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Internal Combustion Engines: A role to fill for transport in an energy conscious environment

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Abstract— **This paper compares the advantages and disadvantages of internal combustion engines (ICE) as the power-plant for vehicles with respect to energy consumption, energy transfer efficiency and energy source. Comparisons to electric and other alternatives drive systems are discussed. Significant technological gains in electric control and motor efficiency in recent times has brought the electric vehicle in its many forms to a position where it can compete on nearly all vehicle performance levels with a conventional ICE-powered vehicle. The electric vehicle's niche has shifted from a novelty or performance constrained vehicle to one which can fill the role of a general-purpose vehicle for most applications. Unfortunately, the most significant barrier to widespread use of electric vehicles is yet to be overcome. In spite of extensive research into electrical energy storage devices, none of sufficient capacity and appropriate physical properties is yet available at viable cost to allow fully electric vehicles to attain the endurance to make them attractive as the sole vehicle for most consumers' needs. Internal combustion engines possess significant and enduring benefits for vehicles. In spite of physically limited available efficiency improvements, internal combustion engines still represent a very viable option for vehicle power plants into the future. In a full analysis, ICE vehicles can compete with electric vehicles, especially if the IC fuel can be generated in a way where the energy transfer compares, in a life cycle analysis, with the energy transfer of electrical storage devices required for electric vehicles.**

Keywords- internal combustion engine; energy; life cycle analysis; alternative vehicle powerplants

I. INTRODUCTION

The net efficiency delivered by internal combustion engines in vehicles varies significantly with application. A typical large sized sedan in Australia operating with a spark ignition (SI) engine produces net efficiencies in the order of 22% for highway cycle and less than 12% for city cycle operation [1]. These efficiencies are with respect to propulsion energy compared to the heat energy available in petrol. The thermodynamic limit of efficiency for a spark ignition internal combustion (IC) engine is based on the Otto cycle. This is the idealized cycle for spark ignition engines and its efficiency is dependent on the compression ratio (CR). For realistic compression ratios, the ideal efficiency is above 60%. That efficiency can never be achieved in reality due to losses associated with engine friction and heat transfer efficiency, but values approaching 50% are realistic. Therefore some scope exists to improve the performance of internal combustion engines with respect to efficiency, but limits exist at efficiencies approximately twice the values typically achieved today.

Advances in electronic control, electrical storage batteries and electric motor performance have allowed electrically powered vehicles to compare favorably with internal combustion engine (ICE) powered vehicles with respect to drivability and performance [2]. Seminars on electric vehicles in 1972 [3] discussed the same intrinsic obstacles to increased market share for electric vehicles that still face us today; most notably, the effectiveness of the electrical energy storage device. In spite of over three decades of significant development in battery technology and in particular in electronic control technology, electric vehicles are not the common choice of consumers today because problems associated with electric storage have not been resolved. One significant driver for replacement of ICE powered vehicles in the 1970s was air pollution in cities. That problem has been alleviated to some degree as a result of improved ICE emission control. In the period since 1970, other problems have caused fluctuation in the demand for viable electric vehicles. Sustainable ICE fuel sources and, in recent times, global warming associated with Green House Gas (GHG) emissions have re-ignited the debate about electric vehicles. The significant aspect primarily addressed by this paper is the comparison of the energy conversion efficiency of ICE powered vehicles to that of electric vehicles. Comments on other alternative power plants are also made. That leads to questions about the primary energy source, energy storage and energy transfer rates. The question of consumer attitude and market demand for vehicles is also considered.

For clarification, the term 'natural environment' will be used throughout when referring to the situations affecting the ecosystem. The term 'environment' will be specific to the context of its use.

II. WHAT PERSONAL TRANSPORT IS BEST?

A. Introduction

Any consideration of sustainability by a society will require an assessment of transport [3-12]. Increasing use of personal motor cars has not diminished in the face of increasing awareness of GHG emission concerns and of current and future oil price and availability issues. The personal motor car, once acquired, is by far the cheapest transport option when ongoing operating costs are compared to alternatives such as public transport [6]. Therefore if a vehicle is owned for whatever reason, its use for personal transport becomes extremely appealing. With rapidly increasing living standards in China and India generating the associated increase in ownership of personal motor cars, the impact on the natural environment of motor vehicles is an issue with escalating significance [13].

