safety regulations and entail considerably more risk than the present system (Kant et al, 1974).

Storage

Hydrogen's properties create a number of problems related mainly to storage but also to combustion. The fundamental problem with hydrogen storage is leakage.

There are three major ways to store hydrogen:

1. as a pressurised gas,
2. as a cryogenic liquid, and
3. as a metal hydride.

On-board steam reformation of methanol is also an indirect hydrogen storage method.

Storing hydrogen as a pressurised gas is not feasible for transport because of the great weight and volume of the containers necessary to provide sufficient fuel (Billings, 1975). Cryogenic liquid hydrogen is used in the U.S.A. and U.S.S.R. in the aerospace industry but presents considerable difficulties for use in road transport. The main problems of cryogenic storage are:
(a) the present cost is two to three times the cost of gaseous hydrogen.

(b) cryogenic containers to store hydrogen must be super insulated and of a very sophisticated construction. They are thus a very expensive initial investment.

(c) "flash-off" and "boil-off" in cryogenic containers occurs during filling of the tank. A large volume of gas is lost when the inner parts of the tank are instantaneously cooled. Boil-off occurs after the tank has been filled, as heat penetrates the 'super-insulated' container at a rate determined by the container's quality (Billings, 1975). In general cryogenic storage loses about 2 percent per day but may reach 7 percent per day (Loder, 1979).

(d) the lower energy density of liquid hydrogen would require a 91 litre (20 gallon) tank of petrol to be replaced with a 332 litre (73 gallon) hydrogen tank (Deslandes, 1974).

(e) cryogenically stored hydrogen holds a greater danger of accidental explosion than most other fuels (Loder, 1979).

In the case of metal hydrides, hydrogen is stored by bringing a large volume in contact with a solid or powdery form of the metal (e.g. magnesium or vanadium), where it is held by weak bonds. Hydrogen is released as the pressure-temperature equilibrium is reversed. This is achieved by using exhaust heat to supply the necessary dissociation energy (Deslandes, 1974). The metal hydrides
are then recharged with hydrogen by supplying the gas at a medium-low pressure and by dissipating heat from the tank. Approximately half of the tests so far have shown no deterioration in the metal hydride's ability to be recharged (Loder, 1979).

This method appears to offer the best hydrogen storage option in terms of safety and storage, although cryogenically stored hydrogen has an energy content four times that of a magnesium/nickel hydride (Loder, 1979). Metal hydride storage is being actively researched in the U.S.A. For example a 1973 Chevrolet was operated on both cryogenic hydrogen and an iron-titanium hydride tank. Both systems yielded adequate engine performance but it was concluded that the metal hydride system was superior especially in economic terms. A 1975 Pontiac has also been operated on a highly refined iron-titanium system using exhaust heat to effect the hydride dissociation. This system sustained the 7375 c.c. (450 cubic inch) Pontiac motor to speeds of up to 110km/hr.-145km/hr. (Billings, 1975).

Currently, however, hydrogen stored as a metal hydride or cryogenic liquid cannot compete with petrol on an energy content basis. Liquid hydrogen has only about 20 percent of the energy content of petrol per unit weight. Considerable work is being done on producing lighter more compact metal hydrides which may significantly improve hydrogen's energy-weight disadvantage (Billings, 1973). Metal hydrides plus storage
tank may amount to a weight of 320kg (700 lbs.) (Deslandes, 1974).

Combustion

No serious technical difficulties arise in actually operating conventional test ICE's on hydrogen, as demonstrated by the innumerable successful experiments in the U.S.A. in normal driving conditions (Escher, 1975).

Some modifications however need to be made to overcome problems of induction manifold backflashing, pre-ignition and rough combustion. These may be listed as follows:

(1) lower compression ratios to 8:1 to overcome high flame speed characteristics,

(2) use of a gas metering carburettor,

(3) modification of the cam shaft to alter valve overlap characteristics,

(4) the introduction of sodium cooled exhaust valves,

(5) a capacitive discharge electronic ignition system,

(6) adjustment of spark-timing (retardation) and exhaust gas recirculation,

(7) the use of water induction or injection; this is required to dilute the charge and overcome hydrogen's high flame speed - lean operation has also been employed,
some attention must be given to materials because hydrogen can cause metal embrittlement at elevated pressures and normal ambient temperatures (Kant et al, 1974, Escher, 1975).

hydrogen's wide ignition limits require the use of high pressure injection or timed injection into the inlet part next to the valve (Deslandes, 1974).

Other more comprehensive system changes may also be used which require significantly more alterations to the present vehicle. Such broad changes yield better performance especially in terms of fuel economy, e.g. the Hydrogen Induction Technique involves modifying the cylinder head and providing a separate intake manifold for the hydrogen (Kant et al, 1974).

Diesel engines are more difficult to run on hydrogen because hydrogen's high auto-ignition temperatures cannot be met by compression. Auxiliary ignition using pilot injection or a glow plug can overcome this problem to a limited extent (Kant et al, 1974). Alternative engines such as gas turbines, Rankine-cycle and Stirling-cycle engines can be operated successfully on hydrogen. The use of hydrogen offers the potential for a reduction in their combustor size and NOx emissions by employing ultra-lean mixtures.

An alternative to combusting pure hydrogen is the use of hydrogen as an enriching agent for conventional
petrol (hydrogen enriched gasoline). It has been demonstrated that a small amount of hydrogen mixed with air and petrol produces a mixture which can be burned in normal ICE's at ultra-lean conditions. This results in increased engine efficiency and reduction of NO\textsubscript{x} and CO emissions (Hoehn, Baisley and Dowdy, 1975).

This may be achieved by two methods:

(1) The use of bottled H\textsubscript{2} gas and (2) on-board H\textsubscript{2} gas generation. The bottled gas method suffers from storage limitations already discussed. The on-board H\textsubscript{2} generation is a superior solution with hydrogen being produced by partial oxidation of gasoline in an auxiliary gas generator. A net gain in total energy conversion is obtained because the fuel loss associated with hydrogen generation is exceeded by the gain in engine thermal efficiency resulting from ultra-lean combustion (Hoehn, Baisley and Dowdy, 1975).

**Fuel Economy and Emissions**

Hydrogen enrichment has shown promising results in terms of emissions reduction and energy savings. The bottled gas version coupled with a catalytic converter used in a vehicle powered by a 5.7 litre V8 motor achieved emissions results of 0.24g/km HC; 0.02g/km CO; and 0.24g/km NO\textsubscript{x}. All these fall below the U.S. E.P.A. 1976 Federal Emissions Standards. The energy consumption per km of this vehicle was 25 percent below that of the same
conventionally powered car over the same cycle with emissions controls designed to meet 1976 standards. These standards were exceeded for all three pollutants by the conventionally powered car. It is also of relevance that in the case of the hydrogen enriched vehicle evaporative emissions controls, vacuum spark advance, exhaust gas recirculation and air injector reactor systems were all disconnected.

Computer estimates have been made of the energy and emissions characteristics of a vehicle fitted with an on-board hydrogen generating system using the constraint that it must achieve engine performance approximately the same as the bottled gas version. Compared to a conventional car of the same specifications it was estimated to have a 21 percent decrease in energy use and an 80 percent reduction in NO\textsubscript{x} emissions over the U.S. E.P.A. Federal Driving Cycle. A catalytic converter would be expected to reduce HC and CO to Federal Standards (Hoehn, Baisley and Dowdy, 1975).

NO\textsubscript{x} is the only emission of concern from pure hydrogen fueled engines. Emissions of NO\textsubscript{x} may be excessively high or fall well below current U.S. standards depending on the system used. Engines running on hydrogen have achieved as low as 1 ppm NO\textsubscript{x} emissions and as high as 7000 ppm. (Deslandes, 1974). Water injection appears to achieve the best results with levels of 0.12g/km and 0.01g/km for cars tested over the U.S. Federal Driving Cycle. These are well below the
original 1976 U.S. standard of 0.2g/km (Billings, 1975). Water injection reduces the high peak combustion temperatures characteristic of hydrogen. Efforts to reduce NO\textsubscript{x} emissions usually result in some sacrifice in power output. For example lean operation may result in emissions of 1,000 ppm NO\textsubscript{x} but engine output is only about 78 percent of the same engine running on petrol (Deslandes, 1974).

Conclusions to Hydrogen

The technological problems which confront the production and use of hydrogen as an alternative automotive fuel are serious but may not be insurmountable given sufficient time and resources invested in solving them. Economic and human factors do however lead to an overall pessimistic assessment of hydrogen in the short, medium and perhaps long term future. Hydrogen will always remain a highly dangerous substance and its disseminated use and distribution throughout a city must raise serious safety and security questions. Already in Victoria some local authorities have been reluctant to grant approval for L.P.G. facilities because of the inherent problems of storing gaseous fuels (CHOICE, 1979). An L.P.G. accident in October 1979 in N.S.W. caused widespread reaction including removal of all L.P.G. vehicles from the road temporarily in N.S.W. Hydrogen has yet to be commercially proven in terms of production and the problem of hydrogen's
incompatability with existing fuel distribution systems is another serious economic drawback (Gillis, Pangborn and Vyas, 1975).

Two studies of hydrogen's potential in the U.S.A. arrived at the following conclusions:

It is very unlikely that the automotive transportation system will evolve of its own accord in the direction of using hydrogen as a fuel for private vehicles before the year 2000... In summary the introduction of automotive hydrogen appears extremely difficult. While evolutionary paths can be hypothesized, commercial incentives are missing at this time. (Kant et al, 1974).

Another study considered that the gradual phasing in of hydrogen will occur via its use in public transport such as buses and trains. However its optimistic conclusions point to important political and economic imponderables:

With continued support, dedicated research and a national commitment, hydrogen will have a significant impact on this nation's energy economy (U.S.A.). (Billings, 1975).

In Australia hydrogen is considered a very marginal, long term fuel possibility, which will certainly not have any impact on energy use in transport in Australia until well into the next century, if at all. (ATAC, 1978, Energy Advisory Council, 1979).
(iii) *Ammonia* \((\text{NH}_3)\)

With major modifications ammonia can be used in internal combustion engines but at present serious obstacles stand in the way of its widespread use.

