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REVIEW

Factors affecting the efficiency of hybrid engines

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ABSTRACT

The paper examines the underlying science determining the performance of hybrid engines. It scrutinizes a full range of orthodox gasoline engine performance data, drawn from two sources, and how it would be modified by hybrid gasoline vehicle engine operation. The most significant change would be the elimination of the negative consequences of urban congestion, stop-start, and engine driving, in favour of a hybrid electric motor drive. At intermediate speeds there can be other instances where electric motors might give a more efficient drive than an engine. Hybrid operation is scrutinised and the electrical losses estimated. There also remains scope for improvements in engine combustion.

Keywords: Hybrid Intensity Combustion; Urban Pollutants; Brake Thermal Efficiency

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1. Introduction

The engine in a fuel-propelled vehicle can also generate electricity. This can be battery-stored, and used to power an electric motor to drive the vehicle more economically than could an engine. This condition arises under those of poor engine efficiency, such as during urban congestion. The generated electrical energy can be further supplemented by electricity generated at the wheels, from the regenerative braking of the vehicle. Such a hybrid vehicle can be driven by either the engine or a battery-powered electric motor, whichever is the more efficient and less polluting. The hybrid vehicle drive system is complex, involving six different possible energy exchanges: engine/wheels, engine/generator, generator/battery, battery/motor, motor/wheels, and wheels/battery. These can occur on a time scale of seconds. Power losses arise from the inefficiencies of engine, electric generators, electric motors, and the charging and discharging of batteries. Optimising the system to give maximum overall energy efficiency is complex and necessarily continual. This leads to a classic Hybrid Vehicle Routing Problem (Hybrid VRP) that aims to minimize the fuel, emissions and driving costs by determing an appropriate driving Mode between electric and fuel propulsion model[1]. Though a number of optimization algorithms[1] and uncertainty analysis[2] have been proposed for Hybrid VRP, the tank-to-wheel efficiency of hybrid engine has not been thoroughly investigated for the consideration of practical routing.

The present paper aims to investigate the factors (driving Modes, engine and electric powertrain efficiencis) affecting the tank-to-wheel efficiency of hybrid engine using comprehensive engine test data from two sources. One comprises urban road driving tests, the other carefully controlled laboratory tests. The two sources yield detailed changes in Brake Thermal Efficiency (BThE) with either Vehicle Velocity or

Brake Mean Effective Pressure (BMEP) over wide ranges of conditions. The two data sets are first presented separately, then in a combined form, to cover the full range of engine power, in the context of optimising the overall Hybrid engine operation[3,4].

2. Brake thermal efficiencies

2.1. Congested urban driving test data

Hybrid engines are examined. Engine efficiencies and emissions depend not only upon engine loading and its rate of change, but also upon the general driving conditions. These aspects have been carefully monitored in road tests[5,6]. Karabasoglu and Michalek[5] discussed the effects of the driving Mode upon the performances of electric and hybrid vehicles. Some of the valuable, urban measurements of Khalfan *et al.*[6], of the changes in BThE, with vehicle velocity can be seen in **Figure 1**. These involved a normal, non-hybrid, car engine, under a variety of congested urban, stop-start, driving conditions, in Leeds, UK. A figure shows results from a variety of closely monitored journeys of a four cylinder, 1.8 litre, Ford Mondeo car, running rather inefficiently, at fluctuating low speeds and low loads, with frequent stoppages. Brake Thermal Efficiencies, ranged between about 0.08 and 0.26. Detailed descriptions of the separately identified road sections were discussed[6]. Data were collected methodically, under these congested conditions. A standard ultra-low sulphur/RON95, gasoline was the fuel, with a heat of reaction of 43 MJ/kg.

A sufficient fuel supply could maintain a flame in low, highly fluctuating, gas velocities, with vehicle stoppages. The temporal changes in the performance of the car were closely monitored during each separate journey. There were many impulsive decelerations, accelerations, and halts. Car speed, power, and velocity were measured. Fuel consumptions over the short road sections, typically of about 0.5 km length, were found from measured flow rates. Averaged thermal efficiencies are to be found in the paper for each road section.

