Potential of Series Hybrid Drive Systems to Reduce Fuel Use and Emissions in Domestic Vehicles

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SUMMARY

Hybrid vehicles use both an internal combustion engine and an electric motor to provide propulsion resulting in reduced fuel consumption and emissions when compared to the conventional approach. In this study computer modelling was employed to assess the potential of series hybrid drive systems to reduce fuel use and emissions in domestic vehicle transport. Selected reference vehicles equipped with conventional drive systems were compared with those same vehicles equipped with a selected range of series hybrid drive system options to assess their potential for fuel use and emissions reduction during two standard drive cycles simulating urban and aggressive driving patterns respectively. The modelling emphasis was placed on efficient drive systems, component downsizing, efficient combustion cycles and control strategies. The computer simulations indicated the potential for significant reductions in fuel use and emissions by domestic vehicles equipped with series hybrid drive systems when compared to domestic vehicles equipped with conventional drive systems. Series hybrid drive systems equipped with a Diesel cycle engine as the internal combustion component of the on-board power source showed the greatest overall reductions. Computer simulations also accounted for the input from the main electrical grid network (for on-board battery recharging) and its effect on fuel use and emissions and found potential for even further reductions particularly in regions where the source of grid electricity has a low environmental impact.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

For the last 100 years the reciprocating internal combustion engine (ICE) powered vehicle and the fossil oil that it is reliant upon has dominated our transport culture. In terms of land-based domestic and commercial transport, we would be completely lost without it. Most goods and services are transported by it. We use it to get to work, pick up the children, do the shopping and for some of us the domestic vehicle is an extension of our personalities. It has become an indispensable business and recreational tool of modern contemporary society.

The conventional ICE powered vehicle initially gave us freedom, the ability to go wherever and whenever we wanted and to do it relatively cheaply. Now, however, our ever-increasing search for more mobility and the transport of goods and services has imprisoned modern society into high levels of emissions, pollution, increasing oil dependence, oil depletion concerns and the creation of resource wars in search of more energy (oil) to pursue our need for travel, transportation and the proper running of a modern society. This is because transport in general registers the most rapid increases in energy consumption and remains almost entirely dependent on oil because of few substitution possibilities to less carbon intensive fuels (IEA, 2000b). In most affluent countries the ICE powered vehicle meets 75 to 80 percent of personal travel (Sperling, 1996a).

Alternatives to conventional transport have been tried in the form of electric vehicles and vehicles with alternative ICE power plants such as gas turbines. However these alternatives have failed to make any impression in the competitive automotive market place. The evidence for this is the fact that essentially all domestic vehicles are powered by either the Otto cycle or Diesel cycle engine (Gruden, 2003b). Reasons for the success of the reciprocating ICE in the domestic transport vehicle market include (Dorfell, 2003a):

- 100 years of research and development;
- have become highly cost-effective in design, manufacture and use;
- cost of fuel refining and distribution is relatively low;
- large-scale investment in manufacturing and infrastructure, over many decades;
- low cost due to high production volumes; and
- alternative fuels or alternative drive systems requires high investment cost that nobody is willing to pay for in a society that is based on cost calculations and

competition.

In Europe 80% of passenger traffic and 75% of goods are transported by domestic vehicles and trucks. Automotive production currently runs at almost 50 million cars per year world-wide. 20 to 25% of world primary energy is involved in mobility (Gruden, 2003a). At present there are approximately 750 million domestic vehicles on the roads of the world and 90% of these are powered by the Otto cycle engine (Gruden, 2003c).

1.1 Approach and Methodology of the thesis

The aim of this study was to evaluate the potential of series hybrid drive system technologies to reduce fuel use and emissions in conventional domestic vehicle transportation. This will be achieved by developing a simplified computer model to predict fuel use and emissions levels in conventional vehicles and in vehicles equipped with series hybrid drive systems. The approach is to make comparisons between a number of conventional vehicles equipped with Otto cycle or Diesel engines with the same vehicles equipped with a number of series hybrid drive system options. The comparisons are made by simulating vehicle operation over two test drive cycles. The two drive cycles simulate typical city driving and typical open road driving patterns respectively.

The overall objective is to assess the potential effect of series hybrid drive systems on fuel use and emissions compared to conventional petrol (Otto cycle) powered domestic transport, and to make comparisons to the emerging Diesel powered domestic vehicle fleet. Diesel cycle powered vehicles have always been more fuel-efficient than their Otto cycle counterparts but have mainly been used in heavy transport. A push toward their use in domestic transport is becoming evident particularly in Europe where they are being seen as an effective option to reduce fuel consumption and therefore oil dependence and to comply with ever more stringent emissions regulations. To this end it is informative to have information on the effectiveness of series hybrid drive system technology relative to the emerging conventional domestic Diesel transport fleet and incorporating Diesel technology as part of series hybrid drive system architecture.

The objectives can be summarised as follows:

- ascertain fuel consumption and emissions of conventional Otto cycle and Diesel cycle ICE vehicle drive systems;

- evaluate series hybrid drive systems incorporating the Otto or Diesel cycle as the on-board power source;
- examine vehicle emissions and fuel consumption using drive cycles that represent city driving and aggressive highway driving patterns;
- ascertain the road loads associated with driving a vehicle (conventional or series hybrid) over the prescribed drive cycle pattern;
- evaluate fuel consumption by both conventional drive systems and series hybrid drive systems;
- asses the emissions species produced and amount by both conventional drive systems and series hybrid drive systems; and
- make comparisons between conventional vehicle drive systems and series hybrid vehicle drive systems with respect to fuel use, emission species, and overall system efficiency.

1.1.1 *Thesis outline*

The following is an outline of the sections contained in the rest of this document:

Chapter 1: Introduction.

This section gives an overview of the issues confronting society with respect to transport, fuel use and emissions. It looks at society's relationships with transport and the effect on the environment, health implications and oil dependence issues. It also looks at ways of reducing fuel use and emissions.

Chapter 2: Current domestic transport technologies.

Technologies that make up the current domestic transport fleet were examined including their relationship with domestic transport, the effect of part load efficiency on fuel use and emissions and current alternatives to conventional ICE powered domestic transport including electric storage vehicles and fuel cell vehicles.

Chapter 3: Hybrid vehicles.

This section defines hybrid vehicles and outlines their advantages.

Chapter 4: Series hybrid drive systems.

Issues specific to the series hybrid drive system are considered and including drive system energy flow comparisons, effect of component down-sizing on fuel use and emissions, adaptability to other potential on-board power source technologies, operational, design and marketing issues and the modelling approach used.

Chapter 5: Reference vehicle model.

The various parameters involved in modelling the reference vehicle are explained including: general vehicle parameters, drive cycles, transmission parameters, road load parameters, fuel use, emissions, system efficiency and model validation.

Chapter 6: Series hybrid drive system model.

Modelling the series hybrid drive system in a vehicle was similar to the reference vehicle but in addition, included battery parameters, electric motor parameters, on-board power source parameters, power controller parameters, vehicle weight parameters, use of grid recharging as well as fuel use and emissions.

Chapter 7: Results and discussion.

This section interprets the predictions created by the model and discusses the various relationships, in terms of fuel use and emissions, between the chosen reference vehicles and the series hybrid drive system options.

Chapter 8: Conclusions and future work.

Conclusions that can be implied from the predicted results are discussed along with the directions that any future work should take.

1.2 The Autocentricity of modern society

The reason the reciprocating ICE has come to dominate land based transport is no fluke. Although the ICE has a poor thermal efficiency (maximum efficiency of approximately 33% for the Otto cycle (CAE, 1996) and 42% for the Diesel cycle (Gruden 2003d)) and has a poor part load efficiency (Nyland et al, 2002a), no other form of potential transport power source has been able to completely replace it.

The conventional domestic ICE powered vehicle has become an integral and indispensable part of modern society making it very difficult to replace. Any potential replacement has to be an equivalent in all (not some) of the following areas:

- practicality;
- flexibility;
- versatility;

- convenience;
- reliability;
- running cost;
- capital cost; and
- market acceptance.

However the advent of concerns relating to local pollution, global warming and health effects due to the emissions from conventional vehicles is forcing a change in the way society approaches the concept of, particularly, domestic transportation. These concerns have resulted in emissions regulations such as the U.S and California emissions standards (MIT, 2004a) that have forced car manufacturers to consider alternative transportation drive sources that are less toxic to humans and the environment.

Domestic transport makes ever-increasing use of non-renewable fossil fuels and the combustion of these fossil fuels in vehicle engines results in ever increasing levels of pollution. Therefore transport technologies that have the ability to significantly reduce vehicle emissions and fuel use must be seen as being of great importance for society.

The efficiency of domestic vehicles has showed steady improvement in recent years however trends leading toward larger, heavier, and more powerful vehicles has offset these efficiency gains, resulting in only minor gains in overall fleet fuel economy (Fig. 1-1). This trend is exemplified by the fact that, although fuel use per unit weight of vehicle has actually declined significantly in recent years, the average vehicle weight has also increased markedly in the same time period (Fig. 1-2) (IEA, 2001b).

Improved fuel efficiency has also been offset by the growth in travel of light duty vehicles. This growth in travel is expected to remain strong into the future implying that the transport sector will continue to be one of the biggest challenges for reducing oil dependence and meeting the Kyoto agreement targets (IEA, 2001b).

Figure 1-1. Fuel efficiency trends of domestic transport over two decades for various countries (IEA, 2001b).

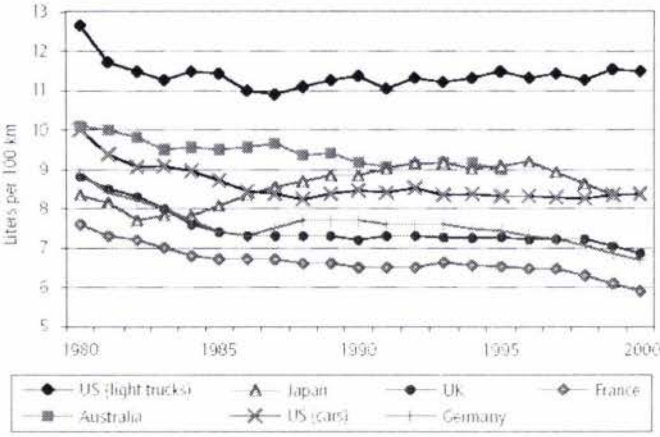
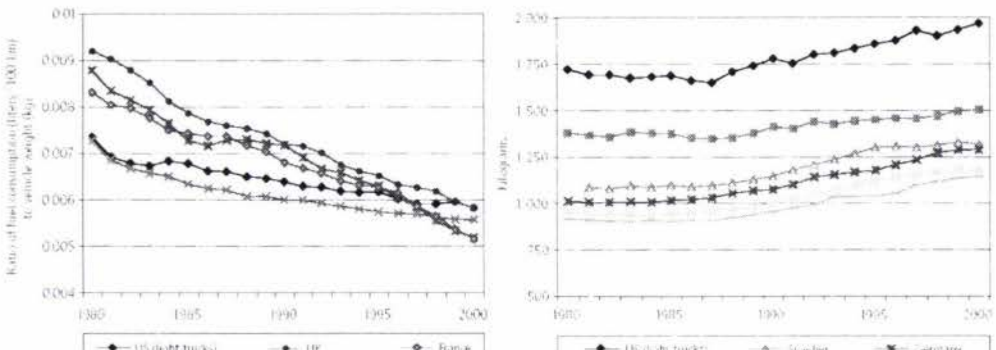


Figure 1-2. Fuel use per unit weight and average vehicle weight for various countries (IEA, 2001b).



People have a love affair with the ICE vehicle that has been built up over the past 80 to 90 years. The domestic ICE vehicle delivers goods and services, we celebrate occasions with it, television programs are devoted to it, and some services are not possible without it (Ambulance, Fire engine). Governments are therefore not expected to make policy decisions that would significantly restrict modes of transportation. The transport sector is a major and necessary component of modern life. It accounts for approximately 25% of world-wide energy usage, and employs a significant proportion of the workforce in many countries. Reductions in fuel use and emissions from the transport sector have to be achieved without major disruptions in transportation patterns (Ortmeyer, 2001).

The modern domestic ICE vehicle gives us the freedom and ability to effectively go wherever we want to, whenever we want to. When that freedom is taken away, life becomes somewhat more difficult. A case in point is the car-less days scenario that was implemented in New Zealand during the oil crisis of the late 1970s. On the 30th July 1979, New Zealand introduced a drastic fuel conservation measure (in addition to banning petrol sales on weekends), the banning of the operation of all privately owned petrol powered motor vehicles weighing 2000 kg or less (except for motorcycles) for one day a week. Suddenly, much more organisation was required to achieve the every day requirements that had become second nature with the automobile. How do I get the family groceries? How do I get to work? How do I pick up the children from school?

Modern cities are built, not with humans in mind, but with the domestic vehicle in mind, including inner city high rise parking buildings, easy availability of support infrastructure, roading networks to get as near as possible to public amenities. "There is plenty of evidence that human settlements have become autocentric with urban design infrastructure and policy making focused on accommodating the car" and "The rapid proliferation of automobiles has a been a major influence on urban and suburban landscapes since the turn of the century" (Sperling, 1996a). It is possible to purchase and eat food without having to get out of your car. In some countries you can go to the movies and not get out of your car. It is difficult to comprehend a modern developed society not dominated by domestic transport.

In other areas of energy use and production there are viable alternatives to the use of fossil oil. In the electricity sector there are alternatives such as coal, gas or nuclear based electricity production as well as the renewable energy alternatives in the form of wind, hydro, solar, and biomass. However in the transport sector, the basis for most personal, domestic transportation is petrol and diesel derived from fuel oil and this will continue to be the case well into the future.

Essentially everything we do and all goods and services, at some point, are reliant on transportation. This transportation requires fuel and most conventional vehicle fuel is derived from fossil oil which is non-sustainable and in addition, the combustion of oil is detrimental to the environment and our health.

Thus, it could be argued that our predilection with ICE powered domestic transportation and our evolutionary need for mobility has led to our current predicament of localised pollution and excessive fuel use.

1.3 Environmental impacts

Domestic vehicle transport is responsible for over half of all urban air pollution and a quarter of all greenhouse gas emissions (Sperling, 1996b). Today's vehicles powered by petrol and diesel produce 90% of carbon monoxide (CO) and 50% of the hydrocarbon (CH) and nitrogen oxide[1] (NO_X) emissions in urban areas (Kyoungho, 2002). These levels are likely to be even higher in regions of low industrialisation.

1.3.1 *Carbon dioxide*

Radiation from the sun penetrates the Earth's atmosphere and hits the surface of the planet where a proportion is absorbed and a further proportion is radiated as heat (infra-red radiation). Under normal circumstances this heat energy would simply be radiated back out into space, however if this radiation is trapped near the surface of the earth by atmospheric compounds such as carbon dioxide (CO_2), this causes the surface to heat up (the so called green house effect) and hence the long term effect known as global warming, which has been attributed to melting ice caps, rising sea levels and temperatures and adverse weather patterns (EPA, 2002b).

Around the world the transport sector is responsible for over 21% of global, human produced, CO_2 emissions (IEA, 2002a). In the OECD it is even higher at approximately 28% (IEA, 2002). In New Zealand we have the highest level of transport emissions in the OECD at 45% of the total (EECA, 2002). We also have the fastest growth rate of CO_2 emissions in the OECD along with the second highest car ownership rate in the world (second only to the United States) (EECA, 2002).

The World Energy Outlook (IEA, 2002b) has indicated that rising oil consumption in the transport sector will be a major source of increased CO_2 emissions over the projected period out to 2030. Transport sector emissions are expected to rise to approximately 25% of global energy related CO_2 emissions. Most of the increase is from road transport (IEA, 2002b). Increasing demand is even more significant in large developing regions such as China and India, due to sharp increases in vehicle ownership, road and freight transport. This will have a further effect on CO_2 emissions (IEA, 2002b).

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[1] For the rest of this document references to NO_X implies $NO + NO_2$

1.4 Health concerns from emissions

Vehicle emissions have been linked with premature death, hospital and emergency visits, some cancers, asthma and other respiratory diseases (Clark and Shay, 2002). European studies indicate that mortality due to vehicle related air pollution is twice the accident road toll (Fisher et al, 2002). In the U.S. it is estimated that 50,000 to 120,000 premature deaths are associated with exposure to air pollutants (Clark and Shay, 2002). We live in a world where smoking is banned in certain areas, industrial processes and the use of hazardous chemicals are closely monitored, yet we condone the use of a transport system that pumps out huge levels of emissions that are just as harmful. We allow this because of the vitality of transport to modern society.

The following is a summary of the types of pollutants/toxins that are present in the vehicle exhaust gas stream as a result of combustion and their health impacts (MFE, 2004) (this dos not include the effect of any exhaust after treatment).

1.4.1 *Carbon monoxide*

- Results from incomplete combustion due to insufficient oxygen or insufficient residence time at high temperature. Excessively lean conditions during Otto cycle operation can lead to incomplete and unstable combustion and high CO levels (EPA, 2002b).
- Reduces the oxygen carrying capacity of the blood since CO binds more readily to hemoglobin than oxygen does, which leaves less hemoglobin available for transferring oxygen around the body. The heart and brain are particularly sensitive (Fisher et al, 2002).
- Results in a decrease in work capacity in healthy adults.
- Can impact on the developing foetus resulting in reduced birth weight in non-smokers.
- Sources are typically Otto cycle motor vehicle emissions (MIT, 2004a).

1.4.2 *Unburned hydrocarbons*

- Significantly affected by fuel composition (Heywood, 1988a).
- Result from incomplete combustion.
- Discharged into the atmosphere when some portion of the fuel remains unburned or just partially burned.

- Include a wide range of compounds, some of which are toxic air pollutants.
- Otto cycle engines are a major source (MIT, 2004a).
- Precursor to ozone creation (toxic) and smog formation.
- Are a known infrared sink (EPA, 2002b).

1.4.3 *Oxides of nitrogen*

- Occur directly from combustion processes and as a result of the conversion of NO gas in the atmosphere during interaction with the exhaust gas stream.
- Concentration during combustion depends on combustion temperature, fuel composition, air/fuel ratio and combustion reaction time (crucial for the Diesel cycle) (Gruden, 2003b).
- Are linked with premature death, hospital and emergency department visits aggravated asthma and other respiratory problems, the elderly being particularly susceptible.
- Typical sources are motor vehicle emissions (particularly the Diesel cycle).
- Can form nitric acid (toxic) with water in the eye, lung, mucus membrane and skin.
- Long term exposure to nitrogen oxides increases susceptibility to respiratory infections resulting in lowered resistance to such diseases as pneumonia and influenza.
- Asthmatics exposed to high concentrations of NO_x can suffer lung irritation and potentially lung damage.
- Contributes to acid rain, nutrient overload that deteriorates water quality, and fine particulate matter formation (increases haze and decreases visibility) (Bushanam et al, 2004).
- Reacts with common organic chemicals and ozone to produce a variety of toxic products.
- Is a known infrared sink (EPA, 2002b).

Emissions produced by domestic vehicles are felt most where there is the highest concentrations of these vehicles – urban areas.

1.5 Oil dependence

The IEA (2000c) has indicated; "Oil consumption has become a major policy concern in the context of both increasing oil-import dependence and rising CO_2 emissions.

Transports central role and its deep influence on daily life make rapid changes difficult to achieve. Its weak responsiveness to energy price movements and the turnover of its infrastructure make it a crucial and difficult factor in oil security and climate change."

Petroleum fuels account for more than 95% of energy use in transport in nearly every IEA country, and oil combustion is a major source of emissions. Transport has become the dominant oil-consuming sector in most IEA countries, oil use in the sector has increased steadily over the past 30 years and now represents nearly two-thirds of total IEA oil consumption. Thus, the oil dependence problem is largely a transport problem (IEA, 2001a).

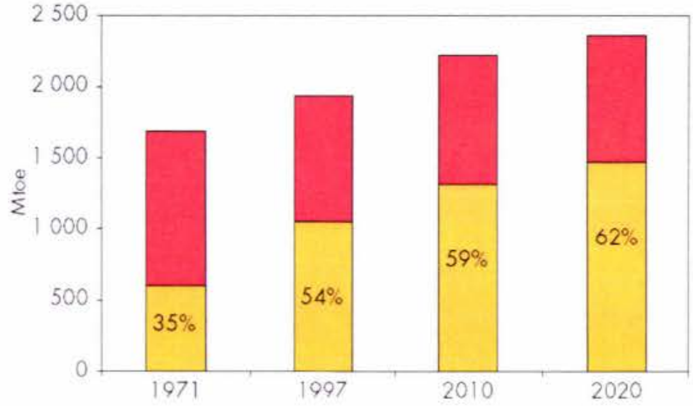
Reducing oil use and emissions in transport is difficult due to the unresponsiveness of vehicle travel to changes in the travel environment or to the costs of travel. A 10% increase in fuel prices usually results in only a 1%-3% decline in travel (IEA, 2001a). Generally people have limited choices about how or how much they travel once they have chosen their location of residence and work. Fuel costs are generally only a small factor in the decision making process (IEA, 2001a) and are generally only a small percentage of the overall expenditure of an individual or family.

The IEA (2000c) has indicated that there will be an increasing global oil demand in the transport sector through to the year 2020 in the OECD (Fig. 1-3). This increase will climb faster than any other sector (2.4%). Note that the transport sector includes all forms of transportation e.g. planes, trains, boats, as well as domestic and commercial road transport. However, domestic road transport makes up over 80% of the transport oil demand (Atlas project, 1999).

The IEA further indicated that by 2020, transport will account for over half of total world oil demand (IEA, 2002a).

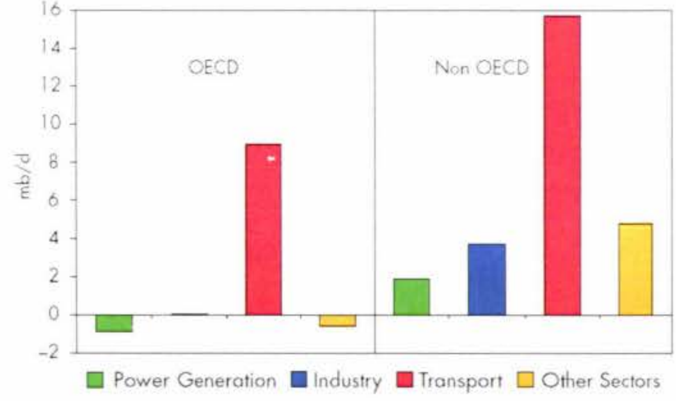
Oil consumption is expected to significantly increase over the period 1997 to 2020 in non-OECD Asia. In 1997 this region was a net importer of 5.8 million barrels per day, by 2020 this is expected to rise to 25.2 million barrels (IEA, 2000a).

Figure 1-3. Transport sector proportion of total OECD oil demand (IEA, 2000c)[2].



Most of the expected incremental oil demand from now until 2020 is expected to come from the transport sector (Fig. 1-4). In OECD countries, transportation accounts for virtually all oil demand growth. In non-OECD countries, although oil demand growth occurs in all sectors, the vast majority of the growth is still in the transport sector. In the OECD, incremental oil demand in other sectors such as power generation and industry is actually decreasing (IEA, 2000a).

Figure 1-4. Incremental oil demand by sector between actual demand in 1997 and assumed demand in 2020 (IEA, 2000a).



The IEA has indicated the following with respect to transport (IEA, 2000d):

- oil demand growth over the last decade resulted largely from an increasing demand for mobility;
- in OECD countries the transport sector accounted for practically all of the increase in oil demand;

[2] 1 Mtoe ~ 41.88 PJ Ref: Oil industry conversions, Website, http://www.eppo.go.th/ref/UNIT-OIL.html

- the past 25 years have revealed a direct relationship between GDP and growth in mobility; and
- world transport demand has followed economic output and this relationship is expected to persist.

The contemporary view is that increasing economic output and improvements in GDP are necessary which implies that oil demand in the transport sector will continue to increase with the flow-on effect of increased emissions and increased oil dependence.

1.6 Global peak in oil extraction

Modern society is completely reliant on transport and therefore fuel to function properly. However when the fuel (oil) runs out is less relevant than when supply can no longer match demand.

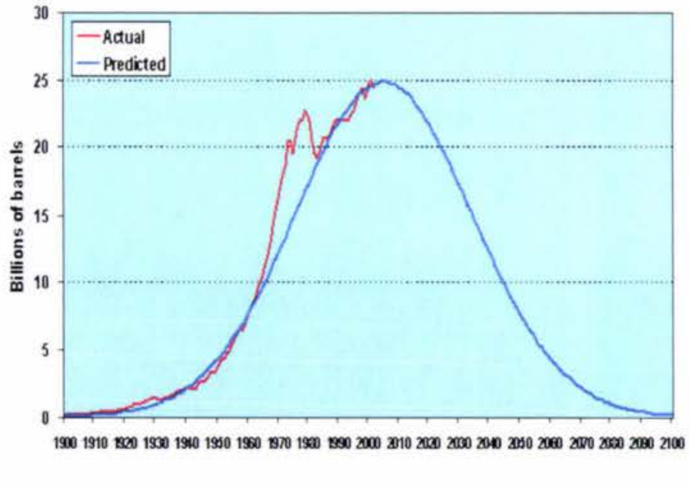
The global peak in oil extraction is the point when half of the total global oil resource has been consumed (Peak oil, 2005). This implies that after this point oil supply will no longer be able to match an ever-increasing oil demand unless demand drops off at the same rate, which would seem unlikely. Several sources indicate that the peak in global oil supply is predicted to occur by the end of the decade or sooner (Campbell, 1999; Campbell and Laherrère, 1998; Laherriera, 2001; Bentley, 2003; ASPO, 2003; Uoregon, 2003). Beyond this point oil prices will rise significantly unless demand declines.

Figure 1-5 shows the actual and predicted fuel use from the year 1900. Fuel use since 1900 has followed the line of prediction quite closely apart from a deviation through the 1970s and early 1980s (a time of excessive fuel use followed by an oil crisis). The line of prediction is actually the familiar bell curve (Guassian distribution). This prediction line indicates that we are very close to the peak of total oil extraction. Abnormal events such as excessive fuel use or events such as the Gulf war can affect the timing of this peak. The curve also indicates the relative cost, ease of extraction and availability, relative to this peak. The left-hand side of the peak represents oil that is widely available, easy to extract, of good quality and is relatively cheap (per barrel) implying that the retail price (price at the pump) will also be relatively cheap. The right-hand side of the peak represents oil that is less widely available (more wells needing to be drilled in less accessible places, such as offshore), extraction is more difficult (advanced technology is required to access the oil) and the oil is of lower quality. All this increases the cost.

The following needs to be considered when estimating oil production and resources (World Watch Institute, 2002):

- No significant new oil reserves have been found since the 1970s. This may reduce the oil reserves that could be added to the proven reserves.
- Consumption of oil is not a constant process. Between 1990 and 2000, annual oil consumption increased by 14% and trends indicate that this process will continue. Thus, if demand goes up, the time remaining before the exhaustion of the supply gets shorter.
- The last few hundred billion barrels of potentially extractable oil may actually be economically unrecoverable.

Figure 1-5. Bell curve of actual and predicted annual fuel use since 1900 (World watch institute, 2002).



This last point - the energy cost of exploration, extraction and production of oil needs to be considered. When the energy cost of recovering a barrel of oil becomes greater than the energy content of the oil itself, production will stop no matter what the price is (Hubbert, 1982).

Hirsch (2005) presented a paper to the United States Department of Energy (USDOE) concerning the peaking of global oil. The following is a summary of some of the points made.

- Waiting until world conventional oil production peaks before initiating a crash program of mitigation leaves the world with a significant liquid fuel deficit for two decades or longer.

- Without timely mitigation, the world supply/demand balance will only be achieved through massive shortages, accompanied by huge oil price increases, both of which would create a long period of significant economic hardship world-wide.
- The date of world oil peaking is not known with certainty. This complicates the decision-making process. A fundamental problem in predicting the oil peak is uncertain and politically biased oil reserve claims from many oil producing countries and the oil companies themselves.
- As recently as 2001, authoritative forecasts of abundant future supplies of North American natural gas proved to be excessively optimistic. Oil and natural gas geology is similar in many ways, suggesting that optimistic oil production forecasts deserve to be viewed with considerable scepticism.
- Increased fuel efficiency (of existing vehicles) alone will be neither sufficient nor timely enough to solve the oil shortage problem in the short term. To preserve reasonable levels of economic prosperity and growth, production of large amounts of substitute liquid fuels will be required.
- Government intervention will be essential. Economic and social impacts of oil peaking will otherwise be chaotic, and crash programme mitigation will need to be properly supported. How and when governments begin to seriously address these challenges is yet to be determined.
- Improved fuel efficiency in the world's transportation sector will be a critical element in the long-term reduction of liquid fuel consumption, however, the scale of effort required will inherently take time and be very expensive.
- Crash programmes represent the fastest possible implementation – the best case. In practical terms, real-world action is certain to be slower.
- Oil peaking discussions should focus primarily on prudent risk management, and secondarily on forecasting the timing of oil peaking, which will always be inexact. If peaking is imminent, failure to act aggressively will be extremely damaging world-wide.
- World oil peaking represents a problem like none other. The political, economic, and social stakes are enormous.

At the time of writing (Sept 2005), crude oil had reached $67.10 per barrel. Is this solely due to the effects of the American invasion of Iraq and associated market jitters over guarantee of supply and the often-quoted supply-demand scenario, or is there a deeper reason? Once the war in Iraq was over it was expected that oil prices would return to pre-war levels. This has not happened and the current price spikes and general trend to higher fuel prices may indicate that global reserves of oil are not able to cope with increased oil demand. Is this evidence that we are beginning to see the effects on the price of oil as we get closer to the predicted peak in global oil production/extraction? The price of oil makes it even more imperative that we produce technology that reduces our dependence on this resource. It is definitely in the best interest of governments to put in place incentives to allow this to happen.

Due to transport oil dependence and the transport requirements of goods and services, any increase in the cost of fuel will effect the cost of these goods and services. These costs will have to be passed on to the consumer in the form of price hikes or even price spikes (Campbell, 2002). This can have inflationary effects and thus have a significant negative effect on national and international economies. The only solution to this predicament is to use less oil.

