(ii) Revision of Other Components of Vehicle Design

(1) Introduction

A fundamental part of re-assessing the efficiency of present vehicles has been a step-by-step examination of each component of the vehicular system which is responsible for utilising some portion of the engine's total energy output.

Research has resolved itself into a variety of specialised fields each of which is attempting to improve the characteristics of some component of motor vehicles.

Broadly the main components are:

(1) vehicle weight
(2) aerodynamic properties
(3) rolling resistance (e.g. tyres)
(4) the transmission system
and
(5) accessories

The propulsion system per se has already been discussed. This section considers the most important innovations in the search for improvements to each of the components listed above and where necessary explains the scientific and technological bases of the changes.
Factors discussed in this section are pertinent primarily to fuel usage. Each factor is discussed individually and the magnitude of its effect on fuel consumption under various conditions is considered. Each factor influences emissions through its effect on the amount of fuel burned to perform a specific task, which in turn partly determines the emission control system necessary to meet standards. However detailed exploration of this general link is not warranted. Ultimately it is the emissions characteristics of the final product which are of prime concern and these are predominantly determined by the combustion system used.
(2) **Vehicle Weight Reduction**

It is widely acknowledged that the single most important determinant of vehicle fuel economy is vehicle weight. (Wirst, 1974).

This close correlation is largely attributable to the fact that vehicle weight primarily determines the engine and drivetrain size. The power output of a vehicle necessary to meet performance expectations is several times more than that needed to overcome the major frictional forces during normal vehicle cruising and is directly proportional to weight (Borcherts et al, 1978). Larger engines consume more fuel and operate in a more throttled condition during cruising.

For a specified driving cycle, fuel consumption can be shown to decrease approximately linearly as vehicle weight decreases. This is demonstrated by figure 3.10 which shows a linear line-of-best-fit of energy consumption per vehicle km versus vehicle weight for 1971 and 1972 model cars available in the U.S.A. Data was measured by the U.S. Environmental Protection Agency. The axes are labelled in equivalent metric quantities. The original graph shows Imperial units. Other graphs of similar data show an almost linear decrease of fuel economy with vehicle weight increase.
Similarly another study showed that in mid-1973 the U.S. Fleet of automobiles with curb weights\(^1\) between 942kg (2076 lbs) and 1055kg (2325 lbs) had an average fuel economy of 8.4km per litre (23.8 m.p.g.); those between 1339kg (2951 lbs) and 1565 kg (3450 lbs) had 6.0km per litre (16.0 m.p.g.); and those between 1792kg (3951 lbs) and 2019kg (4450 lbs) had 4.8km per litre (13.7 m.p.g.) (McGillivray, 1976). These averages represent results from simulated urban driving conditions using the U.S. E.P.A. dynamometer driving cycle test procedure.

---

1. Curb weight is the weight of the car unloaded but fueled. Inertia weight is curb weight plus 136kg for occupants.
It has been shown that each 45kg (100 lbs) increase in vehicle weight results in a fuel economy loss of 1 to 2 per cent (Orski, 1974). It has also been reported that a variation of 10 per cent in weight gives rise to a change in fuel economy of approximately 3 per cent. (Advisory Council on Energy Conservation, 1977). A further study states that for every 45kg reduction in weight a 0.71 km/per litre (0.30 m.p.g.) saving in fuel results (Krzyczkowski et al, 1974). The magnitude of the fuel saving ultimately depends upon the test method and a number of ways of expressing the results are evident. There is however a general concensus that reduced weight yields reduced fuel consumption.

There is considerable variation in fuel economy between types of vehicles of the same weight over the same driving cycle and between the fuel economy of future vehicles of the same weight (French, 1976).

Other design innovations may improve the fuel economy of specific vehicles without varying the weight. The graph shown in figure 3.11 gives the fuel economy versus weight of U.S. cars for 1974 (Curve 1); the predicted fuel economy for the best cars in 1975 (Curve 2); the potential fuel economy for the U.S. car fleet in 1980 (Curve 3) and; the theoretical limit of fuel economy improvements for
cars of specific weights with conventional I.C.E.s (Curve 4) (All data are in equivalent metric quantities - original graph in U.S. m.p.g. and pounds).

<table>
<thead>
<tr>
<th>Vehicle inertial weight (Kg)</th>
<th>Fuel economy kg/1</th>
</tr>
</thead>
<tbody>
<tr>
<td>907</td>
<td>29.0</td>
</tr>
<tr>
<td>1134</td>
<td>27.8</td>
</tr>
<tr>
<td>1358</td>
<td>25.6</td>
</tr>
<tr>
<td>1582</td>
<td>23.4</td>
</tr>
<tr>
<td>1814</td>
<td>21.2</td>
</tr>
<tr>
<td>2041</td>
<td>19.0</td>
</tr>
<tr>
<td>2268</td>
<td>16.8</td>
</tr>
<tr>
<td>2494</td>
<td>14.6</td>
</tr>
</tbody>
</table>

Figure 3.14 Fuel economy vs weight of U.S. cars for 1974

The points labelled A, B, C and D represent respectively the sales weighted average 1974 fleet fuel economy the same figure for 1975 assuming a similar model mix the desirable minimum, sales - weighted average fuel economy for 1980 and the value which may be reached.

Over the past two decades there has been a trend in most countries towards larger heavier cars. This is especially true in the U.S.A. where the weight of popular models has increased by up to 683kg (1100 lbs) between 1956 and 1974 (e.g., Chevrolet Impala and Ford Galaxie 500). On
average the standard size American car has gained about 363kg (800 lbs) in the past twelve years and is more than 1814kg (4000 lbs). Similarly in Europe average vehicle weight has risen from 1200kg (2650 lbs) in 1960 to above 1400kg (3080 lbs) in 1974 (Orski, 1974). The overall impact on fuel economy of large increases in weight of vehicles has been partly offset recently, by the introduction of a range of new, smaller models and an interest in small imported vehicles (Pierce, 1975).

Overall however there has been a deterioration in the average fleet fuel economy of American vehicles since 1940 from about 6.5 kms per litre to 5.2 kms per litre (18.4 m.p.g. to 14.5 m.p.g.) in 1974. This is largely though not entirely attributable to weight increases (Pierce, 1975).

The same general trend applies to Australia although average fuel economies are higher. Aggregate data of trends as outlined above are not so easily obtained. One survey showed that the average fuel consumption of the Australian passenger car has been steadily rising. In 1963 the average was 9.6 litres/100km (29.4 m.p.g). By 1971 this had risen to 12.1 litres/100km (23.3 m.p.g.) and by 1976 was 12.6 litres/100km (22.4 m.p.g.). These increases are the outcome of a number of factors, vehicle weight increase being only one. (Johnson, Trayford and Van Der Touw, 1979).
In an analysis of the factors which accounted for the increase in U.S. transportation energy use between 1960 and 1970, it was reported that the growing energy intensiveness of transport modes accounted for 18 per cent of the increase in vehicle weight growth in vehicle weight contributed significantly to this increase (Hirst, 1974).

Thus it can be seen that a substantial amount of energy can be conserved by a widespread shift towards smaller, lighter vehicles. A brief outline is given of the methods which could be employed to reduce vehicle weight while maintaining vehicle safety standards.

A reduction in the average weight of a fleet of motor vehicles could be achieved by:

(1) decreasing the size of vehicles manufactured, e.g. manufacture fewer vehicles above a certain weight or curtail production of vehicles above a specified weight by setting a ceiling on production weight.

(2) maintaining the size of the present fleet of vehicles in terms of length and width while reducing the weight of individual components through innovative materials and design.
Case (1) would involve a decision by vehicle manufacturers to wean the market away from large heavy vehicles. It would be preceded by careful economic planning and market analysis. Legislative action might be important in prompting such moves.

It could be achieved with minimal technological innovation. The case described in (2) would involve technological changes in terms of materials, design and mass production techniques to maintain the size, image, performance and luxury of the vehicles produced.

The options for technological innovation in vehicle weight reduction fall into two main categories: (a) materials and (b) electronics. Heavy iron and steel components can be replaced with composite plastics which include graphite and glass reinforced plastics, light weight metal alloys, aramids\(^{(1)}\) and high strength steel and aluminium. The use of electronics to replace heavy mechanical components such as conventional ignition systems offers other significant advantages in terms of control of the combustion process.

\(^{(1)}\) Poly aromatic polyamides
From a review of the literature, table 3.15 has been compiled which summarises the technological changes that may be used to reduce vehicle weight. The vehicular system has been divided into 3 subsystems:

(1) The propulsion system which incorporates the power unit and all components directly associated with its efficient operation e.g. the cooling, ignition, fuel and electrical systems.

(2) The transmission system which includes the gearbox, suspension, brakes, rolling gear and accessories.

and (3) The chassis and body.

<table>
<thead>
<tr>
<th>SUB-SYSTEM</th>
<th>COMPONENT</th>
<th>INNOVATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion system</td>
<td>Engine</td>
<td>- decrease engine size through other reductions in body weight.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- construct engine block from cast aluminum instead of cast iron.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- make engine head from lightweight alloy instead of steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- introduce transverse front engine, front wheel drive vehicles to improve space utilisation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- use lighter alternative engines such as gas turbines and vapour engines.</td>
</tr>
<tr>
<td></td>
<td>Ignition and carburettion</td>
<td>- use microprocessors, electronic</td>
</tr>
<tr>
<td>Component</td>
<td>Details</td>
<td></td>
</tr>
<tr>
<td>--------------------</td>
<td>-------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>I. Ignitions, fuel injection and turbocharging to replace bulky mechanical parts such as coils, distributors, pumping systems and carburettors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling system</td>
<td>- introduce aluminium radiators with special plastic tanks.</td>
<td></td>
</tr>
<tr>
<td>Fuel storage</td>
<td>- use galvanised plastic fuel tanks.</td>
<td></td>
</tr>
<tr>
<td>Transmission system</td>
<td>- microprocessor, computer controlled transmission system to replace mechanical parts and optimise the transmission engine coupling.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- radar controlled transmission which responds to the traffic environmental ahead.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- gears and drive mechanisms of high strength steel and alloy materials.</td>
<td></td>
</tr>
<tr>
<td>Driveshaft</td>
<td>- graphite reinforced driveshaft.</td>
<td></td>
</tr>
<tr>
<td>Brakes</td>
<td>- plastic and light alloy parts.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- aluminium drum brakes.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- aluminium disc brake spindle.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- downgauged upper and lower control arms.</td>
<td></td>
</tr>
<tr>
<td>Suspension</td>
<td>- high strength plastic leaf springs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- light stamped aluminum alloy suspension parts.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- graphite reinforced plastic and steel composite for upper and lower rear suspension arms.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- graphite reinforced plastic wheels.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- shock dampers of polypropylene foam.</td>
<td></td>
</tr>
<tr>
<td>Body</td>
<td>Chassis</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td></td>
</tr>
</tbody>
</table>
| **Accessories** | - axles of lightweight alloy.  
- less air-conditioning, power steering and other weight adding and power consuming extras.  
- graphite reinforced plastic accessory drive brackets. |
| **Outer Surface** | graphite reinforced plastic, plastic or light gauge sheet steel for door skins, bonnet, boot, grill, light frames, roof canopy and minor body parts, such as fenders, hub caps, bumpers etc.  
- aluminium for bumper attachements.  
- urethane bumpers and molded flexible urethane exterior body surface (plastic skin) |
| **Frames** | - light gauge sheet steel, closed box body sections, resistance welded and filled with low density rigid urethane foam.  
- passenger compartment of monolithic structure molded of epoxy laminate and fibre and sprayed with a foam of chopped fibre and resin - structure internally pressured, oven cured and injected with polyurethane foam.  
- seat frames of aluminum.  
- front and rear assemblies of aluminium.  
- main frame of graphite reinforced plastic.  
- door guard beams of plastic composites. |
Table 3.15 Summary table of possible avenues for vehicle weight reduction.

This summary represents a wide range of possibilities available to manufactures to reduce the weight of their vehicles. A great variety of combinations are possible but rapid and sweeping changes are precluded by the time lags involved in increasing the supply of alternative materials, changing mass production methods and encouraging consumer acceptability.

For these reasons most motor vehicle manufacturers are planning programmes for phased weight reductions. Ford in its U.S. lightweight vehicle programme can reduce vehicle weight of its larger cars by 35 per cent (a 570kg reduction) to place them in the 1225kg (2700 lb) inertia class.
(Borchets et al., 1978). Similar studies with lightweight vehicle technology have revealed possible weight reductions of between 454kg and 817kg (Friedman, 1978). More modest estimates suggest the substitution of 900kg (1980 lbs) of cast iron and steel with 470kg (1034 lbs) aluminium, 490kg (1082 lbs) of steel with 315kg (695 lbs) of steel and plastic composite (McGillivray, 1976).

One summary suggests that the resultant weight reductions could translate into fuel consumption savings in individual vehicles of between 4 per cent and 36 per cent (Orski, 1974). In the U.S.A. an in-depth study of vehicle weight reduction scenarios estimated that gross fuel savings from a range of possible changes in vehicle weight class distributions amounted to between 4.8 per cent and 20.1 per cent of 1973 U.S. gasoline usage (McGillivray and Olsson, 1975).

The effects of vehicle weight reductions may not be confined to the automobile industry. Sophisticated analyses have been made in the U.S.A. to assess the economic impacts of widespread changes in materials usage and design on the whole economy. McGillivray concluded that the economic impacts of an extensive shift to smaller vehicles or of substantial materials substitution would be of little consequence. (McGillivray, 1976). G.N.P. and national employment would be reduced by less than 1 per cent. The steel industry would be impacted most
significantly and the petroleum industry would experience a fall in gasoline sales.

The value of vehicle weight reductions in terms of net energy savings has also been closely examined, especially in relation to the substitution of steel with aluminium and plastics which themselves consume large amounts of energy in their manufacture. Conclusions on this point differ greatly. Two studies concluded that the increase in energy due to the widespread use of aluminium would be small compared to the liquid fuel savings which would result from lighter vehicles (McGillivray, 1976; Fels, 1974).

Another study concluded that the substitution of aluminium or plastics for steel is expensive and not effective from an energy savings viewpoint (Krzyczkowski et al., 1974). It has been suggested that dramatic increases in the use of plastics may create supply problems as these are petroleum based products and a large escalation in demand could also stress industrial capacity. (Reitze, 1977). This point requires close examination particularly from an Australian standpoint.

Other important considerations related to large scale substitution of aluminium and plastics include the environmental impact of expanded bauxite mining and the non-recyclability of most plastics.
These are beyond the scope of this study.

Conclusions to Vehicle Weight Reductions

In summary it is feasible through materials substitution, design change, engineering innovation and marketing to produce greater numbers of smaller, lighter commercially acceptable vehicles; to substantially reduce the weight of large vehicles; and to change the vehicle weight mix distribution by cutting back the production of large heavy vehicles. The major drawbacks in these methods are the time lags involved in substantially altering the character of a vehicle population and the relatively slow response of the vehicle manufacturing industry to changes which involve disruption of established mass production patterns, profit structure and selling. The speed with which changes are adopted are also related to historical precedent. In Europe smaller cars have been dominant for some years and some European manufacturers such as British Leyland and Volkswagen are aiming to produce a "50-50" car. This vehicle will have a cruising speed of 50 m.p.h. (80 km/hr) and achieve 50 m.p.g. (17.7 km/l). There is also considerable development of "city cars" which weigh between 180kg and 545kg and have a fuel economy up to 24.8 km/l (70 m.p.g.) American and Australian manufacturers are not prepared to design vehicles which approach such values (Krzyczkowski et al, 1974).
This is possibly due to an envisaged lack of consumer acceptability of the type of vehicles such low fuel economy would necessitate.
(3) Aerodynamic drag reduction

A variable proportion of the energy used in keeping a vehicle in motion results from aerodynamic drag. Aerodynamic drag differs according to the profile of a vehicle and in particular with the protuberances such as tyres, rear vision mirrors, roof "gutters" and other accessories such as "roof racks". (Borcherts et al, 1978).

The drag force \( F_D \) on a vehicle is primarily determined by the drag coefficient \( C_D \) and can be calculated according to the following equation.

\[
F_D = \left( \frac{1}{2} \right) \rho S C_D A V^2 \quad \ldots \quad (1)
\]

Where \( S \) is the air density (kgm\(^{-3}\))

\( V \) is the velocity of the vehicle (m/s\(^{-1}\))

and \( A \) is the frontal area (m\(^2\))

(Borcherts et al, 1978)

Similarly the horsepower (H.P.) necessary to overcome aerodynamic drag can be calculated using

\[
\text{HP} = \frac{A C_D V^3}{56855} \quad \ldots \quad (2)
\]

Where \( V \) = air speed relative to the vehicle (km/hr)

(Product Engineering, 1967)

(1) The original equation had a constant derived to obtain Imperial Units. The constant shown is for metric units.
Equation (2) shows that as the air speed relative to the vehicle is doubled the horsepower requirement to overcome aerodynamic drag increases eightfold. Hence the relative contribution of aerodynamic drag to fuel consumption increases as vehicle speed increases. Figure 3.12 shows how the horsepower needed to overcome rolling resistance (discussed later) and aerodynamic drag varies according to vehicle speed.

![Figure 3.12 The relationship between aerodynamic drag and rolling resistance.](chart)

Source: Product Engineering (1967)

The relationship of aerodynamic drag to vehicle speed means that the fuel economy of a given vehicle may improve up to a maximum speed of between 56 km/hr and 65 km/hr and then will decline as speed increases. In the range between 72 km/hr and 105 km/hr each additional 16 km/hr decreases
fuel economy between 0.64 km/l (1.8 m.p.g) and 0.85 km/l (2.4 m.p.g.) (Pierce, 1975).

This relationship can be shown for vehicles with different drag co-efficients. Figure 3.13 below shows this for vehicles with $C_D$ values of 0.25, 0.50 and 0.70. The average family car has a drag co-efficient of about 0.45 (Advisory Council on Energy Conservation, 1977).

**Figure 3.13 The effect of aerodynamic drag on fuel economy.**

Source: Pierce (1975)
A reduction in aerodynamic drag is obtained by reducing the drag co-efficient. The limits on the magnitude of this reduction in passenger cars is about 0.3 - 0.35 for reasons associated with safety and performance standards such as the size of interior volumes and consumer acceptability (Borcherts et al., 1978).

The resultant improvement in fuel economy depends on the operation speed of the vehicle and its size; e.g. for a small car used in city driving the impact of aerodynamic on fuel economy may be negligible. In the case of a larger car operated for long distances at high speeds a 20 per cent saving may be possible (Advisory Council on Energy Conservation, 1977). In general if $C_D$ values are lowered from the 0.4 to 0.5 range to the 0.3 to 0.4 range an improvement of between 1.6 and 2.4 km/l (4-6 m.p.g.) may be realised for individual vehicles (Friedman, 1978).

A fundamental way of reducing aerodynamic drag is to design cars whose profiles at the points of inflection correspond to portions of cubic curves, i.e. curves which have the general equation $C = x^3 + y^3$ where $C$ is a constant. This equation yields a curve with a continuously varying radius which promotes smooth flows of air over the body. This principle is being used in the design of "bubble" shaped electric vehicles (Product Engineering, 1967). Designing cars upon this principle can result in more
sweeping changes by requiring the relocation or re-design of existing engines (Advisory Council on Energy Conservation, 1977). Numerous other changes promote a reduction in the drag coefficient of a vehicle. Some of these include:

1. Enclosing the underbody in a streamlined hood. This has the potential to reduce the $C_d$ by 17 per cent.

2. Redesigning or eliminating all protuberances to give a completely smooth outer surface. e.g. streamlined headlamp doors, and elimination of roof "gutters".

3. Blending all glass areas with the body contour to obtain a flush glass silhouette.

4. Placing air dams below the front and rear bumpers.

5. Adding on devices to improve present vehicles.


Conclusions to Aerodynamic Drag Reduction

In general improved aerodynamic characteristics can lead to improved fuel consumption. In some cases
however, lowering aerodynamic drag may lead to increases in weight depending on the design changes necessary to meet other criteria particularly safety. In such cases it is necessary to trade-off the fuel consumption penalty due to increased weight against improvements due to a lowered $C_D$ (Borcherts et al., 1978). In warm climates such as in most Australian cities, the reduced interior space brought about by better aerodynamics, might necessitate the use of air-conditioning (Energy Advisory Council, 1979).

Aerodynamic drag improvements alone offer relatively minor fuel consumption savings in urban areas because of the speed relationship shown by figure 3.12 and the possible trade-offs indicated above. They need to be viewed as one factor amongst a range of other factors which together may improve the energy efficiency of motor vehicles. The human factor of consumer acceptability might also be important in determining the extent to which vehicle shape, and thus the interior space relations, can be changed. More radical departures from present vehicle shape and size to achieve large aerodynamic improvement could embrace considerable time lags, for human as well as technological reasons.
(4) Reduction of Rolling Resistance

Rolling resistance occurs between the tyres of a vehicle and the road surface. By definition it is caused when:

"... distortion of the contact surfaces due to the normal force between them destroys the ideal line of contact. This introduces a force with a component called the rolling resistance opposing the motion" (Collocott and Dobson, 1974).

Rolling losses are highly significant at low average speeds (see figure 3.12 in previous section) characteristic of urban driving innovations which substantially reduce rolling resistance will have a greater effect on fuel economy in urban driving than will aerodynamic improvements.

Tyre losses or tyre drag accounts for 85-90 per cent of the rolling resistance of a vehicle. (Borcherts et al., 1978; Product Engineering, 1967). The remainder of rolling resistance is accounted for by friction in bearings, lubricants and seals.

As tyre drag is the major source of rolling resistance, a simplified expression for rolling resistance may be written as:
\[ p^R(t) = \gamma(t) C_R W \]

Where \( p^R(t) \) is the powered required to overcome rolling resistance.

\( C_R \) is the co-efficient of rolling resistance (generally in the range 0.01-0.02)

\( W \) is the vehicle weight.

\( \gamma(t) \) is the vehicle profile.

(Borcherts et al., 1978)

Where weight is an important factor in determining rolling resistance but tyre characteristics are of prime importance in determining \( C_R \). The energy loss in tyres is caused by hysteresis\(^{(1)}\) during flexing of the tyre on the road surface. In simple terms the tyre does not give back all the energy used to deform it.

The amount of energy lost through tyres depends upon a number of factors.

1. tyre pressure
2. the basic material
3. the tread pattern
4. the cord material

\(^{(1)}\) Hysteresis is a retardation or lagging of an effect behind the cause of the effect.
(5) the construction (crossply or radial) and  

Rolling resistance also depends upon:

(1) ambient temperature; colder temperatures lead to greater losses.
(2) condition of road surfaces; rough roads increase friction.
(3) wheel alignment and corner characteristics.
(4) lubricants (Borcherts et al, 1978)

The reduction of rolling resistance depends largely upon tyre design. In general steel belted radials offer the minimum rolling resistance (up to 25 per cent less than crossply tyres) and textile cased radials offer a reduction of about 20 per cent over crossply tyres (Advisory Council on Energy Conservation, 1977). In mixed City and country driving (Pierce, 1975) claims existing cars with steel belted radials travel about 25 per cent farther on a litre of petrol than a car with crossply tyres.

With a view to further improving fuel consumption, entirely new designs for tyres are being investigated. The elliptic tyre being
developed by Goodyear in the U.S.A. is capable of substantial reductions in rolling resistance. A vehicle fitted with elliptic tyres travelled 13.8 per cent farther than an identical vehicle fitted with standard radials and 23.2 per cent farther than one with crossply tyres. This test was achieved by shifting the three vehicles simultaneously into neutral at 40km/hr and allowing each to roll to rest. (Shuldiner, 1977). Translated into fuel economy benefits these tyres have realised fuel economies 3 to 7.5 per cent higher than radial tyres. This benefit diminishes rapidly above 80km/hr.

The elliptic tyre has an aspect ratio of 65 compared to 78 for a standard radial and is termed a low aspect tyre (Shuldiner, 1977). The advantage of low aspect tyres is shown in figure 314 which compares the horsepower loss due to tyre rolling effects of a 1134kg (2500 lb) vehicle as a function of vehicle speed. Although horsepower losses due to rolling resistance are shown to increase with vehicle speed, their relative contribution diminishes above about 80km/hr.

(1) Aspect ratio is defined as the section height divided by the section width.
The elliptic tyre allows inflation to 241 kN/M² (35 p.s.i) compared to 166 kN/M² (24 p.s.i) for an average conventional radial, which may give a reduction in rolling resistance of up to 34 per cent (Shuldiner, 1977). Preliminary tests also indicate that the tyre gives a smoother ride and better handling due to its basic design and circumferential tread pattern. A disadvantage of elliptic tyres however is that they cannot be used on existing wheels. It is expected that elliptic tyres will be fitted to mass produced cars in the U.S.A. in the 1980's but a considerable period of time will be required before significant aggregate fuel savings could be reaped from this innovation. In general, the use of lighter wheels and suspension systems carrying less unsprung weight permits smaller, lower loss tyres to be used (i.e. tyres with lower
hysteresis under most conditions) (Pierce, 1975).

Conclusions to Reduction of Rolling Resistance

In general, lower fuel consumption from reduced rolling resistance can be best and most widely achieved through design innovations in new vehicles. The magnitude and significance of the aggregate fuel savings likely from this method alone, will depend upon the comprehensiveness and swiftness of the changes. In the short term, efforts by owners to reduce the fuel consumption of existing vehicles by considering better tyres are likely to be traded-off against the capital cost of the decision. The option to buy radial tyres may not, for economic reasons, be available to all car owners. The removal of any excess weight from present vehicles may achieve only small savings in fuel but be cost effective. Reduced fuel consumption from less rolling resistance is only one contributing factor in the total fuel savings resulting from wider improvement in vehicle weight, lubricants and frictional power losses. Without computer analyses which take all factors into consideration it is impossible to state precisely the benefits to be gained in this area. Clearly it is one important area in the design of more fuel efficient vehicles.
Transmission Improvements

The characteristics of transmission systems are key determinants of the fuel consumption patterns and possibilities in present and future motor vehicles. An insight into the fundamental importance of the transmission system is demonstrated by the well known fact that a car with an automatic transmission consumes more fuel to perform a given task than the same car with a manual transmission (all other factors being equal).

Examination of some basic engineering concepts explains the importance of the transmission in the vehicle system. The transmission determines the manner in which power is transmitted from the engine to the road. At low load factors increasing amounts of energy are used in overcoming mechanical and fluid friction, in pumping losses from drawing fuel into cylinders with a partly closed throttle, and in running auxiliaries. These conditions cause the road load curves of most present cars to lie in regions of low thermal efficiency through most urban operating conditions. At idle, efficiency is zero and good efficiency is generally only achieved when accelerating or cruising at high speeds (Advisory Council on Energy Conservation, 1977).

Automatic transmissions add to this poor performance by introducing factors such as torque
converter slip, oil pump consumption, greater use of lower gears, higher idling speeds and lack of a high cruising ratio. These factors result in poor fuel economy compared to the corresponding manual car. Up to 20 to 30% more fuel can be consumed by a vehicle fitted with an automatic transmission compared to a manual transmission. (Environment Protection Authority of Victoria, undated).

Table 3.16 shows the magnitude of the differences between Ford cars fitted with the two types of transmissions over a range of driving cycles in the U.S.A.

<table>
<thead>
<tr>
<th>Type of Driving</th>
<th>CITY CYCLE</th>
<th>CITY/HIGHWAY CYCLE *</th>
<th>HIGHWAY CYCLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km/l</td>
<td>m.p.g.</td>
<td>km/l</td>
</tr>
<tr>
<td>Manual transmission</td>
<td>9.8</td>
<td>27.6</td>
<td>11.5</td>
</tr>
<tr>
<td>Automatic transmission</td>
<td>8.9</td>
<td>25.2</td>
<td>10.2</td>
</tr>
<tr>
<td>Per cent difference</td>
<td>8.7%</td>
<td></td>
<td>11.1%</td>
</tr>
</tbody>
</table>


Table 3.16 Comparative fuel economy of vehicles with manual and automatic transmissions.

* City/Highway rating based on a mix of 55 per cent city and 45 per cent highway driving.
These differences can be very significant if a high proportion of the vehicle population has automatic transmissions. This is true in the U.S.A. where 85% of all cars being sold have automatic transmissions (Coan, 1977). There is thus considerable potential for reducing fuel demand by either cutting back the production of automatic vehicles or improving the performance of these transmissions. Similarly, entirely new concepts in transmissions can improve the performance of these transmissions.