**Production**

Ammonia can be produced on a large scale by reacting hydrogen from coal or water with air using electricity as a power source. However this process is at present very expensive. A study in the U.S.A. ranked production and distribution of ammonia as the third most expensive fuel option from a choice of twelve (Kant *et al.*, 1974). The production of hydrogen from coal for ammonia synthesis is unrealistic in economic terms because coal can be converted directly into liquid hydrocarbons or methanol (Kant *et al.*, 1974). The water process requires large amounts of electricity which would necessitate an expansion of electric energy production which in itself might be problematic.

**Adapting to Ammonia**

The major advantages associated with ammonia are:
(a) resource availability is good provided electricity can be obtained,

(b) ammonia has an octane number that allows the use of higher compression ratios which results in improved thermal efficiencies,

(c) the absence of carbon means that HC, CO and CO$_2$ emissions are eradicated. However high NO$_x$ levels have been obtained (Deslandes, 1974),

(d) the technology of the synthesis process is developed although commercial production would still have to be demonstrated.

Ammonia however has considerable technological drawbacks associated with using it in present vehicles. These can be listed as follows:

(a) It has a low heat of combustion which necessitates the supply of about twice the weight and three times the volume of ammonia relative to petrol for an equivalent amount of power (Kant et al., 1974).

(b) Ammonia with its high heat of vaporisation and low heat of combustion necessitates the use of about eight times as much heat as needed for petrol to generate an equivalent amount of energy as vapourised fuel. Engine exhaust heat may be sufficient for this purpose because of ammonia's low boiling point (-33.5°C) (Kant et al., 1974).
(c) Supercharging would be required for equal performance, and a small amount of hydrogen would be required under part load.

(d) Hot spark plugs with wide gaps and high voltage ignition would be required. Redesign of combustion chambers to encourage rapid ignition due to ammonia's low flame speed may also be necessary. This may involve increasing the residue time in the combustor and tripling the combustor size (Kant et al., 1974, Gillis, Pangborn and Vyas, 1975).

(e) Ammonia has low lubricity so special attention to bearings would be required.

(f) Ammonia is highly corrosive to materials containing copper, brass and zinc. Maintenance problems may become more severe if ammonia was used.

(g) The toxicity of ammonia is high (exposure to 100 ppm for prolonged periods is dangerous) and elaborate precautions would be required to prevent inhalation. Ammonia is extremely irritating and highly dangerous to eyes and respiratory tracts. It is highly incompatible with present distribution systems.

(h) The use of ammonia involves heavy bulky storage. The equivalent of 91 litres of petrol would weigh 175kg as ammonia compared to 66kg and would have a volume of 205 litres (Gillis, Pangborn and Vyas, 1975).

(i) Ammonia is a poor diesel fuel.
Conclusions to Ammonia

At present ammonia is a very peripheral alternative fuel option and is likely to remain as such. One American study concluded that ammonia will be used as an automotive fuel (Gillis, Pangborn and Vyas, 1975). Ammonia's toxic qualities make it extremely unattractive for use in cities. The only immediate advantage ammonia would appear to offer is the potential for exhaust emission reduction although NO\textsubscript{x} may be a problem and emissions of raw ammonia would prove troublesome in large quantities (Gillis, Pangborn and Vyas, 1975). Ammonia's compatibility with present vehicles and distribution systems is extremely poor, ranking eighth out of nine in one American study (Kant et al., 1974).

(iv) Hydrazine (NH\textsubscript{2}-NH\textsubscript{2})

Hydrazine has been used as a high energy propellant in rockets in the past and has recently been assessed as a potential automotive fuel (Kant et al., 1974).

Hydrazine may be synthesized by one of two processes.

(1) The Raschig process

This is summarised by the following two equations:
\[
\begin{align*}
\ce{NH_3 + NaOCl + NH_2Cl + NaOH} &
\ce{NH_2Cl + NH_3 + NaOH + NH_2 - NH_2 + NaCl + H_2O}
\end{align*}
\]

(2) The Urea process

This is given by the equation:

\[
\begin{align*}
\ce{NH_2CONH_2 + NaOCl + 2NaOH + NH_2 - NH_2 + NaCl + Na_2CO_3 + H_2O}
\end{align*}
\]

(Kant et al, 1974).

The cost of these processes is excessively high and the first has the inherent limitation that ammonia must first be generated. For large scale production an entirely new synthesis process would need to be developed to make hydrazine an economic proposition.

In terms of engine compatibility and technological problems hydrazine suffers similar but even more severe limitations to ammonia. Hydrazine corrodes metals containing cobalt, copper, pure iron, lead, manganese, magnesium, tin and zinc and is sensitive to the presence of water. Both inhalation of and skin contact with hydrazine are dangerous (Kant et al, 1974).
Conclusions to Hydrazine

It is unlikely that hydrazine will find any widespread application in automotive transport systems. There may be a more suitable system developed based on one or more of the alternative engines discussed later. However the toxicity and synthesis problems of hydrazine would render it problematic for widespread use in cities.
3.2.2. MOTOR VEHICLE TECHNOLOGY

3.2.2.(a) Introduction - Assessment Methodology

Motor vehicle technology can be discussed in terms of the scale of change which it involves in comparison to the present system. Three levels of change will be used in this review: small scale changes, medium scale changes, and large scale changes.

These classifications are somewhat arbitrary but provide a conceptual aid for considering the massive range of developments in this area. They are used particularly in the drawing together of overall conclusions at the end.

The placing of developments in one or other of these classifications is not done by hard and fast rules but the criteria used are summarised in the following way:

(i) Small scale changes have been considered as those which can be effected almost immediately with minimal disruption or change to present automotive systems or production. These changes consist largely of "add-on" devices such as many of the emissions control systems and fuel savings devices, e.g. electronic ignitions. In one way or another small scale changes are all subject to the control of the individual car owner.
(ii) Medium scale changes are those which require more fundamental design modifications during vehicle manufacture. These design modifications are directed towards finding entirely new designs or advanced versions of the I.C.E.\(^{(1)}\) (e.g. stratified charge engines), and comprehensively revising other components of the vehicle system, e.g. improving aerodynamics and reducing vehicle weight. Such changes in general require a number of years to achieve because of the changes required in materials and mass production techniques. The period of time required to introduce medium scale changes depends upon how significant the changes are.

(iii) Large scale changes in motor vehicle technology have been considered as those which require introducing entirely new engines and vehicle systems. Included in these are external combustion engines such as steam engines and Stirling-cycle engines and even more fundamental changes such as electric and hybrid vehicles. These changes would generally involve considerable time lags (perhaps of the order of 20 years) before they could become significant in terms of urban fuel consumption and emissions. They would also involve large changes in present mass production techniques, capital investment and ancillary services.

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\(^{(1)}\) Internal combustion engine is often referred to as I.C.E.
3.2.2. (b) **Small Scale Technological Changes**

(i) **Post-production Changes to the Existing I.C.E.**

These changes consist of alterations undertaken by individual vehicle owners in an effort to improve the fuel consumption, performance or comfort of their motor vehicles. Owners may change the characteristics of the ignition system, the transmission system, the electrical system, the carburettion system or the aerodynamic performance of their vehicle. They may also consider the use of alternative grades of lubricants, which secondarily alter fuel consumption especially in cold weather and the addition of power consuming auxiliary drives which increase fuel consumption. Most of these changes ultimately affect emissions but usually this is not a consideration to the owners.

These changes are carried out in a variety of combinations on a wide range of vehicles and in a highly independent manner without effective legal control. Consequently there is a paucity of reliable scientific data on the effects that each individual change or combination of changes has on fuel economy and emissions.

Further to this, and of particular importance in Australian cities is the lack of knowledge on the extent and type of deliberate tampering which cars fitted with emissions control systems undergo after their purchase (Mowle, 1979). These changes are particularly
relevant to determining deterioration factors in emissions control systems, these are important for

(a) accurate emissions inventories based on the number and age of cars in the population.

(b) adoption of effective counter-measures in the form of either unalterable emissions control systems or public education, and

(c) so that setting emissions standards for new vehicles may be considered with a fuller knowledge of the performance of current emissions control technology and the scope for improvement.

Deliberate tampering with emissions controls has not been considered in this study. Despite the information obstacles associated with post-production changes to motor vehicles, these changes are obviously a widespread phenomenon and thus they deserve more attention in Australia if only in a qualitative manner (Mowle, 1979).

This section examines some of the more common "add-on" devices and systems which are currently available for use in motor vehicles.
Electronic ignitions were the subject of an empirical investigation which is discussed in detail in Chapters 4 and 5. It is necessary to briefly discuss the principle of operation of these add-on devices so that it may be understood how they are meant to affect fuel consumption and emissions.

There are three basic types of electronic ignition, based on how the spark is generated. (Gunton, 1978).

They can be listed as follows:

(1) Coil energy storage - inductive discharge system.

(2) Capacitor energy storage - capacitive discharge system.

(3) Combined capacitor and coil energy storage - reactive discharge system.

Each of these systems may involve two basic means of timing the spark: mechanical triggering or electronic triggering. In the first case normal
Contact breaker points are used and in the second case either magnetic or optical methods are used. In all three cases above, the capacitor and inductive discharge circuits are connected in parallel with the existing ignition coil to provide a higher voltage and sometimes longer duration spark discharge across the spark plug gap.

In a normal mechanical triggering system the contact points switch the current from each spark plug and allow sufficient time for a charge to build up in the coil between each discharge. However the nature of the points' mechanical operation causes a number of problems related to timing and duration of the spark discharge. First, in a normal ignition the high voltages passing across the points' surface causes pitting (burning), which changes the critical gap setting, and diminishes their conductive ability. Mechanical wear in the rubbing block of the point set also affects the duration of the spark discharge. These factors can have an adverse effect on fuel consumption and emissions.

When a mechanically triggered electronic ignition is fitted, the contact breaker points are used only for signalling the point of ignition and not for switching high electrical currents. This extends their useful life and allows them to remain at the correct setting for a longer period, thus improving combustion
efficiency.

In the case of an electronically triggered ignition the points are removed and replaced with either magnetic or optical sensors which eliminate the mechanical errors due to the points. These are known by the general name of contactless ignitions.