Fuel supply can be likened to the operation of a tap, if we require a greater amount we simply open the tap a bit more. However it may be that we have reached a point where we have opened the tap as far as it will go. If this has occurred, it will be no longer possible to supply any increase in demand.

1.7 Methods of Reducing Fuel Use and Emissions in conventional vehicles

1.7.1 *Weight reduction*

Vehicle weight has a significant effect on vehicle performance. It also has a significant effect on the fuel use and emissions of a vehicle. The energy required to ascend an incline or to overcome inertial resistance of a vehicle can be modelled by:

Equation 1-1. $$E = m\,g\,h\cos(\varphi)$$
$$= m\,a\,d$$

where

E = energy required

m = mass

g = gravity

h = height

φ = angle of ascent

a = acceleration

d = distance

The energy required (E) varies linearly with mass (m). Thus, reducing the mass of the vehicle by, for example, 50% will reduce the energy required by 50%, thus, reducing fuel use and emissions. As a general rule of thumb, reducing weight by 10% reduces fuel consumption by 5% (OTA, 1995).

1.7.2 *Aerodynamic design*

Aerodynamics effects the vehicle by creating a drag force on the vehicle that the drive source has to overcome in order to travel at a certain speed. The drag force on the vehicle due to the wind resistance can be modelled by the relationship:

Equation 1-2. $R_{air} = 0.5\ A\ C_D\ \rho\ V^2$

where

R_{air} = air resistance

A = frontal area of the vehicle

C_D = drag coefficient

ρ = air density

V = velocity

The air resistance force is linear with respect to the frontal area of the vehicle, air density and the non-dimensional drag coefficient but varies with the square of the velocity of the vehicle. Thus, the major component effecting the air resistance force is the speed of the vehicle. Essentially for every doubling of speed there is a 4-fold increase in air resistance. Although it may be difficult to reduce speed and frontal area as a means of reducing aerodynamic drag, reducing the drag coefficient is a significant way of reducing the energy required to over-come this resistance to motion and therefore fuel use and emissions.

1.7.3 *Reduced rolling resistance*

In any vehicle, due to the presence of gravity, there is a certain amount of resistance to motion at the points where the vehicle directly or indirectly contacts the road surface resulting in friction that needs to be overcome. For conventional vehicles these points of frictional contact are the tyres, the road surface, and the friction that exists within the bearings in the hub of the wheel. The following can be used to model rolling resistance (Gomez, 2003):

Equation 1-3. $R_{roll} = m\, g\, (C_R\, (1 + V/160))$

where

m = mass

g = gravity

V = velocity

C_R = tyre friction coefficient

The rolling resistance force is dependent on mass and velocity. Thus, reducing either of these variables will result in a reduction in this resistance to motion and the consequent energy required. There is a trade off here since it is difficult to produce tyres that on the one hand have good grip on the road but at the same time have a low friction coefficient.

1.7.4 *Alternative fuels*

Cleaner fuels can considerably reduce emissions. For example compressed natural gas (CNG) when combusted has the following stoichiometry (Queens, 2005):

$$CH_4 + 2O_2 + 7.52N_2 \Rightarrow 2CO_2 + 2H_2O + 7.52N_2$$

If this is compared to combustion of iso-octane (conventional standard petroleum fuel):

$$C_8H_{18} + 12.5O_2 + 47N_2 \Rightarrow 8CO_2 + 4.5H_2O + 12.5N_2$$

These stoichiometric relationships indicate that one molecule of natural gas when combusted produces significantly fewer emissions than iso-octane. However they are very simplistic and do not take into account:

- calorific content of the fuel;
- the air fuel ratio used; and

- dissociation of nitrogen and combination with other gasses such as oxygen during high temperature combustion in the Otto and Diesel cycles.

Natural gas still produces significantly less emissions when compared to other competing fuels, ranging from a 25% reduction in average CO_2 emissions to an almost 100% reduction in CO emissions when compared to conventional vehicles powered by Otto cycle engines (Yagnik, 2005).

Fuels of particular interest due to their potential for reduced environmental impact are biofuels. These fuels are derived from plant and animal material in such a way that the overall carbon balance is zero. The CO_2 produced during the combustion of the fuel is in balance with the CO_2 consumption that is necessary to form the fuel. Fuels such as bioethanol and biodiesel are liquids and could be easily distributed through existing transport fuel infrastructure with only minor modifications. However, there would still be environmental and health implications due to localised emissions in urban areas, for example, increases in levels of nitrogen oxides from combustion of biodiesel is an issue as is the amount of land area required to produce the required amounts of fuel needed to supply a large transport fleet (Dorfell, 2003a). However, blending biofuels with existing fuels is a commonly accepted method of extending existing fuel supply and reducing the potentially significant impact on biofuel supplies. Biofuels such as bioethanol and biodiesel can also be produced from Whey (by-product of milk processing) and from tallow (by-product of meat processing) respectively.

Hydrogen is considered as the most favourable future fuel and it is considered likely that the fuel cell will provide the energy to drive domestic vehicles at some point in the future (Dorfell, 2003a). However hydrogen fuel in vehicles requires a new fuel supply infrastructure. The German project "Wasserstoff-Wirtschaft" was aiming for a countrywide hydrogen supply infrastructure by the year 2020, but high costs have forced a delay until 2050 (Dorfell, 2003a). The United Kingdom aims for general availability of hydrogen/fuel-cell technology in transport from 2012. The fuel-cell technology itself is far from maturity and the energy source for producing the hydrogen is unclear. Hydrogen may be the future medium for energy transport and high-density energy storage in vehicles but it must be produced by sustainable means that minimize production emissions, otherwise, the case for hydrogen as the future fuel is undermined (Dorfell, 2003a).

1.7.5 *Improved engine efficiency*

Improving engine efficiency is significant method for reducing fuel use and emissions however there are limitations. A conventional Otto cycle ICE has a maximum efficiency of 33% (CAE, 1996), whereas the indicated efficiency is approximately 40% (Nam, 2004a). The indicated efficiency is a measure of the engine efficiency when frictional effects and other associated losses such as pumping losses are neglected. It is the maximum efficiency that the Otto cycle ICE could achieve under ideal conditions and has remained the same for the last three decades implying that there is a limit to what can be achieved with this technology (Nam, 2004a). The Diesel cycle ICE (for use in domestic transport) is inherently more efficient that than the Otto cycle with a maximum efficiency in excess of 40% (Gruden, 2003d). This technology offers significant potential to reduce fuel use and emissions when compared to the Otto cycle.

1.7.6 *Reduced accessory loads*

Accessory loads such as air conditioning, electric windows and other electrical loads in a vehicle are not directly related to the drive system of the vehicle. The trend in recent years has been toward higher electrical/accessory loads increasing the load on the engine and therefore increasing fuel use and emissions. Accessory loads involving comfort and safety are also taking increasingly larger amounts of vehicle power thus vehicles require greater engine power (Dorfell, 2003b).

1.7.7 *Reduced idling loss*

Whenever a conventional vehicle is being operated but is stationary or decelerating, the ICE is still operating but not driving the wheels. Thus, significant energy is being wasted. The ability to turn off the engine during periods of zero motion or deceleration can represent significant saving in overall fuel use and levels of emissions.

1.7.8 *Reduced braking and deceleration loss*

In a conventional vehicle a certain amount of energy is required to accelerate the vehicle and then maintain the vehicle at a certain speed. When the vehicle decelerates or is slowed down by the use of the braking system, the energy that was used to accelerate the vehicle and maintain a certain is speed is lost, essentially as heat through the braking and cooling system and fuel loss through the engine. Thus, new energy from the fuel has to be supplied to re-accelerate the vehicle. Significant reductions can be made in fuel use and emissions if this waste energy could be recovered and reused in the drive process.

1.7.9 *Reduced heat loss*

In any conventional domestic vehicle ICE a significant amount of energy is wasted and essentially ends up as heat that is released to the environment. In an Otto cycle ICE, for example, the maximum efficiency is approximately 33%, implying that at least 67% of the energy in the fuel is wasted, most of it ending up as heat though a small proportion may be used for heating purposes in the vehicle (CAE, 1996). Significant reductions could be made in fuel use and emissions if waste heat energy could be recovered and reused in the drive process.

Harnessing this waste heat (as is done in industrial combined heat and power (CHP) and combined cycle plants) in future designs of thermal and non-thermal transport drive source devices could be a key element in significantly increasing thermal efficiency and therefore reducing fuel use and emissions.

1.7.10 *Mass transport*

The subject of domestic road based mass transport (buses, carpooling etc) is not strictly related to the concepts dealt with in this study however it needs to be emphasised that if there were no vehicles powered by internal combustion engines there would be no pollution from transport or problems with a diminishing resource to power the transport sector. To this end reducing the number of vehicles on our roads is one simple method of reducing fuel use and emissions in the transport sector. Although it may be naive to think that society could exist without individual domestic transport, the reality is that mass transport is potentially still one of the best methods of reducing fuel use and emissions particularly if the advanced technology systems that will be discussed in this study are considered. To this end it must be emphasised that although advanced vehicle drive systems may have the ability to significantly reduce fuel use and emissions there is no replacement for simply reducing the number of vehicles and the problems that these vehicles cause and will continue to cause. However, as far as mass transport is concerned, it will not be considered further.

1.7.11 *Efficient alternative vehicle technologies*

Alternative engine technologies to the ICE or improvements in current technologies that increase overall efficiency have the potential to significantly reduce fuel use and emissions. ICE thermal engine efficiency is governed by the Carnot cycle and this limits the efficiency that can be attained. The Carnot cycle (Warhaft, 1997) is defined by:

Equation 1-4. $\eta = (T_H - T_C)/ T_H = 1 - T_C/T_H$

where

η = thermal efficiency

T_H = heat of the reactants (combustion temperature)

T_C = heat of the products (exhaust temperature)

The Carnot equation implies that efficiency is a function of the temperature difference between reactants (fuel and air) and products (exhaust). Thus there is a limit to what can be achieved with current conventional ICE technology as far as reduction in fuel use and emissions are concerned.

Problems associated with the conventional reciprocating ICE are:

1. The conventional ICE is designed for the peak operating requirements of the vehicle, but most of the time the engine will never actually encounter the power requiring conditions for which the engine has been designed. Thus the conventional vehicle engine is considerably overpowered for the average operating requirements.
2. The ICE has poor part load efficiencies (Nam, 2004a; Gruden, 2003c; Nyland et al, 2002a) and since the majority of its operation is well away from its optimum operating point it is thus operating very inefficiently with resulting high fuel use and high levels of emissions.

Vehicle system technologies that are designed for the average operating conditions and ensure that the drive source is operated closer to its optimum operating point (i.e. maximum efficiency) should have significant advantages in their ability to reduce fuel use and emissions.

A typical New Zealand car has an average fuel economy of 10 litres per 100 kilometres and the average distance travelled is approximately 14,000 kilometres per year (EECA, 2002). This represents an annual fuel cost of \$2100 (petrol cost at \$1.50/L). Thus, vehicle technology that could reduce fuel use by, say, 50% can save the average car owner, on average, over $1000 per year. As the cost of fuel rises (which it is predicted to as we get closer to the peak in oil extraction and beyond) these savings will rise. Reductions in fuel use will also have a flow-on effect in terms of reduced oil imports and oil import costs which in turn has a flow-on effect to improved balance of trade figures.

In recent years large reductions in vehicle emissions and fuel consumption have been made possible by vehicles making use of hybrid electric drive systems (drive systems that incorporate an electric motor and batteries to augment the conventional drive system). These vehicles consume considerably less fuel and emit considerably fewer emissions compared to current technology vehicles. They are also considerably more efficient in terms of overall energy use.

Hybrid vehicles such as the Toyota Prius have been given an EPA (Environmental Protection Agency) fuel economy rating of 3.9l/100km in the city and 4.6l/100km on the highway (EPA, 2005). The Prius has been certified as a Super Ultra Low Emission Vehicle (SULEV) and an Advanced Technology Partial Zero Emission Vehicle (AT-PZEV) in California and those states adopting California standards. The Prius has also been certified by the Internal Revenue Service (IRS) as eligible for a $2,000 clean-burning fuel tax deduction. The Prius is one of the few mass-produced vehicles to qualify for this federal tax benefit.

Hybrid vehicles will be considered in more depth in Chapter 3.

2.0 CURRENT DOMESTIC TRANSPORT TECHNOLOGIES

2.1 Internal combustion engine technologies

For more than 100 years, petrol (Otto cycle) and Diesel cycle ICEs have prevailed as the exclusive drive unit in road transportation with the Otto cycle being the main driver in domestic transport. None of the other power units invented to date have been able to make use of the energy content of fuel oil with the same or better efficiency than the Otto or Diesel cycle. When summing up all the properties required to smoothly operate a vehicle over wide speed and load ranges and a long lifetime, all alternative concepts have never succeeded in edging the Otto and Diesel cycle engines out of their top positions (Gruden, 2003b). However the reciprocating ICE due to its design and mass production has created enormous problems in terms of its use of a fast diminishing resource and the creation of emissions that effect our health and the health of the environment.

There are essentially two types of ICE in conventional domestic transport, the Otto cycle and the Diesel cycle. These two technologies are also a component of the series hybrid drive systems that are considered in this study. An in-depth discussion of the mechanical or thermodynamic operation of the reciprocating ICE is not required nor is it relevant. It suffices therefore to give a short overview of the technology as it relates to this study.

The primary difference between the Otto and Diesel cycles is the method of igniting the fuel. The Otto cycle uses a spark plug to ignite a compressed, pre-mixed air/fuel mixture in the cylinder. The Diesel cycle operation compresses air only in the cylinder, to a high pressure, raising its temperature to a level that will instantaneously ignite fuel that is injected in to the compressed air mass (EPA, 2002a).

There are also differences in the way the load is regulated in the respective engine cycles. In the Diesel cycle the speed and power of the engine is regulated by altering the air/fuel ratio. This is achieved by altering the amount of fuel that is injected into the cylinder. Fuel in the Diesel cycle always combusts in conditions of excess oxygen (high air/fuel ratios) (MIT, 2004b).

In the Otto cycle engine the air/fuel ratio is close to stoichiometric conditions. This is accomplished by use of a valve in the induction pathway that simply varies the amount of air/fuel mixture that enters the cylinder (MIT, 2004b). However this valve arrangement creates significant losses and inefficiencies due to increased pumping losses and a reduction in volumetric efficiency (Stone, 1992b). Throttling results in about 25% of the total friction losses (Nam, 2004a).

Diesels also have the ability to make use of considerably higher compression ratios due to the type of fuel that they use and this increase in compression ratio required for compression ignition improves the thermal efficiency and helps markedly in giving the Diesel engine its efficiency advantage over the Otto cycle engine (Stone, 1992a).

To summarise, Diesel cycle engines tend to be more efficient than Otto cycle engines due to (Stone, 1992b; MIT, 2004b):

- having higher compression ratios;
- always operating with considerably higher air/fuel ratios;
- higher mechanical efficiency since pumping losses are reduced;
- power output being controlled by the amount of fuel injected into the cylinder not by throttling and its associated losses; and
- During compression the behaviour of air (only air is inducted in a Diesel cycle) is closer to the ideal air cycle than a fuel/air mixture.

The Diesel power unit has achieved a high status in transport. The world wide share of Diesel engines in passenger vehicles is now approximately 20% (Gruden, 2003d), whereas in freight transport on the roads and by water the share approaches 100%, diesel being the only cost effective alternative (Gruden, 2003d).

The other ICE technology considered in this study is the 2-stroke Diesel cycle. This cycle differs from the 4-stroke cycle in that there is one power stroke for every one revolution of the crankshaft as opposed to 2 revolutions of the crankshaft in the four stroke cycle.

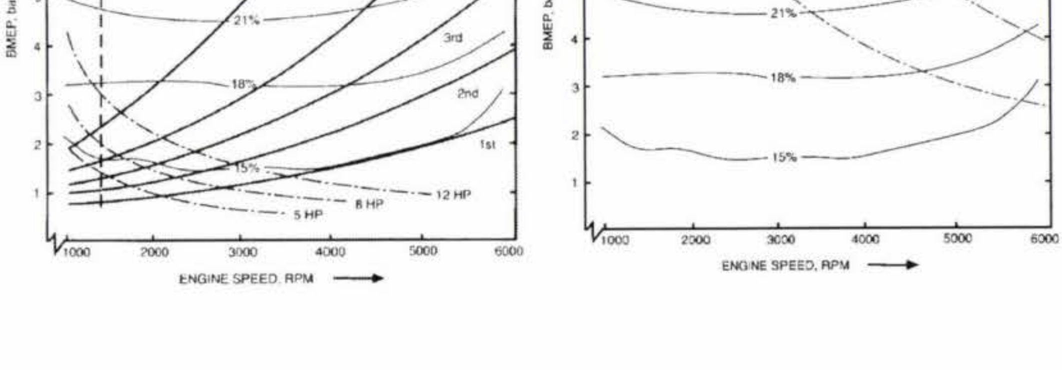
Where very high power is required and high power density for applications such as shipping, the 2-stroke Diesel cycle is unrivalled (Gruden, 2003d). This technology is also used in locomotives where a large Diesel cycle 2-stroke reciprocating engine drives a large generator that in turn provides electricity for large electric motors that drives the wheels. The efficiency of the 2-stroke Diesel cycle is also very high with the engines used in shipping having reported efficiencies of up to 53% (Gruden, 2003d). Large 2-stroke Diesel engines are the most efficient thermal units devised by man. When waste heat can be used as well, these engines can have efficiencies in excess of 80% (Gruden, 2003d).

Due to the potential efficiency, power density and volumetric density advantages of the 2-stroke Diesel cycle, there is a significant amount of research being conducted on this technology for use in domestic transport. Research being conducted in Finland (Janhunen and Larmi, 2004), has produced a Diesel cycle 2-stroke engine for a conventional domestic vehicle that has 2 cylinders, a total capacity of 1.3 litres and produces 100kW at a maximum efficiency of 48%. Compare this with a maximum efficiency of 33% for a 4-stroke Otto cycle engine. The reason for this high efficiency is the inherent advantages that the 2-stroke cycle has with regard to less pumping losses and the advantage of a power stroke per cycle.

2.2 Part load efficiency

The efficiency of a conventional reciprocating ICE is highest for only a small range of torque and rotational speed values (Fig. 2-1). This is the zone of maximum efficiency and lowest emissions. During normal driving conditions, the ICE will rarely enter this zone (CAE, 1996).

Figure 2-1. Efficiency vs. rotational engine speed and cylinder pressure for a 135hp and a 16hp ICE. Source: CAE (1996).



The engine efficiency of a vehicle is highly dependent on engine speed and load ratio. For stop/start urban driving or congested motorway gridlock where a vehicle is unlikely to use more than the first three gears, and engine speed is generally less than 3000 rpm, the engine efficiency can be less than 17%. For an engine speed of approximately 4000 rpm and using fifth gear (rural or motorway driving) the efficiency can reach approximately 30%.

The 5hp (3.73kW) and 12hp (8.95kW) lines (Fig. 2-1) represent a typical load under urban and motorway conditions respectively (most of the power of an engine is used for acceleration and hill-climbing) and indicates an efficiency of less than 15% and 18% respectively. Note that for the average conventional vehicle, urban driving loads will be the majority of the loads that the vehicle will experience indicating that most of the time the vehicle engine will be operating at less than 15% efficiency. Overall system efficiency can drop even further when significant engine idling is taken into account. Figure 2-1 also shows how the 5hp, 8hp and 12hp power outputs relate to energy efficiency if the 135hp (100kW) ICE is replaced with a 16hp ICE. The smaller engine now operates closer to the maximum efficiency island over a greater range of output. What is required is a technology that can make use of this concept.

2.3 Current alternatives to conventional domestic transport technologies

2.3.1 *Electric vehicles*

In most viable road transport scenarios, one of the key elements is the storage of sufficient energy on board the vehicle to give sufficient range of operation. Conventional vehicles store energy, mainly in the form of petrol and diesel, derived in the main, from fossil oil. The chemical energy storage capability (lower heating value) of diesel and petrol is approximately 41.4 MJ/kg and 44 MJ/kg respectively resulting in a high energy density (Heywood, 1988b). Hence only a comparatively small amount of fuel is required to travel each kilometre. For example, a petrol vehicle with an average fuel economy of 8l/100km and a tank size of 50L will be able to travel 625 km on one "charge" (tank of petrol). This fuel will only take up a volume of 0.05 m^3 and have a weight of only 37kg. The tank technology required to store this energy on-board is relatively simple (the petrol tank).

Advantages of petrol and diesel include:

- easy to transport;
- can be stored for long periods of time with minimal degradation;
- only requires minimal safety handling requirements;
- is widely available; and
- all of the energy available in the fuel can be used.

However, the use of petroleum fuel has two major disadvantages:

1. fossil oil, from which petrol and diesel is derived, is a finite, non-sustainable resource; and
2. the combustion of these fuels has negative environmental and human health implications.

The requirement for alternative technology vehicles such as electric vehicles, particularly storage electric vehicles, is to provide a storage capability that rivals the range and power of conventional vehicles using traditional fuels whilst making use of the far more efficient electric drive train and other advantages such as cleanliness and quietness. An electric motor is greater than 90% efficient with high part load efficiency (EERE, 2005; EE Tech, 2004; Dorfell, 2003b), whereas a typical ICE drive train (Otto cycle) has an efficiency that varies between 15 and 33% (CAE, 1996). Since urban motoring accounts for the majority of travel this implies that for the majority of the time that the vehicle is operating, it will be operating very inefficiently.

The peak efficiency of the total drive train in electric vehicles can be high. Assuming that the battery, controller and electric motor have efficiencies of at least 90%, this implies that peak system efficiency of the electric vehicle could be at least 72% (this does not take into account the efficiency of the generated electricity). They are also able to regenerate some of the energy lost during deceleration and braking further increasing this efficiency to over 90% (Dorfell, 2003b).

2.3.2 *Electric drive*

An electric motor converts electrical energy from the energy source unit(s) to mechanical energy that drives the wheels of the vehicle. Unlike a traditional vehicle powered by an ICE, where engine torque is low at low engine speed and does not reach a maximum until at least the middle of the engine speed range, an electric motor provides full torque at low speeds (maximum torque at zero motor speed) and almost constant torque across the entire motor speed range (Nam, 2004c; Riley Enterprises, 2005). A vehicle needs high torque at low speeds for initial acceleration then demands less torque as cruising speed is approached, thus the electric motor characteristics are well matched to the load requirements of a conventional vehicle. The ability to have high constant torque across the speed range, particularly at zero motor speed implies that a transmission is not required. In a conventional vehicle the transmission is designed to match the torque of the engine to the torque requirements of the load. Due to the high constant torque of the electric motor this torque matching is not required. These advantages lead to a far less complex and more efficient power-train (Riley Enterprises, 2005).

Electric propulsion is becoming a more attractive option for automobiles. This is due to the increase in the performance of electric motors over recent years. Direct current (DC) motors used in early electric vehicles of the 1970s had torque densities of approximately 3.1Nm/kg whereas modern brush-less permanent magnet motors for transport applications have torque densities approaching 25 Nm/kg (Lipman and Sperling, 2000). Compare this with a modern 4-door sedan such as the popular Toyota Corolla, which produces 150 Nm of torque (Carfolio, 2005). This level of torque could be achieved with a modern electric motor that weighs only six kilograms. The California Air Resources Board (CARB) indicated that weight, volume, and cost of the electric motor and controller had reduced significantly and now the motor controller combination is smaller and lighter than a comparable internal combustion engine, cheaper to manufacture (in similar production volumes) and to maintain (Lipman and Sperling, 2000).

The introduction of electric drive into vehicles could create the opportunity for significant savings in greenhouse gas emissions that are not possible with any other transportation or energy option (Sperling, 1996b).

To summarize, the electric motor has the following advantages when compared to the conventional ICE (EERE, 2005; EE Tech, 2004; Lipman and Sperling, 2000; Dorfell, 2003b):

- very high efficiency of greater than 90%;

- very high part load efficiency;
- low cost when mass-produced;
- is a proven, mature technology;
- has very few moving parts, giving them high reliability; and
- high torque means a conventional transmission is not required.

This potentially leads to a reduction in cost, complexity, and weight of the vehicle and makes the vehicle simple to drive.

The fact that most rail systems are either electric (electric power source from the grid) or based on the common Diesel electric argues strongly for the practicality, efficiency and power of electric propulsion. What is required is an efficient energy storage and/or supply system to make use of these very efficient drive units.

2.3.3 *Batteries*

A battery stores electricity in the form of chemical energy. The standard automotive lead acid starting battery, found in every conventional domestic vehicle, is similar to the technology required for electric vehicles.

The feature of the battery electric vehicle that has limited its widespread use is the low energy density and/or power density of conventional battery systems. Power density is important as this governs vehicle performance and high power demand limits the effective range that the batteries can provide (CAE, 1996). This is a similar situation to reducing the fuel tank size of a conventional vehicle and therefore the effect that this has on range.

A disadvantage of batteries is that of weight. The heavier a vehicle is the more energy that is required to accelerate and maintain constant speed. During urban operation inertial effects are at their highest, absorbing up to 50% of the energy required, with energy use (fuel consumption) closely related to the number of stops and starts and evenness of traffic flow. Inertial acceleration and deceleration are proportional to vehicle mass (CAE, 1996).

Batteries for modern domestic transport use have high efficiencies in the order of 90% (Dorfell, 2003b) however the comparatively poor energy storing capability implies high mass and volume is required in order to store a certain amount of energy. A small car with a 45l fuel tank can store the equivalent of approximately 400 kWh of chemical energy. Assuming an advanced battery for transport use has an energy density of 330 Wh/l and 165 Wh/kg, a battery equivalent to the 45l petrol tank would require approximately 1.2 m^3 of space and weigh 2424 kg. Assuming the drive train of an electric vehicle is 5 times more efficient than an ICE it would still require 0.24 m^3 and 485 kg of batteries. This leads to unreasonably high weight, space and cost requirements. The range of a pure electric vehicle with practical battery weight will always be limited. If battery charging infrastructure was available (with rapid recharge capability) this could encourage wider use of battery electric vehicles but it will remain a niche market because people and society require more versatile individual domestic transport devices (Dorfell, 2003b).

Table 2-1 gives comparisons of the various energy densities of a range of fuels and of various electricity storage options. Fuels such as petrol have at least 30 times the energy density of the best battery storage systems. Advanced batteries such as lithium ion and metal-air batteries have 3 to 11 times the energy density when compared to lead acid batteries but are currently far more expensive.

An additional disadvantage of conventional batteries is the number of times that they can be "cycled". This represents the number of times that a battery or storage device can be completely run down (flattened) and then recharged again before it is effectively dead and needs to be replaced. Batteries can only be cycled a maximum of 2000 times, although typically less (Table 2-1), which will have an effect on overall running costs.

The effect of battery replacement, loss of efficiency with time and the costs of battery replacement are important issues however the basis of the study was to assess the potential of series hybrid drive systems to reduce fuel consumption and emissions in domestic vehicles. All vehicles including current parallel hybrids suffer to some degree from the problems mentioned (Toyota claim 8 years for their NiMH battery pack with a replacement cost of US$1000) and would simply be going over ground already extensively covered elsewhere in literature. Thus, these issues were not considered to be relevant to the study.

2.3.4 *Ultra-capacitors*

Alternatives to battery storage are Ultra-capacitors (or super-capacitors). These are high specific energy and power versions of electrolytic capacitors (devices that store energy as an electrostatic charge). Ultra-capacitors are being developed for vehicles as primary energy devices for power assist during acceleration and hill climbing, as well as recovery of braking energy. They are also potentially useful as secondary energy storage devices in electric vehicles, providing load-levelling power to chemical batteries. Additional electronics are required to maintain a constant voltage, because the voltage drops as energy is discharged (USDOE, 2001a; Miller and Smith, 2005; OTA, 1995).

Table 2-1. Energy storage comparisons (Key, 2001; Heywood, 1988b).

Storage type	Energy density (MJ/kg)[3]	Power density (W/kg)	Commercialisation	Cycles	Charge time	efficiency
Fuel						
Hydrogen	120	N/A	Emerging			
Natural gas	45	N/A	Mature and available			
Propane	46.4	N/A	Mature and available			
Ethanol	26.9	N/A	Available			
Methanol	20	N/A	Available			
Diesel	41.4	N/A	Very mature and available			
Petrol	44	N/A	Very mature and available			
Batteries	(Wh/kg)			2000	hours	70-90%
Lead acid	35	300	Very mature and available			
Nickel cadmium	35	200	Mature and available			
Lithium Ion	90	180	Available			
Nickel metal hydride	60	200	Available			
Zinc air	350	60 - 225	Emerging			
Aluminium air	400	10	Emerging			
Sodium sulphur	170	200	Available			
Ultra capacitors	<15	2000-10,000	Emerging	100000+	secs	90%
Flywheels	10 -100	1000-10,000	Emerging	10000	mins	90%

Ultra-capacitors have a number of advantages over conventional batteries such as higher power density, a fast recharge time and extremely high cycle life (Table 2-1), giving an ultra-capacitor storage bank longevity similar to that of a conventional ICE. However, their energy density is comparatively low compared to batteries implying that their

[3] 1 MJ = 277.78Wh

application in battery electric vehicles is limited. However very high power density implies that they may be more applicable to hybrid vehicles where power density is more critical than energy density as the storage element in hybrid vehicles is seen more as load levelling device than as a high capacity storage element.

A potential application of ultra-capacitors is for absorbing the electrical energy produced by electrically driven vehicles during regenerative braking. In this process, the vehicle is slowed down by the main drive motor, which converts the vehicle's kinetic energy to electrical energy that can then be stored by the ultra-capacitors. When the vehicle needs this stored energy for acceleration, or other power needs, it is released by the ultra-capacitors almost instantly. It has been indicated that this process can recapture up to 40% of the electrical energy used by such vehicles (Varakin et al, 2002).

2.3.5 *Flywheels*

Flywheels store kinetic energy within a rapidly spinning wheel-like rotor or disk. Flywheels have a long history in automotive applications. All of today's transport based internal combustion engines use flywheels to store energy and deliver a smooth flow of power from the abrupt power pulses of the engine due to reciprocating motion of the pistons (USDOE, 2001b; OTA, 1995)).