Firstly, existing automatic transmissions may be improved in the short term by introducing converter lock-ups which prevent slippage in high gear. In conjunction with this, four or five speed designs could give higher top gear ratios and thus improve fuel economy (Advisory Council on Energy Conservation, 1977). It has been estimated in the U.S.A. that four speed automatic transmission with converter lock-up could improve the fuel economy of each size class of vehicle by 9% (Pierce, 1975). Another study estimated gains of between 9 and 13% (Little, 1974). One study concluded that this improvement would result in low additional costs to the customer and low technical risk (Hurter and Lee, 1975).
Manual transmissions do not offer the same scope for improvement. Higher final drive gearing, five-speed gear boxes and overdrives offer some potential.

Manual and automatic transmissions may be replaced in the future by continuously or infinitely variable transmissions (C.V.T. or I.V.T.). Two fundamental types exists; traction drive and hydromechanical drive. This type of system is capable of matching the engine operation with the load on a continuous basis so that the engine can be kept in a region of high thermal efficiency. In this way the vehicle speed and engine speed are not directly related as in conventional transmissions (Coon and Wood, 1974).

With C.V.T. it has been estimated that between 25 and 30% better fuel economy relative to a three speed automatic could be achieved (McGillivray, 1976; Advisory Council on Energy Conservation, 1977). Another study estimated a 23% gain (Hurter and Lee, 1975). A C.V.T. could offer 30-50% better acceleration compared to a 4 speed manual car capable of equal horsepower. Noise output would also be lowered because engine r.p.m. and accessory drive speeds would be lowered (Little, 1974).
Continuously variable transmissions could therefore greatly improve the efficiency of operation of present engines, but periods of inefficient operation would still occur. Still further improvements might be possible to remedy this problem. These could include intermittent use of the engine, an energy storage system and regenerative braking. Such technological advances could conceivably halve present fuel consumption in urban driving but would involve great expense, extra weight and highly complex control systems (Advisory Council on Energy Conservation, 1977).

Some qualifications have been made in a number of studies regarding the improvements outlined above. These can be summarised as follows, based upon studies by Little (1974), Hurter and Lee (1975) and the U.K. Advisory Council on Energy Conservation (1977).

(1) torque converter lock-ups may involve drive-ability problems.

(2) the addition of a fourth gear to automatic transmissions would require substantial changes in design and tooling.

(3) when emissions requirements and driveability are taken into consideration fuel economy benefits between 9 and 14% may be substantially reduced.
This appears to depend highly upon the particular
dynamometer test procedure used to measure the
emissions.

(4) C.V.T. has not yet been proven commercially viable.
Problems in terms of cost durability, reliability and
control still need to be solved. High technical
risks are involved.

Conclusions to transmission improvements

Overall there is scope for very substantial
improvements in motor vehicle efficiency through
improving transmissions. It may be possible to do this
with only marginal increases in cost over present
systems. It is also significant that no other single
change to the current, basic vehicle is capable of
producing as large benefits in terms of fuel economy
(exclusive of introducing an alternative power system)
Alternatively a shift away from automatic transmissions
to manual transmissions would engender considerable fuel
savings without technological innovation. However such
a shift may be undesirable in terms of consumer accept-
ability. This applies to the U.S.A. where a major
study on automobile improvements concluded that manual
transmissions do not offer the same convenience and
based upon empirical observation would probably be
unacceptable to customers (Little, 1974). Major changes
in either the technology of transmissions or shifts to
more efficient manual transmissions would embrace large time lags to achieve aggregate fuel savings in transport. Currently no vehicle manufactures have made any firm commitment to new transmission systems or to changing their mix of vehicles in favour of manual transmissions. Nevertheless the long term potential for success of new transmission systems is high and a large research effort is occurring in this area (Hurter and Lee, 1975). It is impossible at present to predict precisely which of the options outlined here will ultimately bring about the fuel savings possible by changing transmissions. In the U.S.A. at least, there appears to be a significant lifestyle factor to be contended with before manual transmissions could become more acceptable. The aversion to manual transmissions observed by Little, (1974) may start to soften as fuel economy becomes an increasingly important factor in choosing a motor vehicle. New transmission systems could only be considered for mass production after all driveability problems were eliminated. This would be essential for consumer acceptability.
Accessories or auxiliary drives consist of generators, radiator fans, water pumps, air pumps, power steering and air conditioning compressors. These devices consume horsepower in excess of that used to propel the vehicle.

Currently most auxiliary drives are designed and coupled to the engine in such a way that they operate at sufficient capacity at low engine speeds. At times the accessory drive functions at a higher speed than the engine. Therefore at higher engine speeds they operate at surplus capacity and at both low and high engine speeds they engender a substantial power drain. It has been calculated that for a large car, the generator, fan, air conditioning compressor and power steering pump consume 5 brake horsepower (b.h.p.) at 1000 r.p.m. and 20 b.h.p. at 4500 r.p.m. (Advisory Council on Energy Conservation, 1977). In standard American cars air conditioning, power brakes, and power steering consume 10% of rated engine power. (A.T.A.C., 1978). In most cases no attempt is made to avoid unnecessary power losses at higher speeds although the technology appears to be available.

A reduction in fuel penalties due to accessories can be achieved through use of a continuously variable drive or variable ratio auxiliary drive, which couples the accessories to the engine. These systems
vary the operation of the accessory to suit the speed and operating condition of the vehicle thus eliminating some of the excess power consumption. A constant speed drive has a similar effect (Advisory Council on Energy Conservation, 1977). It is more costly and complicated to fit such systems and this may be a reason why they have not yet experienced widespread acceptance (Pierce, 1975).

Other systems are also under development. These consist of:

1. Viscous drive with temperature control.
2. Viscous drive with torque limited speed.
3. Gear or pulley changes to obtain two or more speeds.
4. Hydrostatic drives.
5. Friction drives with temperature control.

and
6. Speed limited friction drives.

(Conon and Wood, 1974).

The cost and complexity of these and other systems which are available may not warrant the fuel savings. It has been reported, for example, that a constant speed drive for accessories without air conditioning would only save approximately 1% in fuel consumption whilst with air conditioning it may save about 3%. Benefits might be marginally higher with a continuously variable accessory drive (Little, 1974).
The specific fuel consumption penalties of different combinations of auxiliary drives depends upon the individual vehicle and its operating condition. One report states that air conditioning can be responsible on average for a 17% fuel loss and power steering for a 14% loss (Environment Protection Authority of Victoria, undated). These values vary to different degrees. One study gives an average penalty of 9% for air conditioning which may rise to 20% in hot weather city driving (Orski, 1974). According to another study power steering results in a penalty in urban driving of only 1% and 3% in longer, high speed driving. It states an average fuel loss for air conditioning of 10-15% (Shinnar, 1975).

It is clear that the losses in fuel economy due to accessories vary widely and are highly dependent upon the assessment method and conditions. Table 3.17 summarises some variations which have been found in fuel penalties due to various accessories and highlights the problem of placing strict values on such items.
<table>
<thead>
<tr>
<th>TYPE OF ACCESSORY</th>
<th>FUEL ECONOMY PENALTY, URBAN OPERATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan</td>
<td>about 1%</td>
</tr>
<tr>
<td>Power Steering</td>
<td>about 1%</td>
</tr>
<tr>
<td>Alternator</td>
<td>7-8%</td>
</tr>
<tr>
<td>Automatic Transmission</td>
<td>14-15.5%</td>
</tr>
<tr>
<td>Automatic Transmission</td>
<td>5-6%</td>
</tr>
<tr>
<td>Automatic Transmission</td>
<td>0-6%</td>
</tr>
<tr>
<td>Air Conditioning 29°C</td>
<td>13%</td>
</tr>
<tr>
<td>Air Conditioning 21°C</td>
<td>9%</td>
</tr>
<tr>
<td>Power Steering, Air Conditioning</td>
<td>7.7%</td>
</tr>
</tbody>
</table>

Source: After (Austin and Hillman, 1973)

Table 3.17  Effect of Engine Accessories and Convenience Devices.

Power consuming extras have become more common over the past ten years. In the U.S.A. in 1975 75% of all new cars were fitted with air conditioning, (Pierce, 1975). The higher incidence of auxilliary drives has been cited as a major reason for the general deterioration in fuel economy of automobiles in the U.S.A. and Australia (Harbeson, 1974; Environment Protection Authority of Victoria, undated).

Conclusions to Accessories

In summary it is possible to reduce the fuel penalty resulting from accessories by the technological methods discussed. On the other hand, some power
consuming extras such as power steering may disappear over a period of time if vehicles are gradually reduced in weight (A.T.A.C., 1978). However, the optimal and most effective way is to manufacture fewer cars with power consuming extras but the problem associated with doing this is difficult to solve. If cars are manufactured with such conveniences over a sufficiently long period of time it becomes hard to reverse the trend because consumer expectations rise coincidentally. In the case of a car population with a high incidence of accessories subject to the control of the driver, (e.g. air conditioning) it may be possible through an energy conservation programme, to encourage prudence in their usage. Alternatively a programme which sought to encourage a more utilitarian, even ascetic attitude towards motor vehicles might assist in discouraging the general trend towards greater luxury at the expense of fuel economy. This approach however is essentially one of trying to change lifestyles and perceptions and might be politically less acceptable than a purely technological one. In the final analysis the price of petrol may cause a trend away from accessories which cause significant fuel penalties.
3.2.2(d) Large Scale Technological Changes

(i) Alternative Combustion Systems

(1) Introduction

Research is being undertaken around the world into developing propulsion systems for motor vehicles which do not necessarily rely on high-octane gasoline and which are more efficient than the conventional I.C.E. This research has been encouraged by the rising price and diminishing supplies of oil and the consequent enactment in some countries (e.g. U.S.A.) of legislation requiring that car manufacturers meet specified fuel economy goals for the vehicles they produce. However the major impetus has been the legal requirement to simultaneously meet fuel economy standards and more stringent emissions standards. As has been already shown this is becoming more and more difficult by simply modifying the existing internal combustion engine.

In the U.S.A. legislation has been passed which states that in 1978 each car manufacturer within the U.S.A. must have had a minimum production weighted average\(^{(1)}\) fuel economy of 21.6 m.p.g. (7.7 km l\(^{-1}\)) and

\(^{(1)}\) Production weighted average takes into account the number of vehicles manufactured with specific fuel economy ratings to determine the average fuel economy for each firm.
by 1985 an average of 33.0 m.p.g. (11.6 km l\(^{-1}\)). In 1977 the overall fleet average was 22.3 m.p.g. (7.9 km l\(^{-1}\)) but this included foreign cars. Because the method of assessment here is production-weighted this still allows car manufacturers to produce large cars with lower fuel economy than the required average (Borcherts et al, 1978).

The fuel economy ratings of a car manufacturer's various models are determined by the Federal Test Procedure (E.P.A. Urban/highway driving cycle) and the limitations and inadequacies of this are discussed in Chapter 4. Non-compliance carries substantial fines of $5 for each tenth of a mile that the firm's weighted average fuel economy falls below the required standard, multiplied by the number of new cars it makes in a model year (Coan, 1977). The existence of this fine might become a substantial impetus to innovation because:

"During this period (1978-1985) emission standards, which limit the options for increases in fuel economy, are to be tightened, making the achievement of the required improvement in fuel economy even more difficult".

(Borcherts et al, 1978).

In Australia no legislation has yet been passed requiring fuel economy standards to be met by car manufacturers. However the Federal Chamber of Automotive Industries has voluntarily adopted a schedule of self-regulation whereby it plans to meet certain fuel economy goals by specific dates as shown
in Figure 3.15. The Federal Government views this as a direction which is highly preferable to Government regulation (Endersbee, 1979).

FIGURE 3.15  Federal Chamber of Automotive Industries proposals for new passenger car average fuel consumption and comparable U.S. legislated requirements.


The aim of developing alternative propulsion systems is ideally to perfect a unit which (a) is capable of being mass produced and fitted to some form of motor vehicle, (b) is versatile in its primary fuel requirement and relies on fuel types which will not be in short supply in the foreseeable future, (c) is inherently efficient in the combustion process it employs and thus is a very low emitter of harmful
substances, (d) has acceptable performance ability as an urban and rural vehicle and (e) is not prohibitively expensive to produce.

This type of system obviously circumvents the need for complicated emissions control technology by either not producing the pollutants in the first instance, by burning them in the engine or by producing them in low quantities. The type of fuel which the system uses is obviously of critical importance in terms of emissions characteristics.

This section examines the most important alternative combustion systems being considered as potential replacements for the internal combustion engine, with a major emphasis on the fuel economy and emissions characteristics of each.

The major options for providing alternative combustion systems in motor vehicles are:

- Brayton-cycle engines
- Rankine-cycle engines
- Stirling-cycle engines

Peripheral to these major options are a number of less widely pursued developments including the solar powered vehicle and the orbital engine. These however do not constitute major options at present and are therefore not dealt with in this study.
Before discussing fuel economy and emissions characteristics of each type of power system, a brief resume is given of the fundamental operating principles of each.

Two types of engines may be distinguished by thermodynamic analysis of the way each derives its motive power. If the energy in the fuel must first be converted to heat to provide power for the engine then the engine may be termed a "Q-engine" or heat engine (Lauck, Uyehara, and Myers, 1963). Examples of Q-engines include Rankine-cycle and Stirling-cycle engines. If the internal energy of the fuel need not be converted to heat then this may be termed an "E-engine" of which the conventional I.C.E. and diesel engines are examples. Other examples of E engines include gas turbines and electric cars based on electrochemical cells. Other classification schemes involve distinctions between combustion engines and direct energy conversion devices such as electric motors. Combustion engines are classified as internal where the fuel is burned in the "expander" or external where fuel is burned externally to the expander which provides the engine's useful work (Ayres and McKenna, 1972).
(2) **Brayton-Cycle Engines**

A Brayton cycle is a constant pressure cycle of operations and is used in gas turbines. Brayton-cycle engine and gas turbine are often used interchangeably (Collocott and Dobson, 1974; Reitze, 1977).

The automotive gas turbine is one of the simplest engines. It is lighter than the conventional I.C.E., runs smoother and can use a variety of gaseous and low grade liquid fuels. Successful versions can have as few as four major moving parts, compared to eighty three in a V8 Otto-cycle engine (1). There are no reciprocating parts or cooling system, few frictional contacts and minimal lubrication requirements.

**Operating Principles**

In its simplest form the gas turbine comprises a centrifugal compressor, a combustor and a turbine wheel which is linked to the compressor by a shaft. (Reitze, 1977, Fletcher, 1974). This is termed the simple cycle gas turbine and is shown in Figure 3.16.

---

(1) Otto-cycle is the name given to the combustion cycle of conventional reciprocating internal combustion engines.
Air enters the compressor and its kinetic energy is increased by compression to about four atmospheres which results in heating of the air. The heated air enters the combustion chamber where fuel is injected and ignited in a high pressure high velocity, continuous combustion process. The combustion products expand rapidly and drive the turbine wheel which spins the shaft. The power generated is used to drive the compressor and the surplus energy is used to perform mechanical work in the form of power output.

In automotive applications it is necessary to increase the thermodynamic efficiency which is achieved by adding a power turbine on the same axis as the original shaft but on a separate shaft. The exhaust gas temperatures normally exceed the combustor inlet temperatures so that heat can be recovered from the burning by addition of a regenerator or heat exchanger to heat intake air as shown in Figure 3.17 below. This cycle is termed R.F.T.C. (Regenerative free power turbine cycle).
FIGURE 3.17  Regenerative cycle gas turbine with free power turbine.


Not shown in the diagram is the reduction gear required to reduce the output shaft speed to approximately one-tenth of the power turbine speed. This is required because at idle the first stage or compressor turbine rotates at about 20,000 r.p.m. which increases to 50,000 r.p.m. as the vehicle accelerates. The burning gases pass through this turbine to drive the second stage or power turbine which at maximum vehicle speed rotates at about the same speed as the first stage turbine. Reduction gear is needed to reduce this speed for transmission purposes (Reitze, 1977).
Fuel economy and emissions

The Brayton-cycle engine has a number of advantages with regard to its emissions and fuel economy. Different types of gas turbines tested to date have shown a wide range of fuel economy performance, a few of which compare favourably on specific test cycles with a conventional U.S. reciprocating engine of equivalent power output. Figure 3.18 shows some of these results.

![Figure 3.18 Brayton-cycle engines](image)

Fuel economy compared with engine-cycle characteristics.
Source: Wright, Greenwald & Dewann (undated)
In general however, fuel economy as shown by Figure 3.18, is a fundamental problem of gas turbines. At full throttle or high speeds the gas turbine consumes fuel at a lower rate than the conventional I.C.E. but at idle or low power operating conditions, fuel consumption is much higher (Fletcher, 1974; McGillivray, 1976). This is a result of the engine’s operating characteristics. The engine runs at very high speeds over the entire operating range of the car, but much of this range does not require high power (Crossland, 1974). Consequently road tests of gas turbine experimental vehicles have yielded very poor fuel economy. For example, the General Motor’s AGT-1 which was fitted to a Cutlass Coupe gave 3.7 km l⁻¹ (10.4 m.p.g.) in the city and 6.8 km l⁻¹ (19.2 m.p.g.) on the highway (Reitze, 1977).

Considerable research is being carried out around the world to remedy these problems. Chrysler, Ford, General Motors, American Motors, Caterpillar tractors, International Harvester, Rover Daimler-Benz, Citroen, Fiat, Volkswagen and six Japanese car manufacturers are all involved in research; the U.S. Federal Government with N.A.S.A. provide technical support to Chrysler. It is expected that engines developed in this programme may produce fuel economies equivalent to a conventional vehicle with a six cylinder engine (Brogan, 1976).

The Brayton-cycle engine has been ranked second only to the Stirling-cycle engine in terms of fuel economy
potential, and possibly superior in an advanced stage of development (Jet Propulsion Laboratory, 1975). Other studies have been less optimistic about the gas turbine's overall performance. They conclude that it may offer some potential as a replacement for large truck diesel motors but not for widespread automotive use (Advisory Council on Energy Conservation, 1977).

Emissions performance of the gas turbine is favourable for carbon monoxide and hydrocarbons approaching full throttle but poor for nitrogen oxides. This can be partly explained by its operating characteristics and the conditions needed to satisfy fuel economy criteria.

Carbon monoxide is formed in the gas turbine by any combination of the following (a) inadequate mixing qualities around the primary zone (the volume immediately surrounding the igniter), (b) too rapid cooling of the post-flame products by quenching on the cool combustor walls, (c) too rapid cooling by the addition of air in the intermediate and dilution zones (zones progressively further from the igniter in the direction of the turbine outlet). In general CO formation is highest during part load conditions because of low efficiency and low temperatures (Fletcher, 1974).

Hydrocarbon emissions result from similar inadequacies of the combustion process but are further exacerbated by oversized fuel droplets and by temperatures
much lower than the stoichiometric temperature.

Despite these limitations the gas turbine is in general a lower emitter of CO and HC than the I.C.E. because:
(a) large amounts of air are injected in the compressor and fed to the burner which results in a lean fuel-air ratio and (b) the combustion process is continuous and takes place at high temperatures. This avoids the rapid cyclic heating and cooling in the cylinder of the I.C.E. Experiments have proven that it is possible to reduce HC and CO to levels well below 1976 U.S. standards over the full operating range of the gas turbine (Crossland, 1974). No data were supplied to support this claim.

Nitrogen oxide formation results from the high temperatures associated with combustion in the gas turbine. These substantially increase as full throttle is approached. Research into reducing fuel consumption is considerably dependent upon raising combustion temperatures even further. The use and further development of ceramics technology to produce high temperature components is achieving this objective (Reitze, 1977; Howarth et al, 1975). So far gas turbines have been unable to meet 1976 U.S. standards for NO\textsubscript{x} (Crossland, 1974). The dual goals of low NO\textsubscript{x} emissions and low fuel consumption are thus particularly antagonistic in this system.
Table 3.18 below shows typical emission results of a number of gas turbine systems which have been tested, compared to typical values for a conventional uncontrolled engine. These results highlight the problem of NO\textsubscript{x} emissions and suggest that CO and HC emissions would be a problem at idle in the gas turbine. They do however show a marked improvement over the conventional engine.

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>HC</th>
<th>NO (As NO\textsubscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spark ignition (uncontrolled) (fixed operating cycle)</td>
<td>350</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Gas turbine (uncontrolled)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idle</td>
<td>100</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Full power</td>
<td>1</td>
<td>&lt;1</td>
<td>15</td>
</tr>
<tr>
<td>1976 U.S. Auto standard (approx)</td>
<td>12</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

TABLE 3.18 Comparative emissions of a gas turbine and conventional engine.


Research is being directed towards lowering NO\textsubscript{x} levels but most systems tested have manifested performance and combustion stability problems. Briefly the main methods being considered are (1) modified conventional combustors such as pre-mixed combustors and water injection prior to combustion, and (2) Advanced combustors. These include variable geometry combustors and staged combustion employing a small primary system
which feeds a series of secondary combustion zones. The variable geometry combustor which modifies the fraction of air that enters the combustor primary zone as the engine operating conditions change, has been used with some success. Figure 3.19 below demonstrates this concept and Table 3.19 gives some emissions test results which have been obtained. The results in this table suggest an improvement in emissions performance over the ordinary gas turbine given in Table 3.18. It is important however to note that the results in both these tables are not based on a driving-cycle but on steady-state operation. They may not therefore be indicative of emissions in real urban driving.

FIGURE 3.19  A variable geometry combustor
EMISSIONS LEVELS MEASURED FROM A VARIABLE GEOMETRY COMBUSTOR  
(g/kg fuel)

<table>
<thead>
<tr>
<th></th>
<th>NOx</th>
<th>CO</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976 U.S. Federal Standards</td>
<td>1.39</td>
<td>11.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Variable Geometry combuster</td>
<td>2.5</td>
<td>7.1</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE 3.4** Emissions from a gas turbine employing a variable geometry combustor.

**SOURCE:** After Fletcher (1974).

**Conclusions to Brayton-Cycle Engines**

According to Ayres and McKenna (1972), the gas turbine offers substantial promise as an alternative engine for commercial production despite uncertainties about manufacturing costs and suitability of the engine to mass production techniques. For automotive applications (e.g. 100 h.p. and under) the best system so far developed employs differential turbine configuration which interconnects the input compressor with output turbine via a differential gear. This system
gives up to a 65 per cent reduction in fuel usage over other gas turbines with decreasing load but still keeps maximum torque on the output shaft (Ayres and McKenna, 1972). The major attractions of this type of system as a potential alternative to the I.C.E. are its fuel adaptability in a period of oil scarcity, lower CO and HC emissions than the I.C.E., the potential for reducing fuel consumption, and the progress which has been made in reducing NO\textsubscript{x} emissions. However a gas turbine powered car would be very expensive to manufacture (NEAC, 1979).

Considerable experience by General Electric, has been gained in Brayton-cycle technology, U.S. research having commenced in 1903. Automotive applications have been under development since 1945. However, most manufacturers seem likely to aim for long haul truck, bus and off-highway earth moving machinery markets in the near future (Ayres and McKenna, 1972). Due to present NO\textsubscript{x} and fuel consumption problems, plus technological changeover lag times it is unlikely that the gas turbine could be put into mass production prior to 1987\textsubscript{x} (Reitze, 1977). On the other hand the Energy Research and Development Administration in the U.S.A. evaluated the gas turbine for possible introduction during
1980-1990. They concluded that it offers the promise of eliminating the automobile as a significant source of urban air pollution, dramatically reducing fuel consumption and being saleable (Chen, 1977). All of these U.S. assessments would appear somewhat optimistic in the light of the most recent appraisal from Australia which states that although experimental vehicles have been successfully powered by gas turbines they are essentially unsuitable for normal road use (NEAC, 1979).
(3) Rankine-Cycle Engines

The Rankine-cycle vapour engine or steam engine is an external combustion engine which employs a working fluid in a closed cycle. It is a classical heat engine. Unlike in a regular steam engine, no vapour escapes to the atmosphere (Crossland, 1974; Reitze, 1977).

Rankine cycle engines use a continuous combustion process which takes place at comparatively low temperatures (100°-550°C) and pressures. This has marked benefits with regard to pollutant emission levels including noise.

The vapour engine overcomes a fundamental problem of gas turbines. Gas turbines divert a large proportion of the turbine work into operating the compressor. In the vapour engine the work ratio\(^1\) is high because the feed pump is required to pump only liquid of a small volume compared with the vapour, hence little of the expander work is lost in compression. The cycle in the vapour engine is capable of achieving efficiencies close to ideal over a range of loads and sizes (Wilson, 1974).

\(^1\) The work ratio is the ratio of net work done in the cycle to positive expander work.
Considerable development and sophistication of the Rankine-cycle engine for automotive purposes occurred during the last two decades as a result of large private and government investment projects especially in the U.S.A. These included the Californian Steam Bus Project, California Clean Car Project, 1972, and projects by Energy System Corporation, Lear Motors, Thermo Electron Corporation and Aerojet Liquid Rocket Company. Pritchard Steam Power Pty. Ltd., an Australian Company, converted a 1963 Ford Falcon which achieved 6.0-7.5 km l⁻¹ (17-21 m.p.g.) in city driving (Reitze, 1977).

Operating Principles

A Rankine-cycle by definition is

"A composite steam plant cycle used as a standard of efficiency, comprising adiabatic expansion to condenser pressure and condensation to the initial point"

(Collocott and Dobson, 1974)

It is an idealised cycle used to explain the operation of a vapour plant by eliminating the complicating factors such as

(1) Acceleration and turbulence caused by pressure
(2) Friction
(3) Conduction of heat through the walls and
(4) Irreversible heat transfer

(Zemansky, 1968)

It is used as a standard of efficiency because it represents the theoretical maximum efficiency achievable from a vapour engine (Zemansky, 1968).
The fluid in a vapour engine which may be water or any of a number of organic liquids\(^1\) is alternately boiled, vapourised, superheated and condensed with heat being provided by an external flame. The power is produced while the fluid is in the vapour phase by adiabatic expansion against either pistons or turbine blades until its pressure and temperature drop to that of the condenser (Crossland, 1974 and Zemansky, 1968). Figure 3.20 below shows schematically the basic principle of operation of a Rankine-cycle power plant.

![Elementary Steam Power Plant](image)

**Figure 3.20** Elementary Steam Power Plant

**SOURCE:** Zemansky, (1968).

\(^1\) e.g. (a) Fluorinal 85 (a mixture of 85 per cent Trifluoromethanol and 15% water
(b) A mixture of 57.5 percent pentafluorobenzene and 42.5 percent hexafluorobenzene
(c) Monochlorobenzene
(d) Benzene hexafluoride
Fuel Economy and Emissions

Rankine-cycle automotive engines have to date achieved a wide range of fuel economy performance. For example in the California Steam Bus project, the fuel consumption of the steam bus was six times that of the diesel bus at idle and three to four times higher overall (Reitze, 1977). However the primary aim of this project was to identify technical problems and to educate the public about the need for alternative engines (Crossland, 1974). Similarly in the U.K., Rankine cycle engines are cited as having about double the fuel consumption of a conventional piston engine (Advisory Council on Energy Conservation, 1977). However Jet Propulsion Laboratory (1975) ranked the Rankine cycle engine below the Stirling-cycle and Brayton-cycle engines because of its poor fuel economy.

Other studies have given favourable fuel economy reports. Figure 32 below shows the fuel economy performance of a Chevelle car for a range of average speeds. It shows that at average speeds typical of city driving up to (40 km/hr (25 m.p.h.)) the steam engine version achieved better fuel economy than the petrol engine vehicle. This is because the reciprocating steam engine has some degree of thermal energy storage and a torque-speed curve suitable to stop-start operations of city driving. Above about 48 km hr\(^{-1}\) (30 m.p.h.) fuel economy deteriorates (Wilson, 1974).
The U.S. E.P.A. considers that criticism of the Rankine-cycle engine for its poor fuel economy is no longer valid. They predict that with planned modifications the vapour engine will show better fuel economy than the I.C.E. (Crossland, 1974). As with other external combustion engines its adaptability to inexpensive hydrocarbon fuels such as kerosene and diesel oil, make it particularly attractive in a period of unstable oil supplies. Pritchard Steam Power Pty. Ltd., has produced a 6 passenger steam car in Australia capable of between 8.8 and 10.6 km l⁻¹ (25-30 m.p.g.) using kerosene as a fuel. The bottom range of this consumption was at 97 km/hr while the best fuel economy was achieved at an average speed of about 45 km/hr which is closer to urban values (Pritchard Steam Power, 1979).
Rankine-cycle engines are characterised by very low emissions. At present this is their major advantage over other engines. In laboratory testing of engines they have recorded emissions levels well below the 1976 U.S. Federal Standards. Table 3.20 below shows the average emissions results for the four major U.S.E.P.A. funded projects. Data are in grams per kilometre with grams per mile equivalents in brackets underneath. It must be noted that these data are from laboratory based engine testing not vehicle dynamometer testing based on road conditions.