When convenience and comfort are taken into account, alternatives to the personal motor vehicle are difficult to sustain unless external effects are operating. Those effects could be policy driven by government authorities for the purpose of influencing an externality such as demand for oil based fuels. In other scenarios, effects such as traffic congestion could have a direct impact on the vehicle owner's choice.

The 'best' transport option for individuals is therefore a very challenging concept to investigate. In spite of the magnitude of any forces compelling people to choose one form of transport over another, the environmental impact (natural and otherwise) of the choices will be lessened by the efficiency of energy transfer achieved by the technology employed.

B. Effect of vehicle performance requirements

The realistic limits for vehicle configuration for personal transport are extremely broad. In general, it is common for one end of the spectrum to be large 4WD vehicles and the other end human-powered vehicles, typically bicycles. Acquiring a large vehicle for a particular purpose currently overrides negative aspects associated with that choice. For example, an owner is quite prepared to pay a premium for use of a large 4WD vehicle through increased fuel and general maintenance costs, even if the vehicle is required for only occasional towing.

The ongoing operating cost of a vehicle is therefore not the primary criterion used to inform a consumer's decision on what type of vehicle to use; primarily because those costs are currently low. This makes defining the suitability of acquiring a vehicle difficult. A Life Cycle Assessment (LCA) can identify a natural environmental cost for a vehicle, but unless some value is concurrently assigned to personal considerations such as convenience, trip times, and safety, for example, an LCA cannot inform decisions about the appropriateness of vehicle type for personal transport. Also, if the externalities identified by an LCA are attributed a cost via a mechanism such as carbon pricing, an LCA could help quantify vehicle operating costs in the future.

In gauging the total effect on the natural environment of ownership of a particular vehicle, an LCA allows comparison on those grounds between similar vehicles. For vehicles of the same capability, an LCA becomes a good decision-making tool for consumers concerned about the natural environment. This has to be considered in isolation from the appropriateness of the vehicle, but can and should influence the decision about vehicle ownership [4]. Importantly, for the direct comparison of vehicle configuration types which can achieve the vehicle performance requirements, an LCA will identify the total environmental impact of the vehicle when all externalities are considered.

III. EFFECT OF PROPULSION TYPE ON VEHICLE CONSUMER APPEAL

A. Electric vehicle intrinsic drawbacks

A fully electric vehicle or battery-powered electric vehicle (BEV) is frequently referred to as a 'plug-in', meaning that all energy used by the vehicle is acquired through an electric recharge. Several major vehicle manufacturers have recently marketed versions of the plug-in. Mitsubishi are set to release a fully electric vehicle, the MiEV, in the near future in Australia [14]. Pricing of this vehicle and its competitors is difficult to specify with estimates ranging from AU$35,000 to twice the retail price of the Toyota Prius (totaling AU$75,000) [15]. The motor vehicle companies acknowledge that price will be the primary barrier to consumer acceptance. Government subsidies could well conceal the real cost of the vehicle.

The MiEV is a small commuter vehicle with a maximum range under optimum operating conditions of 160 km. It compares in performance and usability to any number of small IC powered vehicles that retail for less than AU$15,000. The most significant aspect of the use of such a plug-in is that it requires up to eight hours of recharge from a 240 V, 15 A domestic electrical outlet. This, of course, is for a recharge from completely discharged to fully charged. Frequently, for provincial city or suburban city use, the distance travelled for a single day (between nightly recharges) may be 40 km or less, meaning that a typical recharge might be for only two or three hours. The MiEV has the capacity for a fast recharge but it requires a 3 phase 50 kW power source, which no typical domestic dwelling would have access to, but in a commercial operation such recharge capacity could be useful. Although the purchase cost of the MiEV would be a barrier in itself, the most significant obstacle to general acceptance would be the inability of the vehicle to make trips in excess of 100 km without access to at least a 240 V recharge source and 8 hours of recharge time. Such electric vehicles would have a quite specific market appeal and in general could not fill the role currently filled by the vast majority of ICE powered vehicles.