The major advantages of electronic systems are:

1. Their ability to ignite lean air-fuel mixtures. This is discussed further in this chapter when considering lean-burn.

2. Higher voltage spark generation, able to discharge faulty spark plugs.

3. Provision of precise timing of spark discharge throughout the entire r.p.m. range. In particular they reduce misfire under heavy load conditions by providing a constant spark.

4. Their output voltage during starting is generally unaffected by the drop in battery voltage when loaded by the starter motor. This improves starting especially from cold and reduces battery wear.

An add-on electronic ignition, although able to reduce the adverse effects of a poorly maintained
engine, particularly one in which the points and plugs are worn or fouled, appears to have few advantages in terms of efficiency or power output, over a properly turned standard ignition. This is because once the air-fuel mixture is ignited electronic ignitions cannot improve the combustion process. Combustion chamber design, the characteristics of flame propagation and other more fundamental design features are the most important factors after ignition of the mixture. Electronic ignitions only ensure maximum ignition efficiency (Fisher and Waar, 1972). As a result add-on electronic ignitions are generally assessed as having only a small effect on fuel economy and emissions (Blackmore, 1977).

(2) Thermostatic Fans

These devices are designed to ensure that optimum engine running temperature is maintained throughout the vehicle operating cycle. They are available with automatic or manual over-ride switches. In the case of a cold start, when fuel consumption and emissions of HC and CO are at a maximum (discussed further in Chapter 5), it is desirable to allow the engine to heat as fast as possible. Most cars operate a normal fan cooling system which impedes engine warm-up in the morning. The use of a thermatic fan prevents this delay by only operating when the engine reaches a pre-determined temperature and cooling is required.

(1) Thermatic fan is a commonly used abbreviation for thermostatic fan.
Normal fans which draw engine horsepower continually also result in fuel economy losses during higher speed cruise conditions when the flow of air over the radiator is sufficient to keep the engine cool. A thermatic fan enables detection of conditions when assisted cooling is not required and thus this eliminates unnecessary power drain. Fans can take up to 7 h.p. from total engine output (Blackmore, 1977). Another significant advantage of a thermatic fan is that it prevents engine overheating in heavy traffic conditions. The normal fan's cooling capacity is a function of engine r.p.m. For extended periods of low vehicle speed some engines may overheat resulting in high fuel consumption and emissions (this is because vapourisation occurs in the carburettor which is calibrated for liquid flow demands) and possible engine damage. (Harrow, 1977). The thermostatic fan when operating, functions at a constant high velocity ensuring adequate cooling in dense traffic situations.

No emissions data were found in the literature on the effects of thermatic fans but the most significant effect would probably be in shortening the vehicle warm up period. This could only be checked through controlled dynamometer testing though the reduction in emissions would likely depend directly on how much the warm up time was shortened. The same reasoning would apply to fuel economy. It has however been shown in the U.S.A. that the adverse effect of normal fans on fuel economy
is generally of the order of only 1% (Austin and Hellman, 1973).

(3) **Other Methods**

Electronic ignitions and the mostatic fans were the only add-on devices found in the literature which can be easily fitted to existing vehicles at a comparatively low cost and do not involve any significant trade-offs in terms of vehicle performance or driveability. Other devices all involve compromises which may be unacceptable to the individual motorist. These devices and some of their problems can be summarised as follows:

(a) **Water injection** - residual water in the combustion chamber after the motor is turned off causes corrosion and pitting problems on cylinder walls (Personal communication. H. Van Leeuwin, Inst. Mech. Engrs).

(b) **Non-restrictive exhaust systems** - suitable mainly for vehicles with V8 engines which are more affected by exhaust back pressure than other vehicles. Complexity, initial cost and increased noise levels may not justify any small gains in fuel economy or emissions (Layne, Lahue and Clark, 1978). No data are available.
(c) **Alterations to carburetion and intake manifolds**

Alterations to these components of the vehicle system involve significant trade-offs in driveability, power output and cost which probably do not justify any fuel economy gains. Claims of reduced fuel consumption and emissions by manufacturers tend to be qualitative (Layne, Lahue, and Clark, 1978).

(d) **Alterations to head design** - These changes tend to be restricted, for economic reasons, to cases where motors need to be totally reconditioned. Their main advantage is in increases in compression ratio which improve thermal efficiency and can reduce fuel consumption, HC and CO emissions but raise NO\textsubscript{x} emissions. For fuel economy reasons alone the cost of these alterations are apparently not warranted (Layne, Lahue and Clark, 1978).

(e) **Turbocharging**

The principle of operation of turbochargers tends to limit their usefulness to conditions of heavy load such as for vehicles towing caravans or trailers or for larger heavy duty trucks particularly diesels. Turbochargers are extremely expensive as add-on devices ($1,600 - Personal communication Turbochargers. Sales, W.A.) and are only standard equipment on expensive European vehicles (Porsche, Saab). Under ideal conditions turbocharging of petrol driven
vehicles may give up to 14% HC, 13% CO and 8% NOx reductions (Layne, Lahue and Clark, 1978). They do not however give improvements in fuel consumption but enable increased power output when necessary for no change in fuel consumption.
(ii) **Emissions Control Systems**

This section describes the common techniques of emissions control. The use of these emissions control systems is a major issue in the current world and Australian debate concerning the need to conserve oil and to reduce atmospheric pollution in urban areas. Thus, this section also specifically examines the debate in Australia and attempts to clarify some of the commonly held views.

(1) **Overview**

Most emissions control systems (lean mixture systems being a notable exception) have in common the characteristic that they tend to cause the engine to operate less than optimally. The conventional I.C.E. was not initially conceived with air pollution constraints as design criteria. Consequently most efforts to take this into account now meet with either performance or fuel economy problems. Emissions control systems are designed to counter emissions from three major sources. 

(a) Crankcase. (b) Evaporation from the fuel system. (c) Engine exhaust. These are briefly discussed and the relative importance of each in Australia is gauged.

(a) **Crankcase Emissions**

Crankcase emissions are termed blowby gases and result from combustion gases passing between the cylinder wall and piston rings on the exhaust stroke, into the crankcase where they are vented to the atmosphere in uncontrolled vehicles. These gases consist mainly of
hydrocarbons from unburned or partly burned fuel and lubricating oil vapour. Also present are $H_2$, $CO$, $CO_2$, $H_2O$, $N_2$, $O_2$ and $NO$ (Patterson and Henein, 1972). It has been estimated that crankcase emissions are responsible for 20-25 percent of the hydrocarbon emissions from an uncontrolled vehicle (Watson, 1971, Patterson and Henein, 1972). A declining proportion of total hydrocarbons in urban atmospheres are coming from this source. In Australia new vehicles have been fitted with positive crankcase ventilation (P.C.V.) since prior to 1970 and by 1985 emissions from crankcases in Australian cities will be negligible (S.P.C.C., 1979). P.C.V. virtually eliminates emissions from crankcases.

(b) Evaporative Emissions Controls
Evaporation from the fuel system concerns hydrocarbons only and consists of distillation losses from the carburettor float bowl or leaking joints or gaskets and evaporation losses directly from the fuel tank. Most evaporative emissions occur when the vehicle is stationary due to high under-bonnet temperatures after the vehicle is stopped (hot soak) and through diurnal fuel heating and cooling. Carburettor fuel temperature can reach $54^\circ C$ during warm weather operation and $82^\circ C$ during hot soak conditions. Under these conditions fuel readily evaporates (Watson, 1971, Patterson and Henein, 1972). The main factors governing evaporation are (a) maximum fuel bowl temperature, (b) amount of fuel in the bowl, (c) amount of afterfill and (d) the distillation curve of the fuel.
Similarly, fuel in the fuel tank heats and cools in a diurnal process and according to operation, fuel tank temperature may rise as high as $43^\circ$C when ambient temperature is $29^\circ$C. Fuel and vapour inside the tank expand and HC vapour is expelled. The main factors governing this process according to Patterson and Henein, (1972) are:

1. the initial and final fuel temperatures.
2. the volume of the tank not filled with fuel.
3. the composition of the fuel especially the light $C_4$ and $C_5$ ends.
4. the presence of a pressure relief cap.
5. the area of the liquid vapour surface.
6. the length of time or degree of agitation of the tank near the maximum temperature.

The effects of most of these factors can be minimised thus the importance of evaporative emissions from motor vehicles in Australia is diminishing due to control systems which have been in effect for a number of years. For example in Sydney in 1976, evaporative emissions accounted for 86 tonnes per day (31 percent of hydrocarbons from light duty vehicles) and by 1985 they are expected to account for 25 percent of the total (i.e. 68 tonnes per day), despite an overall increase in motor vehicles and kilometres travelled (S.P.C.C., 1979).

It is important to mention briefly that evaporative emissions are not limited to the motor
vehicle itself but occur at each stage of storage and transfer of petroleum products. Despite improvements in some areas evaporative emissions from these sources are expected to rise in Sydney from 54 tonnes per day in 1976 to 67 tonnes per day in 1985 if no further controls are implemented (S.P.C.C., 1979). It can thus be seen that effective control of evaporative emissions needs to be tackled on two fronts; the vehicle and the refining and distribution system.

(c) Exhaust Emissions

Engine exhaust emissions arise as a result of the combustion processes discussed under medium scale changes and are emitted from the exhaust pipe. They are the most important component of motor vehicle emissions and the hardest to control. In 1971 in Sydney exhaust sources accounted for 67.5 percent of daily hydrocarbon emissions from motor vehicles (Iverach et al., 1976), in 1976 for 57.2 percent and in 1985 it is expected to be 73.1 percent (S.P.C.C., 1979).

(2) Range of Control Methods

The range of control methods for crankcase emissions and evaporative emissions is small. The crankcase emissions are controlled solely by positive crankcase ventilation (P.C.V.). Evaporative emission controls usually consist of a carbon packed canister used to absorb hydrocarbons vented from the fuel tank and carburettor. These are subsequently purged into the carburettor during vehicle running and burned (S.P.C.C.,...
undated). If these systems are functioning correctly they have a neutral effect on fuel economy. An alternative method of evaporative loss control is crankcase storage. The crankcase volume is made large enough to accommodate evaporative losses which are purged in the normal way by P.C.V. (S.P.C.C., undated).

