MODELLING AND TESTING OF LONG RANGE BATTERY ELECTRIC VEHICLE PERFORMANCE

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ABSTRACT

There are two significant issues facing road transport in the medium to long term: the depletion of cheap oil reserves and the need to reduce carbon emissions. A long term solution for passenger cars could be the introduction of battery electric vehicles (BEVs). However, one of the main problems associated with the current generation of BEVs is their short range relative to conventional internal combustion engine (ICE) cars.

To investigate this issue, a long range battery electric vehicle, the UltraCommuter (UC), was constructed by the University of Waikato in partnership with HybridAuto Ltd. This paper describes the development, modelling and testing of the UC and its performance in the 2007 World Solar Challenge.

INTRODUCTION

In New Zealand (NZ), transport accounts for over 40% of carbon emissions in the energy sector (MED, 2007a) with private cars accounting for about 25% (FRST, 2006). At current growth rates, based on a ‘business as usual’ scenario, carbon emissions from transport would approximately double by 2050 (MED, 2007b).

To counter this predicted growth, the Ministry for Economic Development (MED) proposed, in its 2007 energy strategy document, a number of initiatives for reducing carbon emissions. The strategy includes the in-principle decision to halve carbon emissions from domestic transport by 2040, and for New Zealand to be one of the first countries to widely deploy electric vehicles. It is interesting to note that in the strategy document oil depletion is not considered as important as carbon emissions.

New Zealand is of similar physical size to the United Kingdom (UK) but has a population of only 4 million and over 2 million licensed private cars (LTNZ, 2005). Due to economics, NZ has a far less developed public transport infrastructure compared to the UK. As such New Zealander’s are more dependent on private cars for both short and long journeys. Therefore, battery electric vehicles (BEVs) in NZ will require a longer range than BEVs in countries where public transport is more developed. In this investigation, long range BEV means over 500 km with 80% discharge of the battery pack, so that the performance is directly comparable to conventional internal combustion engine vehicles (ICEV).

A key factor that led to the predominance of the petrol car over the battery electric car is that the energy density of petrol is approximately 300 times greater than that of lead-acid batteries, thus giving the ICEV superior range. This coupled with cheap and abundant oil meant BEVs were relegated to niche markets such as milk delivery floats, golf buggies and mobility scooters.

However, recent improvements in battery performance mean that BEVs could become a mainstream vehicle technology. In Figure 1 it can be seen that the energy density of rechargeable (secondary) batteries has increased significantly since electric vehicles were first introduced. The earliest BEVs used lead-acid batteries, which have an energy density of approximately 30-40 Wh/kg. Batteries such as Ni-Cad and Ni-MH have superior energy density but are lower than state of the art battery technologies such as Lithium-ion and Lithium-polymer that have energy densities ranging from approximately 100 – 200 Wh/kg.

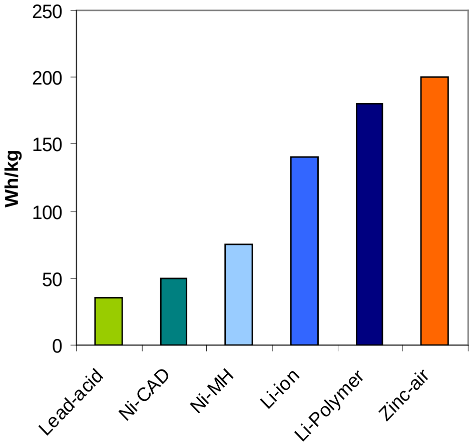

Figure 1: Energy Density of Batteries

There are however some issues that need to be addressed when BEVs are considered for wide spread deployment in NZ, in particular relating to the lack of public transport infrastructure. Therefore, to achieve a level of comparable mobility, long range BEVs with a performance similar to existing ICEVs will be required to satisfy NZ's ambition of wide spread electric vehicle deployment, in the short to medium term. As such, this work examines the technical requirements needed to achieve long range BEVs and discusses the development of a vehicle to achieve these requirements.