Over the 200,000 km expected life of a small ICE powered vehicle which achieves a life-long fuel consumption average of 6 L/100 km, 12,000 L of fuel will be consumed. Assuming an average petrol price of AU$1.30/L, the purchase price alone of the MiEV will exceed both the purchase price of an equivalent ICE powered vehicle and all cost of the fuel it would use in its life ($15000 + \frac{200000}{100} \times 6 \times 1.3 = \$30600$).

B. Alternative electrical storage systems

When a vehicle's operating requirements are not able to be met by BEVs because of the problem of recharge time, this can be overcome by using replaceable batteries that are charged separately from the vehicle. Battery cost would consequently be a major consideration and potentially an optimized range-weight-cost combination for particular battery technology could prove to be effective. Major motor vehicle manufacturers are exploring such options. Renault, for example, is involved in developing the Quickdrop system [16].

Chieng [17] and others have contributed to the improvement of Vanadium redox batteries. The concept shows promise in that only the electrolyte, a liquid, needs to be replaced to recharge the battery. Poor energy density has been a major drawback to date.

C. *Electric hybrids- a more usable concept*

To overcome the intrinsic problem associated with battery recharge and to optimize fuel efficiency of the ICE power plant, Hybrid Electric Vehicles (HEVs) have been developed. Several manufacturers have successfully marketed various versions of HEVs with varying emphasis on the role of the electric portion of the drive. To decrease the proportion of on-board fuel used, plug-in hybrid electric vehicles (PHEVs) are one end of the spectrum and when the battery electric system is used more as an accumulator for ICE efficiency the design concept is called charge-sustaining hybrid (CSHEV) [4].

From the driver's viewpoint, HEVs are essentially very similar to ICE powered vehicles in most respects. The one feature that is notably different is that the net fuel consumption, especially the city cycle, is significantly lower. Of course, that is counterbalanced by a much higher purchase price in comparison to ICE vehicles with comparable performance. Based on the Toyota Prius, at retail prices of approximately AU$40,000, and achieving an average of 5 L/100km compared to 8 L/100km for an ICE powered equivalent, the cost of reduced fuel consumption over a 200,000 km life is about AU$8,000 on current fuel pricing. This doesn't compensate for the purchase price which, on a conservative estimate, is U$20,000 higher than an ICE powered equivalent vehicle. As with BEVs, HEVs do not represent a cost benefit over the vehicle life.

D. *Alternative energy storage technologies*

A very large number of alternative energy storage systems have been attempted. These include technologically relatively simplistic systems such as compressed air, which can have low capital cost per vehicle, but result in high operating costs due to energy transfer inefficiencies. Although online media presentations by compressed air vehicle manufacturers [18] claim impressive performance, the net energy conversion of compression by an electric source then expansion in a mechanical motor are physically inefficient. Heat recovery from ambient air could assist efficiency and other technologies including hybrid use [19] could make compressed air a viable vehicle propulsion technology.

A version using liquid nitrogen as the energy storage medium has been considered [20]. In environments requiring very low emissions, such vehicles can find a niche, but typically would only compete with BEVs.

The following is an analysis of liquid nitrogen energy storage for vehicles and explains why such alternatives are not commonly used. Using ambient air to heat and boil the liquid nitrogen produces a large increase in the volume of the nitrogen. That volume change can drive a motor and be used for vehicle propulsion. On first impressions, the concept looks promising, but some basic analysis shows that even though the liquefied nitrogen stores energy at about the same energy for weight as does a lead-acid battery, and the cost of the stored energy is about 20 times more (based on current retail prices) than the energy stored in a charged battery when sourced from a domestic connected grid. A further disadvantage is the extra storage volume required for liquid nitrogen as compared to an equivalent battery. If considered as a competitor to petrol fuel energy storage, considering only 30% efficiency for petrol conversion in an IC engine and 90% in the nitrogen motor, the ratio of energy delivered to the vehicle per unit volume for liquid nitrogen compared to petrol is of the order of 1:50.

