A Hybrid Internal Combustion Engine/Battery Electric Passenger Car for Petroleum Displacement

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A hybrid internal combustion engine/battery electric passenger car for petroleum displacement

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This paper examines the potential of the hybrid electric vehicle in substituting petroleum fuel by broad-based electrical energy. In particular a hybrid car is considered. The way in which the powertrain can be controlled and the effect component ratings have on achieving the petroleum substitution objective are described. It is shown that a hybrid vehicle can be designed that can achieve a petroleum substitution of between 20 and 70 per cent of the equivalent internal combustion engine vehicle, be capable of entering environmentally sensitive areas and yet be capable of a range at high and intermediate speeds that is limited only by the size of its fuel tank.

NOTATION

E_1 energy input to the i.c. engine (J)
E_2 energy input to the electric traction system (J)
F objective function
g_r gear ratio
L_1 petroleum energy weighting factor
L_2 electrical energy weighting factor
x torque split ratio

1 INTRODUCTION

The disruption to the world's oil supplies that occurred in 1973 and 1978 helped focus international attention upon the finite nature of this particular energy resource. It also prompted the adoption of energy conservation policies and emphasized the need to transfer energy demand away from oil to other sources of energy, such as natural gas, coal and nuclear. As a result of such policies the inland deliveries of petroleum products, expressed as a percentage of the total energy consumed, dropped from 50 to 40 per cent over the period 1973–85 (**1**).

Although such an energy transfer is feasible in many energy sectors, it is more difficult in the transport area, due to the operational requirements placed on many of the vehicles. Some energy transfer has been achieved in the rail system by the use of increased electrification but in the road sector such an energy transfer is more difficult as the 'free ranging' nature of the majority of vehicles requires the energy store to be on-board the vehicle itself. Consequently, in the period 1973–85, the use of petroleum in the road transport sector, expressed as a percentage of the total inland deliveries of petroleum products, increased from 12 to 39 per cent (**1**).

A transfer of energy from oil to electricity, with its associated broad fuel base, can be achieved to a limited extent in the road transport sector by the increased use of electric vehicles. However such vehicles are limited in range due to the amount of energy that can be realistically stored on-board the vehicle without unduly affecting payload. As a consequence of this, electric vehicles must be used in situations where daily usage is well defined, for example in urban delivery duty. Indeed, it has been in such vehicles as the urban milk delivery vehicle or milk float that relatively low performance electric traction drives have been traditionally applied with a great deal of success. Currently the demand is for urban electric vehicles to be developed with greater traffic compatibility in terms of speed and range. It is in such vehicles as the 'Freight Rover Sherpa' and the 'Bedford CF' one tonne vans that higher performance electric drives have started to appear (**2**).

Although urban delivery vehicle applications will help to reduce the dependence of the road transport sector on petroleum-based fuels, the major part of this market requires vehicles that are not limited in range and have a performance compatible with today's internal combustion (i.c.) engine vehicles. The use of advanced traction battery technology to overcome the range limitation of electric vehicles is one possible solution. However, this would still result in a vehicle limited in range and may in itself create additional problems. For example, due to the much greater on-board stored energy, the charging time required will be greater than at present while the higher continuous rating of the traction components required to achieve high-speed performance compatible with today's vehicles will need careful attention.

The range limitations of the pure electric vehicle can be overcome by using a hybrid i.c. engine/electric drive which incorporates both an i.c. engine and an electric traction system. Although such a vehicle can be designed to meet a number of end objectives, it has been argued (**3**) that a vehicle which seeks to remove the range limitation of the electric vehicle while substituting a substantial amount of petroleum fuel by electrical energy is the vehicle most worth pursuing. With the emphasis of the vehicle design biased towards the electric drivetrain the intention may be to operate in an all-electric mode under urban conditions and to use the i.c. engine for long-distance motorway driving. The hybrid mode could then be used for extending urban range and/or improving vehicle accelerative performance on accelerator kick-down.

