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Short communication

Hydrogen fuel cell hybrid vehicles (HFCHV) for Birmingham campus

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ABSTRACT

The design of a campus mail delivery vehicle powered by 350 bar hydrogen feeding a 1.2 kW PEM fuel cell to charge a lead acid battery pack is described. Five vehicles supplied to the campus at the University of Birmingham to measure the performance and to evaluate relevance to fleet operations are discussed. It is shown that the performance is better than that of a standard diesel van in two drive cycles, one following an academic circuit around the campus, the other doing multiple mail delivery stops. The acceleration and drive cycle compliance are found to be adequate on campus and the efficiency is significantly better than the diesel. The need for extension of range and increase in power and acceleration to meet standard urban drive cycles is clearly demonstrated.

1. Introduction

A serious problem on University campuses across the UK is the large number of internal combustion engine (ICE) vehicles with their consequent inefficiencies and emissions. For example, the University of Birmingham operates a fleet of 110 vehicles for delivery and other duties, mainly diesel vans like the Ford Connect. The total fleet mileage is 2 million miles per annum contributing 400 tons of carbon to the environment together with toxic emissions of carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HCs) and particulates.

On campus, the diesel vans display poor efficiency, doing 28 mpg on mail delivery cycles, corresponding to 0.26 km MJ^{-1} (SI units). This is considerably less than the 36 mpg for the standard urban cycle and 45 mpg for the combined urban and extra-urban cycles. The diesel Connect van is designed for motorway use and is not suited to a campus with a 20 mph speed limit, short roads and many stops. Battery plug-in electric vehicles should be more appropriate for this campus environment. The University therefore operates five battery plug-in vehicles including a John Deere truck used by the gardeners and a Mega pick-up in the Botanical gardens. The problem of these vehicles is short battery life caused by deep discharge. Fleet operations have shown that the lead acid batteries can fail in 2 years, an uneconomic lifetime. This paper considers how hydrogen and fuel cells can be combined in a hybrid battery plug-in vehicle to give improved performance in two campus drive cycles. Hybrid hydrogen fuel cell vehicles have been explored theoretically in a number of previous papers [1–4] but most operational hydrogen hybrids have been combustion engine Prius vehicles [5,6] which continue to emit NO_x. The purpose of this study was to introduce a new design of lightweight hydrogen fuel cell hybrid on campus, to test several vehicles in two drive cycles and to point out improvements necessary in future. An earlier paper [7] described the preliminary results.

2. Hybrid vehicle design

2.1. Power-train components

To avoid the problems of pure battery electric vehicles (which suffer limited driving range and short battery lifetime due to deep discharges), the vehicle was designed with a fuel cell battery charger which topped up the lead acid accumulator when the vehicle was idle. The 1.2 kW Ballard Nexa PEM fuel cell was used, as it was compact and relatively low cost, and provided the durability required for the demanding operating environment. The stack efficiency quoted by Ballard was 38% (LHV) at full power and 48% at half power inclusive of parasitic loads. This was consistent with measurements taken from the stacks installed into the vehicle fleet.

Overall, fuel cell reliability has been excellent to date, providing over 2000 h of operation across the fleet and 2000 km travelled with no technical problems or observable degradation. Experimental