E. *On board conversion from fuel energy to electric energy*

In isolation from any technological considerations, one means to overcome the limited range of BEVs is to convert fuel (solid, liquid or gas) directly into electrical energy on board the vehicle. In light of impressive electrical to mechanical efficiency from modern electronically controlled motors (which can exceed 90%), it is an appealing goal to create electrical power directly from the fuel.

The endurance problem of BEVs can be overcome by on-board conversion of fuel energy to electric energy with an ICE powered generator. Advantage can be taken of high ICE efficiency under specific operating conditions in such a configuration.

Fuel cell technology can also achieve this and is in use in various countries. Hydrogen has proven to be a viable fuel for fuel cells. An added advantage in creating the infrastructure to produce hydrogen for fuel cell powered vehicles is that hydrogen is also a good ICE fuel. Consequently, during the transition to fuel cell vehicles, current ICE vehicles can be serviced by the hydrogen supply infrastructure [21].

F. *Conclusion*

Many reasons are driving the shift to alternative power plants for vehicles. Zero (low) emission vehicles in pollution sensitive environments, decreased or eliminated GHG emissions and a desire to reduce dependency on oil-based fuels are some of the more dominant factors. An overall assessment of the total effect of implementation of wide spread use of these alternative vehicle propulsion systems also requires a thorough analysis of the total energy efficiency. Thomas [22] compared many aspects of the implementation of current and projected technology over the next century. LCAs can be used to compare vehicle propulsion systems on an efficiency basis, but cannot inform a vehicle purchaser beyond the natural environmental impact. Future ongoing operating costs of vehicles can be estimated from the results of LCAs if the costs of externalities are included via carbon pricing. The total energy conversion efficiency of the propulsion system is therefore important through the ongoing energy consumption of the vehicle and through the energy associated with the manufacture.

IV. Direct Energy Conversion Efficiency at the Vehicle

A. *Introduction*

The standard measure for fuel consumption for ICE vehicles is litres per 100 km. This is a clear comparator for vehicles using the same fuel, but is misleading for comparison of vehicles operating on different fuels. The most notable current discrepancy relates to the comparison of petrol and diesel fueled vehicles. The available energy per volume of diesel is higher than that for petrol. A measure of that energy, the heating value (HV) is generally defined on a per mass basis and is about 45 MJ/kg for diesel and 47 MJ/kg for petrol. The density of petrol is about 0.87 that of diesel, resulting in the energy of diesel being about 10% higher on a volume basis. A true comparison of efficiency between fuel types is more complex because the energy associated with the production of the fuel is not apparent to the end user.

The cost of fuel is also not a good comparator with respect to the energy content. For example, in Australia at the moment, ethanol for motor vehicle use does not attract the same taxes as petrol and therefore the cost to the consumer is not a good indicator of the energy associated with its production. Australian governments have a long history of using taxes and tariffs on fuels to modify demand and alter government revenue [23]. It has influenced fuel consumption patterns.

B. Spark Ignition (SI) ICE

The fuel efficiency of a SI, homogeneous charge engine is load dependent. For reduced load, the engine is required to do work via throttling to induct a lower pressure charge. The notable proportion of friction is load independent while thermodynamic efficiency also varies with engine speed and load. A typical performance as shown in **Error! Reference source not found.** reflects a very narrow operating range for optimum efficiency. That optimum efficiency peaks at 35%, but over a usable range of engine speeds this figure is only marginally higher than 30%.

The power required for level cruise of a typical family sedan ranges from 8 kW at 60 km/hr to 17 kW at 100 km/hr [1]. In **Error! Reference source not found.**, at the required output torque (equating to brake mean effective pressure (BMEP) in the plot), the efficiency varies significantly from less than 10% for 60 km/hr motoring to approximately 20% at highway cruise speed.

