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Golf Car Application Based Performance Analysis of a Generic Neighborhood Fuel Cell Vehicle (NFCV) Powertrain

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Abstract

In this work, a preliminary lay out of hybrid fuel cell-battery vehicle is developed and a 2012 GEM eL Golf car is evaluated and designed for analogous vehicle requirements. Packaging of electrified powertrain modules have been assessed and proposed. Further, the conceptual design is simulated as a series hybrid PEM fuel cell-Li-ion battery vehicle model in Powertrain System Analysis Toolkit (PSAT®) software. The output performance of the vehicle with the proposed electrified powertrain components is obtained, analyzed and the results are deemed satisfactory and in par with the performance of the conventional vehicle. This design can be implemented in the long run to general vehicles also, thus creating independence from fossil fuels.

Keywords: Electrified powertrain; Fuel cell; Golf car; Hybrid vehicle

Introduction

Currently, there is a global race in the contemporary automotive industry to improve fuel economy and emissions without compromising the reliability and performance [1].

The emergence of electrified powertrain as an alternative to conventional mechanical powertrain has established a new era in the automobile technology [2]. The electrified powertrain has been commercialized in various forms including hybrid (HEVs), plug-in hybrid (PHEVs), electric vehicles (EVs) and recently Fuel cell Vehicles (FCVs). (Figure 1) point to the number of Alternative Fuel Vehicles launched by prominent automotive manufacturers from the year 1992-2012 [3]. The research trend portrays that by the end of next decade, EVs, HEVs and Fuel cell Vehicles (FCVs) will be able to compete with the conventional vehicle in the market [1-2]. Recently, numerous researchers are focusing specifically on FCVs [4-14].

Fuel cell vehicles (FCVs) based electrified powertrain is emerging as a viable technology for attaining improved vehicle energy usage, efficiency enhancement and trivial emissions. These features however are obtained at the expense of increased hybrid convolution, constricted packaging and additional cost. Further, the infeasibility of efficient performance in transient conditions and e and bidirectional energy flow in the commercially available fuel cell systems restricts the regenerative braking and leads to hybridization of fuel cells with supplementary energy storage devices [15-16]. In [16], the role of energy storage devices in an electrified powertrain for fuel cell vehicle is analyzed.

In this paper, a 2012 GEM eL Golf car [17] was analyzed and designed for similar vehicle requirements. The fuel cell would draw its fuel from a hydrogen cylinder located onboard. In order to assist the fuel cell with transient loading, a battery pack would optimize the design. Thus the vehicle would use the fuel cell as its primary source of power, and the batteries as backup for transient power requirements, such as starting the fuel cell, accelerating the vehicle and driving uphill. During normal driving, the fuel cell will provide the power to the vehicle and excess energy from the fuel cell will charge the batteries. A novel hybrid controller for optimized battery and fuel cell interaction is also proposed. The original idea was developed and proposed in [14] by the author.

The simulation of the performance of hybrid vehicle was carried out by using the Power train System Analysis Toolkit (PSAT). The basic research shows that there is much promise in the innovation of a hybrid hydrogen fuel cell and Li-ion batteries based golf car, with respect to both the environment and the cost subject to demand and supply of the commercialized technology.

This manuscript is divided into 6 sections. Background and motivation is described in Back Ground and Motivation section. NFCV powertrain components overview has the description of the basic components of the proposed electrified powertrain. Simulation Results and Hardware in the loop experimental analysis is outlined Powertrain Simulation and Analysis and Hardware in the Loop Validation respectively. Conclusions and practical considerations are entailed in Conclusion and Practical considerations section.

Back ground and Motivation

As apparent from the name, Golf cars application is not limited only to the leisure game at the local country club, but similar vehicles have significant transportation demand at the airports, malls, hospitals etc. etc. It is more appropriate to termed them as neighborhoods electric vehicles (NEV). Recently, there is a demand of NEVs as personal mobility vehicle. The city departments of transportation also allows NEVs with certain modification to golf cars on the roads with speed limit up to 25 mph .The standard golf cart (or "golf car") holds two to four people and their clubs. (Figure 2) shows the typical neighborhood drive cycle of a typical golf car.

