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Simulation of a Fuel Cell Hybrid London Taxi

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Abstract

Zero emission vehicles are set to play an important role in the reduction of greenhouse gasses, particularly in urban environments. To that end, a fuel cell and high voltage battery hybrid powertrain is proposed for installation within a conventional London taxi vehicle. Simulation studies of a proposed hybrid vehicle powertrain are presented and compared to the required performance targets of the vehicle. In addition, a comparison is also made with the conventional diesel variant. The proton exchange membrane fuel cell system proposed is based on evaporatively cooled technology, hence system complexity is reduced when compared to conventional liquid cooled systems. The high voltage battery is assumed to be based on lithium polymer technology which in addition to high performance has the additional benefit in that it may be constructed from a number of individual modules thus allowing more flexibility during packaging. Both inboard and hub motors are considered and in both cases rear wheel drive is assumed such that the turning circle of the vehicle can be maintained. High pressure gaseous hydrogen storage is proposed with simulation studies used to determine the amount of fuel required in order to achieve the prescribed range of 250km whilst maintaining a constant battery state of charge.

Keywords: fuel cell, PEM fuel cell (proton exchange membrane), HEV (hybrid electric vehicle), simulation

1 Introduction

The impetus to reduce carbon emissions of road vehicles had led to significant advancements in alternatives to conventional internal combustion engined (ICE) vehicles. The development of hybrid propulsion systems which utilise a combination of ICE and battery power can lead to significant improvements in vehicle emissions. However, they do not offer zero tailpipe emissions which are desirable for congested inner city areas. Fuel cells are often considered as offering the best long term prospect as an alternative to the ICE, especially during urban use as their peak efficiency is more closely matched to the road load requirements, thus reducing fuel consumption. Of the various types currently under development, proton exchange membrane (PEM) technology is generally regarded as the most suitable for road vehicle applications. When used in a hybrid arrangement in conjunction with a battery, the benefits of both technologies can be exploited.

According to Transport For London statistics [1] there are over 21,000 licensed taxis in London, thus elimination of emissions from a proportion of these vehicles could have a significant impact on overall vehicle pollution levels in the city. A study of driver's preferences for fuel cell taxis [2] has indicated that financial benefit principally influences the acceptance of drivers in the short term whereas environmental benefits are more important longer term. In addition, drivers also commented that they were most satisfied with the reliability, top speed and acceleration of the conventional vehicle. Interestingly, as taxis are closely regulated by the Public Carriage Office (PCO), drivers generally reported that there would be no rise in concern with regards to the safety when using an approved fuel cell vehicle when compared to a conventional diesel equivalent. Here these requirements have been considered with regards to the development of a fuel cell battery hybrid powertrain for a London taxi. Previous work has discussed the use of a PEM fuel cell as a range extender [3] although this configuration requires the battery to be plugged in to recharge. Whilst it is envisaged that this option would be available on the vehicle, this study has assumed that no charging will take place in order to allow a refuelling time which is comparable to that of a conventional ICE vehicle.

2 Vehicle Requirements

In order for a fuel cell based taxi to be authorised for use in London it must be designed to meet the stringent requirements of the conditions of fitness regulated by the PCO. In addition, its performance and cost should be comparable to that of the conventional LTI TX4 vehicle. With that in mind, an LTI TX4 will be considered as the base vehicle and as many off the shelf components as possible shall be used. The basic performance targets are provided in Table 1:

Table 1: Vehicle performance targets

Acceleration	Better than TX4
Top Speed	75 mph
Range (not including battery)	250 km
Refuelling Time	< 10 minutes
PCO Regulations	Compliant
Gradability	>25%
Temperature range	-18°C to +37°C
CO_2 Emissions	0 g/km

3 Powertrain Configuration

A series hybrid powertrain architecture has been proposed as an alternative to the conventional ICE propulsion system of the LTI TX4 taxi (Figure 1).