In the case of exhaust emissions a whole range of methods exist. Perhaps the most successful of these are lean mixture systems and these have been considered in some detail later in this section. The other major exhaust emissions control methods can be listed as follows, based upon an undated report from the S.P.C.C. entitled "Control of Pollution from Motor Vehicles".

(a) Air Injection - is designed primarily to reduce HC with a minor reduction in CO by introducing air close to the exhaust valve where exhaust gases are still hot enough to burn.

(b) Exhaust Manifold Reactors - are used where air injection is inadequate. They are designed to keep exhaust temperatures high enough to allow further oxidation to occur after air has been injected. They consist of a thermally insulated chamber in which exhaust gases are thoroughly mixed and further oxidised by injected air.

(c) Ignition Timing - is used in combination with a number of other control methods. Timing ignitions
to reduce emissions must be compromised with power, performance and general driveability. The extent to which ignition timing is used depends upon the degree of emissions control needed, e.g. spark retardation is used to control NO\textsubscript{x} emissions in some cases (Patterson and Henein, 1972).

(d) Vacuum Retard Capsule - is used to retard timing during idle but does not operate during deceleration due to a delay device. It is used to reduce emissions of CO and HC at idle and becomes inoperative if the vehicle overheats.

(e) Deceleration Controls - these are a general group of emissions control methods used to avoid excessive HC emissions from the rich mixture surge supplied to the combustion chambers during deceleration. These controls keep the throttle butterfly valve open more than is normal for the idle position and thus allow more air in to burn the rich mixture. A vacuum limiting valve can also be employed to achieve the same purpose.

(f) Exhaust Gas Recirculation - this system is used to reduce NO\textsubscript{x} emissions by recycling exhaust gases to the combustion chamber which reduces peak combustion temperatures. Exhaust gas recirculation does not normally operate during idle or deceleration and the amount of exhaust gas recycled depends upon the airflow rate through the carburettor or some other indicator of engine operating conditions.
(g) Air Temperature Control - is designed to reduce the choke time necessary during cold starts by improving cold-engine driveability. It achieves this by supplying warmed intake air from the exhaust manifold to the carburettor air intake. This has the effect of reducing HC emissions in most cars.

(h) Exhaust Catalysts or Catalytic Converters - these systems are currently not used in Australia because of high fuel lead levels which destroy catalytic substances. However they are in use in the U.S.A. and Japan where they are employed to control HC, CO and NO\textsubscript{x} simultaneously. A catalytic converter placed in the exhaust system in a similar manner to a muffler contains an oxidising agent to oxidise hydrocarbons and carbon monoxide while a reducing catalyst converts nitrogen oxides to nitrogen and oxygen. A wide range of exhaust catalysts have been effective in controlling emissions (e.g. alumina pellets and noble metals such as platinum, Patterson and Henein, 1972), but most suffer some deterioration problems.

All these systems are essentially "add-on" modifications to current motor vehicles, and have gained a reputation for causing poor driveability and reduced fuel economy, due to the compromises in vehicle operation which must be made. This is examined later in this section. The concept of lean mixture systems however offers potential for reducing emissions and fuel consumption simultaneously. The discussion which follows examines these systems in detail.
Lean Mixture Systems

The concept of lean mixture, lean burn or weak mixture systems as they are variously known, is being developed within a broader context. In terms of further developing the conventional spark ignition engine to meet the increasing constraints of lower fuel consumption and lower emissions, lean mixture systems represent a significant advance in basic I.C.E. design. Lean burn systems, being based upon the present spark ignition engine, have the potential to make a more immediate contribution to alleviating the energy-emissions problem.

Lean burn systems include all spark-ignited, carburetted engines which operate on fuel-air mixtures lower than those normally used. A multitude of different methods has been developed to achieve satisfactory performance on lean mixtures. These include:

1. Better mixture preparation by vapourisation of the fuel in the inlet manifold by sonic atomisation. This produces a very fine aerosol dispersion. Individual fuel injection into the parts or cylinders can also be used.

2. Microturbulence to improve cylinder charge homogeneity and flame speed, e.g. by inlet valve throttling or inlet port vortex generators.

3. High energy ignition systems, e.g. electronic ignitions.
(4) **accurate control of spark timing.**

(5) **raising operating temperatures by fitting higher temperature thermostats at the cooling water outlet from the engine block** (Adams *et al.*, 1971; Coon and Wood, 1974).

A characteristic in common however with all lean burn systems is their high-octane, high "anti-knock" fuel requirement. This is true for systems with conventional compression ratios of 9:1 or systems with increased compression ratios. (Coon and Wood, 1974).

In general the use of lean mixtures without these concurrent changes in basic engine design (carburettor and injection system; inlet manifold; combustion chambers; compression ratios, cam profile, valve timing and ignition components) leads to poor performance characterised by rough idling, overheating, misfiring, running on, or poor starting (S.P.C.C., undated). These problems are primarily associated with the lower ignition flame temperatures which lead to slower combustion, increased cycle-to-cycle variation and sensitivity to the cooling effects of intense turbulence and the cylinder walls (Ward, 1977). Leaner mixtures are less problematic in lightweight vehicles with small capacity engines. In this class of vehicle it is possible to meet present Australian emission standards with little more than alterations to the
engine which allow it to run on leaner mixtures. In some cases fuel injection also needs to be used (E.P.A. Victoria, undated; Adams et al, 1971; S.P.C.C., undated). A fully developed weak mixture engine may be able to use air-fuel ratios as low as 19:1 (Advisory Council on Energy Conservation, 1977).

The difficulties surrounding air-fuel ratios in present engines have been developed in the next section - medium scale changes. Lean mixture systems seek to overcome some of these difficulties by designing engines to operate on air-fuel ratios which are optimal for low emissions and high fuel economy, whilst compromising minimally on power output. The greater part of the technology needed to achieve this has already been developed and proven successful. It therefore remains for vehicle manufacturers to decide whether or not to adopt it. (Advisory Council on Energy Conservation, 1977).

Many lean mixture systems tested so far and those in commercial production (e.g. Chrysler's ELB system) have demonstrated positive benefits. Up to 30 per cent better fuel economy has been achieved but this is considerably dependent upon driving conditions. (Advisory Council on Energy Conservation, 1977).

Tests over the U.S. Federal Driving Cycle have shown that compromises between emissions and fuel
economy are still important. For example, computer simulation testing in the U.S.A. of a 2040kg (4500lb) Chevrolet Impala estimated that when tuned for maximum fuel economy a 22% improvement over the standard vehicle was possible. When NO\textsubscript{x} emissions constraints were considered, this improvement was reduced to 12 per cent. However these tests were designed to evaluate the lean burn system per se, against some baseline system and therefore the lean burn system did not incorporate the same emissions control equipment as the standard vehicle (Dowdy, Hoehn and Griffin, 1975). With some form of additional emissions controls it might be possible to diminish the trade-off which was predicted.

Similarly, testing of a 5700 cc (350 cu. inch) Chevrolet engine modified for lean burn operation, achieved a 10% improvement in fuel economy when optimised for this parameter. When tuned to meet the same level of NO\textsubscript{x} emissions as the stock vehicle only a 6% improvement was possible (Dowdy, Hoehn and Griffin, 1975). More research is being done to mitigate these trade-off problems and better overall performance in fuel economy and emissions can be expected.

Lean burn systems have also been developed in the U.S.A. for 360 - 400 cubic inch displacement motors (5900 to 6560 cubic centimetres). One of these uses a three-venturi carburettor system. This system
has the potential to minimise fuel consumption but to meet U.S. emissions standards it must be used with a lean burn reactor system and exhaust gas recirculation which in the past have had the effect of reducing fuel economy by 10 per cent in urban driving. (Adams et al, 1971).

More advanced versions have met with success in reducing both fuel consumption and emissions. Instead of a three-venturi system these versions use a variable venturi atomiser system which operates at an air/fuel ratio of 18:1\(^{(1)}\). For the U.S. Federal Driving Cycle these systems have produced average fuel economy improvements of between 5 and 10 per cent. Table 3.10 summarises the fuel economy and emissions results for a 1971 Ford Galaxie with a 5750 cc (351 cubic inch) engine and 2045kg (4500lb) inertia weight. All data has been converted to metric units with Imperial unit quantities in brackets underneath. All data is based upon the U.S. F.D.C.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Vehicle & Fuel Economy & Emissions \\
\hline
Ford Galaxie & 10\% & 20\% \\
\hline
\end{tabular}
\caption{Fuel Economy and Emissions Results for a 1971 Ford Galaxie}
\end{table}

\(^{(1)}\) The commercial name for the system referred to here is "Dresserator" produced by Dresser Industries Inc.
<table>
<thead>
<tr>
<th>ENGINE</th>
<th>FUEL ECONOMY</th>
<th>EMISSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km/litre</td>
<td>HC g/km</td>
</tr>
<tr>
<td></td>
<td>(m.p.g.)</td>
<td>(g/mile)</td>
</tr>
<tr>
<td>Baseline (has 5.4 0.9-1.4 21-24 2.6-2.7</td>
<td>vacuum advance)</td>
<td>(15.1) (1.5-2.2) (34-39) (4.2-4.4)</td>
</tr>
<tr>
<td>Dresserator alone 5.6-6.6 0.5-0.6 3.7-4.4 0.6-0.8</td>
<td>(no spark advance)</td>
<td>(15.8-18.7) (0.8-1.0) (6-7) (1-1.3)</td>
</tr>
<tr>
<td>Dresserator and 5.6 0.2 2.5-3.1 0.9</td>
<td>manifold reactor</td>
<td>(15.8) (0.3) (4.5) (1.5)</td>
</tr>
</tbody>
</table>

Table 3.10 Fuel economy and emissions of a U.S. lean burn system.


The emissions values in Table 3.10 all meet 1979 U.S. standards but fall slightly short of the original 1976 proposals. It is worth noting however that emission controls in these tests did not involve catalytic converters.