Modern flywheels employ a high-strength composite rotor, which rotates in a vacuum chamber to minimise aerodynamic losses. A motor/generator is usually mounted on the rotor's shaft both to spin the rotor up to speed (charging) and to convert the rotor's kinetic energy to electrical energy (discharging). A high-strength containment structure houses the rotating elements and low-energy-loss bearings stabilise the shaft. Interface electronics are needed to convert the alternating current to direct current, condition the power, and monitor and control the flywheel (USDOE, 2001b; OTA, 1995).

Flywheels, like ultra-capacitors have the advantage of high power density, high cycle life and fast recharge times and thus could be used in combination with a conventional internal combustion engine in a hybrid configuration to provide power assist. However, to have commercial success they would need to provide higher specific and volumetric energy densities than what is now available. Although flywheels are being used in some bus applications, more work needs to be done to make flywheels safe and effective for vehicle applications. Current flywheels are still very complex, heavy, and large for personal vehicles. In addition, there are concerns regarding the safety of a device that spins a mass at speeds of 60,000 – 100,000rpm. Other issues include low volumetric efficiency, maintenance requirements, expense of flywheel technology and materials and also the gyroscopic forces associated with spinning a disc at very high speed (USDOE, 2001b; OTA, 1995).

With all these storage options research continues and advances continue to be made.

2.3.6 *Fuel cells*

An alternative to the storage of electricity in batteries or other storage devices is the use of fuel cells. Fuel cells are electrochemical devices similar to batteries in that a chemical reaction produces the electricity. The difference is that fuel needs to be continuously supplied to the fuel cell for it to produce this electricity (Nyland, 2002b; Sperling, 1996c).

Fuel cells are highly efficient (ranging from 40 to 70%), reliable and require minimal maintenance. They can be designed to use a variety of hydrogen containing fuels, such as natural gas, LPG, propane. Other sources can also be used such as methanol/petrol/diesel via a hydrogen reformer (device that converts these sources into elemental hydrogen for use in the fuel cell). Fuel cells also have very low emissions and when hydrogen and oxygen are the respective fuel sources these emissions are simply water and some heat (Nyland, 2002b; NASA, 2002).

The fuel cell is capable of directly producing electrical power without noise, combustion and conversion to mechanical energy in between and the associated losses. Energy can be stored as a fuel with high energy-storage density and an electric motor can be used to propel the car. This technology promises to make use of the advantages of electric propulsion without being restricted to short range (Dorfell, 2003b).

At present the only really viable technology for conventional vehicle use is the proton exchange membrane (PEM) fuel cell due to its high power density (>1kw/L) (Nyland, 2002b; Dorfell, 2003b), acceptable operating temperature, durability, ability to vary its output quickly to meet shifts in power demand and reasonably quick start up. However, PEM fuel cells are sensitive to fuel impurities. The other fuel cell technologies are mainly for stand-alone power generation applications (Fuelcells2000, 2002). A subgroup of PEM fuel cells are Direct Methanol Fuel Cells (DMFC). These are similar in operation to PEM fuel cells but the anode in the DMFC converts the methanol directly into hydrogen without the need for a reformer (Sims et al, 2001).

The practical efficiency of this fuel cell system including gas purification is approximately 40 %. This is much worse than a Li-Ion battery (90 %) and is also not much of an advantage over the Otto cycle ICE and less than the maximum efficiency of the Diesel cycle ICE although the fuel cell has better part load efficiencies (Dorfell, 2003b).

Fuel cells are currently viewed as the long-term solution to the problem of finite traditional fuel resources and the environmental and climate change problems associated with their use. The fuel economy of a fuel cell vehicle running on pure hydrogen is projected to be up to 250% better than conventional Otto cycle ICE vehicles. The estimates for the fuel economy of fuel cell vehicles running on methanol using reformers is up to 125% better, the reduction when compared to the use of pure hydrogen is due to losses in the reforming process (Sims et al, 2001).

However there are still a number of issues that need to be addressed in the development of fuel cells:

- Fuel cell vehicles require an on board H_2 source, which is usually achieved through the use of bottled hydrogen but this is bulky, heavy and has safety issues. Hydrogen has by far the highest specific energy density per kg (Table 2-1) but since it is such a light gas, compression is required. It is this containment requirement that in turn adds weight that reduces the overall energy density.
- Storage of compressed hydrogen is costly and complicated. A solution is on-board reformers that use conventional liquid/gaseous fuels, however, these add weight, complexity, reduced space, high cost and an emissions penalty during the conversion of fossil fuels to hydrogen. Some types of fuel cells can make use of gas fuels directly, without a reformer, such as methane but this reduces the overall efficiency of the fuel cell and also produces emissions although these are less than for a comparable ICE (CAE, 1996). There are also issues related to development of hydrogen supply infrastructure.
- Conventional vehicle ICEs are cheap at approximately US$50/kW-$100/kW, while

fuel cell technology is at least US$600/kW (Sims et al, 2001). To this must be added the cost of hydrogen storage and supply technology.

- Uncertainty with respect to platinum supplies: fuel cells such as the PEM require platinum to ensure proper operation of the fuel cell as it operates as a catalyst to speed up the rate of reaction of the hydrogen and oxygen to produce electricity. As the production of fuel cell vehicles increases in the future this will put pressure on platinum reserves. It is estimated that platinum demand in automotive and residential applications could reach 16 tonnes per year by 2010. At present the platinum market is in deficit. Demand for platinum grew much faster than supplies during the period 1997 - 2002 (Cowley, 2002). Thus the current effect that conventional domestic transport is having on reserves of fossil oil may have the same effect on the reserves of platinum. This will in turn have an effect on platinum prices and therefore fuel cells and vehicles powered by fuel cells.

Another current alternative to conventional domestic transport technologies are the hybrid vehicles. These will be discussed more fully in the next Chapter.

3.0 HYBRID VEHICLES

What is required from current conventional transportation is a vehicle that strikes a compromise between conventional ICE vehicle technology and the "Holy Grail" of zero fuel use technology. Zero fossil fuel use vehicles, such as pure electric vehicles (depending on source of electricity) are limited until technology such as fuel cell vehicles becomes a viable option for the domestic market, or a breakthrough in storage technology enables storage vehicles such as battery vehicles to be comparable to conventional transport in terms of range and power. Vehicles with this type of compromise technology do now exist and are collectively known as hybrid vehicles. As the name suggests, the technology consists of a combination of a conventional ICE (from conventional vehicle technology), batteries and an electric motor (from electric vehicle technology).

Hybrid vehicles make use of an internal combustion engine and an electric drive system to drive the vehicle. The size of the internal combustion engine can vary from a small motor generator set to extend the range of the batteries, up to a standard size, vehicle engine that not only charges the batteries and directly runs the electric motor via a generator but can also provide direct drive if required. The primary advantage of the hybrid concept is considerably improved fuel economy and a considerable reduction in emissions by having the ICE running at a constant speed where it can be operated most efficiently. Most emissions of conventional ICE powered vehicles occur under hard acceleration, hill climbing and urban stop start driving conditions (CAE, 1996). An additional advantage of hybrid vehicles is that the combination of an ICE with an electric motor enables the use of a smaller ICE. Smaller engines use less fuel, partly because they are used, on average, at higher load levels than larger engines, in relation to the maximum power of the engine (Nyland et al, 2002a).

Hybrid vehicles would appear to be the short term, logical solution to the problems of vehicle fuel use and emissions. Toyota is the main suppler of hybrid vehicles and now have total cumulative global sales of over 381,000 units since their release (Taipei Times, 2005). However this is still very low compared to the numbers of conventional domestic vehicles produced annually (~50 million) and the total number of vehicles currently on the roads of the world (~750 million).

Hybrid vehicles have the ability to make use of 'regenerative braking'. When a conventional vehicle slows down under engine braking or when using the conventional braking system, energy is lost and new energy (fuel) is required to re-accelerate the vehicle. In a hybrid vehicle, using the electric motor as a generator, some of this energy can be recovered and stored in the storage system to be reused to supply power to the electric motor (Badin et al, 2001).

Hybrid vehicles can potentially achieve better fuel economy and reduce emissions because:

- the ICE never idles therefore there is no idling fuel loss;
- the ICE operates closer to its most efficient operating points therefore avoiding part load energy loss;
- during deceleration and braking, energy that would otherwise end up as fuel loss and waste heat can be saved (regenerative braking);
- the ICE is designed for the average operating requirements, not peak operating requirements;
- significant downsizing/weight reduction of some or all of the drive line components (for example a smaller ICE) is possible;
- batteries store excess energy during low load scenarios; and
- the whole vehicle system is optimized for higher overall efficiency.

In any ICE the thermal efficiency (η_b) can be modeled by (EE Tech, 2004):

Equation 3-1 $\eta_b = \eta_i (1+(fmep / bmep))^{-1}$

where

fmep = friction mean effective pressure (a measure of engine friction)

bmep = brake mean effective pressure (a measure of engine efficiency)

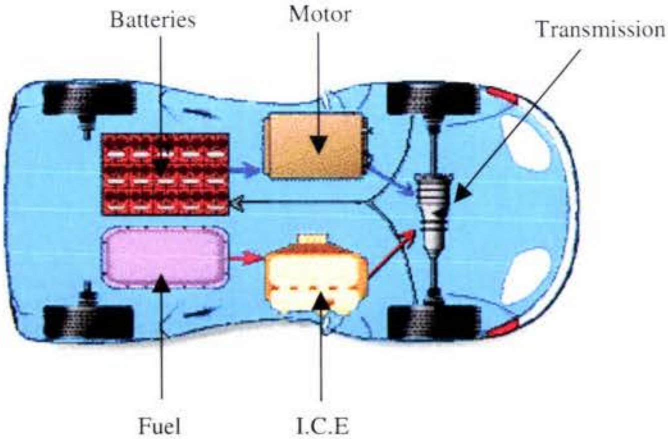
η_i = indicated efficiency (a measure of the maximum efficiency of the ICE when friction and pumping losses are neglected)

Fmep is a function of engine speed (i.e. higher engine speed results in higher engine friction) and Bmep is a function of engine torque and capacity and a measure of the efficiency of the engine (Nam, 2004a). Equation 3-1 implies that the most efficient operating points are when the load is at a maximum for a given engine speed (fmep/bmep term is small) or the engine is at its most efficient when operating at maximum torque (not maximum power). This also helps to explain why large Diesel marine two stroke engines are so efficient (as high as 53%) as they produce large amounts of torque at very low engine speeds (Gruden, 2003d). This highlights the advantage that hybrids have over conventional vehicles; the engine operates at higher loads and thus higher efficiencies, while the battery (or other energy storage device) operates during low engine efficiency modes.

3.1 Parallel hybrids

In a pure parallel configuration a conventional ICE drives the vehicle and the electric motor works in parallel with the ICE to also provide drive for the vehicle (Fig. 3-1). Under low load (such as urban driving) the motor acts as a generator that charges the batteries. Under high loads such as accelerating or hill-climbing, the stored energy in the batteries is used to power the electric motor to provide extra torque (in parallel with the ICE torque). During deceleration the electric motor again functions as a generator to charge the batteries. The Honda Insight is an example of a parallel hybrid vehicle.

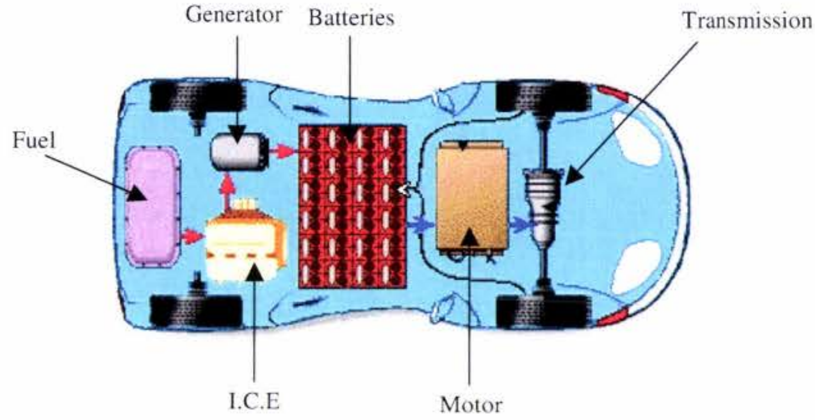
Figure 3-1. Parallel hybrid drive system (York Tech, 2000).



3.2 Series hybrid drive system

In a pure series configuration a conventional ICE runs a generator that charges the batteries and can also provide power directly to the electric motor when required (Fig 3-2). Only the electric motor can provide vehicle propulsion (there is no physical connection between the ICE and the wheels). Under low load the ICE only operates when the battery state of charge (SOC) drops below a certain level. Thus at low loads it is predominantly operating as a zero emissions vehicle. A commercially available domestic example of this configuration is the Renault Kangoo (Renault, 2003).

Figure 3-2. Series hybrid drive system (York Tech, 2000).



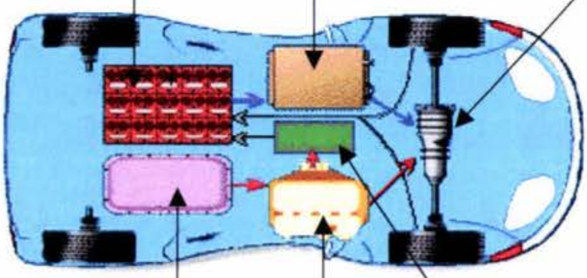
The Christchurch City shuttle bus, built by Designline, a Dunedin company, is another example of a series hybrid vehicle (Designline, 2002). In this case, a high efficiency micro turbine charges batteries that provide electricity for the electric motor, which in turn drives the wheels. During deceleration the electric motor functions as a generator to charge the batteries.

3.3 Dual mode hybrid drive system

The dual mode hybrid is essentially a parallel hybrid but uses a combination of series and parallel technology to power the vehicle (Fig. 3-3). The vehicle operates as a series hybrid below a certain speed (generally city driving speeds) and operates as a conventional parallel hybrid for the rest of the time. This has certain advantages for urban driving conditions when the vehicle can run as a zero emissions vehicle similar to an electric vehicle, the penalty however is increased complexity (Moore, 1996). The Toyota Prius is an example of the dual mode parallel configuration.

The hybrid vehicle concept is not just confined to the ICE battery hybrid configuration. Many other hybrid configurations are possible and have their own advantages and disadvantages. The ICE battery hybrid however, is the only currently commercially available hybrid configuration for domestic vehicle use.

Figure 3-3. Dual mode hybrid drive system (York Tech, 2000).



"A vehicle that is intended to operate with an established pure electric drive range, yet with the capability of extending that range if required with internal combustion power, will provide value to the end use consumer. Value will be demonstrated through operating cost savings, emissions reduction and improved quality of life" (EPRI, 2002).

Hybrid drive system technology when compared to conventional drive system technology, has the following potential to:

- produce considerably less air pollution;
- produce considerably less greenhouse gas emissions;
- consume considerably less fuels;
- have lower operating costs and improved reliability resulting in longer lifetimes; and
- be easier to drive due to high constant torque and smooth acceleration at low speeds.

This study deals specifically with the series hybrid drive system for reasons considered in more depth in the next chapter.

4.0 SERIES HYBRID DRIVE SYSTEMS

Domestic transport needs to find technology that can reduce fuel use and emissions and at the same time be viable in the market place. Alternative technologies have been tried with limited success but have not been able to compete with conventional technology for many reasons (Section 1.0, 1.2). Series hybrid drive systems have the potential to reduce fuel use and emissions similar to that of parallel hybrid technology if not better although currently the series hybrid architecture makes no real impact in the domestic vehicle market. Most light-duty hybrid vehicles at or near production make use of the parallel or dual mode configuration (Eudy, 2002).

Series hybrid drive systems combine the use of an internal combustion engine or other power source, batteries and an electric motor in a similar way to parallel hybrid vehicles. However, only the electric motor provides drive for the vehicle. By severing the conventional, physical connection between the engine and the wheels, the engine can be operated at its optimal combination of speed and torque, thereby having a high efficiency (Wallen, 2004a). This physical dislocation of engine and drive-line allows the engine to be significantly down sized with the battery bank providing the extra energy, when needed, for short duration, high load scenarios such as hill climbing and overtaking. The result is the potential for considerable reductions in emissions and fuel use (Wouk, 1997).

Most fuel use and emissions of conventional ICE powered vehicles occur under hard acceleration, hill climbing and urban stop/start driving conditions (CAE, 1996). However in the series hybrid drive configuration, due to the high part load efficiency of the electric motor and dislocation of the ICE and drive line, the ICE of the on-board power source (OPS) operates at its maximum operating point irrespective of the load application.

Since the maximum efficiency for an ICE can be found at full torque and about the middle of the engine's operating speed range (Strandh, 2002a), the engine size should be chosen in such way that the majority of the load points of the application, are found within this region. A series hybrid drive system can be designed such that its ICE operates only within the region of maximum efficiency and lowest emissions/fuel use (Wouk, 1997).

It is known that an ICE consumes far more fuel and generates considerably more emissions compared to the fuel consumption and emissions in stationary operation. This is due to the wide variation in operating point (varying loads and varying engine speeds) that is found during conventional operation of the ICE in domestic transport vehicles (Jonasson, 2002a; Strandh, 2002b). In the series hybrid drive system, the ICE operates essentially as a stationary engine and therefore should have significantly less fuel use and emissions when compared to conventional operation.

In the series hybrid, the operation of the power source is essentially independent of the driver and is related primarily to the state of charge (SOC) of the battery which is dependent on the load on the electrical system (mainly the electric motor). One of the main advantages of this approach is that control of the ICE is completely taken away from the driver due to the physical dislocation of the drive source and drive-line and is controlled by the energy management system. The power from the OPS is used to charge the batteries and/or provide power directly for the electric motor. In a conventional drive system and to a lesser extent in a parallel hybrid drive system, control of the ICE is by the driver which in most cases will be less efficient. For example, in the Honda Insight (parallel hybrid), the electric motor is used to assist the ICE for requirements such as hill-climbing and acceleration (Badin et al, 2001). This implies that when the electric motor is not in use the vehicle is driven similarly to how a conventional vehicle would be driven. The more direct control of the ICE that can be taken away from the driver the more efficient the ICE can be operated and the more scope there is for improving fuel economy and reducing emissions. Individual driving habits have a marked effect on fuel efficiency and levels in conventional vehicles (EECA, 2002). Thus, removal of this variable through the use of series hybrid drive systems has the potential for significant reductions in fuel use and emissions.

In a conventional vehicle drive system the ICE has to supply a widely varying load, thus significant part load inefficiencies are created with the resultant effect on fuel use and emissions. In a series hybrid drive system the ICE component of the OPS is supplying a constant load (the generator), implying continuous maximum efficiency can be obtained and part load inefficiencies can be eliminated.

Essentially, a series hybrid vehicle can be viewed as a conventional battery electric vehicle with the addition of an OPS to recharge the batteries so as to increase the range and/or power of the vehicle. A pure electric vehicle can have a significant extension of range with the edition of a surprisingly small OPS. The amount of electricity supplied by the source is generally not enough to fully recharge the batteries under normal driving conditions but can greatly extend the range of the vehicle. As an example, an electric van with a battery capacity of 34 kWh and a range of 160 km had its effective range doubled with the addition of a small 3kW OPS (Wouk, 1997). The Renault Kangoo (Renault, 2003) is a commercial example of this approach. It is a city centre parcel delivery can, although it can also be used for domestic purposes and also includes optional, cheap, grid recharging. All series hybrid drive systems have the potential to be recharged via access to the grid, where available, which enables them to make use of more efficient grid electricity and increase their overall system efficiency. This does not take into account the source of the electricity and any associated losses in production, supply and distribution.

Only 6 to 8 kW is actually necessary to keep a car moving at cruising speeds and less than this in city driving (CAE, 1996). Thus, a small 10 kW motor/generator in a series hybrid drive system configuration would give the vehicle comparable range to a conventional vehicle under average driving conditions, particularly given the hybrid system advantage of regenerative braking. This 10 kW generator would only require a small ICE to drive it (reducing volume and weight) with the resultant reduction in fuel use and emissions.

In a "Full" series hybrid drive system, the "range extender" concept is expanded in that the OPS is larger to be able to cope with average city as well as motorway driving load conditions and the requirement to power the electric motor directly as and when required. The battery pack itself is generally smaller than in a pure electric vehicle. The purpose of the battery pack is to (HIL, 2000):

- provide power to the electric motor under zero emissions driving conditions and under conditions of peak power requirements (hill climbing, acceleration) in conjunction with the OPS;
- store energy that would otherwise be lost during deceleration and braking; and
- act as a storage element or buffer between the OPS and the electric motor.

Therefore a large capacity to allow the vehicle to travel a large distance on battery power only, as would be the case in a pure electric vehicle, is not required.

The size of the battery pack is largely determined by constraints such as battery type, the required battery only range (energy density) and the power requirements of the vehicle (power density). These have a significant effect on overall battery weight and therefore vehicle weight which has a flow-on effect to fuel use, emissions and also vehicle performance.

The trade off when compared to a pure electric vehicle, is increased fuel use and emissions. However a series hybrid can be as fuel efficient, or even better, with less emissions when compared to an electric vehicle if the source of electricity for the pure electric vehicle is taken into account. For example if the source of electricity is a coal-fired plant then the emissions from a hybrid can be less (Lipman and Sperling, 2000).

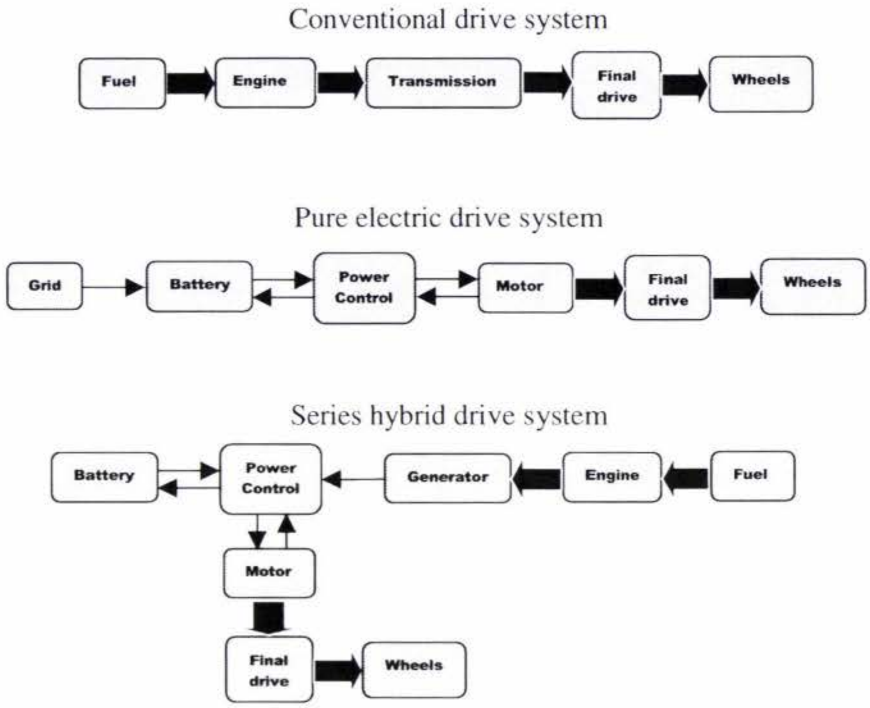
Vehicles equipped with series hybrid drive systems and current productions vehicles such as the Toyota Prius (dual mode hybrid) have the ability to run in zero emissions mode i.e. the electric motor driving the vehicle derives its power from the battery pack only. This can be an advantage in areas such as city centres as it shifts the source of the pollution away from population centres. It also means that these vehicles can be driven in areas that restrict vehicle tail pipe emissions or make use of strict air quality regulations such as CARB (Sec. 2.3.2)(Olsson, 2000).

4.1 Comparisons of energy flow paths

Figure 4-1 shows the different energy flows that are present in the conventional, pure electric and series hybrid drive systems. The large arrows represent mechanical flows of energy and the thin arrows represent electrical flows of energy. The conventional drive system is very simple, the energy flow is mechanical only and this flow is unidirectional. Thus it is not possible to regenerate any energy (from deceleration and braking) in this system.

The pure electric drive system is also relatively simple except that now there is a combination of electrical and mechanical flows of energy in the system. The fuel for the system in this case is electricity from the grid. This system has bi-directional electrical flows of energy between the motor, power controller and battery; the battery accepts power from regenerative braking (via the electric motor) and also supplies power to the electric motor. These power flows are controlled by the power control unit.

Figure 4-1. Comparison of energy flows in conventional, pure electric and series hybrid drive systems.



The series hybrid drive system is an electrical combination of conventional and pure electric drive systems. This system also makes use of bi-directional electrical power flows, however in this case power is also available from a generator which can flow to the battery or to the electric motor as well as the bi-directional flows that are evident in the pure electric vehicle. Again, these power flows are controlled by the power control unit.

4.2 Down sizing

Prior research has tended to focus on comparisons between series hybrid vehicles and conventional/parallel hybrid vehicles that have the same or similar engine capacities when gauging any differences in fuel use and emissions (Wallen, 2004b; Jonasson, 2002). However this has tended to obscure any real advantage that the series hybrid may have in emissions and fuel use since components have to be added to the engine (such as electric motor, generator, batteries and control electronics) and thus the overall weight of the vehicle is significantly heavier than a conventional vehicle. Since weight is a significant determinant in fuel use and therefore emissions it thus effects the legitimacy of the comparisons.

The approach used in this study was to make use of the primary advantage of the series hybrid drive system being its ability to significantly scale down the size of the ICE and other ancillary components since its only real purpose is to charge the battery pack and occasionally provide power directly for the electric motor. This implies that the weight of the OPS can be significantly reduced and thus the overall weight of the vehicle will be similar to that of the original vehicle and thus a more effective gauge of the ability of the series hybrid drive system to reduce fuel use and emissions can be realised.

Down sizing the ICE is a very effective way of reducing fuel use and emissions. It is known (Leduc et al, 2003; Nyland et al, 2002a) that poor engine efficiency occurs at low load conditions relative to the engine optimum load operating points, and this part load inefficiency increases as the engine capacity increases. It has also been shown (Leduc et al, 2003) that reducing the capacity of an engine in a conventional vehicle while keeping all other vehicle and engine parameters the same (for example power and torque) can significantly reduce fuel use and emissions. In a series hybrid drive system (as has been indicated), the ICE is not physically connected to the wheels therefore does not drive the vehicle. Thus the ICE can be significantly reduced in size to a level that is equivalent to the average power requirements of the vehicle and the generator output that it is driving. A combination of significant engine capacity reduction (and therefore weight reduction) and efficient operation should lead to considerable reductions in fuel use and emissions.

Downsizing can also be applied to other components such as the battery pack. As previously indicated, the battery is primarily used as a bi-directional buffer between the OPS, the regenerative braking system and the load (mainly the electric motor). Its capacity and therefore size can be significantly downsized compared to the battery back in a conventional battery only electric vehicle. The size being dependent on the power requirement of the battery pack only. A major disadvantage of pure electric vehicles is the weight penalty associated with the requirement of a large battery pack to accommodate a reasonable vehicle range which can be eliminated in vehicles equipped with series hybrid drive systems.

In a conventional drive system or a parallel hybrid drive system the ICE will be, generally, considerably larger than in a comparable series design since the ICE in the conventional/parallel configuration is used to propel the vehicle. For example the ICE in the Toyota Prius is 1500cc and in the two seat Honda Insight the ICE is 1000cc (Nam, 2004d), whereas the Renault Kangoo series hybrid vehicle has only a 500 cc engine (Renault, 2003). In the series hybrid approach the fuel efficiency and emissions of the technology are more independent of these parameters. Thus allowing a smaller ICE component and therefore potentially less emissions and fuel use.

In the parallel hybrid concept both the electric motor and the ICE drive the wheels this implies that the engine can be reduced in size and a mechanical combination of the respective power of the electric motor and the ICE can be made use of. However the parallel concept under certain load conditions will be making use of the ICE to solely drive the wheels and therefore carry the bulk of the load. Thus there is a limit to how small the ICE can be made and where it can be placed (since there is still a physical connection between engine and wheels).

In the series approach some drive component counterparts in the conventional system may not be required. For example due to the torque characteristics of the electric motor (Section 2.3.2), a conventional transmission is not required. This represents a reduction in weight with the flow on effect to reduced fuel use and emissions. Ancillary components may also be lower in weight.

4.3 Adaptability to other technologies

The electrical power source for hybrid drive systems is not necessarily confined to the ICE/battery system. Many other options are available to replace the ICE such as fuel cells, Stirling cycle engines and micro-turbines although none of these are currently in commercial production for domestic vehicles. The aforementioned alternative hybrid options have efficiency advantages over the ICE with the potential to reduce fuel use and emissions compared to current reciprocating ICE hybrid systems (CAE, 1996).

These particular options however are not particularly compatible with the conventional drive system or parallel hybrid configuration. Fuel cells, for example, have no moving parts therefore the only possible option is a series hybrid configuration which is seen as being more appropriate to supporting fuel cell vehicles which are widely seen by the automotive industry as the long term future of domestic automobile transport (Olsson, 2000). Turbines have poor part load efficiencies and so have poor fuel economy when used in conventional vehicles where part load operation is common. Turbines also have very high rotational speeds making them difficult to adapt to conventional/parallel hybrid automobile drive systems (Sperling, 1996d). However turbine technology can be easily adapted to the series hybrid configuration since the turbine is only used to drive a generator which is the approach used in some hybrid buses (Section 3.2).

The ICE component of the series hybrid drive system can also be easily optimised for various requirements such as type of fuel (diesel, petrol, gas and in particular bio-fuel) or tuned to have minimum emissions and/or fuel use due to operating at constant speed. This is not as easy to achieve in a conventional vehicle system or even a parallel hybrid drive system as the ICE is directly related to performance in these vehicles.

An interesting hybrid configuration is that of the Stirling cycle engine/battery/electric motor configuration which could be potentially advantageous for the future. The Stirling engine is an external combustion engine potentially far more thermodynamically efficient than the ICE and hence could be ideal as the drive source for the generator of a series configured hybrid vehicle (CAE, 1996).