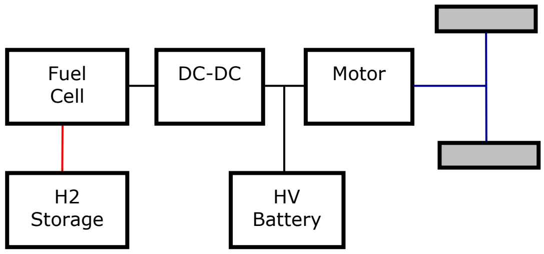

Figure 1: Powertrain configuration

Given that the internal combustion engine has been removed, the use of an electro-hydraulic power steering pump has been assumed. In addition, application of a slip control boost system (SCB) will allow the use of regenerative braking whilst maintaining the PCO requirement for fitment of an anti-lock braking system (ABS).

The high level control regime implemented assumes that the vehicle will operate on battery power only if the fuel cell power requirement is less than its peak efficiency point. This takes account of the battery state of charge, hence even at low vehicle speeds the fuel cell may operate in order to charge the battery. For power demands above the peak efficiency point of the fuel cell, the vehicle is effectively driven directly from the fuel cell with the battery assisting during transients. Hence, the powertrain configuration is a series hybrid configured as a range extender by operating the fuel cell system at its peak efficiency point where necessary. To further improve efficiency, energy is captured to charge the battery during braking.

4 Vehicle Components

4.1 Fuel cell system

The proton exchange membrane fuel cell system considered is based on technology developed by Intelligent Energy as published previously [4]. A 192 cell evaporatively cooled fuel cell stack is shown in Figure 2.

Figure 2: 192 cell evaporatively cooled fuel cell stack

Thermal management of the fuel cell stack itself is via an evaporative cooling technique which reduces system complexity when compared to conventional liquid cooled fuel cells. A single 192 cell evaporatively cooled stack is capable of achieving in excess of 18kWe over a 0-150A range (Figure 3).

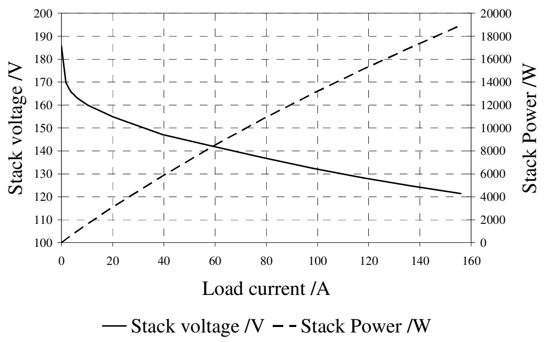

Figure 3: Single fuel cell stack polarisation curve

A fuel cell system typically combines the use of one or more fuel cell stacks along with the required auxiliary components such that useful electrical (and often thermal) power can be provided. When considering a fuel cell system based on the 192 cell stack above, an air delivery subsystem is employed such that oxygen can be delivered in a suitable quantity to the cathode of the fuel cell stack and a similar subsystem manages the hydrogen stream required by the anode. In addition, a thermal management system is used to remove the heat generated by the fuel cell stack, and in the case of the evaporatively cooled fuel cell stacks this subsystem also ensures that the membranes are correctly humidified for the operating conditions. An electrical subsystem in conjunction with an electronic control unit (ECU) is utilised to manage the overall operation of the fuel cell system. These auxiliary devices are a parasitic to the fuel cell system with the resulting difference in fuel cell stack (solid line) and system efficiency (based on the lower heating value of the fuel) shown in Figure 4.

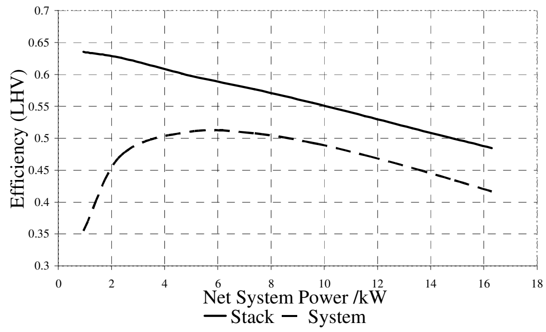

Figure 4: Single stack fuel cell system efficiency

For practical applications a single stack fuel cell system module is limited to provide a maximum continuous rated power of 15kWe.