A significant advance in lean burn operation was achieved by Chrysler in the introduction of their electronic lean burn system. The basic principle of this system lies in its extremely fine control of the combustion process at air-fuel ratios in the range 15:1 to 18:1. This enables control of the production of pollutants especially NOx (as distinct from preventing their escape after formation) and the use of smaller amounts of fuel.
E.L.B. involves use of a conventional carburettor with fuel metering changes to provide lean mixtures and precise ignition timing. Lean mixtures cannot be depended upon to burn efficiently unless ignited at precisely the correct time.

The required ignition timing varies enormously over the range of vehicle operating conditions and depends upon the complex interaction of many engine variables. The E.L.B. system incorporates five sensors, which feed information to a spark control computer (microprocessor) which in turn determines when the spark is fired. The factors which this system responds to include:

1. Speed advance.
2. Vacuum advance.
3. Start-up advance.
4. Throttle position.
5. Throttle opening speed.
7. Time of idle.

Response and processing time is of the order of milliseconds (Chrysler Australia Ltd, 1979).

Royal Automobile Club road tests in Perth have demonstrated that the E.L.B. system offers considerable fuel economy benefits. A 4000 cc, six cylinder automatic Valiant sedan with air-conditioning was tested over a metropolitan test cycle (predominantly...
It yielded a fuel economy of 7.3km/l (20.6 m.p.g.) which was 20-30% higher than comparable vehicles under similar conditions without E.L.B. (R.A.C., 1979).

This result was achieved without other changes in design (e.g. weight reduction or aero-dynamic considerations). It may therefore be inferred that there remains potential to improve fuel efficiency even further. To encourage larger savings in overall urban fuel consumption such technological advances could be fruitfully applied to smaller vehicles. Although the fuel economy of the vehicle tested represented a significant improvement, the value of 7.3km/l falls well below desirable fuel economy objectives. The Federal Chamber of Automotive Industries' proposal in Australia for passenger car fuel consumption objectives indicates that for 1979 an average of approximately 9.4km/l for new cars would be possible and highly recommended. (see figure 3.15) (Endersbee, 1979).

It is apparent from this analysis that fully developed lean burn systems do offer reductions in fuel consumption and emissions though lead emissions would remain a problem if leaded fuels were used to meet the high octane and anti-knock requirements of these systems. The range of reductions in fuel consumption is greatly dependent upon the system being tested and the test conditions. According to references consulted in this study it may lie somewhere
between 6 and 30%. It is difficult therefore to assess the overall impact on energy consumption of a widespread move to such systems. It is also clear that the attraction of lean mixtures lies in the relative ease with which the present I.C.E. can be adapted to use them. This avoids costly changeovers in terms of production methods and infrastructure which are necessary for more sweeping changes. For this reason it is conceivable that the benefits to be gained from lean burn might have a tendency to hinder more fundamental changes in propulsion systems, which may have a greater potential to reduce energy use and emissions. One study concluded that the average potential of lean burn systems to reduce vehicle fuel consumption would be at the lower end of the range; in the order of 6% and that, "... they should therefore only be considered a stop-gap measure until a more efficient engine system can be developed." (Hurter and Lee, 1975).
Lubricants

The fundamental aim of better lubricants is to reduce friction primarily in the ring-belt area of engines and in other moving parts and to improve engine warm-up periods. In the past graphite, teflon and other solid lubricants have been considered as engine oil additives but have not been adopted.

A comparatively new solid additive, molybdenum sulphide (MoS₂) has been extensively tested and shown to yield average improvements in fuel consumption of the order of 5 percent with values ranging between 2 percent and 12 percent (Little, 1974). It has also been demonstrated that this additive has other desirable effects such as smoother running and reduced wear. It has negligible effect on emissions.

The use of better lubricants is chiefly in the hands of individual vehicle owners but efforts can be made to encourage awareness of the effect of this factor on fuel economy. The use of superior additives in oil may not be cost effective from a fuel economy point of view, but would probably result in economic advantages overall (Little, 1974).

Individual car owners can also improve the fuel economy of their vehicles by considering carefully the various grades of lubricants which are used throughout the vehicle.
As suggested earlier the aim of choosing the best lubricant for a particular purpose under a given set of conditions, of which weather is the most important, is to minimise friction. The magnitude of the friction force is dependent, amongst other factors, upon the viscosity of the lubricant used. Choice of the lowest viscosity lubricant for the engine, axles and transmission may yield a range of fuel economy benefits depending upon the conditions.

In the U.S.S.R. efforts are made to ensure that all vehicles use the lowest viscosity oil possible. The intensely cold weather which prevails during much of the year makes it possible to reap considerable benefits from this method. This practice is used in conjunction with engine heating prior to starting. The major methods are air heating, electrical heating and infra-red heating. This lessens the tendency of vehicles to suffer from cold-start fuel penalties (Afanasyev, 1974). A range of fuel economy benefits from the use of low viscosity lubricants has been reported. These are summarised in Table 3.11.

In general, improvements in fuel economy of the order of 2-5 percent can be gained by using lower viscosity lubricants in engines, axles and transmissions. The major benefits are from the engine oil component. These benefits can be obtained at zero additional cost to the vehicle owner. The major obstacle lies in creating sufficient awareness of energy conservation in
Table 3.1 Fuel economy from lubricant changes

<table>
<thead>
<tr>
<th>Test</th>
<th>Lubricant Change</th>
<th>Result (% improvement in fuel economy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>British Passenger Cars</td>
<td>SAE 30 to SAE 10W</td>
<td>Up to 5%</td>
</tr>
<tr>
<td>British Passenger Cars</td>
<td>SAE 30 to SAE 5</td>
<td>Up to 18%</td>
</tr>
<tr>
<td>G.M. Constant Speed Test (Warmed-up)</td>
<td>Low Viscosity Engine Oil</td>
<td>Up to 5%</td>
</tr>
<tr>
<td>G.M. Driving Cycle Tests (Various, Warmed-up)</td>
<td>Low Viscosity Engine Oil</td>
<td>3-4%</td>
</tr>
<tr>
<td>G.M. Constant Speed and Highway (Warmed-up)</td>
<td>SAE 20W-50 Engine and SAE 90 Rear Axle to SAE 10W and SAE 80W</td>
<td>2-3%</td>
</tr>
<tr>
<td>G.M. City/Suburban Cycle (Cold Start)</td>
<td>High Viscosity Commercial Engine and Axle Lubricants to Low Viscosity Equivalents</td>
<td>5%</td>
</tr>
</tbody>
</table>

Source: Davison and Haviland, (1975)

NOTE:

(a) no details of the test procedures for the British cars were available.
(b) All G.M. testing was done with various dynamometer driving schedules.
(c) All lubricants used complied with standards necessary to maintain sufficient engine and parts protection.

general so that the benefits might have some broader impact on total fuel demand. Although no data are available it could be expected that a reduction in the vehicle warm-up period due to lower viscosity lubricants would have a beneficial effect on emissions.
(iv) **Vehicle maintenance and durability**

An important factor in determining aggregate fuel consumption and emissions of the present vehicle population is the condition of the individual vehicles. The condition of the vehicle covers not only the engine tuning (carburettor and ignition system setting), but also the state of the emissions control system. Faulty or badly maintained emission controls cause high fuel consumption and are ineffectual in controlling emissions.

A survey published by the Advisory Council on Energy Conservation (1977) in the U.K. showed the results of random testing of 4451 vehicles in use on U.K. roads to determine their condition. The results shown in Table 3.12. demonstrate the generally poor state of maintenance of many vehicles.

**Table 3.12** Percentage of a large sample of cars in the U.K. with various engine system maladjustments.

<table>
<thead>
<tr>
<th>PROBLEM</th>
<th>PERCENT OF 4451 VEHICLES WITH THE PROBLEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact breaker requiring attention</td>
<td>58.4%</td>
</tr>
<tr>
<td>Poor sparking plugs</td>
<td>27.2%</td>
</tr>
<tr>
<td>Ignition timing over advanced 6° +</td>
<td>25.5%</td>
</tr>
<tr>
<td>Ignition timing over retarded 6° +</td>
<td>12.1%</td>
</tr>
<tr>
<td>Mixture over-rich at cruise</td>
<td>57.0%</td>
</tr>
<tr>
<td>Mixture over-rich at idle</td>
<td>58.1%</td>
</tr>
</tbody>
</table>

Further testing demonstrated that cars chosen at random showed an average improvement in fuel economy of just over 5 per cent which rose to 7 per cent if only those vehicles needing breaker points adjustment were included. Advisory Council on Energy Conservation, 1977). Testing of U.S. vehicles has shown that substantial reductions in HC and CO and up to 20% reductions in fuel consumption can be achieved by correct tuning (Atkinson and Postle, 1977) although 6% is a typical value.

At present poorly maintained vehicles involve a human factor; the motorist's perceived importance or awareness of keeping a vehicle well tuned. However a number of things can be done technologically to reduce the susceptibility of the vehicle to this human factor.

(1) replacing present mechanical and electro-mechanical components with purely electronic components. An example of this is the use of contactless electronic ignitions discussed in an earlier section. Capactive discharge electronic ignitions which extend the life of breaker points result in less attention being required to engine tuning than with conventional systems.

(2) using longer lasting spark plugs.
(3) replacing carburettors which are susceptible to maladjustment with locking ones that can only be altered by a service agent with special tools.

(4) improving vehicle tappet systems so that less frequent adjustments are required.

The Advisory Council on Energy Conservation, (1977) states that improving these components of the vehicle can result in the maintenance of good engine tune for 80 000km with only minor attention, thus preventing deterioration in fuel economy and emissions from these causes. Basic vehicle maintenance practices which will give the best fuel economy and emissions performance for a specific vehicle, should give attention to the following factors, in order of decreasing importance.

(a) Idling mixture strength and engine idling speed.

(b) Basic ignition timing/dwell angle.

(c) Vacuumatic ignition advance.

(d) Centrifugal ignition advance.

and (e) Spark plug condition.

(Atkinson and Postle, 1977)
Despite the apparent fuel advantages to individual vehicles of maintaining engine tune, the overall fuel savings may be relatively low. In New Zealand these have been estimated to be approximately 1% of total petrol use (Kneebone and Walkins, 1977).