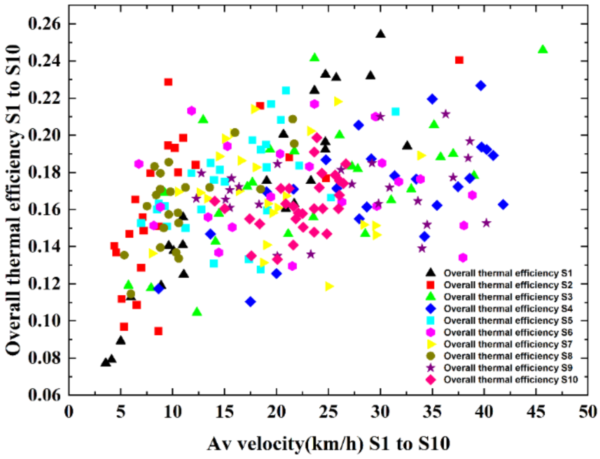

Figure 1. Separate BThEs in each journey section, as a function of mean vehicle velocity[6].

With the decline in vehicle velocity, associated with the increasing congestion, there is initially both an increasing scatter in the low values of BThE, and an increasing decline in their mean values. This is a consequence of the lower engine power, idling, and frequent stoppages, followed by minor accelerations. At a speed of 4 km/h (1.1 m/s), there were 14 starts from idle per km. Twenty one of the 290 journeys had, on average, a stop/start every 100 m, mainly a consequence of queuing at traffic lights. As the average velocity fell below about 12 km/h (3.3 m/s), combustion became inadequate. It was intermittently inefficient, and exhaust gas concentrations of unburned hydrocarbons and carbon monoxide sharply increased[6]. With a hybrid engine, there would be little or no combustion in such a regime, and battery/motor power would prevail. At the highest average velocity limit of 40 km/h (11.1 m/s) and above **Figure 1** shows the BThE to attain a value of about 0.25, at which combustion would be just of acceptable quality.

Figure 2 provides a more selective, smaller proportion of the data in **Figure 1**. It was selected to be devoid of any stop/start idling data. As a result, the plot of BThE against vehicle average velocity is more selective and, not surprisingly, more consistent. With a hybrid vehicle, the higher values of BThE would blend with a more ordered, and more efficient, combustion regime.

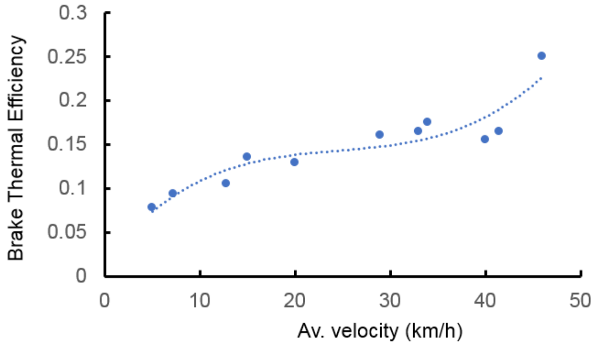

Figure 2. Non-idling data plots of BThE against Average Velocity, from **Figure 1**.

2.2. Laboratory test data

The second engine data base is a more controlled one. Data were derived from more normal controlled combustion, in a successful laboratory study to improve gasoline engine combustion at Honda R and D, by Ikeya *et al.*[7]. They were able to raise maximum values of BThE from 0.39 to 0.45, at an engine speed of 2,000 rpm, with a 91 RON gasoline fuel[7]. This was achieved by increases in the stroke/bore ratio, exhaust gas recirculation, EGR, and the compression ratio. These changes were achieved by changes in the pattern of tumble flow. The successfully measured BThE/Brake Mean Effective Pressure, BMEP, relationship is shown in **Figure 3**. These data, along with those in **Figure 1**, provide the combined data base for the present study, over a full operational range.

In **Figure 3**, the two, lower, broken, performance curves are those for the original conventional engine. The improved performances, after a number of changes, are shown by the upper continuous curves. The changes increased the maximum value of BThE from 0.39 to 0.45.