4.4 Operational, design, and marketing issues

Longer journeys or high speed driving over more arduous terrain (hill-climbing, overtaking) that requires more power are perceived to be the domain of the parallel configuration (Wouk, 1997; Sperling, 1996d). This extra power is achieved through a cumulative, mechanical, combination of the electric motor and the ICE. However continuing advances in electric motor performance and reduction in weight and cost may change this perception (Section 2.3.2). Electric motors also have the advantage of full torque at zero engine speed obviating the need for complicated clutch arrangements and transmissions (Nam, 2004c; Riley Enterprises, 2005). Thus, the series hybrid is more than equipped for the functions indicated. It would appear to be a mindset built up over 100 years of ICE dominance that electric motors themselves cannot compete with the ICE as a primary drive source. With respect to electric vehicles the problem has not been the electric motor but rather the on-board source of power for the electric motor.

It has been suggested (Jonasson, 2002) that the series hybrid technology has lower efficiency compared to that of the parallel hybrid technology due to the number of energy conversions that are required to propel the vehicle. However this is not the only methodology for producing series hybrid drive. By taking energy directly from the generator to the motor and bypassing the battery under certain circumstances, reduces the number of energy conversions and hence improves the overall efficiency (Aoyagi et al, 2001). In the parallel approach, although there are less energy conversions to provide vehicle drive, the conventional internal combustion engine component of the technology still takes a significant proportion of the propulsion of the vehicle thus the driver is more in control of vehicle with the inherent losses due to part load inefficiencies and driving habits. In fact Volvo has indicated (Moore, 1996) that the series approach is more efficient overall.

Modern car design tends to be constrained by where the ICE/transmission can be placed since the ICE and drive motor/generator/transmission must be physically connected). This results in a penalty of design complexity and flexibility (Moore, 1996; Wouk, 1997). However, this constraint can be removed when designers can consider series hybrid drive systems since the drive motor and OPS are not physically connected and can therefore be placed anywhere that is convenient in the vehicle. This allows vehicle characterises such as aerodynamics, centre of mass, internal space, handling, centre of gravity, external design and various other variables to be optimised.

The hybrid drive system implies that the storage capability of the battery bank can be crucial to the operational characteristics of the system. For example, the size of the battery bank may have a direct effect on the amount of available power for hill-climbing or overtaking. This storage capability may be more crucial for the series hybrid since no physical connection between the OPS and the electric motor exits implying that this approach is completely reliant on the battery to provide the power not provided by the OPS.

The lack of acceptance in the market for the series hybrid drive system architecture compared to its parallel counterparts may be due to the similarity with the pure electric vehicle and the associated negative public image due to the lack of range and/or power and the lack of flexibility, practicality and infrastructure that has been inherent with this technology. History has shown that the electric vehicle has never gained any significant share in the domestic passenger vehicle market. The parallel configuration functions and drives more like a conventional vehicle and therefore may be seen as being more palatable to the market in the short term since it is effectively still a conventional vehicle with the electric motor being used to augment the conventional drive system. They are also perceived as being more powerful since the ICE still contributes a significant proportion of the total power available to the load application and therefore more amenable to conventional driving requirements.

It has been suggested (Sperling, 1996d; Riley Enterprises, 2005) that series hybrids will show more potential in the future compared to their parallel counterparts due to being able to benefit more from expected advances in electric drive, generator and battery/super capacitor technology.

The main players in the auto industry are bound by economic constraints and thus any new technology that is considered to be environmentally friendly must also be competitive in the market place. This implies that vehicles with alternative primary drive systems that are more similar to conventional drive systems will tend to be favoured in the short term. Hence parallel hybrid drive systems will be seen as preferable to series hybrid drive systems.

Primary drivers for a move toward more environmentally friendly domestic transport are laws such as the CARB regulations in California and various other regulations that look to reduce emissions from domestic transport. Other regulatory reforms such as meeting Kyoto protocol targets have also been a driver. However these initiatives are not far reaching enough to have a significant effect on the type of vehicles sold and their ability to reduce fuel use and emissions.

4.5 Modelling

Software simulation has the advantage of testing a system to see if it warrants further analysis or where further research should be concentrated (reduces following dead ends) and can ascertain viable results quickly (aids in rapid prototyping) without the cost and time penalties associated with physical design and testing.

The use of vehicle modelling is increasing as physical testing becomes more expensive and computing becomes faster and cheaper. Once a model has been set up, results can be produced quickly. However it is still necessary to validate the model results against real world results to calibrate or check the model (Stone, 1992b).

Simulation/modelling software is available and has been used to model hybrid drive technology as well as conventional drive systems, examples being: Advisor (Senger, 1998a) and PERE (Nam, 2004b). PERE (Physical Emission Rate Estimator) is a spreadsheet based approach to calculating fuel use in conventional domestic and heavy duty vehicles, pure electric vehicles, fuel cell vehicles, parallel hybrid vehicles and motorcycles. PERE is currently being investigated by the USEPA (United States Environmental Protection Agency) and has been shown to be quite accurate in its predictions (Nam, 2004c).

A model was developed in this study to calculate fuel use in conventional and series hybrid vehicles also using a spreadsheet based approach and making use of some elements of PERE, and emissions modelling using commercially available software (Chemwork6) (Dwyer, 2005) and used as a source of emissions data only. The data is then used in the model to predict overall emissions, as explained in the next chapter.

5.0 REFERENCE VEHICLE MODEL

Computer modelling was employed to compare conventional vehicle drive systems and series hybrid drive systems in terms of fuel use and emissions. The emphasis of the modelling was on consistency, i.e. the same modelling methodology was applied to both the conventional vehicle drive systems and the series hybrid drive systems. In this way the results achieved from the comparisons could be considered to be valid. In this Chapter the methodology of the model and the individual parameters involved will be examined.

5.1 Methodology Overview

- **Input vehicle parameters:** These parameters include engine capacity, maximum power, maximum torque, maximum vehicle speed, maximum engine speed, frontal area, drag coefficient, payload weight, curb weight and total vehicle weight.
- **Test drive cycles:** In this study two test drive cycles were considered (NYCC and US06). From the test drive cycle model, calculations are undertaken to determine the values of the parameters; initial speed, final speed, time taken, average speed and acceleration for each second of operation.
- **Transmission:** The transmission and final drive convey the power of the ICE to the wheels. Calculations were undertaken to evaluate parameters such as selected gear, gear ratio, gear shift point and engine speed.
- **Road-load:** This involved the calculation of the energy required to carry out an individual task (such as acceleration) and therefore the road-load in the test drive cycle, given the vehicle parameters that have been input. The road-load calculation step involves evaluating the following parameters; inertial resistance, air resistance, rolling resistance, distance travelled, time, and transmission efficiencies.
- **Fuel use:** This involved knowledge of the road-load and knowledge of the engine frictional characteristics under certain load scenarios which are dependent on parameters such as engine speed, engine capacity, and the various losses in the engine.
- **Emissions:** This step involved calculations to determine the level of the various gaseous emissions that exist during combustion. The approach here was to find inherent relationships that exist between emission species and the air/fuel ratio, which is particularly important for Diesel cycles.

With this modelling technique it was not possible to take into account variables such as driving style and behaviour which can have a significant effect on fuel use and emissions (EECA, 2002). Thus the effect of the driver has been ignored.

Values were calculated for fuel use and for the amount and type of emissions produced during combustion on a second by second basis. At the completion of the drive cycle a summation of these values was carried out to give a total fuel consumption value and a value for total emissions produced for a particular vehicle/technology during the particular drive cycle considered. This was then compared to the distance travelled during the drive cycle and thus a value for fuel economy (l/100km) and emissions (g/km) was calculated.

5.2 General vehicle parameters

The reference vehicles chosen and their specifications are shown in Table 5-1. These vehicles represent a cross section of vehicles based on fuel type and usage category.

Table 5-1. Vehicle Parameters for 4 selected reference vehicles (Carfolio, 2005; UK car buyers guide, 2005).

Parameter	Daihatsu Charade	Toyota Corolla	Volkswagen Polo TD	Volkswagen Bora TD
Designation	REF1	REF2	REF3	REF4
Engine capacity	989cc	1598cc	1422cc	1887cc
Fuel type (section 5.7.2)	iso-octane	iso-octane	cetane	cetane
Max power (kW)	43.3	81	55	75
Engine speed @ max power (RPM)	6000	6000	4000	4000
Max torque (Nm)	90	150	155	240
Frontal area (m^2)	1.8	2.05	2.04	2.11
Drag coefficient	0.31	0.3	0.3	0.3
Tyre friction coefficient	0.01	0.01	0.01	0.01
Curb weight (kg)	740	1220	1267	1427
Payload weight (kg)*	80	80	80	80
Total vehicle weight (kg)**	820	1300	1347	1508
Max. Speed (km/h)	158	188	163	187

* The payload weight is defined to be any extra weight over and above the curb weight of the vehicle. In the model the payload weight was considered to be the weight of the driver which has been defined as 80kg.

** Total vehicle weight is defined as the vehicle curb weight plus the payload weight.

5.3 Drive cycle model

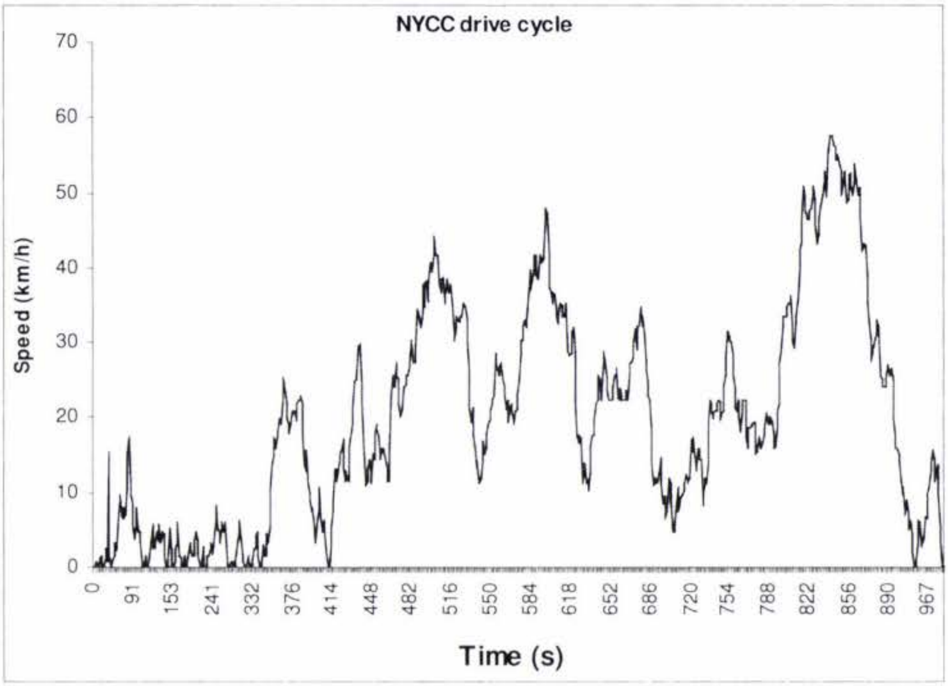
Test drive cycles are a collection of specific load scenarios (such as periods of acceleration, deceleration and constant motion) that a vehicle is put through as a means of assessing fuel consumption and levels of emissions (Fig. 5-1). These are then compared with other vehicles that are driven over the same cycle so that an absolute comparison can be made. The drive cycles chosen are readily available drive cycles that are in common usage for the purpose of determining fuel consumption and emissions of a particular vehicle. In this study the different reference vehicles and series hybrid drive system configurations will be compared via the NYCC and US06 drive cycles.

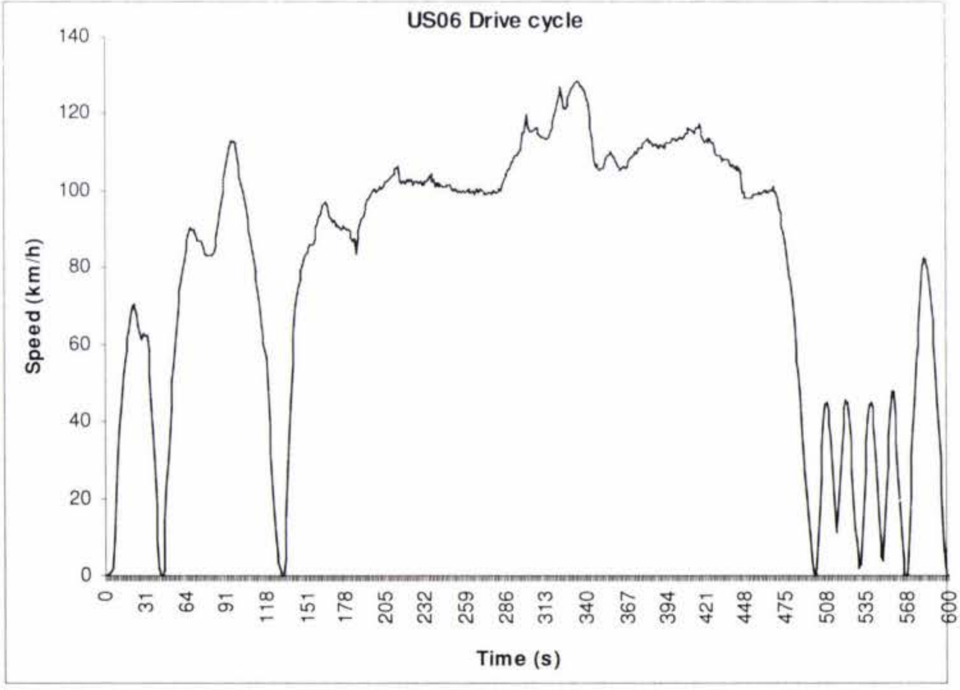
The NYCC (New York Composite Cycle) is a harsh urban cycle designed to simulate city driving conditions (Dieselnet, 2005). It is characterized by low average speeds, frequent stops, fast, short duration accelerations and decelerations, and overall low average loads i.e. typical urban or city driving loads that would be encountered in peak hour traffic. The cycle is for a journey of four kilometres with an average speed of 19.8 km/h (including time spent at zero speed), and a maximum speed of 56 km/h.

Other drive cycles were initially considered, for simulating city driving. These included a Japanese standard driving cycle known as the 10 – 15 drive cycle (J10-15), a European standard drive cycle known as ECE 15, and a standard American drive cycle known as Federal Test Procedure 72 (FTP 72). However it was found that none of these cycles fully simulated harsh urban driving scenarios that are increasingly found during peak traffic conditions, such as inner city driving and motorway grid-lock.

The US06 drive cycle is characterized by higher average speeds, longer accelerations and decelerations, less time spent at zero speed and higher average loads (Dieselnet, 2005). This drive cycle essentially models more aggressive driving that would be encountered in extra urban and motor way driving conditions. It does not solely model driving on a motor way where constant speeds prevail and therefore is more typical of ex-urban/city to city driving. The cycle is for a journey of 12.8 kilometres with a maximum speed of 128.5 km/h and an average speed of 81.2 km/h.

Figure 5-1. Speed versus time plots of NYCC and US06 drive cycles over 4 km and 12.8 km respectively (Dieselnet, 2005).





It was my initial intention to create a drive cycle which incorporated hill-climbing for the purposes of fuel consumption and emissions comparison, however this would have added unnecessary work, complication and reduced validity given the availability of dedicated, standardised test drive cycles for the task. The purpose of a drive cycle is to essentially assess energy in versus energy out, whether the energy is expended while overcoming a hard acceleration or an inclined surface is essentially the same in this context. Thus the use of explicit hill-climbing would not have added any extra information that was not already available from the drive cycles considered for the purposes of comparison. Note that these drive cycles are also implemented on a dynamometer where the concept of hill-climbing is redundant.

5.3.1 *Initial speed and final speed*

The initial speed and final speed were the 'per second' speed point couples at the start and end of a time point (1 second). Thus at some arbitrary instant during the drive cycle, the final speed at the end of one time point is the initial speed of the beginning of the next time point and vice versa.

5.3.2 *Average speed*

The average speed during a 1-second interval is the arithmetic average of the initial and final speeds:

Equation 5-1. $V_{ave} = (V_1 + V_2) / 2$

where

V_1 = initial speed

V_2 = final speed

The time of duration of the test cycles and calculations therein is considered to be in seconds.

5.3.3 *Acceleration*

Acceleration was defined as the ratio of the change in velocity to the change in time. It is calculated from the speed and time difference of a certain load scenario, for example to accelerate from some initial velocity to some final velocity:

Equation 5-2. $a = \Delta V / \Delta t = (V_1 - V_2) / t_1 - t_2$

where

a = acceleration

t_1 = initial time

t_2 = final time

5.4 Transmission model

In a conventional vehicle the power and torque of the ICE are transmitted to the wheels via the transmission. This device is essentially a number of gears that attempt to match the positive non-linear torque characteristics of the ICE to the variable requirements of the load.

5.4.1 *Transmission methodology and efficiency*

Conventional vehicle transmissions can vary in efficiency from 87% to 99% for manual transmissions and 60 to 95% for automatic transmissions (Nam, 2004a). In this study all vehicles making use of a transmission were considered to have a 5 speed manual transmission. The efficiency of the transmission can be affected by the load scenario being considered, for example, under urban conditions more gear changes will be required than during an open road load scenario. Thus clutch operation will be required more often in an urban environment. This implies more time spent by the engine not actually driving the wheels and thus a certain amount of clutch slippage that is not encountered as frequently under an open road scenario. The result is that the transmission is likely to be less efficient under urban driving conditions than during open road conditions. The efficiency of the conventional vehicle transmission has been chosen to be 95% during open road conditions and 92% during urban conditions.

The transmission in the reference vehicle was modelled along similar lines to that found in Nam (2004a; 2004f). The ratios in each gear (including final drive ratio) are given in Table 5-2. An equation for engine speed is then used, being a simplified derivation of that found in Nam (2004b):

Equation 5-3 $N = R\,(N_{max} / V_{max})\,V$

where

N = engine speed (RPM)

V = vehicle speed (km/h)

R = final drive ratio in a particular gear

N_{max} = maximum engine speed (RPM)

V_{max} = maximum vehicle speed (km/h)

The shifting points in the gearing system are the speeds at which a conventional transmission would change from one gear to another. The gear shifting points (Table 5-2) were derived from that found in Nam (2004a).

Table 5-2. Vehicle gear shift points and gear ratios.

Drive Cycle Speed (km/h)	Gear number	Gear ratio
0-29	1	4
29-40	2	2.22
40-64	3	1.44
64-80	4	1
80+	5	0.9

The algorithm for calculating the engine speed in the model is as follows;

If V < 29 km/h then N = 4 * (max_RPM / max_speed) * (V<29)

If 29 < V km/h < 40 then N = 2.22 * (max_RPM / max_speed) * (29<V<40)

If 40 < V km/h < 64 then N = 1.44 * (max_RPM / max_speed) * (40<V<64)

If 64 < V km/h < 80 then N = 1.00 * (max_RPM / max_speed) * (64<V<80)

If V >80 km/h then N = 0.9 * (max_RPM / max_speed) * (V>80)

It has been indicated that the values chosen for the transmission shift points do not affect overall system efficiency and fuel consumption greatly (Nam, 2004a) such that an even simpler model that relates engine speed to vehicle speed in top gear could be used. However, this was not found to be the case. In particular it was found that changing the gear shift points had a significant impact on fuel use. This is because changing the gear ratio at a higher vehicle speed, for example, implies a higher engine speed resulting in increased fuel use due to high engine speed at low load. Thus the ICE is running less efficiently due to operating away from its optimum fuel efficiency point.

Note that in Nam (2004a) the same gear shifting pattern is adopted for both drive cycles and load scenarios. This is not entirely realistic as urban driving is characterised by frequent gear changes at low vehicle speed and therefore engine speed, whereas highway driving is characterised by gear changes at higher average engine speed. However, maintaining the same scheme for both scenarios ensures an element of consistency across the model although it may tend to give a slight over estimate of fuel use during the NYCC drive cycle.

The transmission model in this study also incorporates a gear check mechanism, similar to that found in Nam (2004a) in that in a particular gear it is possible that the amount of torque required to undertake a particular load scenario is more than can be supplied by the ICE. Under these conditions, the transmission model selects a lower gear. The algorithm is as follows:

If gear = n and load torque > maximum torque then gear = n –1

where n = gear 2 to 5. Note that (for simplicity) only one iteration of this algorithm is applied which may lead to a minor underestimate of total fuel use for the reference vehicles. The load torque in the above algorithm is calculated from:

Equation 5-4. $T = 30000\, R_L / (\pi\, N)$

where

T = torque

R_L = road-load (kW) (section 5.5)

N = engine speed (RPM)

The maximum torque in the above algorithm is the maximum torque that is available at a particular engine speed and is acquired by scaling generic vehicle engine torque curves (Nam, 2004a) and then finding a polynomial fit for the resultant curve. The torque curves are modelled by a 5^{th} order polynomial of the form:

Equation 5-5. $T=a+bx+cx^2+dx^3+ex^4+fx^5$ where x = RPM of the engine

The coefficients for each reference vehicle are given in Table 5-3.

Table 5-3. Coefficients for the various vehicle torque output curves.

	REF1	REF2	REF3	REF4
Coefficient	Charade	Corolla	Polo	Bora
a	-6.3618143	-6.2003833	-0.34775335	-0.44658459
b	0.13102244	0.21170259	0.010427445	0.088969182
c	-8.35E-05	-1.35E-04	1.82E-04	1.79E-04
d	2.67E-08	4.32E-08	-1.24E-07	-1.39E-07
e	-4.02E-12	-6.49E-12	3.00E-11	3.53E-11
f	2.22E-16	3.59E-16	-2.53E-15	-3.04E-15

5.4.2 *Final drive efficiency*

The final drive is the last set of gearing before the power of the engine is finally transferred to the wheels and also includes the differential gear. The final drive gear, like the transmission, is also a source of energy loss in the system and thus its efficiency was chosen to be 98% (Nam, 2004a).

5.5 Road-load model

The road load can be defined as the power required to overcome the various resistances to vehicle motion such as air resistance, rolling resistance and inertial resistance. These accumulated resistances are overcome by the power developed by the internal combustion engine of the vehicle.

5.5.1 *Air resistance*

Any object that moves in air creates air resistance such that energy must be supplied to overcome this resistance to push the object through the air. In other words air resistance is a force that acts negatively against the movement of the object – in this case a vehicle. Air resistance is proportional to the square of the speed of the vehicle, the frontal area that the air 'sees' and the coefficient of friction that is a function of the shape of the vehicle and the materials that the body is made from and coated with. In the overall model, air resistance (Senger, 1998b) was modelled by:

Equation 5-6. $R_{air} = 0.5\, A\, C_D\, \rho\, V^2$

where

R_{air} = air resistance (kgm/s^2)

A = frontal area of the vehicle (m^2)

C_D = drag coefficient of the vehicle (non-dimensional)

ρ = Air density at standard temperature and pressure (STP) and equals 1.2 kg/m^3

V = velocity of the vehicle (m/s)

This equation is used if the vehicle is travelling at a constant speed (zero acceleration). However if acceleration is non-zero then the average velocity is used to determine the air resistance:

Equation 5-7. $R_{air} = 0.5\ A\ C_D\ \rho\ [(V_1+V_2)/2]^2$

where

V_1 = initial velocity

V_2 = final velocity

Notes and assumptions:

Actual wind speed is not taken into account in the model. The drag coefficient neglects effects due to roof racks or open windows etc. Air resistance is proportional to the square of the vehicle velocity which implies that vehicle speed is the largest contributor to air resistance.

5.5.2 *Rolling resistance*

All domestic vehicles make use of wheels to provide vehicle motion. Wheels are characterised by having rubber tyres that make the physical connection between the wheels and road surface. The wheels themselves are connected to the vehicle through the use of some sort of bearing. Both of these result in a frictional force that must be overcome. Energy loss in the tyres is mainly through deformation of the tyre as it contacts the road and then reforming to its original shape (CAE, 1996). Thus rolling resistance is a force that acts negatively on the movement of the vehicle. Rolling resistance is modelled by the following equation (Gomez, 2003):

Equation 5-8. $R_{roll} = m\ g\ [Cr\ (1 + V / 160)]$

where

R_{roll} = rolling resistance (kgm/s^2)

m = mass of the vehicle (kg)

V = velocity of the vehicle (km/h).

g = gravitational effect (9.81 m/s)

C_R = coefficient due to tyre friction and bearing friction (non-dimensional). In this study the value for the coefficient due to tyre friction is 0.01

Notes and assumptions:

The contribution to rolling resistance from temperature effects, different road surfaces, tyre pressure and wheel alignment was not considered.

5.5.3 *Inertial resistance*

Newton's first law essentially states that an object that is not acted on by a force either moves in a straight line (at constant velocity) or is at rest. Newton's second law essentially states that given a constant mass the rate of change of the velocity of an object is equal to the force acting on the object (Alonso and Finn, 1981a). Every object has inertia relative to its mass. To move an object it is necessary to apply a force to it. To accelerate a vehicle of a certain mass it is necessary to overcome the inertial resistance of the vehicle. Inertial resistance can be modelled by (Senger, 1998b):

Equation 5-9. $R_{inert} = m\ a$ (cf. $F = m\ a$)

where

R_{inert} = inertial resistance (kgm/s^2)

m = mass of the vehicle (kg)

a = acceleration of the vehicle (m/s^2)

Notes and assumptions:

A negative value for inertial resistance indicates deceleration. Deceleration was assumed to occur under "engine braking" conditions for a conventional vehicle. This means that the throttle (Otto cycle engine) is at its smallest opening position (idling position) and the speed of the engine and therefore fuel use is governed by the speed of the vehicle working backwards through the transmission and clutch, forcing the engine to rotate. This represents energy that is lost, as fuel is used, but no increase in vehicle speed is attained. This is similar to the vehicle idling condition but uses more fuel.

5.5.4 *Road load energy requirement*

In order to calculate the amount of energy that is required by the vehicle to overcome a certain load scenario (including over-coming the resistive forces of initial resistance, air resistance and rolling resistance) it is necessary to determine the distance that the vehicle has travelled while being operated on by these forces, for example, how far has the vehicle travelled while carrying out a uniform acceleration. The distance travelled is modelled by (Alonso and Finn, 1981b):

Equation 5-10. $d = u\,t + 0.5\,a\,t^2$

where

d = distance travelled (m)

u = initial velocity (m/s)

t = time to reach final velocity (s)

a = acceleration of the vehicle (m/s^2)

Notes and assumptions:

Acceleration is assumed to be uniform. For a vehicle travelling at constant speed (zero acceleration), the distance is the product of velocity and time and the above equation reduces to:

Equation 5-11. $d = v\,t$

where

v = final velocity

For a vehicle accelerating from stand-still (0 velocity) to some final velocity then Equation 5-10 reduces to:

Equation 5-12. $d = 0.5\,a\,t^2$

The energy required to accomplish some load scenario, for example, acceleration or the energy required to overcome the negative forces of rolling resistance and air resistance while travelling at constant velocity is modelled by (Alonso and Finn, 1981c):

Equation 5-13. $E = F\,d$

where

E = energy required (J)

F = force required (kgm/s^2)

d = distance that the force is working over (m)

This equation can be expanded to:

Equation 5-14. $E = (R_{air} + R_{grad} + R_{mech})\,d$

$= [0.5\,A\,C_D\,\rho\,[(V_1 + V_2)/2]^2 + m\,g\,C_g + m\,a]\,(u\,t + 0.5\,a\,t^2)$

5.5.5 *Road-load calculation*

The road-load is simply the ratio of energy required to the time taken to give a value related to the power required to overcome all the resistances that oppose the motion of a vehicle. This power is supplied by the internal combustion engine. Note that the power from the ICE to the wheels is transferred through a transmission which also has a small amount of resistance that must also be overcome by the power of the ICE (section 5.4)

The full road load equation is therefore:

Equation 5-15. $R_L = (R_{air} + R_{grad} + R_{mech})\,d\,t\,/\,(\eta_{fd}\,\eta_t)$

where

R_L = road load (kW)

t = time (s)

η_{fd} = final drive efficiency (98%)

η_t = transmissions efficiency (urban = 92%, ex-urban = 95%)

5.6 Engine model

5.6.1 *Torque and power*

Engine torque is defined as a measure of the engine's ability to do work. Engine power is defined as the rate at which this work can be done (Heywood, 1988c). In an internal combustion engine, torque is essentially a function of the force being applied to the piston while power is a function of the torque and engine speed.

Torque and power are related by the following equations:

Equation 5-16. $T = 30000 P / (\pi N)$

Equation 5-17. $P = \pi T N / 30000$

where

P = power (kW)

T = torque (Nm)

N = engine speed (RPM)

5.6.2 *Brake mean effective pressure*

Brake mean effective pressure (BMEP) is essentially the average pressure across all strokes and across all cylinders (CAE, 1996). For example in a single cylinder 4-stroke engine this is the average of the pressures that occur during combustion, exhaust, compression and induction. It is a measure of the work output of an engine (Stone, 1992a). It is also a more effective measure of work output between different ICEs and therefore tends to be a better measure of engine efficiency (Carambola, 2005).

BMEP can be defined by the following equation:

Equation 5-18. $BMEP = P / [(V_d) (N / 60 n)]$

$$= 2 n \pi T / (V_d)$$

where

n = 1 for two stroke, 2 for four stroke.

P = power (kW)

T = torque (Nm)

N = engine speed (RPM)

V_d = engine capacity (m^3)

The above equation implies that the ICE is most efficient at maximum torque since any torque less than this will give a lower BMEP value. This also implies that matching the required torque of a given load scenario to the torque of the engine at a given RPM will result in the lowest fuel use and the lowest emissions.

5.6.3 *Engine friction*

Engine friction is the inherent friction that exists due to the interaction of the various components in the engine, for example the friction that exists between piston and cylinder wall, bearing friction etc. This engine friction also includes resistance due to pumping such as the energy required to draw air/fuel into the cylinder or to overcome valve train and injector losses in a conventional engine (Heywood, 1998e; MIT, 2004d). Engine friction is a necessary component in determining fuel use as it is another source of resistance in the system that the power of the engine needs to overcome. For example when a conventional vehicle engine is idling, the torque being developed by the engine is used to overcome resistive forces opposing motion in the engine such as rubbing friction and pumping losses which consumes fuel. As the engine speed increases the resistive losses increase resulting in more torque needing to be developed by the engine to overcome these extra resistive losses, which consumes more fuel. The engine frictional component was derived from that found in Nam (2004a; 2004d). The equation relating base friction and engine speed is:

Equation 5-19. $k = k_0 + k_1 (N / 60)$

where

k = base engine friction relationship(kJ/L)

k_0 = engine dependent friction coefficient (kJ/L s)

k_1 = speed dependent friction coefficient(kJ/L)

N = engine speed (RPM).