Using the 192 cell fuel cell stack module as a building block, multiple stack fuel cell systems have been considered. The stacks are assumed to be connected in series in order to reduce DC-DC converter complexity and increase the availability of off the shelf components. System balance of plant components may either be multiples of units used on the single stack fuel cell system or combined to provide the total system requirement. The parasitic required for auxiliary components is then estimated from a combination of known single stack system data and either bench test results or manufacturers data, with the optimum solution chosen for each multiple stack configuration. In addition to system efficiency data, fuel consumption is also required for component sizing studies; this can again be scaled from single stack data. As an example, the system efficiency (solid line) and hydrogen consumption for a twin stack fuel cell system is shown in Figure 5.

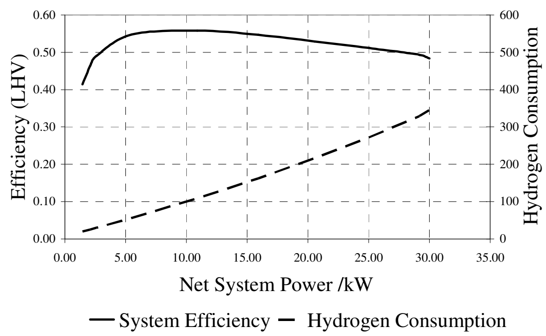

Figure 5: Twin stack system efficiency and hydrogen consumption

4.2 High voltage battery

Due to relatively high power density, manufacturing cost and robustness, a battery pack built from a number of lithium polymer modules is considered. This technology also has the particular advantage that the overall battery pack may be shaped to fit the individual packaging requirements of the application. Given that a number of electrical and electronic components have been developed for the hybrid and electric vehicle markets in the 400V range, this voltage was also considered here. For the initial component sizing exercise 94 cells of 40Ah capacity to provide 14kWh were considered with a charge/discharge efficiency of 98% assumed.

4.3 Motor and gearbox

Two motor options were consider, one hub mounted and one inboard. In both applications rear wheel drive was assumed such that the turning circle of the vehicle could be maintained. The inboard motor has peak torque and peak power of 550Nm and 100kW respectively and is able to deliver a continuous power output of 55kW. The hub mounted motors deliver peak torque and power of 750Nm and 120kW per wheel. A gearbox of ratio 4.186:1 was assumed for use with the inboard motor option.

4.4 Hydrogen storage

Hydrogen storage at 35MPa was considered so as to allow compliance with existing UK hydrogen infrastructure. In practice, it is envisaged that vehicles would initially be introduced into service via controlled fleets from a central depot. A fueller similar to that planned for the fleet of hydrogen buses to be introduced in London in 2010 could then be considered [5].

4.5 VM Motori diesel engine

An engine map based on the peak torque and power of 240Nm @ 1800RPM and 75kW @ 4000rpm respectively was used for the standard VM R 425 engine.

5 Vehicle Simulation

Lotus Vehicle Simulation software [6] has been used to size components and assess performance of a fuel cell hybrid variant when compared to the conventional LTI TX4 vehicle. This software package uses a reverse simulation technique in order to allow the calculation of steady state performance, acceleration and behaviour when subjected to specific drive cycles. The vehicle model is constructed from a combination of a library of hardware components and overall vehicle control logic.
The acceleration of the hybrid vehicle should be comparable to that of the production vehicle, it should be able to achieve a maximum speed of 75mph and should be able to pull away on a 25% gradient. So that the vehicle only requires fuelling once a day the range should be at least 250km. In addition, the vehicle must be able to sustain a motorway cruising speed for at least 10 minutes so as to allow provision for travel to the major airports in London.

5.1 Vehicle parameters

A TX4 shell weight has been estimated as 1520kg based on a kerb weight of the basic vehicle of 1890kg.The engine weight with oil is 220kg and the gearbox, fuel tank and other ancillaries were estimated at 75kg.
The weight of the fuel cell hybrid vehicle was then estimated as shown in Table 2.

