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An On-Road Evaluation of a 1500 kg Multi-purpose Hybrid Vehicle with Trimodal Energy Storage

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SUMMARY

Hybrid vehicles using both internal combustion engines and electric motors represent one way to significantly reduce liquid fuel consumption. The Department of Mechanical Engineering at the University of Queensland has designed and constructed a prototype hybrid vehicle which is described in this paper. Our demonstration project envisioned halving the central business district and urban fuel consumption of a large passenger or light commercial vehicle by reducing the capacity of its engine and adding regenerative braking and an all-electric range. We aimed to maintain the same acceleration and gradeability by using energy storage, as well as achieve a top speed of 120 km/h. A transmission has been installed in a 1680 kg kerb weight passenger vehicle. It consists of a 1.3 litre gasoline internal combustion engine, two 13 kW separately-excited, direct current, electric traction motors, a 38 kg alloy-steel flywheel which spins to 7800 rpm, and 105 kg of lead-acid batteries. Only conventional technology which is readily converted to mass production has been used. The system is microprocessor controlled and has proven its reliability in use on public roadways during 1982.

INTRODUCTION

Automobiles require far less mean power in suburban traffic than they do in highway operation. Engines of large capacity provide high speed cruising and acceleration, while inefficient automatic transmissions make the car driveable in suburban traffic where the power demands are moderate. The normal combinations of engine and transmission of today's automobiles are not energy efficient; they also generate extra pollutants because of the large range in power demand. Electric DC traction motors are ideal for automobile use but inefficient batteries prevent electric vehicles from being viable even in suburban traffic. Much research is now underway on improving the thermal efficiencies and performance of internal combustion engines. Ideally, however, energy storage should be used to meet peak power demands which are relatively small even when accelerating at a velocity of 100 km/h. A hybrid transmission with both battery and flywheel storage offers similar performance to current vehicles but has an overall thermal efficiency at least twice that now available. The concept of a hybrid vehicle is not new, and many combinations of internal combustion engines and energy storage components have been developed or investigated. Our design stems from an overall systems approach to the problem and our basic philosophy is that, in a stochastic power demand situation, the efficiency of power production should be a maximum during the most probable period of use.

HYBRID VEHICLE CONCEPT

Easingwood-Wilson et al (5) measured the power required by a 970 kg Ford Escort 1.3 litre gasoline driven automobile in central Glasgow, U.K. Their main conclusions are:

(a) acceleration is symmetrical around zero and never exceeds 2.5 m/s^2;

(b) required power does not exceed 20 kW, while the time averaged positive and negative power output to the drive-shaft is 1.5 kW (the engine is capable of approximately 42 kW);

(c) the vehicle is stationary 40% of the time;

(d) the average speed is 15 km/h;

(e) the average engine efficiency is 10.0%.

McConachie (8) recently obtained data for a 1500 kg Ford 4.1 litre automobile with automatic transmission in suburban Brisbane, Australia. McGarvie (9) repeated those test procedures with a 1500 kg Ford 3.3 litre automobile with a 4 speed manual transmission. Some general conclusions are:

(a) acceleration is symmetrical around zero and never exceeds 2.5 m/s^2 (98% confidence limits);

(b) required power does not exceed 40 kW (98% confidence limits), while the average positive power output to the propeller shaft is 7 kW (the engine is capable of approximately 92 kW);

(c) the vehicle is stationary between 8% and 36% of the time;

(d) the average speed ranges from 15 km/h (city) to 50 km/h (suburban);

(e) the average engine efficiency, while not measured, is probably less than 10%.

(f) the energy consumed at the driveshaft varied between 540 and 760 kJ/km.

Since approximately 75% of the fuel used for transportation in Australia is burnt under urban conditions similar to those measured for the two Ford vehicles, a passenger vehicle designed to emphasize fuel economy should cater primarily to low average power, low speed driving cycles. In addition, a versatile vehicle suited to Australian conditions should be of adequate size (around 1400-1500 kg kerb weight with current construction methods), be capable of a top speed of around 120 km/h and a 400 km range between refuelling stops, and possess acceleration capabilities that will be road compatible and satisfactory to most drivers. The hybrid vehicle envisaged to satisfy these demands will possess average theoretical power plant efficiencies twice those of conventional vehicles in the 0-60 km/h range, and be able to drive in an all-electric mode during the periods of worst fuel economy and atmospheric pollution (stop-start driving with long delay periods).