The fuel use related to the frictional component can be defined by (Nam, 2004a):

Equation 5-20. $F_R = k (N / 60) V_d / E_{fuel}$

where

F_R = fuel rate (g/s)

V_d = engine displaced volume (litres)

E_{fuel} = energy content of the fuel (lower heating value) (kJ/g)

Note that the base engine friction relationship differs for different ICE cycles and from year to year which, for the conventional vehicles used in this study, are shown below for the 2005 model year (Nam, 2004a).

Conventional Otto cycle:

Equation 5-21. $k = 0.15 + 0.001545\ (N / 60)$

Conventional Diesel cycle:

Equation 5-22. $k = 0.0474 + 0.00333\ (N / 60)$

In the series hybrid drive system, non-conventional engines are used as the on-board power source and these have different base friction relationships (Section 6.6.8).

The relationship for base friction is known to underestimate friction by 50% during idle conditions (Nam, 2004a). In PERE this has been accounted for by multiplying the k_0 term in the base friction relationship at idle by a factor of 1.5 (Nam, 2004a). The same approach was used in this study.

5.7 Fuel use model

5.7.1 *Methodology*

The approach is to create a model that reasonably accurately predicts fuel use in conventional vehicles. Once attained, this same model can then be used to accurately predict fuel use and emissions in vehicles equipped with series hybrid drive systems. Thus consistency becomes inherent in the modelling process This ensures reliable results can be obtained when comparing series hybrid drive systems with conventional vehicle drive systems.

For each second of the drive cycle, the relevant drive cycle, the road-load, and ICE variables are calculated. This process culminates in the calculation of fuel use. When the drive cycle is completed, the fuel use for each second of operation is accumulated to give a sum of the total fuel use. Calculations are then undertaken to calculate the fuel economy (l/100km).

5.7.2 *Fuels*

Conventional fuels used in modern domestic transport are not "pure" hydrocarbon compounds, but are in fact a combination of hydrocarbons of differing carbon chain lengths (MIT, 2004c). The varying nature of the composition of these fuels makes them difficult to model. Thus a better approach is use pure hydrocarbon compounds that represent these fuels. The fuels used in the modelling process (Table 5-4) are iso-octane (to represent conventional Otto cycle fuel) and cetane (to represent conventional Diesel cycle fuel).

Table 5-4. Fuel Properties (Heywood, 1998b).

	FUEL	
PROPERTY	iso-octane	cetane
Formula	C_8H_{18}	$C_{16}H_{34}$
Molecular Weight.	114.23	226.44
Density (l/kg)	1.36	1.182
Air/fuel ratio (stoichiometric)	15.13	14.82
LHV (kJ/g)	44.3	44

5.7.3 *Fuel consumption calculation*

Fuel use in a conventional vehicle can be split into two parts:

1. Fuel use during idle and deceleration

Fuel use during idle is proportional to the power required to overcome the amount of friction involved in keeping the engine operating at an idle condition (750 RPM in this study). This is essentially a function of the engine friction present at the idle speed, the volumetric capacity of the engine and the type of technology involved (Otto or Diesel cycle).

Deceleration can be considered to be similar to the idle condition except that the engine is now "driven" by the weight of the vehicle as it slows down (assuming that the clutch is engaged) and thus is operating at a higher engine speed with resulting higher friction, and therefore a higher fuel use and emissions. The fuel use related to idling and deceleration is defined by Equation 5-20 (section 5.6.3).

2. Road-load fuel use

When the vehicle is moving (other than during deceleration), the fuel use is now a function of the computed road-load as well as the engine load due to friction. Thus the lower the road load, the higher the proportion of the supplied power is to overcome friction only. This is a partial reason for disproportionately higher fuel use under low load scenarios.

The rate of fuel usage can be modelled via the following equation derived from Nam (2004a):

Equation 5-23. $F_R = [(k\ (N / 60)\ V_d) + R_L / \eta] / E_{fuel}$

where

F_R = fuel consumption rate (g/s)

k = base engine friction relationship(kJ/1)

N = engine speed (RPM)

R_L = road load power requirement (kW)

E_{fuel} = energy content of the fuel (kJ/g)

V_d = engine capacity (L)

η = indicated engine efficiency = 0.4 for the Otto cycle and 0.45 for the Diesel cycle

From this the absolute fuel consumption can be defined:

Equation 5-24. $F_C = F_R \ t$

where t = time

The indicated engine efficiency is a measure of the efficiency of the engine when mechanical losses (pumping, friction) are ignored (Stone, 1992a).

A second model was considered for the estimation of fuel use, which did not consider the effect of engine friction on fuel use but rather made use of calculations to define fuel use as a function of the fuel air mass that entered the cylinder per cycle. This model was based in part on a derivation of the equation found in Stone (1992a) and estimated a value for engine efficiency by defining a relationship between the required torque (a function of the road load), the volumetric efficiency and the air fuel ratio of an ICE at a particular instant dependent on the load scenario. Once the efficiency value was found, the fuel use could be determined by comparisons with the lower heating value (LHV) of the fuel used. This is a far more elegant approach and potentially more accurate. However modelling an accurate relationship between equivalence ratio, volumetric efficiency and torque with respect to defining an accurate ICE efficiency was found to be difficult. Time constraints meant that this model could not be completed to the satisfaction of the author and it was found necessary to replace this model for fuel use estimation with the current model.

An advantage of the current model is that it has been used in other research and has been shown to give accurate predictions of fuel use (Nam, 2004).

5.8 Emissions

5.8.1 *Equivalence ratio*

The equivalence ratio (φ) is a measure of the proportion of air to fuel at any given instant and is dependent on engine operating conditions such as engine load (particularly for Diesel cycle ICEs). The equivalence ratio can be defined as the ratio of the chemically correct (stoichiometric) air/fuel ratio (AFRs) to the actual air/fuel ratio (AFR) (Heywood, 1988d);

Equation 5-25. $\varphi = AFRs/AFR$

The equivalence ratio is used to indicate a fuel rich, fuel lean or stoichiometric condition during combustion. If $\varphi = 1$ then combustion is stoichiometric, if $\varphi < 1$ then combustion is lean (excess air), and if $\varphi > 1$ then combustion is rich (excess fuel).

The equivalence ratio is more important in the Diesel cycle engine as there is a non-constant and non-linear relationship between emission species and equivalence ratio (Section 5.8.6).

5.8.2 *Combustion stoichiometry*

Although it is not necessary to know what is happening during the combustion process to determine fuel use, this information is necessary to determine the type and quantity of emissions that are being produced from the ICE. This is due to the differing ICE operating conditions that affect the type and volume of emission level. For example if the ICE is running lean of stoichiometry (excess air) this will produce a different quantity of certain emissions than if the ICE is running at stoichiometry (exact amount of air) or rich of stoichiometry (air debt). In particular diesel ICEs show a large variation in the air/fuel ratio as this is the main source of power variation in these engines. Thus it is necessary to know what is happening in the engine during combustion to be able to accurately determine what levels of a particular emission species are being produced.

The relationship between chemical reactants and products in a stoichiometric combustion process involving hydrocarbons (Queens, 2005; Heywood, 1998d):

$$C_\alpha H_\beta + \left(\alpha + \frac{\beta}{4}\right)(O_2 + 3.76N_2) \rightarrow \alpha CO_2 + \frac{\beta}{2} H_2O + 3.76\left(\alpha + \frac{\beta}{4}\right)N_2$$

Note that this is for low temperature operation where N_2 is considered to be inert. In general the combustion products consist of more than just CO_2, H_2O, O_2, and N_2. For rich mixtures CO also exists in the products and at high temperatures (>2000K), compounds such as H, O, OH, NO will also be present due to the dissociation of the major species CO_2, H_2O, N_2 and O_2 (Queens, 2005). This is shown by the following relationship:

$$C_\alpha H_\beta + (\alpha + \frac{\beta}{4})(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cN_2 + dO_2 + eCO + fH_2 \\ + gH + hO + iOH + jNO + kN + \cdots$$

When the equivalence ratio (or air/fuel ratio) varies, this has a further significant effect on the gaseous proportions that exist during combustion (Queens, 2005).

For the most part the overall amount of exhaust emissions is dependent on the amount of fuel that is consumed in the engine. If no fuel is consumed then there will be no emissions. However the proportion of a particular species is dependent on other factors, such as combustion temperature and in particular the proportion of oxygen and nitrogen to fuel that is present at combustion. The variation of these proportions is also dependent on the load scenario, and the ICE technology being considered (Otto or Diesel cycle, two stroke or four stroke). Due to the complicated nature of combustion stoichiometrics, computer software (Chemwork6) is used to calculate the precise proportion of species present during the combustion phase in an ICE. Chemical stoichiometry is then used to calculate the actual amount of each gas that is present at combustion from the amount of fuel used resulting in a table of emission quantities for each load scenario. The sum of these emission quantities forms the total emissions for each drive cycle.

The gaseous emissions produced by the model are those produced during the combustion itself, not at the tail pipe. The emissions at the tailpipe of a conventional vehicle are affected by the various modern emissions control equipment used on modern vehicles and further interaction of the hot gases with the atmosphere. A better indicator of the emissions produced by a conventional ICE vehicle (and for the purposes of comparison) is based on the gases produced during the combustion (power) phase of the engine cycle which is a better comparator of different engine technologies.

In the combustion chamber of an Otto or Diesel cycle ICE, a mixture of fuel and air is detonated with the resultant increase in temperature and pressure doing work on the piston forcing it down in the cylinder. The combustion itself and the heat released interacts with the walls of the cylinder (boundary) and heat transfer occurs across this boundary such that combustion could be considered to be an isothermal process. However, the act of combustion is essentially many explosive reactions that occur so rapidly that the heat energy produced will not be transferred across this boundary quickly enough to dissipate all this energy, hence the quick temperature rise in the cylinder. Under this scenario the combustion process can be considered to be adiabatic.

There are two broad groups of vehicle emissions:

1. primary or direct emissions including CO, CO_2, HC, NO_x and particulates; and
2. secondary pollutants that are the results of primary pollutant interaction with the atmosphere (MIT, 2004a).

In this study only primary pollutants were considered.

5.8.3 *Otto cycle emissions*

In the Otto cycle, air and fuel is drawn into the cylinder during the induction phase and then compressed and ignited to do work on the piston. The reactants, in this case iso-octane, oxygen and nitrogen, react to form a number of gaseous products during equilibrium combustion, some of which are considered to be pollutants. Since an air/fuel mixture is initially drawn into the cylinder, it has essentially a pre-set stoichiometry. The equivalence ratio varies over only a very small range, typically 0.95 to 1. In modern engines this equivalence ratio is controlled so that it cannot exceed stoichiometry (equivalence ratio of 1) except under certain conditions such as full load (Heywood, 1988f). Some engines are also designed to burn lean under low load scenarios to reduce fuel use and lower emissions of pollutants such as carbon monoxide (Stone, 1992c). Therefore the torque and hence the power of the engine, is essentially defined by the volumetric efficiency of the induction pathway which is varied by the use of a throttle valve arrangement (Heywood, 1988c; Stone, 1992a). When the valve is closed the volumetric efficiency is small and therefore only a small amount of air and fuel is drawn into the cylinder. This small amount of fuel will only produce a small amount of torque and therefore power. Since the equivalence ratio does not vary, the products of combustion are dependent solely on the amount of fuel entering the cylinder. In this study due to the variation in equivalence ratio being small for the Otto cycle engine it has been set at 1 i.e. stoichiometric across the engine speed range and load scenario.

5.8.4 *Diesel cycle emissions*

In the Diesel cycle, air alone is drawn into the cylinder during the induction phase and then compressed. Near the end of the compression stroke a small amount of diesel is injected into the cylinder, which is auto ignited by the elevated temperature of the compressed air. The torque and therefore power of the engine is defined primarily by the air/fuel ratio (a diesel engine has no valve system in the induction pathway to restrict the incoming air) (MIT, 2004b). The reactants in this case are cetane, oxygen and nitrogen, and the products are the same as those found for the Otto cycle but in different proportions. In a diesel engine the equivalence ratio will vary anywhere from 0.2 to approximately 0.8 (MIT, 2004b). This has a profound effect on the composition of product species during equilibrium combustion. In this study the Diesel engines considered are turbo-charged which makes use of exhaust gases to drive a compressor that forces more air into the cylinder, thereby increasing the volumetric efficiency. Thus the volumetric efficiency is very high and has been set at 1. In an actual engine this is not strictly true, but since the volumetric efficiency range is small in diesel ICEs this will not affect the results and aids in the simplicity of the model where the main purpose is comparison.

5.8.5 *Emissions species considered*

The emissions species modelled in this study were CO_2, CO and NO_X. Particulate emissions and hydrocarbons were not modelled since they are more complex than could be undertaken in a simplified modelling structure since hydrocarbon emissions are not only one compound but a whole host of compounds, some of which are considered to be toxic. In the case of particulate emissions, diesel soot is in the same size range as a number of other particles from a number of other sources. This makes measuring soot difficult, as it is difficult to separate from these other particles. It is also apparent that, to date, it has not been possible to accurately determine the exact mechanisms of soot formation with any great accuracy (Gruden, 2003b). Thus it was decided not to model particulate emissions.

5.8.6 *Emissions calculation*

The calculation of the emissions phase of the model makes use of the program "chemwork6" (Dwyer, 2005) to determine the relative emission species stoichiometry during combustion. This information is then used in the model itself to calculate the amount of a particular emission species on a second by second basis. Chemwork6 is essentially a collection of Matlab files designed to work under the Matlab environment (Matlab, 2005). Essentially it takes input (Table 5-5) and produces a series of output screens that indicate the input and output chemical species at the different phases of the combustion cycle. The most important output gives the chemical species present during the latter stages of the combustion/expansion phase prior to the exhaust stroke. A typical output for this phase of the combustion for iso-octane and cetane is shown in appendix A.

Table 5-5. Input data used for chemwork6.

Engine Profile	Otto cycle	Diesel cycle
Cycle	Mixed	Mixed
Input pressure (atm)	1	1
Input temp. (K) (ambient)	300	300
Comp. ratio	10	20
Equiv. ratio	1	variable
Exhaust Pressure (atm)	1	1
Fuel type	C8H18	C16H34

The use of this approach for the combustion of iso-octane in the Otto cycle is relatively straight forward as the equivalence ratio is assumed to be stoichiometric thus the only variation in the amount of pollutant species produced is due to the amount of fuel consumed. The relative proportions of these pollutant species are set out in Table 5-6.

The use of this approach for the combustion of cetane in the Diesel cycle is more complicated as it is now necessary to take into account the affect of varying the air/fuel equivalence ratio. The results of the simulations are set out in Table 5-7. The non-linear relationship between the relevant pollutant species and equivalence ratio is displayed in Figure 5-2.

Figure 5-2. Relationship between CO_2, CO, NO_X and equivalence ratio for a Diesel cycle ICE.

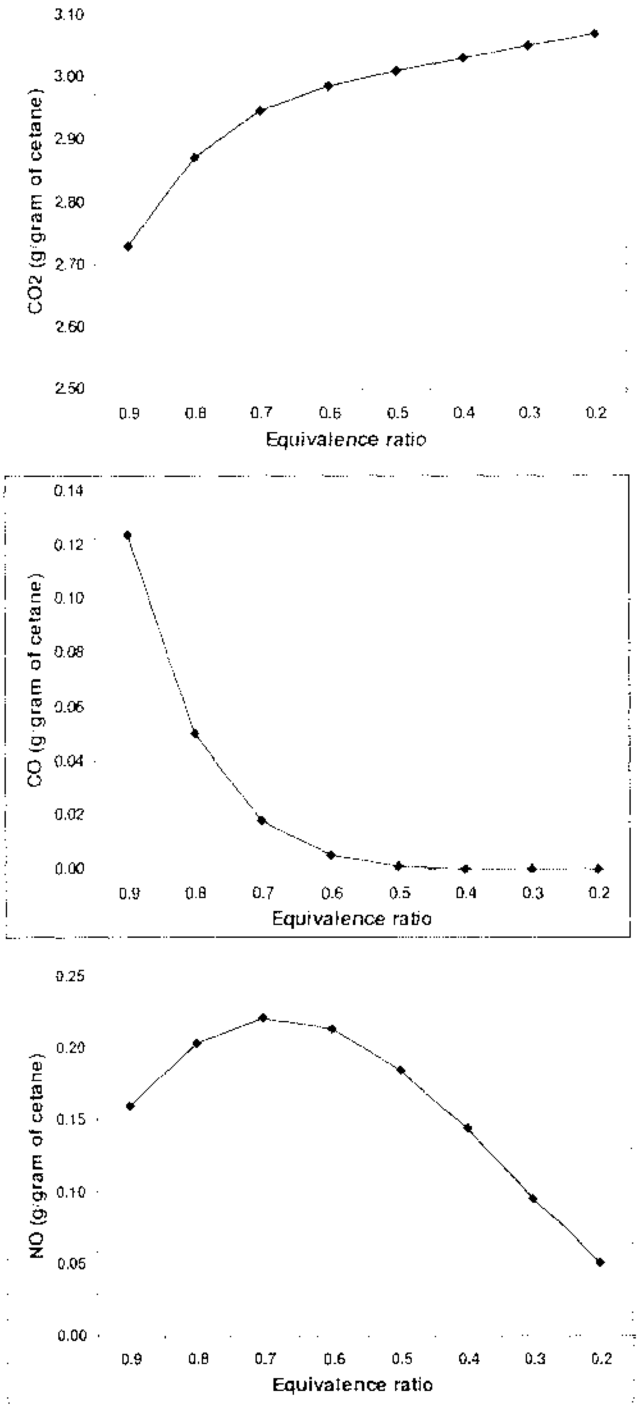


Table 5-6. Pollutant gases in proportion to equivalence ratio used during Otto cycle combustion of iso-octane.

			Reactants (mol)			Products (mol)			Products (g)		
Temperature (K)	Pressure (kPa)	Equivalence ratio	C8H18	O2	N2	CO_2	CO	NO	CO_2	CO	NO
2643	4189	1	1	12.5	47	6.5068	0.9723	0.2992	2.8346	0.2695	0.0889

Table 5-7. Pollutant gases in proportion to equivalence ratios used during diesel combustion of cetane.

			Reactants (mol)			Products (mol)			Products (g)		
Temperature (K)	Pressure (kPa)	Equivalence ratio	C16H34	O_2	N_2	CO_2	CO	NO_x	CO_2	CO	NO_x
2687.0	9198.0	0.9	1.0	27.2	102.4	14.0384	1.0018	1.2072	3.2021	0.1454	0.1877
2554.0	8898.0	0.8	1.0	30.6	115.2	14.7744	0.4072	1.5382	3.3700	0.0591	0.2392
2396.0	8581.0	0.7	1.0	35.0	131.6	15.1534	0.1441	1.6713	3.4564	0.0209	0.2599
2221.0	8247.0	0.6	1.0	40.8	153.5	15.3601	0.0423	1.6163	3.5036	0.0061	0.2514
2032.0	7895.0	0.5	1.0	49.0	184.2	15.4931	0.0095	1.3944	3.5339	0.0014	0.2169
1830.0	7522.0	0.4	1.0	61.3	230.3	15.5996	0.0013	1.0859	3.5582	0.0002	0.1689
1612.0	7127.0	0.3	1.0	81.7	307.1	15.6992	0.0001	0.7187	3.5810	0.0000	0.1118
1380.0	6707.0	0.2	1.0	122.5	460.6	15.7993	0.0000	0.3829	3.6038	0.0000	0.0596

The non linear relationship between gaseous emission (Y) and equivalence ratio (x) can be modelled by a 7th order polynomial (found by the use of Lagrangian Interpolation) of the form:

Equation 5-26. $Y = a+bx+cx^2+dx^3+ex^4+fx^5+gx^6+hx^7$

The values found for each of the coefficients of the 7th order polynomial are set out in Table 5-8 for each pollutant species.

Table 5-8. Coefficients for the pollutant species.

	Species		
Coefficient	CO_2	CO	NO_x
a	4.07	-0.00404	0.671
b	-5.993	0.06132	-10.6018
c	28.628	-0.37158	70.1803
d	-61.264	1.1662	-235.618
e	38.194	-2.0455	458.819
f	56.944	2.0184	-519.306
g	-97.222	-1.2065	315.278
h	39.683	0.7035	-79.365

5.9 System efficiency

The system efficiency of a conventional domestic reciprocating ICE vehicle is essentially the ratio of energy out to energy in for a given load scenario. The energy in is the fuel (iso-octane = 44.3 MJ/kg, cetane = 44MJ/kg) and the energy out is, in this case, energy expended in overcoming a load scenario such as climbing a hill or more importantly the energy required to complete a specific test drive cycle:

Equation 5-27. η_{sys} = energy out / energy in

$= R_L / (F_C E_{fuel})$

where

η_{sys} = system efficiency

R_L = road load energy requirement (kJ)

F_C = absolute fuel consumption (g)

E_{fuel} = energy content of the fuel (kJ/g)

5.10 Model validation

Validation of the fuel economy results from the simulated drive cycles and conditions is difficult for a number of reasons:

- Published data has quite high variance.
- Published data does not always indicate the type of drive cycle used to create the results or if a dynamometer was used to simulate the drive cycle.
- Some published data can be misleading as it may be used to sell a particular vehicle.
- Effect on fuel use and emissions due to driving style; it is well known that fuel efficiency and emissions are heavily affected by driving style (LTSA, 2001).
- It is difficult to obtain accurate data for a particular vehicle driven on a particular drive cycle.
- No independent testing conducted to international standards.

The following points must be noted about the predictions for fuel use and emissions from the model used in this study:

- The cycle used to represent city driving (NYCC) does not take into account cold start/running conditions and therefore may under estimate fuel use when compared to published data.
- The cycle used to represent more open road driving (US06) is an aggressive driving pattern and may tend to overestimate fuel use when compared to published data.

- Fuel use predictions are really only applicable to the drive cycles considered and are therefore only an approximation to any real world scenario.
- The model makes use of simplistic assumptions in a number of areas.
- The main point of the study is to make accurate comparisons between conventional domestic transport drive systems and series hybrid drive systems, therefore the prediction accuracy for the conventional vehicles was deemed to be less important than model consistency across both conventional and series hybrid drive system architectures.

There were also several approaches in the model that could introduce inaccuracies:

- the transmission is assumed to have the same primary gear ratios for all vehicles;
- shift points are the same for all conventional vehicles; and
- the fuels used in the model (cetane and iso-octane) differ in their properties from that found in conventional fuel.

However, although there may be differences between the results achieved from the model for fuel use and emissions compared to various published data for the reference vehicles, this is not completely relevant as the same model that is used to predict fuel use in the conventional reference vehicles is also used to predict fuel use in the vehicles equipped with a series hybrid drive system. Thus any inaccuracies that are evident in the predictions for the conventional reference vehicles will also be evident for the series hybrid drive system equipped vehicles. Therefore the overall approach of the study which was to compare and contrast conventional drive systems with series hybrid drive systems with respect to fuel use and emissions, has not been compromised due to the inherent consistency in the model approach.

Note that the Renault Kangoo mentioned elsewhere in this document (pg 40,44,48) could have been used to potentially verify the model. However, there was a lack of vehicle parameter information, for example, control strategies governing allowable depletion of batteries (which differ from the battery chemistry used in this study), regenerative breaking input and power flow control strategies used. There were also unknown specifications for the individual components that makes up its drive system such as power densities, efficiencies, weights etc. The Kangoo is primarily an electric vehicle with a petrol engine used mainly as a "range extender" to extend the range of the electric only performance as and when required to give a "piece of mind" solution to the potential problem of the batteries depleting during operation and does not charge the batteries during operation, which is a significant departure from the approach taken in this study. Thus it is not a series hybrid in the sense that was implied in the study and implies that its use as a verifiable model or as a comparison for the series hybrid models used in this study is limited.

6.0 SERIES HYBRID DRIVE SYSTEM MODEL

6.1 Methodology overview

The methodology used to model a vehicle equipped with a series hybrid drive system is similar to that found in Chapter 5 to model the conventional reference vehicle.

- **Series hybrid drive system parameters:** Included the same parameters that were used in the reference vehicle model with the additional parameters for engine weight and devices such as batteries, electric motor, power controller and generator that do not exist in the conventional reference vehicle. Incidentally a generator does exist in a conventional vehicle (alternator) and its function is essentially the same (power for battery charging and on-board electrical systems), of course it outputs far less power and the electrical load in the series hybrid drive system is far higher.
- **Test drive cycles:** These were the same as for the reference vehicle and involved the same parameters.
- **Transmission:** The series hybrid drive system does not require a conventional vehicle transmission. The power required by the load application and supplied by the electric motor is transferred to the wheels by a single gear and differential unit which does not require modelling but does have an efficiency associated with its operation.
- **Road-load:** The energy requirements of the vehicle are now supplied by an electric motor as opposed to an ICE. The electric motor also interacts with the battery:
  1. by drawing energy from the battery bank to propel the vehicle; and
  2. by acting as a generator when the vehicle is decelerating and braking such that some of the energy used is returned to the battery for later use.

  The motor also interacts with the on-board power source (OPS) since under certain circumstances the power from the generator (part of the OPS) can bypass the battery and go to the motor directly as a means of increasing efficiency. The battery component also interacts with the OPS as the OPS charges the batteries.
- **Fuel use:** This calculation follows a similar pattern to that employed in the reference vehicle model, the difference being that fuel use is now somewhat independent of the load on the vehicle. The fuel use being attributable to an ICE driving a generator in a similar scenario to the operation of a stationary generator set. Fuel is only used when the ICE component of the OPS is on and is essentially a function of the state of charge of the battery and/or the electrical load on the system. Fuel use is also a function of the amount of energy regeneration from the regenerative braking system. Thus overall fuel use is the result of interactions

between the battery, the OPS, the regeneration system and the type of energy management/control protocols employed.

- **Emissions:** The calculation of type and quantity follows a similar pattern to that employed to model the reference vehicle, the difference being that no emissions are created while the vehicle is stationary. They are only created when the ICE component of the OPS is on, which, in the case of the series hybrid drive system, is essentially a function of the state of charge of the battery and/or the electrical load on the system.

As with Chapter 5, the above methodology and the calculations required were evaluated for each second of operation during the drive cycle. However, since the ICE is not operational all the time this is reflected by periods of the drive cycle where no fuel use or emissions are recorded. At the completion of the drive cycle a summation of the fuel consumption and emissions was carried out resulting in absolute fuel consumption and emissions level values for the particular technology option and particular drive cycle considered. This was then compared to the distance travelled during the drive cycle and thus a value for fuel economy (l/100km) and emissions (g/km) was calculated. There was also input from the electrical grid network to recharge the batteries under certain circumstances.

Only where the following parameters used in the series hybrid drive system vehicle model differ from the reference vehicle model, will they be explained here.

6.2 Storage (battery) model

The battery is simply modeled as an energy source for system energy requirements in the vehicle (predominantly the electric motor) and as a "sink" for energy generated from the OPS and regenerative braking system. It is assumed that the battery bank can absorb all available input from regenerative braking and from the OPS. This significant simplification is justified for a basic model. It is also justified based on current and future on-board storage devices (such as ultra-capacitors) having this capability.

Although alternatives exist to battery storage systems (such as ultra-capacitors, flywheels, compressed air), only batteries were considered in the model. The battery operation acts within the constraints defined by its efficiency during charge and discharge and its power and energy density.

6.2.1 *Battery type*

The battery technology chosen for use in the series hybrid architecture is the nickel metal hydride (NiMH) technology as used in both the Toyota Prius and the Honda Insight hybrid vehicles (Fredrikson, 2004; Wallen, 2004c; Kelly et al, 2001; Hermance, 2004). This technology was chosen because it;

- is currently used in commercially available vehicle technologies;
- has a flat discharge voltage curve between 80% state of charge and 20% state of charge;
- has high specific power density (power output per weight unit);
- has relatively high specific energy density (stored energy per unit weight); and
- has a long life time.

6.2.2 *Battery specific power density*

A potentially significant disadvantage of the series hybrid approach is that, due to the electric motor being the only drive source for the vehicle, under certain load scenarios the battery has to supply a significant amount of power to the motor, thus to supply a certain level of peak power requires a certain battery size. This implies that there will be a minimum weight of battery defined primarily by the power density (kW/kg). Under maximum load scenarios where the maximum power of the electric motor is being employed such as when overtaking or hill-climbing, the required power is supplied by a combination of power from the battery and power from the generator (Iwai, 1998). Thus the peak power required by the battery is the difference between the system power requirements and the maximum power supplied by the generator (component of the OPS).

The above scenario can be avoided by employing a larger generator however that requires a larger ICE incurring fuel consumption penalties due to increased ICE capacity and increased weight. In a series hybrid drive system the ICE does not operate at peak output but at a level of power equal to the maximum torque (to reduce fuel use by operating at maximum efficiency) and can also operate at a level below this (the maximum fuel efficiency point) dependent on the required load and energy management scenario. Thus there is scope for increasing the power of the ICE during these infrequent time periods where peak power output is required with only a minimal effect on fuel use. It further implies that under certain load requirements minimal fuel use operation of the ICE could also be achieved. However, this control approach is not currently modelled, the simplified approach being to model the ICE component of the OPS as operating constantly at maximum torque. This may lead to higher fuel use and emissions than could other wise be achieved.

The NiMH battery employed in the Toyota Prius has a power density of 1250 W/kg (Hermance, 2004) and this was the value adopted.

6.2.3 *Battery weight*

Battery weight is a function of its specific power density, motor power and generator output which is a function of the ICE operating point, specifically, power output at maximum torque. Thus total power output is the sum of battery power output and generator power output. This implies that battery power output is the total power output minus generator power output and therefore battery weight is the ratio of battery power output to battery specific power density:

Equation 6-1. $W_{bat} = (P_{mot} - P_{gen}) / SP_{bat}$

where

W_{bat} = battery weight (kg)

P_{mot} = electric motor peak power (kW)

P_{gen}= generator power output (kW)

SP_{bat} = battery specific power (kW/kg)

This weight does not include the weight associated with the packaging and mounting the battery pack in the vehicle and is considered separately (section 6.8).