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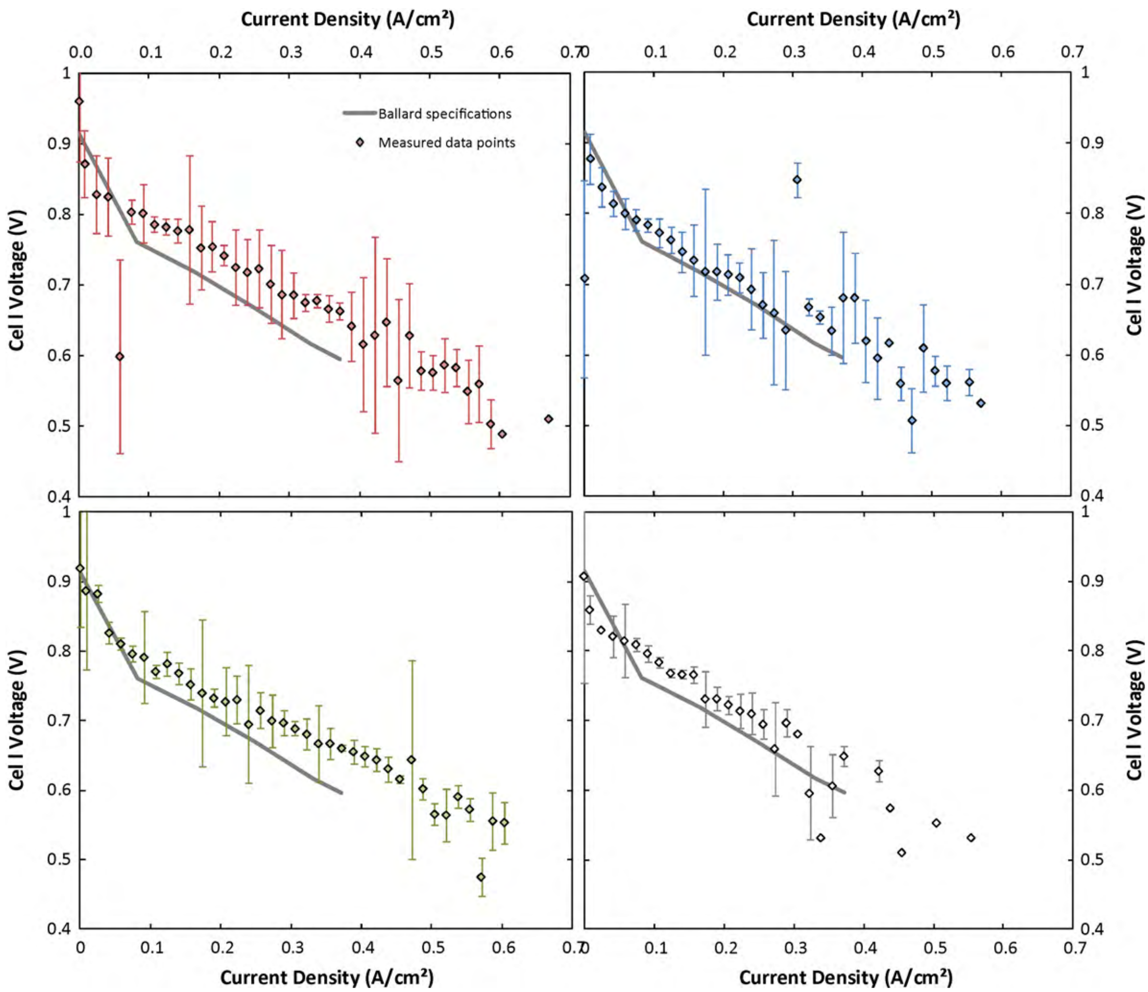

Fig. 1. *V–I* curves taken from the Ballard Nexa stacks installed in each vehicle.

V–I curves for the stacks in four of the vehicles are shown in Fig. 1, and demonstrate that the PEM fuel cell performance is consistent between stacks and against manufacturer's specifications – despite incidences of fuel starvation, excessive current draw, rapid power cycling, ambient temperature extremes and vibration/shock received during operation.

Since electrical energy storage was not a problem for the hybrid vehicles, the battery pack was downsized from a typical 300–400 kg to 60 kg. This held 21.5 A h of charge at 48 V (0.95 kWh) at a 30 min discharge rate, which was typical for campus driving conditions.[1] These batteries provided the 10–15 kW of power required for peak acceleration, providing the short bursts needed from the 4 kW rated GE motor.

To provide an adequate driving range, 0.6 kg of hydrogen was stored in a 350 bar compressed cylinder, giving 20 kWh of chemical energy storage (LHV) which could be converted to 7.6 kWh of electricity at the rated stack efficiency. The hydrogen storage tank was an aluminium core, fibre wound cylinder supplied by Dynetek (Canada). Rapid refuelling was possible with the hydrogen tank being charged to 350 bar in 4 min on average. Although the vehicle could still be plugged in to the electricity grid for a 6 h trickle charge, the rapid hydrogen refuelling gave improved flexibility in operation.