The concept of a hybrid electric vehicle capable of substituting petroleum fuel is not new, Bosch (**4**) and Volkswagen (**5**) having built vehicles in the 1970s. More

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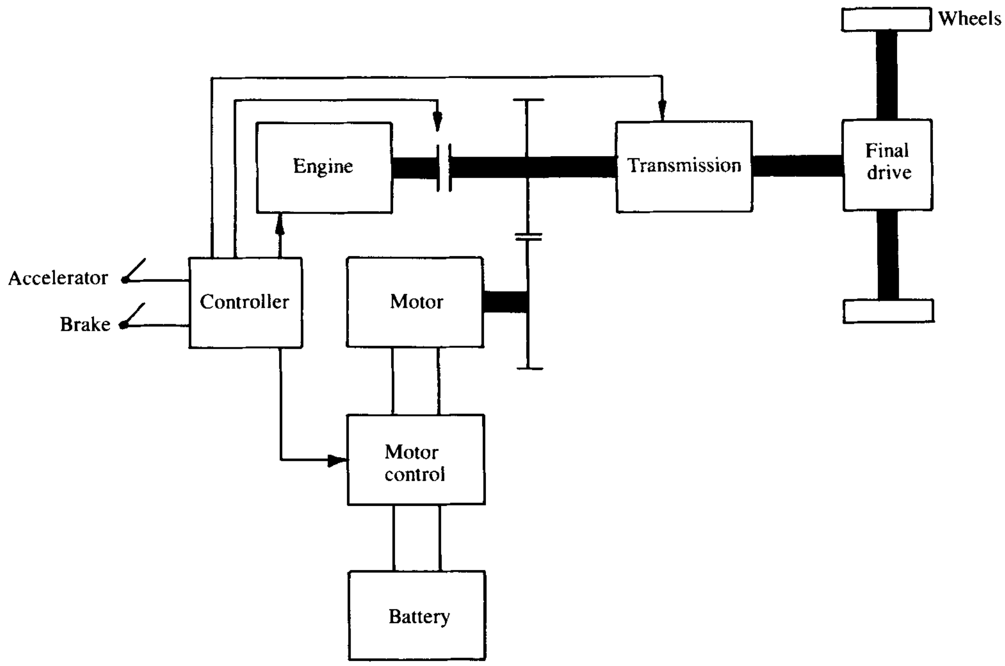


Fig. 1 A parallel hybrid electric vehicle drivetrain

recently, the advent of the Electric and Hybrid Vehicle Research, Development and Demonstration Programme in the United States of America initiated the design and construction of a Near Term Hybrid Vehicle (NTHV) with the principal aim of substituting petroleum fuel by 'wall plug' electricity (**6**, **7**).

As part of the NTHV programme a large number of conceptual studies were conducted but on vehicles aimed at the American passenger car market. In this paper optimization studies were conducted, but now on a vehicle suitable for the European medium-sized passenger car market. Such optimization studies are important as, with two sources of traction power available, the way in which they are controlled, and their relative sizing, is fundamental to the way the vehicle performs.

In order to optimize the control and component rating of the hybrid drivetrain, the performance and energy consumption of the vehicle over standard driving cycles is assessed using the road vehicle simulation program Janus (**8**). Janus is a flexible road vehicle simulation program capable of predicting the energy use and performance of vehicles with a variety of powertrain configurations and has been used previously to study the performance of advanced i.c. engine vehicles (**9**) and hybrid electric vehicles (**3**).

Before examining in detail the optimum control strategy for the drivetrain, Section 2 defines the hybrid arrangement under study. A description of the optimization process using an appropriate cost function is then presented in Section 3 followed by a method of translating the resulting control structure into a sub-optimum algorithm capable of being implemented in real time. Using the optimum control structure the effect of component ratings on the vehicle's performance is evaluated in Section 4, while Section 5 discusses the practical implementation of an overall vehicle control algorithm. Finally, in Section 6, an indication of the vehicle's potential for substituting petroleum fuel by electricity is given.