<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>1976 FEDERAL STANDARDS (g/mile)</th>
<th>1976 FEDERAL STANDARDS (g/mile)</th>
<th>1976 FEDERAL STANDARDS (g/mile)</th>
<th>1976 FEDERAL STANDARDS (g/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen oxides</td>
<td>0.25 (0.40)</td>
<td>0.093 (0.149)</td>
<td>0.24 (0.38)</td>
<td>0.11 (0.18)</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>0.25 (0.41)</td>
<td>0.033 (0.053)</td>
<td>0.13 (0.21)</td>
<td>0.11 (0.18)</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>2.11 (3.40)</td>
<td>0.197 (0.317)</td>
<td>0.43 (0.70)</td>
<td>0.27 (0.43)</td>
</tr>
</tbody>
</table>

**TABLE 3.20** Emissions performance of four experimental Rankine-cycle engines.

**SOURCE:** After Crossland (1974).

Similarly in the California Steam Bus Project the average steam bus emitted 83 percent less NOX, 36 percent less HC and 37 percent less CO than the average diesel bus tested (Reitze, 1977).
The steam car tested by Pritchard Steam Power Pty. Ltd. achieved emissions performance well within Australian 1976 idle standards. Table 3.21 shows the results of idle tests compared to the average for a number of uncontrolled petrol driven cars under the same conditions. This however does not give a true indication of the vehicle’s on road performance in various traffic conditions.

<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>PETROL CAR</th>
<th>PRITCHARD STEAM CAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon monoxide</td>
<td>0.5 - 0.79%</td>
<td>0.013%</td>
</tr>
<tr>
<td>Hydrocarbons (ppm)</td>
<td>200 - 3000</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Nitrogen oxides (ppm)</td>
<td>500 - 1000</td>
<td>115</td>
</tr>
</tbody>
</table>

TABLE 3.21 Idle emissions test results for the Pritchard Steam Car.


The Steam Engine Systems Corporation also developed a reciprocating steam automotive plant in conjunction with the U.S.E.P.A. which also produced substantially lower emissions than 1976 U.S. Federal Standards. Table 3.22 below shows these results. Data are in grams per km with grams per mile equivalents in brackets underneath. These results further confirm the low emissions for Rankine-cycle engines shown in Table 3.20.
TABLE 3.22 Emissions results of a reciprocating steam Automotive plant

<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>1976 g/km FEDERAL STANDARD (g/mile)</th>
<th>STEAM ENGINE SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOₓ</td>
<td>0.25 (0.40)</td>
<td>0.09 (0.14)</td>
</tr>
<tr>
<td>CO</td>
<td>2.11 (3.40)</td>
<td>0.11 (0.17)</td>
</tr>
<tr>
<td>HC</td>
<td>0.25 (0.41)</td>
<td>0.02 (0.03)</td>
</tr>
</tbody>
</table>


Lead emissions from vapour engines may be eliminated entirely because the system is versatile in its fuel requirements and does not need leaded fuels.

Conclusions to Rankine-Cycle Engines

On the grounds of very low emissions levels (including noise), the proven potential to lower fuel consumption and fuel adaptability, the vapour engine could prove to be a desirable substitute for current engines. Reitze (1977) suggests that the Rankine-cycle engine is still a leading candidate as an alternative to the I.C.E. Steam engines have had over 200 years of development, innovation and modification and there seems to be few insurmountable technical problems facing their widespread use in motor vehicles. Economic obstacles appear to be the major impediment. At the moment
the production cost of a steam engine is about double that of an I.C.E. (Advisory Council on Energy Conservation, 1977). Pritchard Steam Power Pty. Ltd. estimate that the steam engine will not be produced in quantity inside four years (Pritchard Steam Power, 1979). The National Energy Advisory Committee assessment of Rankine-cycle engines suggests that this is an optimistic prediction because at present levels of development they cannot compete with either liquid or gaseous hydrocarbon fuelled conventional engines (NEAC, 1979). The cost factor is a particularly large drawback.
(4) **Stirling-cycle Engines**

The Stirling-cycle engine is one of the most efficient combustion systems known. Tested engines have achieved approximately 50 percent efficiency compared to about 10 to 15 percent for an I.C.E. Their inherently high efficiency gives them potential for very high fuel economy (Reitze, 1977; Advisory Council on Energy Conservation, 1977).

**Operating Principles**

The Stirling-cycle engine is an external combustion, closed cycle reciprocating piston power plant which utilises a gaseous internal working fluid. The most commonly used fluid is hydrogen. It was the first of the so-called "air engines" (Ayres and McKenna, 1972; Reitze, 1977).

By classical definition it is a heat engine because it derives its work output from the difference in heat supplied from a reservoir at high temperature \( Q_H \) and the heat rejected at a lower temperature \( Q_C \) (Rice, 1974). Work output, \( W \), is equal to \( Q_H - Q_C \) (Zemansky, 1968).

The basic sequences of its cyclic operation are shown by figure 3.22.
Figure 3.22 Cyclic operation of the Stirling-cycle engine.
Source: Zemansky (1968)

The explanation of these sequences is best understood with reference to a pressure-volume diagram which shows the ideal theoretical operation of the Stirling-cycle engine based upon the simplifying assumptions of:

1. an ideal gas,
2. no leakage of gas,
3. no heat loss or gain through cylinder walls,
4. no heat conduction through the regenerator, and
5. no friction.

This is shown by figure 3.23
An extract from Zemansky (1968) explains the processes shown by this diagram.

"1→2 While the left piston remains at the top, the right piston moves halfway up, compressing cold gas while in contact with the cold reservoir and therefore causing heat $Q_l$ to leave. This is an approximately isothermal compression and is depicted as a rigorously isothermal process at the temperature $\theta_C$.

2→3 The left piston moves down and the right piston up, so that there is no change in volume, but gas is forced through the regenerator from the cold side to the hot side and enters the left-hand side at the higher temperature $\theta_H$. To accomplish this, the regenerator supplied heat $Q_R$ to the gas. Note that the process 2→3 is at constant volume.

3→4 The right piston now remains stationary as the left piston continues moving down while in contact with the hot reservoir, causing the gas to undergo an approximately isothermal expansion, during which heat $Q_R$ is absorbed at the temperature $\theta_H$.

4→1 Both pistons move in opposite directions, thereby forcing gas through the regenerator from the hot to the cold side and giving up approximately the same amount of heat $Q_R$ to the regenerator that it absorbed in the process 2→3. This process takes place at practically constant volume."
The regenerator acts as a thermal storage device (Rice, 1974).

Stirling engines for automotive purposes have an engine configuration shown by figure 3.24. This shows a Beta type Stirling engine, distinct from the Alpha type used above to describe the basic operating cycle which is the same for all Stirling engines. Gamma type engine configurations also exist but explanations of the differences between these types is not necessary.

Figure 3.24 Beta type Stirling Engine
Source: Reitze (1977)
The rhombic drive mechanism shown in this diagram converts the reciprocating piston and displaces motion into a rotary output for a single cylinder thus avoiding the need for an unbalanced crankshaft (Ayres and McKenna, 1972).
Fuel Economy and Emissions

G.V. Phillips Company of Holland have worked on the Stirling engine since 1938 and have produced a car which achieved 6.2 kms per litre (17.6 m.p.g.) in a test with a comparable conventional American, emission controlled car which achieved 4.6 kms per litre (12.8 m.p.g.) (Crossland, 1974).

Ford and Phillips entered an agreement in 1972 to further develop a swash-plate drive\(^{(1)}\) four-cylinder double acting Stirling engine for automotive application. The test engine was rated at 170 horsepower and installed in a 1975 Ford Torino. It achieved 25 percent better fuel economy than the standard Torino over a transient city-suburban test route (Reitze, 1977).

The Jet Propulsion Laboratory in California has made some tentative calculations of the fuel conservation potential of the widespread introduction of Stirling-cycle engines. They concluded that at an investment cost of U.S.\$8 billion, the Stirling engine could be expected to save 2 million barrels of petroleum per day by the year 2000. To increase petroleum supply by this amount would require about U.S.\$20 billion investment (Jet Propulsion Laboratory, 1975).

---

\(^{(1)}\) A swash-plate replaces the crankshaft and permits a four-cylinder Stirling engine to give four power-strokes for every rotation of the swash-plate compared to two for every rotation of the crankshaft.
In these terms such an investment appears favourable but to generate capital of $8 billion for a sweeping change in engine technology would require intense political pressure upon automotive industries. Such an investment might not be justified in terms of energy conservation and emissions reduction alone.

The high efficiency of the combustion process in the Stirling engine yields generally low emissions levels. The combustion process is easily controlled and can be pre-set to an optimum air-fuel ratio.

The United Stirling Company of Sweden has published emissions results from a number of their test engines. These results are summarised in Table 3.23. In general the Stirling-cycle engine has met CO and HC standards but NOₓ levels have been slightly over in a number of tests. These tests have also shown that this can be reduced by exhaust gas recirculation.

Table 3.23 Emissions results for Stirling-cycle Engines.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>2.11 (0.2%) (3.40)</td>
<td>0.6 (0.9)</td>
<td>0.007-0.03%</td>
</tr>
<tr>
<td>HC</td>
<td>0.25 (0.41)</td>
<td>0.1 (0.1)</td>
<td>0.01 (0.01-0.02)</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.25 (0.40)</td>
<td>0.4 (0.6)</td>
<td>0.6-1.2 (1.0-2.0)</td>
</tr>
</tbody>
</table>

Source: After Crossland (1974); Rice (1974).

Note: (1) Data in brackets are in grams per mile.
(2) All other data not shown as percentages are in grams per km.
Emissions characteristics including noise and vibration are generally satisfactory for present standards but it is not yet conclusively known whether low gaseous emissions will be maintained over 50,000km of operation.

Conclusions to Stirling-cycle Engines

Overall assessment of the Stirling-cycle engine as a replacement for the I.C.E. in the U.S.A. is favourable despite a number of technical and cost problems (Jet Propulsion Laboratory, 1975; Committee on Motor Vehicle Emissions, 1973). It is feasible that production models may be available in the U.S.A. as early as the 1980s (Crossland, 1974; Reitze, 1977). However in Australia Stirling-cycle engines are not even considered in a major assessment of alternative engines (N.E.A.C., 1979).

Much of the more recent work is being directed towards production of smaller versions (80-100 horsepower range) and to overcoming problems related to air-fuel ratio control, sealing, the swash-plate drive mechanism, noise, high temperature technology, durability and mass production suitability (Rice, 1974; Reitze, 1977; Crossland, 1974).

At the moment however, cost and overall economic impact appear to be the major impediments to its introduction. At present the cost of a mass produced Stirling
engine is in the vicinity of 1\(\frac{1}{2}\) to 2 times that of an equivalent diesel engine and several times that of a conventional I.C.E. (Rice, 1974; Advisory Council on Energy Conservation, 1977). The large capital costs of a changeover are also a serious drawback. An attraction of the Stirling engine which may lead to a different direction in its development is its suitability to a hybrid vehicle. Hybrid vehicles are discussed in depth in the next section. G.M. has carried out considerable research and experimentation with Stirling-cycle engines in hybrid vehicles (Reitze, 1977; Ayres and McKenna, 1972).
(ii) **New Vehicle Systems**

(1) **Electric Vehicles**

So far all the potential vehicle propulsion systems which have been discussed have involved some form of combustion process in the vehicle. In this sense electric powered vehicles constitute by far the most radical alternative to current private transport methods, deriving their motive power from an on-board electrochemical reaction.

They constitute a radical departure from the current situation for a number of other important reasons. These may be considered as follows:

(a) electric vehicles offer the greatest potential for overcoming the liquid fuels dilemma in motorised transport. Their primary energy supply may be based upon any form of centralised electricity production whether it be coal, nuclear, hydroelectric, geothermal, wind, solar or any other source which may appear in the future. In this way they can offer security from the vicissitudes of the world oil situation plus future flexibility in their primary energy requirements with the advantage of a homogenous end product - electricity.

(b) they virtually eliminate all emissions from the vehicle itself. This includes air pollutants and noise.
It has been suggested however, that electric vehicles in large quantities have the potential to pollute or smother radio communications networks i.e. electronic pollution (Darke, 1975). The pollution which may be attributed indirectly to the electric vehicle originates at the primary power source in the process of generating electricity. The need for mobile source control is thus eliminated and replaced with the fundamentally easier problem of stationary source control, though this is not entirely without problems e.g. $SO_2$ from coal combustion and nuclear waste disposal.

(c) present commitment to the internal combustion engine is immense both in financial and human terms. The widespread manufacture, operation and servicing of electric vehicles would involve huge changes in present industrial and commercial infrastructure, raw-materials requirements, capital investment, production techniques and workforce skills. Electric vehicles would in general require considerably more adaptation, at all levels of society, than each of the alternatives considered so far.

Upon brief examination the potential contribution of electric vehicles to alleviating the two basic problems of transport energy supply and emissions control is great. It is necessary however to examine this potential in the light of the most
recent achievements in electric vehicle technology and with due consideration to the time factor implicit in any assumptions about the future role of electric private transport.

It is impossible to attempt to review all the multifarious detail of electric vehicle technology. Unlike the propulsion systems reviewed to this point, the variations in electric vehicle design and operating principles are huge. Innumerable companies around the world, small and large are involved in electric vehicle development and testing (Shacket, 1979). It is therefore only feasible to give a broad state-of-the-art summary, pointing to the major obstacles, major directions and above all the major unknowns of electric vehicle technology. From this it is possible to gain some insight into the near and long term potential of electric vehicles for reducing oil dependence and urban air pollution.

The major obstacle confronting the use of electric vehicles is the inability of current batteries to meet a number of important criteria, the most important of which are energy density and power density.

Energy density is the amount of power a battery can produce for a specified length of time relative to its own weight. This is expressed in
Energy density essentially determines how far the vehicle may travel after the batteries are charged. Power density is the amount of power available at any one time and is expressed as W/kg. Power density affects peak output and determines the vehicle's top speed and acceleration (Shacket, 1979).

The lead-acid battery in most cases has demonstrated inadequate performance in both these parameters. Considerable research into improving this situation is being undertaken in many places including Australia and advances are being made. In general lead-acid batteries are capable of energy densities in the range 30-35 Whr/kg with a theoretical capability of 171 Whr/kg (CSIRO, 1979). In contrast petrol, at 20% thermal efficiency has an energy density of 2600 Whr/kg (Graves, 1978). Reports of advances in lead-acid technology are revealing values of up to 60 Wh/kg (NEAC, 1978).

Although entirely new battery concepts offer greater improvements in energy and power density, the lead-acid battery appears to offer an attractive shorter term option. The reasons for this are related to the 120 years of development already invested in lead-acid batteries, their cheapness and reliability, the availability of lead on a world wide basis and the proven recycling potential of lead (CSIRO, 1979).
In the longer term alternative battery systems of which there are over 30 being investigated, offer better performance characteristics for private vehicles and other heavier duty purposes.

Table 3.24 summarises the energy and power density specifications which these systems will need to meet to provide adequate performance for the different classes of vehicles.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Energy Density (Whr/kg)</th>
<th>Power Density (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small car</td>
<td>30-70</td>
<td>60-80</td>
</tr>
<tr>
<td>City car</td>
<td>50-100</td>
<td>70-110</td>
</tr>
<tr>
<td>Delivery Van</td>
<td>60-120</td>
<td>80-130</td>
</tr>
<tr>
<td>Delivery Truck</td>
<td>60-100</td>
<td>60-120</td>
</tr>
<tr>
<td>City Bus</td>
<td>60-180</td>
<td>60-90</td>
</tr>
<tr>
<td>Family Car</td>
<td>150-300</td>
<td>140-250</td>
</tr>
</tbody>
</table>

Table 3.24 Battery performance Standards.

Source: After CSIRO (1979).

Note: All batteries should attain a minimum cycle life of 1000. One cycle or operating cycle is defined as the number of times the fully charged battery system can be completely drained of energy (Shacket, 1979).
The major batteries being considered for these purposes are:

(1) Lead - acid (improved).
(2) Nickel - zinc.
(3) Nickel - iron.
(4) Zinc - chlorine (Cl₂).
(5) Lithium - titanium disulphide.
(6) Lithium - sulphur.
(7) Sodium - sulphur.
(8) Iron - air.
(9) Zinc - air.

These are not listed in any order of advancement.

Of these systems the U.S. Department of Energy cites the nickel-iron, nickel-zinc and lead-acid systems as warranting research and development as near term options. (Edison Electric Institute, 1979).

The current performance standards of each system and an indication of the potential of each has been summarised in Table 3.25. The column headed "depth of discharge" indicates the extent to which the battery is normally drained of energy under urban driving conditions. This is also referred to as "depth of cycle" (CSIRO, 1979; Shacket, 1979). The energy density shown in this table also depends upon the discharge rate e.g. a lead - acid battery
discharged over 5 hours driving might yield up to 35 Whr/kg but over 1 hour it will yield 22 Whr/kg. Neither source stated what discharge rate these data apply to. The 5 hour rate is most likely. The values shown are the most common values currently achieved by each system. Isolated cases of breakthroughs occur around the world at various times, e.g. Japan claims it has developed a nickel-iron system capable of 84 Whr/kg (Shacket, 1979).
<table>
<thead>
<tr>
<th>Battery System</th>
<th>Theoretical Energy Density (Whr/kg)</th>
<th>Energy Density (Whr/kg)</th>
<th>Peak Power Density (W/kg)</th>
<th>Life (number of cycles)</th>
<th>Depth of Discharge %</th>
<th>Cost $/kWhr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead - acid (improved)</td>
<td>171</td>
<td>35</td>
<td>50-150</td>
<td>500</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Nickel - zinc</td>
<td>321</td>
<td>66</td>
<td>150</td>
<td>400</td>
<td>65</td>
<td>150</td>
</tr>
<tr>
<td>Nickel - iron</td>
<td>267</td>
<td>55</td>
<td>50-100</td>
<td>1500</td>
<td>90</td>
<td>400</td>
</tr>
<tr>
<td>Zinc - chlorine (Cl₂)</td>
<td>-</td>
<td>95</td>
<td>-</td>
<td>250</td>
<td>-</td>
<td>200</td>
</tr>
<tr>
<td>Lithium - titanium disulphide</td>
<td>480</td>
<td>132</td>
<td>132</td>
<td>120</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lithium - sulphur</td>
<td>625</td>
<td>70</td>
<td>50</td>
<td>250</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sodium - sulphur</td>
<td>664</td>
<td>180</td>
<td>220</td>
<td>300</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Iron - air</td>
<td>918</td>
<td>81</td>
<td>30-40</td>
<td>200</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>Zinc - air</td>
<td>1347</td>
<td>110</td>
<td>80</td>
<td>550</td>
<td>90</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.25  Current performance of prominent battery systems

Source: (After C.S.I.R.O. 1979; Loder, 1979)
It is apparent that some of these systems are approaching energy density values appropriate for the family car and other heavier duty use. However, as is shown by the table the length of life suffers severe limitations at present. Each system has a number of other developmental problems not shown by the table. These must be solved before the majority of these systems could be considered for use in private vehicles.

Some of the major problems can be summarised as follows:

(1) With nickel-zinc the main problems relate to its recharging inefficiency, its short life cycle and the tendency for the formation of zinc denrites or fronds between the separators in the cell (CSIRO, 1979). Zinc formations have tended to short-circuit the cells. Nevertheless some sources indicate that a commercially available version of this cell will be available in the 1980's (Shacket, 1979).

(2) Nickel-iron systems have low recharging efficiencies, poor power delivery, require better venting to remove excess hydrogen which is given off during charging and they require cooling. (Shacket, 1979).

(3) The iron-air and zinc-air systems need more development to improve their peak power output
and low recharging efficiency (CSIRO, 1979).

(4) Zinc-chlorine systems require a safe but practical method of storing chlorine (Shacket, 1979).

(5) Sodium-sulphur batteries suffer from extremely high temperatures (300°C) which are required to keep the metals molten and the battery operational. They also experience leakage, corrosion and self-discharge problems. Safety and complexity are a problem in private car applications (Graves, 1978; CSIRO, 1979; Shacket, 1979).

(6) Lithium-sulphur is another high-temperature battery which has similar problems to the sodium-sulphur battery but with the added disadvantage that lithium is a relatively scarce and costly element (CSIRO, 1979).

Each of these battery systems has its peculiar advantages and disadvantages as partly shown by table 3.25 and the points listed above. Each of the large number and variety of companies and research organisations have a preference to one or two of these systems. Great amounts of time, energy and funds are expended all over the world in improving testing and developing complete vehicle systems to further the possibilities of each type of battery.
In this atmosphere of diverse research and development it is highly improbable that reliable or meaningful prognosis can be offered concerning the likely outcome of these efforts. New batteries such as the zinc-chlorine system which have promising potential, (eg. projected energy density of 165 Whr/kg (Shacket, 1979)), but which seem to be a longer term option might suddenly experience an important breakthrough. It is therefore of little value to review specifically the achievements of each particular system at this point.

It is of value however to consider in general terms some of the objectives in electric vehicle transport. Table 3.26 shows the legislated standards for demonstration vehicles in the U.S.A. (1978) and table 3.27 shows the near term electric vehicle performance objectives as a comparison (1979).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>Personal Use (Note 1)</th>
<th>Commercial (Note 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>0-50 km/h</td>
<td>15 sec</td>
<td>15 sec</td>
</tr>
<tr>
<td>Gradeability</td>
<td>@ 25 km/k</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Gradeability Limit</td>
<td>for 20 sec</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Forward Speed</td>
<td>for 5 min</td>
<td>80 km/h</td>
<td>70 km/h</td>
</tr>
<tr>
<td>Range (SAE 227a)</td>
<td>EV</td>
<td>50 km-Cycle</td>
<td>50 km-B cycle</td>
</tr>
<tr>
<td></td>
<td>HV</td>
<td>200 km-Cycle</td>
<td>200 km-B cycle</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>EV</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>HV (Note 2)</td>
<td>1.3 MJ/km (non-elec)</td>
<td>9.8 kj/km kg (non-elec)</td>
</tr>
<tr>
<td>Battery Recharge Time</td>
<td>from 80% discharge (100 or 220 vac)</td>
<td>10 hours</td>
<td></td>
</tr>
</tbody>
</table>
Safety: NHTSA Stds + others
Emissions: FED. Stds
Recharge Control: YES
State-of-Charge Meter: YES
Odometer: YES
Heater: Available as Option
Documentation: YES

Notes:
1) SAE 227 Test Procedure apply
2) Non-Electrical Consumption must be 75% of total energy consumed.

SOURCE: EDISON ELECTRIC INSTITUTE (1979)
TABLE 3.27 NEAR-TERM ELECTRIC VEHICLE OBJECTIVES

<table>
<thead>
<tr>
<th>Objective</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Passenger Capacity</td>
<td>4 Adults</td>
</tr>
<tr>
<td>Max. Curb Weight</td>
<td>Open</td>
</tr>
<tr>
<td>Min. Urban Range-Kilometres (miles)</td>
<td>121 (75)</td>
</tr>
<tr>
<td>Max. Initial Cost (1975 dollars)</td>
<td>5,000</td>
</tr>
<tr>
<td>Min. Life-Kilometres (miles)</td>
<td>161,000 (100,000)</td>
</tr>
<tr>
<td>Max. Life Cycle Cost - 1975 $/km ($/mile)</td>
<td>0.09 (0.15)</td>
</tr>
<tr>
<td>Max. Electric Recharge Energy in Urban Driving - KWh/km (KWh/mile)</td>
<td>0.32 (0.5)</td>
</tr>
<tr>
<td>Max. Recharge Time-Hours</td>
<td>6</td>
</tr>
<tr>
<td>Safety Features</td>
<td>Meet Federal Motor Vehicle Safety Standards</td>
</tr>
<tr>
<td>Min. Unserviced Park Duration-Days</td>
<td>7</td>
</tr>
<tr>
<td>Min. Ambient Temperature Range-C (F)</td>
<td>-29 to + 52 (-20 to + 125)</td>
</tr>
<tr>
<td>Min. Top Speed-km/hr (mi/hr)</td>
<td>97 (60)</td>
</tr>
<tr>
<td>Min. Acceleration-Seconds for 0.48 km/hr (0.30 mph)</td>
<td>9</td>
</tr>
<tr>
<td>Min. Merging Time-Seconds for 40-89 km/hr (25-55 mph)</td>
<td>18</td>
</tr>
</tbody>
</table>

Similarly, it is possible to identify in general terms some of the broader problems which electric vehicle technology faces. Unlike much of the discussion so far concerning presently available technological improvements to automobiles, electric vehicles primarily require significant technological advances, particularly in the battery systems. If it is assumed however that these advances in power supply do occur other substantial changes in society must be made before electric vehicles can penetrate the market sufficiently to have an observable effect on energy and emissions in cities.

For the U.S.A. a Public Law has been enacted (Section 13, Public Law 94-413) which states four specific areas which require further study (Edison Electric Institute, 1979).

(a) **Institutional factors** - these are primarily concerned with identifying and finding solutions to the major economic and political factors which confront the introduction and spread of electric vehicles. The most important of these is the massive impact on the present motor vehicle industry and all the subsidiary and ancillary activities which depend upon it. Most assessments in this area conclude by
considering the very substantial role which governments will have to play in effecting a smooth transition. This aspect has been considered in some detail in Australia (McMahon, 1975).

(b) Long range materials demands and pollution effects stemming from the use of electric vehicles — the range of materials required, including energy sources and the type of pollution which electric vehicles might ultimately engender are different to the present situation with the ICE and require long range planning to adequately appreciate.

(c) Safety standards and regulations — electric vehicle technology introduces vastly different safety requirements and standards which need to be thoroughly examined and planned for in advance of any move towards electric vehicles, e.g. working with high voltages, sealing from water, fuse systems, electronics controls etc (Edison Electric Institute, 1979).

(d) Regenerative braking — this technological innovation essentially involves using the force of the slowing vehicle to turn the motor into a generator and feed current back to charge the batteries. This system takes the stress off conventional braking systems, extends the range of the vehicle and allows between 10 and 40% energy retrieval. Battery life and efficiency are improved (Shacket, 1979).
Considerations under item (b) above are of the most direct relevance to this study and so have been considered in some detail.

Calculations have been made in many countries to assess the ability of the electricity generating capacity to cope with the demands of an electified vehicle population. At present in Australia electric vehicles could be operated at an overall energy efficiency\(^{(1)}\) of 15-20 per cent compared to 10-15 per cent for petrol driven vehicles. However, presently available battery cars operating in urban conditions have an overall energy efficiency of 0.66 km/kWh compared to 0.83 km/kWh for ICE vehicles (Pryor, Curtin and Glazebrook, 1975). Considerable scope exists for raising the energy efficiency of the electric vehicle because the efficiency of electricity generation and battery performance have the potential to be improved. e.g. Current Australian power plant efficiencies are about 35 per cent (CSIRO, 1979).

On the basis of current efficiencies several studies have reported that a large changeover to electric vehicles would not pose any electricity supply problem. The Association of Consulting Engineers, Australia reports that between 1.5 and 7 per cent extra electricity would be required to supply electric

\(^{(1)}\) This refers to the percentage of energy used which is actually converted to motive power.
car loads (NEAC, 1978). The South East Queensland Electricity Board estimated that if 50 per cent of the local road transport were made electric about 7 per cent extra electricity would be required. This is roughly equivalent to a year's growth in electricity demand (C.S.I.R.O., 1979). An Australia wide analysis indicated that if half the total passenger kilometres in Australian capital cities were shared equally between cars and electric trains and trams, an increase of only 7 per cent over 1972/3 total electricity consumption would be required (Chapman, 1975). It also estimated that 25 per cent of the petrol consumed in Australia in 1972/3 could be saved by this method.

Other overseas studies have revealed a similar situation i.e. that in most cases the impact of an electric vehicle current load would be roughly equivalent to one year's growth in electricity supply (NEAC, 1978). Additional exercises using more ambitious assumptions have also been carried out. For example, in Britain, it was assumed that all existing transport could be electrified. This resulted in an estimate of 25 per cent more electricity being required (CSIRO, 1979). In assessing these estimates it is necessary to keep in mind that the actual length of time which would be required to build up this load is very large and in this sense the impact of electric vehicles on generating capacity would be minimal (NEAC, 1978).
In assessing the feasibility of introducing electric vehicles on a large scale it is not sufficient to only consider the amount of extra electricity required but also how this electricity will ultimately be supplied to the vehicles. The two major options are at home recharging or a battery exchange system operated on a similar principle to that of today's service stations. Other support systems would also be important such as parking meter recharging points in streets and car parks.