The mechanical and electrical integration of these components was in a series–parallel hybrid configuration, as shown in Figs. 2 and 3. The fuel cell was operated in parallel with the battery pack when driving to provide greater peak power, and in series to recharge the battery pack when no power was demanded by the motor. A simple timer based control strategy was employed, where the fuel cell was started with the vehicle ignition, and was stopped

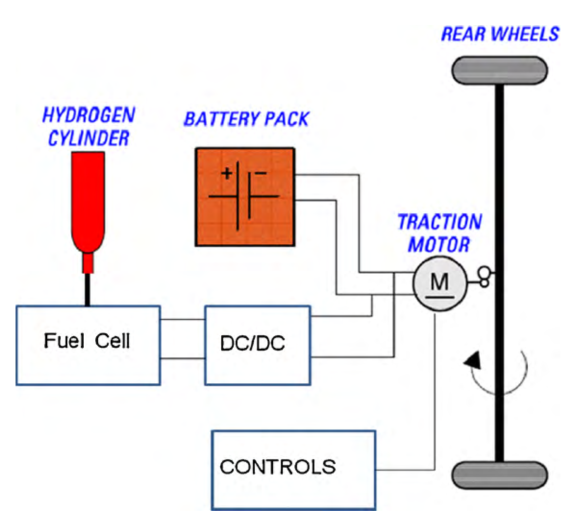

Fig. 2. Mechanical drive system layout.

[1] When measured at the standard 10 h rate, the batteries could provide 50% more energy (32 A, or 1.50 kWh).

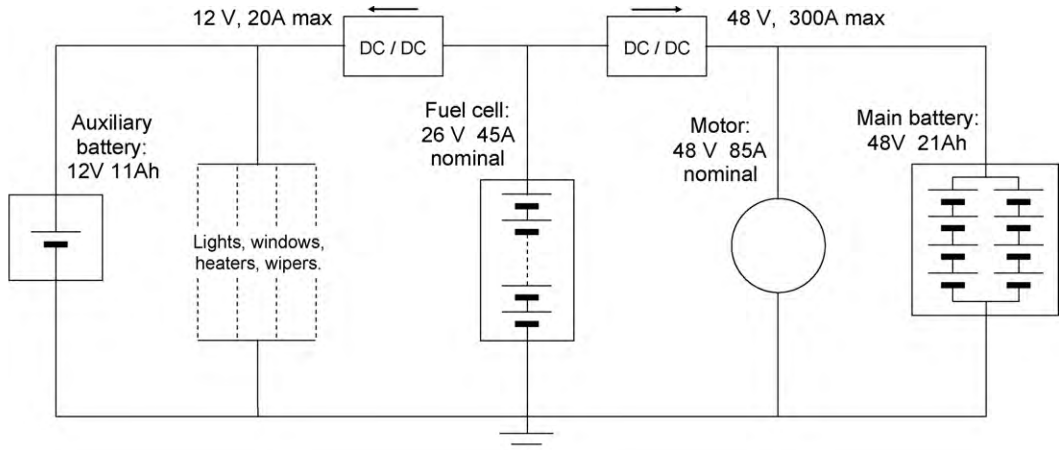

Fig. 3. Electrical drive system layout.

7 min after the ignition was turned off again. This time was chosen to allow the fuel cell to replenish the battery pack to more than 95% state of charge after the typical drive cycles experienced on campus. The 24–48 V DC/DC converter attempted to provide as much current as requested by the motor and main battery pack up to a limit of 50 A, hence the fuel cell operated at full power for the majority of a drive cycle, and decreased output only once the battery pack approached full state of charge.

2.2. Vehicle design

A major objective of the campus vehicle design was achieving a low mass so as to maximise energy efficiency. By utilising an aluminium chassis and lightweight GRP body panels, the design weight was 500 kg. However the finished vehicles weighed 667 kg due to additional batteries, chassis material to protect the fuel cell, and several data logging systems that were installed. Although the vehicle weight was one-third over the design value, it was still around half that of a typical European 4-seater vehicle, demonstrating the substantial improvements that can be made over today's vehicles.

By reducing the weight and thus the power requirements of the vehicle, the production cost was also substantially lowered. The Microcab vehicle development cost was approximately $700k compared with $420 million for a typical electric vehicle development programme [8]. A major benefit of hybridisation was the expensive stack component which could be reduced from 70 to 100 kW for a typical fuel cell vehicle to just 1.2 kW, so the Ballard Nexa system cost only £4000. The hydrogen tank cost an additional £4000, and the batteries were £800.

Standard parts such as wheels and windscreens were obtained from production vehicles to reduce cost. The chassis was a sandwich structure and the steel frame was assembled around it to contain the fuel cell, motor and hydrogen tank. The layout of the parts is shown in Fig. 4. The fuel cell, its hydrogen tank and electric motor were packaged in the rear compartment over the back axle. The sandwich chassis allowed the 8 × 12 V lead acid traction batteries to be arranged under the passenger compartment floor to give a low centre of gravity.