The hybrid power plant (see Figure 1) consists of an internal combustion engine of approximately 1.3 litre capacity driving the ring gear of an epicyclic gear train. The sun gear is connected to a flywheel with a maximum speed of 7800 rpm and an inertia which can be varied to alter the characteristics of the vehicle. The sun gear is also connected by a chain drive to a DC generator with a maximum speed of 7800 rpm and a rated torque of 40 Nm. The planetary gears are connected to the propeller shaft, to which a chain drive also connects a DC motor with electrical and mechanical characteristics identical to the generator. Both motor and generator have a maximum terminal voltage of 200 volts. The propeller shaft is coupled to a normal rear wheel drive vehicle differential which has a 3.5:1 ratio.

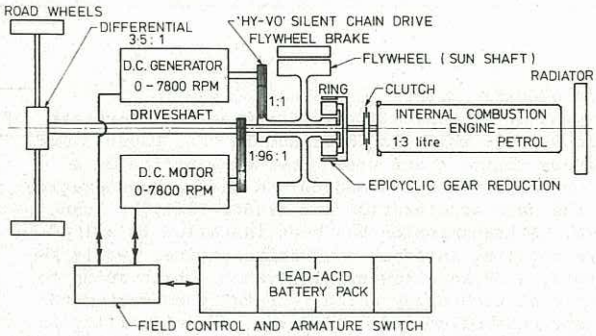


Fig. 1 Schematic of Hybrid Transmission

Figure 2 shows the speed map associated with the three shafts of the epicyclic gear box. The engine speed varies from 1000 - 5500 rpm and the engine power (1.3 litre engine) at full throttle from 8.5 to 46.5 kW. Although the engine may turn at up to 6000 rpm to achieve maximum vehicle speed for short durations, a maximum continuous speed of 5000 rpm is recommended.

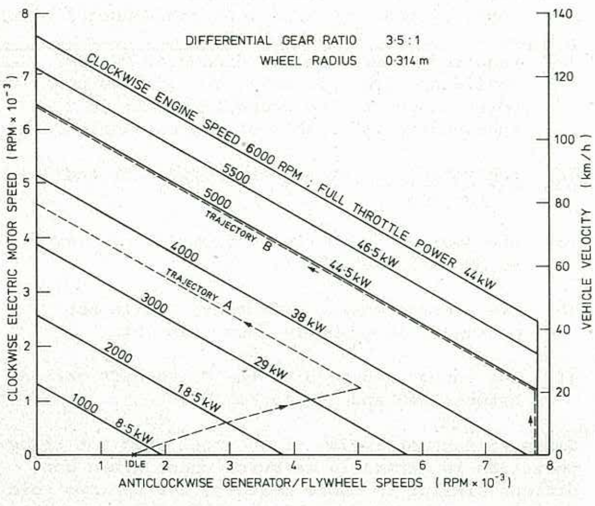


Fig. 2 Speed map for epicyclic gear box

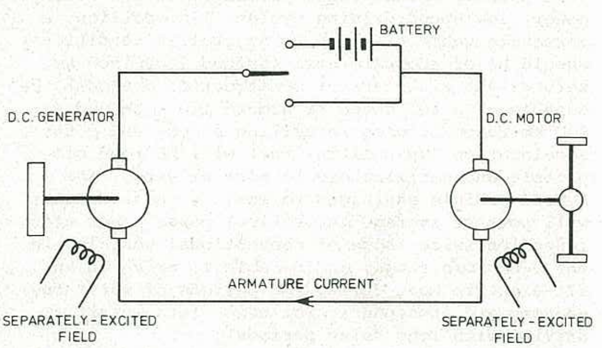


Fig. 3 Electrical Circuit

The armature of the motor and generator may be electrically connected in series (Figure 3). Control is accomplished by varying the currents in the field circuits of each electrical machine. This controls the magnitude and direction of the armature current and thus the power flow from one machine to the other. In this manner the function of the identical machines which normally operate as a motor and a generator may be reversed to operate as a generator and a motor, respectively. A lead-acid battery pack may be connected in series with the armatures of the two electrical machines. The batteries may also be switched across either the motor or the generator armatures individually.