Golf cars use regular lead-acid batteries to propel an electric motor. Golf cars are designed for periodical use with certain required periods of charging from regular power outlet [13]. The two power variances available are 36 volt or 48 volt along with 24 volt and 72 volt options

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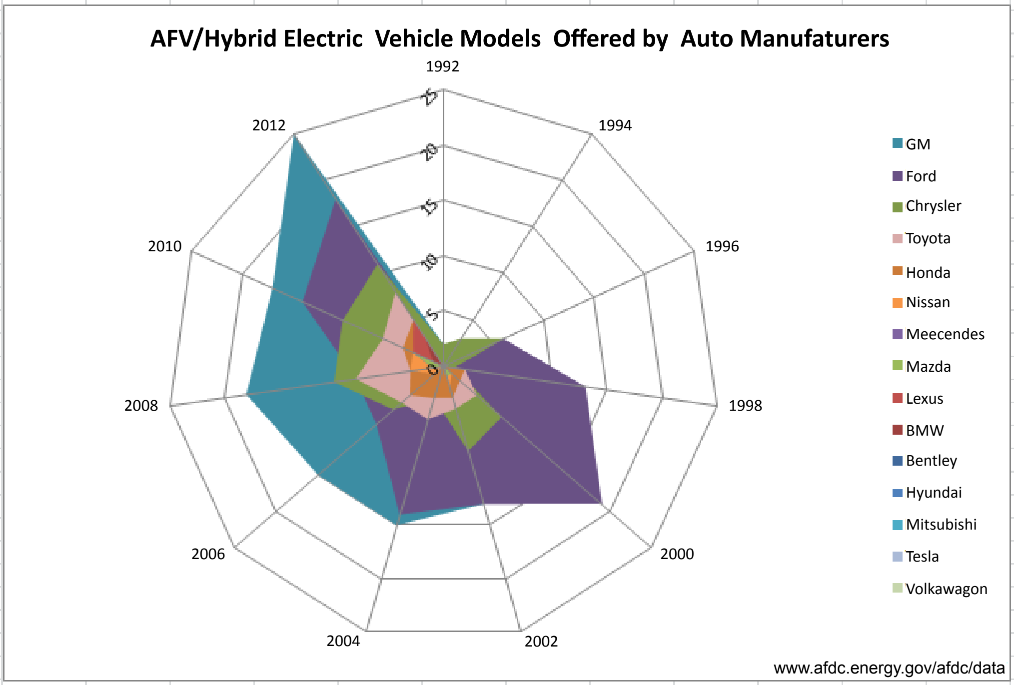

Figure 1: Electric, Hybrid Electric and Fuel cell Vehicles offered by Auto Manufacturers.

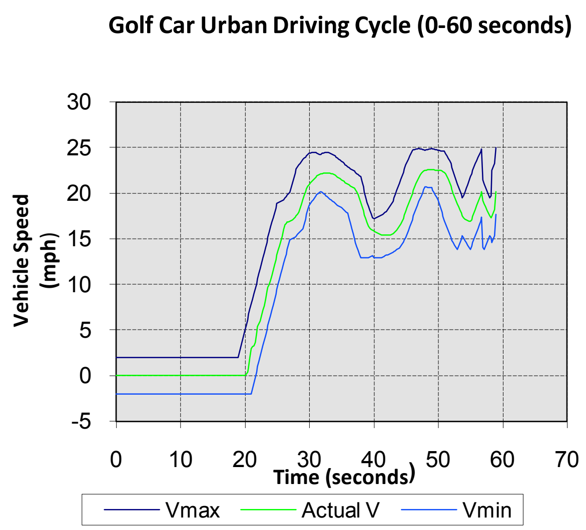

Figure 2: Golf car Neighborhood drive cycle.

in some models. A design proposal is desirable that can perplexed the conventional le lead-acid battery powered hurdles and provide round the clock smooth ride specially at public places with substantial mobility requirements. The proposed design should be reliable with a capability to drive the vehicle for extended duration s without compromising the performance and with negligible requisite to recharge or refuel.

