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INNOVATION IN TRANSPORT VEHICLES IN AUSTRALIA

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INTRODUCTION

Over the last fifty years the Australian way of life, as indeed that of most developed countries has become heavily dependent on energy used for transport. Our cities in particular consume as much as 75% of the 67 megalitres of liquid fuel burnt daily for transport purposes in Australia. In the national interest and that of the individual consumer, it is mandatory that methods of liquid fuel conservation be examined (5). At present, predictions of the length of time that the world's crude oil supply will last, suggest that production could peak in the year 2010, with as much oil left to be produced after 2030 as we have produced up until 1983 (2,9). Synthetic fuels (shale, gas, oil and coal) could be expected to provide about 10% of the consumption in the year 2000 and an increasing proportion from thereon. However, Australia's crude oil reserves presently give us a level of 70% self-sufficiency which is expected to hold for this decade but decrease in the longer term. A strategy of oil conservation will extend this period of self-sufficiency and reduce the required production capacity (and the capital money requirements) for any future synthetic oil plants.

These incentives have promoted much research world-wide into the techniques of reducing the fuel consumption of our vehicles. The internal combustion engine is currently undergoing further intensive development work to improve its efficiency and emission characteristics. This work is primarily performed by automotive manufacturers and their consultants. Passenger vehicles are undergoing a weight reduction programme and this is the quickest and most economic method of reducing fuel consumption by design changes alone. However, the indirect costs associated with a reduced level of crash protection in the lighter body shells are likely to increase (10). The benefits achievable from current programmes are estimated to ultimately yield a 30% decrease in fuel consumption (14). Many new engine cycles and designs have been proposed and developed as well, but an option which has received much attention since 1975 is that of the hybrid vehicle. A hybrid vehicle in the broadest sense possesses multiple energy sources for its propulsion. The major alternative form of energy other than oil, available nationally and in sufficient quantities, is electricity derived from our massive coal resources.

Australia is in a good position to greatly reduce the liquid fuel consumption of its urban transport fleet by partial substitution of coal-derived energy for oil. Electric trains are the first step and this programme has begun.

The next stage is the partial use of energy stored in electro-chemical batteries to assist the existing internal combustion engines in public transport buses and commercial delivery vehicles This form of energy assistance in buses would maintain the flexibility of the vehicle to travel on any route, unlike trolley buses which rely on capital intensive overhead lines for electric power.

Electricity can be economically stored in lead-acid batteries whose practically achievable energy density of 0.1 MJ/kg far exceeds the other options of low speed 8000 rpm steel flywheels (.01 MJ/kg) and hydraulic accumulators (0.06 MJ/kg). Conversely the practically achievable power density of batteries (30 W/kg) is inferior to flywheels and hydraulic accumulators (greater than 1000 W/kg). Batteries also have the disadvantage of a much lower expected lifetime (200 to 500 deep discharge cycles) before replacement than do the last two items. The lead-acid combination is likely to remain the most economically viable electro-chemical battery in this decade (11).

THE TYPES OF HYBRID VEHICLE DEVELOPED

Hybrids using a combination of heat engine and electrical storage batteries are not new. There was one patented in 1906 but interest did not revive until the 1960s, paralleling that of all-electric vehicles. A developmental programme was begun in the USA during 1976 by the Department of Energy and since then other programmes have operated in the UK, Europe, Australia and Japan.

The early and still popular concepts of hybrid vehicles operate along two principles. Firstly, batteries are charged from the electricity grid and so electrical energy is substituted for petroleum energy when the vehicle is driven. Secondly, the batteries supply a form of energy storage to the vehicle which enables the heat engine to operate continually at a point closer to its peak efficiency than it would be in a conventional vehicle. This reduces the amount of fuel used to drive the vehicle without generally depleting the batteries.