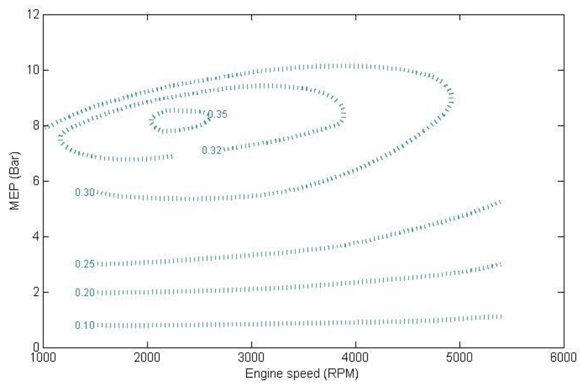

Figure 1: Typical SI engine efficiency map (Adapted from Stone [24]

C. Compression Ignition ICE

The Diesel cycle represents an idealized compression ignition (CI) engine and in comparison to the Otto cycle for the same CR is slightly less efficient. Because a diesel engine is able to operate at a higher CR and in general can operate without throttling, typically the fuel consumption of CI ICE powered motor cars is lower than that of an equivalent SI ICE powered vehicle.

To some extent this is the result of the energy density of the fuel as described in section IV.A. Recent efforts to optimize efficiency via high pre-induction compression such as super-charging and turbo-charging and very high fuel injection pressures have produced reductions in fuel consumption.

Quoted comparisons for fuel consumption between a diesel and SI version of the same vehicle indicate that diesel options achieve about a 25% better fuel consumption on a per liter basis reflecting an energy efficiency benefit of approximately 16% [25].

Small passenger cars operating high pressure diesel engines can achieve highway fuel consumptions as low as 4 L/100km [26].

D. Electric hybrid

The prime design intent of electric hybrids is improved fuel efficiency. Published data for the Toyota Prius [27] indicates that the city cycle fuel consumption is very similar to the highway cycle at about 5 L/100km. Various configurations of drive train can be selected for optimum efficiency for a particular application and optimized for highway cruising with optimum aerodynamics and rolling resistance. Moderate sized HEV passenger cars can achieve fuel consumption as low as 3 L/100km on petrol. In the case of the Prius and any HEV of the type, highway cruise efficiencies are achieved by operating the ICE engine very near to its optimum efficiency point. In doing so, the engine is configured in such a way that it reduces the maximum power available from the engine for the displacement used. When used in a conventional ICE powered vehicle the configuration would generally be selected considering optimizing power from a specific displacement. The large improvement on the city cycle efficiency of a HEV over a conventional ICE power vehicle is a combination of ICE efficiency in the HEV and regenerative and optimum energy conversion. See Section IV.B for an explanation of ICE efficiency.

E. Battery electric vehicles

The energy transfer between the stored electric energy and propulsion energy in BEVs is very efficient. While operating, the efficiency of modern motors is typically above 90% and as high as 93% at optimum efficiency. The electronic control is also very efficient with quoted data [28] suggesting 97% is not unrealistic. The rolling resistance of the vehicle is somewhat compromised by the vehicle weight which is inherently high because of the batteries. Typically that extra mass equates to the equivalent of six to eight passengers for a vehicle designed to carry four passengers. That can result in deficits in the order of 15% for the rolling drag.

For a small four seat commuter car, the energy input from the electric charging source gives approximate endurance of 100 km per 12 kW hrs. At current domestic electricity costs of 18.3 c/kWhr, this equates to approximately $2.20 per 100 km. Typically, a similar ICE power vehicle would operate on the city cycle at 6 L/100km. At the current petrol retail price, (as used in the analysis of Section III.A) that equates to $7.80 per 100 km. On these figures, the electric vehicle seems a very attractive option.

One very significant advantage of BEVs is that while no drive force is required by the vehicle, that is, while either stationary or coasting, no energy is being consumed. In addition, regenerative braking (recovering the kinetic energy of motion as stored electric energy during braking) is also quite effective and efficient in BEVs.