One study in the U.K. indicated that a battery exchange infrastructure for lead-acid batteries would be impractical and expensive in comparison to the present petrol system. A network of battery exchange points for sodium-sulphur or zinc-air batteries would be similarly expensive and inconvenient. A battery exchange system, it calculated would become attractive only if petrol prices rose dramatically. An equivalent amount of energy from a battery exchange system would cost twice that of petrol and require large capital investments and a large labour force to procure. On this basis the study suggested that the home recharging option might ultimately be more attractive because it avoids heavy capital outlays, the need to keep an expensive stock of batteries and it does not require a large labour force (Weeks, 1978).
Given this comparatively favourable energy situation, electric vehicles are being specifically assessed in terms of their potential to reduce oil demand. To achieve this in the U.S.A., the U.S. Department of Energy has set a number of goals for electric transport, for which they are progressively increasing their research and development support. This has risen from a value of U.S. $5m in 1977, to U.S. $30m in 1978 with a proposed amount of U.S. $37.5m (A.T.A.C., 1978). By 1986 the aim is to have a battery system with an energy density of 90 Whr/kg, a cycle life of 1000 and which will be capable of powering a vehicle for 322km (200 miles) (ATAC, 1978).

By setting these progressive targets the U.S.A. hopes to replace a significant proportion of its oil demand with electricity. The ultimate U.S. goal as it stands now, is to assist in commercialising a competitive electric vehicle industry capable of placing 10 million vehicles (approximately 10% of the current U.S. vehicle population) on the road by 2000 with an annual saving of 100 million barrels of oil (Edison Electric Institute, 1979). It is worth noting however that if common estimates of U.S. automotive oil demand by the year 2000 (5375 million barrels, Gillis, Pangborn and Vyas, 1975) prove correct then this goal, if achieved will represent a 2.0% saving in oil. In fact 1975 automotive energy demand
in the U.S.A. was equivalent to about 2580 million barrels; 100 million barrels represents only 4.0% of this demand (Gillis, Pangborn and Vyas, 1975). If on the other hand it was possible to substitute electric vehicles for all second and third vehicles in the U.S.A. (26 million in 1978) this would save 400 million barrels of oil per year by 2000; an 8% saving in oil by 2000. (Jackson, 1978).

It is clear that electric vehicles developed to a satisfactory level of performance and used on a very large scale have the potential to help eliminate the extreme dependence on oil which characterises current transport systems. The time required to do this is however very great as shown by the U.S.A. analysis. Electric vehicles would achieve this goal by substituting oil with presently more abundant sources of energy such as coal and nuclear energy, which are themselves exhaustible resources. The use of coal and nuclear energy also involves significant environmental impact. In the longer term the use of solar, wind or geothermal power may be possible for electric vehicle purposes (Pryor, Curtin, and Glazebrook, 1975).

As suggested in the introduction to this section the use of electric vehicles does however offer potential environmental advantages over present urban transport systems. A study by the Southern California
Edison Co exemplifies these advantages by a comparison between the total air pollution characteristics of the present petrol vehicle with that of the electric vehicle. This is summarised in table 3.28.

<table>
<thead>
<tr>
<th>TOTAL POLLUTION CONTRIBUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Vehicle</td>
</tr>
<tr>
<td>Power Plant</td>
</tr>
<tr>
<td>Refinery</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>Gasoline Vehicle</td>
</tr>
<tr>
<td>Vehicle</td>
</tr>
<tr>
<td>Power Plant</td>
</tr>
<tr>
<td>Refinery</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Table 3.28 Estimated comparative air pollution from electric and gasoline powered vehicles in California in 1980.

Source: Edison Electric Institute (1979)

(1) The data in this table were given in grams per mile equivalent. As it is for comparative purposes only, it has not been converted to grams per km.
(2) The data for power plant and refinery have been obtained by considering gross emissions resulting from these sources in the course of producing the energy to power each vehicle type and converting them to a gram per mile equivalent to facilitate comparisons.

(3) Refinery and power plant emissions are based on the characteristics of oil refinery and oil fired plants in Southern California.

As can be seen, overall emissions for the electric vehicle are markedly less than for the petrol vehicle. The study concluded that automobile contributions to ground level pollutant concentrations (except $SO_2$) could be reduced by over 90% in the Los Angeles Basin, if electric vehicles replaced conventional automobiles. It points out that the degree and effectiveness of control over elevated stack emissions is currently much greater than that possible over mobile sources (Edison Electric Institute, 1979).

In general the widespread use of electric vehicles could make a substantial contribution towards mitigating urban atmospheric emissions though the total environmental impact of such a sweeping change would require a much deeper and broader analysis. The Federal Government of Australia in 1975 pointed out that any
environmental assessment of electric cars would need to include:

... social and economic factors as well as physical environment factors such as air pollution, noise and energy use.

Overall the available evidence suggests a limited role for electric vehicles in Australian cities before 2000. This evidence can be summarised as follows:

(1) The introduction of electric vehicles for large scale private use depends on a range of unknowns the most important of which relates to technological breakthrough.

(2) The actual market penetration process, assuming performance problems are overcome will be slow. This is related to:

(a) the limited ability of manufacturers to rapidly change production techniques, (b) the speed with which an entire urban infrastructure can be changed to cater for electric traction, and (c) the number of potential buyers of electric vehicles. A recent comprehensive survey of some Melbourne households revealed that only 11 per cent of the surveyed vehicles could be replaced by electric vehicles under present socio-economic and travel patterns (Graves, 1978). Another study
by the Bureau of Transport Economics, using a realistic set of assumptions for the current situation, estimated that only about 10 per cent of the total stock of cars and station wagons in Australia could be substituted for electric vehicles. Electric vehicles it gauged, would also need to compete with conventional vehicles for that 10% (NEAC, 1978).

Unlike the U.K. and other European countries where electric vehicles have been used for commercial purposes for many years, Australia has had little on-road experience with electric traction. In the U.K. about 50,000 commercial electric vehicles are in operation, primarily as delivery vans for bakers and milk vendors (CSIRO, 1979). By comparison Australia has about twenty (NEAC, 1978). The reason for this discrepancy and the general opinion that electric vehicles offer a more promising nearer term solution to transport problems in European cities lies in a land use difference: European cities are less sprawled and so are better suited to the limited range and power of electric vehicles in comparison to I.C.E. cars. Noise reduction benefits in these more compact and densely settled cities might also be more attractive. This is partly supported by the conclusions of a study in the U.S.A. concerning electric vehicle potential.

It is stated "Land use patterns in the U.S.A. make the limited range and slow speed of Ev's significant drawbacks." (Barron, 1978).
In general there is an observable difference in the perception of the electric vehicle in Australia compared to the U.K. This is demonstrated by the conclusions of a number of comparable studies of on-road electric traction in these two countries.

Firstly in Australia a major report to the Federal Government stated that:

"Given the uncertainty concerning when such batteries (capable of + 320 km) will become available, it is impossible to say when a marketable electric car will appear. Market penetration might initially be limited to urban light delivery vans followed by urban vehicles for the two-car household, but the penetration necessary to make a significant impact on total petroleum fuel consumption will require vehicles having favourable purchase prices and running costs compared with those of the IC engined vehicle". (ATAC, 1978).

In W.A. an advisory report to the State Energy Commission was similarly reserved in its assessment of the potential of electric vehicles. It stated:

"The economic and practical electric car has yet to be developed but overseas mass production of electric vehicles is likely to start in the period 1982-1985 and high volume production may well bring the costs down to a level which the private motorist can afford" (Energy Advisory Council, 1979).

It also pointed out the need for testing vehicles in W.A. and improving their performance characteristics for Australian cities.
In spite of the vehicle's short range and the higher initial cost of the total vehicle, there is evidence to suggest that on economic grounds because of the low operating cost, there will be markets where the vehicle will find significant sales. (Advisory Council on Energy Conservation, 1977).

The possible future role of the electric vehicle in Australia is outlined in a report by the Association of Consulting Engineers. They calculate that the electric car could not have a significant impact on the nation until about 1993. By the year 2000 electric vehicles could constitute between 18.5 and 42.0 per cent of all cars and station wagons in Australia. In cities they estimated that the portions might rise to between 24 and 54 per cent (NEAC, 1978). The range of these estimates indicates that there is a considerable uncertainty about the use of electric vehicles in Australia. All estimates are at this time largely speculative.

Conclusions to Electric Vehicles

In conclusion, it is difficult to predict when, to what extent and under what circumstances private electric vehicles will be used. Certainly the electric vehicle seems to offer the most decisive contribution to reducing oil dependence and emissions. In turn however it requires the greatest overall change plus a developmental and phasing-in period commensurate with what it has to offer. To the costs problems found in the previous advanced technologies
must be added the questions surrounding technological breakthrough, and a complete re-orientation of a major section of the economy.
As the term implies hybrid vehicle systems employ a combination of power sources. The rationale for these systems is to maximise the desirable characteristics and avoid the drawbacks of each type of power source in an interactive and complementary way. Hybrid vehicles are comparatively uncommon and have received the least development and testing of all the systems discussed to this point. Hybrid vehicles are omitted from many reports on potential transport options (e.g., ATAC, 1978; NEAC, 1978; Energy Advisory Council, 1979). However, in terms of the possibility of creating a radically different propulsion system, hybrid vehicles appear to offer the greatest scope.

Currently the most commonly investigated system involves some form of combustion engine, (internal or heat) linked with a battery-electric system. The aim of this system is to allow additional power for rapid acceleration and for cruising at higher speeds. The electric system provides peak power demands, while the comparatively small combustion engine is used to attain higher speeds (Shacket, 1979).

Hybrid systems which use a battery in conjunction with a heat engine may be divided into two classes; (1) series and (2) parallel.
The series system has the engine operating at a control speed and load close to the average power level of the vehicle. An engine which operates at a nearly constant load can be both simpler and more efficient, than one which has to meet rapid and variable load changes (Ayres and McKenna, 1972). The available power from the heat engine is converted to electricity via a generating scheme. When the heat engine power output is greater than the vehicle's requirements the net power output is used to charge the batteries. This stored electrical power is converted to mechanical power via an electric motor connected to the drive wheels. Regenerative braking is also used to store normally wasted kinetic energy as electric energy (Shacket, 1979).

In contrast the parallel system delivers power directly from the heat engine to the wheels via a transmission. In this system excess power is used to charge the batteries and the electric motor is driven by the heat engine to become a generator. When stopping, the electric motor is used for regenerative braking. By using this method it is possible to run entirely on one or the other system e.g. petrol in higher speed urban or country driving and electric use in the city or peak-hour travelling.

The two hybrid systems have received considerable attention to date because of their
potential for combining two already well developed techniques; the I.C.E. and the lead-acid battery. However, an innumerable range of combinations and permutations are possible. For example the primary energy conversion mechanism may be an I.C.E., an external combustion engine (e.g. Stirling or Rankine cycle engine), a gas turbine (Brayton-cycle engine) or a fuel cell. The secondary system or power storage method may be an electrical storage battery, thermal storage battery of flywheel (Ayres and McKenna, 1972).

Some examples serve to clarify the possibilities.

(a) "Minicar", developed by the University of Pennsylvania and Minicars Inc., as a commuting vehicle, utilises an I.C.E. and a DC electric motor with a small lead-acid battery. It has the capacity for conversion to a small steam engine as the prime mover (Ayres and McKenna, 1972).

(b) General Motors have developed a system known as "Stir-lec" which employs an 8 h.p. Stirling engine as a battery charger and a 20 h.p. AC induction motor as a drive unit. It achieved performance comparable to that of a small conventional vehicle (Ayres and McKenna, 1972).

(c) Daihatsu of Japan have developed a lightweight passenger automobile based upon a hybrid configuration
of zinc-air or iron-air batteries with high-powered lead-acid batteries. The iron-air system travelled 260km at 40km/hr. The zinc-air system achieved distances between 455 and 496km at 40km/hr depending on the vehicle size (Shacket, 1979).

(d) Electric passenger Cars Inc., San Diego, have developed a system called the Hummingbird Hybrid Mk I which uses advanced batteries (unspecified type) and an on-board gasoline generator to extend range. Performance is suitable for urban travel: Top speed, 105km/hr; 0-48km/hr in 10 s; range up to 241km at 56km/hr; stop-start range 161km (Shacket, 1979).

(e) Volkswagen have developed an advanced hybrid system using a 1600 cc petrol engine and DC shunt motor. It has been developed for use as a taxi and is fitted to a Volkswagen "Kombi" van. Its performance in the hybrid mode is less than a conventional van with a maximum speed of 104km/hr and acceleration of 0-100km/hr in 31 seconds. Fuel economy is 8.5km/l (24 m.p.g.) (Shacket, 1979).

Other types which have been tested include a diesel/lead-acid battery system by Mazda and a lead-acid/nickel-cadmium battery system by General Electric. (Shacket, 1979). Petrol engine/flywheel systems have also been tested but these are more suited to larger applications such as public transport.
(This is discussed in the following section on public transport technology).

The major advantages of hybrid systems can be listed as follows;

(1) They are regarded as unlimited range vehicles when a combustion engine is employed. Electric/electric systems however suffer from similar range limitations as ordinary electric vehicles (Shacket, 1979).

(2) Performance characteristics approach more closely these of the conventional vehicle, acceleration and high speed capabilities being the most important parameters.

(3) Some alternative combustion systems are more suitable to hybrid vehicle operation than as sole power plants, e.g. Stirling engine. This gives added potential for improved fuel economy and emissions.

(4) Hybrid vehicles offer potential for considerably improving fuel economy over that of ordinary vehicles, i.e. fuel economy in terms of liquid fuel energy expended in travelling a given distance. This excludes the associated electric energy use. In this way they offer some liquid fuel conservation potential.

(5) Hybrids normally use small internal combustion
engines including diesels, or other alternative power systems such as Stirling engines. These are frequently operated at constant speed and load. The potential to reduce emissions using these systems is thus greater than in a conventional system.

The energy use and emissions characteristics of hybrid vehicles are not widely documented although the envisioned improvements in these two areas are the prime motivation for their development (Automotive Engineering, 1976). Available data does indicate that some improvements are being realised but the literature suggests that more work is probably required to reap large fuel savings.

The Hybricon Centaur developed by Hybricon Inc., California uses a normal 32 h.p. ICE and a battery-electric system. It has achieved a combined range of 257km on 15 litres of petrol which is equivalent to a liquid fuel economy of 17.1km/l (48.3 m.p.g.). However the vehicle is mini-sized (the original vehicle was a Honda 600 sedan) and weighs only 990kg. Some conventional small cars are capable of similar or better performance and fuel economy. (Shacket, 1979).

Other heat/engine electric systems have reported fuel economy gains in the range of 30-100 per cent compared to conventional systems of identical
weight and performance. The magnitude of the improvement tends to increase with larger vehicles such as delivery vans, large passenger cars and buses. These improvements have been found to occur while meeting 1976 U.S. Federal emissions standards with the use of catalytic converters (Automotive Engineering, 1976).

Despite these advances there are a number of important technological problems which require solving before most hybrid systems could be considered for general production. Some of these relate to drivetrain performance during regenerative braking, design of the entire drivetrain network to fit a commercial vehicle, (with due consideration to access, servicing and safety) engine lifetime under operating conditions peculiar to hybrids and supplying power to vehicle auxiliaries (Automotive Engineering, 1976).

The most important technological problem however, which bears upon the hybrid vehicle's commercial competitiveness, is its complex control system. This determines the vehicle's driveability and its consumer acceptability. In general private vehicle applications of hybrid systems have been found to offer insufficient improvements in fuel economy over the comparable conventional system to warrant their added cost and complexity. Hybrid systems would in general, be significantly more
expensive to produce than pure combustion or electric systems (Automotive Engineering, 1976).

Conclusions to Hybrid Vehicles

In conclusion, hybrid vehicles are farther from achieving widespread acceptance and usage in urban transport than are pure electric or alternative pure combustion systems. It is impossible to forecast to what extent they might eventually be used in private transport. At present they appear to be better suited to innovative public transport systems are are achieving greater acceptance in this field. In an advisory report to the U.K. Department of Energy hybrid vehicles were summarised thus:

"Some development has been attempted of Hybrid Battery Electric Vehicles. However cost, weight and formidable engineering problems make it unlikely that this type of vehicle will be further developed despite its potential advantages."


In Australia the potential advantages of hybrid vehicles in terms of energy savings and air pollution control have been recognised (NEAC, 1979). However in their present state of development the National Energy Advisory Council (1979) concluded that hybrid vehicles could not compete economically with conventional engines mainly because they require complete engine systems with the associated complex controls.
3.2.3 PUBLIC TRANSPORT TECHNOLOGY

3.2.3(a) Introduction

To this point the discussion has been centred upon improvements and changes in private transport with a view to reducing energy consumption and emissions. The considerable attention given to advances in private transport technology in the literature reflects the very large contribution this sector makes to urban energy demand and air pollution problems. Very much less attention is given to ways of improving the energy efficiency and emissions characteristics of public transport partly because in most cases its total energy demand and emissions contribution in cities is comparatively small and partly because its energy efficiency is relatively high especially if well patronised. Most current improvements to public transport are nevertheless geared to improving its inherent energy efficiency. This is especially true of electrified systems.

It is also significant that the potential of public transport improvements to make important contributions to energy savings and air pollution abatement, is usually considered low. In Australia a Federal Government advisory report suggested that in the next 5 years, modal shifts from cars to public transport could only be expected to save 0.7 percent of total transport energy, and in 15 years only about 0.8 percent (ATAC, 1978). This issue however, relates to more than just modal efficiencies and is therefore discussed more fully in Chapter 5.
The technological improvements in public transport modes appear to be directed more to improving the attractiveness of public transport by making it faster, more convenient and comfortable; essentially, in making it a more glowing competitor to the private car. One study summarises the situation succinctly when it states:

...if the public transport facilities are to be used...then a "solution" - approach demands that these facilities give a quality of service which will be as nearly compatible as is possible, with that provided by the private vehicles they are intended to replace...- hence the need for new improved transport techniques (O'Flaherty, 1972).

In this way public transport's major potential to reduce energy use and emissions lies not so much in its own inherent advances in energy efficiency and emissions characteristics, but in its ability to replace some private vehicle travel.

To this end research is being carried out in many parts of the world especially Japan, Europe and the U.S.A. into upgrading existing conventional public transport services such as buses and trains, and into producing more technologically ambitious and sophisticated systems such as the Bay Area Rapid Transit system (B.A.R.T).

Examination of the reported material on this subject suggests two distinct types of development; (1) variations on conventional public transport systems - near term options, and (2) entirely new concepts in public transport - long term options. The first type are those
which tend to invoke the conclusion that important improvements or additions to established public transport systems can be made without great technical, economic, social or political obstacles, e.g. Light Rail Transit (L.R.T.) developments or alternative bus systems. The second type of developments are characterised by technological feasibility, but engender a more reserved, appraisal because of their "space-age" image and the immense social, economic and political barriers which would accompany their implementation, e.g. a complex network of personalised rapid transit (P.R.T.).

This section is a brief overview of some of the current endeavours in the field of public transport technology, based upon near and long term options.
3.2.3(b) Variations on conventional systems - Near term options.

(i) Introduction

A wide range of options for upgrading conventional systems of public transport are being pursued throughout the world. The immense variation in detail of the individual systems is not considered in this overview, but rather, the fundamental approaches are examined with particular reference to their likely impacts upon energy and emissions.

Experimentation is occurring in most modes of public transport in an effort to perfect more competitive systems than are presently operating. Ferries appear to be the notable exception. The introduction of the hydrofoil and hovercraft in various parts of the world to improve speed and comfort for commuters seems to be the only major advance to date. In contrast, buses and more particularly electric rapid rail transit are receiving much attention. Electric rail transit has received a great development impulse not only from the rising price and scarcity of oil, but also from administrative anxiety in many parts of the world over probable congestion levels if road traffic continues to grow as projected (Pole, 1973).

The major developments in conventional bus and rail transport can be summarised as follows:
Buses
* Dial-a-ride bus schemes (demand responsive systems)
* Battery operated buses
* Battery-trolley buses
* Electric busways
* Increased capacity buses, (e.g. articulated buses)

Rail
* Electrification and upgrading of duo-rail systems
* Heavy Rail Systems e.g. BART and The British Rail
  Advanced Passenger Train (A.P.T.)
* Light rail transit and trams
Dial-a-ride or dial-a-bus schemes have been examined in a number of cities, including Adelaide, as a means of providing a suitable public transport service to very low density suburban areas (Pushkarev and Zupan, 1977). Regular fixed route bus services in such areas tend to be wasteful of energy and other resources because total demand for mobility per hectare of urban land is too low and spread irregularly throughout the day.

These schemes involve a relatively small degree of technological innovation, the major changes being most often limited to a reduction in the size of the vehicle used (vans are commonly employed) (Fels, 1974), the addition of radio communications similar to that of a taxi service and in some instances computer controlled despatching may be considered (Arrillaga, 1975).

The aim of dial-a-bus schemes in the context of this study is three fold. Firstly, they are intended to provide an alternative to the private car in areas where conventional bus systems are inappropriate. Secondly, by providing this service, dial-a-bus schemes offer the potential for energy conservation and emissions reduction by replacing some private car travel in areas where car dependency is high. The provision of public transport services in fringe areas where they are unlikely to be well patronised is also based upon some notion of social equity.
Thirdly, by using a smaller, more energy efficient technology (e.g. vans) on a demand-activated basis, dial-a-bus schemes have been seen as offering the potential for improving the inherently poor fuel efficiency of public transport services in low density areas.

In practice these schemes have generally fallen short of their original objectives. Examination of some relevant data shows what has occurred.

In a comprehensive energy analysis of various U.S. urban transportation systems, two dial-a-bus schemes were evaluated; one based upon a petrol driven van and one upon a diesel powered van. They were compared to two different weight classes of private vehicle: 1635 kg (3600 lb) and a 910 kg (2000 lb) vehicle. Using certain occupancy assumptions for each system, based upon empirical evidence, Table 3.29 compares the results of this analysis on a seat kilometre and passenger kilometre basis. The table shows clearly that on a seat kilometre basis there is an insignificant difference between the larger car and the petrol dial-a-ride scheme, whereas the diesel scheme does offer some energy advantage on this basis. This parameter is essentially a measure of the technical efficiency of the mode, and is insufficient to describe overall energy efficiency. When loadings are taken into consideration the energy efficiency of the dial-a-ride scheme is found to be generally poorer than the automobile.
Table 3.29 Comparative energy assessment-dial-a-ride schemes with conventional automobiles in the U.S.A.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Automobile</th>
<th>Dial-A-Ride</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1635 kg</td>
<td>910 kg</td>
</tr>
<tr>
<td>Vehicle Capacity (seated passengers)</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Assumed Average Occupancy (passengers per vehicle)</td>
<td>1.9 (30%)</td>
<td>1.9 (50%)</td>
</tr>
<tr>
<td>Energy (MJ) Consumed per Passenger Kilometre</td>
<td>4.25</td>
<td>2.19</td>
</tr>
<tr>
<td>Energy (MJ) Consumed per Seat Kilometre</td>
<td>1.33</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Source: After Fels (1974).

The fundamental problem of such schemes is not the technical efficiency of the vehicles used, but of the loadings attained. Fels (1974) concluded that, in spite of the personalized service which these systems offer, they simply do not guarantee energy savings over the automobile unless their average occupancy is considerably higher.

A further study from the U.S.A. based upon data from ten different cases, shows this low occupancy problem more clearly by comparing dial-a-ride schemes with three other modes of transport. Table 3.30 summarises these results. This table shows that on average, Dial-a-ride
schemes are about 2.4 times less efficient than the automobile in terms of energy expenditure per passenger kilometre. However, they have the potential to be 2.6 times more efficient if high loadings could be achieved. It should be noted that it is not valid to compare the energy efficiency of a conventional bus operating in areas of high public transport patronage (as shown here) with that of dial-a-ride operating in marginal areas. It has been included to demonstrate that dial-a-ride schemes have been unable to match typical bus efficiencies.

Table 3.30  Energy efficiency of Dial-A-Ride compared to other modes of Passenger Transport.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Seating Capacity</th>
<th>Occupancy</th>
<th>Fuel Economy km/l (m.p.g.)</th>
<th>Passenger KM's per Litre (per gallon)</th>
<th>Maximum Efficiency Passenger KM's per litre (per gallon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automobile</td>
<td>5</td>
<td>2.2</td>
<td>4.9 (13.8)</td>
<td>10.8 (30.5)</td>
<td>24.5 (69.1)</td>
</tr>
<tr>
<td>Taxi</td>
<td>4</td>
<td>0.7</td>
<td>4.9 (13.8)</td>
<td>2.8 (7.8)</td>
<td>19.6 (55.2)</td>
</tr>
<tr>
<td>Dial-A-Ride</td>
<td>19</td>
<td>1.47</td>
<td>3.3 (9.4)</td>
<td>4.6 (13.0)</td>
<td>63.0 (178.0)</td>
</tr>
<tr>
<td>Conventional Bus</td>
<td>50</td>
<td>15.00</td>
<td>1.7 (4.8)</td>
<td>25.5 (72.1)</td>
<td>87.2 (246.2)</td>
</tr>
</tbody>
</table>

Source: After Arrilaga, 1975.
Another factor which must be considered in assessing the energy conservation potential of these schemes is whether the kilometres travelled are actually replacing car travel or whether the dial-a-ride scheme is deriving its patronage by inducing demand. If the latter applies, there is no net-saving in energy, but rather a net-increase. In this case the benefit of the scheme is in its social role of meeting latent demands for mobility which would otherwise be unfulfilled.

The ability of demand responsive systems such as dial-a-bus to reduce gross emissions in urban atmospheres is inextricably linked to their ability to reduce energy use which has already been shown to be poor if not counter-productive. Similarly for emissions, private vehicle travel must be reduced to some extent to obtain meaningful reductions, and for this reason it is unlikely that such systems will have anything to offer.

A report by the Urban Institute in the U.S.A. addressed itself to assessing the potential of higher occupancy travel to simultaneously reduce emissions and fuel consumption. It pointed out that although 80 percent of all kilometres travelled in the U.S.A. are by private cars, 58 percent of these are for family business, education, social activities and recreation and that occupancy ratios for these purposes are already greater than two. It concluded that in the future;

It is doubtful that transit or paratransit services (such as dial-a-ride) can effect savings in pollution or fuel consumption per passenger trip
for low density trips; if such trips (in the categories mentioned) are to be made, the private automobile may well be the most efficient mode for the purpose (Krzyczkowski, et al, 1974).

Based upon present operating experience in the U.S.A. the same report disclosed that currently dial-a-ride systems produce three times as much congestion, energy use and pollution as private cars providing similar services.

In general, dial-a-ride systems in the U.S.A. have not met with encouraging results. A report which dealt with the problem of providing viable transit strategies for suburban communities summarised these systems with the following statement;

Dial-a-ride cannot generally be justified as a transit strategy on either productivity or fuel efficiency grounds...Actual performance would be about...eight to fifteen passenger miles per gallon. This range is typical of that by automobiles on short trips (Hirst, 1974). Given that not all dial-a-ride passengers are displaced from automobiles, one must conclude from a narrow fuel conservation standpoint that dial-a-ride buses are best left parked in the garage (Piper, 1977).

An overview of dial-a-ride systems in Great Britain concluded that in some cases, under British conditions, they can provide a superior service to conventional buses. In terms of costs however, they cannot compete with fixed route services, and for this reason are unlikely to become widespread (Grimmer, 1978). A comparative assessment of demand and fixed route bus services in the U.K. found that both types are equally attractive to passengers but that demand responsive systems operated at lower overall efficiency (Tunbridge, 1978).
Conclusions to Dial-A-Ride Schemes

In conclusion, it appears unlikely that technological improvements to bus services in the form of dial-a-ride systems will make any significant contribution to energy conservation or lower emissions. The development of more advanced methods of control such as computerised despatching are being considered for both conventional bus systems and dial-a-ride systems in an effort to reduce energy usage and overall costs (Knox, 1979; Arrillaga, 1979). The foregoing evidence however would suggest that the fundamental problem of providing public transport in suburban areas is not technological. Rather, it indicates that the low density nature of most suburban areas makes the private car an indispensable part of behaviour and lifestyle, and precludes the success of any alternative transport methods.
(iii) Battery Operated Buses

The use of battery powered vehicles in public transport suffers from many of the technological limitations outlined in the discussion on electric vehicles, although performance standards are not as stringent. Similarly the rationale for their development is linked to the need to move away from a system of transport wholly dependent upon oil and to avoid the noise and air pollutants emitted by diesel buses particularly in city centres.

Battery buses are particularly suited to inner area or C.B.D. use where rapid acceleration and range limitations are not severe problems, and where significant environmental advantages could be reaped from a reduction of noise, aromatic emissions and smoke.