OVERVIEW OF THE ULTRACOMMUTER

The background of the UC development team is in the design of solar racing cars. The best solar cars can typically drive at over 100 km/h for several hours using approximately 2 kW power. However, solar cars are not practical vehicles for passenger transport although a significant portion of the design considerations for these vehicles are translatable into the design of BEVs. As such, solar car design methodology has been applied to the UC to achieve a practical passenger vehicle that uses relatively low power at highway speeds.

The key features of the UC are low aerodynamic drag, lightweight, high electrical to mechanical efficiency and the use of Lithium batteries. The power equation for vehicles travelling at a constant 100km/h was used to determine the critical parameters for the

UC. The power requirements of the UC with a conventional ICEV and ICEV converted to battery electric were then compared.

The UC prototype, shown in Fig. 1, was completed in October 2007 and participated in the Greenfleet Class of the 2007 World Solar Challenge (WSC), completing 2000 km of the route from Darwin to Adelaide.

Figure 2: UltraCommuter at 2007 WSC

Modelling the UltraCommuter power requirements

To determine the feasibility of the long range UC BEV its power requirements were compared to that of a conventional ICEV and ICEV converted to battery electric under the same operating conditions. The latter investigation also enabled the feasibility of converting existing ICEV to battery electric to be assessed.

The analysis of the required power for each vehicle is relatively straightforward: the vehicle specifications shown in Table 1 were used to calculate the power required for propulsion during highway driving. In previous work, a simulation of the UC BEV showed little difference in energy consumption between 100 km/h highway driving (70 Wh/kg) and variable speed urban driving (67 Wh/km), (Simpson et al, 2005). Therefore, in this study the power required to propel the cars at a constant speed was calculated and used to determine the distance that they could travel using either the energy stored in the batteries or petrol. To simplify the analyses, information regarding acceleration, braking, cornering, hills and headwinds were not considered. The analyses were based on vehicle speeds of either 85 km/h or 100 km/h, to simulate highway driving and the speed of the UC when tested. As such, the power required to propel a vehicle travelling at constant speed on a straight, flat road with no headwind is given by Equation (1):

$$P_c = \frac{C_d \, A \rho V^3}{2} + M \, g \, RR \, V \qquad (1)$$

Where:

Pc = Power to propel car (W)

C_d = Drag coefficient

A = Frontal area (m^2)

ρ = Air density (1.2 kg/m^2)

V = Speed (m/s)

M = Mass (kg)

g = Gravity (9.81m/s/s)

RR = Rolling resistance

For a typical ICE saloon, specification data was obtained from a number of sources, for example (Bosch, 2004). It was found that the C_d value of a typical ICE saloon is between 0.3 and 0.4. An ICE saloon suitable for conversion to battery power was assumed to have a C_d of 0.31 as this would offer the best performance. A computational fluid dynamic analysis of the UC (Fig. 3) predicted a C_d of 0.25. Furthermore, it was found that the frontal area (A) of a typical ICEV was 2.3 m^2, giving a C_dA of 0.71 m^2 whereas the UC had a frontal area of 1.7 m^2, giving a lower C_dA of 0.425 m^2.