Often the terminology "parallel" and "series" configurations is applied to the method by which the heat engine and electric motor are combined in a vehicle. These configurations involve different design philosophies and a vehicle is not normally easily converted from one system to the other. The parallel system connects both heat engine and electric motor directly to the transmission. The heat engine propels the vehicle with the electric motor (which can also act as a generator for battery charging or regeneration of vehicle kinetic energy). The electric motor provides extra low speed torque, extra power for acceleration, or the means to drive the vehicle at sustained low speeds in choked city traffic. A suitable control system coordinates the operation of the two power sources for easy operation by the driver. Because of the dual power sources, the battery, electric motor and heat engine can be individually smaller than in a pure heat engined or all electric vehicle. In a series system, the electric motor and heat engine are connected in series. The heat engine is allowed to run at a constant speed in its most efficient state to power a generating system to charge batteries. The batteries in turn are used as in all-electric vehicles to drive an electric motor. This system is inferior to a parallel system in overall efficiency, with presently available machines.

The two concepts of electric energy substitution and energy storage to improve operating efficiency can be applied simultaneously or individually to both the parallel and series combinations.

Major companies such as General Electric, Ford, General Motors, VW, Fiat, Briggs and Stratton, Lucas Chloride EV Systems (UK), as well any many smaller companies have developed and given limited demonstrations of hybrid passenger vehicle prototypes. Companies such as Mercedes Benz, Chloride and Man have developed prototype hybrid buses (2,8,12,13). Twenty hybrid buses based on a Mercedes chassis are undergoing road evaluation trials in Germany. Most recent practical prototypes have conformed to the parallel configuration for best efficiency and have aimed to achieved liquid fuel consumption reductions by electrical energy substitution. Typically, an all-electric range of 60 km is specified as well as top speeds of around 100 km/h, (70 km/h for a bus). The 300 to 400 kg of batteries required for this range (3 to 4 tonnes for a bus) as well as the weight of the electric motor commonly push the overall vehicle weight to over two tonnes for a 4 door sedan seating 5 adults. Liquid fuel economy can normally be reduced by around 30 to 50% although the primary energy used to perform the transportation task is often substantially unchanged (1,15). Electrical energy substitution does however reduce the reliance on a single source of fuel, and yields most of the benefits of an all-electric vehicle including the absence of emissions in congested city and suburban areas and quietness of operation. The hybrid can also overcome the disadvantages of a limited daily range, poor acceleration and a low speed normally attributed to all-electric vehicles.

HOW HYBRIDS COULD BE UTILIZED IN AUSTRALIA

Road transportation tasks in Australia are diverse and are presently divided into categories which determine whether amongst others, a heavy truck, light delivery van, bus, large passenger sedan are used. This division is sub-optimal as further sub-division can produce more specific tasks. The vehicles in the present categories do not produce their maximum possible fuel economy for all of their tasks because they have been designed to suit a broad range of duties. For example, a light delivery van is typically capable of a top speed of at least 100 km/h whereas the majority of its task might be performed in suburban and city areas where a speed limit of 60 km/h or less is imposed by law, and certainly by the traffic conditions. It has also been designed for a range between refuelling stops of perhaps 500 km whereas its average daily range may be only 100 km. The overall economics of sub-dividing vehicle task further than at present requires examination as capital charges, registration fees and maintenance costs would presumably increase if two specific duty vehicles were to replace a more general purpose vehicle. However, this sub-division has already occurred throughout this century and it is found necessary for an organization to own many different types of vehicles mentioned previously rather than a single type of vehicle - say a heavy truck which is quite capable of performing functionally the duties of all other categories, i.e. light delivery duties, passenger transportation, but with a decrease in fuel economy and convenience. Hybrid vehicles allow the sub-division of most vehicular categories into more specific task-oriented groups. When designing a vehicle to operate over a more restricted range between refuelling stops, it is possible to increase the fuel economy by more optimum design. The ultimate in design can be achieved with a vehicle required to operate at a constant speed and load. Road system design and traffic management play a very important role in approximating this goal by reducing the number of times a vehicle has to stop and accelerate.