The result is a low recharge energy requirement for comparative motoring compared to the energy available in fuel that is used in equivalent-sized ICE powered vehicles. Included in the above energy consumption values is the effect of the efficiency of battery charging. The recharge discharge efficiency of modern batteries of any type is still no better than 80% [29] and is dependent on discharge current (power). Since this is the only source of energy for a BEV, it should always be considered in energy analyses for the vehicle. In spite of this, a BEV is still significantly more efficient than an ICE powered vehicle when comparing the electric energy input to the fuel energy equivalent. Based on the 15% net efficiency for the ICE powered vehicle and 35 MJ/L for heating value, the ratio of efficiencies of energy conversion for an ICE powered vehicle (fuel energy to motive energy) to a BEV (recharge energy to motive energy) is approximately 1:6.

Unfortunately there are two very large inefficiencies that the BEV is subject to which are not regularly disclosed by promoters of the technology. For the first, in general, and especially in Australia, the energy supplied to a BEV from the grid has come from a heat engine powered source. The major source in Australia is coal or gas fired power stations. The efficiency of the energy conversion at the power generation stage is about 40% to 50% [30] and transmission efficiency is typically less than 90% [31]. When this is taken into account, the net efficiency of an electric vehicle from fuel source to propulsive energy is approximately double conventional ICE power vehicles. This margin would possibly be reduced to parity with ICE powered vehicle efficiency if the optimum efficiency can be achieved in the ICE of a vehicle (see Section I).

The second inefficiency of BEVs that is not directly apparent is the energy associated with the manufacture of the batteries. It is manifested to some degree in the cost of the batteries/vehicle, but an LCA would identify and could quantify that energy cost via carbon pricing.

F. *ICE efficiency for on board energy conversion*

The most telling detail of the analysis of HEVs is the achieved fuel consumption of a vehicle that is sourcing all its energy from on-board fuel via an ICE. No substantial efficiency gain is achieved by the hybrid characteristics of an HEV at highway cruise speed because the energy transfer is essentially constant. Therefore, the ICE achieving that fuel consumption is capable of achieving that fuel consumption without the hybrid features; that is, in a conventionally configured ICE powered vehicle operating with the engine specifications employed in the HEV.

The use of an ICE in the constrained configuration allowing the fuel consumption achieved by HEVs restricts the maximum power that the ICE can produce from the engine size. That lack of maximum power is offset by simultaneous drive from the ICE and the electric portion of the hybrid drive. Because that maximum power output is not required for extended periods in general, the hybrid configuration achieves comparable driving performance to a conventional ICE powered vehicle which operates with the engine configured for maximum power. Significantly, hybrid drives make better use of the most efficient operating range of the ICE, achieving efficiencies close to optimum ICE efficiency over a much larger operating range than conventional ICE power plants.

The power-to-weight ratio of an engine is a major design consideration. Reduced weight directly improves acceleration and reduces fuel consumption. Complex structural considerations for safety and performance are influenced by engine mass. The prime engine configuration modification employed in the Prius engine is an increased compression ratio and reduced compression stroke volume via valve timing [27]. This arrangement uses a conventional ICE. That engine with a reduced CR and full induction stroke configuration would produce a higher maximum power with essentially the same engine mass. The reported GHG LCA advantage of an HEV could therefore be achieved with a conventional ICE powered vehicle at highway cruise speeds by using the engine configuration employed by HEVs. Regenerative braking and other efficiency gains for city cycle operation, such as no energy use for idle and coasting, give the HEV its notable fuel consumption advantage in city cycle use.

G. *Conclusion*

A comparison of propulsion systems via an LCA is necessary to identify what net energy transfer efficiencies exist in alternatives to ICE powered vehicles. This requires an analysis of manufacturer energy transfers and should consider the primary energy sources. Obtaining optimum efficiency for the ICE of conventional vehicles brings their efficiency to similar values to BEVs without considering the energy transfer required for manufacture, which would inevitably favour the ICE powered vehicle.