These challenges can be addressed by implementing a hybridized powertrain consists of existing electric motors, Proton Exchange Membrane (PEM) fuel cell and a Li-ion battery bank managed by smart hybrid control protocol. The main source of propulsion will be hydrogen fuel cell with the battery bank as backup power for periods of

Figure 3: 2012 GEM eL Golf car [20].

peak demand like starting-up PEM fuel cell, acceleration, uphill drive and other transient conditions. The proposed smart hybrid control protocol will be implemented for the power managements under diverse load condition. Li-ion batteries have enhanced efficiency with comparatively less packaging and weight requirements than a lead acid battery. There is an additional initial cost to the proposed electrified powertrain components but as the results will show that performance overcomes the cost in the long run.

The model considered for the research analysis and design is the 2012 GEM eL Golf Car as shown on manufacturer's website in (Figure 3) and the specifications are listed in (Table 1).

NFCV powertrain components overview

The additional essential electric powertrain components for the proposed golf car platform are PEM fuel cell, Li-ion battery, and a smart hybrid controller.

PEM fuel cell

Proton Exchange Membrane (PEM) fuel cell was devised

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Power train	
Motor	Heavy duty DC motor with continuous 5 hp rating and 12 hp peak during acceleration
Transmission	Single-speed gear reducer with integral differential
Top Speed	25 mph
Range	Up to 30 miles driving
Battery Pack	Six 12 V flooded electrolyte batteries
Onboard Charger	72-volt battery system with on board charger
Weights and Measures	
Curb Weight	1235 pounds
GVW	2300 pounds
Payload capacity	1065 pounds
Dimensions	Length: 144 inches , Width: 55 inches; Height: 70 inches
Cargo Capacity	700 Pounds
Wheelbase	114 inches
Flat Bed	70 inches x 48 inches
Turning Radius	17 feet

Table 1: Specification of 2012 Gem eL Golf car [17].

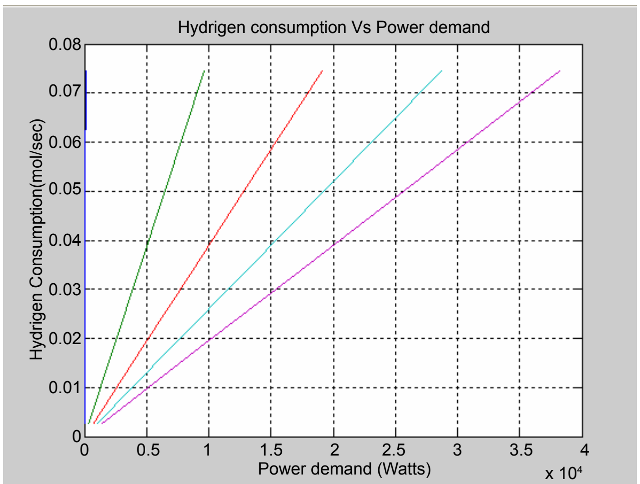

Figure 4: Consumption of Hydrogen at different ranges of Power Demand.

at General Electric (GE) in 1955 as an off shoot of the research accomplishments of Thomas Grubb and Leonard Niedrach [11-13]. Being an environmentally friendly power source, scholars are exploring the usage of PEM fuel cells for both mobile and stationary applications [13]. The traction power produced by fuel cell is based on the reduction reaction of oxygen from the atmosphere with the hydrogen as fuel to produce water vapors. The reaction set is as follows:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

$$½\, O_2 + 2e^- \rightarrow O^{-2} \quad (2)$$

The cumulative reaction is:

$$H_2 + ½\, O_2 \quad H_2O \quad (3)$$

Employing the chemical reaction of equation 3 and using the manufactures parameters [18], the equivalent molar quantity and quantity of hydrogen consumed per hour-Amp is simulated in MATLAB® environment and plotted in (Figure 4) for different ranges of power demand. The overall reaction in the cell is the electrochemical oxidation of hydrogen to form water. The electrons flowing through the external circuit are capable of performing useful work due to the energy released by reaction [13]. Also, the fuel cell output power and current density variation at different values of cathode pressure is plotted in (Figure 5). As can be inferred from (Figure 4, 5), PEM fuel cell is capable of providing steady state traction power. For transient conditions, a high energy density battery bank can be implemented as a backup power source.