The transmission operates during vehicle acceleration by following a trajectory on Figure 2 such as those designated A and B. Trajectory A begins from an engine idle speed of 700 rpm, a flywheel speed of 1400 rpm, and a zero vehicle speed. Initially engine power is transferred to both the rear wheels and the flywheel, enabling full torque to be generated. The battery may be connected in series with the motor and generator and assists in the acceleration of both the vehicle and the flywheel. Upon reaching the desired engine power, the motor and generator fields are manipulated to maintain vehicle acceleration at constant engine speed.

The engine is maintained at near full throttle and therefore maximum efficiency (Figure 4); the motor and the generator are also in an efficient operating range. When the flywheel speed decreases to 500 rpm, it is clamped and the transmission enters a mechanically linked, efficient cruise mode. In this mode, the selection of a small displacement gasoline engine whose peak power just matches the peak power requirement at 130 km/h (1.3 litre) ensures maximum fuel economy.

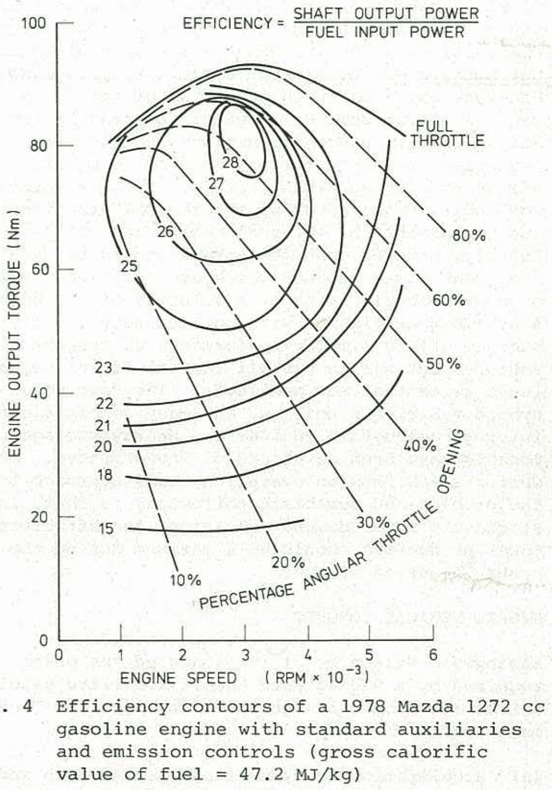


Fig. 4 Efficiency contours of a 1978 Mazda 1272 cc gasoline engine with standard auxiliaries and emission controls (gross calorific value of fuel = 47.2 MJ/kg)

Trajectory B is followed if the driver demands maximum vehicle acceleration over the full speed range. It begins with the engine at full throttle and a speed of approximately 4000 rpm, a flywheel speed of 7800 rpm, and a zero vehicle speed. Field controls on the motor and generator guide the transmission at constant flywheel speed until the engine reaches its maximum practical speed of 5000 rpm. Engine speed is then held constant until the flywheel clamps at a speed of 500 rpm; the vehicle then cruises at speeds between 110 and 130 km/h.

An option exists to include the battery in the motor/generator circuit. At any stage during operation, vehicle acceleration may be halted and the flywheel brought to rest by reducing the demand on the accelerator pedal.

The transmission is ideally suited for regeneration of vehicle kinetic energy into the flywheel during braking. The engine is disengaged in this mode, thus allowing the flywheel to be energised from the motor (which acts as a generator) and the generator (which acts as a motor). If the vehicle is brought to rest, the flywheel may be moving at any speed between 1400 rpm and 7800 rpm depending on the grade. Future acceleration trajectories must then start from those initial conditions; alternatively, the flywheel energy may be used to charge the lead-acid battery pack during long delays between periods of acceleration.

To operate the vehicle in an all-electric mode, the engine is automatically switched off and disengaged from the transmission. The flywheel is energised at low power from the battery and then de-energised at high power to provide vehicle acceleration. Cruising is handled by the battery being directly connected across the motor. Strict limitations on vehicle weight, available space for the power plant and luggage carrying capacity all restrict the weight of lead batteries that can be carried. This in turn restricts the range and top speed of an all-electric vehicle. We must therefore compromise on battery weight and voltage between the all-electric parameters and the characteristics required for operation of the vehicle in hybrid mode, unless an option to use parallel and series battery connections is exercised in the hybrid and all-electric modes respectively.

