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Consumpton Comparison of Different Modes of Operation of a Hybrid Vehicle

Dr. Mukhtar M. A. Murad[*1], Dr. Jasem Alrajhi[2]
[*1,2] B.Sc., M.Sc., Ph.D., Department of Automotive & marine Engineering Technology, College of Technological Studies - PAAET, P.O. Box 42325, 70654 Shuwaikh, Kuwait
ajasem@gmail.com

Abstract

A test rig representing a hybrid system comprising of an engine unit coupled with a hydraulic dynamometer, a D.C. series motor serving as torquer, an alternator and a battery pack of 10 lead-acid batteries had been used for the performance analysis.

The planetary gear drive was incorporated in the transmission in order to have a continuously variable transmission and the possibility of charging the batteries.

An analysis is presented which illustrates the comparison in Kuwait when working in three modes of operation namely all mechanical, all electrical and the hybrid mode. The performance evaluation results in the possibility of avoiding costly field tests and the specific analyses might yield useful rules regarding a control system fitted in the vehicle to obtain the optimum mode according to road conditions.

Keywords: CONSUMPTON , hybrid, vehicle, operation, comparison

Introduction

Internal combustion engines have been considered major power source for automotive vehicles ever since these were introduced. However, the recent trend, rather inevitable requirement of reduced pollutant emissions and improved performance conditions, had led to the serious consideration of alternative energy sources for transport area.

A number of purely electric vehicles and hybrid vehicles incorporating a conventional i.g. engine and high performance battery system are being developed at a fast pace (1-6, 10-12). The energy economy of electric and hybrid vehicles has been evaluated in terms of the distance travelled by the vehicle divided by the amount of energy required to travel that distance (7). The performance characteristic of electric and hybrid vehicles are then correlated with factors such as vehicle mass, speed, distance travelled, battery type, and type of components (7, 8).

The present work gives an analysis illustrating the comparison of costs of operations under local conditions in Kuwait, when working in three modes of operation namely all mechanical, all electrical and the hybrid mode. For this purpose a test rig representing a hybrid traction has been used.

Experimental Apparatus

The test rig has been described in detail in Ref. (9). The general layout is given in Fig. (1). The rig comprised mainly and engine coupled to a step-up manual gear box having four forward speed ratios and one reverse gear ratio. The planetary gear drive consisted of the sun gear driven by the engine and was coupled to the alternator. The annular gear of the planetary train was coupled to the hydraulic dynamometer and another automotive gear box having same speed ratios as for the step-up gear box. On its opposite side, a D.C. machine was coupled across the step-down gear box such that the D.C. machine could be used to carry the total load (purely electrical) or share the load (hybrid).

The electrical equipment consisted of a D.C. series motor (Torque) having different field resistances, a variable potentiometer, bridge-connected rectifiers, change-over switches, battery bank, external battery charger, and the speeder (Alternator). The electrical circuit is shown in Fig. (2).

Consumption Comparison Analysis

All Mechanical Mode

It is assumed that the vehicle is running with a constant speed of 50 km/h on the level road for which the computer specific fuel consumption is 7.6 lit/100 km.

Since the petrol cost at the present time in Kuwait is 65 fils/lit the energy cost when using the engine will be 3.04 fils per km.

Evidently this sum gives the fuel cost only irrespective of all other costs such as maintenance, depreciation etc.

All Electrical Mode

For pure electrical mode, the cost of battery charging has been calculated experimentally. A charger efficiency of 80% generally used for battery charging, was taken as against experimentally obtained value of 73%. The local electrical energy cost of 2 fils/kWh was used to calculate the cost of the charging 10 batteries.

The calculations for the motor power input for a certain speed on the level road at a particular gear ratio and experimentally determined motor efficiency would lead to knowing the current input, discharge current, the discharge time and hence the distance covered by the vehicle.

The cost of electrical energy supplied during that time excluding the cost of battery, motor and control system depreciation could be obtained.

For a particular application the electrical energy cost comes out to be only 22.35% of the cost of petrol.

Hybrid Mode

From the engine performance characteristics at full load that were obtained experimentally, the minimal fuel consumption ranges between 2300- 4200 R.P.M. Thus the hybrid vehicle can be made to operate economically for a careful selection of rotational speeds within this range.

In case the vehicle is being operated under these circumstances, the power required is less than what is produced by the engine. The extra power could be usefully employed to operate the alternator to charge the batteries.

Thus $P_{br} = P_e = P_x$ (1)

Where P_{br} = Brake power at full load (kW)

P_e = Engine power (kW)

P_x = Extra power (kW)

As a consequence of road resistance, the power required by the vehicle would be less than that produced by the engine. The required extra power would then be supplemented by the torquer operated by batteries while still running the engine in the economical mode.

Thus $P_r = P_e + P_x$ (2)

where

P_r = required power to drive the vehicle (kW)

P_e = Engine power (kW)

P_x = Extra power (kW)

If the power required to drive the vehicle is equal to the economical power, then alternator and torquer are not functioning at all.