Li-ion batteries

In the contemporary automotive industry, the two primary battery choices for hybrid and electric vehicles are nickel metal hydride (Ni-MH) and lithium-ion (Li-ion). Having as much as twice energy density, the Li-ion has an edge over Ni MH [19].

With a nominal voltage of 3.6 V and a usual charging voltage of 4.1 V, the charging procedure for Li-ion battery is "constant current/constant voltage". The charging profile of a typical automotive Li-ion battery is simulated and plotted in (Figure 6).

The backup battery bank can provide instantaneous power during transient conditions. The chemical reactions during the discharging produce relatively little heat for a golf car or similar vehicle application. A relatively simple cooling system is adequate, and operation is possible in a wide range of ambient temperatures [20-21].

Hybrid controller

The hybrid control protocol is required to set and efficiently manage the traction load demand. (Figure 7) shows the proposed block diagram of the Controller.

In the proposed control strategy, the battery power module will provide the required transient power e.g. during starting-up, acceleration, and sudden load changes etc. Power obtained from the hydrogen reaction through fuel cell will assist the traction demand of constant speed and cruising. During low traction demand periods, the residual energy from the fuel cell will be utilized to charge the battery bank. The traction power demand for all the possible neighborhood drive cycles will be managed as

- Fuel cell start up power will be provided by the battery bank (switch S1 will be closed)
- The motor start up draws high starting current, rises steadily from zero to several times rated current

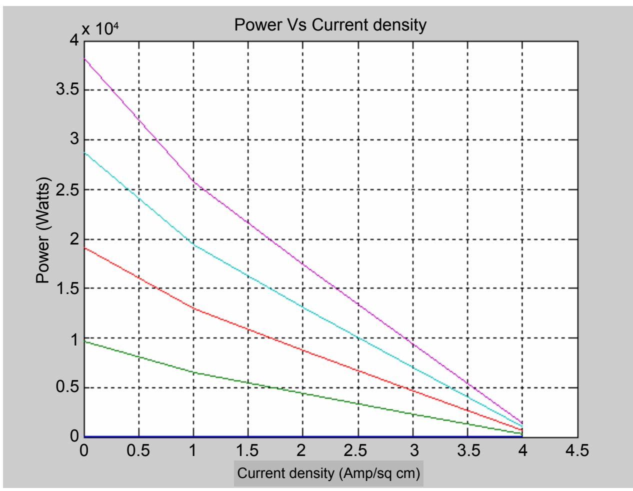

Figure 5: Power VS Current Density at different values of Cathode pressures.