The three forms of energy storage present in this hybrid vehicle complement each other. The gasoline engine provides both high power and high energy densities. The conventional-speed steel flywheel offers the combination of a reliable high power density source but low energy density, whilst lead-acid batteries can be operated to obtain a large energy density at the expense of power density. The performance capabilities and versatility of this vehicle can be altered greatly by the choice of relative sizes of each of these forms of energy storage. A commuting passenger vehicle might possess small flywheel and battery storage units to enable adequate acceleration and small non-polluting electric range, whilst being primarily reliant on gasoline fuel. The electric range might be increased by removing the flywheel and downsizing the gasoline engine, and substituting batteries to provide primarily an electric vehicle. A sports car might rely on a gasoline engine and flywheel alone to give superior acceleration capabilities together with fuel economy. A twenty-seater or larger bus might use a slower running diesel engine coupled with large battery storage primarily used for acceleration. There are many possible combinations but all offer an increase in liquid fuel economy.

Vehicle design was performed with the aid of two computer simulation programmes. An EAI 681 analogue computer was used initially to assess the effects of parameters such as engine size, flywheel size, gear ratios and battery voltages and thereby aid the specification of vehicle components. A Hewlett Packard Model 85 digital computer was subsequently used to simulate both the vehicle and its control system and allow the vehicle to effectively be driven from the keyboard. This allowed refinement of the control system concepts.

The hybrid vehicle consists of seven major components: the vehicle itself, an internal combustion engine, an epicyclic gear box, two electric motors, a flywheel, and a lead-acid battery pack.

All these components affect the driving characteristics of the vehicle. We made some preliminary decisions with the aid of the analogue computer simulation, including:

(a) selecting an existing vehicle of 1500 kg kerb weight capable of a top speed of 130 km/h;

(b) using a 1.3ℓ gasoline engine rather than diesel because of fuel availability, noise, atmospheric pollution, and speed range considerations;

(c) using identical DC motors continuously rated at 120 volts, 150 amps producing 13.4 kW at 3100 rpm, but able to operate with up to five times rated torque for short durations;

(d) using a flywheel with an inertia of approximately 0.7 kg m^2, at up to 7800 rpm where it contains 230 kJ. Such a flywheel is suitable for accelerating the all-electric vehicle, and is large enough to accept the regenerative energy resulting from a vehicle deceleration from 60 km/h to rest, without excessive flywheel speed. Alternatively it can store the resultant energy from a 35 m hill with downgrades of up to 15%.

(e) using a 60 volt, 90 amp hour lead-acid battery pack weighing 105 kg.

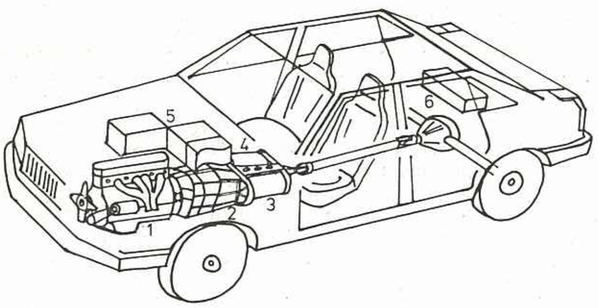
TRANSMISSION CONSTRUCTION

A gear box which incorporates the selected components was designed and constructed. The housing is fabricated from mild steel plate and houses the all-alloy steel flywheel which surrounds the epicyclic gear train. The flywheel diameter is 320 mm and has been subjected to a finite-element stress analysis to maintain peak stresses at 140 MPa. Gyroscopic effects have no noticeable effect on normal vehicle operation.

Lubrication to bearings and chains is provided by a gear pump driven by the epicyclic ring gear shaft. Hydraulic actuators automatically operate the engine clutch and flywheel brake, supplied by high pressure oil from a separate electric jacking pump and accumulator. The accumulator reduces the on-off cycle frequency of the pump.

The vehicle has controls similar to current vehicles with automatic transmissions, including an accelerator pedal, footbrake, and gear selections of park, drive, low, second, reverse, and an additional electric mode. Vehicle energy is transferred to the flywheel on the release of the accelerator pedal, computed to provide a braking effect similar to that due to engine braking in conventional manual vehicles in second gear. (See Fig. 6).