2 THE BASE HYBRID VEHICLE

Although a large number of hybrid i.c. engine/electric traction drive system arrangements are possible the configuration selected as having the greatest potential for use in a passenger car application is shown in Fig. 1. In this parallel arrangement both the electric traction motor and the i.c. engine are capable of driving the road wheels directly, and independently, through a common transmission. Such an arrangement offers the potential for maximizing the overall transmission efficiency between either prime mover and the road wheels, although, when both prime movers are operative, a compromise must be achieved. Although minor gains are possible if each power source is fed through its own, independent, transmission the efficiency benefit of such an arrangement must be carefully balanced against the added complexity, weight and cost.

To examine the potential of the hybrid drive as a means of displacing petroleum fuel a set of vehicle parameters typical of a mid-range European passenger car are defined in Table 1. Included in this table is a comparable parameter set for a conventional i.c. engine vehicle. Because the hybrid arrangement has two on-board energy sources the selection of the engine and traction motor rating must be carefully balanced. In this base hybrid vehicle specification the i.c. engine is sized to meet the maximum level road speed and is capable of sustaining 120 km/h on a 2 per cent gradient. The electric traction motor is rated so as to give adequate all-electric performance and also, when combined with the i.c. engine, provides the required acceleration demand placed on the vehicle. This value is comparable with that of a similar i.c. engine vehicle. The performance curves for the i.c. engine and the traction motor selected are shown in Fig. 2. Also shown in Fig. 2 is the combined torque capability of the drive system and the road load requirement in top gear. Throughout this paper, whenever any changes are made to the size of a component the installed power capacity of the vehicle is

Table 1 Base vehicle data

	Parallel hybrid	Conventional
Vehicle weights:		
kerb weight	1640 kg	950 kg
test weight	1900 kg	1200 kg
Vehicle parameters:		
C_D	0.35	0.35
C_R	0.01	0.01
A	1.95 m^2	1.95 m^2
Component sizes:		
i.c. engine	35 kW, 5000 r/min	55 kW, 5000 r/min
traction motor	35 kW, shunt	—
battery	lead–acid EV2-13 E_5 = 150 kJ/kg (42 W-h/kg) wt = 300 kg	—
final drive	3.5 : 1	3.5 : 1
transmission	4 speed automatic gear ratios	4 speed manual
	1st 3.5 : 1	3.5 : 1
	2nd 2.4 : 1	2.4 : 1
	3rd 1.3 : 1	1.3 : 1
	4th 1.0 : 1	1.0 : 1
Performance:		
0-60 mile/h (driver only)	14 s	12 s
Maximum speed:		
i.c. engine only	130 km/h	145 km/h*
hybrid	145 km/h	

* at 5000 r.p.m.

modified so as to maintain an acceleration performance and level road speed similar to those values defined in Table 1.

The battery system selected for use in the base hybrid vehicle is a high-performance lead–acid battery. In any hybrid electric vehicle a major limitation in sizing the battery is the allowable maximum discharge power density the battery can withstand. The selection of a 300 kg lead–acid battery for the base vehicle imposes a severe discharge condition on the battery during hard acceleration at high speed. However, during normal operation battery discharge rates are substantially reduced and are within acceptable bounds.