As stated, 75% of the petroleum used for transportation in Australia is burnt in urban conditions where most commonly a legislated speed limit of 60 km/;h is applied with occasional freeways allowing 80-100 km/h. However, vehicular traffic congestion, intersections, pedestrian traffic and road terrain all contribute to produce much lower average speeds for most journeys.

Since 1979, Australia has participated in world-wide hybrid vehicle research through a group within the Department of Mechanical Engineering at the University of Queensland who have been supported by the National Energy Research Development and Demonstration Programme to develop and demonstrate two different systems which would be applicable to Australian conditions. The group began by identifying the requirements of road vehicles for the transport task. They selected four routes within the environs of Brisbane as being representative of traffic conditions in that city. Each main arterial road on these routes carries in excess of five thousand vehicles per day. The routes traverse the central business district, inner suburbs, outer suburbs and dual-highway to the south of the city and are characterized by the typical probability density distributions of velocity shown in Figure 1.

Average speeds range from 18 km/h in the central business district, 35 to 50 km/h in the suburban routes, and to 65-80 km/h on the highway route. Logically, as the average trip speed decreases, there is an increase in the time spent with the engine at idle producing no useful work for an expenditure of fuel. These low speed routes which are characterized by peak driveshaft power requirements of 40 kW and average requirements of only 7 kW in a 1500 kg vehicle, are ideal for hybrid and electric vehicles. Conversely, at the other extreme, high average speed routes have a small percentage of time spent at idle, a peak driveshaft power requirement which remains at 40 kW but an average requirement of 15 kW. These and higher speed routes are best suited to conventional heat engined vehicles which have optimally sized engines, and gear ratios, with a direct mechanical link between the engine and roadwheels. Most Australian passenger vehicles operate with an engine peak power to vehicle weight ratio of 60 kW/tonne but University of Queensland research has highlighted a figure of only 25 kW/tonne as being necessary to satisfy 98% of all vehicle requirements on Australian roads (4). A common criticism of hybrid vehicles is that they are not economic because they carry a redundant electric drive system which is not continuously utilized. This criticism can equally be directed at conventional engined vehicles which carry a redundant engine capacity which is seldom utilized and which causes higher fuel consumption.

A reduction in average traffic speed does not only create sub-optimum conditions for the fuel economy of vehicles. It also creates noise and exhaust emission pollution for pedestrians as these low speed routes are normally associated with shopping and business districts where easy access and proximity to vehicles is essential to their livelihood. A move to all-electric vehicles, hybrids which can drive on battery power only for a short distance, or to those which are very fuel efficient at low speed would yield several benefits in modern cities.

The two hybrid prototype vehicles developed within Australia at the University of Queensland were chosen from twelve initial design proposals (6,7,15). They were chosen as representing the greatest probability of being technically and economically feasible in this decade whilst incorporating novel ideas. The first major concept envisaged a vehicle which could substitute for Australia's large family sedans of around 1500 kg mass. It would be capable of a top speed of 120 km/h, adequate acceleration to meet traffic compatibility, and importantly an all-electric range powered by lead-acid batteries.

Figure 2 shows a schematic layout of the components whilst Figure 3 depicts the method which which the batteries are connected into the system.