6.2.4 *Battery specific energy density*

The battery specific energy density is essentially the energy per unit weight of the battery. The NiMH batteries used in the Toyota Prius have a specific energy density of approximately 45 Wh/kg (162 J/kg), and this was the value adopted (Panasonic, 2005).

6.2.5 *Battery capacity*

The amount of energy stored in the battery is a function of the weight of the battery pack and the specific energy density of the batteries. The NiMH batteries used in the

Toyota Prius are made up of a number of D sized cells (Kelly et al, 2001) connected in such a way so as to maximize power density, not energy density. The battery energy capacity was defined by the following relationship:

Equation 6-2. $E_{bat} = W_{bat} \, SE_{bat}$

where

E_{bat} = battery energy capacity

W_{bat} = battery wieght

SE_{bat} = battery specific energy density

6.2.6 *State of charge*

The maximum state of charge (SOC) of the battery was defined as the maximum amount of energy that is stored in the battery during normal running of the vehicle and is set at 80% of maximum battery capacity. The minimum SOC of the battery is defined similarly and is set at 20% of maximum battery capacity. These two values are the same as those adopted by Wallen (2004c).

Both the maximum and minimum SOC values were used by the energy management system to determine operation of the OPS and regeneration input energy to the battery and were determined by the energy use of the system.

The current SOC is the energy capacity of the battery at a particular instant during the operation of the vehicle during the drive cycle. This value is continually updated by the energy inputs from the regenerative braking system, OPS and outputs such as systems power requirements. The current SOC is also compared with the maximum and minimum battery SOC values to determine the requirement status of system elements such as regenerative braking and the OPS.

6.2.7 *Charge and discharge efficiency*

Charge efficiency can be defined as the amount of energy that will actually be stored in the battery (given an energy input), the rest of the energy ending up as heat. Dorfell (2003b) indicates an optimal battery cycle efficiency of 90%. This assumes an optimal charging regime (fast charge, accurate cut-off, no extended overcharging or overheating of the battery) which may not always be the case. Thus, the charge efficiency was set at

85%.

Discharge efficiency can be defined as the amount of energy that can be taken from the battery (given a load, mainly the electric motor), the rest of the energy ending up as heat. Nam (2004c) indicated a discharge efficiency of 95% for a NiMH battery pack, again this would assume optimal discharge rates that may not occur and thus the discharge efficiency was set at 90%.

Note that it was assumed that the control electronics keeps the batteries operating on the flat portion of the discharge curve and optimizes charge and discharge characteristics to maintain the above efficiencies.

6.2.8 *Methodology*

A fully charged battery is considered to contain a certain amount of energy (J). The SOC of the battery at any given instant is equal to the current energy value of the battery pack minus the energy that has been used by the load (for example the electric motor) plus any energy supplied from regenerative braking and the OPS. Thus:

Equation 6-3. $SOC_{curr} = SOC_{init} - E_{mot} + E_{OPS} + E_{regen}$

where

SOC_{curr} = state of the battery charge at any given instant

SOC_{init} = previous state of charge of the battery

E_{mot} = energy used by the motor to overcome a load scenario

E_{OPS} = energy supplied to the system by the OPS

E_{regen} = energy supplied to the system from regenerative braking

The above equation is updated on a second by second basis throughout the drive cycle.

The value of SOC_{curr} dictates the control strategy of the series hybrid drive system. For example if the SOC_{curr} drops below the minimum value then this will activate the charging system. The amount of energy required to start the ICE component of the OPS was not considered to be significant enough to be modelled and was ignored.

The SOC of the vehicle battery pack can be variably set at the beginning of a test drive cycle. Currently this value is set such that each of the vehicles equipped with the series hybrid drive system options will be able to complete the entire NYCC drive cycle without requiring input from the charging system (OPS) during operation. The initial SOC is also set such that each vehicle has the same amount of battery capacity above the battery minimum SOC level.

There are also two methodologies adopted to deal with the SOC that exists at the end of a test drive cycle:

1. If the battery SOC at the end of the drive cycle is less than at the beginning of the drive cycle then the OPS will run until this initial charge value is reached. This is done to reflect the correct amount of fuel used and emissions produced.
2. If the battery SOC at the end of the drive cycle is less than at the beginning of the drive cycle then the amount of energy required to recharge the battery bank will be supplied by grid electricity. The purpose of this is to evaluate the affect on emissions and fuel use from being able to recharge the batteries using grid power.

6.3 Electric motor model

The electric motor in a series hybrid drive system is the only drive source that propels the vehicle. This has the advantage of simplifying the modelling methodology. In this study the electric motor is simply a device that provides power and torque up to a maximum set by the drive requirements of the vehicle. The maximum power of the electric motor is set by the maximum power of the ICE of the original reference vehicle. For example, because REF1 (Table 5-1) has an ICE with a peak power of 43.3 kW, the peak power of the electric motor of the series hybrid drive system was set at this value to achieve an element of similarity of performance in the vehicle to the original reference vehicle specifications. The electric motor has the advantage of maximum torque at zero engine speed and can be designed to have a flat torque curve across its useable engine speed range (Section 2.3.2). This obviates the need for a transmission to match the torque of the motor to the load hence this was not modelled for the series hybrid drive system.

6.3.1 *Motor power*

In a conventional drive system the ICE is designed for the peak operating requirements that the vehicle is likely to encounter during its proposed use. Thus, vehicle specifications literature will quote values such as peak power output and peak torque values. However the electric motor has two types of ratings, continuous output and peak output (EVAoSD, 2005). The continuous output refers to the maximum output that the electric motor can deliver under normal operating conditions. However the electric motor also has the ability to operate at two to three times this continuous value for a short period of time and hence the necessity for the two ratings. This type of operation makes it very amenable to a drive system that is designed for the average operating requirements of the vehicle (as in the series hybrid drive system) where peak operation is only required for short periods (for example overtaking or hill-climbing). Thus the peak operating requirements of the reference vehicle are matched to the peak operation of the electric motor.

6.3.2 *Motor specific power and weight*

Electric motor weight is defined by mass per peak kW of output. Currently, modern electric motors have power densities of 1 kg / kW of peak output or greater (EE tech, 2004) and this was the value adopted. The motor weight does not include the weight associated with mounting the motor in the vehicle as this is covered in section 6.8. The relationship is:

Equation 6-4. $W_{mot} = P_{ref} \, SP_{mot}$

where

W_{mot} = motor weight (kg)

P_{ref} = original reference vehicle ICE peak power (kW)

SP_{mot} = motor specific power (kg/kW)

6.3.3 *Motor efficiency*

Motors used in modern electric/hybrid vehicles have efficiencies that can exceed 90%. Electric motors also have very high part load efficiencies in excess of 90% across the load range (EERE, 2005; EE Tech, 2004). Thus the efficiency of the electric motor was considered to be a constant and was set at 90%.

6.3.4 *Final drive*

This will be modeled in the same way that it is modeled in the reference vehicle (Section 5.4.2).

6.4 Energy regeneration model

In a series hybrid vehicle drive system the electric motor drives the wheels. During deceleration assisted braking, the momentum of the vehicle forces the motor to turn in a similar way to the way momentum of a conventional vehicle forces the conventional ICE to increase in speed. However in a conventional vehicle this increase in speed of the ICE simply results in wastage of fuel whereas in a series hybrid drive system, the forced turning of the motor essentially forces the motor to act like a generator, generating energy that can be stored in the battery. It is also possible to gain further energy from braking making use of "magnetic brakes" that extract more energy from the braking process. In a conventional vehicle this energy is essentially lost to heat through the brake disks/pads. However the magnetic braking process was not explicitly modelled.

Potentially, up to half of the energy supplied for acceleration of the vehicle (inertial work) can be recovered by means of regenerative braking and reused for propulsion purposes (Kuchita et al, 2002). However other sources indicate up to 40% is achievable (Varakin et al, 2004). In this study a level of 30% for regenerative braking has been used as this level is currently achieved in the Toyota Prius (Wallen, 2004c).

6.4.1 *Regeneration energy status*

The regeneration status is an indicator of the state of electrical regeneration in the system. Energy regeneration is only possible when the vehicle is decelerating/braking and was modeled by the following algorithm:

If $a < 0$ THEN Regen status = on
ELSE Regen status = off

where a = acceleration ($a < 0$ indicates deceleration).

6.4.2 *Regenerative braking output*

Regeneration output concerns the actual amount of energy that it is possible to regenerate during deceleration and braking. If a vehicle accelerates then this has a certain energy requirement associated with it. If the vehicle then decelerates back to zero velocity there is, in theory, the same amount of energy is available through regeneration. However the theory falls short in practice for a number of reasons (OTA, 1995):

- discharge and charge efficiencies and the technology of the battery pack reduce its ability to absorb quickly the potentially high power pulses of the motor when acting as a generator;
- the efficiency of a motor when acting as a generator is generally not as high as when acting as a motor;
- losses in the gear train (although this is very minor);
- regenerative braking generally only applies to two wheels of the vehicle; and
- not all the inertial energy can be recovered since this would require the vehicle to completely return to its initial speed using regenerative braking only with no input from conventional braking.

Regenerative braking follows the following algorithm:

IF Regen status = on then

$E_{regen} = (0.5\, m\, (v^2 - u^2))\, \eta_{regen}$

IF Regen status = off then

$E_{regen} = 0$

where

E_{regen} = regenerative energy output (J)

m = mass of the vehicle (kg)

u = initial velocity (m/s)

v = final velocity (m/s)

η_{regen} = proportion of the inertial energy that it is possible to regenerate.

6.5 On-board power source (OPS) model

The OPS provides power to recharge the battery bank and when required provides power to the electric motor directly. In the case of the series hybrid drive system configuration the OPS consists of a downsized Diesel or Otto cycle ICE (compared to the original reference vehicle) which drives an AC generator (alternator) designed to produce the power requirements equivalent to the average load. An ICE is most efficient when operating at its maximum torque. Thus the output power of the generator is matched to the same power level that occurs at this torque value. For example if the output requirement from the generator is 10 kW then this is the required power that should be available at the maximum torque of the ICE component of the OPS.

In the reference vehicle model, the ICE output varied and was dependent on the requirements of the load, which has an effect on fuel use due to the poor part load efficiency of the ICE. In the series hybrid drive system model, the ICE (via the generator) is used for charging purposes only or for supplying power directly to the load (electric motor) where appropriate. Thus the load can be considered to be constant.

6.5.1 *Generator efficiency*

Mechanical energy from the ICE turns a generator (alternator) to create alternating current (AC), this process is similar to that employed in a conventional vehicle to charge the starting battery. The alternator in a conventional vehicle makes use of the battery direct current (DC) voltage to create a magnetic field, which the alternator uses to create the output AC voltage and therefor these devices are not very efficient. However modern generators for hybrid vehicle use employing powerful permanent magnets to create the magnetic field have very high efficiencies ranging from 94 – 97% (Uidaho, 2005; OTA, 1995) and a value of 95% was chosen.

6.5.2 *Generator output*

The generator is designed to convert most of the mechanical energy of the ICE into electrical energy. The generator output is defined as the power equivalent of the continuous maximum operational torque of the ICE minus the losses due to inefficiencies in the generator:

Equation 6-5. $P_{gen} = \eta_{gen} \pi T N / 30000$

where

P_{gen} = power output of the generator (kW)

η_{gen} = generator efficiency

T = ICE maximum torque (Nm)

N = engine speed (RPM)

6.5.3 *Generator weight*

Generator weight (W_{gen}) is a function of generator power output (P_{gen}) and generator specific power density (SP_{gen}). Modern generators for hybrid vehicle use have specific power densities of 1 kg/kW of output (OTA, 1995) thus:

Equation 6-6. $W_{gen} = P_{gen} / SP_{gen}$

6.5.4 *OPS status*

The OPS is only on under certain circumstances:

1. the battery pack charge level has dropped below the minimum SOC; or
2. the power level required by the load (mainly the electric motor) is greater than can be reasonably supplied by the battery alone, in which case the OPS also supplies energy to the load. This would generally only occur under aggressive driving scenarios (hill-climbing, overtaking).

Note that recharging also occurs above the minimum SOC until the maximum SOC is reached or the vehicle becomes stationary. Note also that 2 above is not explicitly modelled.

The algorithm is as follows:

IF $V = 0$ then OPS = off

IF current SOC < minimum SOC then OPS = on

IF current SOC > maximum SOC then OPS = off

6.5.5 *OPS output*

The OPS output is a function of the power output of the generator, which in turn is a function of the power output of the ICE that drives it. It is modeled via the following algorithm:

IF OPS = on then

$E_{OPS} = 1000\, P_{gen}\, t\, \eta_{gen}$

IF OPS = off then

$E_{OPS} = 0$

where

E_{OPS} = energy output from the OPS (J)

P_{gen}= power output from the generator (kW)

t = time (s)

η_{gen}= efficiency of the generator

6.5.6 *Internal combustion engine*

In the series hybrid drive system the ICE operates at its maximum efficiency and in terms of the modelling process is assumed not to deviate from this operational mode. This implies that the parameters required to define this operation are essentially constants derived from the values for maximum power, maximum torque and engine speed for a particular ICE and can be obtained from manufacturers or specification databases (Table 6-1).

Table 6-1. Engine parameters for the series hybrid drive system options.

Paramater	Daihatsu Mira engine	MIT engine	Smart TD engine	2-stroke TD engine
Engine capacity	660cc	250cc	800cc	400cc
Max torque (Nm)	64	27	100	100
Power at max torque (kW)	27	24	21	21
RPM @ max torque	4000	8500	2000	1000
Engine weight (kg)	43.3	27	46	35
Equivalence ratio	1.00	1.00	0.2 - 0.85	0.2 - 0.85

In a conventional vehicle engine the maximum power and the maximum torque occur at different engine speeds. However the power that occurs at maximum torque can be calculated from:

Equation 6-7. $P = \pi T N / 30000$

where

P = power (kW)

T = torque (Nm)

N = engine speed (RPM)

This parameter is required as the ICE is designed to operate at its most efficient point, which is at maximum torque, not maximum power. Thus the power at maximum torque is calculated and is also used to set the output of the generator.

Four different ICE technologies were chosen as the basis for the series hybrid drive system model:

1. Commercial naturally aspirated Otto cycle engine found in the Daihatsu Mira (Carfolio, 2005; UK car buyers Guide, 2005).
2. ICE (motor cycle engine) developed as an OPS for a series hybrid drive system vehicle by Massachusetts Institute of Technology (MIT) (Edwards and Richard, 2000).
3. Commercially available turbo charged Diesel cycle engine found in the Smart Turbo Diesel (Carfolio, 2005; UK car buyers Guide, 2005).
4. The fourth ICE is a hypothetical 2-stroke turbo charged Diesel cycle engine.

The 2-stroke turbo diesel (TD) engine is a scaled version of the Smart TD engine. A 2-stroke diesel engine has approximately twice the power output of a conventional four stroke diesel engine of the same capacity (Janhunen and Larmi, 2004). Thus the capacity was defined to be half that of the Smart TD but with the same power and torque levels and with engine speed levels scaled accordingly. This power plant is hypothetical, although active research is on-going in this area (Janhunen and Larmi, 2004). Thus any results gained making use of this power plant must be treated with caution. However it is included for comparison purposes with the knowledge that this technology has the potential to be a very efficient, lightweight power source that is ideal for a series hybrid drive system application.

The operation of the ICE is governed by the overall operation of the OPS.

6.5.7 *Engine weight*

Where ICE weight is available from manufacturers it has been used. Where data was not available certain assumptions were made.

Estimates for the power density of Otto and Diesel cycle ICEs have large variance. However, it is known that electric motors have power densities that are the same or better than conventional power units found in domestic transport (Lipman Sperling, 2000). Thus in the absence of reliable data for the weight of an ICE to be used in a series hybrid drive system, the power density of an ICE was defined to have the same power density as that employed for the electric motor.

In general diesel engines are heavier than petrol engines of the same displacement

(Nam, 2004e). Thus Diesel cycle engines were defined to be 5% heavier than an equivalent Otto cycle engine.

2-stroke cycle engines are lower in weight than their 4 stroke counterparts per kW of output. However the 2-stroke Diesel cycle ICE weight is defined as a function of the weight of the engine itself and the weight of the equipment required to pressurize the inlet air stream. Thus a relatively arbitrary value of 75% of the weight of a conventional Diesel 4-stroke engine (of the same peak output) was chosen.

6.5.8 *Engine friction*

Engine friction as it pertains to the engines employed in the series hybrid drive system is essentially the same as discussed in Section 5.6.3 for the conventional reference vehicles.

The equations used to model friction for the reference vehicle ICEs can also be applied to the ICEs used in the series hybrid drive system. However there are some notable differences. Each of the four engines considered for the series hybrid drive system have slightly different friction relationships (k), due to the type of technology being considered (Table 6-2). These frictional relationships are taken from the commercial model known as PERE (Nam, 2004b). With respect to the hypothetical 2-stroke Diesel engine, engine friction was considered to be 50% lower than that found in a conventional 4-stroke engine (MIT, 2004e).

Table 6-2. Friction relationships for the various engines used in the series hybrid drive system.

Engine	Friction relationship (k)
Daihatsu Mira	0.15+0.00155 (N/60)
MIT	0.19+0.0000068 $(N/60)^2$
Smart TD	0.0474+0.00333 (N/60)
2-stroke TD	0.024+0.00167 (N/60)

where N = engine speed (RPM)

6.6 Power controller/inverter model

In any vehicle system where there are substantial electrical power flows, a controller is required to correctly manage them. The controller incorporates an inverter (an electronic device that converts between DC and AC power flows within a system) and various electronic control hardware and firmware. The controller must be able to handle the peak system power requirements.

In a series hybrid drive system, control is relatively straight forward compared to that required in a parallel hybrid drive system where mechanical, parallel interaction between the electric motor and the ICE driving the wheels must be managed as well. Essentially the controller for the series hybrid system in this model controls energy use by the motor, detects when charging is required by the batteries, controls energy input from the OPS and from the regeneration system to the battery pack.

In this study the controller/inverter was not explicitly modeled.

6.6.1 *Control strategy*

It is known (Heywood, 1998f) that an ICE is most efficient at peak torque and most fuel efficient at approximately 70-80% of peak torque, (OTA, 1995). Since one of the goals of this study is to reduce fuel use and emissions by reducing the capacity and weight of the ICE and the weight of other associated components, a control strategy is required to attempt to fulfil this goal. A fundamental problem with the series hybrid approach is that energy required for maximum power output comes from a combination of the battery and generator (part of the OPS) which has an effect on the size of these two components and the ICE such that if it was to operate at its most fuel efficient operating point there would be less power from the generator to help with peak power requirements. However, an efficient control strategy is to enable the ICE to operate (statically) at different engine operating points depending on the load scenario encountered. For example if the ICE was able to operate at maximum power for high load scenarios such as overtaking or hill climbing this would reduce the power requirement from the battery pack (and therefore reduce its mass) by producing more power from the generator. This, however, would result in a fuel use and emissions penalty due to operating the ICE at peak power output. However these high load scenarios only occur infrequently and for short durations (seconds). Thus the fuel use and emissions penalties would be minor and would be countered by reduced weight. If the ICE were also able to operate at the maximum fuel efficiency point for low load scenarios such as city/suburban driving conditions, this would significantly reduce fuel use and emissions and represents the majority of load scenarios encountered. For all other load scenarios the ICE would operate at peak torque (to provide maximum efficiency).

Due to the simplicity requirement of the model and the overall goal of the study being to make comparisons between conventional technology and series hybrid drive system technology, it was decided to opt for a more simplistic control strategy.

The energy management methodology adopted was as follows:

1. The battery pack initially had a set SOC at the beginning of the drive cycle. Its value is primarily set by a requirement for the vehicle to be able to traverse the NYCC drive cycle on battery power only. This value was also affected by a requirement that each vehicle have the same capacity in the battery pack at the start of the drive cycle.
2. The battery SOC at the completion of the drive cycle was returned to the original SOC by assuming that this difference in energy is supplied by the OPS. However in this study grid recharging was also taken into consideration. Thus for this situation the difference in energy is supplied by the grid.
3. When the vehicle is not moving (for example stopped at a controlled intersection or in traffic gridlock), there is no load on the system (i.e. the OPS is off), there is no input from regenerative braking and thus the electric motor is off.
4. When the vehicle is moving the energy usage is defined by the load scenario, for example, the amount of energy that is required to undertake acceleration. This energy is deducted from the initial SOC to give the current SOC of the battery pack. Thus every time a load scenario is undertaken a new current SOC is defined.
5. The current SOC of the battery is also determined by input from the OPS. Regeneration energy has priority over OPS energy when it is available (to maximise efficient use of system resources). If the current SOC is greater than the maximum SOC then the status of both the regenerative input and OPS will be off. If the current SOC is between maximum and minimum SOC then the status of the OPS will be off and the status of regeneration will be on (if decelerating). If the current SOC is less than the minimum SOC then the status of both OPS and regeneration will be on. Thus it can be seen that the current SOC will vary during the course of a drive cycle and vary on a second by second basis.

In a conventional battery the internal resistance rises as the battery capacity rises during the charging process. This implies that the electrical load on the generator will reduce during the charging process and not keep the ICE component of the OPS running at its optimum operating point. Thus it was assumed that the energy management and control system will make sure that the engine is operating at optimum all the time by also delivering energy from the generator to the motor as well as charging the battery.

6.6.2 *Inverter/controller efficiency*

An inverter/controller (Sec. 6.6) creates the necessary inter-conversions between the battery/OPS/regenerative power flows and the system load (mainly the electric motor). These inter-conversions result in losses in the inverter. However modern electronics making use of advanced high power control devices such as MOSFETS (metal oxide silicon field effect transistors) and IGBTs (insulated gate bi-junction transistors) along with efficient control algorithms have made modern inverters very efficient with efficiencies in excess of 97% (EE Tech, 2004) and this was the value adopted.

6.6.3 *Inverter/controller power density and weight*

Inverter weight (W_{inv}) is a function of system maximum power requirement (defined mainly by maximum motor power output, P_{mot}) and inverter specific power density (SP_{inv}) which was set at 11 kW/kg (EE Tech, 2004). The relationship is:

Equation 6-8. $W_{inv} = P_{mot} / SP_{inv}$

6.7 Vehicle weight model

6.7.1 *Shell weight*

Vehicle shell weight is defined as the curb weight of the vehicle minus those components of the original conventional vehicle that are required to make the vehicle operational i.e. the power-train. These components include engine, transmission, cooling systems, ignition system (including battery), alternator and associated wiring. These components represent approximately 20-25% of the curb weight of a vehicle (Maeder, 2000). Note that other literature (OTA, 1995) indicated a "zero engine body weight" (without power train and with secondary weight reductions accounted for) of 50–54%. This is a significant discrepancy. The zero engine body weight was set at 80% of the original conventional vehicle curb weight.

6.7.2 *Mounting weight*

The series hybrid drive system components thus far have been attributed a weight based on their specific energy or power density. However there is also a weight associated with their mounting and packaging requirements in the vehicle. It was obviously difficult to ascertain what this weight would be with any degree of accuracy. Thus a relatively arbitrary approximation of 40 kg has been chosen.

6.7.3 *Total weight*

When modelling a hypothetical series hybrid vehicle specification, data bases are of no use since no vehicle data exists. It was the intention of this study to model a series hybrid drive system architecture based on the concept of a hypothetical vehicle conversion i.e. a vehicle that has had the conventional drive apparatus removed and replaced with a series hybrid drive system. This is a reasonably conventional approach – the Renault Kangoo Series hybrid van is a converted conventional Renault Kangoo (Renault, 2003).

The weight of a conventional vehicle is a function of the accumulated weights of the individual components such as body shell, engine/transmission, fuel tank etc. The weight of any hypothetical converted series hybrid vehicle can be calculated similarly. The weight of the series hybrid vehicle was calculated as follows:

Conventional vehicle kerb weight – drive train and required accessories = shell weight.

Series hybrid vehicle kerb weight = shell weight + motor weight + battery weight + ICE weight + inverter/controller weight + generator weight + mounting weight.

The total vehicle weight also includes a payload weight, equivalent to the weight of an average driver and is set at 80 kg.

6.8 Use of grid recharging

In a pure electric vehicle the batteries are charged via plugging into the grid (the high power electrical network supplying electricity for domestic residential and commercial industrial use). Thus an electric vehicle can be charged from home or anywhere where there is access to grid supply. This same recharging process can be applied to "plug-in" hybrid vehicles to charge the on-board batteries. The ability to recharge from the grid will effect fuel use and emissions. In this study overall fuel use was investigated with and without input from the grid.

There is of course an emissions penalty associated with grid charging of batteries if this electricity is produced from thermal plant (and potentially a fuel use penalty if this plant is oil fired). However the potential emissions created by electricity production are created at the point of generation, and generally located away from city centres where a large proportion of vehicle pollution is created. Thus, I felt that an in depth look at these emissions was not warranted (even though their impact is relevant in the wider context of global warming). If this were to be included, realistically, a vehicle life cycle analysis would also be required which is beyond the scope of the study. However it is instructive to look at the effect of grid power (for battery recharging) on emissions and fuel use from domestic vehicles. Thus, since the larger proportion of fuel consumption and emissions occurs in urban areas, the effect of emissions from power stations was not considered to be relevant to the goals of the study.

It was assumed that the grid will only be used to account for the difference that exists at the end of a test drive cycle between the current SOC and the initial SOC. The grid recharge calculation is:

Equation 6-9. $E_{grid} = SOC_{ini} - SOC_{cur}$

where

E_{grid} = energy required from the grid (J)

SOC_{ini} = state of charge of the battery at the beginning of the drive cycle (J)

SOC_{cur} = state of charge of the battery at the end of the drive cycle (J)

6.9 Drive cycle model

The test drive cycles used and the relevant calculations performed were similar to the reference vehicle with the exception of the transmission. In the series hybrid drive system, power is transferred to the wheels via a single gear and differential rather than a multi-gear transmission and clutch arrangement as in a conventional vehicle. Thus there is less energy loss in this simplified arrangement and a value of 98% was used.

6.10 Road load model

The energy required to undertake a load scenario in a vehicle equipped with a series hybrid drive system was calculated in exactly the same way as it was for the reference vehicle, using the same equations for air resistance, rolling resistance and inertial resistance. Differences are due to electrical losses in the system from the electric motor, inverter/controller, battery discharge and a mechanical loss due to the final drive. The energy required (W) calculation was:

Equation 6-10. $W = F\,d$

$$= (R_{air} + R_{roll} + R_{inert}) * d / (\eta_{bd}\ \eta_{inv}\ \eta_{mot}\ \eta_{fd})$$

where

F = force (kgm/s^2)

d = distance traveled (m)

R_{air} = air resistance force

R_{roll} = rolling resistance force

R_{inert} = inertial resistance force

η_{bd} = battery discharge efficiency

η_{inv} = inverter efficiency

η_{mot} = motor efficiency

η_{fd} = final drive efficiency

The actual road-load power (R_L) is the ratio of the energy required to the time period:

Equation 6-11. $R_L = W / t$

where

R_L = road-load (kW)

W = energy required (J)

t = time (s)

Under certain circumstances the battery discharge efficiency (η_{bd}) may not be required in the model when the motor is getting power directly from the generator and bypassing the battery, it would be replaced by a generator efficiency term, however this is not currently modelled. Thus at present the model may be over-estimating fuel use to some degree.

6.11 Fuel use model

Absolute fuel use for the series hybrid drive system is similar to that described in Section 5.7, for the conventional drive system, the fundamental difference being that fuel is only used when the ICE component of the OPS is actually operating.

Fuel use is essentially dependent on the battery SOC. When the battery charge drops below a certain level, the ICE component of the OPS turns on to recharge the battery bank. This process is also affected by the amount of generative energy available.

Since the ICE operates at a constant speed and drives a constant load (the generator), fuel use is essentially a function of the amount of time that the OPS is operational. At the end of the drive cycle it is assumed that the battery is restored to its initial state of charge. The amount of energy required to be supplied by the OPS or the grid is defined by the difference between the initial battery SOC and the battery SOC after a test drive cycle has been completed.

Note that similar to the reference vehicle, fuel use in the series hybrid drive system is a function of; inherent engine friction relationships (speed dependent), engine capacity, engine cycle (Otto or Diesel) and road-load. Thus the same fuel use equation applies (Equation 5-23).

The following is an algorithm for the fuel use process during the drive cycle:

If OPS status = off then

$F_C = 0$

Else $F_C = [(k\,(N / 60)\,V_d) + (R_L / \eta)]\,t / E_{fuel}$

where

F_C = fuel consumption (g)

k = engine friction term

N = engine speed (RPM)

V_d = engine capacity (L)

E_{fuel} = energy content of the fuel (kJ / g)

R_L = road-load (kW)

t = time period (s)

η = indicated efficiency

As for the reference vehicle, fuel consumption was calculated on a second by second basis and these values are summed at the end of the drive cycle to gain a value for total fuel use for operation of the ICE component of the OPS during the selected drive cycle. Once the drive cycle is completed the batteries are recharged back to their initial SOC that existed at the beginning of the drive cycle (if this is required). At this point two options exist:

1. the energy to recharge the batteries comes from the generator component of the OPS; or
2. the energy to recharge the batteries comes from the grid.

For option 1, the fuel required to recharge the batteries (from operation of the ICE component of the OPS) is added to the fuel use total from operation of the ICE during the drive cycle to gain an overall fuel use. For option 2, the overall fuel use is due to the operation of the ICE component of the OPS during the drive cycle only. From fuel use and knowledge of drive cycle length a value for the economy (l/100 km) can be calculated. There are two categories to be considered.

1. Economy without grid

This is simply the economy that is the sum of the fuel used during the drive cycle and the amount of fuel required to return the battery bank back to the original state of charge. This was accounted for by the following algorithm:

If fuel = petrol then

F_C = Sum (drive cycle fuel use + battery recharge fuel use) * (petrol fuel density)/(drive cycle length)

If fuel = diesel then

F_C = Sum (drive cycle fuel use + battery recharge fuel use) * (diesel fuel density)/(drive cycle length)

2. Economy with grid

If energy to recharge the batteries comes from the electrical grid network then the fuel use is simply the fuel used during the drive cycle only and was accounted for by the following algorithm;

If fuel = petrol then

F_C = Sum (drive cycle fuel use) * (petrol fuel density)/ (drive cycle length)

If fuel = diesel then

F_C = Sum (drive cycle fuel use) * (diesel fuel density)/ (drive cycle length)

6.12 Emissions model

Emissions from the reference vehicles equipped with any of the series hybrid drive systems options, were modelled in a similar way to the reference vehicle emissions model with the exception that emissions from the series hybrid drive systems equipped with a Diesel cycle as the ICE component of the OPS are not the result of a variable equivalence ratio as they were for the Diesel cycle reference vehicles. The ICE in a series hybrid drive system option operates at a constant speed equivalent to the peak torque and drives a constant load (generator), this implies the use of a constant equivalence ratio. However, as far as the calculation of the emissions is concerned the same equations are employed as those used for determining the emissions for the reference vehicles.