The transmission is microprocessor controlled; it receives inputs from the accelerator pedal and gear selector, and feeds modulated analogue output information to a servo-motor on the engine throttle, to the motor and generator field controllers, and logic outputs to the hydraulic clutch and flywheel brake actuators. The transmission was tested in mid-1981 on a computer-controlled laboratory road-load simulator which possesses regenerative capabilities; it has since been installed in a Ford passenger sedan in the manner depicted in Figure 5, and has been successfully tested on public roadways in the city of Brisbane. The transmission was designed to fit in the available engine space and to connect up to the existing rear-wheel drive-train. The emphasis throughout the project was directed towards employing currently available technology in the design of mechanical components. In addition, it was felt that both passenger and luggage space should not be impaired with the result that batteries are installed in readily accessible areas of the engine compartment. The position of the centre of gravity of the engine and transmission system is not substantially altered from that in the conventional vehicle and road testing has confirmed no adverse affects on vehicle handling. The overall kerb weight of the vehicle is 1680 kg, with the engine and prototype transmission weighing 390 kg, batteries 105 kg, and auxiliary components 90 kg. This compares with an overall kerb weight of 1380 kg for the same vehicle shell fitted with a 4.1 litre engine and automatic transmission, of which the engine and transmission weigh 290 kg.



1. GASOLINE ENGINE
2. TRANSMISSION INCORPORATING STEEL FLYWHEEL
3. DC GENERATOR
4. DC MOTOR
5. TRACTION BATTERIES
6. MICROPROCESSOR & ELECTRONIC CONTROLS

Fig. 5 University of Queensland Hybrid Gasoline-Electric Vehicle layout.

TRANSMISSION PERFORMANCE

Based on data obtained from laboratory tests on the engine and transmission system, the digital simulation programme was able to predict accurately the vehicle acceleration performance, and system efficiencies. Efficiencies of the transmission measured on a dynamometer were within a tolerance of 10% of the computer predicted efficiencies. Figure 6 shows computer predicted levels of vehicle acceleration from rest to a top speed of 60 km/h, beginning with flywheel speeds ranging from 1400 to 5000 rpm. The 60 volt lead-acid battery pack is included in the armature circuit during these accelerations. The maximum level of acceleration in a 4.1 litre vehicle with a conventional automatic transmission which satisfies 98% of all Brisbane City demands is 2.5 m/sec^2 (Bullock (4)). Furthermore, the power required to supply this acceleration on a level road is sufficient to cater for all hill climbing required.

With the present control algorithms employed in our hybrid vehicle, acceleration available on a level road increases as the flywheel is added to the system as an energy source. This occurs at successively lower vehicle speeds as the initial flywheel speed is increased as shown in Figure 6. It can be seen however that the hybrid vehicle can easily cope with the summarised 98th percentile demand curve plotted for Brisbane City (population one million). The sharp increase in acceleration as the flywheel begins to supply power is characteristic of the present control algorithms and could be altered to a smoother profile as suggested on Figure 6 if necessary.

At present, one level of regenerative torque is available at any particular road speed when the accelerator pedal is released. On a level road, this yields the deceleration rates shown on Figure 6 during a vehicle stop from 60 km/h. Regeneration is presently to the flywheel only but could also include the batteries. At speeds below 10 km/h regeneration is not present. Although the amount of deceleration available has been tailored to give reasonable driveability in city and highway traffic optimum efficiency would be obtained if variable levels of regenerative torque were available from the brake pedal prior to actuation of the mechanical wheel brakes.

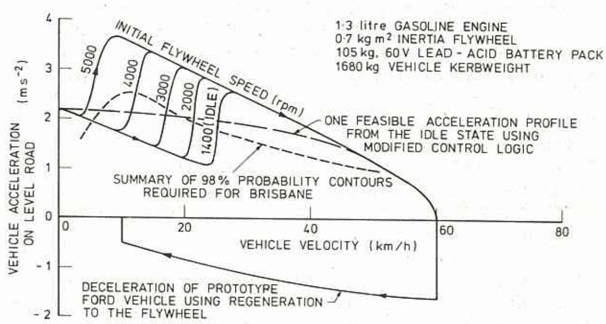


Fig. 6 Summary of hybrid vehicle acceleration performance.

Dynamometer tests confirm the computer predicted overall efficiency contours for the engine-transmission combination plotted on Figure 7. These are steady-state efficiencies obtained by operating the system at constant engine, flywheel and drive-shaft speeds without the battery in circuit.