3 CONTROL OF THE HYBRID ELECTRIC DRIVETRAIN

3.1 General

With the hybrid arrangement shown in Fig. 1 it is possible to operate the drive in a number of different ways, or modes. As the use of these different operating modes is fundamental to the operation and control of the hybrid drive it is important to clearly define what these modes are. This is done in Table 2. Although it is clear that the regenerative braking mode should be used to recover vehicle kinetic energy during braking, how the other modes should be utilized is much less obvious. This statement is particularly true of the hybrid mode when both the i.c. engine and electric traction motor drive the road wheels together. The picture is further complicated as the battery charge mode, the primary i.c. engine mode and the primary electric mode are all essentially hybrid modes. However, they differ from the true hybrid mode in that one or other of the two prime movers is the principal power source and is only augmented by the other when it, the principal source, is unable to provide the requested output torque. In contrast in the true hybrid mode either one of the two prime movers is capable of providing all the necessary torque but to improve drivetrain efficiency the load is shared in some way between the two prime movers. How the load should be shared, or indeed if this mode should be used at all, is unclear.

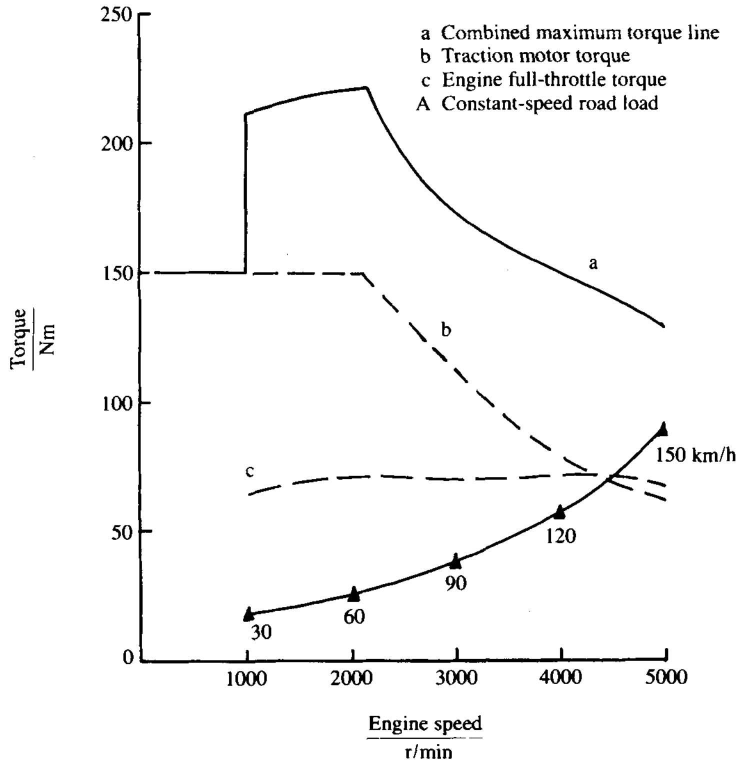
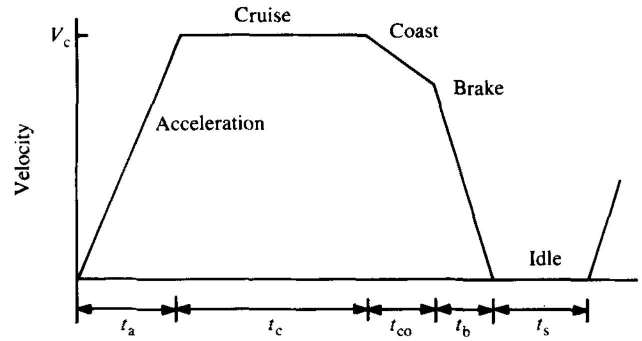


Fig. 2 Base hybrid electric vehicle performance curves

Table 2 Possible operating modes

Mode	Description
Electric mode	All propulsion power supplied by the electric traction system
i.c. engine mode	All propulsion power supplied by the i.c. engine
Primary electric mode	The electric traction system provides the principal torque but when necessary its maximum torque is augmented by the i.c. engine
Primary i.c. engine mode	The i.c. engine provides the principal torque but when necessary its maximum torque is augmented by the electric traction system
Hybrid mode	Both the i.c. engine and the electric traction system together, in some way, provide the propulsion power
Battery charge mode	The i.c. engine provides both the propulsion power and power to charge the batteries with the traction motor acting as a generator
Regenerative braking	During braking the vehicle kinetic energy is returned to the battery with the traction motor acting as a generator
Accelerator 'kick-down'	Essentially a primary i.c. engine mode when increased torque is provided to give acceleration