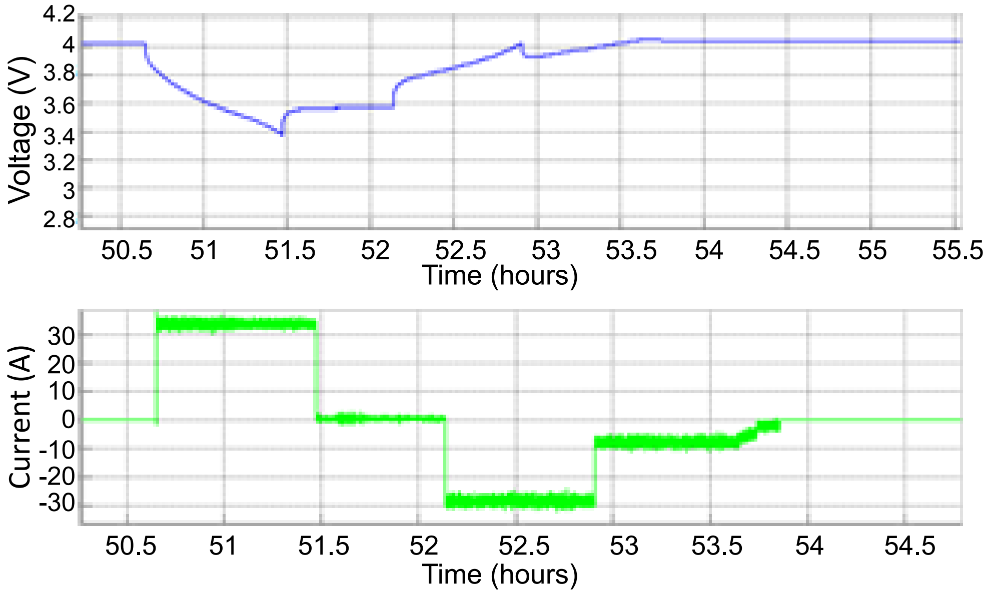

Figure 6: Constant current -Constant voltage Charging profile of Li-ion batteries.

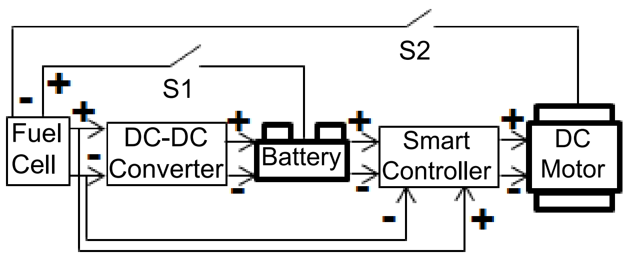

Figure 7: Proposed block diagram of hybrid controller.

- Charger through dc-dc converter starts charging the battery.
- For short period of time switch S2 will be closed to draw the current from the fuel cell
- However, the moment it crosses the maximum limit of the fuel cell current (say 2A), VI becomes higher than V_{set}.
- The op amp based comparator goes to high level. Which will activate S1 and S2 turns off.
- Control circuit common terminal is connected at the battery source only.

The implementation of the proposed hybrid control strategy requires simulation and hardware in the loop validation of neighborhood drive cycle scenario in conjunction with all the components of the proposed FCV powertrain. Currently, there are many FCV modeling packages are available like ADVISOR® from National Renewable Energy Laboratory, HYZEM® from Ricardo consulting Engineers, AMESIM® from LMS and PSAT® from Argonne National Laboratory.

For the analysis of neighborhood fuel cell vehicle, the vital components of the FCV hybrid electric powertrain are integrated and simulated in PSAT.

Powertrain Simulation and Analysis

The neighborhood fuel cell golf car has been simulated as a fuel cell series vehicle electrified power train in Powertrain Simulation Analysis Toolkit (PSAT) environment [22].

The FCV traction power demand under neighborhood drive cycle, fuel cell gross output power, and the output power of the battery bank to match the transient are given in (Figure 8-10) respectively.

Evaluating and comparing the power demand and the drive cycle of the golf car with the fuel cell stack and battery bank output power profile, it is apparent that the fuel cell electric powertrain is agile to deliver adequate traction power effectively.

Once it is determined that the proposed FCV powertrain is cable of meeting traction demands, the second step is to investigate the packaging feasibility of the fuel cell, hydrogen tank and other electric powertrain components on a 2012 golf car platform.

Hardware in the loop validation

For packaging purpose, 1kW PEM fuel cell is considered and the specifications are listed in (Table 2).

Table 3 shows the specification of 18650 Li-ion cell [19-21]. The batteries chosen were Li-ion 16.4 V. The selection is comparable to the battery pack which has been developed, designed and packaged by the advanced battery research group of Illinois Institute of Technology Chicago's Center of Electro Chemical Science & Engineering [19-21].

Packaging of the electrified powertrain components on the golf car platform

Based on the space availability, fuel cell and the hydrogen tank can be placed on the trunk bed. Battery bank and hybrid controller unit could be incorporated beneath the seat and electric motor at its usual place in the front area. The proposed layout is outlined in (Figure 11).

The capacity sizing can be calculated from the given dimensions in (Tables 2 and 3) as Fuel Cell=915.36 in^3, Battery bank= 397.61 in^3.