Currently in France, there are a number of battery bus systems operating. One system in Tours has met with considerable success. It operates on a 7.2 km route through the central city with a terminus at the railway station where battery recharging occurs. Maximum speed is between 45 and 50 km/hr but this is not a problem in city use. The system operates at a comparatively high energy efficiency of approximately 0.30 MJ per passenger km.\(^\text{(1)}\) (Edison Electric Institute, 1979) (See Table

\(^{(1)}\) Calculated from data given in the reference.
in previous section). Its major drawbacks are related to low battery life (high operational costs) and maintenance problems. Lowering operational costs for electric buses is primarily dependent upon improving batteries which represent 20-25 percent of the total cost of this French system, compared to 5 percent for electricity.

Electric buses are also being experimented with and used on specific transit lines in the U.S.A. and Germany. The systems used to date have been successful in satisfactorily providing replacement services for diesel buses on short haul, feeder and shuttle operations. Range limitation is currently about 80 km (Shacket, 1979). In Japan two 80 passenger battery buses have been in commercial operation for some time. The City of Osaka in which they operate reports however that they cost about three times as much to run as a diesel powered bus (Chartered Institute of Transport, 1974). Britain is also experimenting with battery operated buses, and expects to be able to match the operating costs of diesel services. Buses range from 50 passenger capacity in Manchester (Chartered Institute of Transport, 1974) to 26 passengers in Crompton (Pole, 1973).

Conclusions to Battery-Operated Buses

The technology and operational efficiency of battery operated buses has been largely proven. It remains for technological and production advances in battery
systems to make battery buses suitable to a wider range of operations at a competitive price compared to diesel systems. However, it is unlikely that the substitution of battery buses for diesel buses will effect significant reductions in overall energy use and emissions by attracting people from their cars. The major benefits will probably be seen in cost savings and in making the public transport system less vulnerable to any sudden dramatic cuts in oil supply. City centres would benefit environmentally from a switch to battery buses. The total fuel savings and emissions reductions in Australian cities from a widespread switch to battery buses would however be comparatively small. If such a shift included replacing trains a net fuel penalty could be incurred. This is developed further in Chapter 5.

The Director General of Transport in Perth points to the fundamental limitation of technological changes in buses at the present time when he states:

Possibly different forms of power unit will also be used (for example, electric with a mixture of overhead powerlines and batteries) but these will have absolutely no influence on the usefulness of buses to passengers as a means of getting around (Knox, 1979).
(iv) Battery-Trolley Buses

The advantages and limitations of battery operated vehicles have been discussed. Trolley bus systems which operate entirely off electric current supplied by overhead wires provide a small degree of freedom from oil constraints and price rises and generally produce less environmental impact than diesel buses. However, their major disadvantage is route inflexibility in being constrained to an unsightly network of overhead wires and for this reason they have generally been removed in favour of diesel buses.

Combination battery and trolley bus systems have been investigated to simultaneously overcome the limitations of both systems. The principle of this method is to provide a limited network of strategically placed overhead wires (about 15% of the route) which serve to power the vehicle and recharge the batteries at predetermined intervals. For the remainder of the route, the bus is free to operate on battery power which overcomes the route flexibility problem (Weeks, 1978).

The feasibility of such a system for 80 passenger double-decked buses was investigated in the U.K. The study concluded that this type of system could be made to operate in most towns which currently have an urban bus system. This could be done with minor changes to service characteristics, and with significant environmental benefits in terms of noise, smoke and vibration reduction (Weeks, 1978).
The major drawbacks of the systems investigated were their high capital costs and running costs and high primary energy consumption. Compared to a system based on conventional oil, the battery-trolley bus system would consume twice as much primary energy. It concluded that the battery-trolley bus system would have the same primary energy consumption as that of a comparable diesel bus system based on "syncrude", although the fuel cost for the battery-trolley bus would be about half. The major advantage of the system would be its avoidance of oil scarcity and price rises, and hence, its potential as an investment in the future security of public transport (Weeks, 1978).

Conclusions to Battery-Trolley Buses

Similar conclusions can be drawn regarding the energy conservation and emissions reduction potential of this system as those concerning battery operated buses. In addition it is also significant to note that the introduction and widespread use of either a battery, a battery-trolley or a pure trolley bus system would embody considerable time lags while conventional systems were replaced.
(v) **Electric Busways (Dual-mode operation).**

The concept of electric busways as a form of dual-mode transport has been investigated in detail in Perth (Elliott, 1979). Dual-mode transport (D.M.T.) seeks to combine the flexibility characteristic of present diesel bus services with the advantages of segregated corridors used by railway services. In its most advanced form, a dual-mode bus would pick-up and set down passengers on ordinary streets, and then link-up with an Automated Guideway Transit system (A.G.T.) where the driver would leave the bus and allow it to continue its journey under automatic control. Such a system could be propelled by batteries or a conventional diesel engine in the free-mode and electricity in the guided mode. If batteries were used, recharging in the A.G.T. mode could be facilitated.

A more modest system which has been suggested for Perth (Elliott, 1979) would involve essentially the same principle except that manual control would be maintained in the segregated right-of-way during electric operation. One of the most important features of the proposed system is seen to be the elimination of steps and thus boarding difficulties for those who are in some way physically disadvantaged (e.g. handicapped persons, elderly people, mothers with prams etc.). This would be achieved by designing buses and bus platforms (as opposed to bus stops) with matched heights plus laterally guided control and air-bag suspension, to ensure a perfect alignment between the bus floor level and platform level.
It is difficult to assess the impact of such systems in terms of energy and emissions, because virtually none exist. Consequently no definitive statement of energy usage was given, but it was suggested that an electric busway compared to an equivalent train system would be better for station spacings less than 2.81 km, but worse above this distance. In Perth, average station spacing is 1.2 km, so that energy savings might be expected if electric busways replaced train services.

In terms of total energy use, the difference between an electric busway and electric rail may be small. The most significant factor in both these systems is that they would not be dependent upon oil. In the case of the electric busway this would only be completely true if the buses used in street running were battery operated.

Conclusions to Electric Busways

As with the other systems discussed, the energy conservation and emissions reduction potential of this concept would depend upon its attractiveness to the public and thus ultimately upon its patronage levels. The author of the studies in Perth points out that the advantages of the electric busway concept over a comparable rail system are largely theoretical. It is also pointed out that experience around the world has shown that proposals for busways in favour of rapid rail have been unanimously rejected by the public at large. Whether such aversions
are justifiable or fallacious is largely a matter of conjecture because there are no operational schemes to testify to the performance of the busway concept. In view of the already immense problems involved in initiating modal splits in favour of public transport and the already proven performance of electric rail systems, Governments would be justified in viewing with caution any proposal for new systems which could further alienate people from public transport. This would be especially true if only minor differences in the overall energy use of the systems being considered could be expected.
(vi) **Increased Capacity Buses**

For heavily used routes during peak hour operation, where access to a railway service is not available, it is desirable to increase the capacity of individual buses. This both saves on operating costs in terms of drivers and on energy consumption and emissions.

Only two options exist for increasing the capacity of buses operating on public roads, and these both have well defined limits. Firstly, double-decked buses can be used as in London and Sydney and secondly, articulated buses which are used in overseas cities (Chartered Institute of Transport, 1974) and which have been recently introduced in Perth.

The ability of such technical innovations to effect significant fuel savings and emissions reductions depends almost entirely on the intensity of their usage over a limited period of the day (usually morning and evening peak periods). In turn, the degree to which such systems are patronised depends largely upon the speed and quality of service which they provide. Unless provided with separate lanes on highways or entirely segregated busways, such increased capacity buses still suffer from being unable to avoid the congestion characteristic of peak periods.

The degree to which the presence of segregated corridors for public transport affects patronage is
demonstrated by data from Perth. The data show that in those corridors with railway and bus services a significantly higher percentage of C.B.D. oriented journeys-to-work are by public transport e.g. the figures for Midland, Fremantle and Armadale are 54, 45 and 52 percent respectively compared to an average of 39 percent for the whole of Perth (Wildermuth, 1977).

It is also worthwhile to note that a survey carried out by the Western Australian Institute of Technology pending closure of the railway service in the Fremantle Corridor suggested that 73 percent of railway patrons would use the replacement articulated bus service all the time. The rest would partly or completely change to private transport. Such estimates would need to be verified by actual survey work.

Thus where energy conservation and emissions reduction are a primary objective, and where these depend upon attracting private car users, the use of L.R.T. or conventional electric trains should also be investigated. These systems have been shown to be more energy efficient, (see Chapter 5), offer a high level of service in peak hours where increased capacity is required, and are free of congestion problems, which makes them attractive to commuters.
Rail

(vii) Electrification and Upgrading of Duo-Rail Systems.

The major near term options for developing the energy conservation and emissions reduction potential of urban rail systems can be discussed under this single heading. Duo-rail systems can be approached by dividing them into two main categories;

(1) Heavy rail systems, and
(2) Light rail transit (L.R.T.) and trams.

The first category consists of conventional train systems and the second category comprises conventional tram systems, together with the comparatively new concept of L.R.T. which constitutes a transitional or 'intermediate technology' between the two.

Monorial systems which have been considered and introduced in some countries (e.g. Japan and Germany) as a means of improving rail services, are not generally regarded as an important near or long term option in rail transport. This is chiefly because innovations in light weight duo-rail systems make the latter more attractive, particularly, from the point of view of switching and safety arrangements (O'Flaherty, 1972; Hebert, 1976). Monorails generally offer no advantages over duo-rail from a construction or environmental standpoint (O'Flaherty, 1972). This section reviews the potential of duo-rail systems for conserving energy and reducing emissions and attempts to highlight some of the important technological developments in both categories.
Heavy Rail Systems

Electrifying and upgrading conventional heavy rail systems involves a minimal amount of technological innovation and is a commonly employed method for maximising the utility of existing public transport facilities or extending them. Within this general approach there exists a considerable range in the quality and sophistication of electric rail systems. The choice of system largely depends upon how much capital is available for investment in public transport.

The technology of electric rail systems is already proven and no detailed discussion is given here of the technical differences between the systems available. The major difference is seen in how the power is provided and whether the system is automated. The two major forms of power supply are overhead wire systems or third rail systems. There is some debate about the relative merits of these systems in economic and energy terms (Ogilvie, 1978). The aim here is to provide an overall view of the possibilities of these systems in contributing to energy conservation and air pollution abatement.

As with all the improvements discussed so far, the fundamental aim of rail electrification or extension is to provide an attractive alternative to the private car by providing a modern image to an old type system (Loder, 1979). Its success or failure in this regard largely determines its contribution to energy conservation and emissions reduction. Many new systems are designed
expressly to do this. For example Tyneside in Britain has designed a new rapid transit project expressly to attract the urban motorist away from the car in an effort to reduce congestion and pollution (Pole, 1973). This involves the use of interchange complexes at rapid transit stations to provide easy access from one form of transport to another. This is designed to encourage the development of a fully integrated city-wide public transport system.

This modern image must however provide more tangible benefits. In competing with the private car, rail, like other public transport systems is benefited by any time advantages it may offer over private vehicles. It has been suggested that on the whole, passengers will not be diverted from car to train unless travel time is saved (O'Flaherty, 1972).

The time factor in terms of actual train speed and frequency of service, was particularly important in designing the Bay Area Rapid Transit system (B.A.R.T.) which operates in San Francisco, California. This system is one of the most advanced heavy rail systems in use and was introduced to reduce traffic congestion and pollution (Pole, 1973). It derives its power from a third rail and so has no overhead wire network. It is operated automatically from a central computer, but has manual override facilities on board if required (Shacket, 1979). BART is designed to maintain schedule speeds of between 70 and 80 km/hr, station stops of 20 seconds, and with a
maximum speed of 130 km/hr. In peak periods, service frequency is 90 seconds, and during the remainder of the day does not exceed 20 minutes (O'Flaherty, 1972).

In general, electric trains offer time savings over their diesel counterparts, and when either is operated on a full or part express basis during peak hours, they usually offer time savings over comparable road based systems. However, time savings also depend considerably on land use as in most public transport questions.

The time factor alone has in most cases proven inadequate to explain sustained increases in patronage which have occurred after conventional railways have been electrified. Instead the phenomenon is termed "the spark effect" (Personal Communication, Commissioner for Electrification, Qld. Railways) and is probably attributable to a combination of improved commuting time and greater comfort which usually accompanies electrification. The human factor in electric trains is a substantial consideration in their greater patronage, more so than any other form of public transport.

The attractiveness of rapid rail as a means of encouraging greater public transport use is partly attested to by the number of cities around the world which are considering some form of electric duo-rail system. In 1972 this stood at sixty-two including Brisbane (O'Flaherty, 1972). In 1979 in excess of fifty cities had recently
upgraded or planned to upgrade their urban rail systems (F.O.R., 1979).

The effectiveness of electrified and upgraded railway systems as has been said, depends on how well they can attract car patrons away from their vehicles. The magnitude of this change is the main determinant of the energy conservation potential of such systems. However, energy savings also depend on the system's inherent energy efficiency which is reflected by the amount of energy expended per passenger kilometre. Because of the wide range of different systems and operating conditions including land-use patterns, it is not possible to give a definitive statement of energy efficiency which will be true in every instance. Each particular system must be analysed separately as has been done for Australian cities (in Chapter 5). All the assumptions used in calculating such efficiencies must also be clearly stated. The importance of this is also explained in Chapter 4.

Similar studies in other countries show considerable variation according to how the data are derived. In the U.K., one report shows that a 12 coach electric train set operates at an average of 0.20 MJ per passenger kilometre, whilst its diesel counterpart operates at 0.45 MJ per passenger kilometre. Diesel buses are shown to operate at about 0.65 MJ per passenger kilometre (Chartered Institute of Transport, 1974). This however conflicts markedly with other values which show that diesel buses in the U.K. operate at 1.10 MJ per passenger kilometre with
diesel and electric trains operating at 2.62 and 2.35 MJ per passenger kilometre respectively (Maltby, 1978). This latter data includes inter-city trains which are inherently more energy consuming, because of their higher speeds.

In the U.S.A. diesel buses are shown to be less energy intensive than diesel trains, (Ross and McGowan, 1972; Rice, 1972) which is considered to be the general trend in those Australian cities where diesel bus and rail services operate.

The literature indicates that there is some variation in the relative efficiencies of diesel trains versus buses, and in some cases electric trains may be less energy efficient than buses. For example, in the case of BART an energy efficiency of 1.6 MJ per passenger kilometre has been estimated, whereas for urban buses an average of 1.5 MJ per passenger kilometre is likely (Fels, 1974). Considering however that these estimates are based on fairly broad occupancy assumptions, this difference may not be significant.

These examples highlight the problems of comparing modal efficiencies. Precise knowledge of how these calculations have been performed and exactly what they refer to is required before specific comments can be made. Often such information is not supplied.
Despite the express limitations of these modal efficiency comparisons, it can be concluded with reasonable certainty that electric trains are less energy intensive than their diesel counterparts in performing an identical task.

All the efficiencies given so far are based upon existing systems using current technology but there is further scope for reducing energy consumption in electric rail systems, and this is being actively pursued especially in the U.S.A. Some of this research revolves around the use of flywheels which store a portion of the vehicle's kinetic energy during braking which would otherwise be lost as heat. The stored energy is used to supplement energy requirements during acceleration. Testing of conventional electric rail cars in New York City fitted with flywheels has shown a 30 percent reduction in energy consumption, and it has been estimated that if all 7,000 cars were fitted with flywheels, U.S.$20 million per annum could be saved in electricity consumption (Environmental Science and Technology, 1976).

The U.S. Urban Mass Transportation Administration is also developing two new rapid transit cars which will employ an advanced energy storage/flywheel propulsion system. These have been termed Advanced Concept Trains (ACT-1). It is believed that the state-of-the-art in rapid rail transit could be significantly forwarded by these developments which are designed to substantially reduce power consumption and operating costs. By substantially reducing energy usage and costs, transport
authorities might gain the necessary lee-way to put more trains in service, and to air-condition existing non-air-conditioned cars without significant increases in operating costs (Environmental Science and Technology, 1976). This in turn might improve service attractiveness and result in higher patronage.

Other technological innovations being investigated to improve the energy efficiency of electric trains include the application of thyristors, (Foley, 1974) and regenerative choppers (Environmental Science and Technology, 1976). The latter concept is similar to regenerative braking which puts energy back into the batteries in an electric vehicle, as the vehicle is slowing down. Regenerative choppers put energy back into the third rail, but this is only advantageous if a second train is in close proximity or when a load is on the line.

It is clear that the energy efficiency factor in electric train systems is an important criterion, particularly in considering plans for new developments when it is desirable to use the most up-to-date technology available. It has been suggested however, that energy efficiency alone is perhaps of less importance than the question of fuel supply per se. This is based upon the premise that overall, there is little difference in total energy consumption between electric rail traction and diesel traction (Advisory Council on Energy Conservation, 1977), although the potential exists to improve electric rail performance by more efficient power generation and
the methods described. Foley (1974) suggests, that in pure energy terms the diesel engine has a conversion efficiency from 25 to 35 percent, and that if one takes into account power station efficiency, the overall efficiency of electric traction is only 15 to 25 percent, thus giving the diesel an apparent advantage. However, he further points out that diesel fuel will be subject to world oil price jumps or supply cuts in the case of import dependence, whereas electricity which can be generated from a number of sources within most countries, is not subject to the same disadvantages. This security and sustanability advantage of electricity applies not only to rail systems, but equally to all forms of electric transport. The idea of electrifying transport systems as an insurance policy against the vicissitudes of the world oil situation has been widely expressed (Advisory Council on Energy Conservation, 1977; Hendry, 1974; Pole, 1973).

With specific reference to railways however, Foley makes the following statement:

Finally there is the long-term future. We will be moving out of the oil era before the turn of the century. We will face during the coming decades the increasingly difficult problems which will occur as world oil supplies become tighter. A rail network capable of operating without dependence on oil would seem a necessity for this time. In the face of this one over-riding consideration - that there should be a transport network which could service the whole country in the case of interruption of oil supplies - there is an unanswerable case for the electrification of all but the most lightly-used branch lines.

The point about such a decision is that it plays safe with the country's future. If those optimists who still deny any possibility of oil scarcities are right, there will be no waste of oil; we will be able to burn it in the power
stations to power an electrified network. If the pessimists (who call themselves realists) are right, there is going to be nothing we can do with our diesel locomotives in the absence of fuel to drive them. A fully-electrified rail network in the end is a question of national security (Faley, 1974).

In Australia however, recognition of this idea has not yet fully permeated transport planning thinking despite the decision by Brisbane to electrify its rail system and the recent Eastern Suburbs electric rail extension in Sydney. For example, Knox (1979) states that:

It is extraordinarily unlikely that there will be so little oil and it will be so expensive, that rail cannot run on it.

Instead, studies in Australia refer to the problems of assessing the relative efficiency of diesel and electric systems as a major issue and overlook the energy security aspects (ATAC, 1978). The possibility that diesel systems with technological improvements might be as efficient as electric systems is suggested (Knox, 1979). It is also stated that the capital costs of electrification schemes are a large disincentive, and that on economic grounds they could only be considered justifiable in metropolitan and suburban areas (ATAC, 1978). In Perth, the case for electrification is seen as being particularly weak in financial and energy terms, (Knox, 1979) although there is some disagreement over this judgement (P.O.R., 1979; Chartered Institute of Transport, 1974).
Conclusions to Heavy Rail Systems

In conclusion a number of points can be made concerning the potential of electric and upgraded heavy rail systems to conserve energy and reduce emissions.

(1) The main determinant of this potential is their patronage levels, particularly how many drivers can be attracted from their vehicles. Widespread technological developments designed to improve conventional rail systems in the fields of comfort, noise, speed, safety and economy of operation are directed towards making rail travel still more attractive to the motorist.

(2) In considering technological innovations in electric rail systems, human factors such as comfort and convenience which make rail travel attractive, are perhaps of more importance than those designed specifically to improve technical efficiency.

(3) As energy conservation depends mostly upon maintaining or increasing the passenger task, the role of land use which facilitates rail travel also becomes highly relevant; this will be pursued later.

(4) Electric rail systems employ proven technology and further technological innovations are available now.

(5) In the event of greatly increased demand for public transport, the ability of rail systems to quickly move large numbers of people is well documented. Loading flexibility is an important element in an
uncertain future. For example, recent oil shortages such as those in California meant that BART was packed to capacity.

Hendry (1974) concludes that because rail based public transport has these features, it is the only possible solution to the transport problem in large cities.

Pole (1973) in speaking of British cities states:

...rail rapid transit should form the backbone of all new urban passenger transport plans, and it should be firmly backed up by bus, taxi-bus and internal combustion engine or electric car loan schemes to provide the necessary flexibility for outlying low-density areas.
(2) **Light Rail Transit (LRT) and Trams**

Light Rail Transit.

Light rail transit or light rapid transit as it is jointly known is an electrically propelled medium to high capacity duo-rail system. Light rail transit is grouped with trams because both systems are designed for on-street use. Trams are generally exclusive in their on-street operation, while LRT systems usually have a combination of on-street and separate right-of-way operation. In this sense LRT systems incorporate the characteristics and advantages of trams with the capabilities of conventional train systems in a single mode of transport.

L.R.T. has a number of other advantages. In operating in city traffic, pedestrian malls (as is done in Europe) and residential streets, LRT must conform to higher performance and environmental standards than conventional trains. In general LRT systems have greater acceleration and braking capabilities and lower vibration and noise characteristics. For example, in Adelaide an environmental impact assessment of noise for various transport options in the city's north east area revealed that the L.R.T. system had an "acceptable distance"\(^1\) in residential areas of 75m. A diesel busway, freeway and

\(^1\) "acceptance distance" is defined as the distance from the centre of the transport corridor where the predicted noise is no more than 5 dB(A).
electric heavy rail system by contrast had values of 210m, 375-450m and 340m respectively (Department for the Environment, 1979).

In general LRT systems can meet high standards of environmental amenity. In Europe they have been integrated with pedestrian malls and city parks with minimal environmental impact (Department for the Environment, 1979). Systems which employ overhead wiring in urban areas are often criticised on the grounds of their visually intrusive nature. However, L.R.T. systems which employ the simple single wire can be easily integrated into city and suburban areas, especially where tree planting is used to screen the wiring (Department for the Environment, 1979). With regard to overhead wiring, it has been stressed that:

All motor traffic requires overhead lighting in addition to a multitude of traffic signs and it can be argued that the inconspicuous presence of properly designed overhead wiring is a small price to pay for the other environmental advantages of the semi-metro concept (1) (Walker, 1973).

No L.R.T. systems currently operate in Australia. Consequently no empirical data are available on L.R.T. energy use in Australian cities. Adelaide was to have commenced construction of a 15.6 km L.R.T. line in its north east area but this proposal was revoked in

(1) Semi-metro or stadtbahn are other names for light rapid transit.
September, 1979 by the new Government. However, the environmental impact assessment which analysed the various options made some simple estimates of air pollution and energy impacts for 1996. It concluded that the L.R.T. option would have little overall impact on air quality although it was also admitted that the lack of data on air quality made meaningful predictions impossible. It predicted that with no public transport improvements in the study area, emissions of hydrocarbons and carbon monoxide might be 4 to 5 percent higher in 1996 than with these improvements (Department for the Environment, 1979).

Similarly with regard to energy, the study estimated that because of the preponderance of private car travel, the impact on total transport energy use in the area under any public transport option would be minimal. It did however conclude that the light rail option would result in marginally less overall energy consumption and the freeway option in marginally more overall consumption than the other options. Table 3.31 summarises some of the data used to arrive at these conclusions. The energy efficiency values have been calculated for this study from the other data in the table.
Table 3.31  Relative energy efficiencies of each public transport option in the North East of Adelaide (1996).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Busway</th>
<th>Light Rail</th>
<th>Heavy Rail</th>
<th>Freeway</th>
</tr>
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<tbody>
<tr>
<td><strong>Vehicle kilometres per day</strong></td>
<td></td>
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</tr>
<tr>
<td>Cars</td>
<td>9,471,000</td>
<td>9,471,000</td>
<td>9,471,000</td>
<td>9,646,000</td>
</tr>
<tr>
<td>Public Transport</td>
<td>54,900</td>
<td>42,900</td>
<td>40,900</td>
<td>50,400</td>
</tr>
<tr>
<td><strong>Total Energy use (MJ/day)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cars</td>
<td>38,900,000</td>
<td>38,900,000</td>
<td>38,900,000</td>
<td>39,600,000</td>
</tr>
<tr>
<td>Public Transport</td>
<td>851,000</td>
<td>602,000</td>
<td>840,000</td>
<td>782,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>39,800,000</td>
<td>39,500,000</td>
<td>39,800,000</td>
<td>40,400,000</td>
</tr>
<tr>
<td><strong>Energy Efficiency of Public Transport MJ/Vehicle km</strong></td>
<td>15.5</td>
<td>14.0</td>
<td>20.5</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Source: Department for the Environment (1979).

A number of points can be noted from this table.

(i) Under the light rail and heavy rail options, the total kilometres of public transport are significantly less than under the busway or freeway options. This is due to the role of buses being limited mainly to feeder operations.

(ii) The light rail option offers the most energy efficient total public transport system and heavy rail requires
the highest overall input of energy on a vehicle kilometre basis.

(iii) The difference in energy efficiencies between the public transport options is due purely to technological factors. The light rail system is the most technologically efficient of all the public transport systems.

(iv) The greater total transport energy use under the freeway option is due mainly to envisaged additional car travel.

(v) The analysis does not permit calculation of the energy efficiency per passenger km. However, it is significant to note that in 1996 it is expected that the L.R.T. system and Glenelg tram will perform 15.1% of all public transport passenger kilometres compared to 2.1% in 1977. The role of buses in this regard is expected to drop from 69.0% to 54% (D.G.T., South Australia, 1978).

It is important to note that the predictions shown in Table 3.3 are based upon a fundamental assumption which may or may not prove correct; that is, that travel patterns in the study area in 1996 will not vary from the present observed patterns which show 92% of total kilometres being travelled by private passenger car and less than 1% of public transport. In addition, it assumes that the total kilometres of private car travel will increase by between 24 and 26 percent above 1977 levels and that under
all public transport options the same amount of car travel will occur. This assumes that all forms of public transport are equal in their ability to attract motorists. Evidence generally supports the observation that rail systems have a superior ability in this regard. For example, in a study to determine whether to retain the Airedale and Wharfedale rail routes in West Yorkshire, U.K., it was estimated that if the services were replaced by buses, 70% of rail patrons would transfer to private car on weekdays and 50% on Saturdays (Sully, 1978). The services were retained.

If car travel patterns outlined above do not occur, then a substantially different picture in terms of energy and emissions might emerge. An important limitation on the ability of present car travel trends to be maintained is the oil situation which has been described in some detail. In its discussion of energy considerations the South Australian Department for the Environment (1979) stated that;

It has been assumed that the price of oil will increase and that oil supplies will dwindle in the future. Those forms of transport which are not dependent on oil should be adopted to minimise the effect of these conditions. In the case of a sudden oil shortage, systems using electrical energy from indigenous resources would be least affected.

It is impossible to predict with any degree of accuracy what effect this situation will have on car travel. If however by 1996 it is causing the public transport alternative to appear more attractive than suggested by
the Adelaide assessment, then the estimates of energy and emissions savings potential of the LRT and other public transport options are probably understated. In fact, given their own stated limitation on oil supply the basis for the energy and emissions estimates are questionable.

Conclusions to L.R.T.

In conclusion, a number of points can be made regarding LRT systems.

(1) In general L.R.T. systems offer the opportunity to provide a rapid rail transit system at a lower cost than heavy rail systems which often involve expensive underground sections (Department for the Environment, 1979). It is estimated that subways in the U.S.A. cost about $31 million per kilometre (Szabo, 1976).

(2) They combine the advantage of on-street service, characteristic of trams with the speed capacity and safety of separate guideway operation characteristic of trains.

(3) In medium size cities such as Perth, LRT offers a potential to expand rapid rail services where heavy rail systems could not be justified. The Energy Advisory Council of the S.E.C. in W.A. has cited LRT systems as a better financial solution than electrification of existing heavy rail services (Energy Advisory Council, 1979). This is then supported by evidence from cities in North America such as Calgary.
and Edmonton which have approximately 0.5 million
people and have constructed new LRT lines. In
addition, in 1976, 212 cities in 34 nations were
developing new light rail systems on the grounds that
they offer the most cost effective provision for
their transport needs (Szabo, 1976).

(4) The technology of LRT systems is already available
and proven. This is a significant advantage over
systems which require technological breakthroughs
or testing such as some of the bus systems outlined
previously.