The efficiency of the system is low at vehicle speeds below 10 km/h but improves quickly as vehicle speed increases and as the amount of power being transmitted via the electrical path relative to the mechanical path is decreased (as the generator/flywheel speed approaches zero). The noticeable changes in the contours at engine speeds around 3000 rpm are caused by the control logic on the engine throttle valve demanding torque from the engine in preference to maximum efficiency as it does below 3000 rpm.

When the system clamps the flywheel and operates on the vertical line through zero generator/flywheel speed on the speed map of Figure 7, all power is transmitted mechanically and efficiency contours of the engine transmission combination shown in Figure 8 are obtained. These values were measured during dynamometer tests with the transmission having run for approximately five hours. Mechanical losses have noticeably reduced since the transmission has performed sixty hours operation in road tests. Nevertheless mechanical efficiencies of the transmission alone appear to be up to 95% at a transmitted power of 24 kW. The torque demand curves for both level road cruising and 0.5 m/s^2 acceleration are plotted to show that the vehicle still has driveability in its mechanical drive mode with the particular 3.5:1 differential ratio selected even without resource to the electrical components which produce an infinitely variable gear ratio. A lower differential ratio would undoubtedly improve the vehicle economy but would require that a gear reduction be added to cater for low speed acceleration demands, e.g. a 2.92:1 differential ratio improves the cruise efficiency by approximately 18% over the 40 to 60 km/h range, as shown in Figure 8. In addition, a 1.5:1 gear reduction would significantly improve the low vehicle speed efficiency as shown in Figure 7.

While Figure 8 depicts steady state efficiency contours, actual vehicle acceleration trajectories are altered because of the trajectories followed. A trajectory similar to "A" on Figure 2, but from rest to 60 km/h, passes through efficiencies depicted on Figure 9. The battery is not included in the armature circuit. Efficiencies are initially low as a portion of the energy input from the engine is stored in the flywheel rather than output to the driveshaft. When the appropriate engine speed is reached, efficiency increases above those plotted on Figure 7 because stored energy in the flywheel is being used to supplement the liquid fuel-derived power from the engine. Curves for initial flywheel speeds of 1400 rpm and 4000 rpm are shown, with respective average efficiencies of 17.6% and 20.0% being achieved for the whole acceleration cycle. The latter case is typical of acceleration in city driving after regeneration, perhaps at traffic lights.

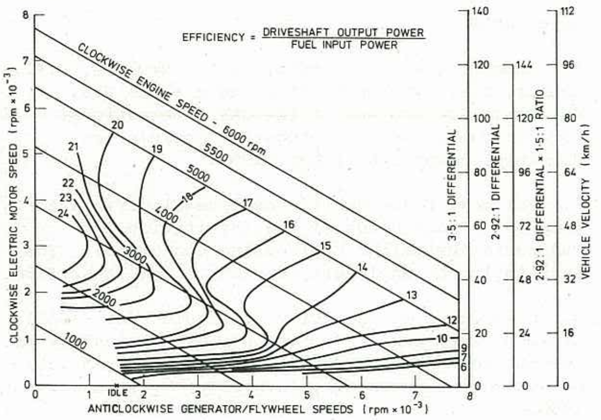


Fig. 7 Steady-state efficiency contours of the engine-transmission combination.

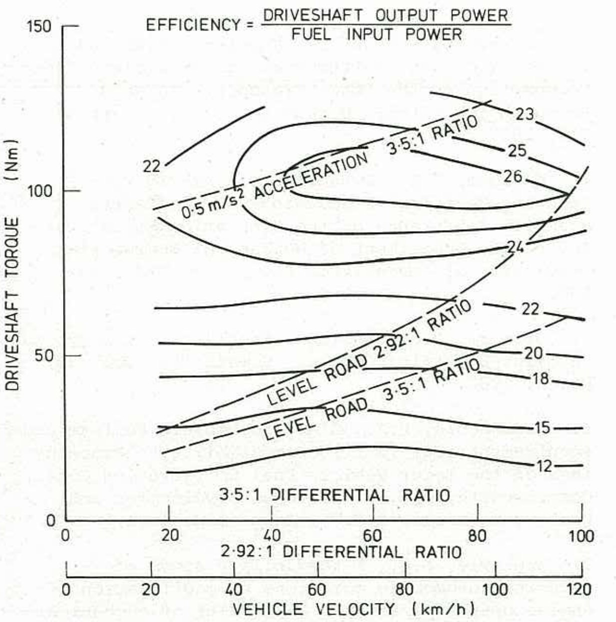


Fig. 8 Efficiency contours of the engine-transmission combination during flywheel lock up.