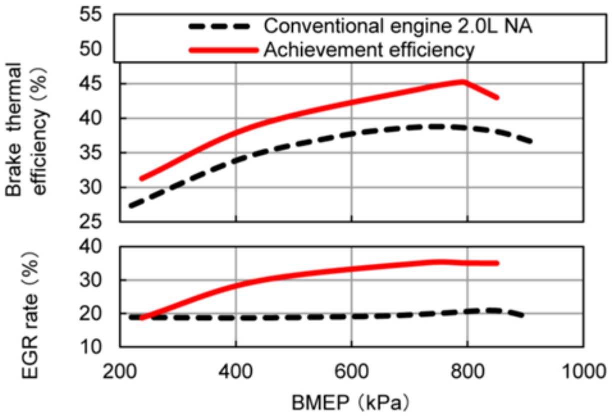

Figure 3. Brake thermal efficiencies with conventional engine (broken curves), and after changes (full curves). Engine speed, 2,000 rpm[7].

It is desirable to couple the low vehicle velocity data in **Figure 1** with the more reactive BMEP data in **Figure 3**. This is done by using the commonality of the BThE values in both figures and extrapolating the lowest values of BThE in **Figure 3** to link with the higher values of that parameter, between 0.18 and 0.25, in **Figure 1**, in a unifying plot of BThE against BMEP. The lower, conventional engine, broken curve of BThE in **Figure 3** is the more appropriate one for this coupling. It is apparent that the low vehicle velocity data in **Figure 1** would entail an increasingly sharp decrease in the extrapolated values of BThE from **Figure 3**, ultimately to the very low value of 0.08. The results of the coupling of the two curves are shown in **Figure 4**, with BThE values as a function of BMEP. It will be shown that this relationship is an invaluable aid to an understanding of hybrid control of an engine with these characteristics.

For values of BMEP above 180 kPa, the engine speed remains constant and this enables an estimate to be made of how the engine power varies with BMEP. The fuel energy supply rate to the engine, and hence its power, is closely proportional to BMEP/BThE. This value increases approximately linearly with BMEP. Note that the efficiency of the IC engine decreases sharply at low loads (BMEP < 180 kPa), where it is more efficient for hybrid electric vehicle switching to electric-only propulsion.

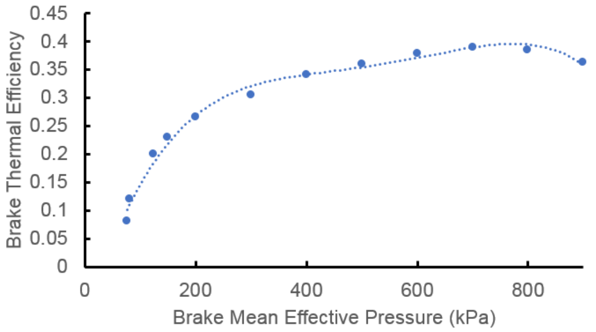

Figure 4. Full range composite-car engine plots of BThE against BMEP. Engine speed, 2,000 rpm.

3. Efficiencies of generators, batteries and motors

The functioning of hybrid engines depends upon the efficiency of several key electrical components. In this Section hybrid operations are scrutinized and the electrical losses estimated. Each component is considered in turn. First, is the electric Generator. Engine speeds had wide fluctuations about their mean, whilst the Generator, driven by the engine, had a fluctuating speed that reached 10,000 rpm[8]. The generated energy showed large fluctuations, over a somewhat greater regime. Two principal types of rotary generator are discussed[8] with powers of 42 Kw and 60 kW. The Switched Reluctance, SR, type had an efficiency of 0.934 in the urban driving Mode, and the Interior Permanent Magnet, IPM, type had an efficiency of 0.92, in both city and highway driving Modes. The higher the speed and torque, the higher the generator efficiency.

The associated batteries are partly characterised by the amount of energy they can store efficiently. Cheng *et al.*[9] reviewed hybrid type batteries, particularly the Mg-Li batteries with a Mg anode. They have high energy densities and good charge/discharge efficiencies. The theoretical energy density of a Mg-Li/$LiFePO_4$ hybrid battery can be up to 246 Wh/kg (885.6 kJ)/kg. Not all the electrical energy transferred into a battery is fully retained. Neither is all the energy so stored subsequently released and fully utilised. Pesaran and Keyser[10] have thoroughly reviewed the efficiencies of charging and discharging of electric vehicles, EV, and hybrid electric vehicles, HEV, together with the thermal characterisations, of the batteries. A Battery Efficiency is defined as ({electrical energy in – electrical energy out} – heat generated)/(electrical energy in – electrical energy out). In 15 experiments, 40% had an efficiency of at least 0.96. This covered data for valve-regulated lead-acid, lithium-ion, and nickel-zinc batteries. An overall mean battery efficiency is the product of the two mean values for charging/discharging.