In a similar way to the emissions approach for the reference vehicle, emission level was calculated on a second by second basis (when the OPS is on) and these values are summed at the end of the drive cycle to gain a value for the total emission production for the operation of the ICE component of the OPS. Again the batteries could be recharged from generator component of the OPS or from the grid.

If the former is chosen, the emissions produced as a result of charging the batteries are added to the emissions produced in total from operation of the ICE during the drive cycle to gain an overall emissions production value. If the latter is chosen, the overall emissions production is due to the operation of the ICE during the drive cycle only.

From total emission production and knowledge of drive cycle length, a value for the total emissions output was calculated (g/km).

As with fuel use, the affect of grid recharging is considered with respect to the amount and type of emissions species produced. Thus the following categories need to be considered:

- CO_2 emissions with and without grid input;
- CO emissions with and without grid input; and
- NO_x emissions with and without grid input.

As an example the following is for CO_2 emissions:

1. CO_2 emissions without grid

This is the sum of the emissions produced during the drive cycle plus the amount of emissions produced when returning the battery bank back to the original state of charge:

Total CO_2 = Sum (drive cycle CO_2 + battery recharge CO_2) / (drive cycle length)

2. CO_2 emissions with grid

This is the emissions produced during the drive cycle only:

Total CO_2 = Sum (drive cycle CO_2) / (drive cycle length)

6.13 System efficiency

The system efficiency for the series hybrid drive system is based on the approach taken in Section 5.9, and should result in better overall system efficiency since there is no idling loss, no deceleration loss and during times of low load the vehicle runs under battery power only making use of energy that has been previously stored from regenerative braking and from stored energy that was not required to propel the vehicle.

When grid input is considered however, the calculation is more complicated since now electricity from the grid instead of fuel is used to recharge the vehicle battery pack back to the initial state of charge. Thus this electricity has to be included in the system efficiency calculation. There are two scenarios to be considered:

1. no fuel is consumed during the drive cycle and the grid is used to recharge the batteries back to their initial state of charge; and
2. fuel is consumed during the drive cycle and the grid is also used to recharge the batteries back to their initial state of charge.

For Case 1 the vehicle is essentially operating as an electric vehicle since the only source of energy is "off board". In this case the system, essentially, includes battery, electric motor and the inverter/controller only. Energy out of the system is the energy to power the electric motor to overcome the road-load. Energy in to the system is the energy from the grid to replace the energy lost from the battery pack. Under normal circumstances, the system efficiency in an electric vehicle can be viewed as the product of the individual efficiencies of the components that exist in the drive-line:

Equation 6-12. $\eta_{sys} = \eta_{bat}\ \eta_{mot}\ \eta_{inv}$

However the energy out is affected by regenerative braking energy inputs to the system and these do not come from the grid. These inputs reduce the amount of energy that is required to undertake vehicle motion to overcome the road-load. Thus:

Equation 6-13. η_{sys} = energy out / energy in

$$= (\eta_{inv}\ \eta_{mot}\ (\eta_{bc} + \eta_{bd}) / 2\ ) / (1 - (E_{RegenT} / E_{Dr}))$$

where

η_{inv} = inverter efficiency

$(\eta_{bc} + \eta_{bd})/2$ = arithmetic average of the battery charge and discharge efficiencies

η_{mot} = motor efficiency

E_{RegenT} = total energy from regenerative braking during the course of the drive cycle

E_{Dr} = total energy required to complete the drive cycle

Case 2 is an extension of the approach used to quantify the system efficiency of a reference vehicle (Section 5.9.1). However this equation needs to be altered to include a term relative to the electrical energy input from the grid:

Equation 6-14. η_{sys} = energy out / energy in

$$= E_{Dr} / [(F_C\ E_{fuel}) + (SOC_{ini} - SOC_{fin}) / \eta_{bc}]$$

where

SOC_{ini} = initial state of charge of the battery at the beginning of the drive cycle

SOC_{fin} = final state of charge of the battery at the end of the drive cycle

η_{bc} = charge efficiency of the battery pack

Note that this efficiency is a pump to wheels efficiency, and thus does not take into account the efficiency with which the electricity to charge the batteries is generated.

7.0 RESULTS AND DISCUSSION

The results and discussion have been divided into:

1. Fuel use: results of comparisons between each reference vehicle and four series hybrid drive system options with respect to fuel use with and without electrical grid input.
2. Emissions: results of comparisons between each reference vehicle and four series hybrid options with respect to CO_2, CO and NO_X emissions with and without electrical grid input.

The figures in this chapter all use the following key:

REF1: subcompact Otto cycle reference vehicle based on a Daihatsu Charade.

REF2: mid-range Otto cycle reference vehicle based on a Toyota Corolla.

REF3: subcompact Diesel cycle reference vehicle based on a Volkswagen Polo.

REF4: mid-range Diesel cycle reference vehicle based on a Volkswagen Bora.

SH1: series hybrid drive system based on a 660cc naturally aspirated Otto cycle ICE.

SH2: series hybrid drive system based on a 250cc naturally aspirated Otto cycle ICE.

SH3: series hybrid drive system based on an 800cc turbo-charged Diesel cycle ICE.

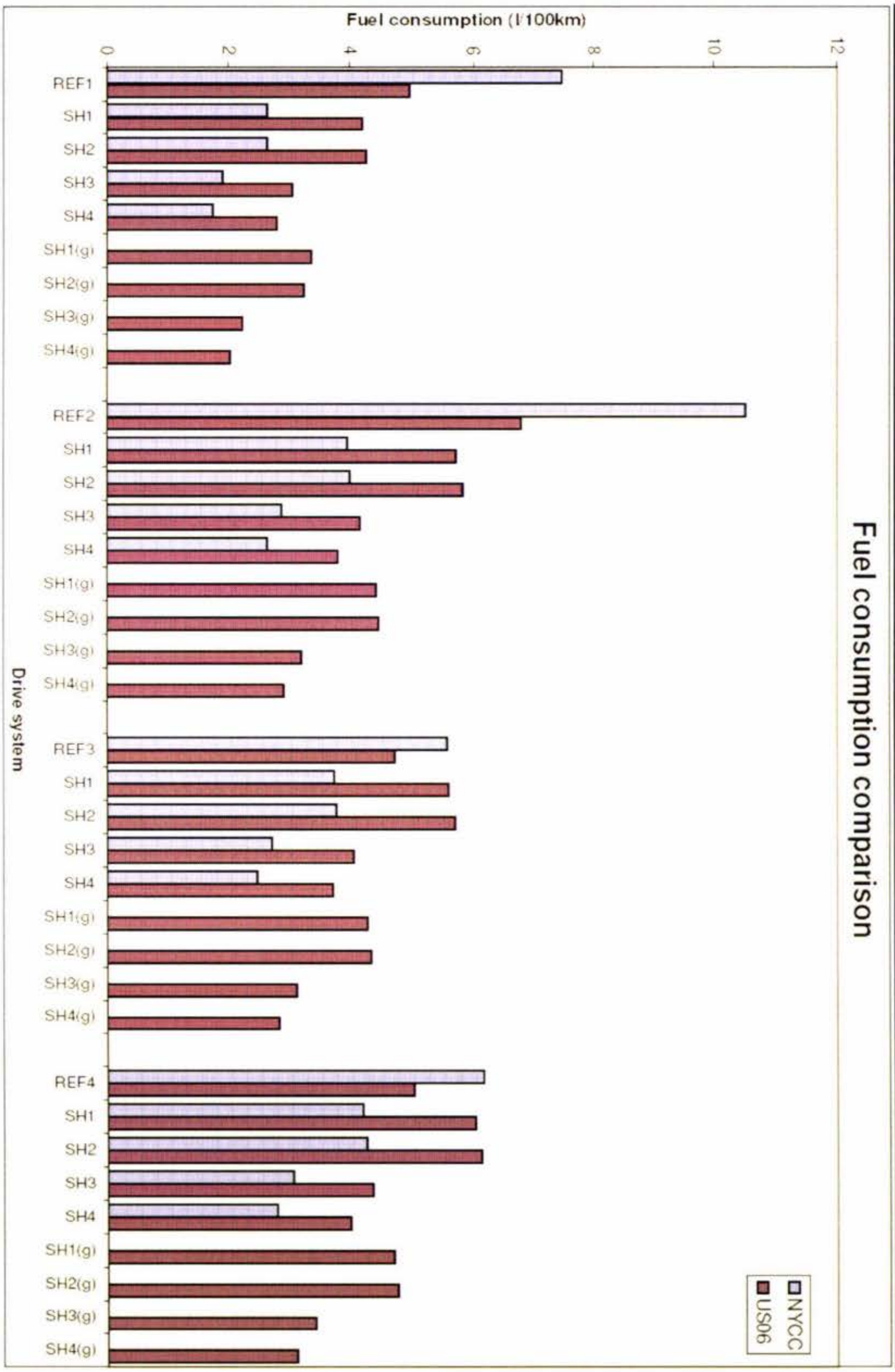
SH4: series hybrid drive system based on a hypothetical 400cc turbo-charged two stroke Diesel cycle ICE.

A "g" after the reference designation indicates a series hybrid drive system option making use of electrical input from the grid.

7.1 Fuel Use

Significantly reduced fuel use by all the series hybrid drive system options was apparent when compared to any of the reference vehicles. This is particularly evident when comparisons were made with the NYCC drive cycle, the largest reductions coming from the diesel options (SH3, SH4). Less pronounced reductions were shown during the aggressive, open road drive cycle (US06) by the series hybrid options, although the reductions due to SH3 and SH4 were still significant. Fuel consumption comparisons are displayed in Figure 7-1.

Figure 7-1. Fuel use versus drive system option.



Reductions by the series hybrid drive system options during the NYCC drive cycle were due to:

- no idling loss;
- partial regeneration and storage of inertial energy from regenerative braking;
- ICE operating within its most efficient operating points;
- high efficiency primary drive source (electric motor);
- minimal part load energy loss (due to high part load efficiency of the electric motor);
- reduced engine capacity;
- system designed for average operating requirements, not peak; and
- battery storage of excess energy during low load scenarios and returning it during high load requirements.

Less pronounced reductions during the US06 drive cycle were due to:

- idling loss of conventional drive systems less significant during open road load scenarios;
- less energy from regenerative sources (proportionately less deceleration and braking periods);
- the conventional vehicle ICE operating closer to its optimal operating points;
- less part load energy loss in the conventional drive system; and
- the ICE in the series hybrid OPS required to operate more often due to higher average loads.

Greater reductions by the diesel series hybrid options, SH3 and SH4 were due (in addition to the above) to a more efficient engine cycle. SH3 showed a 74% reduction in fuel use during the NYCC drive cycle and a 39% reduction in fuel use during the US06 drive cycle when compared to REF1. SH4 (2-stroke diesel) showed a further reduction in fuel use (greater than 76% during NYCC) which can be attributed, in the main, to lower pumping and frictional losses associated with this technology.

Reductions in fuel use by the series hybrid drive system options when compared to REF3 and REF4 were less pronounced, SH1 and SH2 showing an increase in fuel use during the US06 drive cycle. REF3 and REF4 are powered by a Diesel cycle ICE and are more fuel efficient than REF1 and REF2 which has had an effect on the comparisons with the series hybrid drive system options. SH1 and SH2 are series hybrid options where the ICE component of the OPS is a less efficient Otto cycle engine, such that the advantages of the series hybrid drive system approach is compromised slightly by the use of this technology under higher load scenarios as are simulated by the US06 drive cycle when compared to reference vehicles powered by the more efficient Diesel cycle.

SH3 and SH4 however still showed significant reductions in fuel use during the NYCC drive cycle and reduced but still significant reductions in fuel use during the US06 drive cycle when compared to REF3 and REF4. Again this is due to SH3 and SH4 incorporating the more efficient Diesel cycle as the ICE component of the OPS.

Further fuel use reductions were evident by each of the series hybrid drive system options when grid power was used to recharge the battery bank back to the initial SOC that existed at the beginning of the drive cycle. No fuel use was evident during the NYCC drive cycle by any of the series hybrid options when compared with any of the reference vehicles due to grid input and the capacity of the battery bank being sufficient to traverse all of this drive cycle on battery power only.

When the US06 cycle is considered, due to the higher average loads and therefore heavier demand on the electric motor and therefore battery pack, it does not have enough capacity to complete the drive cycle on battery power alone and thus power from the OPS is required with corresponding higher fuel use. The difference between initial and final SOC during the drive cycle is again replenished with grid power resulting in less fuel use than when the grid is not used. Fuel use by SH3 and SH4 (series hybrid drive system options incorporating a Diesel cycle ICE without grid input) was less than SH1(g) and SH2(g) (Otto cycle series hybrid options with grid input) due to the effect of an efficient Diesel cycle ICE that exists as the ICE component of the OPS in these options.

For the vehicles equipped with a series hybrid drive system, the battery capacity will have a significant affect on the reported fuel use and emissions level when making use of grid electricity input, particularly for the simulated urban scenario. This potential to reduce fuel use is also dependent on the average load and the initial battery SOC. In a real world scenario this would only be applicable to urban driving where access to the grid is more apparent, whereas on longer journeys in non urban environments, access to the grid is less likely such that reported values for the US06 drive cycle are for illustration only. The main point is to show the potential effect of the grid on fuel use in series hybrid drive systems (particularly in an urban environment) where this feature is available.

7.2 Emissions

In conventional vehicles the amount of emissions produced is affected by any exhaust after treatment devices used, such as catalytic converters. The amount of emissions from a particular drive system were calculated from the result of the combustion processes that occur within the conventional ICE or within the ICE component of the series hybrid OPS. This is a more effective way of making emissions comparisons between different technologies. Gaseous emissions considered were:

1. Carbon dioxide.
2. Carbon monoxide.
3. Nitrogen oxides.

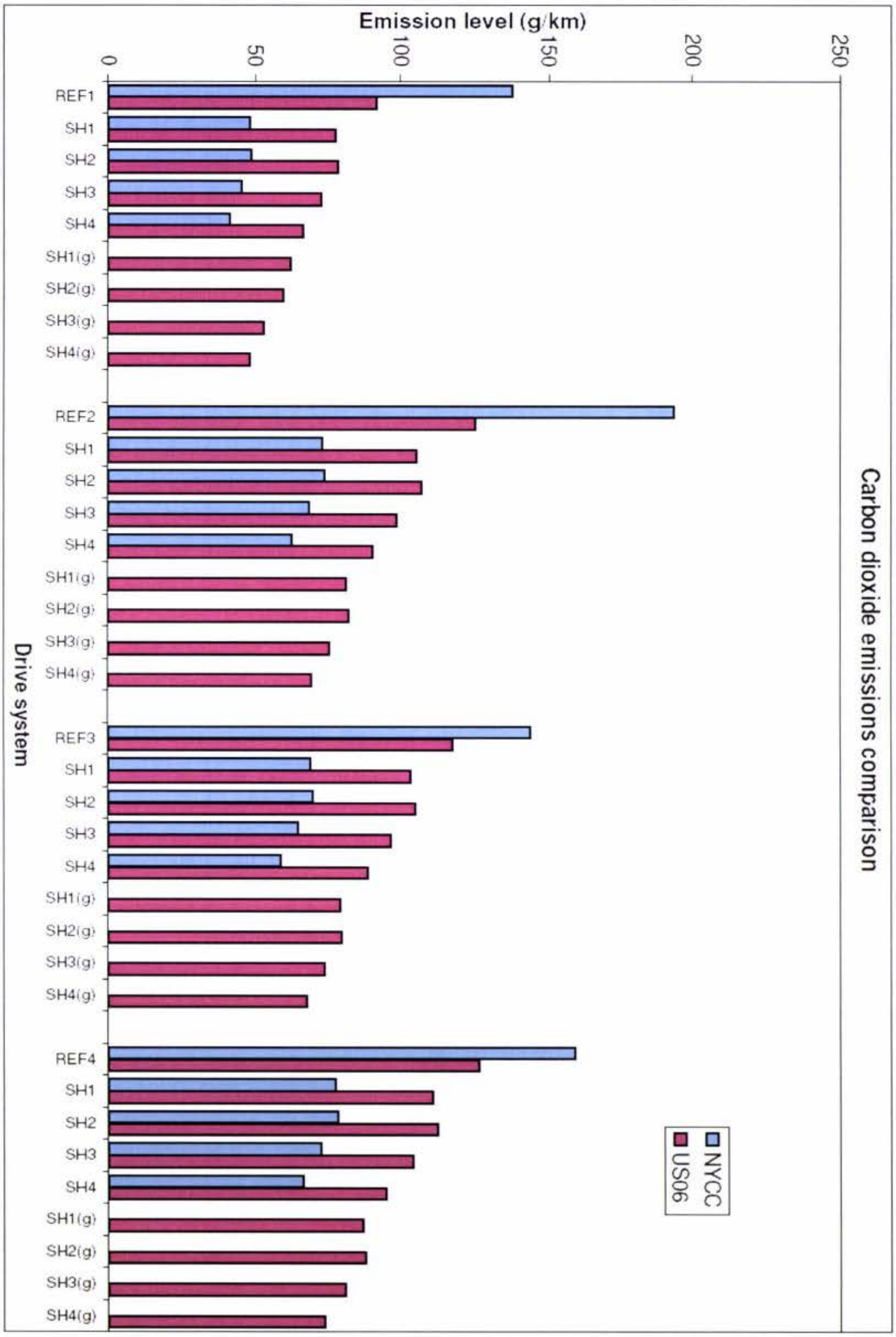
7.3 Carbon dioxide emissions

CO_2 emissions are essentially a function of fuel use and to a minor extent, equivalence ratio - particularly for the Diesel cycle ICE (Fig. 5-2). Thus the overall trends for CO_2 emissions are similar to those found for fuel use. CO_2 comparisons are displayed in Figure 7-2.

Significantly reduced CO_2 levels by all the series hybrid drive system options were evident compared to any of the reference vehicles, particularly for the NYCC drive cycle. The largest reductions coming from SH3 and SH4 although the improvement over SH1 and SH2 was only minor.

The significant reductions in CO_2 emissions by SH1 and SH2 during the NYCC and US06 drive cycles (although less pronounced) compared with REF1 and REF2 are essentially a function of fuel use. These two series hybrid drive system options make use of an Otto cycle engine as the ICE component of the OPS. This type of engine cycle has a fixed equivalence ratio (set at 1) that is independent of load and engine speed hence the percentage reductions in CO_2 were exactly the same as the percentage reductions in fuel use. Thus the reasons that were given for the reductions in fuel use due to the series hybrid drive system can be equally applied here.

Figure 7-2. Carbon dioxide emissions versus drive system option.



The slightly higher reductions achieved by SH3 and SH4 compared to SH1 and SH2 during both drive cycles were a function of fuel use, the inherently higher efficiency of the Diesel cycle and a variable equivalence ratio. Figure 5-2 shows that at low equivalence ratios (low load scenarios such as are encountered during the NYCC drive cycle), CO_2 levels were approximately 10% higher than during higher load scenarios. Thus even though SH3 incorporates a larger capacity ICE than SH1 and SH2 the efficiency of the cycle and its relationship with the equivalence ratio led to further reduced CO_2 levels. Reductions by SH4 were even more marked due to the use of a lighter, more efficient technology (Diesel cycle 2-stroke ICE) due to lower frictional and pumping losses.

CO_2 levels for the Otto cycle vehicle are approximately 2.5 grams per gram of iso-octane combusted compared to a minimum of approximately 2.7 grams of CO_2 per gram of cetane combusted. However Diesel cycle vehicles have far better fuel economy for engines of similar size (Fig. 7-1) thus they consume less fuel (cetane) and therefore they produce less CO_2 per kilometre.

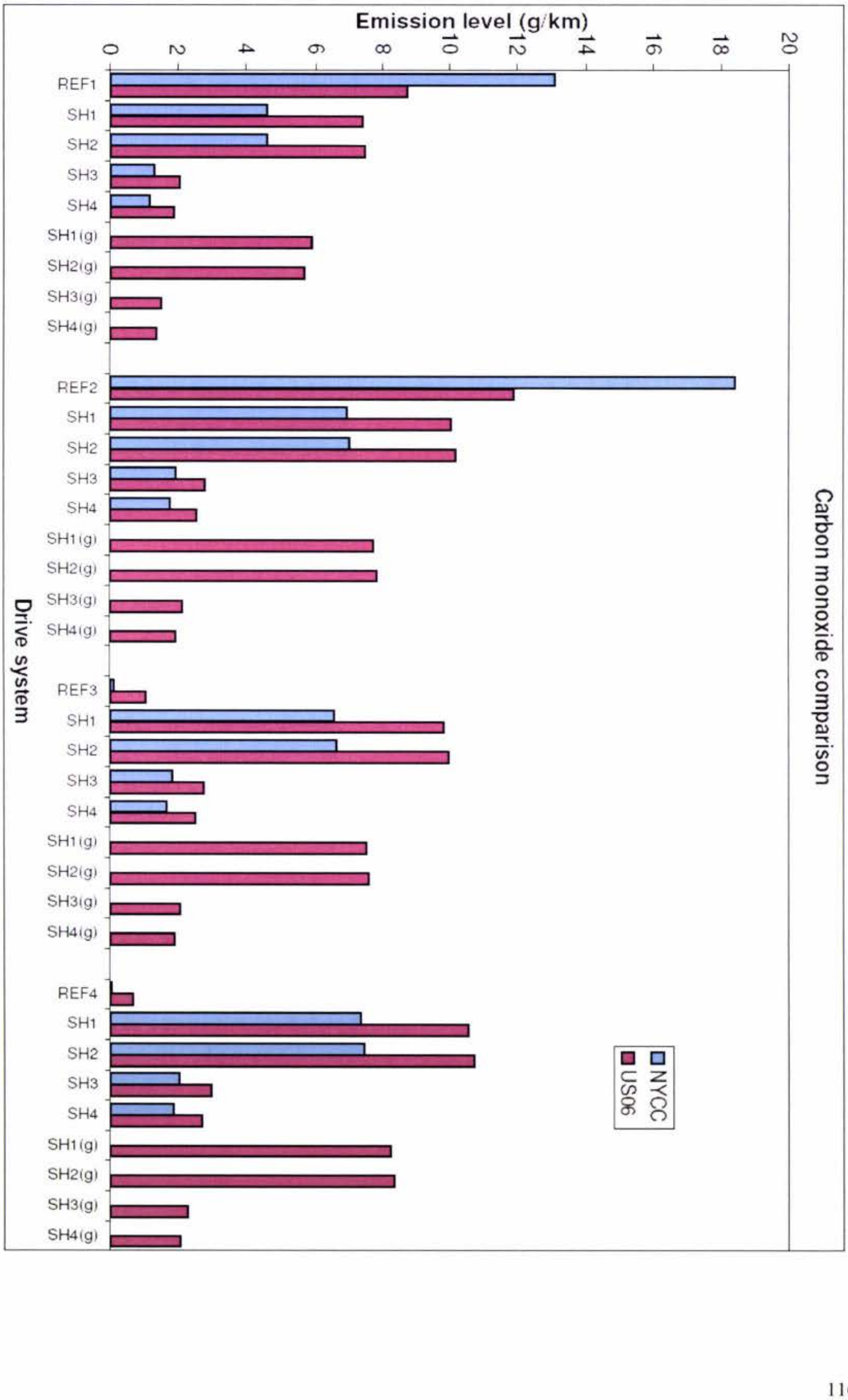
The emission levels shown by REF3 and REF4 CO_2 comparison graphs are essentially a mirror image of those seen for REF1 and REF2 and the discussion concerning these two graphs can also be applied here.

Further reductions in CO_2 were evident when grid electricity was used as part of the drive process. No CO_2 was produced during the NYCC drive cycle for any of the series hybrid drive system options with grid input when compared to all the reference vehicles and reasons for this are the same as for the fuel use case. During the US06 drive cycle, emissions were present and again the reasons are the same as the fuel use case.

7.4 Carbon monoxide emissions

CO emissions are a function of fuel use and air/fuel equivalence ratio. This is more crucial for the Diesel cycle ICE where a significant non-linear relationship exists between CO level and equivalence ratio (Fig. 5-2). Otto cycle engines have essentially a constant air/fuel equivalence ratio and therefore their CO emissions are essentially a function of fuel use only. The comparisons are displayed in Figure 7-3.

Figure 7-3. Carbon monoxide emissions versus drive system option.



Significant reductions in CO levels shown by SH1 and SH2 during the NYCC drive cycle were evident compared to REF1 and REF2 and are essentially a function of fuel use due to REF1, REF2, SH1 and SH2, incorporating an Otto cycle ICE and the use of a fixed equivalence ratio. The reduction in CO level being the same percentage as for the reduction in fuel use. The reasons given for this reduction in the case of fuel use (and CO_2) can also be applied for the CO reductions.

Similarly, the reduced but still significant reductions in CO levels shown by SH1 and SH2 during the US06 drive cycle are for the same reasons as given for the fuel use case.

The reductions in CO levels by SH3 and SH4 when compared to REF 1 and REF 2 during both the NYCC and US06 drive cycles is very significant (as high as 91% during the NYCC drive cycle and 78% during the US06 drive cycle). SH3 and SH4 incorporate a Diesel cycle ICE as the ICE component of the OPS. Diesel cycle CO levels are non-linearly related to equivalence ratio (always less than 1) leading to more complete combustion due to an excess of oxygen and less fuel being converted to CO during the combustion process. The result, in conjunction with the attendant advantages of the series hybrid drive system approach, is significantly lower levels of CO.

REF3 and REF4 CO comparison graphs showed a trend reversal with SH1 and SH2 having significantly higher levels of CO compared to REF 3 and REF 4 during both the NYCC and US06 drive cycles again due to the non-linear relationship between CO level and equivalence ratio. Under low load, emission levels of CO from Diesel cycle engines are very low (practically zero) due to the low equivalence ratio, and very low compared to levels associated with Otto cycle engines.

SH3 and SH4 showed significant reductions in CO compared to SH1 and SH2 but still significant increases compared to REF3 and REF4 during both drive cycles. This would seem to be an illogical result. SH3 and SH4 are series hybrid drive system options making use of a Diesel cycle engine as the ICE component of the OPS and this would suggest that the series hybrid drive system approach should reduce CO levels compared to the reference vehicles as has been the trend for CO_2 emissions and fuel use. However the reasons are again due to the significant non-linearity that exists between CO and equivalence ratio. Under low loads at low engine speed CO levels from Diesel cycle ICEs are essentially zero. As the load and engine speed increases (and therefore the equivalence ratio), the level of CO increases disproportionately up to a maximum at the maximum equivalence ratio. The Diesel cycle ICE in the series hybrid drive system operates at maximum efficiency, however this also means operating at an elevated equivalence ratio near the maximum (0.8–0.9). Thus at this higher efficiency, constant load operation, there are disproportionately higher levels of CO .

The situation is worse for the Otto cycle ICE since it burns a pre-mixed charge of fuel and air, thus the stoichiometry is pre-set and is generally maintained at an equivalence ratio of 1. The amount of CO released per gram of iso-octane combusted is approximately 0.238 grams. However because the equivalence ratio does not vary, this amount of CO is always produced. Thus the series hybrid options incorporating an Otto cycle ICE to drive the generator produce significantly higher levels of CO compared to REF3 and REF4 as well as to those series hybrid options incorporating a Diesel cycle ICE.

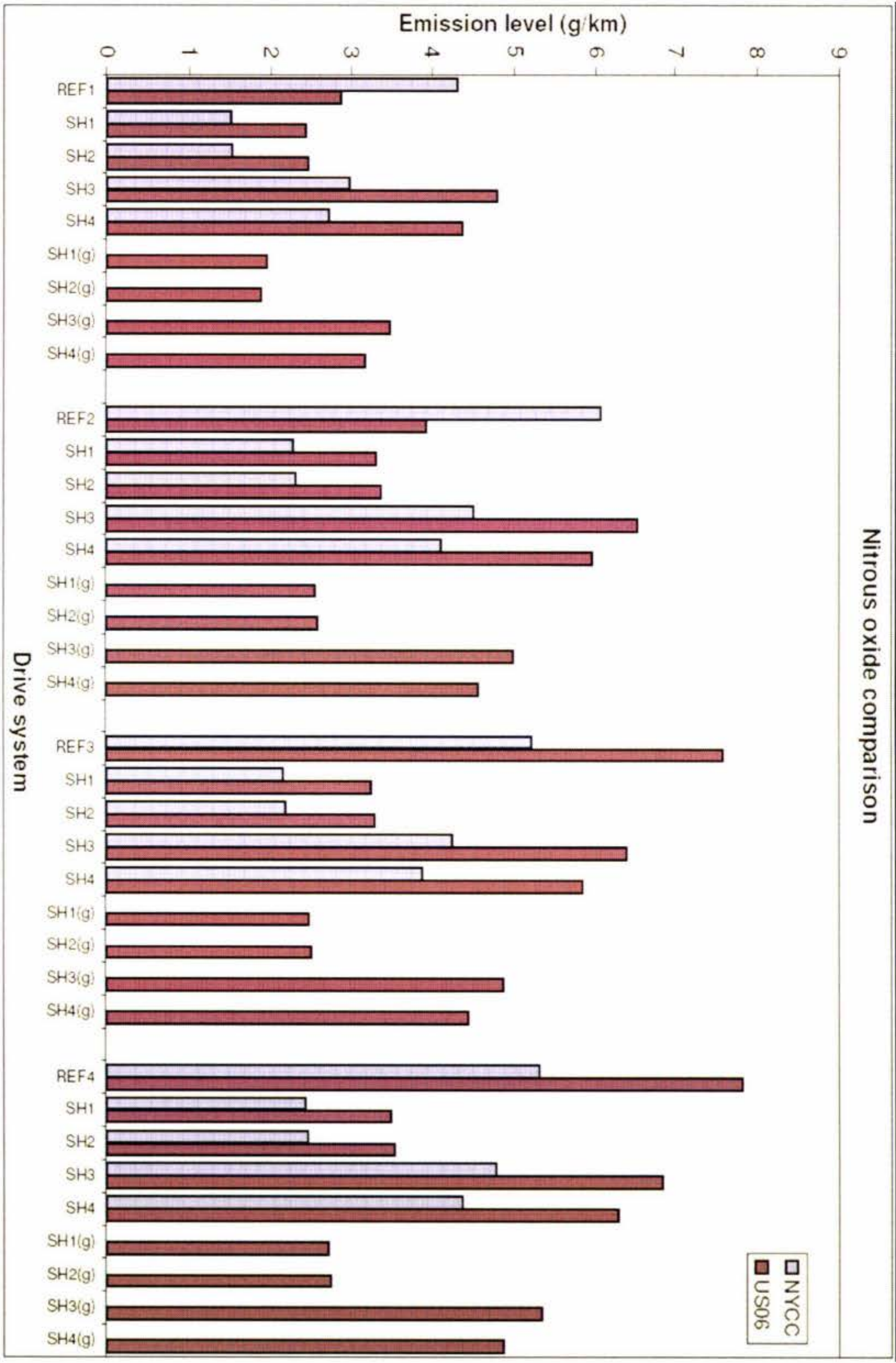
Further CO reductions are evident when grid power is used to recharge the battery packs back to their initial SOC. No CO emissions were produced by any of the series hybrid options during the NYCC drive cycle when compared with all the reference vehicles when input from the grid was considered. The reasons given for this result for the fuel use case can also be applied here. However during the US06 drive cycle CO emissions for all series hybrid drive system options with grid input showed an increase when compared to REF3 and REF4, the increase being very significant for SH1(g) and SH2(g).