Table 2: Hybrid vehicle weight estimation

Shell	1520 kg
Motor	86 kg
Inverter	16 kg
Fuel cell system	140 kg
H2 storage	80 kg
Battery pack	90 kg
Misc fittings	10 kg
Total	**1942 kg**

Additional vehicle parameters used in the simulation are provided in Table 3.

Table 3: Vehicle parameters

Parameter	Value
Wheelbase	2.886 m
Distance of C of G from front axle	1.1 m
Height of C of G	0.6 m
Frontal area	2.78 m^2
Drag coefficient	0.46
Tyre rolling radius	0.325 m
Drive efficiency	0.95
Rolling resistance constant	11.61
Rolling resistance polynomial v	-0.0642
Rolling resistance polynomial v^2	0.0043

5.2 Acceleration and top speed

Considering the vehicle parameters is Tables 2 and 3 along with the components discussed in Section

4, the acceleration and maximum speed of the vehicle in its conventional form along with hub and inboard motor fuel cell hybrid configurations is shown in Table 4. It should be noted that the figures quoted are obtained using a combination of propulsion from both the battery and fuel cell system.

Table 4: Vehicle performance prediction

Benchmark	Inboard Motor	Hub Motors	Conventional TX4
Drive Ratio	4.214:1	N/A	6.027:1 (3rd gear) 4.1:1 (4th gear)
0-30mph /s	4.5	6.78	4.65
0-60mph /s	12.25	14.32	17.43
30-50mph /s	4.06	4.83	6.9
50-70mph /s	8.81	5.52	14.21
Maximum speed /mph	81.3	127	88

5.3 Gradability analysis

The torque required at the road wheels to allow the vehicle to progress from a stationary start is given by equations 1 and 2:

$$F = mg\sin\Theta + R_t \quad (1)$$
$$T = Fr \quad (2)$$

Where:
F = force (N)
m = vehicle mass (kg)
Θ = gradient angle (degrees)
R_t = static rolling resistance (N)

Analysis for the three configurations considered is shown in Table 5:

Table 5: Gradability analysis

Benchmark	Inboard Motor	Hub Motors	Conventional TX4
Maximum Wheel Torque /Nm	2302	1500	4015
Maximum Gradient /%	27	18	56

Given that the gradability target for the vehicle is 25%, it is clear that the ratio of the internal planetary gearset render the hub motor option unsuitable for this application.

5.4 Motorway cruising

Although the batteries are able to provide power in addition to the fuel cell system, it is interesting to consider the top speed of the vehicle when powered only from the fuel cell system (Table 6).

Table 6: Maximum speed: fuel cell only

	192 cell stack	2 x 192 cell stack	3 x 192 cell stack
Maximum speed (fuel cell only) /mph	41	58	70

It is clear that the sustained top speed of the vehicle on fuel cell power alone is somewhat limited when considering use of a single stack fuel cell system. Whilst in purely urban environments this may be acceptable, a value closer to the normal motorway cruising speed of the conventional vehicle may be desirable.

With this in mind, the only motorway journey performed regularly by a London taxi is considered; the 10 mile section between the city centre and Heathrow Airport [2]. Simulation of the vehicle with each of the three fuel cell size options is considered for the motorway section of this journey (Table 7). For simplicity energy recovered into the batteries via regenerative braking is neglected

Table 7: London to Heathrow Airport motorway section

	192 cell stack	2 x 192 cell stack	3 x 192 cell stack
Segment time period at maximum speed : fuel cell only /min	14.6	10.3	8.6
Hydrogen consumed at 70 mph /kg	0.42	0.41	0.4
Time taken to recharge batteries /min	45.6	12.1	0

If the vehicle travels at 70mph the journey time of the motorway segment is 8.6 minutes. The hydrogen consumed in order to complete this journey has been calculated based on addition of the fuel used during the journey to that required to recharge the batteries. During this recharge period it is assumed that the fuel cell system operates at its maximum efficiency point, which equates to 6kW for the single stack fuel cell system and 12kW for the twin stack fuel cell system. Hence, the recharge time could be reduced if efficiency is sacrificed.