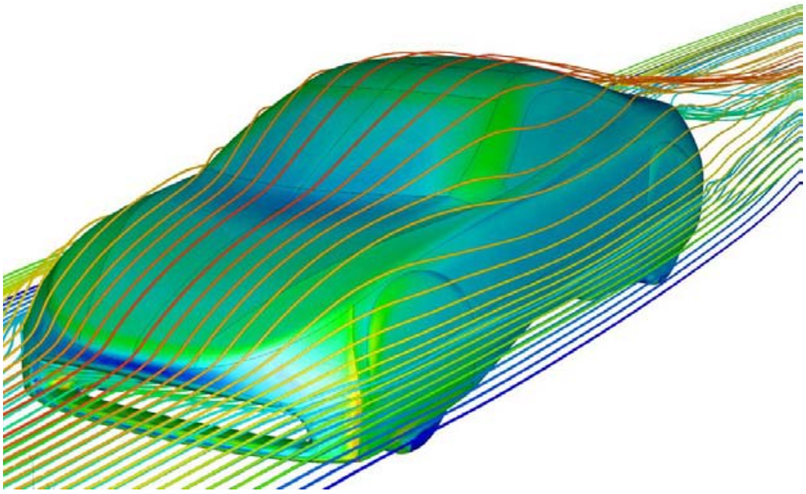

Figure 3: CFD Model of UC

In addition, it was assumed that the typical ICE saloon had a mass of 1270 kg including 80 kg driver and 30 kg petrol. For the ICE saloon converted to battery it was assumed that the total mass was 1235 kg (IC engine removed) including 80 kg driver and 300 kg batteries. The UC was analysed for two masses, 710 kg and 865 kg. The former related to a battery pack of 135 kg with an energy density of 96 Wh/kg and the latter of 300 kg and energy density of 178 Wh/kg. In both cases it was assumed that the driver had a mass of 80 kg. The low relative mass of the UC was achieved by using high strength to weight ratio components. For example the chassis shown in Fig. 4 was made from aluminium honeycomb composite and had a mass of 62 kg, excluding suspension and wheels whereas steel chassis’ can have a mass of approximately 200 kg.

Figure 4: UltraCommuter chassis

For all vehicles the rolling resistance (*RR*) is dependent on tyre type, speed, pressure, road surface and condition and is usually between 0.01 and 0.02 (Bosch, 2004). The *RR* of a typical ICEV was therefore conservatively assumed to be 0.014. The UC however was fitted with low rolling resistance tyres with an *RR* of approximately 0.008.

As discussed earlier, several different types of battery are currently available for BEVs. In this work, commercially available Lithium batteries developed for electric vehicles were used in the testing and calculations. The energy density of the Lithium batteries used in the UC during testing was 96 Wh/kg giving 10.4 kWh at 80% discharge. To verify the mathematical model, the same vehicle data, operating conditions and batteries as the actual UC were used.

Further calculations were undertaken with the UC using commercially available Lithium batteries with an energy density of 178 Wh/kg and a capacity of 42.6 kWh at 80% discharge. The ICE converted to battery electric was also modelled with the same battery type and capacity.

It was assumed that the vehicles would only discharge 80% of the available battery capacity as a repeated 100% discharge could significantly reduce battery life. The manufacturers claim that the batteries could be 80% discharged between 800 and 2000 times depending on type. As depth of discharge would normally be less than this, it is possible that the batteries could last over 10 years or the life of the vehicle.

It was also assumed that the electrical energy for the UC was converted to drive by a motor and controller with an overall efficiency of 0.92. Such high efficiencies arise from the use of brushless DC motors built into the wheel of the vehicle, which eliminate the need for a gearbox and transmission. In comparison, a typical ICEV has an overall petrol-to-wheel conversion efficiency of approximately 0.18 (Ahman, 2000). In this work an overall value of 0.2 was used to take into account increased efficiency for constant speed driving at 100 km/h. Finally, the ICEV converted to battery power was assumed to have an overall efficiency of 0.8 because it would not include brushless in-wheel motors and therefore, losses would be incurred in mechanical transmission.

Table 1: Vehicle properties

Vehicle	Mass batt or petrol (kg)	Total Mass (kg)	C_dA (m^2)	RR
UC tested	135	710		
UC calculated	135	710	0.425	0.008
UC calculated	300	865	0.425	0.008
ICE battery	135	1235	0.71	0.014
ICE Petrol	30	1270	0.71	0.014

Testing the UltraCommuter power requirements

The UC testing was undertaken during the 2007 World Solar Challenge (WSC). The WSC is a biennial event where solar powered cars drive from Darwin to Adelaide in the fastest time. The UC was entered in the Greenfleet class which is for demonstration of new vehicle technologies only and therefore not a race. As such Greenfleet entrants are expected to complete the route in 6 days, driving approximately 500 km/day.