2.3. Campus demonstration

To allow the vehicles to be built and tested on campus, financial support was obtained from the regional Development Agency, Advantage West Midlands (AWM) who injected £1 million for the capital items, EPSRC who put in £1.5 million to fund 5 researchers investigating the hydrogen supply chain, and DBERR (now DECC) which gave a grant of £1.3 million to support the small companies in the consortium. In addition 60 small companies in the region contributed to the supply chain project with £1 million of effort.

A filling station was installed behind the School of Chemical Engineering to refuel the vehicles with hydrogen at 350 bar. Green hydrogen was sourced from Green Gases Ltd., who use anaerobic digestion of agricultural waste to power carbon-neutral electrolysis, and then deliver the produced hydrogen to the campus in steel cylinder packs. The hydrogen was pressurised using a compressed air pump to store at 400 bar in the Air Products refueller. Then hydrogen was dispensed into the vehicle by a trained operator. This operation took an average of 3–5 min to pump 0.6 kg of hydrogen into the composite storage tank. The hydrogen was fed to the Ballard Nexa PEMFC system which recharged the batteries, giving approximately 40–80 km range. At the moment this is sufficient for 5 days of campus operation, so that refuelling is a weekly task. The results of the hydrogen refuelling tests showed that 107 fillings had been completed in the project, transferring 36.5 kg of hydrogen with no leaks or incidents. Some minor issues were experienced with the filling station, including seal replacement twice and contamination immediately after installation which required 10 purgings.

The five vehicles shown in Fig. 5 were delivered in March 2008 and have been tested over the past 18 months to assess their

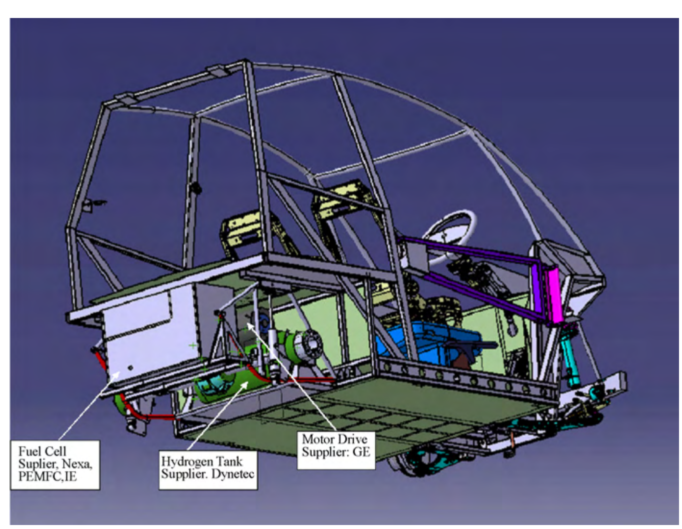

Fig. 4. Design of frame showing the layout of the fuel cell, hydrogen tank and motor.

Fig. 5. Five Microcab vehicles on campus.

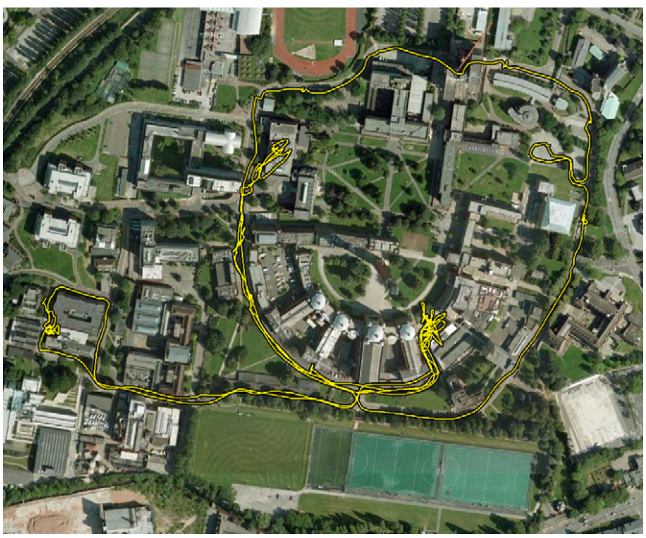

Fig. 6. Map of the postal duty cycle map on campus.

efficiency in two campus drive cycles. The design priorities of acceleration ($1.5\ m\,s^{-2}$) top speed (30 mph) load capacity (200 kg) and access to wheelchairs were attained, however the vehicle range was somewhat less than the design figure of 100 miles.