In the passenger sedan chosen for this demonstration programme, the electric range is limited to 4 km as only 100 kg of batteries can be housed within the engine compartment leaving the interior and rear luggage space undisturbed. If another 100 kg of batteries were added to the rear luggage space, this all-electric range could be magnified to 20 km. However this hybrid can operate on the two principles mentioned previously. The batteries may be charged from the electricity grid to achieve coal-derived energy substitution, or used in conjunction with the remainder of the parallel-design systems which include a 400 kW petrol engine and a 200 kJ energystoring steel flywheel, to increase the average efficiency of that petrol engine whilst not depleting the batteries significantly during a trip. The vehicle is microprocessor controlled and work in the past twelve months has concentrated on the development of several different computer programmes which organize the interaction of the three sources of energy. The programme which is more suited to freeway driving demonstrates primarily the use of a flywheel in conjunction with an internal combustion engine for acceleration assistance and storage of kinetic energy on deceleration of the vehicle. Batteries are connected into the armature circuit of the electric motors via the relays depicted in Figure 3, only during an acceleration "Kickdown" mode to assist the peak torque demand. These peak demand periods normally last for less than 10 seconds. and are seldom required in normal traffic conditions. A 60 volt, 100 kg mass battery pack is used. This programme has been demonstrated in 7000 km of travel to date on Queensland public roadways and is able to reduce the fuel consumption of the vehicle by 30% when compared to its conventional-engined counterpart with automatic transmission. In order to increase this margin in fuel consumption, which is comparable with that which would be obtained is the small internal combustion engine alone was installed in the large, but now lighter, conventional sedan with its automatic transmission, the hybrid vehicle needs to be further optimized for a specific duty. The system cannot be optimized for an all purpose vehicle required to operate over a speed range as large as 0 to 120 km/h without the reluctant addition of perhaps two gear ratio changes on the driveshaft. The present prototype's efficiency on the highway suffers from the lack of suitable overdrive gear ratio to lower the engine speed and raise its overall efficiency during cruise. Presently installed gear ratios were chosen as a compromise to yield acceptable performance in the most probable speed range for suburban driving (30-60 km/h).

The most recently developed programme maintains the batteries in circuit continuously so that if not being discharged to assist vehicle acceleration, then they are being charged by one of the direct-current machines incorporated in the transmission. The programme produces a very driveable vehicle with smooth power transmission. It allows the opportunity for continuous load levelling by reducing the peak power requirement of the internal combustion engine by approximately 6 kW. This programme has been proven to be functionally reliable and is expected to yield significant fuel savings when tailored to a particular driving environment such as city stop-start or suburban.

Most vehicles of over 5 tonnes weight possess diesel engines and have a low power to weight ratio (typically 15 kW/tonne). A conventional multispeed transmission is efficient in these vehicles and a lower degree of traffic compatibility is acceptable. Modification to these classes of vehicle are mentioned later.

Vehicles under 1 tonne weight normally possess good fuel economy and so the financial incentive to increase it further is diminished. The vehicles also satisfy a niche of the consumer market which demands the lowest possible initial cost. The volume available to fit additional components is also scarce.

This hybrid transmission concept is therefore most suitable for heavy vehicles (1 to 5 tonnes) engaged in stop-start driving with long idle periods, and significant kinetic energy losses during deceleration (at least 3 stops per km travelled). It allows efficient high speed travel but its advantage compared to conventional vehicles with smaller engines becomes marginal. For an immediate economic point of view, the transmission is most suitable for installation in a small (up to 5 tonnes), petrol driven city bus which would posses an electric range capability when in congested areas and a more fuel efficient petrol powered running mode for normal driving. The main technical advantages include a stepless continuously variable transmission ratio and an integrated and compact approach to vehicle kinetic energy regeneration for fuel efficiency, as well as an all electric range. The major disadvantages include additional initial cost which is subject to a payback period, additional battery maintenance and replacement costs and increased complexity which must be engineered for reliability.

The second concept demonstrates the application of a small 700 cc diesel or petrol engine arranged in parallel with an electric motor, driving through a manual transmission in a 1500 kg vehicle. This is depicted schematically in Figure 4.

The engine is able to be operated at near its best efficiency throughout its speed range by using it to supply a base load, with 240 kg of batteries supplying the extra power needed for acceleration and hill climbing, and also acting as an energy sink for energy regenerated from the vehicle as it brakes. This concept demonstrates energy substitution. The successful prototype vehicle with a 10 kW diesel engine has a limited range of 50 km with a liquid fuel consumption of 21 km/l (60 mpg) and possesses adequate traffic compatibility in urban areas. Its top speed is 85 km/h and has been designed to meet the 80th percentile level of all acceleration demands. If the batteries are depleted, the vehicle can travel on the diesel engine alone at a lower acceleration performance level. After the vehicle has travelled on its batteries alone up to its maximum capability of 20 km, the batteries may be charged by the engine alone if desired. Further developments and innovations in design using this basic concept but using a more powerful petrol engine will produce vehicles of larger range (100 km) with higher performance and similar fuel consumption. This outcome follows a reduction in the peak power demand on the batteries which dramatically increases their average energy conversion efficiency. This system is immediately applicable to Australia for use in light urban delivery or passenger transport, initially in fleet operated networks for trial studies.