Battery-stored energy enables an electric motor to drive either the engine crankshaft, or the wheels. Electric motor efficiencies, can exceed 90%, under rated load running conditions. The problem in hybrid operation is that they can be less efficient under conditions of variable speed and loading[11]. The power of conventional motors power may fall to 60% to 80% of the rated input energy, at less than 50% rated load. Small changes in motor speed can cause significant increases in power consumption. The use of rectifiers to convert alternating to direct current improves the control of motor speed, and can be advantageous.

An earlier mode of energy conservation was through electric generation in regenerative-braking. Urban driving is such that up to about 40% of the vehicular energy is periodically consumed by electronically controlled braking torques, predominantly at the front wheels. An electric motor provides power to the electrically-powered braking actuators. These incorporate wheel antilock devices, as part of a controlled regenerative braking system, with shared batteries[12]. This is integral to both EV and HEV, and most of the braking energy is now recovered, and battery-stored. Details of the extent of regenerative data braking, its efficacy, and associated energy storage are incomplete. The regenerative braking efficiency has been measured for a parallel HEV during the FTP-75 city cycle[13], and the overall efficiency ranged between 48% and 66%, depending upon the braking time span, and gear/shift numbers.

An attempt is now made to quantify the overall efficiency of the reviewed electrical ancillaries, in relation to their energy consumption in hybrid engines. The actual efficiency of electric machine depends on the speed and load. Typically, the electric motor and generator are between 85% and 90% efficient. And the Li-ion battery widely used as the energy storage device of HEV and EV has 99% charge and discharge efficiency. For the best-case scenario, an efficiency of 0.90 might be appropriate for generators, with a particularly demanding value of 0.98 for batteries, ultimately followed by an exacting electric motor requirement of about 0.90. The overall Conversion Efficiency is 0.90 × 0.98 × 0.90 = 0.79.

No data were found on the effects of continual usage upon this value. More fundamentally, a different approach might have used mechanical modes of energy storage and transfer, involving flywheels, as an alternative to the present electrical one.

4. Combustion in hybrid engines

In a hybrid engine, low quality engine combustion, such as that characterised in **Figure 1**, triggers its own terminations and substitutes an electric motor. The variations of BThE in **Figure 1** cover collective data from many journeys. For a single journey there is less spread of data and a journey would be marked by continually alternations between engine and electric motor power, in a way unique to that journey. Consequently, although motor drive might dominate in an overall sense, there would be periods in which engine drive would occur, and there could be high frequency transitions between the two drives. For a suitable engine drive to develop **Figures 1** and **4** suggests an average pressure should reach 130 kPa, with a BThE value close to 0.2 (0.17, with allowance for Conversion Efficiency). In contrast, with the electric motor drive, the battery energy required for this would have been best generated with an engine, not at a pressure of 130 kPa, but at a higher, and more efficient one, closer to 500 kPa with, from **Figure 4**, a BThE of 0.365 (0.310, allowing for Conversion Efficiency).

Finally, the regime of BMEPs, greater than about 300 BMEP is one in which, as shown by **Figure 4**, there are important increases in BThE with BMEP. Aided by hybrid control, this higher value of BThE is important for both engine performance and the economic storage of battery energy. In terms of road driving performance, this is an important driving Mode, up to a BMEP of 600 kPa, that defines a Cruising Mode.

Beyond this Cruising Mode range, **Figure 4** shows the maximum value of BThE of 0.39 occurs at the highest value of BMEP of 800 kPa. Allowing for the Conversion Efficiency, this Thermal Efficiency becomes 0.33, which compares with a value of 0.31 at 500 kPa. However, there is little advantage in this small increase in BThE over a comparatively large increase of 300 kPa in BMEP. This is particularly so, when account must also be taken of the high vehicle velocities that are usually associated with such high pressures. Importantly, these create increasingly high aerodynamic, power-consuming, drag forces acting on the vehicle. These increase with the square of the velocity[14]. Consequently, increasing the higher values of BMEP gives diminishing economic return, which soon disappears. Economic efficiency, expressed as distance travelled, in kilometres, per litre of fuel consumed, decreases in this high-speed regime.