V. Life Cycle Assessment of Conventional ICE Powered Vehicles, HEVs and BEVs

LCA is a very complex concept. It is very dependent on the data used and the extent to which interconnected and consequential processes are leveraged by the algorithms employed. In general, GHG emissions are a reasonable basis to compare the total energy performance of vehicles and are the measure used by LCA. If carbon pricing becomes internationally standardized, GHG emissions will be factored into cost. Estimates of future costs of currently produced vehicles can be projected from LCA generated GHG emissions and converted to cost via an estimated carbon price.

LCA of HEVs and BEVs and comparisons of each with conventional ICE powered vehicles have been carried out, including Samaras and Meisterling [32] who report that the advantage of plug-in HEVs over conventional ICE powered vehicles is 32% with respect to GHG emissions. They report that a similar advantage exists for HEVs over conventional ICE powered vehicles. Other studies [11, 33] indicated similar orders of magnitude of advantage in regard to LCA of the GHG emissions of various forms of hybrid and battery electric vehicles compared to conventional vehicles.

VI. VARIABLE COMPRESSION FOR FUEL CONSUMPTION IMPROVEMENT

An otherwise conventional ICE powered vehicle with variable CR could achieve cruise fuel consumption efficiency achieved by HEVs as discussed in Section IV.F.

Studies on the viability of variable compression [1, 34, 35] through simulation and experimentation suggest that the benefits are worthy of continued research. Further work [1] shows that the majority of the benefit from variable compression ratio (VCR) can be achieved via a step between two CRs. This can potentially significantly reduce the complexity of the VCR mechanism. Various variable compression ratio technologies have been explored in the past but none are yet employed by motor vehicle manufacturers.

Figure 2 shows the output from modeling for the efficiency, including engine friction, for operation of an ICE with a step in CR.

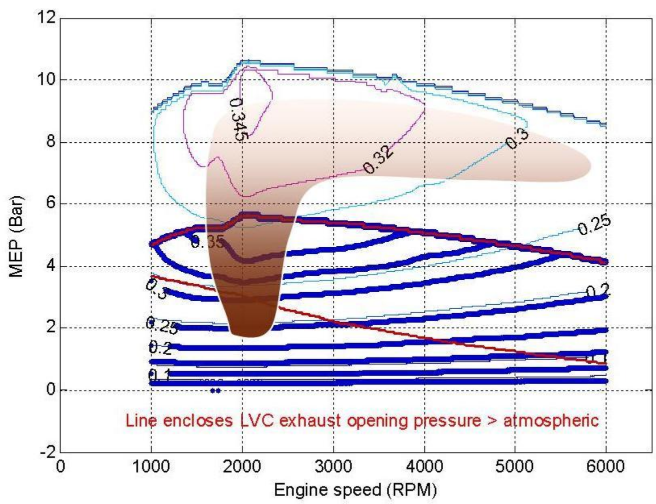

Figure 2: Modeled operating efficiencies for a two position VCR engine. The lower set of contours (thick blue lines) peak at above 35% at a little over 2,000 rpm and produce about 5 Bar MEP. This equates to about 17 kW engine output power for a 2 litre engine.

The lower portion of the plot (thick blue lines) shows that efficiencies that would normally only be achieved at higher engine output power (a function of MEP) at conventional CRs can be achieved at lower power with a change to a higher CR. This requires a reduced induction stroke volume. This would improve the efficiency of the engine in the operating range most used.

Various mechanisms can potentially achieve the desired stepped CR change and would result in an ICE configuration that could achieve fuel consumption equivalent to HEVs for continuous power output at highway cruise speeds.

Improved efficiency at lower power outputs would also result, but without a comparable regenerative braking energy storage system, the overall fuel consumption performance would not compete with HEVs.

Significantly, the complexity associated with the hybrid control, energy storage and electric drive would be removed from the vehicle manufacture, resulting in reduced cost. In an environment where GHG emissions are costed through carbon pricing, a simpler vehicle would result in a notably lower capital expense for consumers. The total effect could be that HEV GHG emissions might be only marginally better than if not similar to those of a VCR ICE powered vehicle.