In Australia concern has been expressed specifically over the durability and effectiveness of present emissions control systems. In a major report to the Federal Minister for Transport the Australian Academy of Technological Sciences, (1979) stated:

We are concerned about the apathy towards air quality exhibited by vehicle owners and the public, the unsatisfactory tuning of vehicles before sale, tampering with emission control systems after purchase and of failure of vehicles in service to meet the required standards due to unsatisfactory tuning.... While recognising that special circumstances may lead to maladjustment of emission control systems in the new cars which were selected for test, it is disturbing to note the apparent ease with which maladjustment could occur and the failure of some distributors to ensure that cars displayed for sale are in properly adjusted condition.... We have also received other evidence indicating the prevalence of tampering with or removal of emission control equipment.

The same report also expressed concern over the normal deterioration of emissions control equipment as reflected by the results of a number of durability tests. These tests showed that an unsatisfactory proportion of vehicles failed to remain within the emissions standards they were originally designed to meet. They concluded that emphasis must be placed on durability and maintenance of emissions controls in the future.
(v) Motor vehicle fuel economy vs emissions

A major controversy in Australia at the moment is the effect of present add-on emission control systems on fuel economy. The arguments for and against emission controls and their effects on fuel economy have been analysed in depth by a number of studies (Australian Environment Council, 1978; Department of Transport, 1978; Australian Academy of Technological Sciences, 1979). Treatment of the subject here will be confined to the basic findings of these studies.

The Department of Transport (1978) report the following results after the changeover from ADR 27 to ADR 27A emissions standards on 1 July 1976.

Table 3.13 Per cent change in ADR 27A Vehicles Fuel Consumption Compared with ADR 27 Vehicles as Received.

<table>
<thead>
<tr>
<th>Mass Category</th>
<th>Light</th>
<th>Medium</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>City Cycle</td>
<td>+ 2.98</td>
<td>+ 12.50</td>
<td>+ 12.62</td>
</tr>
<tr>
<td>Highway Cycle</td>
<td>+ 2.25</td>
<td>+ 12.45</td>
<td>+ 3.41</td>
</tr>
</tbody>
</table>

NOTES

(1) All results significant (One tail t-test 5 per cent probability level)
(2) No significant change after vehicles tuned.
The significant point to note from this table is the relatively slight effect of emissions controls on the light class of vehicles (e.g. Chrysler Galant, Datsun 120Y, Ford Escort, Holden Gemini and Toyota Corolla). It is the medium and heavy vehicle classes which suffer the greatest fuel economy losses.

This general finding is supported by numerous other studies in Australia and overseas. The conclusions to some of these may be summarised as follows:

- Any increase in vehicle fuel consumption that has occurred in the period over which emission controls have been implemented is primarily associated with increased vehicle weight arising from model changes and the inclusion of heavy power consuming options such as air-conditioning, automatic transmission and power steering.

- Some vehicle models have increased consumption as a result of the latest emission standards. These vehicles are generally in the heavier weight categories. Improved engine and emission control system design can offset these fuel consumption increases.

- Some vehicle models have maintained or improved their fuel consumption. These vehicles are generally in the lighter weight categories.

- Removal of emission controls, or making them less stringent, as a fuel conservation measure will not achieve any significant benefit. Such measures will lead to needless deterioration in urban air quality.

We believe that undue emphasis has been placed on the fuel penalty incurred by emission control. We conclude that early vehicles manufactured to ADR 27A suffered a considerable fuel penalty which was compounded by the poor ability of the motoring public to handle vehicles with worse driveability than those to which they are accustomed. Substantial improvement in vehicle design has enabled much of the lost fuel economy to be regained but it is likely that the intrinsic cost in fuel of all vehicles is about 3%.

(Australian Academy of Technological Sciences, 1979).

The Victorian E.P.A. in an undated summary of the factors affecting fuel economy further support the basic contention that improved emissions need not necessarily be synonymous with decreased fuel economy. They also emphasise the interaction between technological and human factors in determining emissions and fuel economy of vehicles with add-on emissions control systems:

- There is no inherent relationship between driveability and emission control; especially misleading is the contention that driveability will become poorer with emissions control... tampering with the emission control system is more likely to reduce fuel economy than to improve it. Tampering always makes emissions worse and causes faster deterioration in engine life expectancy.

- There is no inherent relationship between fuel economy and emission control; especially misleading is the contention that fuel economy will become poorer with emission control. The fuel economy of a car depends heavily on its design and quality of manufacture.

(Environment Protection Authority of Victoria, undated).
Overall it can be concluded from these last two sections that energy conservation and the environment need not necessarily be traded off against one another. The fundamental direction which would appear to be needed is a move towards a technology which is far less prone to human intervention or in fact the perceived need for human intervention. This implies the need for a tightening of emissions control engineering standards or a move towards more fundamental changes in vehicle and engine design than that afforded by add-on systems.
3.2.2.(c) Medium Scale Technological Changes

(i) New Designs and Advanced Versions of the I.C.E.

Since the pollutants which are of concern are the products of incomplete combustion (except lead) they can be eliminated or reduced by ensuring more complete combustion within engines and thus at the same time reduce fuel consumption by an equivalent extent (Draper, 1974). Considerable research is therefore being carried out by motor vehicle manufacturers around the world, to develop new designs of the internal combustion engine. This appears to be due to the realisation that the conventional spark ignition reciprocating I.C.E. may be reaching the limits of its potential to effectively meet both fuel economy and emissions standards:

The propulsion system raises emissions - economy - performance trade-off problems. The modern reciprocating engine has virtually reached the limits of its technological possibilities; no major breakthrough currently seems possible.

(Friedman, 1978)

It is much more difficult to convert existing engines to meet present and future emissions standards than to meet the fuel economy requirements.

(Reitze, 1977)

Thus much research is directed specifically to producing engines which simultaneously have higher fuel economy and which either produce less pollutants in a more efficient combustion process, or burn the pollutants in the engine. Both these cases obviate the need for "bolt-on" emissions controls (De Forge-Dedman and Howard, 1972),
which are so easily altered by car owners.

(1) Limitations of the Conventional I.C.E.

Before discussing new engine designs it is necessary to describe the shortcomings of the conventional spark ignition reciprocating I.C.E. in terms of fuel economy and emissions formation.

A fundamental problem of the conventional I.C.E. is its inability to vary the air to fuel ratio under different operating conditions. Rather, it varies its load by merely changing the quantity of fuel-air mixture supplied to the cylinders and the ratio of air to fuel remains almost constant (Ayres and McKenna, 1972). As a result the conventional engine operates for a considerable portion of urban running on air-fuel mixtures which are inappropriate to the engine load. This leads to higher fuel consumption and emissions.

At a ratio of 14.7:1 of air to fuel there is sufficient oxygen to completely convert all the petrol into carbon dioxide and water. However the complexity of the combustion process and the fact that mixing and distribution of the air-fuel mixture are never completely homogenous means that some carbon monoxide and unburned fuel are generally found in the exhaust (Ayres and McKenna, 1972).

Figures 3.3 and 3.4 show the effect that varying the air fuel mixture has on emissions characteristics. Figure 3.5 shows qualitatively the combined effect of lean and rich fuel mixtures on all three emissions simultaneously. It is clear from this diagram that optimum reduction of CO, HC and NO\textsubscript{x} occurs at very lean air-fuel mixtures of about 19:1 (Adams, 1971).
Figure 3.1 Internal Combustion Engine Exhaust Composition as a Function of Air-Fuel Ratio.

Source: A.H. Rose Jr. (1972)
Figure 3.4: NO\textsubscript{x} production as a function of air-fuel ratio.

Source: A.H. Rose, Jr., et al., (1965)
FIGURE 3.5  Emissions as a function of air-fuel ratio.

(2) Pollutant Formation in the I.C.E.

To fully understand the limitations of the present I.C.E. it is necessary to briefly discuss the processes which lead to the formation of three important pollutants: hydrocarbons, carbon monoxide and nitrogen oxide. These three pollutants are formed by three different processes. This is a major reason why emissions control is fraught with difficulties (Watson, 1971).

Hydrocarbons are formed when some of the fuel is heated in the engine but not burned; they also form directly as evaporative emissions from the fuel tank, carburettor and crankcase. Hydrocarbons consist of a mixture of unburnt petrol and organic compounds such as acids, aldehydes and ketones. Anything which causes incomplete combustion will result in hydrocarbon emissions e.g. a poor spark on a rich mixture.

When a spark discharges at the top of the compression stroke, its flame propogates outwards, towards the cylinder walls. The air-fuel mixture in the vicinity of the walls, particularly in the space between the cylinder wall and the piston itself, remains too cool to be ignited. This is sometimes termed the "quench zone" (S.P.C.C. Watson, 1971). Unburnt fuel in engine crevices such as between the valve head and seat are important sources of hydrocarbon emissions. Watson (1971) estimates that this could be the source of up to
50% of exhaust hydrocarbons.

After each power stroke there remains a mixture of air and unburned fuel which during the exhaust stroke is either swept out through the exhaust valve or escapes past the piston rings as "blow-by", into the crankcase and hence into the atmosphere unless special controls are fitted.

Carbon monoxide also results from incomplete combustion due to either inadequate air in the fuel-air mixture to completely burn the fuel or to insufficient time during the cycle for combustion to go to completion (i.e. for all the carbon to be converted to CO₂) (Heywood, 1971). This is exacerbated by rapid cooling of the combustion gases as the piston moves down during the power strokes. This slows the combustion process and 'freezes' carbon monoxide in the exhaust gases. Figure 3.6 shows the relationship of HC and CO concentrations to the 'cool' cylinder wall.

FIGURE 3.6 Hydrocarbon and carbon monoxide concentrations near to the combustion chamber walls.
The formation of nitrogen oxide is independent of the completeness of combustion. It results from the high temperature which occurs during the burning process, allowing nitrogen and oxygen to combine in the equation $N_2 + O_2 \rightarrow 2NO$. The higher the peak temperature and the more oxygen available the more nitrogen oxide that will be formed. Because of the rapid cooling during the exhaust process, NO has insufficient time to decompose to form an equilibrium and it is emitted to the atmosphere where a portion is subsequently oxidised to $NO_2$ (Heywood, 1971; Watson, 1971). The timing of the spark has an important effect on $NO_x$ levels (S.P.C.C., undated).