Thus $P_e = P_r$ (3)

where P_e = Engine power, (kW)

P_r = Required power(kW)

In order to evaluate the economy of the hybrid mode operation, a procedure is adopted which is described herein and the respective stepwise calculations are also presented.

The engine power required to drive the car on level road is determined for the selected speeds of 2300, 2600, 3000, 3400, 3900, and 4200, R.P.M. within the economical range as mentioned before. The difference of brake power at full load and that required to drive the car at level road gives the extra power available that can be utilized through alternator, battery, torquer and finally to the wheels. The mass rate of fuel consumption for this extra power (from engine to alternator, considering mechanical efficiency only) is obtained. This extra power is then transferred to the wheels considering alternator, battery and torquer efficiencies. The new brake specific fuel consumption termed as B.S.F.C. $_{actual}$ for this extra power is then obtained.

The brake specific fuel consumption under partial load condition, B.S.F.C. $_{partial}$, can be compared with that already obtained as B.S.F.C. $_{actual}$ to give an assessment of the saving in fuel consumption due to hybrid mode.

The values of brake power for the full load operation corresponding to the selected speeds as in Column 1 of Table (1) have been obtained experimentally and presented in Column 2 of the Table. The corresponding values of brake mean effective pressure an those of brake specific fuel consumption are given in Columns 3 and 4 of Table (1), respectively.

In order to obtain the engine power required to run the car at different car speeds at level road for the selected engine speeds, the values of car speed and engine power are calculated as follows:

The car speed

$$V = \frac{\pi\, d_t\, Ne}{60\; i_g . i_b}$$

where V = Car velocity (km/h)

d_t = Effective tyre diameter (m)

i_g = Gear ratio (final drive)

i_b = Back axle ratio

The values of velocity, V, thus calculated for selected speeds are tabulated in Column 5 of the Table (1).

The engine power for the selected car speeds is obtained as

$$P_b = \frac{F_R\, V}{1000\, X\, \eta_t} \quad (5)$$

where P_b = Engine power (kW)

V = Car velocity (km/h)

F_R = Tractive effort (N)

η_t = Transmission efficiency

F_R is calculated as

$F_R = F_r + F_a$ (6)

where F_r = Rolling resistance

$= f_r . G$ (7)

f_r = Coefficient of rolling resistance

= Car weight

and F_a = Air resistance

$= k A V^2$ (8)

where k = Air resistance coefficient

A = Car frontal area (m^2)

V = Car speed (km/h)

The values of engine power, thus calculated by Eq. (5), are given in Column 6 of Table (1).

Column 7 gives the difference of brake power, ΔP_b, of the values of power at full load in Column 2 and the values in Column 6 of engine required to drive the car on level road. The rate of fuel consumption, M_f, for this extra power, ΔP_b, is calculated as

$M_f = \Delta P_b \times$ B.S.F.C. (9)

B.S.F.C. = Brake specific fuel consumption at full load (Column 4)

These values of M_f are tabulated in Column 8.

The actual power available at the wheels, $\Delta P_{b\ actual}$, will be obtained as

$\Delta P_{b\ actual} = \Delta P_b \times \eta$ (10)

where η = Efficiency considering the alternator, battery and torquer efficiencies.

These values are tabulated in Column 9 of the Table. The corresponding values of brake specific fuel consumption will be obtained as

$$\text{B.S.F.C.}_{\ actual} = \frac{M_f}{\Delta P_{b\ actual}} \quad (11)$$

and are given in Column 10.

If this power, $\Delta P_{b\ actual}$, is assumed as a partial load operation, i.e. the engine is running in mechanical mode, then new B.S.F.C.$_{actual}$ can be obtained from the following procedure as:

$$P_b = n \times \frac{\pi d_e^2\ L\ N_e\ P_m \times 10^2}{4 \times 2 \times 60} \quad (12)$$

where n = number of cylinders = 4

d_e = cylinder diameter

L = Engine stroke

P_m = brake mean effective pressure

P_b = Engine power

Having obtained the values of Pm from Eq. (12), the values of B.S.F.C. $_{partial}$ are obtained from the performance map, and are tabulated in Column 11 of Table (1)

The percentage saving in the fuel consumption is given in Column 12 of Table (1). It is apparent that a percentage saving of 3.5 to 35.8 percent is achieved, thus making the hybrid mode of operation economically viable.

Table (1) Saving in Fuel Consumption Under Hybrid Mode

Speed N_e R.P.M.	Brake power P_b kW	P_m Bar	B.S.F.C Kg/kWh $X10^{-3}$	Car Velocity v Km/h	Engine power (level road) P_b kW	ΔP_b kW	Mf kg/h	ΔP_b Actual kW	B.S.F.C Actual Kg/kWh $X10^{-3}$	B.S.F.C Partial Kg/kWh $X10^{-3}$	% Saving
1	2	3	4	5	6	7	8	9	10	11	12
2300	26.5	8.71	310	65.41	6.2	20.3	5.94	17.25	344	536	35.8
2600	30.5	8.95	300	73.94	8.15	22.35	6.36	18.99	334	520	35.8
3000	35.5	9.05	295	85.32	11.2	24.3	6.78	20.65	328	450	27.1
3400	40.0	8.9	295	95.98	15.11	24.89	6.97	21.15	329	365	9.86
3900	44.0	8.5	295	110.9	22.3	21.7	6.00	18.44	325	350	7.14
4200	46.0	8.25	295	119.4	26.53	19.47	5.45	16.54	329	341	3.5