The presence of emissions during the US06 drive cycle due to the reasons already discussed are significantly less than the series hybrid options without grid input but still more than REF3 and REF4. The aforementioned discussion relating to the non-linearity of CO with equivalence ratio also applies in this case.

7.5 Nitrogen oxide emissions

NO_x emissions, in a similar way to CO emissions, are significantly affected by air-fuel equivalence ratio (Fig. 5-2) and is again crucial for the emissions produced by the Diesel cycle ICE. Also, in a similar fashion to both CO_2 and CO emissions, NO_x emissions in the Otto cycle are essentially a function of fuel use only as the air/fuel ratio is essentially constant. NO_x comparisons are displayed in Figure 7-4.

Figure 7-4. Nitrogen oxide emissions versus drive system option.



Significant reductions in NO_X levels shown by SH1 and SH2 during the NYCC drive cycle compared to REF1 and REF2 are essentially a function of fuel use. The reduction in level being the same percentage as for the fuel use case. The reasons given for this reduction can also be applied for the NO_X reductions. Similarly, the reduced but still significant reductions in NO_X levels shown by SH1 and SH2 compared to REF1 and REF2 during the US06 drive cycle are for the same reasons as given for the fuel use case.

Significant reductions in NO_X by SH3 and SH4 were evident compared to both REF1 and REF2 during the NYCC drive cycle although less than that shown by SH1 and SH2. The reasons given for the reductions by SH1 and SH2 are also valid for SH3 and SH4. However, counteracting these reasons is the non-linear relationship between equivalence ratio and NO_X level (Fig. 5-2) which peaks at an equivalence ratio of approximately 0.7 and has a minimum at 0.2. The Diesel cycle ICE in SH3 and SH4 operates at or near peak efficiency at all times. At this peak efficiency the equivalence ratio is approximately 0.85, this results in a NO_X output of approximately 0.19g per gram of cetane combusted compared to 0.05g per gram of cetane combusted at an equivalence ratio of 0.2. This level is also very high compared to the levels of NO_X produced by SH1 and SH2 (Otto cycle ICE), which have their equivalence ratios set at 1 resulting in an output of approximately 0.00782g of NO_X per gram of iso-octane combusted. The result is less reduced levels of NO_X by SH3 and SH4 when compared to SH1 and SH2.

SH3 and SH4 however show significantly increased levels of NO_x when compared to REF1 and REF2 during the US06 drive cycle. The primary reason for this (in addition to the reasons given for the fuel use case) is similar to that indicated above. During more open road driving conditions as simulated by the US06 drive cycle, the OPS is required more often to charge batteries and supply energy to the electric motor due to the higher average loads encountered. This implies that the ICE component of the OPS will be on for a higher proportion of the time and therefore will be producing the same levels of NO_x as during the NYCC drive cycle (due to the constant equivalence ratio) but for a greater proportion of the time, therefore the total amount of NO_x will be greater.

NO_X emissions by REF1 and REF2 are greater during the NYCC drive cycle than during the US06 drive cycle. This is a typical result however the NO_X emissions by REF3 and REF4 showed an opposite result to this, and needs some explanation. Under low load conditions as are found in city driving and as simulated by the NYCC drive cycle, the equivalence ratio is low and this corresponds to a low NO_X level. Under average to high load driving conditions as simulated by the US06 drive cycle, equivalence ratios are required to be higher as load control in a diesel ICE is by variation of the equivalence ratio. The non-linear relationship between equivalence ratio and NO_x level results in a higher NO_X level at higher equivalence ratios up to an equivalence ratio of 0.7. Thus higher load scenarios such as encountered during the US06 drive cycle result in higher NO_X emissions.

Very significant NO_X reductions by SH1 and SH2 during both the NYCC and US06 drive cycles were evident compared to REF3 and REF4. SH1 and SH2 are series hybrid options incorporating an Otto cycle engine whereas REF 3 and REF 4 are vehicles powered by Diesel cycle ICEs. Torque output and therefore power in a Diesel cycle ICE is controlled by variation of the air/fuel ratio equivalence ratio, and NO_X level is a non linear function of said equivalence ratio and is considerably higher than in Otto cycle ICEs due to the combustion characteristics of this cycle. Thus the attendant advantages of the series hybrid drive system operation incorporating the Otto cycle ICE results in significant reductions in NO_X.

Significant NO_X reductions by SH3 and SH4 were evident compared to REF3 and REF4 during both the NYCC and US06 drive cycles. However the reductions were not as significant as those shown by SH1 and SH2. In this case the reductions are almost solely due to the effect of the series hybrid drive system operation that exists in SH3 and SH4. Engine cycle is no longer a large factor as REF3, REF4, SH3 and SH4 all incorporate Diesel cycle ICEs. However the reduction is less marked than it should be particularly during the NYCC drive cycle due to the non-linearity that exists between NO_X level and equivalence ratio. REF3 and REF4 when operating under low load scenarios such as are found during the NYCC drive cycle produce relatively low levels of NO_X due to operating at a low equivalence ratio. SH3 and SH4 however operate at the ICEs most efficient operating point, at a constant engine speed supplying a constant load with a constant, elevated, equivalence ratio. This results in disproportionately higher NO_X level which counteracts the effect of the series hybrid drive system approach.

When input from the grid was considered, a similar trend was evident; SH1(g) and SH2(g) when compared to SH1, SH2 and REF1 show further significant reductions in NO_X emissions during both drive cycles due to electricity replacing fuel as the energy source for recharging the battery back to its initial SOC. SH3(g) and SH4(g) when compared to SH3 and SH4 also showed significant reductions in NO_X emissions during both drive cycles for the same reasoning. No NO_X emissions were evident during the NYCC drive cycle for any of the hybrid drive system options with grid input when compared to any of the reference vehicles. The reasoning is the same for the previous emissions and fuel use cases. However, while SH1(g) and SH2(g) showed significant reductions in NO_X during the US06 drive cycle when compared to REF1 and REF2, there was a significant increase by SH3(g) and SH4(g). These grid assisted hybrid options also created more NO_X than SH1 and SH2. The explanation for this is similar to that used for the non-grid assisted comparisons; the non-linear relationship between NO_X and equivalence ratio for the Diesel cycle and the inherently lower levels of NO_X produced by Otto cycle combustion.

7.6 Hybrid drive system option comparisons

For fuel use, CO_2, CO and NO_X emissions, SH1 and SH2 had very similar results. SH1 incorporates a 660cc Otto cycle engine as the ICE component of the OPS whereas SH2 incorporates a light-weight high performance 250cc Otto cycle engine as the ICE component. This smaller engine translates to a lighter overall vehicle weight and less engine capacity and should therefore translate to reduced fuel use and emissions. However it operates at a very high engine speed; 8500 RPM compared to 4000 RPM for the ICE in SH1. Although the small engine is only a single cylinder unit the high engine speed incurs high frictional and pumping losses resulting in higher relative fuel use that tends to negate the advantage of lower weight. The real advantage of the smaller engine is in its volumetric footprint; being a smaller engine it would occupy a smaller space in the vehicle.

For fuel use, CO_2, CO and NO_X emissions, SH3 and SH4 also had similar results although SH4 consistently showed greater reductions. SH3 incorporates an 800cc turbo-charged Diesel cycle engine as the ICE component of the OPS whereas SH4 incorporates a 400cc 2-stroke turbo-charged Diesel cycle engine. SH4 is lighter, has smaller capacity and runs at a lower speed (incurring lower frictional losses as well as lower pumping losses due to 2-stroke operation) which should translate to lower fuel use and emissions and this was shown to be the case.

7.7 System efficiency

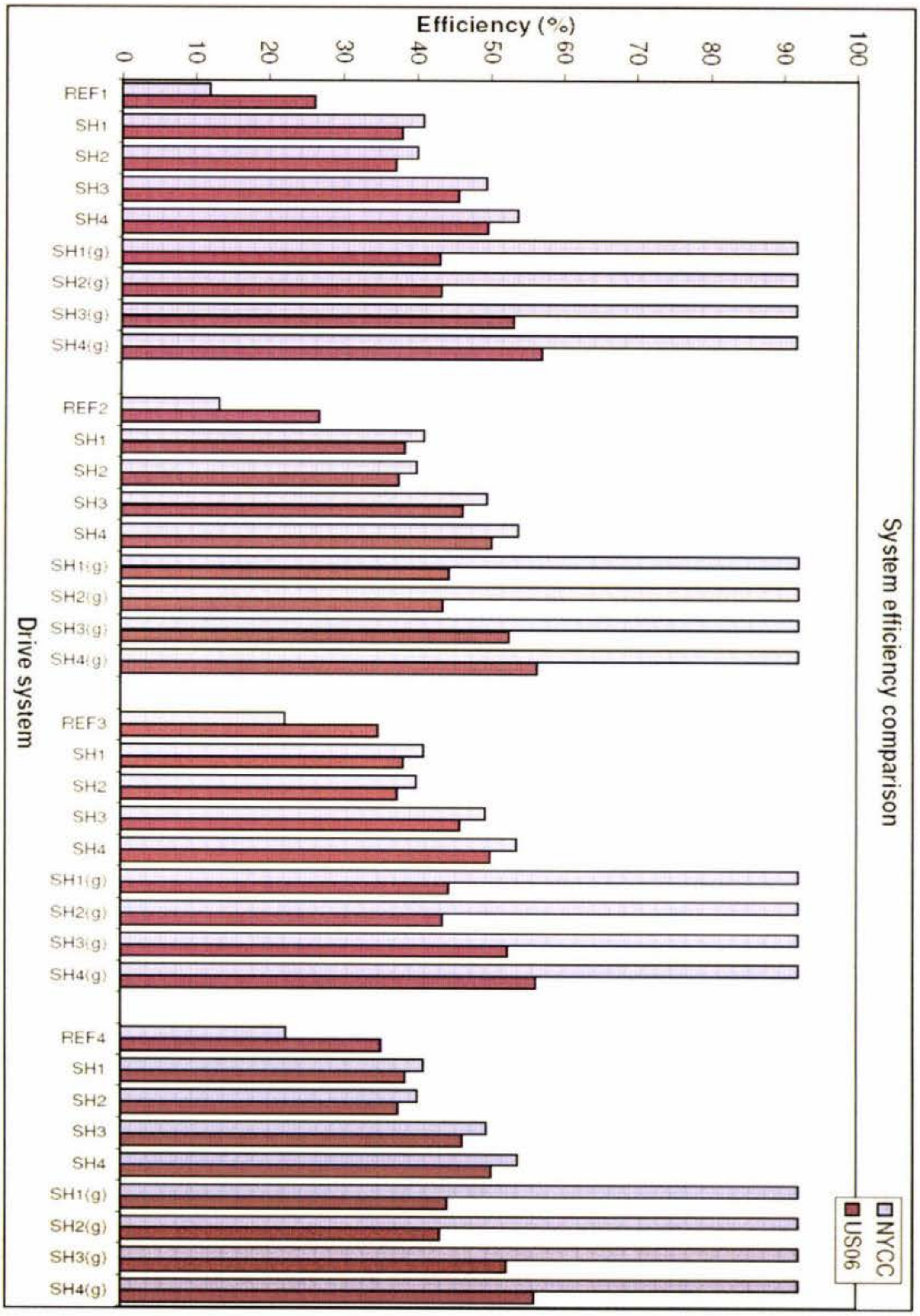
System efficiency can be defined as the ratio of energy out to energy in. In the context of the vehicle drive systems considered, energy out is essentially the energy required to overcome the road-load (in this case a particular drive cycle). Energy in is fuel energy and/or energy from the grid (if this is involved). System efficiency comparisons are displayed in Figure 7-5.

All four reference vehicles exhibit significantly lower system efficiency during the NYCC drive cycle than during the US06 drive cycle. This is to be expected. A conventional vehicle operating under urban conditions is operating well away from the maximum efficiency operating points of the ICE due to the majority of the low loads involved as well as incurring high idling and deceleration losses. There are also higher losses in the transmission. Whereas during more open road conditions such as are simulated by the US06 drive cycle, average loads are closer to the maximum efficiency operating points of the ICE and idling and deceleration makes up a lower proportion of total vehicle operation. There are also lower transmission losses.

Diesel cycle reference vehicles exhibited higher efficiencies than their Otto cycle counterparts due to the use of a more efficient engine cycle. Similarly, the series hybrid options incorporating a Diesel cycle engine as the ICE component of the OPS showed the largest improvements in system efficiency.

All the series hybrid drive system options showed improved system efficiencies when compared to any of the reference vehicles particularly during the NYCC drive cycle. This is essentially due to the same reasons as the fuel use case, however system efficiency during the US06 drive cycle was less than during the NYCC drive cycle (opposite to that for the conventional reference vehicles). This reflects the effect of increased loads during the US06 drive cycle on the system. Higher loads imply higher power draw from the battery system which implies more energy required from the generator, which further implies extended operation of the ICE and thus a higher proportion of total system operation. The result is lower overall system efficiency.

Figure 7-5. System efficiency versus drive system option.



The system efficiency of SH1 is marginally higher than SH2 due to the slightly higher efficiency of the ICE component used in the SH1 system which is mainly due to frictional and pumping effect losses in the ICE component of SH2. Similarly SH4 shows higher system efficiency than SH3 due the higher efficiency of the ICE component of SH4 and again due to reduced frictional and pumping effects in this engine due to 2 stroke operation.

The effect of grid input during the NYCC drive cycle was very significant due to no fuel use and electricity from the grid being used to recharge the battery bank back to the initial SOC. Thus the vehicle is essentially operating as an electric vehicle. Electric vehicle efficiency (ignoring the source of the electricity) is a function of the component efficiencies (battery pack, electric motor, and inverter/controller), which can be very high. When the capacity for energy regeneration from regenerative braking is included, overall system efficiencies can be very high.

The effect of grid input during the US06 drive cycle is less pronounced due to fuel use during the drive cycle from operation of the ICE component of the OPS. This will always lead to lower overall system efficiencies. However these system efficiencies are still higher than their non-grid assisted counterparts due to electricity being used to recharge the battery bank.

8.0 CONCLUSIONS AND FUTURE WORK

The results of the modelling/simulation clearly showed significant reductions in fuel use and emissions during both simulated urban and open road/aggressive driving patterns when series hybrid drive systems were considered as the drive system for the four domestic vehicles considered. In general, the largest reductions were achieved during simulated urban driving patterns by vehicles equipped with series hybrid drive systems that incorporated a Diesel cycle engine as the ICE component of the OPS.

Series hybrid drive systems when incorporated into domestic transportation showed the potential to provide:

- Significant reductions in fuel use during urban driving patterns and less pronounced but still significant reductions during aggressive driving patterns by the Otto and Diesel cycle hybrid options (particularly the Diesel cycle option) and particularly when compared to conventional Otto cycle vehicles.

- Significant reductions in CO_2 emissions during urban driving patterns and less pronounced but still significant reductions during aggressive driving patterns.

- Significant reductions in CO emissions during urban driving patterns and less pronounced but still significant reductions during aggressive driving patterns by the Otto cycle hybrid options when compared to conventional Otto cycle vehicles.

- Significant reductions in CO during urban and aggressive driving patterns by the Diesel cycle hybrid option compared to the Otto cycle hybrid options and conventional Otto cycle vehicles.

- Significant reductions in NO_X emissions during urban driving patterns and less pronounced but still significant reductions during aggressive driving patterns by the Otto cycle hybrid options when compared to conventional Otto cycle vehicles.

- Significant reductions in NO_X emissions during urban and aggressive driving patterns by the Otto cycle hybrid options compared to conventional Diesel cycle vehicles.

- Significant reductions in NO_X emissions during urban driving patterns by the Diesel cycle hybrid options compared to conventional Otto cycle vehicles and less pronounced but still significant reductions during urban and aggressive driving patterns when compared to conventional Diesel cycle vehicles.

- Significant improvements in overall system efficiency particularly by the Diesel cycle hybrid options.

However, along with the potential advantages there were also some potential disadvantages:

- Minor increase in fuel use during aggressive driving patterns by the Otto cycle hybrid options when compared to conventional Diesel cycle vehicles.

- Significantly higher levels of CO during urban and aggressive driving patterns by the Otto cycle hybrid options when compared to conventional Diesel cycle vehicles.

- Significantly higher levels of NO_X during aggressive driving patterns by the Diesel cycle hybrid options when compared to conventional Otto cycle vehicles.

Most emissions occur in built up areas (areas of high vehicle and population density) where most travelling occurs and a disproportionate amount of emissions are produced. The results indicated that the largest reductions in fuel use and emissions were during simulated urban/city driving and further indicated that emissions reduction is essentially a function of fuel use particularly for the vehicles incorporating an Otto cycle ICE. This implies that the major onus should be on reducing fuel use particularly as modern exhaust after treatment technologies can significantly reduce these emissions. Series hybrid drive systems incorporating a Diesel cycle engine (either a 4-cycle or 2-cycle) as the ICE component of the OPS, would appear to be the best overall candidate of the options considered due to their ability to significantly reduce fuel use. The minor increase in CO compared to the reference diesel vehicles, although still considerably less than the reference Otto cycle vehicles, can be reduced by modern after treatment methods.

Carbon emissions can be significantly reduced if fuels generated from biomass can be incorporated into the drive process. The combination of an efficient drive system (series hybrid) and a cleaner fuel potentially represent the best case scenario:

- a fuel that is inherently cleaner than conventional fuels due to being derived from biomass; and
- a transport technology that has the potential to significantly reduce the use of this fuel compared to conventional technology and also reduce localised emissions from this fuel.

Combining the use of fuels derived from biomass with series hybrid technology and an efficient engine technology has the potential to make these fuels a significant contributor to future domestic transport fuel requirements. This can have a beneficial flow on effect to better balance of trade figures due to the reduced cost of the importing and processing of crude oil for the domestic transport market.

The control strategy employed in this study is somewhat simplistic which has the advantage of being relatively straight-forward to model but has the possible disadvantage of a lack of accuracy. One main part of the strategy employs the ICE component of the OPS to operate at maximum efficiency as a means of reducing fuel use and emissions. Maximum engine efficiency occurs at the maximum torque of the engine. However, operation at maximum torque is not the same as operation at maximum fuel efficiency, which occurs at 70-80% of peak torque such that fuel use results predicted by the current model may be an overestimate. The disadvantage of operation at this lower point in the torque curve is lower power output from the ICE and therefore less power output from the generator to charge the batteries and/or supply power to the electric motor. However under certain circumstances such as inner city driving or open road cruising (constant speed) where load requirements of the electric motor and therefore the battery system are lowest, it may be more beneficial to operate the ICE at its most fuel efficient point as opposed to its most mechanically/thermodynamically efficient operating point. The benefits of this would be a reduction in fuel use and a reduction in emissions compared to the hybrid options employing the simplistic control strategy, particularly for the Otto cycle series hybrid options, since emissions are essentially a function of fuel use. It was evident that emissions from Diesel cycle engines are more complicated due to the non-linear relationship between emissions and equivalence ratio. Thus the significant reductions that have been shown to be potentially possible by series hybrid drive systems employed in domestic transport vehicles could be improved if a less simplified approach to the power control strategy was applied.

In conclusion, series hybrid drive system technology when applied in domestic vehicles, making use of the inherent advantages of the series hybrid approach and incorporating; efficient engine operation, the use of an efficient engine cycle, component size reduction and effective control strategy, has the potential to significantly reduce fuel use and emissions when compared to conventional domestic vehicle transport technologies. The ability to incorporate grid power into the drive process has the potential to further reduce fuel use and emissions particularly in an urban environment.

8.1 Future work

No matter how accurate computer modelling is there will always be unknowns, for example, the effect of the driver on fuel use and emissions was not modelled in this study. It is necessary therefore to produce a physical model based on the computer modelling results.

The results contained in this study indicate the potential of series hybrid drive systems to reduce fuel use and emissions. The next logical step in the process is to implement these findings into a real world scenario.

Any physical model would need to be applied in two parts:

1. Optimisation:

This mathematical approach optimises certain variables by applying constraints or boundary conditions on other associated variables in the model. Any variable in the hybrid model can be optimised in this way.

2. Implementation of an optimised model:

The optimised model is implemented in a real world scenario. The easiest and most cost effective approach is in the form of a vehicle conversion; a conventional vehicle would have its drive system removed and replaced with a series hybrid drive system primarily designed from knowledge of an optimised model.

Any future work should also consider the potential increases in system efficiency that are afforded by making use of technology (ICE or other) that can incorporate waste heat in the drive process. A significant disadvantage of the conventional domestic internal combustion engine, which limits its ability to operate with very high efficiencies, is the inability to operate the conventional drive system as a combined heat and power system (CHP). Although waste heat from the engine can be used to heat the interior of the vehicle, a significant proportion of the heat generated in the combustion process is still wasted to the environment. Therefore a significant reduction in fuel use and emissions is possible if this waste heat could be harnessed to help power the vehicle in a similar way to the use of regenerative braking in electric/hybrid vehicles.

The results predicted by the model indicate that the series hybrid drive system for use in domestic transport is definitely worthy of further research however it is the opinion of the author that the only way to fundamentally reduce fuel use and emissions is to consider one of two options.

1. Along with the implementation of alternative technologies such as series hybrid drive systems into domestic transport, reduction of the number of domestic vehicles through the use of mass transport scenarios that incorporate more environmentally friendly alternative drive sources such as those discussed in this study.

Or

2. Replace the reciprocating internal combustion engine as the primary drive source for vehicle transportation. Although hybridisation can reduce fuel use and emissions, further reductions can only be achieved by replacing this technology with an inherently more efficient option.

8.2 Epilogue

An overriding concern for society is that even if we can reduce the average fuel consumption of vehicles significantly, for example, to half the current levels with similar reductions in emissions, this may only have a minimal effect on future global emissions and fuel use. The number of vehicles globally continues to increase and the type of vehicles being purchased is also a concern (heavier, larger, more powerful) which implies more fuel use and more emissions. The long-term answer is to change the way we think about transportation and in particular domestic transportation. This change must be forced on us. Market forces (in the short term) cannot be allowed to dictate the future of transportation.

APPENDIX A

Figure A-1. Chemwork6 output screen: Otto cycle combustion (expansion) phase of iso-octane for an equivalence ratio of 1 (fixed).

Thermodynamic Properties	Initial	Final
p(pascals)	4189008.0109	4188978.2124
T(k)	1226.1119	2643.1689
V(m3/kg)	0.081343	0.18544
H(J/kg)	461877.2918	461861.9218
U(J/kg)	121129.8782	-314953.2592
S(J/kgK)	6929.8415	8765.8151
W(gm/mol)	29.9163	28.29
Finite Mole Fraction NO	0	0
W(comp or exp.(J/kg)		436071.2165
Heat Transfer(J/kg)		0

Close Table

Specie	Initial Mole Fraction	Final Mole Fraction	Initial Mass Fraction	Final Mass Fraction
CH4	0	1.0586e-014	0	6.0033e-015
CH3OH	0	3.4891e-015	0	3.9519e-015
C2H2	0	4.7709e-018	0	4.3912e-018
C2H6	0	2.1127e-027	0	2.2457e-027
C2H6O	0	0	0	0
C3H6	0	0	0	0
C4H10	0	0	0	0
C5H12	0	0	0	0
C6H14	0	0	0	0
C7H16	0	0	0	0
C8H18	0.013073	0	0.049918	0
C10H22	0	0	0	0
C12H26	0	0	0	0
C16H34	0	0	0	0
H2	2.3214e-010	0.0030808	1.5643e-011	0.00021954

Specie	Initial Mole Fraction	Final Mole Fraction	Initial Mass Fraction	Final Mass Fraction
N2	0.76783	0.72373	0.71899	0.71666
NO	0.00022802	0.0049416	0.0002287	0.0052414
H2O	0.029413	0.1337	0.017713	0.085138
CO2	0.026146	0.10755	0.038463	0.16732
CO	3.0216e-010	0.016071	2.8291e-010	0.015913
O2	0.16329	0.005987	0.17466	0.0067719
C6H6	0	0	0	0
O3	9.3866e-011	1.3079e-009	1.506e-010	2.219e-009
CH3	0	3.1543e-014	0	1.6764e-014
H	7.1782e-013	0.00039165	2.4186e-014	1.3954e-005
N	1.514e-018	1.3466e-007	7.0885e-019	6.6669e-008
NO2	1.9586e-005	3.748e-006	3.0119e-005	6.095e-006
N2O	9.0169e-008	1.5307e-006	1.3266e-007	2.3814e-006
HO2	2.5723e-008	4.6013e-006	2.838e-008	5.3685e-006
H2O2	2.3022e-009	6.5709e-007	2.6175e-009	7.9006e-007
HCO	5.483e-023	3.0198e-008	5.3184e-023	3.0976e-008
CH2O	3.2435e-024	1.1864e-009	3.2555e-024	1.2592e-009
O	2.5642e-009	0.00033683	1.3714e-009	0.0001905
OH	8.5867e-007	0.0042011	4.8815e-007	0.0025256
NH3	2.4186e-017	5.7161e-008	1.3768e-017	3.4411e-008
S	0	0	0	0
SO2	0	0	0	0
SO3	0	0	0	0
HMX	0	0	0	0
RDX	0	0	0	0
HCN	3.2766e-027	1.3549e-009	2.96e-027	1.2944e-009
HCNO	5.1848e-032	2.2488e-014	7.4568e-032	3.4201e-014

Figure A-2. Chemwork6 output screen: Diesel cycle combustion (expansion) phase of cetane for an equivalence ratio of 0.5 (variable).

Thermodynamic Properties	Initial	Final
p(pascals)	7895098.2759	7895142.7926
T(k)	1161.3556	2032.008
V(m3/kg)	0.041449	0.074383
H(J/kg)	652917.3798	652968.7286
U(J/kg)	325676.5271	65707.9412
S(J/kgK)	6871.6146	7986.9555
W(gm/mol)	29.5058	28.7687
Finite Mole Fraction NO	0	0
W(comp or exp.(J/kg)		260007.3114
Heat Transfer(J/kg)		0

Close Table

Specie	Initial Mole Fraction	Final Mole Fraction	Initial Mass Fraction	Final Mass Fraction
CH4	0	1.0256e-022	0	5.7193e-023
CH3OH	0	1.067e-021	0	1.1885e-021
C2H2	0	1.8748e-029	0	1.6969e-029
C2H6	0	0	0	0
C2H6O	0	0	0	0
C3H6	0	0	0	0
C4H10	0	0	0	0
C5H12	0	0	0	0
C6H14	0	0	0	0
C7H16	0	0	0	0
C8H18	0	0	0	0
C10H22	0	0	0	0
C12H26	0	0	0	0
C16H34	0.0033939	0	0.026047	0
H2	2.0443e-011	9.2114e-006	1.3968e-012	6.4548e-007

Specie	Initial Mole Fraction	Final Mole Fraction	Initial Mass Fraction	Final Mass Fraction
N2	0.78144	0.759	0.74191	0.73907
NO	0.00015007	0.005948	0.00015261	0.0062039
H2O	0.014424	0.070023	0.0088068	0.043849
CO2	0.013576	0.066142	0.020249	0.10118
CO	2.3535e-011	4.0541e-005	2.2342e-011	3.9472e-005
O2	0.18699	0.098177	0.20279	0.1092
C6H6	0	0	0	0
O3	6.9781e-011	1.6127e-008	1.1352e-010	2.6906e-008
CH3	0	1.8886e-022	0	9.8703e-023
H	4.7109e-014	6.8952e-007	1.6093e-015	2.4159e-008
N	8.4198e-020	1.3949e-010	3.997e-020	6.7912e-011
NO2	2.5292e-005	5.4828e-005	3.9436e-005	8.7679e-005
N2O	8.2561e-008	2.6007e-006	1.2315e-007	3.9788e-006
HO2	1.124e-008	5.1825e-006	1.2573e-008	5.946e-006
H2O2	8.9145e-010	4.04e-007	1.0277e-009	4.7767e-007
HCO	7.3827e-025	7.0593e-013	7.2608e-025	7.1206e-013
CH2O	4.2433e-026	1.8858e-014	4.3182e-026	1.9682e-014
O	5.1491e-010	2.9958e-005	2.7921e-010	1.6661e-005
OH	2.2166e-007	0.00056638	1.2776e-007	0.00033483
NH3	1.5373e-018	3.7566e-011	8.873e-019	2.2239e-011
S	0	0	0	0
SO2	0	0	0	0
SO3	0	0	0	0
HMX	0	0	0	0
RDX	0	0	0	0
HCN	2.5022e-029	2.1142e-015	2.2919e-029	1.9861e-015
HCNO	0	1.1964e-019	0	1.7892e-019

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