3. Two drive cycles

Fig. 6 shows the plan of the University of Birmingham campus with the postal circuit indicated. This was typical of the route that the postal services use each day, and was compared to an academic drive cycle where the vehicles were driven in a loop around the perimeter road, with stop/start cycles reduced to a minimum.

Fig. 7 shows one set of results from the vehicle being driven on the academic cycle. Power from the fuel cell was plotted against time with the velocity results derived from the GPS system, which shows two 5 min runs around the circuit with a 7 min stop in between, followed by 12 min of battery charging. It can be seen that the fuel cell power remained constant at 1300 W during the driving periods and for the first 6 min of the rest periods, after which the power began to drop as the battery became fully recharged. The Nexa stack is capable of handling brief current surges, and so it was seen to produce 1700 W (~60 A at 28 V) for the first 8–11 s of each driving period before settling down to its nominal operating point of 1300 W.

The fuel cell was shown to fulfil its dual role as a power motive source during acceleration, but also as a battery charger when the vehicle was at rest. During the drive, the charge held in the main batteries was depleted by a maximum of 24%, but was seen to be replenished during the 7 min stop and again at the end of the run. 200 runs were carried out around this campus circuit, doing 220 miles and requiring 5 fillings of 0.6 kg hydrogen. The hydrogen consumption of the vehicle was $10.0\ g\,km^{-1}$, giving an energy efficiency of $0.71\ km\,MJ^{-1}$, equivalent to 77 mpg of diesel equivalent. The Microcab therefore offered three times the efficiency of the diesel van control.

These results were contrasted with measurements from a mail delivery duty cycle proposed by the University of Birmingham fleet manager using five drivers from the University pool. Fig. 8 shows the speed, power output and battery status over a 40 min sample from the mail delivery route, illustrating the large number of stationary periods in which the fuel cell recharged the battery. The top line shows the fuel cell power output during this journey. It was evident that the fuel cell was not running steadily but was kicking in each time the vehicle was driven, then decreasing power output as the accumulator was filled rapidly at each stop. Again, this meant that the batteries were not discharged by more than 25% during the drive cycle, and were fully replenished with 6 min of charging after the run finished. Efficiency of the fuel cell could readily be improved by adjusting its power downwards in this situation to better match the power requirements of the drive cycle.

The results from the mail runs were worse in efficiency terms than those from the academic circuit. Altogether 160 mail runs were completed, comprising 175 miles of operation, with 10 fillings and 5 kg of hydrogen transferred. Hydrogen consumption was $17.4\ g\,km^{-1}$, which corresponded to $0.41\ km\,MJ^{-1}$ (44 mpg diesel equivalent). This was an improvement on the diesel van but only half the efficiency of the academic run. The total van mileage was 560 in 216 h giving an average speed of 2.6 mph. The histogram of efficiency results across the entire vehicle fleet is shown in Fig. 9, with the academic and mail runs highlighted.

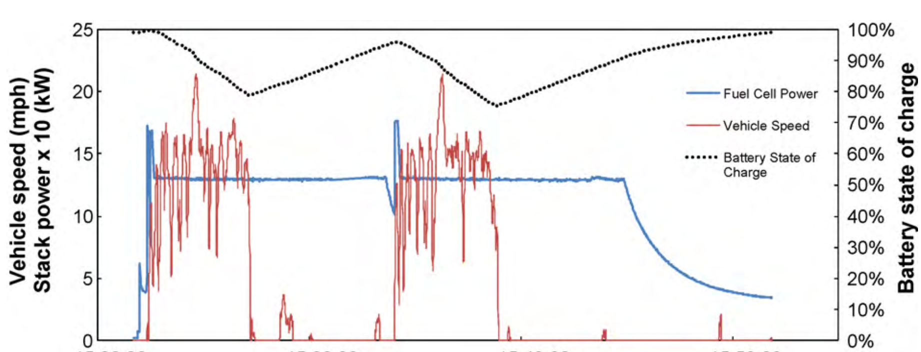

Fig. 7. Fuel cell power and battery state of charge versus vehicle velocity during an academic drive cycle.