Although easier to package, the supplementary energy required from the batteries and hence the corresponding recharge time following sustained motorway operation is much increased compared to the twin stack arrangement. In addition, the overall efficiency is reduced for the single stack fuel cell system compared to the other two options. The triple stack arrangement is the most efficient for this representative journey segment, although the additional packaging requirements and mass increase require attention when considering packaging implications.

In addition to the specific motorway cruising applications, a study of vehicle range as a function of steady state vehicle speed for each of the three fuel cell system configurations has been considered (Figure 6).

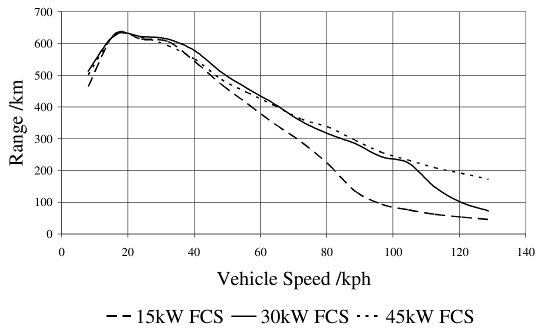

Figure 6: Range as a function of vehicle speed

The range has been determined based on the proposed high level control strategy and use of energy from both the hydrogen storage and high voltage battery pack. It is interesting to note that although the range is greater for the 45kW triple stack FCS at higher vehicle speeds, the range of this configuration between vehicle speeds of 25kph and 60kph is exceeded by the twin stack 30kW FCS. This is due to a combination of the increased mass of the 45kW system and the increased consumption of key FCS balance of plant components due to increased turndown ratio requirements as the overall performance envelope is increased. This increased turndown leads to relatively inefficient operating conditions of some key components available. Given that the vehicle's primary intended use is in an urban environment along with the additional cost and mass of the 45kW FCS, the 30kW FCS can be considered most suitable for the proposed application

5.5 Vehicle range

Analysis of the onboard hydrogen storage requirement of the vehicle has been carried out using the ECE15 + EUDC drivecycle [7]. This cycle comprises four back to back urban segments followed by a high speed extra urban profile. The total energy required at the road wheels to complete the 11.03km drivecycle is 7.96MJ. By taking into account losses in the powertrain and assuming that the battery state of charge is the same at the end of the duty cycle as at the start and that the 30kW FCS is installed, 19.59MJ of energy is required from the hydrogen stored onboard per 11.03km cycle covered. In order to achieve the target of 250km range on hydrogen alone, 22.67 ECE + EUDC drivecycles are to be completed. Hence, the total energy required from the onboard hydrogen is 444MJ. Assuming a lower heating value for hydrogen of 120MJ/kg, 3.7kg of hydrogen is required.

If the energy stored in the battery is also considered, an additional 50.4MJ is available which equates to an additional 28.4km. Hence, the maximum range for the vehicle when considering both onboard energy storage devices is 278km when completing repeated ECE + EUDC drivecycles.

6 Conclusions

An alternative to the conventional diesel powertrain of the LTI TX4 taxi has been proposed. The architecture is a hybrid configuration consisting of a PEM fuel cell and high voltage lithium polymer battery which results in zero CO_2 emissions during use.

Two motor sizes have been considered with 100kW and 125kW peak power respectively. Both are able to achieve the targets of the vehicle which have been derived such that they are comparable to the conventional TX4, although the 125kW motor requires a secondary reduction gear and exhibits slightly lower low speed efficiency. However, the 125kW motor is slightly smaller than the 100kW variant hence may be easier to package.

Three fuel cell configurations based on combinations of a 15kW PEM FCS module were presented. Although maximum range at motorway cruising speed is achieved by the larger 45kW FCS, from a cost and proposed application point of view the 30kW FCS can be considered most suitable.

Use of the ECE + EUDC drivecycle has indicated that 3.7kg of hydrogen is required to be stored onboard the vehicle in order to achieve the 250km vehicle range target on hydrogen alone, with an overall vehicle range of 278km predicted if both onboard energy sources are utilised.

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