(5) As with all public transport options considered so
far, the major energy and emissions benefits from
LRT systems will come from their ability to
substitute for private travel. Their operating
characteristics and appeal offer the potential for
achieving such substitution and their technological
efficiency suggests minimal total energy requirements
compared to other public transport options.
Trams are one of the oldest forms of public transport. They were so important in the transport systems of American cities prior to the arrival of the automobile that the period from 1852 until about 1908 was commonly known as the streetcar era (Schaeffer and Sclar, 1975). They had a similarly important role in Australian cities (Neutze, 1977).

However, after the introduction of Henry Ford's automobile mass production techniques, the ownership and use of cars steadily grew, and many cities around the world, (including Australian cities) embarked upon a systematic programme to abolish tram systems. Trams were seen as an obstruction to the free flow of motor vehicles and their removal was posited by motorists as a way of improving average traffic speeds. This envisaged improvement however was never realised (Jay, 1978). Melbourne is the only Australian city to retain a comprehensive tram system. Adelaide has maintained a single tram line from the city to the beach suburbs of Glenelg.

It is clear from most analyses that trams compare very favourably in energy and patronage terms with other forms of public transport in Australia (Chartered Institute of Transport, 1974; Clarke, 1975). It is important to note however that trams traditionally operate within inner city and central city areas where higher than average urban density and work density is
encountered. This gives trams a distinct operational advantage over bus services which operate in lower density suburbs, though it does not detract from the evidence that trams are highly suited and highly successful in their traditional role.

A number of technological options are available to improve the attractiveness of trams;

(1) The simplest and perhaps most effective in terms of attracting passengers is to operate the most modern and comfortable vehicles available. Melbourne has purchased 101 new 'Z' class trams and has 14 more on order as part of its programme to upgrade tram services (Melbourne and Metropolitan Tramways Board, Annual Report, 1978). These trams are designed to provide an improved level of comfort and performance. They also incorporate a more advanced braking system.

(2) In Europe and North America, many cities have chosen to retain their tramway systems and upgrade them to LRT standard (Department for the Environment, 1979). This, as shown in the discussion of LRT, is designed to maintain the general characteristics of trams while expanding their capabilities.

(3) The use of flywheel technology in public transport vehicles is being investigated as a means of decreasing their energy use (Loder, 1979; Environmental Science and Technology, 1976). It presumably can be applied to tram systems.
(4) Noise levels from trams can be reduced by the use of lighter weight vehicles, better braking systems and better track construction.

**Conclusions to Trams**

In conclusion, the most important technological improvement which can be made to tram systems is to ensure that the vehicles in use are as modern and comfortable as possible; this will ensure patronage levels do not suffer due to outdated technology.

It is not possible to quantify the benefits of trams in terms of emissions. It would seem intuitively correct to suggest that emissions of CO, HC and NO$_x$, in C.B.D.'s would be considerably higher if the travel demands fulfilled by trams were met by private cars. (1) This would result not only from increased total kilometres of travel but also from a congestion factor. Diesel buses in C.B.D. areas also have disadvantages in terms of noise and unpleasant aromatic emissions. As with the other public transport options discussed, the magnitude of overall benefits in terms of emissions, depends primarily on how much private vehicle travel they can eliminate.

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(1) Whether this would significantly affect ambient air concentrations would have to be determined by specific calculations.
3.2.3(c) New Concepts in Urban Public Transport Systems - Long Term Options.

(i) Introduction

The public transport improvements discussed so far under bus and rail are essentially variations of systems which already exist and for the most part involve proven technologies. In addition to these efforts, a great amount of research is occurring around the world especially in Germany, Japan and the U.S.A., on completely new ideas for moving people around cities e.g. personal rapid transport (P.R.T.).

It is important to stress at the outset, that the majority of these systems are not yet fully developed technologically. In most cases, testing procedures are limited to small scale pilot networks and in this sense such systems are far from the possibility of integration into real urban systems.

The aim of this section is to present a broad overview of the systems being considered and to comment upon their feasibility and likelihood of acceptance. Personalised rapid transport is the only system for which energy data are available and is thus treated in more depth.

New concepts in urban public transport are based upon a multitude of variations in tracked vehicle systems. In this sense they most closely resemble conventional tram and train systems. The major technological
variations are found in the propulsion method and the size of the vehicles. All the new systems are based on electricity and are generally fully automated.

(ii) *Alternative propulsion systems*

The major alternative forms of propulsion being considered are:

1. air-cushioned propulsion (e.g. hover trains)
2. magnetic levitation based either on attraction or repulsion
3. gravity vacuum propulsion in a tube

(Pole, 1973).

The principle of the first two systems is to eliminate friction between the vehicle and the track by raising the vehicle off the track during operation. This greatly improves performance capabilities especially speed and ride smoothness. In the case of air-cushioned vehicles this is achieved by using air pressure and in the case of magnetic levitation systems, it is achieved by using an attractive or repulsive electro-magnetic force created by a linear induction motor (LIM). This allows either a suspended or supported vehicle to be employed. These two systems are termed tracked levitated vehicle systems (T.L.V.) (Hebert, 1976). The third system is essentially an advanced version of the pneumatic tube train which operated as early as the 1840's in Ireland and 1870's in New York (Pole, 1973).
The new gravity vacuum tube system works on basically the same principle as the earlier systems; that the train is pushed along a partially evacuated tube by the air pressure behind it, but with the added assistance of gravity. Tubes are sloped down on both sides of each station so that the train operates in a pendulum-like way and requires no on-board engine and few controls. Appropriate air pressures are created by large pumps within the tube system (Pole, 1973). In 1972 it was suggested by Rand Corporation that an advanced system based on this principle could be constructed between Los Angeles and New York and reach a top speed of 16,100 km per hour. Much less dramatic achievements could be realised in urban systems using gravity vacuum tubes, and with the potential of a 70% saving in operating energy. Pole, (1973) suggests that they should not be overlooked when considering new transport plans. However, such systems must necessarily be underground which is an economic drawback.

The first two systems, air cushioning and magnetic levitation, can be applied to a wide size range of vehicles serving a variety of purposes from PRT to high capacity rapid transit; the third system, gravity vacuum tubes, tends to be restricted to a replacement for conventional heavy rail systems. For example, Krauss Maffei in Germany is developing a system of rapid transit termed Transrapid based upon magnetic levitation (Pole, 1973) and in Lyon, France, a hovertrain system termed URBA has been operated for a number of years with some
success. It is a high capacity urban rapid transport system with no moving parts and thus has very low noise levels (68dB(A)) and no vibration (O'Flaherty, 1972).

(iii) **Personal Rapid Transit**

At the other extreme, advanced linear induction motors are finding application in P.R.T. systems. Personal Rapid Transit involves the use of small automated electric vehicles operated on a fixed guideway capable of carrying 2 to 20 people – generally the range is 3 to 12 people. Most of the smaller P.R.T. systems do not involve magnetic levitation or air-cushioning, although some experimentation is occuring in the U.S.A. with larger vehicle P.R.T. systems (Loder, 1979). Other P.R.T. systems involve ordinary DC or AC rotary motors although there is a marked trend towards the new LIM's, because they are simpler, more efficient, lighter, easier to control and provide an easy braking system with the potential for regenerative braking (Loder, 1979).

A variety of P.R.T. systems are being developed in many parts of the world particularly Germany. For example, in Germany extensive testing on the Demag-MBB Cabintaxi and Siemens H-Bahn has been carried out on small test tracks between 1.1 and 1.4 km in length. Siemens H-Bahn is capable of operating vehicle modules with a seating capacity of up to 38. In Japan, a group enterprise involving a university and nine major industrial firms has
been testing on a 6.8 km track, a P.R.T. network involving 4 seat vehicles known as the CVS system.

The only P.R.T. system actually in operation in an urban area is at Morgantown in West Virginia U.S.A. This system runs 45 vehicles each with a 20 passenger capacity over 8.7 km of guideway. It has carried up to 20,000 passengers per day (Loder, 1979).

Little data other than of a purely technical nature are available for these systems and thus it is not possible to discuss their energy and emissions reduction potential on an empirical basis. However, one study, (Fels, 1974) compared the energy usage of two hypothetical P.R.T. systems with that of other conventional forms of transport, and this has given some insight into their likely performance as a public transport mode.

The two P.R.T. systems involved in the comparison utilise completely different technologies. The first, System A is a small car system (6 seats) based upon an overhead monorail guideway manufactured by Rohr Industries and System B is a large car system (10 seats) based on the Transportation Technology Inc. (T.T.I.) air-levitated linear induction motor system (Fels, 1974).

The study assumed that the P.R.T. system would have a slightly lower net average occupancy than the automobile because of an allowance for the shuttling of empty vehicles. Estimates were also made of their average
occupancy during peak hours. These assumptions were based upon the premise that since the P.R.T. systems are really trying to simulate the personalised service of the private car, then it is likely that for the majority of the day, occupancy will be low, as with the private car. In low-density areas there is no evidence to suggest that P.R.T. will be better able to attract higher occupancy rates than the private car. Other studies have also predicted low-occupancy rates for P.R.T. (Pole, 1973). In peak hours however the higher capacity of some P.R.T. vehicles might result in slightly better loadings analogous to that achieved by private cars during car-pooling arrangements (Fels, 1974). This may result during peak periods if P.R.T. is viewed as a convenient public transport mode capable of avoiding traffic congestion, rather than as a replacement equal to the motor vehicle which is its ultimate aim.

The results of the analysis show that on the basis of energy consumption per passenger km, P.R.T. could be expected to perform generally worse than the private vehicle and always much worse than the conventional bus and rail systems. This is shown in Table 3.52.

It can be seen that only in the case of the heavier private vehicle and only in peak hours could the P.R.T. systems be expected to perform better on a per passenger energy basis than private vehicle in the U.S.A. On the basis of this limited analysis, electric operation
appears to be the only energy advantage of P.R.T. systems at the moment.

Table 3.32 Estimated comparative energy efficiency of P.R.T. and other modes of urban transport.

<table>
<thead>
<tr>
<th>Energy (MJ) consumed per passenger kilometre.</th>
<th>Auto</th>
<th>City Bus</th>
<th>Rapid Rail</th>
<th>P.R.T. System A</th>
<th>P.R.T. System B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto</td>
<td>4.25</td>
<td>2.19</td>
<td>1.48</td>
<td>1.59</td>
<td>5.23</td>
</tr>
<tr>
<td>City Auto</td>
<td>910kg</td>
<td></td>
<td></td>
<td>1.59</td>
<td></td>
</tr>
<tr>
<td>Rapid Rail</td>
<td></td>
<td></td>
<td>1.59</td>
<td>5.23</td>
<td>6.44</td>
</tr>
<tr>
<td>P.R.T. System A</td>
<td>(3.24)</td>
<td>(4.05)</td>
<td>peak hour</td>
<td>peak hour</td>
<td></td>
</tr>
<tr>
<td>P.R.T. System B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: After Fels, (1974)

There are many problems involved in attempting to compare systems which have not yet been tested in real urban situations with systems which already exist and for which empirical data on operating characteristics are available. Nevertheless P.R.T. systems and other new concepts in public transport can be discussed and compared with existing systems from an economic standpoint.

P.R.T. systems have not so far demonstrated that they can compete with conventional systems on a cost basis, and this seems to be their major drawback. For example, a 4.7 km extension of single lane guideway involving two new stations in the Morgantown network will cost $A56 million (Loder, 1979). Denver, Colorado investigated a
comprehensive P.R.T. system, but rejected the idea when
the cost estimate of US$1,000 million was made. Similarly
in Los Angeles a US$1,600 million P.R.T. network has gone
no further than the discussion stage (Hebert, 1976). A
P.R.T. proposal for Adelaide was rejected on the basis of
similar enormous capital costs. In the U.K. the high
capital costs of a complex network of P.R.T. guideways has
resulted in a suspension of P.R.T. research in favour of
the Minitram concept (an L.R.T. system) (Pole, 1973).

Conclusions to New Concepts in Urban Public
Transport systems.

In general, new untested and expensive
technologies are being rejected in favour of cheaper
conventional proven ones. A number of comments and
appraisals from the U.S.A. where large amounts of money
have been spent on new mass transit systems, reflects this
growing aversion:

In this time of limited resources and funds, new
technology is being viewed very cautiously by law
makers and urban planners worldwide. For example
France has delayed building lines for its air-
cushioned Aerotrain in favour of a more conven-
tional mode of transportation. Many cities now
are choosing less expensive and more reliable
approaches to solving mass transportation problems.
This means small scale and incremental improvements
in existing systems, instead of trying to make a
generation leap with expensive and uncertain new
technologies (Szabo, 1976).

In an interview, the Chairman of the American
Public Transit Association stated in answer to a question
concerning breakthrough in transport technologies that:
People have been looking for something magical in public transport that will provide all the comforts and convenience of the private automobile without the problems... We have to live pretty much with technical improvements we can see down the road, not with romantic ideas that are impractical—economically, politically and technically (Ronan, 1976).

Similarly in Australia, transport planning bodies view very skeptically the potential of new transport technologies to make significant contributions to solving urban transportation problems. The Director General of Transport in W.A. states:

There have been many suggestions for "new technology" devices claimed to be a panacea to the transport problems in the city. None of them would be a panacea. Most are fundamentally impractical when it comes to fitting them into real cities. All are very expensive on present day estimates... (Knox, 1979).
3.2.4 TECHNOLOGICAL ALTERNATIVES TO TRAVEL

3.2.4(a) Introduction

In the future, it has been suggested, it may become feasible and desirable to entirely eliminate the need for certain types of travel. A wide range of travel purposes could conceivably be affected by advances in technology which make it possible to attain a more expedient way of linking two places together, than is currently provided by vehicular movement.

For example, it is possible that heavy freight movements around urban areas may no longer be required; the journey-to-work may in some cases become unnecessary if the work can be carried out at home; personal and business travel might be reduced if advances in electronics can create a suitable replacement for personal contact under certain circumstances.

In this way, energy use and emissions associated with these types of travel could be virtually eliminated. Such substitutions might also yield other benefits. For example, in the case of eliminating freight transport, urban areas could benefit from a reduction in noise, an improvement in road safety and a reduction in the costs of road maintenance.

Two major areas of research could provide the technology needed for travel substitution: (a) liquid and solid pipeline technology and (b) cybernetics or electronics communication technology. These two approaches have a
number of things in common. They both involve the use of advanced and costly technology, especially in terms of capital costs and they would, if implemented on a large scale, constitute a radical departure from present transport and communications systems. For this latter reason such technological changes would demand considerable economic, social, psychological and political adjustment.
3.2.4(b) Pipeline Technology

The use of pipelines to transport solids and liquids is a well established practice. Table 3.33 shows the types of materials which can be transported and the types of systems which are generally used.

Table 3.33 Types of Pipeline Transport

<table>
<thead>
<tr>
<th>Nature of the material to be transported</th>
<th>Conveying fluid</th>
<th>Facilities known as</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Oil or water</td>
<td>-</td>
<td>Oil or water pipeline</td>
</tr>
<tr>
<td>(2) Gas</td>
<td>-</td>
<td>Gas pipeline</td>
</tr>
<tr>
<td>(3) Solid:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Bulky materials</td>
<td>Liquid</td>
<td>Slurry pipeline</td>
</tr>
<tr>
<td>(b) All kinds of materials</td>
<td>Gas (air)</td>
<td>Pneumatic pipeline</td>
</tr>
<tr>
<td>(c) Packaged materials</td>
<td>Liquid or gas</td>
<td>Capsule pipeline</td>
</tr>
</tbody>
</table>


Items (1) and (2) in Table 3.33 are in common use in urban areas whereas those under item (3) are generally used on a small scale within factories and other business enterprises to expedite the transfer of goods and mail from one point to another.

However, these systems (solid and liquid) have the potential for much wider application. For example,
Slurry pipelines, although most directly applicable to mining industries, have been investigated as a means of dealing with municipal solid waste. For urban functions the various types of pneumatic systems offer the greatest potential. These may be divided into three main sub-groups. (i) The pneumatic conveyor (ii) The pneumatic despatch system, and (iii) The pneum-o-train system.

Table 3.34 shows a list of items which have been handled by pneumatic systems of various types. It can be seen that such systems have demonstrated an ability to handle a versatile range of products, although further investigation would be needed before this success could be extrapolated to large scale urban conditions.

Table 3.34 Partial list of typical materials handled pneumatically.

<table>
<thead>
<tr>
<th>Alfalfa</th>
<th>Chicken</th>
<th>Oats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(4 lbs live pullets)</td>
<td></td>
</tr>
<tr>
<td>Almonds</td>
<td>Clay</td>
<td>Oyster</td>
</tr>
<tr>
<td>Alumina, Powder</td>
<td>Coal</td>
<td>Plastics</td>
</tr>
<tr>
<td>Asbestos, Pits</td>
<td>Copper oxides</td>
<td>Rubber</td>
</tr>
<tr>
<td>Aspirin</td>
<td>Corn</td>
<td>Seeds</td>
</tr>
<tr>
<td>Bentonite</td>
<td>Explosives</td>
<td>Soda ash</td>
</tr>
<tr>
<td>Brewers grain</td>
<td>Fertilizers</td>
<td>Talc</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>Frozen foods</td>
<td>Tobacco</td>
</tr>
<tr>
<td>Cereal</td>
<td>Grain</td>
<td>Wheat</td>
</tr>
<tr>
<td>Charcoal, ground</td>
<td>Gypsum, calcined</td>
<td>Wire</td>
</tr>
<tr>
<td>Cheese</td>
<td>Nitrate</td>
<td>Wood</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole fish</td>
</tr>
</tbody>
</table>

The pneumatic conveyor is an actual pipeline system which typically handles solid-air mixtures. Present use is restricted to a range of industries such as chemical, agricultural, mining and steel. The pneumatic despatch system usually handles smaller items such as parts, messages and mail. Computer control technology offers the scope to greatly increase the capacity of such systems. Pneumatic despatch systems have already been used extensively in England, France, Germany and the U.S.A. for transporting mail (Zandi and Kim, 1974).

The pneumo-train system is used to move heavy weights and employs trains suspended by wheels inside a pipe. These systems have the greatest potential for replacing freight transport although they are uncommon at the moment. Extensive testing has been carried out in Russia and a new town (Etarea) in Czechoslovakia is presently being developed with a freight distribution network based upon an allied principle; the capsule pipeline. The proposed system is designed to cope with fluids, packaged materials and other fragile items. This pneumatic tube distribution system is intended to give the inhabitants a choice of remote shopping by providing 19 delivery return pipelines capable of carrying weights of 4 kg at 2 second intervals (Morris, 1970).

A number of energy analyses have been carried out to compare the overall energy intensiveness of various conventional systems of transport to suitable pipeline alternatives (Zandi and Kim, 1974). These have involved a
number of assumptions which may or may not be valid for a specific set of circumstances. The findings however indicate a generally lower energy requirement for the pipeline system in each case.

One comparison involved a capsule pipeline using spherical and cylindrical capsules and a trucking system for urban freight transport. The results of this energy analysis shown in Table 3.35 reveal that the spherical capsule system offers considerable savings over the trucking system, but that the cylindrical capsule system is not significantly lower in energy requirements.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy intensiveness (MJ/Tonne km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical capsule</td>
<td>0.32 (436)</td>
</tr>
<tr>
<td>Cylindrical capsule</td>
<td>3.93 (5439)</td>
</tr>
<tr>
<td>Truck, urban traffic (average value)</td>
<td>4.03 (5583)</td>
</tr>
</tbody>
</table>


From the work which has been done it appears that the application of appropriate solid pipelines could offer net energy savings in freight transport, plus a range of other advantages which may be listed as follows:
(1) Reduction of traffic in highways and streets
(2) Lessening of air pollution
(3) Reduction of noise levels
(4) Reduction of accidents
(5) Independence from weather, and
(6) Automation.

(Zandi and Kim, 1974).

Before any conclusions can be formed a number of qualifying remarks need to be made about the potential contribution of pipelines to reducing energy and emissions.

In practise these two concerns might be dwarfed by other considerations which are of equal or more importance. Firstly, a much wider range of demonstration projects would be needed to eliminate problems in the areas of;

(a) reliability in day-to-day operation.
(b) long term erosion and corrosion impact (i.e. maintenance costs).
(c) the degree to which the system needs to be automated.
(d) possible damage to conveyed freight.

(Zandi and Kim, 1974).

Secondly, the broader question of societal impacts such as employment and economic implications would have to be resolved before such systems could be introduced as a major part of modern urban infrastructure. In this regard it is worthwhile to note that the energy consumption factor in freight transport and certainly the emissions factor, are of lower importance to commercial interests than consider-
ations such as cost, reliability, time and damage to goods. It remains to be seen whether pipelines can compete in these terms (Zandi and Kim, 1974).

Thirdly, the amount of energy actually consumed and emissions produced for freight purposes in Australian cities is small compared to private passenger transport energy consumption and emissions. Noise would be much more significant however. Greater use of pipelines in rural situations might reap more significant energy savings albeit at a higher capital cost due to the larger distances involved. This would need to be investigated however, before any firm statements could be made.

Conclusions to pipeline technology

Overall it can be concluded that pipeline alternatives to freight transport are long term options if at all. Construction of a significant network of pipes for various purposes would involve long lag times, high capital costs and considerable disruption to urban fabric due to the earthworks or overhead works involved. In the Australian context it is likely that strong opposition would be encountered from those whose livelihood depends upon truck freight movements, and in this sense, pipelines would be politically unpopular. The feasibility of pipeline technology in Australian cities would also have to be examined from the land use standpoint. In low density Australian cities the costs of providing a comprehensive
pipeline system would probably be higher than for more compact cities such as in Europe.
3.2.4(c) **Electronic Communications Technology**

The past ten years has seen a burgeoning in the sophistication and application of electronics in the form of microprocessors and visual transmission devices. Computers and allied techniques of data handling have pervaded every aspect of life. As part of this general revolution, the suggestion has arisen that advances in the application of electronics in the fields of person-to-person communication, might serve to reduce a portion of travel in cities.

Some of the recent technological developments with a potential for reducing travel demands include:

* the wired city.
* teleconferences.
* data transmission.
* remote computer terminals.
* videophone.
* cable television, and
* facsimile services - e.g. electronically transmitted mail and newspapers.

(Knox, 1979; Economic Research Unit Pty. Ltd., 1975).

The use of these systems is centred around new concepts such as:

* the home work centre - work from home with access to computer and communications.
* the neighbourhood work centre - walking distance from home with work space and access to computer and
communications.

* the mobile worker - the use of portable terminals with appropriate capabilities.

* remote shopping.

* remote banking.

* electronic voting.

* electronic education.

* consumer information retrieval system.

* remote medical systems.

* electronic security services.

(Knox, 1979; Economic Research Unit Pty. Ltd., 1975).

In response to some of the developments outlined above, The Interplan Corporation of the U.S.A. performed an analysis of the magnitude of travel savings possible from substituting electronics communication for various trip purposes. Table 3.36 summarizes the results of this analysis.

Subsequent analyses of these trip reductions yielded three estimates of possible reductions in urban area vehicle-kilometres. The report stated that optimistically a reduction of 22% over present levels could result and pessimistically this might only be 14%. The study concluded that a value around 18% would be most likely. If such prognoses can be relied upon, they portend considerable savings in fuel and emissions in the U.S.A.
Table 3.36  Percentage of trips susceptible to communications substitution in urban areas in the U.S.A.

<table>
<thead>
<tr>
<th>Trip Type</th>
<th>Percentage of Trips which could be replaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earning-A-Living</td>
<td>24%</td>
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<tr>
<td>Family Business</td>
<td></td>
</tr>
<tr>
<td>Medical and dental</td>
<td>5%</td>
</tr>
<tr>
<td>Shopping</td>
<td>50%</td>
</tr>
<tr>
<td>Other</td>
<td>25%</td>
</tr>
<tr>
<td>Education, Civic and Religious</td>
<td>25%</td>
</tr>
<tr>
<td>Social and Recreational</td>
<td>5%</td>
</tr>
</tbody>
</table>


However, serious doubts have been voiced, firstly over the ability of these forms of technology to actually replace the face-to-face contacts which travel permits, and secondly, the desirability of such changes even if they can be effected. Apprehension over the latter point revolves around the very nature of human communication and logically, the fundamental cultural role of the city.

The low density use of land in cities is partly in response to the desire for privatisation (Pawley, 1975). However the almost total isolation of individuals into privatised units linked only by electronic communication would appear to be challenging the very nature of urban culture (Schneider, 1979).
In a report to the Commonwealth Bureau of Roads, four major reasons were cited as mitigating the role of telecommunications in replacing travel (Economic Research Unit Pty. Ltd., 1975).

(i) Optimistic forecasts of travel substitution are based upon a premise of mechanistic human communication which overlooks important qualitative aspects of face-to-face contact. The richness of person-to-person communication cannot be simulated by any other mode.

(ii) Telecommunications are at present economically unattractive to the majority of households and businesses.

(iii) An elaborate system of electronic communications devices in the home are seen as being unable to generate sufficient benefits to justify the costs e.g. remote shopping for many suburban housewives would deprive them of an important social ritual; (for those who find shopping a chore readily given up in favour of electronic shopping, there would be a range of other socially meaningful relationships which they would not be prepared to give up to electronic communication).

(iv) The major use of advanced telecommunications facilities is forecast to come from generated demand rather than from substitution for other modes.

An additional problem arises when attempting to assess the impact of telecommunications on physical movement.
Although travel for some purposes may be significantly reduced, there remains the problem that net travel may actually increase due to an increase in the scope and number of contacts which could be made. A worthwhile way of testing such a suggestion would be to examine the travel demand impacts of Citizen Band radios which are currently in widespread use. The possibility that electronic communications might actually bolster travel in cities and thereby exacerbate energy and emissions problems can be summarised thus:

In theory, these developments should greatly reduce the need for many trips in urban areas; however, whether or not they will cause an actual reduction in the total number of trips cannot be said at this time - it may well be, indeed, that (as with the telephone) the end result of the introduction of these electronic aids is an increase in the number of trips, simply because of the ease with which these aids enable preliminary contacts to be established (O'Flaherty, 1972).

Conclusions to electronics communication technology

It remains to be seen if electronics communication can reap the energy and emissions reductions it is theoretically capable of. Viewed in purely technological terms the possible savings are great. For example, it has been estimated in Canada that for two people to make a 644 km trip by car for a 3 hour meeting would require a primary energy input of 1600 kWh. Similarly by plane it would be 2500 kWh. However, by holding a conversation over a videophone, the energy required would be about 40 kWh, or by telephone only 1 kWh (Jackson, 1978). Taking into
consideration the human factors however, the potential is viewed with some reservation by many analysts. Claims of energy savings by substituting electronics communication will remain largely speculative until the more advanced schemes outlined in this discussion become available on a large scale.
3.2.4(d) Overall Conclusions to Technological Alternatives to Travel.

The ability of two important areas of technological endeavour to reduce total travel in urban areas has been examined. The evidence suggests that no insurmountable technical problems confront developments or applications in either of these areas, although in many cases greater refinement is required. Rather, the major problems confronting the introduction and widespread use of these technologies are lifestyle and cultural factors as well as land use factors. The case of telecommunications goes so far as to threaten the very nature of the city and for this reason has received a generally pessimistic assessment in most of the literature. In cases where actual estimates have been made of the potential for reducing energy consumption through technological alternatives to travel the potential has been small. For example, in Canada it was estimated that if 20% of business travellers on intercity travel used telecommunications instead, 3% of energy used in transport could be saved or 1.3% of national consumption (Jackson, 1978).

It can be concluded that achieving reductions in urban energy use and emissions by opting for travel substitutes will not be an easy task, and indeed from a broad perspective such an approach may prove totally at odds with the function and amenity of cities.
3.2.5 Overall Conclusions - Technological Options

A range of technological options have been presented and in so doing were assessed using a variety of criteria. To provide any possibility of an overview from such an array of potential changes is a daunting task. To assist in this process a table has been prepared which contains the majority of criteria used in the assessment. A simple numerical scale was made up so that each change could be systematically reviewed. This table shows several things.

(1) The assessment of any technology involves the human values of the assessor who weights not only the individual values according to his own background and knowledge but the weight given to one criteria rather than another is particularly subjective. This final weighting has not been attempted numerically and therefore no totals have been obtained.