The power from the UC batteries was measured from the current and voltage when the UC was being driven on a flat section of road with no turns or noticeable head or tail wind. Before the start of the test run, the battery pack was fully charged and equalised to ensure each of the 45 batteries had the same voltage and state of charge. The UC was occupied by the driver only, and he kept the speed constant during the test run. The UC was driven until the battery voltage indicated that they were 80% discharged. At that point the discharged battery pack was removed and another fully charged battery pack installed. This process took about 20 minutes and was carried out three times a day. At the end of a day there were three discharged battery packs that were then charged from camp site power supplies over night.

RESULTS

In Table 2 the calculated power required to propel the UC, from both calculations and tests are shown. Also shown is the power of an ICEV and an ICEV electric conversion when driven at 100 km/h. P_c is the power required by the car, P_{batt} and P_{petrol} is the power from the supply source, either battery or petrol respectively. From these results it can be seen that the UC when tested, used only 5 kW power at 85km/h whereas the calculated power was 5.1 kW, slightly more than the test result.

Table 2: Vehicle Power

Vehicle	Speed km/h	P_c kW	Eff	P_{batt} or P_{petrol} kW
UC tested	85			5.0
UC calculated	85	4.7	0.92	5.1
UC calculated	100	7.3	0.92	8.0
ICE battery	100	15.1	0.8	19.8
ICE Petrol	100	15.2	0.2	77.0

Furthermore, the range of the vehicles both from testing and calculations are shown in Table 3. The UC travelled approximately 180km on one Lithium battery pack using 10.4 kWh (80% discharge of a 13 kWh battery) and travelling at an average speed of 85 km/h. The calculated range at that speed was 174 km, showing that the model accurately predicts the UC performance for highway driving.

At 100 km/h the UC power increases to 8 kW but is less than half that of the 19.8 kW of the ICEV converted to battery. This highlights the benefits of designing BEVs to be energy efficient and that converting existing ICEV to battery electric is far from optimal.With a larger, higher specification battery pack of mass 300 kg and 42.6 kWh at 80% discharge, the UC could travel over 500 km at highway speed, more than twice the distance of an ICEV converted to battery. It should be noted that there is adequate space in the UC chassis, to accommodate the larger battery pack.

It can also be seen that the for a petrol car to travel at the same speed (100 km/h) it requires approximately 77 kW of power from the petrol, nearly 10 times that of the UC. This highlights the inefficient use of energy in conventional ICE cars.

Table 3: Vehicle Performance

Vehicle	Speed km/h	Energy batt or petrol kWh	Range km
UC tested	85	10.4	180
UC calculated	85	10.4	174
UC calculated	100	42.6	532
ICE battery	100	42.6	232
ICE Petrol	100	390.0	549

CONCLUSIONS

In its efforts to reduce carbon emissions from transport, the NZ government is considering the wide spread deployment of electric vehicles. New Zealand is dependent on private cars for both long and short journeys due to the lack of public transport infrastructure. Long range electric vehicles that have a range comparable to existing ICE cars could be a solution.

The UltraCommuter BEV was developed to investigate the potential for long range electric cars that have a range comparable to existing ICE cars. When tested, the UC achieved a range of 180 km using 10.4 kWh of battery energy. The model predicted 174 km under the same conditions. The model predicted that the UC is capable of a range of over 500 km at a highway speed of 100 km/h using existing battery technology. The long range of the UC was achieved by having a lightweight chassis, low aerodynamic drag, high drive efficiency and Lithium batteries.

In comparison an ICE saloon converted to battery can achieve less than half this distance. This shows that to achieve a long range, BEVs must be designed specifically as low energy vehicles and not converted from conventional ICE cars.

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