Conclusions

A cost analysis based on the fuel consumption involving the three operational modes has been done. In the pure mechanical mode, the fuel cost has been considered irrespective of all other costs such as maintenance, depreciation etc. In the electrical mode, the comparable cost excluding the cost of battery, motor and control system depreciation has been computed. It has been shown that the energy cost for purely electrical mode is only 22.35 percent of the cost of purely mechanical mode. This might be due to prevailing cheap electricity rates in Kuwait at present.

The cost analysis in the hybrid mode has been evaluated by considering the car performance in the economical speed range where the fuel consumption is

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minimal. The extra brake power resulting from the difference of power at full load and that required to drive the car at level road can be transferred to the wheels through alternator, battery, torquer and wheels i.e. hybrid mode. A comparison of fuel consumption under the hybrid mode and that under partial load conditions gives a percentage saving up to 35.8 percent thus making hybrid vehicle economically viable.

The results presented by Wipke et al. (7) show that all electric and hybrid vehicles that were tested resulted in energy economy under different conditions. The present analyses are also suggestive of fuel economy under hybrid mode and therefore might lead to useful rules regarding a control system fitted in such a vehicle to obtain the optimum performance under different road conditions.

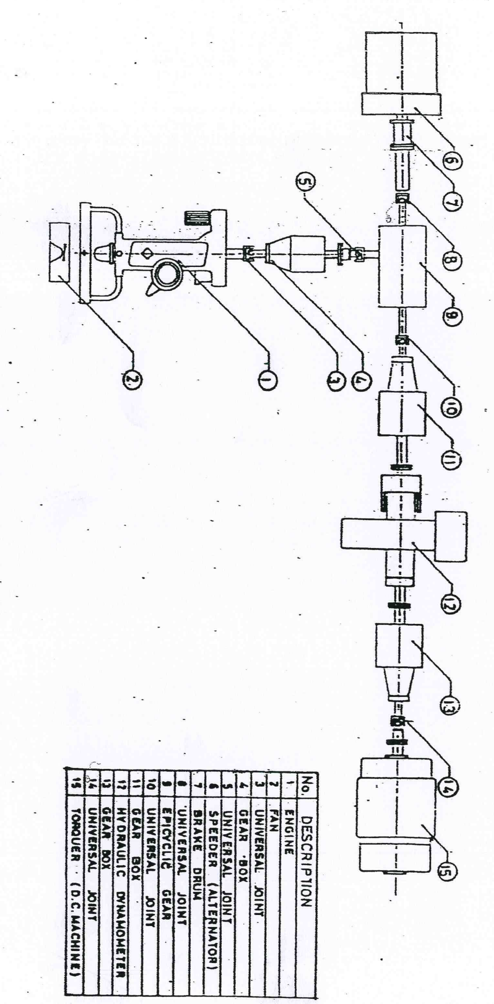

FIG. (1) TEST RIG LAYOUT

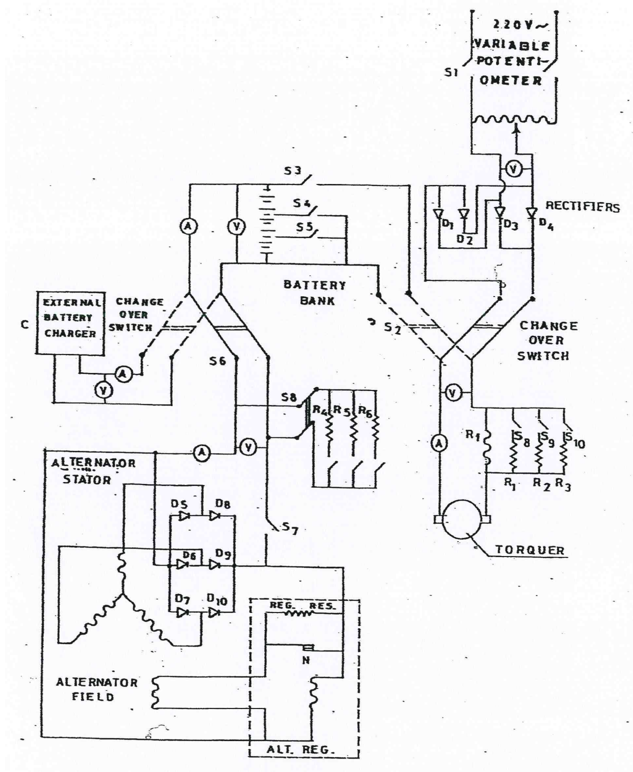

FIG. (2) CIRCUIT DIAGRAM FOR THE ELECTRICAL EQUIPMENT FOR PURE ELECTRICAL AND HYBRID MODES.

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