(2) Virtually all the changes which could have a substantial impact on energy and emissions involve at least one criterion which is classified as a major change or a serious drawback. Those which appear desirable using criteria other than energy and emissions, generally have a lower potential impact on energy and emissions.
(3) It highlights the way directions in new technology must be assessed with a very wide range of criteria in mind. Thus although this table does not claim to provide any \textit{strict} quantitative way of ranking all these changes it emphasises the potential value of a multidisciplinary approach to evaluating new transport technologies.
<table>
<thead>
<tr>
<th>TECHNOLOGICAL CHANGE</th>
<th>TECHNOLOGICAL COST IN FEASIBILITY</th>
<th>ECONOMIC CHANGES IN TECHNOLOGICAL COST IN INFRASTRUCTURE REQUIRED COMPARISON TO PRESENT SYSTEM</th>
<th>CHANGES IN SAFETY REQUIREMENTS COMPARED TO PRESENT SYSTEM</th>
<th>ENERGY EFFICIENCY REDUCTION COMPARED TO PRESENT SYSTEM</th>
<th>EMISSIONS REDUCTION COMPARED TO PRESENT SYSTEM</th>
<th>HUMAN FACTORS</th>
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### Large scale technological change

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### Public transport technology

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<td>Trams</td>
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### New concepts in urban public transport

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### Technological alternatives to travel

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<td>1</td>
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<td>4-5</td>
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</tbody>
</table>

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**TABLE 3.37** Summary of all technological options examined in this study and the range of criteria used to assess them.
**KEY TO TABLE 3.37**

**Technological Feasibility**
1. Available now
2. Some further development required
3. Minor technological advancements still needed
4. Medium technological advancements still needed
5. Major technological breakthroughs still needed

**Economic Cost in Comparison to present system**
1. Cheaper
2. Same
3. Marginally more expensive
4. About twice as expensive
5. Substantially more expensive

<table>
<thead>
<tr>
<th>Economic Cost in Comparison to present system</th>
<th>a) Running Costs</th>
<th>b) Capital Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cheaper</td>
<td></td>
<td></td>
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<tr>
<td>2. Same</td>
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<tr>
<td>3. Marginally more</td>
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<tr>
<td>4. About twice as expensive</td>
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<tr>
<td>5. Substantially more</td>
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</table>

**Changes in Infrastructure required Compared to present system**
1. No change
2. Minor changes
3. Medium changes
4. Major changes
5. Totally new system

<table>
<thead>
<tr>
<th>Changes in Infrastructure required Compared to present system</th>
<th>Safety Compared to Present System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No change</td>
<td>1. Improvement</td>
</tr>
<tr>
<td>2. Minor changes</td>
<td>2. No change</td>
</tr>
<tr>
<td>3. Medium changes</td>
<td>3. Minor problems</td>
</tr>
<tr>
<td>4. Major changes</td>
<td>4. Medium sized problems</td>
</tr>
<tr>
<td>5. Totally new system</td>
<td>5. Major problems</td>
</tr>
</tbody>
</table>

**Energy Efficiency Compared to Present System**
1. Much better (>30%)
2. Better (5-30%)
3. Same or marginally better (0-5%)
4. Worse (5-30%)
5. Much worse (>30%)

<table>
<thead>
<tr>
<th>Energy Efficiency Compared to Present System</th>
<th>Emissions Reductions Compared to present system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Much better (&gt;).50%</td>
<td>1. Much better</td>
</tr>
<tr>
<td>2. Better (5-30%)</td>
<td>2. Better</td>
</tr>
<tr>
<td>3. Same or marginally better (0-5%)</td>
<td>3. Same or marginally better</td>
</tr>
<tr>
<td>4. Worse (5-30%)</td>
<td>4. Worse</td>
</tr>
<tr>
<td>5. Much worse (&gt;30%)</td>
<td>5. Much worse</td>
</tr>
</tbody>
</table>

**Human Factors in change compared to present system**
1. Attractive change
2. No effect
3. Some negative effects
4. Medium negative effects
5. Major negative effects
3.3 Land Use Options

3.3.1. Introduction

Our quest then is to search for non-transportation solutions to the urban transportation problem where such solutions can be expected to a) result in equal or better individual mobility and b) produce a better level of environmental quality in the city. A non-transportation solution is one that involves no new transportation facility or service but instead involves a rearrangement of a particular urban spatial structure such that some part of the present transportation requirement of the city is reduced significantly. (Jerry B. Schneider and Joseph R. Beck, 1974).

This section will review the potential for conserving energy and reducing emissions through changing urban land use. The review is not as lengthy as with the technological options as the literature is not as extensive, and whilst there is some controversy, there is also substantial agreement on most of the major factors.

This review will concentrate on three major areas - the effects of density, centralization and traffic restraints. No land use change can alter energy usage and emissions in the same immediate sense as many of the technological changes. Rather, the land use pattern indirectly has its effect on energy usage and the production of emissions through the following mechanisms:

(a) Influencing the level of private vehicle usage as opposed to public transport, i.e. the modal split.
(b) Determining the trip length distribution pattern, e.g. reducing the length of trips, especially private vehicle trips.

(c) Affecting the overall level of walking, e.g. making it easier to have no need for a vehicle at all for some trips (e.g. social and shopping), i.e. increasing walking (and bicycling).

(d) Influencing the occupancy ratios of public and private transport, e.g. making higher loadings in public transport more feasible or car pooling more attractive.

Thus land use change can have an indirect effect on energy and emissions by making it possible to reduce private vehicle use per capita.

(a) **Density**

The relationship between urban density, energy and emissions has been examined in a number of studies. When questions of environment are being discussed it is a common reaction to consider high urban density as one of the evils that should be avoided to create a clean healthy city (e.g. American Public Health Association, 1946, 1960 and 1974; Brett-Crowther, 1977; Carr, 1977). Berry *et al* (1974) initially confirmed what many suspected in a study of 76 U.S. cities when they found that the cities with the worst air, water and noise pollution, and having the most solid waste

(1) Urban density is defined as the population resident in a particular urban agglomeration area - no non-urbanised area is included.
are large, high density, industrial cities, and the least environmental problems are found in small low density service-oriented cities.

These basic ideas have in the past been a major reason why the lowering of urban density has been planned (Hogan, 1978). However, although higher urban density and lower dispersion of total emissions are clearly linked, the actual production of transportation emissions and its relationship to urban density is not so obvious. In any environmental assessment the total production of transportation emissions must be addressed and urban density needs to be examined by itself as a planning tool capable of influencing both emissions and energy.

To examine more closely their original analysis, Berry et al (1974) analysed their 76 cities and statistically controlled for the effects of city size, manufacturing concentration and income levels and found that the higher density cities were in fact characterised by better air and water quality. The lower density cities had a greater production of emissions. The reason was, they concluded, related to the greater usage of motor vehicles in the lower density city.

A number of other empirical studies have confirmed this finding from actual data on energy and emissions based on vehicle usage patterns.
The New York Regional Plan Association (1974) showed how energy use increases as the density decreases in the New York region. As the density decreased from around 150/ha to less than 1/ha, the per capita energy consumption increased some three times. Darmstadter, Dunkerley and Alterman (1977) also looked at New York in terms of energy and density and showed that transport energy rose steeply and continuously with declining density from a low of around 9000 BTUs per dollar of income in the city centre to about 33,000 BTUs at the periphery of the region.

A study of Mercer county by Fels and Munson (1974) examined three regions of the urban area - the old high density central city of Trenton, the low density middle suburbs surrounding this and the very low density outer suburbs where a great deal of undeveloped land still exists. The three regions are similar to many U.S. and Australian cities in terms of income and car ownership. The travel patterns of the three areas were studied and the data are presented in Table 3.38.

The most important difference to note is in energy per capita values, with the higher density central city area using less than half the other areas. Although no part of the study examined emissions from transport, it would be expected that a similar per capita pattern would emerge due to the link between vehicle usage patterns and emissions. The reasons for
Table 3.38 Energy and Travel Data for Mercer County in the early 70s with relevant economic and land use data

<table>
<thead>
<tr>
<th></th>
<th>Central City</th>
<th>Middle Suburbs</th>
<th>Outer Suburbs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
<td>54 per ha</td>
<td>7 per ha</td>
<td>2 per ha</td>
</tr>
<tr>
<td><strong>Auto ownership per household</strong></td>
<td>0.8</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Income</strong></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td><strong>Trips per person</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(no. per day)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work</td>
<td>0.77</td>
<td>0.85</td>
<td>0.83</td>
</tr>
<tr>
<td>Other</td>
<td>0.83</td>
<td>1.45</td>
<td>1.77</td>
</tr>
<tr>
<td><strong>Trip length</strong></td>
<td>8.1</td>
<td>11.1</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>6.1</td>
<td>9.3</td>
</tr>
<tr>
<td><strong>Portion of trips</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>by auto</td>
<td>0.74</td>
<td>0.92</td>
<td>0.84</td>
</tr>
<tr>
<td>by bus</td>
<td>0.13</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>by walking</td>
<td>0.13</td>
<td>0.36</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Transport energy per capita</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(x 10^6 J per av. work day)</td>
<td>40.7</td>
<td>94.0</td>
<td>105.2</td>
</tr>
</tbody>
</table>

Source: Fels and Munson (1974)
the observed difference between the three areas were considered to be due to:

(a) The middle suburbs residents travel twice as many kilometres per day as central city residents and outer suburbs residents another 50 percent more; this is due to both a larger number of trips and a longer average distance for each trip as the density declines.

(b) The only significant public transport usage occurs in the central city journey to work (13 percent of trips).

(c) Walking is 31 percent of work trips and 36 percent of other trips in the central city. Although there is also high walking in the outer suburbs, they are minor in length compared to the longer vehicle journeys needed in this region.

(d) The number of "other trips" per person per day is correlated with increasing income, and perhaps reflects an affluence factor. There is a possibility however that some walking trips in the complex central city area could be overlooked.

In the study area overall, it was shown that 98 percent of the transport energy use was due to the automobile, though it was responsible for only 66 percent of the trips. The authors suggest that energy conservation would appear to be in the direction of increasing public transport and walking trips as well as making the auto more energy thrifty. Orski (1974) also points out
that great potential exists in the U.S.A. for substituting bicycle trips for auto trips. This is because 40 percent of urban work trips made by car are less than 6km. Safety problems, he suggests, are the major impediments at the moment.

An empirical study of 50 cities around the world was made by Newman and Hogan (1979). They confirmed the density-energy relationship and also found that low density cities (less than 35/ha, but generally 20/ha or less), had much less public transport utilization than medium density cities (35 to 135/ha) like those found most frequently in Europe. They suggested that the mechanism for the lower energy usage in these medium density cities was due to:

(a) greater use of more efficient public transport.
(b) shorter trips because land use patterns place functions closer together, and
(c) greater use of walking.

Further data to support this has been presented by Cheslow (1978), who found in several U.S. cities that higher densities decreased the usage of automobiles, whilst increasing the proportion of public transport, decreased the distance travelled by cars, and suggested much greater use of walking. Pushkarev and Zupan (1977) also provide supportive data from their U.S. urban land use and transport study. It suggests that cities with 5 to 25 people per hectare densities are associated with
insignificant public transport, and in those with 25 to 90/ha densities, public transport increases sharply so that more than half the trips are made by public transport in the latter end of this range.

The modal split between private car, public transport and walking is also clearly seen in its relation to density by a study of San Francisco by the Bay Area Transportation Study Commission (1969). Their results are summarised in Table 3.39 below.

Table 3.39 Relationship of urban density to modal split in San Francisco

<table>
<thead>
<tr>
<th>Residential Density (dwellings per acre)</th>
<th>(Approx. Urban Density persons/ha)</th>
<th>Trips per Person/Day</th>
<th>Distribution of trips by mode (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>under 10</td>
<td>under 12</td>
<td>2.7</td>
<td>Auto 81.9 Transit 4.9 Walk 13.2 Total 100</td>
</tr>
<tr>
<td>10-30</td>
<td>12-36</td>
<td>2.5</td>
<td>Auto 67.0 Transit 13.8 Walk 19.2 Total 100</td>
</tr>
<tr>
<td>over 30</td>
<td>over 36</td>
<td>3.4</td>
<td>Auto 41.9 Transit 21.0 Walk 37.1 Total 100</td>
</tr>
</tbody>
</table>

Source: Bay Area Transportation Study Commission (1969),

This table clearly shows how the use of the private vehicle in San Francisco diminishes with increasing urban density and the use of transit and walking rises to fulfill travel demands.

Apart from empirical studies there have also been a number of simulation studies which examine the density, energy and emissions relationship using computer based models. The pioneering simulation study in land
use, urban form and their implications for energy and emissions was The Costs of Sprawl Study, by the Real Estate Research Corporation (1974). This study was a simulation of several urban patterns based on data that was available from urban areas which most resembled the lay-outs described. The two extremes in land use are detailed in Table 3.40 showing their basic characteristics.

Table 3.40 Comparative land use, transport energy and emissions characteristics for two alternative urban development patterns.

<table>
<thead>
<tr>
<th></th>
<th>Low Density Sprawl</th>
<th>High Density Planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing layout</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% Single Family Conventional</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>25% Single Family Clustered</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Clustered Town Houses</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Walk-up Apartments</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>High rise Apartments (6 storey)</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>17.8/ha</td>
<td>37.5/ha</td>
</tr>
<tr>
<td>Vehicle kms per capita per year</td>
<td>9,592 km</td>
<td>4,823 km</td>
</tr>
<tr>
<td>Motor spirit consumption per capita per year (MJ)</td>
<td>5,450</td>
<td>2,740</td>
</tr>
<tr>
<td>Emissions, kg per capita per year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>20.29</td>
<td>10.20</td>
</tr>
<tr>
<td>HC</td>
<td>2.45</td>
<td>1.23</td>
</tr>
<tr>
<td>NOx</td>
<td>2.39</td>
<td>1.20</td>
</tr>
</tbody>
</table>

The urban forms are characterised at a neighbourhood level based on 10,000 homes, rather than on overall patterns of the total city. The low density sprawl pattern is based on the \( \frac{1}{4} \) acre block in grid formation with some of the homes clustered; the density (17.5 per ha) is higher than many actual suburbs of this design, as it is assuming complete development. The high density planned option has a density (37.5 per ha) equivalent to many of the less dense European cities, many central city areas on the U.S. East Coast and inner areas of Melbourne and Sydney. It has a planned clustering of homes with good access to shops and other community services and a larger quantity of public open space than in the low density option.

The results showed a much higher generation of vehicle kms per capita in the low density sprawl. Concomitant with this was a higher per capita consumption of transport energy, and a higher generation of motor vehicle emissions. The difference was of the order of 50 percent in each parameter and is lower for each of the options in between these two extremes. Thus density changes were suggested to offer some 50 percent savings in energy and 50 percent reduction in emissions.

An Australian simulation study found even greater savings possible. Four possible future cities were studied (Maunsell, 1975) and their characteristics are presented in Table 34.
Table 3.4: A simulation of four possible future cities - Travel, Energy and Emissions characteristics

<table>
<thead>
<tr>
<th>Urban Form</th>
<th>Density (/ha)</th>
<th>Vehicle km (per capita per year)</th>
<th>Energy (MJ per capita per year)</th>
<th>Emissions (kg per capita per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Public</td>
<td>Private</td>
<td>Total</td>
</tr>
<tr>
<td>Spread</td>
<td>15</td>
<td>184</td>
<td>2160</td>
<td>2344</td>
</tr>
<tr>
<td>Cluster</td>
<td>3</td>
<td>1720</td>
<td>1096</td>
<td>2816</td>
</tr>
<tr>
<td>P.R.T.</td>
<td>30</td>
<td>1725</td>
<td></td>
<td>1725</td>
</tr>
<tr>
<td>Compact</td>
<td>75</td>
<td>73</td>
<td></td>
<td>73</td>
</tr>
</tbody>
</table>

Source: Maunsell (1975).
"Compact City" used one sixtieth of the transport energy and produced one fifteenth of the emissions as in "Spread City". However this study was meant to provide a vision of possible new cities rather than being based on any actual urban areas and thus the high density clustered housing of "Compact City" could assume the majority of travel would be by foot or on rapid shuttle trains without considering its actual feasibility. It can certainly be criticised on this basis. An assumption of no private vehicle usage is unlikely to ever be realised.

Sharpe et al (1974, 1977) on the other hand considered the actual urban area of Melbourne and examined a range of potential future urban land uses to see how much energy was involved. Each of the options was a feasible direction that could be taken by Melbourne including outer fringe development, corridor development, satellite development all at the same density and inner area redevelopment at higher density. Their conclusions show that increased density would save energy but by less than 10 percent in the year 2000. Models such as these however, have been criticised by Grigg (1974) for simply "reproducing the status quo". On the basis of other studies, variations in energy usage between cities of different densities offer much greater savings and it may be that some of the feedback mechanisms of higher density into travel patterns were not written into Sharpe's model. It is clear that such simulation studies can appear to be of great value to planners but they need
essential functions in decentralised urban centres might appear to provide an opportunity for reducing other trip lengths. A number of simulation studies have examined this option, for example, Harkness (1973) suggests that average commuting distances could be lowered 20 percent by locating new jobs in twelve satellite centres instead of the central city. This result builds on earlier work by Hemmens (1967) and by Schneider and Beck (1973), which suggested that shifting 1/3 to 1/2 of the jobs from the central city will save 50 percent of travel requirements.

The methodology used in these studies has been seriously questioned by Gilbert and Dajani (1974), but more importantly other simulation studies and most of the empirical data suggest that in fact, the effect of centralisation is to reduce travel demands.

Centralisation is the degree to which a centre has been allowed to develop where work and all other forms of urban activity are concentrated. Centralisation does not necessarily mean that the central city is all office blocks, the inner suburbs laced with other work places and the outer suburbs all houses, as in many modern Western cities. It can mean the interspersion and clustering of houses, jobs, shopping and community centres throughout the urban area (there is some evidence that such land use reduces travel requirements (Markovitz, 1971)); however it does mean that there should be an increasing concentration of all this activity as one moves toward the centre. This can also be expressed as a density gradient of all urban activity which is very
high in the centre and falls away on all sides. The density would also be high on each side of the radial transport links.

The studies by Edwards and Schofer (1976), Romanos (1978) and Sharpe et al (1978), all point to the need for centralisation of urban facilities with radial transport links, rather than a dispersion or scattering in numerous directions.

The mechanisms for this can be seen in terms of journey length and mode of travel. Zahavi (1976) makes the point that urban development based on higher centralisation only leads to longer journeys if density stays the same. On the other hand, scattered work and housing or decentralised patterns, only lead to shorter journeys if people actually live near their work. Furthermore, even if shorter work journeys do occur, other non-work journeys could be very long as scattered social, school, shopping or recreational destinations may be a long way from home.

It has been an aim of planning in decentralised cities to minimise this by providing most facilities in the suburbs. Apart from the considerable expense of doing this (e.g. infrastructure costs), a 'cities in the suburbs' policy (Carver, 1962) is probably counter to one of the great reasons for a city: the diversity of urban activities that is available to its residents. To adapt the 'cities in the suburbs' approach seems to suggest that individuals are just consumers of basic urban services. The
centralisation of urban activity allows an intensely used area to develop where access is provided to the full range of urban diversity. Once a second or third centre is established which attempts to mimic the original centre, then people may find some of their needs in one centre and some in another—hence their journey lengths may be longer overall. It could also be suggested that the character and history associated with many old city centres could never be replaced by secondary centres. Thus their attraction may still remain regardless of whether other centres are available. Whatever mechanism is actually applying in a city it is clear that a simplistic model which suggests greater centralisation, therefore longer distance on a geometric basis, will be inadequate. For example, Paterson (1977) discusses a range of reasons why the location of work near homes in the suburbs does not lead to shorter travel requirements. He suggests that as non-work trips account for 3/4 of all trips over a full week, that people locate for many reasons other than access to work.

Perhaps of more importance than journey lengths to energy and emissions, is the mode of travel, and here it has been shown that the more centralised is urban activity, then the more public transport will be used. Public transport requires high volumes to be viable and a centralised city allows this to occur by gathering together a range of trip purposes into a single destination. The importance of high public transport patronage in determining its effectiveness in reducing energy and
emissions was discussed earlier. Conversely, the more dispersed are urban activities, the more necessary it is to have and to use private transport. A range of trip purposes with a range of destinations cannot be served efficiently by public transport.

The most important empirical study on centralisation is by Thomson (1978), who examined cities around the world including thirty cities in detail, in an attempt to understand their transport characteristics. Although not directly seeking to provide information on transport energy and emissions the study is a major step in understanding the land use patterns which generate high or low vehicle usage and how it is possible to develop better public transport utilisation.

The main thrust of Thomson's work is that the amount of vehicle kms per capita (i.e. the degree of private vehicle usage), is controlled by the degree of centralisation in the city. In Thomson's analysis, centralisation is the most important transportation characteristic of a city. Where urban activity is concentrated in a centre there are shorter journey distances; if the city disperses and becomes decentralised then journey distances are lengthed:

The effectiveness of the sub-centre is as a location for sub-central (or sector) functions, not for central functions. The sub centre is ideal for certain types of organization whose contacts can be largely confined to one sector of the city. These are described as sub-central functions. If, on the other hand, central functions are put in a sub centre, they will
generate more traffic (i.e. more person-kilometres and ton-kilometres) than in the city centre and this traffic will be difficult to serve as efficiently as city centre traffic unless the structure of the transport system is radically changed. One must reject therefore the idea that sub-centres can provide an easy solution to the bursting city centre when this condition arises from genuine central functions. "Great Cities and Their Traffic", J. Michael Thomson (1978).

In addition, a range of other factors come into play when a city is centralised which also affect the generation of traffic - these include the availability of parking facilities, the provision of roads and the commitment to public transport.

The size of a city is not a primary variable in Thomson’s analysis, but rather more important is the intensity of land use; the size of a city can help to intensify land use if the central city is given the primary role, but if decentralisation is the main aim, then city size is irrelevant. The two extremes in this are London and Los Angeles, which are both large, but have totally different land use and transport characteristics. Los Angeles, with 2 percent of journeys by public transport had an average distance for the journey to work of 9.7km and an average for all journeys of 9.0km in 1960; this was predicted to rise to 15.3km and 12.7km respectively, by 1980. By comparison London, with 54 percent of its journeys by public transport has an average of 6.0km for work trips and much less for other trips (Thomson, 1978).
Table 3.42 summarises most of the major characteristics considered by Thomson to define a city and its transport patterns.

Thomson suggests that when the number of jobs in the city centre exceeds 50,000 to 100,000 then the use of cars for commuting becomes limited by lack of space. The degree to which public transport is actually utilised to allow the city centre to grow depends then on (a) the availability of parking spaces (and the enforcement of parking prohibition), (b) the provision of roads to and in the city centre, and (c) the degree to which public transport is provided and promoted.

These generalised relationships are given substance by an analysis of several archetypal cities. They are briefly summarised and the urban land use patterns for each city type are portrayed in figures 3.25-3.28.

Archetype A - Full Motorisation

This urban form has only a small city centre (no more than 100,000 workers) which is mainly a financial quarter. The traditional centre has been abandoned and the employment, shopping and entertainment has been dispersed into small centres or no centres at all. There is therefore no need for a strong radial road system but instead a grid pattern is dominant. Housing is almost all on ¼ acre lots with freeways within 6kms of every house and extensive arterial roads. The only public transport available for such a dispersed urban form would be buses.
<table>
<thead>
<tr>
<th>City</th>
<th>Jobs in City Centre as a proportion of metropolitan population</th>
<th>Jobs in City Centre (x 10^3)</th>
<th>Area of City Centre (km^2)</th>
<th>Jobs per km^2 of City Centre (x 10^3)</th>
<th>Km of Urban Railway</th>
<th>Travel Intensity per km^2 on work journeys by all modes</th>
<th>By car</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Centralized Cities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paris 1970</td>
<td>17.9%</td>
<td>1151</td>
<td>26.0</td>
<td>44.3</td>
<td>464</td>
<td>127</td>
<td>24</td>
</tr>
<tr>
<td>Washington 1968</td>
<td>17.6%</td>
<td>212</td>
<td>10.5</td>
<td>20.3</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>London 1973</td>
<td>16.3%</td>
<td>1200</td>
<td>7.3</td>
<td>43.9</td>
<td>962</td>
<td>130</td>
<td>14</td>
</tr>
<tr>
<td>New York 1970</td>
<td>15.0%</td>
<td>2000</td>
<td>22.3</td>
<td>89.7</td>
<td>3630</td>
<td>239</td>
<td>17</td>
</tr>
<tr>
<td>Tokyo 1973</td>
<td>10.9%</td>
<td>1259</td>
<td>16</td>
<td>78.7</td>
<td>1681</td>
<td>178</td>
<td>11</td>
</tr>
<tr>
<td>Toronto 1967</td>
<td>10.7%</td>
<td>231</td>
<td>12.8</td>
<td>82.5</td>
<td>344</td>
<td>78</td>
<td>29</td>
</tr>
<tr>
<td>Hamburg 1969</td>
<td>9.4%</td>
<td>230</td>
<td>5.0</td>
<td>46.0</td>
<td>274</td>
<td>58</td>
<td>16</td>
</tr>
<tr>
<td>Stockholm -</td>
<td>9.2%</td>
<td>120</td>
<td>9.0</td>
<td>13.3</td>
<td>340</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>Sydney 1966</td>
<td>9.0%</td>
<td>230</td>
<td>2.6</td>
<td>8.5</td>
<td>251</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>Athens 1971</td>
<td>8.2%</td>
<td>210</td>
<td>4.9</td>
<td>42.9</td>
<td>26</td>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td><strong>Less Centralized Cities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boston 1963</td>
<td>10.0%</td>
<td>257</td>
<td>8.8</td>
<td>29.2</td>
<td>37</td>
<td>49</td>
<td>20</td>
</tr>
<tr>
<td>San Francisco 1965</td>
<td>9.4%</td>
<td>283</td>
<td>12.7</td>
<td>22.3</td>
<td>187</td>
<td>45</td>
<td>29</td>
</tr>
<tr>
<td>Copenhagen 1971</td>
<td>8.8%</td>
<td>150</td>
<td>3.2</td>
<td>46.9</td>
<td>125</td>
<td>47</td>
<td>13</td>
</tr>
<tr>
<td>Goteborg 1970</td>
<td>8.8%</td>
<td>40</td>
<td>0.9</td>
<td>44.4</td>
<td>115</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>Chicago 1968</td>
<td>8.0%</td>
<td>547</td>
<td>2.6</td>
<td>210.4</td>
<td>136</td>
<td>191</td>
<td>31</td>
</tr>
<tr>
<td>Vienna 1971</td>
<td>7.9%</td>
<td>135</td>
<td>3.0</td>
<td>43.3</td>
<td>58</td>
<td>44</td>
<td>7</td>
</tr>
<tr>
<td>Melbourne 1964</td>
<td>6.7%</td>
<td>160</td>
<td>2.6</td>
<td>61.5</td>
<td>477</td>
<td>56</td>
<td>17</td>
</tr>
<tr>
<td><strong>Decentralized Cities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baltimore</td>
<td>4.9%</td>
<td>-</td>
<td>-</td>
<td>52.0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pittsburgh</td>
<td>4.6%</td>
<td>-</td>
<td>-</td>
<td>45.5</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Milwaukee</td>
<td>4.5%</td>
<td>-</td>
<td>-</td>
<td>22.8</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Buffalo</td>
<td>3.8%</td>
<td>-</td>
<td>-</td>
<td>19.1</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>3.5%</td>
<td>41</td>
<td>5.6</td>
<td>7.3</td>
<td>0</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Denver</td>
<td>3.0%</td>
<td>42</td>
<td>1.6</td>
<td>26.3</td>
<td>0</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>Detroit</td>
<td>2.0%</td>
<td>80</td>
<td>2.8</td>
<td>28.6</td>
<td>0</td>
<td>27</td>
<td>15</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>1.6%</td>
<td>157</td>
<td>5.0</td>
<td>31.4</td>
<td>0</td>
<td>40</td>
<td>25</td>
</tr>
</tbody>
</table>

The cities analysed by Thomson with this pattern are Los Angeles, Detroit, Denver and Salt Lake City.

Archetype B - Weak Centre Strategy

Historically, these cities have had a strong centre but it has been weakened by suburbanisation due to the automobile. It has a significant but strictly limited city centre which can reach as many as 250,000 workers. It has a radial road network with most city workers travelling by car. This is supported by a public transport system which could include a train service. Most jobs are in the suburbs and are served by high capacity ring roads, with strategic suburban centres wherever radial roads cross ring roads. Cities with this structure examined by Thomson are Melbourne, Copenhagen, San Francisco, Chicago and Boston. All of these cities are caught between the conflicting pulls of Archetype A and Archetype C urban forms.

Archetype C - Strong Centre Strategy

These cities have well established important central cities which have not been diluted by the weak centre compromise to private transport. The city structure is therefore based on radial roads and public transport lines. Ring roads are only provided to divert through traffic around the centre. The public transport service is supplemented often by a central city underground service providing the necessary distribution function in the city. The central city workforce can be greater than 500,000 with strategic sub centres along the
transport routes. In these cities public transport is a major part of the urban transport system. Cities analysed with this structure were Paris, Tokyo, New York, Athens, Toronto, Sydney and Hamburg.