Parameter	Driving cycle A	B	C	D
Maximum speed V_c (mile/h)	10 ± 1	20 ± 1	30 ± 1	45 ± 1
Acceleration time t_a (s)	4 ± 1	19 ± 1	18 ± 2	28 ± 2
Cruise time t_c (s)	0	19 ± 1	20 ± 1	50 ± 2
Coast time t_{co} (s)	2 ± 1	4 ± 1	8 ± 1	10 ± 1
Brake time t_b (s)	3 ± 1	5 ± 1	9 ± 1	9 ± 1
Idle time t_s (s)	30 ± 2	25 ± 3	25 ± 2	25 ± 2
Total time (s)	39 ± 2	72 ± 2	80 ± 2	122 ± 2

Fig. 4 J227 schedule 'a' series of driving cycles

3.2 Optimum control of the hybrid electric drivetrain

In order to examine the hybrid control problem an optimization process has been developed whereby, for a given power and speed demand at the road wheels, that transmission ratio and torque split between the two prime movers which minimizes an objective function

$$F(g_r, x) = L_1 E_1(g_r, x) + L_2 E_2(g_r, x) \quad (1)$$

is found. In this expression E_1 and E_2 are the energy inputs to the i.c. engine and the electric traction system respectively, while L_1 and L_2 are weighting factors that allow total energy use to be biased towards one or other of the two on-board energy sources. The gear ratio g_r and the torque split ratio x are two, independent, control variables that can be varied to minimize the objective function $F(g_r, x)$.

To implement this optimization process over an urban driving cycle such as the ECE-15 (Fig. 3) or the J227a-D (Fig. 4) the torque required at the road wheels to overcome both vehicle drag and rolling resistance, and to provide any vehicle acceleration, is determined at discrete (typically one second) intervals. Over each discrete time interval the power and speed are assumed to be constant. These values are then reflected back through the drivetrain to the on-board energy sources. At each drivetrain component full account is taken of efficiency, which may vary with both torque and speed, so that the calculated energy consumed accounts for both the road load requirement and the system losses. At each time interval the optimization process computes the energy consumptions E_1 and E_2 associated with every possible combination of gear ratio and torque split. For a predefined set of weighting factors, L_1 and L_2, a three-dimensional surface is therefore obtained with the objective function as the dependent

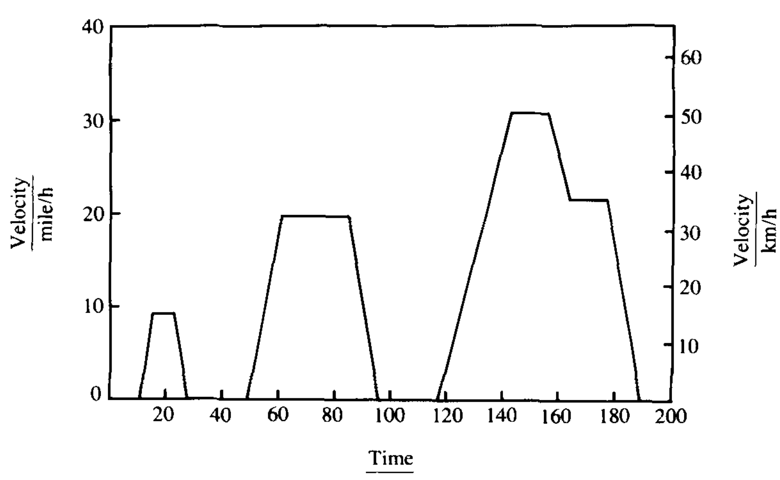


Fig. 3 ECE-15 urban driving cycle

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