DESIGN CHANGES FOR URBAN BUSES

As mentioned in the preceding section, a hybrid transmission system gives little advantage in fuel efficiency to a vehicle weighing more than approximately 5 tonnes powered by a diesel engine through a multi-speed gearbox apart from the important ability to regenerate its kinetic energy on braking. The regenerative ability can be added separately together with other specific ideas which have evolved from the hybrid development programme. The most viable candidate vehicle for modification is the 10 tonne urban public transport bus, which commonly brakes to pick up passengers at up to 4 times per kilometre from speeds between 30 and 60 km/h, and can spend up to 60% of trip times at idle.

An examination of available energy storage components reveals that only hydrostatic pump/motors together with a flywheel or hydraulic accumulators have the necessary power/weight and power/volume ratios to construct a viable regenerative system. This innovation together with a novel method of utilizing idle fuel consumption would be applicable to all buses, regardless of the existing drivetrain arrangement or size. Stored energy would be available to assist the engine to accelerate the bus away from the stop giving better traffic compatibility than existing units. The regenerative system provides a dynamic braking system, which will extend the conventional mechanical brake lining lifetimes significantly and replace conventional hydraulic retarders. A schematic layout of the system is shown in Figure 5. Fuel savings on a bus route with an average of only 3 stops/km could amount o 35% of the existing fuel usage.

CONCLUSIONS

Hybrid vehicles can assist in reducing the national demand for oil. They can achieve this by substituting coal-derived energy in electrochemical storage batteries for oil, and/or by utilizing on-board energy storage to increase the average operating efficiency of heat engines. Their capabilities of a non-polluting and quiet all-electric driving range can be utilized in our cities to improve the environment. The vehicles provide these benefits at the expense of higher initial capital cost which can be recouped in liquid fuel savings, the rate being dependent on the amount of fuel consumed each year. A prototype hybrid passenger sedan incorporating a flywheel and batteries which has been demonstrated in Australia, would typically cost $1500 more if in mass production, and would be subject to a payback period of 6 years if 20,000 km were travelled each year (private motorist), or 1 year for 80,000 km (taxi). System reliability should be as high as existing vehicles providing that appropriate fleet trial vehicles are exhaustively tested and further developed. Immediate economic applications for Australia within this decade are foreseen in urban buses and delivery vehicles in the 1 to 5 tonne mass range. However, if the national goals of liquid fuel conservation, of promoting a shift from oil to coal and providing a large crashworthy vehicle for passenger safety are afforded priority, the hybrid vehicle would become more attractive in the passenger vehicle market. Hybrids would not dislocate current vehicle engine and chassis production lines. They would enhance industries supplying the extra components required, and are able to take full advantage of new developments in the automotive industry which will improve the operating efficiency and convenience of conventional heat engined vehicles.

The development of prototype vehicles in Australia has highlighted novel additions for urban buses of approximately 10 tonnes mass which could be expected to yield diesel fuel savings of up to 35% on stop-start routes.