Thus Thomson has highlighted the question of centralisation in urban land use. This is of course linked to density as high centralisation implies high density, but it widens the density concept to include other than the concentration of housing.

The study by Berry et al. (1974) also confirms the conclusions of Thomson with specific reference to environmental parameters. They conclude after their analysis of 76 U.S. cities that:

(1) The core-oriented urban region with a radial transportation network and a steep density gradient,
   a) displays greater intensity of land use, a lower percentage of land developed and used for residential and commercial purposes and more open space, and
   b) as a consequence of this land use mix and pattern, has superior air and water quality to:

(2) The dispersed urban region, which has a less focussed transport network and lower, more uniform population densities. This urban form
   a) displays urban sprawl, with a higher percentage of residential and commercial land use and less open space than in the core-oriented case, and
   b) as a consequence of this land use mix, has inferior air and water quality.
Figure 3.2a Archetype A: Full motorisation

Figure 3.2b Archetype B: Weak-centre Strategy
Figure 3.27 Archetype C: Strong-centre Strategy

Figure 3.28 Archetype E: Traffic Limitation Strategy
Thus, on the basis of the two parameters discussed so far – density and centralisation – two urban forms may be pictured which produce extremes in the consumption of transport energy and generation of vehicular emissions. They may be called "Sprawl City" and "Tent City". A visual impression of these two forms is shown in figure 3.

**Figure 3.29 "Sprawl City" and "Tent City"**

Low density, dispersed, grid-based
"SPRAWL CITY"
High transport energy and emissions.

High density, centralised, radial-based
"TENT CITY" or "Stellar Pyramid City"
Low transport energy and emissions.

One other matter of relevance concerning these two basic urban forms is that Voorhees et al (1971) in a study of different urban patterns and their relationship to air quality favoured high density corridor
development along radial links to a central city as in the "Tent City". The reason was that although there were high residential and industrial concentrations, the large green areas bordering the development corridors provided greater opportunities for pollutant dispersion than in any more sprawled development. This urban form also means the residents have much closer access to the green wedge/rural area than in a sprawl development.

The other way in which land use changes can be made to affect energy and emissions is on a much more micro-level than the broad urban form patterns discussed so far, this factor is the use of a range of traffic restraint methods.

(c) Traffic Restraint

From the analysis by Thomson (1978) already discussed, it is clear that specific methods for restraining traffic are an essential part of achieving a strong city centre. In fact he has another archetypal city which he analyses and its main emphasis is on traffic restraint.

Archetype E* - Traffic Limitation Strategy

These cities have all the characteristics of the strong centre cities of Archetype C, with the extra factor

* Thomson also discussed Archetype D - Low Cost Strategy which is specifically about cities in developing countries without the capital to build high capacity transport networks. As it is not relevant to this study it is not pursued.
of specific traffic restraints. They have strong centres, well served by public transport including rail or some other segregated system, with a hierarchy of smaller centres that have sectoral, suburban and neighbourhood functions. The major restraint on private traffic is that the road system is not designed for high capacity entry to the centre. Instead, strong radial public transport links are supplemented by motorways which are generally outer ring roads designed to collect and move people out of the city but not to provide access into the central city. Other specific traffic restraints consist of (a) low parking availability, (b) prohibitions in certain streets, and (c) extensive priorities for buses, cyclists and pedestrians.

Cities analysed with these characteristics were London, Singapore, Hong Kong, Stockholm, Vienna, Bremen and Goteborg.

The major techniques for traffic restraint relate to the availability of roads (which is rarely quantified), road location, and the availability of central city parking (Maycock, 1972; May, 1976; Wigen, 1978). Thomson gives a range of parking availability per central city workforce (Table-3.43)

Thomson generates an important rule in understanding urban transport: the quality of peak hour travel by car tends to equal the quality of public transport. The worse the quality of public transport the worse will
Table 3.43 Parking spaces per central city workforce

<table>
<thead>
<tr>
<th>City</th>
<th>Parking spaces per central city worker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athens (1963)</td>
<td>0.027</td>
</tr>
<tr>
<td>Stockholm ( - )</td>
<td>0.042</td>
</tr>
<tr>
<td>Sydney (1966)</td>
<td>0.101</td>
</tr>
<tr>
<td>London (1971)</td>
<td>0.108</td>
</tr>
<tr>
<td>Vienna (1971)</td>
<td>0.119</td>
</tr>
<tr>
<td>Goteborg (1970)</td>
<td>0.123</td>
</tr>
<tr>
<td>Melbourne (1968)</td>
<td>0.238</td>
</tr>
<tr>
<td>Toronto (1967)</td>
<td>0.251</td>
</tr>
<tr>
<td>Washington (1968)</td>
<td>0.268</td>
</tr>
</tbody>
</table>


be the level of congestion before car owners are prepared to accept public transport. Thus, he suggests, all efforts to improve peak hour travel conditions for cars will generally fail unless public transport is simultaneously improved. Each time the situation is improved for cars, it takes more people from the public transport system and fills the roads to capacity again.

It is not hard to see therefore why Thomson recommends a strategy to directly restrain traffic so that public transport may be given a competitive advantage. In so doing there are likely to be advantages in terms of energy and emissions. To go the other way and improve roads to lower congestion appears only to lead to more
motorists, less public transport support and eventually a worse system for public transport; hence the congestion may in fact end up worse and thus also cause a deterioration in terms of energy and emissions.

Many other authors have recognised this principle in transportation planning, for example:

*Cities that have tried to accommodate cars through ambitious highway building programs have found that streets remain congested, commuting becomes increasingly difficult and the quality of the urban environment continues to erode. Traditional remedies aimed at adapting the city to the car have clearly shown themselves to be ineffectual.* (O.E.C.D., 1974).

Thomson (1978) sees many cities in the world which cannot find the competitive equilibrium between private and public transport. This is most noticeable in cities with dominant radial facilities designed for public transport but where private cars have been encouraged through new access roads and a lack of any central city restraints. Paris for example, he suggests, is being swamped by private cars which are given too much competitive advantage in a city structure not designed for such utilisation.

A study by Cheslow (1978) suggests very strongly the importance of automobile restraints, public transport and urban density in the present energy crisis. He states:
If events evolve so that market forces do not push toward higher densities, then is it necessary to have new government controls? If one believes strongly in the nearness of an energy crisis (as many do) then he probably would want strong government action to tighten zoning laws, control or focus new development within and among cities, introduce auto restraints and increase transit investment. These could be necessary as part of national contingency planning for the crisis.

A study by Watt and Ayers (1974) further confirms the theorem that public transport advantages will lead to lower energy usage. They examined the effects on gasoline consumption in 50 U.S. cities of six factors which are subject to change using feasible urban policies. These factors included: (1) gasoline price, (2) commuter transportation efficiency, (3) city density, (4) city area, (5) city interspersion, and (6) urban freeway availability. They found that the proportion of work trips by public transport (a proxy for 'commuter transportation efficiency') accounted for 61 percent of the variance in gasoline consumption per capita. The only other significant factor was freeway availability which accounted for 12 percent of the variance. Both these factors relate to the question of traffic restraint.

To recommend that cities should actively seek to limit parking in their central city, to build fewer roads and especially not to build roads into and through their central regions, to close off many streets from traffic altogether and so on, is to go against most traffic engineering principles. Roads have been built by traffic engineers to reduce the anticipated growth in
congestion and to improve speeds. The way in which average speeds is seen to effect energy consumption and emissions is examined in detail in Chapter 5. However an O.E.C.D. (1974) report concluded:

It has become increasingly apparent that qualitative origin and destination studies and linear-travel-demand projections have become self fulfilling prophecies.

Schneider (1979) goes even further in his criticism:

Traffic engineering which came into being solely to solve the development problems of a deceptive form of mobility, merely delayed the stark realisation that the automobile used as basic transportation is completely incompatible with the good city. Without traffic engineers the automobile would have demonstrated its utter futility between 1920 and 1940 rather than in the 1970s.

Hensher (1977) expands this and suggests the old criteria of increasing average speed and reducing congestion should be replaced by the criteria of accessibility and energy conservation. To do this he recommends planned congestion:

... there is a good argument to manage congestion as part of a policy of maintaining levels of accessibility in such a way that congestion is not necessarily reduced, but controlled at a particular level. Land use plays a major role here, especially rules on population density. (David Hensher, 1977).

A major empirical investigation of the effects of land use on urban travel in the U.S.A. by Neels, Cheslow,
Kirby and Peterson (1977), supports Hensher's basic contention concerning congestion by reference to average traffic speeds. They state:

One of our findings, for example, was that a major opportunity to reduce vehicle miles travelled was via auto speed, in that trip length was strongly associated with higher speeds. Reducing speeds would mean substantially less aggregate travel.

The literature specifically on energy conservation and emissions control which is written by traffic engineers suggests exactly the opposite to this traffic restraint approach. Because stop-start motoring is poor on individual fuel consumption and produces the highest emission levels they suggest that part of the answer is to speed up traffic and reduce congestion (Evans, 1978; Chang and Herman, 1978).

For example in comparing four U.S. cities Chang and Herman (1978) concluded that Los Angeles with its comparatively freer flowing traffic offers opportunities for fuel savings. They state:

We expect that improvements in traffic quality can reduce travel time which in turn, can directly produce a reduction in fuel consumption ... Therefore improving the urban traffic system by increasing its average speed offers considerable fuel economy benefits.

Such solutions overlook the implication outlined here of further promoting private vehicle use and making it even harder for public transport. Such analyses also
tend to be confined to considering the individual vehicle's fuel economy and emissions, rather than the overall effect of the strategies. If freer flowing traffic does save energy and reduce emissions overall then the evidence should support this. However the evidence so far shows that cities with free flowing traffic have the lowest public transport use, the highest transport energy consumption (e.g. Watt and Ayers, 1974) and the worst emissions problems (e.g. Los Angeles, photochemical smog problem).

It is necessary to further investigate such findings by an analysis of Australian cities, their transport, energy and emissions characteristics and how they correlate with land use patterns. The methodology and results of the Australian Capital City analysis are given in Chapters 4 and 5.
3.3.2 Conclusions to Land Use Review

This review has examined three areas of land use change that offer potential for saving energy and lowering emissions. They will be summarized essentially by referring to a number of people who have assessed these particular urban planning strategies.

a. Density

The use of higher density developments was seen to be associated with lower vehicle dependence, less energy and lower emissions.

As prosaic and unattractive as the terms high density and apartment are today in the United States, only by these means can the city be anything but consumptive, wasteful and unstable. The lesson that America must learn from the last half century of unfortunate urban experience is that the city is necessarily and inevitably a fact of high density (Schneider, 1979).

Low population densities and consequent dispersed built up areas should be avoided since higher densities can provide equivalent access with shorter street lengths, fewer motorized or urban rail trips, lower vehicle speeds and consequently lower road track design standards. It is to be noted that high densities do not necessarily involve "high-rise" buildings (World Bank, 1976).

(b) Centralisation

To centralise activities increases the proportion of trips by public transport and may shorten journey distances.
It is also associated with a range of other advantages.

In North America and Australasia too many hospitals, universities, technical and teacher's colleges and high schools and trade schools, suburban office developments, supermarkets, filling stations, theatres, cinemas, pool halls, squash courts and other high and low entertainments have been scattered like confetti along main roads, through characterless expanses of housing, in the name of decentralization... Not houses and gardens, but that formless uncentred litter of facilities on and off public transport routes... is the true and disastrous meaning of "suburban sprawl". Policies of recentralisation should try to gather those activities to support each other... in strong town centres with their own local transport, local government, day and night life, and sense of identity (Stretton, 1976).

c. Traffic Restraint

To restrain private vehicle traffic is to give a competitive advantage to public transport and perhaps eliminate some unnecessary journeys. This policy has received little support in the past but there is evidence of a change in attitude.

By now there is firm evidence that limiting the use of automobiles in urban areas is politically, commercially and technically feasible. Public opinion surveys in France, Sweden, Germany and the United Kingdom have shown that people strongly favor a car-free environment. Merchants are increasingly coming to conclusion that streets freed of traffic bring concrete benefits in terms of bigger crowds, more customers, and increased sales. Perhaps the most convincing proof of the practicality and public acceptance of traffic restrictions is their growing use in the cities of OECD countries. An investigation recently carried out by the OECD Sector Group on the urban environment disclosed that more than 100 cities have banned traffic from portions of their central districts and dedicated them to pedestrian use (OECD, 1974).
According to the literature these three urban planning strategies would appear to offer considerable scope for improving the energy and emissions problems. To make a more quantitative assessment of how much can be achieved in this way it is necessary to make a detailed analysis of present energy and emissions patterns and the land use patterns which occur with them.
4.1 HYPOTHESES

The review of literature in chapter 3 examined the range of technological and land use options which could be employed to lower energy consumption and reduce emissions.

On the basis of this review a number of hypotheses have been generated which will be further examined in this study. Numerous other hypotheses especially ones related to technological changes, could have been pursued but the following were the only feasible ones to consider in the limited time available:

(a) That short term small scale changes in motor vehicle technology of the add-on type are likely to have only minimal effect on energy and emissions.

(b) That the option of encouraging more widespread use of electric public transport technology has some potential for energy and emissions improvements.

(c) That policies to encourage free-flowing traffic do not necessarily lead to overall fuel and emissions reductions.
and (d) that land use changes offer considerable scope for reducing energy and lowering emissions.

A series of data collection procedures were thus developed in order to test these hypotheses. The first hypothesis was examined by a range of tests on some new electronic ignition systems, which are just one of a wide range of devices examined in the literature review.

The second and fourth hypotheses required an examination of Australian cities to investigate how they used transport energy and to obtain their levels of vehicular emissions. Detailed data collection was thus made to first determine how efficient private and public transport modes are, and second to examine how vehicle use and energy/emissions patterns varied with different land use patterns. The third hypothesis was examined partly through the analysis of the electronic ignition testing data and partly through data gathered on Australian cities from a variety of sources.

The various methodologies used are examined in detail in the next section.
4.2 STUDY OF A SMALL SCALE TECHNOLOGICAL CHANGE -
THE ELECTRONIC IGNITION

4.2.1 Introduction

The substantial fuel price rises in Australia early in 1979 and subsequent widespread media coverage of the oil crises in general led to a great deal of attention being paid to the fuel economy of motor vehicles. A full discussion of this general situation was given in Chapter 2. New car advertisers began to include fuel economy ratings in their slogans, and there was renewed discussion of many fuel saving devices particularly in press advertising. Claims of fuel economy improvements (as high as 20%) by a distributor of electronic ignitions (Everett International Pty Ltd) generated considerable discussion over the validity of such claims. The Royal Automobile Club of W.A. among others asserted that in their experience electronic ignitions and other devices do not improve fuel economy and give few other advantages to the motorist.

To clarify these conflicting views a programme of controlled vehicle testing was established to assess the effect on fuel economy and emissions of two types of electronic ignitions: a reactive discharge system and a magnetic triggering system involving removal of the contact breaker points from the distributor. Most attention is paid to the
fuel economy and reduced maintenance benefits of electronic ignitions in the popular press, however an effect on emissions should follow from any alteration to the combustion process. Thus a testing programme was also established to assess the electronic ignitions' effects on exhaust emissions.

The fuel economy testing procedures were also seen as an opportunity to examine some other factors which influence the fuel consumption of a motor vehicle: patterns of trip making in everyday use and driving conditions, particularly average speed. These factors have some implications for energy conservation and emissions reduction through their relationship to lifestyle and traffic management. Examination of these factors was not part of the original hypothesis but consideration of them occurs as a logical outcome of the way some of the data has been presented. They are also relevant in discussing the meaning of the test results.
4.2.2 Methodologies

(a) Energy

(i) Vehicles and Instruments

The testing programme involved the use of three vehicles:

* A 4-cylinder 1600 cc Subaru 4-wheel drive station wagon with manual transmission.
* A 6-cylinder 3050 cc Holden sedan with manual transmission.
* An 8-cylinder 5210 cc Valiant sedan with automatic transmission.

Each vehicle was fitted with an OVAL FUEL PET fuel meter (LS 4150) with digital display capable of reading fuel usage in 10ml increments with an accuracy of ±2%. The accuracy of the fuel meter was checked before installation by passing three 500ml increments of water measured using a volumetric flask through the fuel flow meter. The measured volumes on the digital display in each case were within the stated limits of accuracy.

During the course of the testing each vehicle was fitted with two makes of electronic ignition: a SPARKRITE SX 2000 reactive discharge
system(1) which simply bolts onto the coil and involve no adjustment to any component of the ignition system (it has a simple on-off switch which enables quick return to normal ignition), and a MOBELEC MAGNUM contactless electronic ignition. The latter system involved replacing the conventional mechanical point breaking system with a magnetic triggering device. This also necessitated resetting of the spark timing to ensure optimal performance.

Before testing on the standard route commenced a number of important factors were controlled:

(1) All cars were tuned and timed to manufacturers' specifications and given a new set of spark plugs and breaker points.

(2) Thorough checking was also carried out to ensure the electrical system was in good order. Faulty or weak points in electrical systems are highlighted by high voltage electronic ignitions and lead to poor performance.

(3) In the case of the MOBELEC tests, the timing had to be slightly altered.

(1) two SPARKRITE SX 2000 electronic ignitions were kindly loaned by EVERETT INTERNATIONAL Pty Ltd., PERTH.
(4) All testing was commenced with the vehicles fully warmed up. This eliminates the cold start fuel penalty which is more severe on cold days.

(5) All vehicles were started with no less than three-quarters of tank of petrol as mentioned above.

(6) Efforts were also made to ensure that the vehicles' condition remained as close to constant as possible. For example spark plugs and points were checked periodically and tyre pressures were maintained.

(7) Vehicles were tested firstly with normal ignition and secondly with the electronic ignitions throughout the course of testing.

It is obviously impossible to control all factors of the vehicle system in road testing, but for the short duration each vehicle was tested, the effects of changes due to wear and tear would have been minimal. Easingwood-Wilson, Nowottny and Pearce, (1977) considered that near maximum repeatability in a road test can be achieved by controlling as closely as possible the factors of: (1) Driver behaviour, (2) environmental conditions, (3) testing time, i.e. day and time of day, and (4) fuel measurement, i.e. fuel metering device rather than a brim-to-brim method. Attempts were made in this study to control all these factors.
(ii) Testing Methods

Assessing the effects on fuel economy of the electronic ignitions was divided into two stages.

(1) Standard Route

The first stage involved the use of a pre-determined standard route of 75.3km through the Perth Metropolitan Area which was driven twice with normal ignition and twice with the two types of electronic ignition for each vehicle. The route was chosen on the basis of a number of considerations. These were:

(a) route length - the distance travelled had to be sufficiently long to ensure that any difference in fuel consumption between tests, attributable to the electronic ignition could be determined, and short enough to be practical from an experimental point of view. It was estimated that a range in fuel economy of between about 5km per litre and 11km per litre might be expected for the vehicles being used. Thus with a 75km route a minimum of about 7 litres and a maximum of about 15 litres of petrol would be consumed. This estimated amount of fuel usage was considered sufficient to highlight any differences in fuel consumption between tests over the route.
(b) As stated in the introduction to this section a number of other factors were examined during vehicle testing, e.g. average speed. It was considered important to attempt to simulate, if only very roughly, the pattern of driving in Perth, so as to achieve a representative sample of driving conditions and average speeds in Perth. The only data available to attempt this simple simulation were from the Main Roads Department's 1976 computer estimates of daily travel in the Perth Statistical Division, by road type. This is shown in table 4.1 along with the corresponding break-up for the 75km route used in this study.

Table 4.1 Comparison of the proportion of daily travel by road type in Perth and the standard route.

<table>
<thead>
<tr>
<th>Road type</th>
<th>Perth</th>
<th>Standard Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeway (including C.B.D.)</td>
<td>4.0%</td>
<td>9.2%</td>
</tr>
<tr>
<td>Expressway and Arterial (excluding C.B.D.)</td>
<td>83.8%</td>
<td>77.7%</td>
</tr>
<tr>
<td>Local suburban (excluding C.B.D.)</td>
<td>8.6%</td>
<td>11.1%</td>
</tr>
<tr>
<td>C.B.D. excluding freeway</td>
<td>3.6%</td>
<td>2.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0%</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

Although the values do not correspond precisely, the standard route was considered sufficiently similar to the distribution of travel by road type in Perth for the purpose of this study.
It should be noted that M.R.D. 1976 estimates do not take into account the Mitchell Freeway which more than doubled the amount of freeway in Perth.

The standard route was driven as close as possible to the same time of day for each vehicle - generally evening peak hours\(^{(1)}\). This was done in an effort to simulate 'worst' traffic conditions in Perth and thus gain an idea of the lower range limit of average speeds experienced in Perth driving during congested periods. The same driver was used for the same vehicle to minimise the expression of driver behaviour changes in the data. All drivers drove "normally with the traffic" (Chang et al., 1976) which meant that no unnecessary hard accelerations, braking or overtaking was made and when in free flowing traffic the speed limit was observed. It is recognised however that the only way to completely eliminate the driver behaviour factor is on a dynamometer-driven driving cycle.

Before the first standard route test was made twenty three points were chosen for collecting fuel consumption, distance and time readings. Distance readings for all trips were taken from the Subaru odometer which, after four trips was found not to vary more than 0.1km over the 75.3km route.

\(^{(1)}\) between 1600 and 1800 hours.
Time readings were taken with a Heuer stopwatch on a continuous basis throughout the trip. The twenty three data collection points corresponded to significant changes in driving conditions throughout the route, e.g. from local suburban to arterial or from arterial to freeway. All data collection was done by a navigator and recorded on a standardised logging sheet for the route.

(2) Normal day-to-day Travel

The second stage in the fuel economy testing was to record patterns of normal vehicle use. This was achieved by recording the trip length and fuel consumption for every trip made in the vehicle over a selected period of time, (often a week, although some flexibility had to be maintained) with and without the electronic ignitions. For this purpose each vehicle was supplied with a number of prepared data logging sheets and instructions were given to ensure each trip was recorded correctly. It was considered that analyses of these data would give an indication of the electronic ignitions' impact on fuel economy during normal vehicle usage and provide a useful basis for comparison with the results of the standard route work.

These data were also collected to examine the fuel economy of individual trips which together
comprise the total travel for any vehicle on the road. Motorists who use the brim-to-brim method for calculating their fuel economy are obtaining an average of all these trips. Many motorists keep log books of their vehicles' fuel consumption using this method, but detailed records of fuel consumption patterns such as those in this study are very rare because the instrumentation required to obtain them is not available in most vehicles.

In addition to these procedures an emissions testing programme incorporating fuel consumption measurements was suggested to the E.P.A. in Victoria for the SPARKRITE ignition only. This is outlined in full in the next section. It was envisaged that this source of data, involving tighter control of experimental variables, would provide an extra comparison to the results of the procedures outlined in (1) and (2) of this section.
(b) **Emissions**

(i) **Stationary Testing**

The emissions likely to be affected by the introduction of an electronic ignition are hydrocarbons or unburnt fuel and to a lesser extent carbon monoxide and nitrogen oxide. The reason for this is related to the processes involved in their formation which were explained in detail in Chapter 3. To provide an expedient way of checking exhaust emissions of HC and CO an HORIBA MEXA 300A INFRA-RED HC/CO ANALYSER was borrowed from the Road Traffic Authority in Perth. This analyser is capable of checking exhaust emissions at idle or with the motor revving in neutral. Emissions testing with the vehicle under load would have required a dynamometer which was not available.

The analyser has its own calibration gas. The cylinder supplied with this analyser was certified as 1.59% CO and 320 ppm, n-hexane, both ± 2%. The error introduced by the calibration gas is thus 1.59% ± 0.03%, CO and 320 ppm ± 6 ppm, HC. The instrument manufacturer specifies an error of ± 2% of full scale scale deflection. These two errors can be considered as additive. Thus the errors on readings from the HORIBA analyser can be summarised by Table 4.2.
Table 4.2 Errors using the HORIBA INFRA-RED ANALYSER

<table>
<thead>
<tr>
<th>CARBON MONOXIDE</th>
<th>HYDROCARBONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readings from 0-2%</td>
<td>Readings above 0-400 ppm</td>
</tr>
<tr>
<td>± 0.07%</td>
<td>± 0.23%</td>
</tr>
</tbody>
</table>

For the range of values of CO and HC in this study, the errors due to the calibration gas and mechanical factors in the instrument were the largest sources of uncertainty.

Despite these relatively large errors introduced by the equipment, an effort was made to maximise the usefulness of the data from these emissions tests by controlling test conditions as closely as possible. The following points summarise the procedure used to check exhaust HC and CO with the HORIBA INFRA-RED ANALYSER.

1. All vehicles were fully warmed up to ensure minimal interference from uneven fuel distribution to each of the cylinders and the effect of increasing temperature on HC and CO emissions. On warmer days the bonnet of the vehicle was raised to avoid overheating.

2. The analyser was calibrated and zeroed as per
manufacturer's specifications and was re-calibrated between repeat testing to ensure maximum precision.

(3) Readings were taken at idle and with the engine revving. In both cases the engine was allowed to stabilise before readings were taken. This was done to ensure that the readings were not transitional, resulting from the change in operation from one condition to another.

(4) Each test (e.g. with electronic ignition on) was repeated. This was done by turning the engine off and recalibrating the analyser. The engine was then turned on again and allowed to stabilise before readings were taken.

(5) Testing vehicles with the SPARKRITE system involved switching the ignition between electronic and conventional operation. However with the MOBELEC system emissions testing was done prior to removing the MOBELEC. Emissions readings were taken as for (1) - (4) above with the MOBELEC installed. The system was then removed and the vehicle reverted to normal ignition which involved re-timing the ignition and setting the points to manufacturer's specifications (dwell angle and gap). Emissions were then tested with the normal ignition operating.

Emissions testing by this method however is of limited value for the purpose of this study, and
is more suited to analysing engine and carburettion faults or for policing CO 'at idle' statutory requirements. The R.T.A. purchased the analyser for this latter purpose.

(ii) **Dynamometer Testing**

Accurate emissions testing of vehicles is an exacting task requiring expensive and sophisticated facilities. This point is elaborated further in this chapter. To overcome this problem another means of assessing the effect on emissions of electronic ignitions was considered.

A programme of emissions and fuel consumption testing for the SPARKRITE SX 2000 electronic ignition was suggested to the Victorian Environment Protection Authority's Vehicle Testing Station in Altona and was subsequently accepted. The large amount of work involved in this programme precluded testing of the MOBELEC system in this way. In addition only one MOBELEC system was available whereas two SPARKRITE systems were on hand.

The proposed programme of testing was as follows.

The Commonwealth Department of Transport, (1978) in an assessment of the effect of emissions
controls on the fuel economy of Australian vehicles tested vehicles from three weight categories: 4 cylinder vehicles less than 1190kg, 6 cylinder vehicles from 1190kg to 1475kg and 8 cylinder vehicles greater than 1475kg. The same vehicle weight categories were chosen for this programme. Figure 4.1 summarises the proposal for each weight category.

Figure 4.1 Outline of proposed electronic ignition emissions testing study submitted to the E.P.A. of Victoria

Each 3 weight categories

<table>
<thead>
<tr>
<th>Manual Transmission</th>
<th>Automatic Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without any emissions controls</td>
<td>With emissions controls</td>
</tr>
<tr>
<td>SPARKRITE</td>
<td>RITE</td>
</tr>
<tr>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>With emissions controls</td>
<td>Without any emissions controls</td>
</tr>
<tr>
<td>SPARKRITE</td>
<td>RITE</td>
</tr>
<tr>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>With</td>
<td>Without</td>
</tr>
<tr>
<td>SPARKRITE</td>
<td>SPARKRITE</td>
</tr>
<tr>
<td>(2)</td>
<td>(2)</td>
</tr>
</tbody>
</table>

As indicated by figure 4.1, the proposed programme would involve sixteen tests for each weight category of vehicle resulting in a total of 48 tests overall. Each test would involve driving the vehicle through the ADR27A driving cycle (hot and cold cycles) which is the mandatory dynamometer driving schedule used for emissions testing in Australia. The purpose of the proposed programme was to gain an understanding of the effects of the SPARKRITE ignition in terms of emissions and fuel consumption, on a large combination
of vehicle weights, transmission types and emissions control systems. The advantage of laboratory based vehicle testing is that it allows a much tighter degree of control over experimental variables than that possible in road testing, and provides a firmer basis for comparative work. It does not however, necessarily provide an accurate simulation of real urban driving conditions.