Three broad Modes of combustion clearly emerge: Urban Congestion, Cruising, and High Speed. Efficient combustion is required in all Modes, with the maximum possible BThE in the first two. Combustion is the source of all power in a hybrid engine and should be as efficient as possible, with its improvements pervading all research.

This requires, not only the measures[7], but a variety of others. These include control of engine turbulence[15], possibly in combination with lean burn combustion[16], despite the increased air dilution, decreasing the heat release rate. The use of hydrogen as a fuel might also be considered. Despite its relatively low mass specific energy, the high acoustic velocity of H_2 can yield high subsonic heat release rates[17].

The ability of a fuel to avoid engine knock continues to be important. Chemical kinetics have created new advances, which go beyond a single quest to reduce an Octane Number. These involve the reduction of excitation times for the auto-ignitive heat release rate[18,19]. With this approach, the excitation time is no less important than the autoignition delay time.

5. Modes of driving

The BThE is strongly dependent upon the route followed by the vehicle and the chosen driving Mode. As the vehicle speed fell below 2.8 m/s in the inefficient, highly polluting, urban congestion regime of

Figure 1, concentrations of emitted harmful unburned hydrocarbons, benzene, butadienes and aldehydes, increased to ten times of those produced under the NEDC (New European Driving Cycle), maxima[6]. Similarly, in the New York City driving cycle frequent stops tripled life cycle emissions and increased economic costs of conventional vehicles by 30%[5]. The replacement of inefficient, highly polluting, congested urban combustion by an electric motor, driven by batteries, and charged by a generator driven by flame gases, is a key aspect of hybrid combustion. Again, this is well illustrated by the urban New York City driving cycle, when hybrid and plug-in vehicles cut life cycle emissions by 60%, and reduced costs by up to 20%, relative to conventional vehicles[5].

Figure 4 suggests combustion in the Cruise Mode at higher values of BMEP, is beneficial for both engine direct drive, and battery charging for motor Modes, and can increase BThE. This is confirmed by the urban New York City driving cycle. However, as the vehicle speed increases, so do the parasitic aerodynamic drag forces.

As discussed in Section 4, there are no economic benefits in the High Speed Mode. Similarly, under the Highway Mode test conditions, (Highway Fuel Economy Test, HWFET), there are only marginal reductions in emissions[5], at higher costs, but the higher, the power, the less likely is inefficient combustion. Aggressive driving (US06) reduces the all-electric range of plug-in vehicles by up to 45% compared to milder test cycles (like HWFET).

There are also parallels with the negative aspects of the high speed Mode in that, under highway test conditions (HWFET), electrified vehicles offered only marginal reductions in emissions at higher costs. Under the highway Mode test conditions, HWFET, the higher the power the less likely is inefficient combustion[5], and aggressive driving (US06) reduces the all-electric range of plug-in vehicles by up to 45%, compared with the milder test cycles such as HWFET.

6. Conclusions

Modes of hybrid combustion have been discussed in terms of a composite expression of engine Brake Thermal Efficiency as a function of Brake Mean Effective Pressure, throughout full power range. Three key Combustion Modes within the full range are characterised: Low vehicle velocity Urban Congestion, Cruising Speed at moderate pressure, and High Pressure Combustion. Predictions of BThE and general characteristics in the different Modes have been confirmed by street measurements in Leeds and New York. In congested urban regions important aspects of hybrid control are large reductions in engine emission pollution through electric motor drive and good Brake Thermal Efficiencies in electric generation.

Efficiencies of electric generators, batteries, and electric motors, have been reviewed. The overall conversion efficiency is estimated to be 0.79 for the best-case scenario. Battery power from regenerative braking has also been reviewed. In the charging of batteries, the engine should operate at high Brake Thermal Efficiency.

All the energy originates from engine combustion, different aspects of which require detailed attention to maximise the overall Brake Thermal Efficiency. Brake Thermal Efficiency increases with Brake Mean Effective Pressure, give diminishing economic return, as the aerodynamic drag force increases with the square of the vehicle velocity without considering the effects of downsizing and gear ratios. The economic performance of hybrid vehicle on a journey is dependent on the route and the driving mode, in a predictable way.

Author contributions

Original draft and writing, DB; resources, review and editing, JY.

Conflict of interest

The authors declare no conflict of interest.

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