Regeneration tests on the transmission were performed as our dynamometer can supply power to the driveshaft to simulate the effect of inertia of a vehicle or downhill running. These tests generally confirmed the computer predicted contours of overall efficiency of energy transfer from driveshaft to the flywheel, depicted in Figure 10. A peak energy conversion efficiency of 50% is obtained when both the electric motor and generator are in an efficient operating range and the flywheel losses are relatively small. After sixty operational hours the flywheel took 192 secs to spin down under its own inertia from 7500 rpm to rest, absorbing 1.2 kW in mechanical and aerodynamic losses at a typical operating speed of 4000 rpm. Mechanical losses continue to decrease as the number of operating hours increases. Aerodynamic losses alone on the flywheel were approximately 0.25 kW at 4000 rpm rising to 1.3 kW at 7000 rpm.

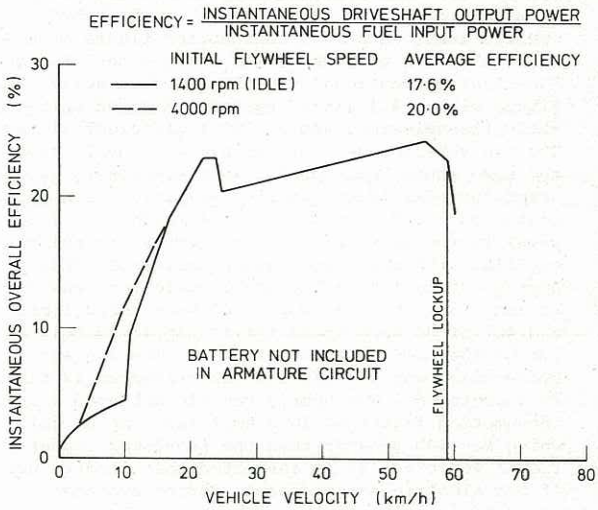


Fig. 9 Instantaneous efficiency of the engine-transmission combination during a vehicle acceleration to 60 km/h

Figure 10 also shows the trajectory followed by the generator/flywheel during deceleration of the vehicle from various initial vehicle speeds to rest on a level road. The level of regenerative torque applied to the electric motor has been selected for driveability so that the efficiency contours must be a function of the control logic applied. Flywheel speeds do not increase at vehicle speeds below about 20 km/h (and the efficiency is depicted as zero) because the power input to the flywheel from regeneration balances the mechanical and aerodynamic losses. Regenerative power is a maximum in the range 40 - 60 km/h and is lowered at higher speeds as the aerodynamic drag on the vehicle provides a greater proportion of the 98th percentile of deceleration demanded by drivers.