The relationship of air-fuel mixture to fuel economy and exhaust emissions has resulted in research into producing engines which will operate on weak petrol-air mixtures. The following discussion briefly examines some of these efforts.

In this and the ensuing chapter a number of specific engine designs will be described. The operating principles of each of these engines are important in understanding their energy use and emissions characteristics. Thus the discussion of each engine's energy and emissions performance is preceded by an italicised section describing how each system works. This has been done to enable more detailed examination of each engine if required.
(3) **The Stratified Charge Engine**

The purpose of the stratified charge engine is to improve the efficiency of fuel utilization. This improves fuel economy and reduces emissions by preventing their formation. The principle common to all stratified charge engines is their capacity to vary the ratio of fuel to air within the combustion chamber, during different parts of the combustion cycle (McGillivray, 1976; Crossland, 1974).

**Operating Principles**

In a stratified charge system a small amount of a rich mixture of fuel is produced adjacent to the spark plug, which when ignited provides a powerful ignition source to efficiently ignite a large amount of lean mixture elsewhere in the combustion chamber. Air fuel ratios of between 16:1 and 50:1 have been achieved in this way (Surgeon General, 1962).

There are a number of ways to achieve the desired stratified mixture, but basically they can be divided into two types:

1) Those with a divided chamber termed pre-combustion type and 
2) Those with an open chamber (Reitze, 1877).

The pre-combustion type shown schematically in Figure 3.7 essentially has two combustion chambers
and two carburetors per cylinder (S.P.C.C., undated).

FIGURE 3.7 Pre-chambered stratified charge engine
SOURCE: S.P.C.C., (undated)

The pre-chamber intake valve or auxiliary inlet valve supplies a small rich volume of atomised mixture from a separate small carburettor to the pre-chamber which houses the spark plug. The weak mixture is supplied to the main chamber by a separate, larger carburettor via the main chamber inlet valve. The rich mixture is ignited by the spark plug in the pre-chamber which then provides a powerful flame front which ignites the lean mixture in the main chamber. A controlled degree of turbulence in the pre-chamber and turbulence in the main chamber, produced by suitable placing and sizing of the passage joining the two chambers, ensures that the mixture in the main chamber
is burned rapidly and completely (Ayres and McKenna, 1972; S.P.C.C. undated).

This system is presently capable of operating at an overall air-fuel ratio of about 16:1 (Advisory Council on Energy Conservation, 1977). It is known as C.V.C.C. (Compound vortex controlled combustion) and is currently being marketed by Honda. Ford and Porsche have also developed an engine of this type. It is an inherently low pollutant emitter and is capable of producing better fuel consumption under stringent emissions standards than the previous system. However, it produces between 10 and 30 per cent less power than a conventional engine of the same size (Advisory Council on Energy Conservation, 1977; S.P.C.C. undated).

Other problems with the system include knocking, necessitating use of high octane petrol and the use of a conventional compression ratio of 9:1 to prevent detonation of the rich mixture in the pre-combustion chamber.

A variation of the C.V.C.C. has been developed by the Azure Blue Corporation, El Dorado, California which is easily adapted to existing vehicles. The pre-combustion chamber which is built into a special spark plug, screw into the engine block and a dual-ratio carburettor and dual-ratio induction manifold are built into a special cylinder head which can be fitted to a standard engine.
The carburettor supplies a mixture with an air-fuel ratio of 6:1 to the pre-combustion chamber and one with 16:1 to 18:1 to the main chamber. Some of the lean mixture is forced into the pre-combustion chamber during compression where ignition occurs at an optimal ratio of 13.7:1. The flame produced is injected into the main chamber at sonic velocities through orifices separating the two chambers. Turbulence occurs in the main chamber resulting in complete and rapid combustion of the leaner mixture. Hydrocarbon emissions of about 10ppm, nitrogen oxides of about 35-37 ppm and low CO content have been claimed (Chemical and Engineering News, 1969).

The open-chambered stratified charge engine as shown in Figure 3.8 involves a single combustion chamber.

![Diagram of stratified charge engine]

**FIGURE 3.8** Schematic representation of the stratified charge principle.

Air is taken in through a specially designed air intake port which gives a high velocity swirl to the air. Fuel is injected at high pressure directly into the cylinder during compression at an angle counter to the swirl of air, where it is entrained and transported toward the centrally located spark plug. The spark plug supplies a high energy, long duration spark source and on ignition the flame spreads outwards in a concentric fashion towards the cylinder walls. However the mixture surrounding the core is so weak, especially under conditions of partial load, when it is almost pure air, that combustion will not spread to the outer areas of the cylinder. The problem of flame quenching referred to previously is largely overcome (Ayres and McKenna, 1972).

This method of combustion permits control of the pre-flame reaction time by timing the fuel injection before the spark discharge which prevents auto-ignition or "knocking" and it is not as sensitive to octane quality. However it generally requires electronically controlled timing of both ignition and fuel injection. The Texaco T.C.C.S. (Texaco Controlled Combustion System) and the Ford Proco (programmed combustion) are systems of this design.
Fuel Economy and Emissions

The following advantages in terms of energy conservation and emissions control can be gained from the principles of open-chambered stratified charge engines:

1) The anti-knock qualities of this engine allow the compression ratio to be increased up to a value of 12:1 which gives an increase in efficiency of about 15 per cent. Above 12:1 there is a risk of temperatures in the cylinder rising above that required for spontaneous ignition of the fuel (Advisory Council on Energy Conservation, 1977).

2) The anti-knock qualities also make it versatile in its fuel requirements. This is a distinct advantage in terms of furthering available fuel supplies since all oil cannot yield high octane gasoline (Little, Inc. 1974). Fuel can be of low octane quality and may require very low or no lead-alkyl additives. Texaco's system will operate on high-cetane diesel fuel or high-octane petrol (Reitze, 1977). Generally any grade of distillate through to diesel fuel will operate in this type of system, with little change in exhaust or fuel economy.

3) The system operates on a lean fuel-air ratio and thus greater fuel economy is realised especially under part load conditions when a lean mixture is all that is necessary. Emissions of CO and HC are reduced and the use of unleaded fuels means that lead aerosols can be eliminated and a catalytic converter can be employed to
further reduce other emissions. Fuel economy in this system is better than in the divided chamber system but emissions performance falls slightly below the latter (Reitze, 1977).

4) Super-charging can be achieved without consideration of octane number and pre-ignition. Supercharging allows improved performance by compressing air prior to mixing with the fuel. This affords consumption of a greater mass of charge in a single piston stroke (Ayres and McKenna, 1972). All load control can be by fuel control as in a diesel, which eliminates throttling and inlet pumping losses (Little Inc., 1974). More detailed knowledge is needed concerning the various mixing processes such as fuel jet air entrainment, diffusion, mixing due to swirl and innovative thinking is required in areas such as injection nozzle design, ignition of lean mixtures, control of cylinder air motion and turbulence (Wood, 1978).

5) These engines allow the use of high pressure fuel injection. The U.S. Army's TACOM engine currently being developed to replace conventional Jeep engines will achieve 40 per cent better fuel economy using this method (12.7 km l⁻¹, 36 m.p.g. in urban traffic) (Reitze, 1977). This data applies to vehicles without emissions controls (Crossland, 1974).

Considerable work still needs to be done on emissions control in open chambered stratified charge systems. Those tested in the U.S.A. in large vehicles have required intake throttling at low idle, low air
flows and catalytic converters to meet emissions standards. This appears to stem from an inability to maintain charge stratification under all conditions (Little Inc., 1974).

In contrast the C.V.C.C. pre-combustion system has achieved good emissions results with minimum trouble. Table 3.14 shows the results of tests on a number of C.V.C.C. engines. It is clear from these results that stratified charge systems offer substantial reductions in emissions. Some of the data (test 2) suggests that fuel economy benefits can also be gained. All data is based upon the LA-4 driving cycle.

The C.V.C.C. engines tested meet the original 1975 U.S. Federal Standards of CO 3.4 g/mile, HC 0.4 g/mile and NO\textsubscript{x} 3.1 g/mile with a wide range of fuel types (Date et. al. 1975).

Conclusions to the stratified charge engine

Overall a variety of opinions can be found amongst important automotive engineering assessors, about the significance of the stratified charge engine as a means of achieving simultaneous reductions in energy usage and emissions. A study by the Jet Propulsion Laboratory states that the stratified charge engine is:

...a variant, of the basic Otto engine with no major long term advantages but would constitute an acceptable near term alternative... 
(Jet Propulsion Laboratory, 1975).
<table>
<thead>
<tr>
<th>VEHICLE TYPE (transmission)</th>
<th>Curb Weight (kg)</th>
<th>ENGINE TYPE</th>
<th>ENGINE DISPLACEMENT in³ cm³</th>
<th>EXHAUST EMISSIONS g/km (g/mile)</th>
<th>Fuel economy km/l (m.p.g.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Honda Civic (MT)</td>
<td>540</td>
<td>CVCC</td>
<td>91  1488</td>
<td>1.50 0.15 0.86 (2.42)(0.24) (1.38)</td>
<td>10.8 (30.6)</td>
</tr>
<tr>
<td></td>
<td>718</td>
<td>CVCC</td>
<td>119  1950</td>
<td>1.32 0.11 0.55 (2.12)(0.18) (0.89)</td>
<td>9.4 (26.5)</td>
</tr>
<tr>
<td>2 GM Vega 1972 (MT)</td>
<td>718</td>
<td>Original</td>
<td>140  2295</td>
<td>6.6  1.32 2.36 (10.6)(2.13) (3.80)</td>
<td>7.3 (20.6)</td>
</tr>
<tr>
<td></td>
<td>1080</td>
<td>CVCC</td>
<td>140  2295</td>
<td>1.63 0.16 0.72 (2.62)(0.26) (1.16)</td>
<td>8.0 (22.7)</td>
</tr>
<tr>
<td>3 Chevrolet Impala 2041</td>
<td>Original</td>
<td>350</td>
<td>5736</td>
<td>12.01 0.97 1.50 (19.33)(1.56) (2.42)</td>
<td>4.4 (10.5) (12.6)</td>
</tr>
<tr>
<td>1973 (AT)</td>
<td>2138</td>
<td>CVCC</td>
<td>350  5736</td>
<td>1.79 0.17 1.07 (2.88)(0.27) (1.72)</td>
<td>4.4 (10.5) (12.6)</td>
</tr>
</tbody>
</table>

**TABLE 3.14** Comparative emissions and fuel economy of C.V.C.C. and conventional engines

**SOURCE:** After Date *et. al.* (1975)
The Aeropace Corporation for the U.S. Environmental Protection Agency suggests that the stratified charge engine

... occupies a favourable position vis-a-vis other alternative engines

(Reitze, 1977).