VII. VEHICLE ENERGY SOURCES

A. Introduction

One of the driving forces for reduced fuel consumption is the benefit of reduced dependency on oil-based fuels. Electric vehicles of any form can make direct use of alternative/renewable energy sources that are generated electrically. These sources could be systemic sources such as wind, solar, hydro, geothermal or any other (perhaps yet to be invented) grid-delivered energy source. Current grid capacity in Australia would require increases to substantially substitute current oil-based energy for vehicles with electrically sourced energy [36].

B. Electrical energy sources

Potential exists to use domestic sized renewable sources. As an example, suppose a domestic household electrical energy consumption is approximately 12 kWhr/day and fuel consumption for vehicle use is approximately 6 L/day. Based on the electrically sourced equivalent as described in Section IV.E, to substitute all the fuel used via a BEV would require an additional 12 kWhr/day of electrical energy. To substitute that 12 kWhrs to the grid, a domestic photovoltaic system using current technology would require approximately 16 m^2 of collector area (based on Southern Queensland solar radiation levels) and cost approximately $25,000.

LCA on photovoltaic systems [37] suggests that the energy produced by current commercially available systems for the first eight years of their life replaces the LCA energy of the system. Allocating an effective operating life of 24 years for the system requires that, effectively, only two-thirds of the energy produced by the system is available to reduce the fuel consumption of the vehicle.

Other renewable sources, including grid-based systems, have varying energy payback time frames for their implementation, but all have the effect of reducing the effectiveness of net energy conversion efficiency of electrically-based vehicle propulsion systems.

Of course, without renewable or alternative electrical energy sources, EVs will be essentially replacing oil based fossil fuel use with coal and natural gas based fossil fuel use in an electric power generation plant.

C. ICE power vehicles can make direct use of renewable/alternative fuels

The vast array of potential fuel sources for ICEs suggests that the use of ICE powered vehicles will always be viable [4]. Bio-fuels generated from cropping, algae, by-products from organic processing and current waste products are potential fuel sources. Direct conversion of electrical energy into hydrogen is also an option for ICEs.

To determine the net efficiency of the use of such fuels would require LCAs. Consideration of the systems/products' previous use would also be required. For example, cropping for the purpose of fuel production would directly affect the use of the land for food production. Renewables that sourced bio-materials as by-products of a production process would need to consider the alternative use of that material. Consideration of the use of plant stubble, for example, as a bio-fuel would need to consider the effect of reduced organic material in the soil that would result.

Analysis of such complex interaction of processes and energy transfer is a substantial undertaking and would require the incentive of substantial benefit from the widespread use of the fuel that resulted. The continued use of the 400 million ICE powered vehicles [4] currently in service throughout the world is one such incentive. The transition to vehicles with better fuel efficiency is essential and a transition that maintains the use of ICE power plants could prove to be a net energy consumption benefit.

VIII. Conclusions

Currently and for the immediate future, the cost of alternatives to ICE powered vehicles is a barrier to an increase in their market share. Economies of scale will potentially reduce the cost, but the prospect of significant reduction in GHG emissions is not likely from widespread replacement of ICE powered vehicles with electric or other alternatives.

The primary energy source and the best technology for its transfer to propulsion in vehicles is a major consideration. This is likely to govern future trends for vehicle drive configurations.

LCA of electric alternatives indicate marginal net benefits from their use relative to current ICE power vehicles. ICE powered vehicles with potentially improved fuel efficiency will reduce and possibly eliminate any net fuel efficiency benefit from electric alternatives, especially when the primary energy source for the electric vehicle is produced from fossil fuel based heat engines.

VCR is a major technology yet to be exploited by engine manufacturers and has particular application in SI ICEs. The large range of fuels that SI engines can use relative to CI engines is an added benefit to the potential efficiency gains associated with VCR. Those fuels can be bio-mass or other alternatives in origin.

The internal combustion engine has a very significant role to play in the short and medium term as a power plant for personal transport vehicles. Development of ICEs to improve efficiency and increased power to weight is justified and supported by the comparison, using LCA, of the efficiencies of alternatives.

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