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FIGURE 1

PROBABILITY DENSITY DISTRIBUTIONS OF VELOCITY FOR TYPICAL ROUTES

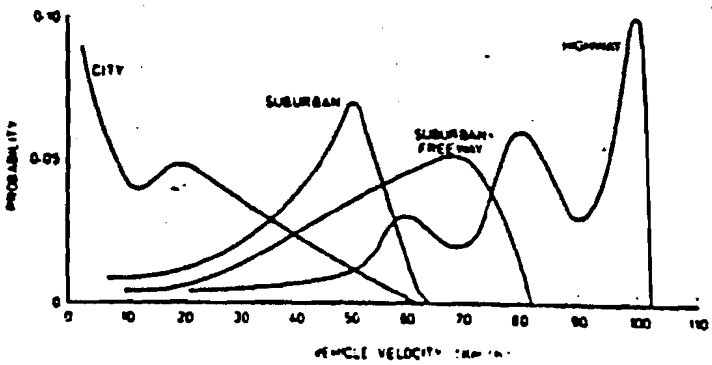

FIGURE 2

SCHEMATIC OF HYBRID TRANSMISSION (PETROL-FLYWHEEL-BATTERY)

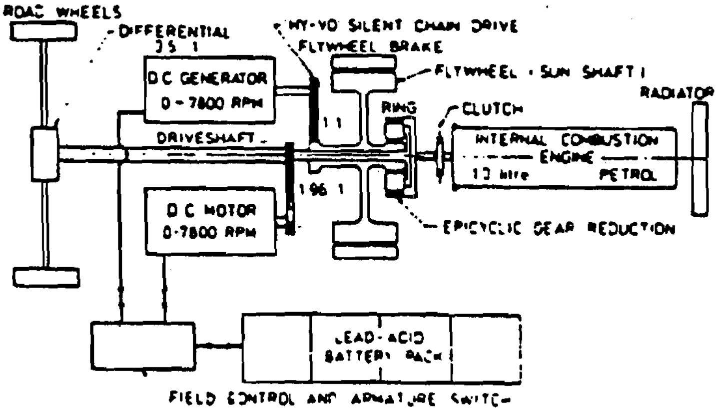

FIGURE 3

ELECTRICAL CIRCUIT FOR HYBRID TRANSMISSION

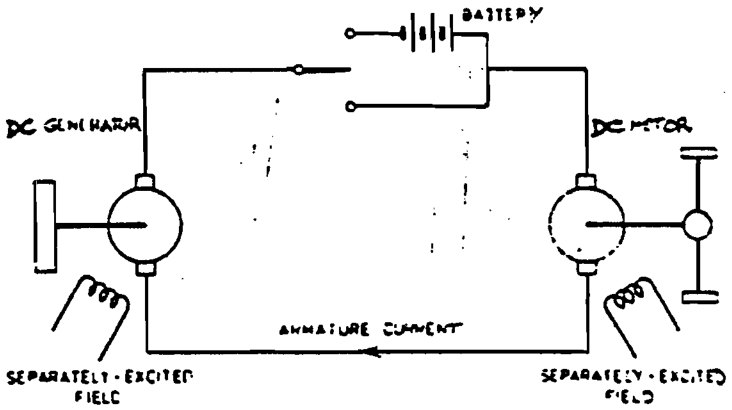

FIGURE 4

SCHEMATIC OF HYBRID TRANSMISSION (DIESEL-BATTERY)

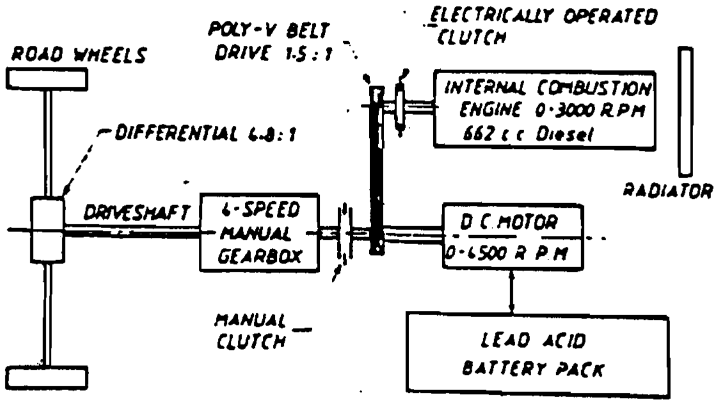

FIGURE 5

SCHEMATIC OF A BUS REGENERATIVE SYSTEM