The National Academy of Science considered that Honda's C.V.C.C. system was the most promising of engines to meet the 1976 emission standards. They state

the system most likely to be available in 1976 in the greatest numbers - the dual catalyst system - is the most disadvantageous with respect for first cost, fuel economy, maintainability and durability. On the other hand the most promising system - the carburated stratified charge engine, which may not be available in very large numbers in 1976 is superior in all these categories.

(Committee on Motor Vehicle Emissions, 1973)

The ultimate future of the stratified charge engine as a contender for widespread automotive use is still uncertain. Automotive firms around the world seem able to produce stratified engine automobiles. Whether or not they will do so depends on an array of economic and political pressures. The question is whether considerations of fuel conservation and pollution control are significantly strong to warrant such a large scale shift in engine design (Reitze, 1977). To many automotive firms this option is "hard" compared to the "soft" option of lean burn engines.
A wide variety of rotary engines exist at different stages of development and operation (Chinitz, 1969). It is unnecessary for the purpose of this review to consider these in any detail. The rotary engine, although it has been the subject of considerable attention and funding over the past twenty years, (N.S.U. Motorenwerke, A.G., Curtiss-Wright Corporation, Toyo Kogyo Company, General Motors, Citroën and Daimler - Benz) has largely failed to provide satisfactory commercial performance in terms of energy conservation and emissions reduction (Reitze, 1977, Crossland, 1974). General Motors when it entered rotary engine development as a N.S.U. licensee, expected that the Wankel version would make up a considerable portion of the 1980 U.S. car market. (Crossland, 1974). However, there is evidence to suggest that G.M. is now withdrawing from this field (Dunne, 1976 and Lund, 1976).

Operating Principles

The reasons for the lack of success in achieving fuel consumption and emissions standards higher than the conventional engine can be explained in terms of the rotary engines' basic operating principles.

The rotary engine is a simpler version of the Otto-cycle internal combustion engine and has about half
as many parts. It is small and weighs less than conventional engines of the same power output and thus has a better power to weight ratio in all cases; up to 30 per cent engine work advantage and 50 per cent in size have been estimated. Multi-rotor engines can be made to obtain more power. Inherently it is a smoother running motor generating less vibration which is also important for noise reduction.

The principle of operation of the Wankel rotary engine, the only version in commercial production, is shown in Figure 3.9

![Diagram of Wankel Rotary Engine]

**Figure 3.9** The Wankel Rotary Engine

SOURCE: Ayres and McKenna, (1972).
It has a single rotor of rounded triangular shape which rotates eccentrically in a single casing with a doubled lobed cross-section. This is the path followed by the convex rotor during its eccentric rotation and at each instant the rotor is in contact with the combustion chamber at three points. The three compartments so formed have a continuously variable size and shape. In terms of the Otto-cycle engine the Wankel rotary is thermodynamically similar to the "two-stroke" version; the rotor is comparable to the piston, the rotor housing is comparable to the cylinder and a flywheel which provides the power take-off is similar to the crankshaft. However, the Wankel eliminates the need for a complicated valve system for fuel-air intake and exhaust removal (Ayres and McKenna, 1972, Reitze, 1977).

A mixture of fuel and air is introduced in an intake phase into a confined chamber. The rotor pressurises the mixture in the compression phase at the end of which the mixture is ignited and the gases expand to provide the engines work in the power phase. The exhaust gas phase removes burned and unburned gases. Each of three compartments goes through all four phases of the cycle during one revolution of the rotor and hence there are three power strokes per revolution and each compartment is always in a different phase to the other since they are disposed at 120 degrees (Ayres and McKenna, 1972).
Fuel Economy and Emissions

The rotary engines poor fuel economy (1973 Mazda, 30 per cent below piston engine of same weight) and high emissions of CO and HC (two to five times the HC and one to three times the CO) are a result of numerous design inadequacies. Emissions of NO$_x$ are on the other hand 25-75 per cent lower than a comparable conventional piston engine (Crossland, 1974).

Toyo Kogyo of Japan has made some recent advances by improving fuel economy and lowering HC and NO$_x$ emissions. Basic modifications were made to the rotary engine including improved design and materials in the apex and corner seals, stratification of a leaner air-fuel mixture and upgrading of the thermal reactor and catalytic converter (Yamamoto and Muroki, 1978).

One of the major problems is that precise construction of the central chamber is essential to ensure a close fit for the rotor which must maintain separation of the compartments. If leakage occurs inefficiencies and losses reduce power and increase fuel use and emissions. If the rotor is too tight jamming and overheating can occur. Precision must be maintained over wide variations in pressure and temperature.
The rotary engine's problems have arisen from leakage through the apex and side seals and from cooling and lubrication difficulties. High surface area to volume ratios and crevices result in wall quenching and inefficient combustion especially under part-load conditions. The quenching effect which results in excessive cooling, poor fuel economy and high CO and HC emissions, keeps NO\textsubscript{x}\textsuperscript{e} emissions low. Although the Wankel rotary is ideal for the use of thermal reactors adjacent to the combustion chamber parts to control emissions, it encounters similar emissions control problems to that of the conventional I.C.E. (Ayres and McKenna 1972, Crossland, 1974).

Conclusions to the Rotary Engine

The assessment of Wankel rotary engines in their present stage of development is pessimistic. (Advisory Council on Energy Conservation, GRAD, 1975). Some believe that its use and development should be discouraged (Daniels, 1973). However, there is some indication that in a modified form, the rotary may have its fuel economy and emissions improved. A stratified charge version with carburettion instead of fuel injection has been proposed by Curtiss-Wright and Daimler-Benz (Advisory Council on Energy Conservation, 1977, Crossland, 1974). Further, a supercharged rotary engine with charge stratification has been suggested by the Rand Corporation as an alternative
which will dominate over the Diesel, Stirling and Rankine Engines (Kirkwood and Lee, 1975). This assessment is based upon envisaged improvements in sealing methods and theoretical estimations of the effects of supercharging based upon known effects in reciprocating engines (McGillivray, 1976). Despite its generally poor fuel economy, the Wankel engine can operate on low octane gasoline (66-67 octane) which is beneficial in terms of refining requirements, including avoiding the use of lead additives (Hesketh, 1974).

In terms of offering a widespread and potentially more efficient system than the present, the rotary engine at present is still very peripheral in importance.
The diesel engine

Diesel engines or compression ignition engines are cited as offering substantial reductions in fuel consumption and emissions (Advisory Council on Energy Conservation, 1977, McGillivray, 1976). In the U.S.A the fuel savings potential of the diesel has been assessed under three sets of conditions: (a) highway driving (b) mixed duty urban driving and (c) in taxi-cab service. The results of these tests are 5%, 30% and 50% improvements respectively (U.S.E.P.A. July, 1974). A further fuel economy advantage of the diesel is that on average only 5-7% of the energy of crude oil inputs is consumed in producing diesel fuel, while 10-17% is a usual range for motor spirit (Reitze, 1977; N.E.A.C., 1979). An Australian report by the National Energy Advisory Committee ranked the diesel as capable of between 20 and 40 per cent reductions in fuel consumption over comparable gasoline engines (N.E.A.C., 1979).

Diesel engines are capable of very substantial reductions in emissions of CO, HC and to a lesser but significant extent, NO. Studies from Britain show that on average diesels may emit 92% less CO, 88% less HC and 54% less NO. (Crossland, 1974). This is related to the higher compression ratio, higher air fuel ratio higher peak temperatures and the absence of throttling load control (Reitze, 1977). Diesel exhausts also contain no lead.
The diesel does however have a number of significant disadvantages. The power/weight ratio is considerably lower, which results in larger heavier engines at higher initial cost for equivalent power output; acceleration is also relatively poor. Emissions from improperly tuned diesel engines are a problem. These include smoke, odour, nitrogen oxides, sulphur oxides and particulates (McGillivray, 1976). Noise and vibration emissions and starting problems have also led to considerable consumer aversion to diesel engines.

Perhaps the most significant emissions disadvantage of the widespread use of diesel engines is their high level of benzo-(a) pyrene, a known carcinogen (see Chapter 2).

Despite the technological advantages of the diesel engine in terms of energy and emissions, assessments concerning its potential have been generally pessimistic. For example, the Jet Propulsion Laboratory (1975) state:

Particulate emissions and objectionable odour are fundamental problems whose solution is not in sight. In view of these considerations and the higher initial cost of the diesel, its widespread use in personal automobiles is not justified.
Similarly NEAC, (1979) conclude that substituting 25% of Australian motor spirit with diesel by 2000 could save only 3.5% of Australia's crude oil requirements. They also state with regard to the diesel's potential market penetration that:

It seems unlikely then, that diesel engines will achieve substantial local passenger car market penetration unless a local manufacturer is prepared to make and market a large number of such engines.

(NEAC, 1979).

Vehicle manufacturers generally do not express great enthusiasm for diesel engines where these are not already included in the production line (McGillivray, 1976). Higher costs are a fundamental reason for this (Australian Academy of Technological Sciences, 1979).

From this brief analysis it would appear that the diesel will need to become significantly more advantageous to the average motorist before the market could stimulate the majority of manufacturers into considering the investments required to produce diesels. Such advantages may only occur if the technological problems particularly driveability associated with adapting diesels to small vehicle use are overcome. The spark ignited diesel engine may offer some potential in this direction (NEAC, 1979).