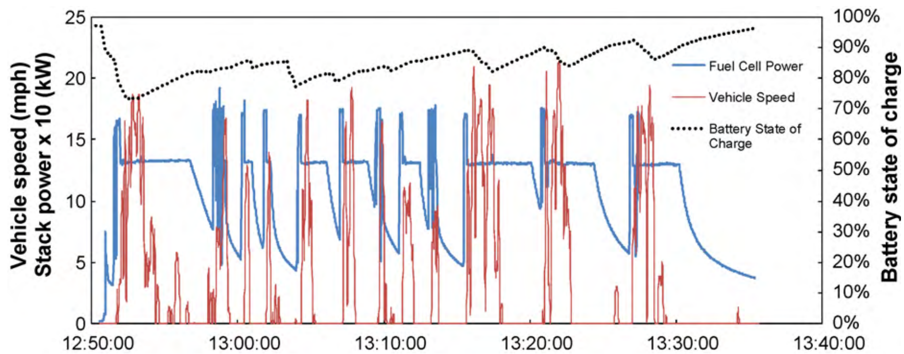

Fig. 8. Mail delivery route with fuel cell power, battery state and velocity measurements.

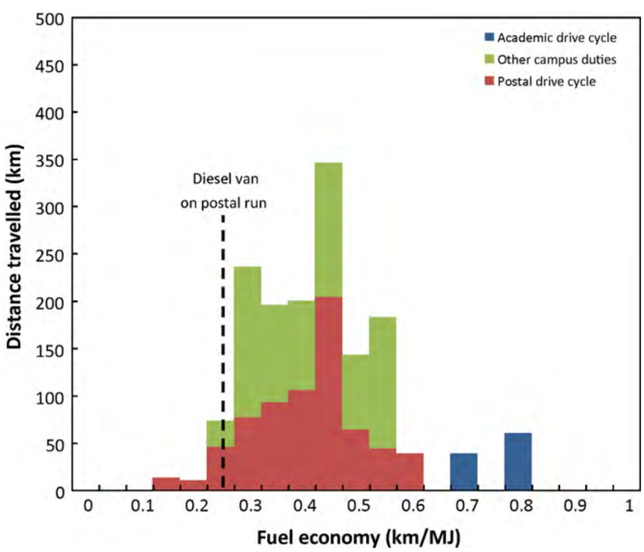

Fig. 9. Distribution of driver efficiencies on mail and other runs.

Possible explanations for this result are:

- Mail delivery staff need training in 'eco-driving' techniques.
- The fuel cell was not operating in its optimum range.
- Regenerative braking was deactivated.

This last point was significant because one of the original design features was that braking energy could be recuperated. As the battery size was reduced, it was not possible to absorb the large pulse of braking energy, and burn-out of the DC converter was experienced. It is therefore important to install more surge buffering in the system to recycle some of this energy.

Some other difficulties discovered during the runs were:

- Overheating of the fuel cell.
- Battery drain from parasitic currents.
- Cold start in winter.
- Hydrogen leak on blue car which was automatically sensed and fixed.
- Low availability of blue car.
- Errors in hydrogen level indicator.

4. Future drive cycles

Although it was clear that the combination of 10 kW of batteries plus 1.2 kW of fuel cell driving the electric motor was sufficient to power the Microcab through the campus drive cycles, a key question was whether the design was powerful enough to satisfy the urban duty cycle. Therefore, the ECE15 duty cycle was investigated and the Microcab performance was tested. It was apparent that the vehicle could reach the accelerations required and the speeds in the first two parts of the cycle, but failed to reach the speeds demanded in the third part. In addition, the 1.2 kW fuel cell was not sufficiently powerful to recharge the batteries fully at the stops, causing eventual battery depletion. Therefore, the design is being upgraded to give more fuel cell and battery power to satisfy ECE15 performance. The next stage will be to evaluate such an upgraded design.

5. Conclusions

Five hybrid hydrogen fuel cell vehicles have been tested on the University of Birmingham campus, the largest fleet test in England to date. The results show that the hydrogen filling of Microcab vehicles with green hydrogen could operate successfully on the University of Birmingham campus.

Summarising the benefits of the hybrid design, the key advantages are:

- Economic fuel cell but extra cost of hydrogen tank.
- Lighter and cost-effective battery pack.
- No deep discharge, consequent battery life benefit.
- Fast refuel with hydrogen or slow plug-in charging overnight.

The vehicles operated on the campus drive cycle with good performance in terms of acceleration, cruise speed and range, satisfying the two campus drive cycles. However, the regenerative braking system was not adequate and will be improved in future. Work is currently underway to investigate improved control strategies for the electrical power train, with the aim of optimising the fuel cell efficiency and thus fuel economy of the vehicles.

Further optimisation is required in terms of efficiency and reliability and a more powerful hybrid drive train is needed for the ECE15 urban drive cycle.

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