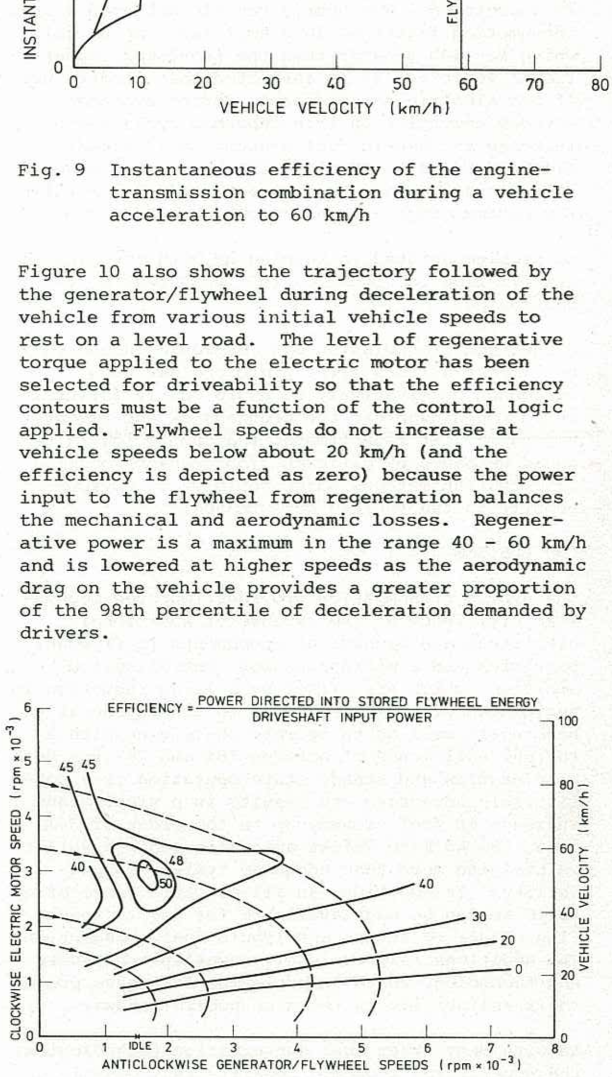


Fig. 10 Efficiency contours of energy transfer from driveshaft to flywheel during vehicle deceleration.

ROAD TESTING

Initial road tests have been performed over suburban and city routes referred to by Bullock (4). The routes were selected to be representative of average to high traffic densities - in excess of five thousand vehicles per day. The city route of 18 km cycle length is a typical route that would be traversed on several trips by a taxi or courier vehicle in the city. Moderate grade variations are present (maximum about 10%) and the speed limit is 60 km/h. No freeway driving was involved. The average speed during the tests was 18 km/h with approximately 33% of the time spent at idle. The 1680 kg kerb weight hybrid vehicle achieved a fuel consumption figure of 6.4 km/ℓ (15 mp US gal) which was 32% greater than an identical conventional vehicle of equal weight but fitted with a 4.1 litre engine, a 3 speed automatic transmission, and a 2.92:1 differential ratio. The two vehicles were driven simultaneously over the same route, maintaining acceleration rates and speeds as near identical as possible. The suburban route consisted of main arterial roads (not freeways) to the south of Brisbane. They are relatively flat with only minor grade variations (max. approximately 10%). The total cycle loop was 22.5 km long, 60% of which was of 60 km/h speed limit and 40% of 80 km/h speed limit. Approximately 12% of the time is spent at idle. The average cycle speed was 50 km/h and was traversed 12 times in succession. The hybrid vehicle achieved a fuel consumption figure of 10.0 km/ℓ (23.5 mp US gal) which was 34% greater than the identical conventional vehicle. It is estimated that limited use of the electric range feature during average workday commuting on this suburban cycle would increase the hybrid fuel economy to 10.5 km/ℓ (24.7 mp US gal). Maximum flywheel speed reached during the complete test cycle was 4000 rpm whilst the maximum engine speed reached was 3600 rpm.

No problem existed in keeping up with the general traffic flow in either cycle. Road testing is continuing.

Subsequent transmission systems would undoubtedly be lighter as this first prototype has been designed conservatively to avoid costly failures which would handicap the progress of the research programme. It is estimated that up to 150 kg could be saved by different (but conventional) construction methods which would be of obvious benefit to the vehicle performance.

CONCLUSIONS

The hybrid transmission provides improved mechanical efficiency at the expense of additional electrical and mechanical components (a flywheel, batteries and a microprocessor control system), additions which are offset by a large reduction in engine capacity. The ability to use regenerative braking as well as to operate the engine with a thermal efficiency of between 18% and 28% for both acceleration and steady state operation is a considerable advantage and results in a significant increase in fuel economy up to the order of 34% in a 1680 kg kerb weight automatic vehicle whilst maintaining more than adequate traffic compatibility. In addition, an all-electric range of up to 10 km can be made available for use in reduction of air pollution and liquid fuel consumption. The additions rely on readily available hardware and technology which in prototype form have proven their reliability in tests on public roadways.

As with many other fuel conservation technologies, the superficial economic benefits rely heavily on the future escalation of oil prices. It is accepted that a general upward trend greater than the rate of inflation is inevitable as crude oil supplies dwindle towards the year 2025 (1) and alternative fuel sources such as shale oil which are more costly to produce begin to enter the market place. However, on present estimations, an additional retail cost of US$1300 for such a hybrid vehicle in mass production, could be recouped in liquid fuel savings in two to six years depending on distance travelled. Battery replacement should be allowed for every three years. However, indirect savings to a nation in altering the balance of trade, reducing the road carnage by allowing the use of large crash-resistant vehicles and by adding a new dimension of possibilities in the reduction of air pollution in cities, creates an unquestionable case for detailed examination of this option.

ACKNOWLEDGEMENTS

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