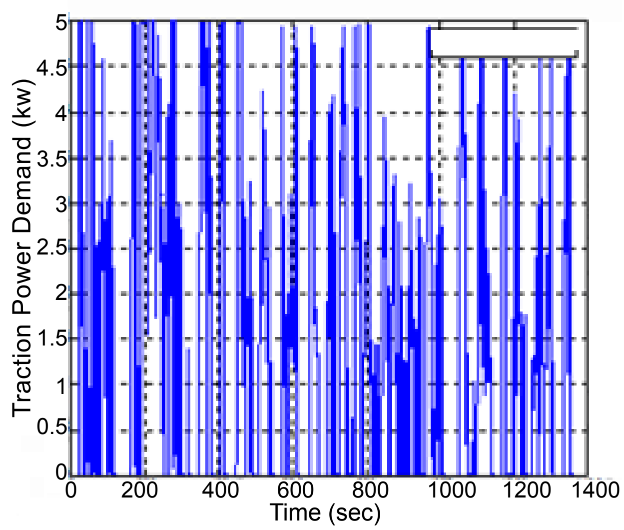

Figure 8: The golf car traction power demand for neighborhood drive cycle.

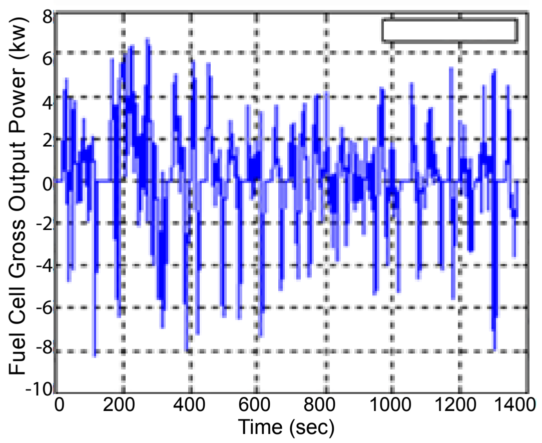

Figure 9: Estimated fuel cell stack output traction power.

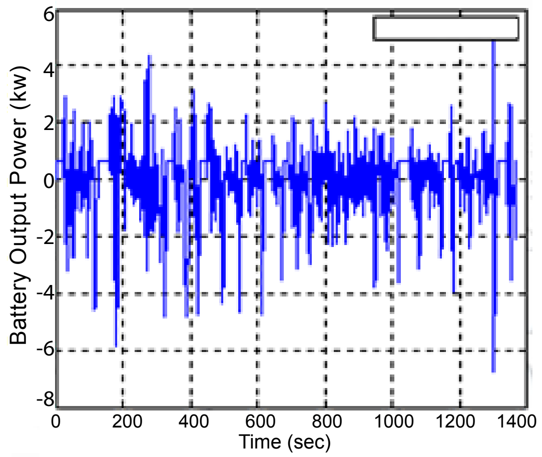

Figure 10: Battery output power to mitigate the transient transaction power demand.

Physical	Dimensions	17.5"wx 27.13"d x 20"h (44.5 cm w x 69 cm d x 51 cm h)
	Weight	146 lbs/66 kg
	Mounting	19" or 23" rack mount configurations
Performance	Rated net power	Continuous 1000 Watts
	Rated current	40A or 20A,depending on voltage
	DC voltage range	24 or 48 VDC nominal
	Estimated MTBF	22,000 hours
Fuel	Composition	Standard industrial grade hydrogen (99.95%)
	Supply pressure to unit	25 to 100 psig; 172 to 689 KPag; 1.72 bar to 6.89 bar
	Consumption	7.7 slpm @ 500 Watts; 15 slpm @1000 Watts
Operation	Ambient temperature	32ºF to 115ºF; 0ºC to 46ºC
	Relative humidity	0-90%
	Altitude	-197 ft. to 13,800 ft.
	Location	Indoors or installed in Outdoor Enclosure
Safety	Compliance	UL; CE
Emissions	Water	Max. 30 mL/kWh
	Noise	53dBA @ 1 meter

Table 2: Specification of an Independence 1 KW PEM Fuel Cell [18].

Nominal voltage	3.67 V
Nominal capacity	2.0 Ah
Energy	7.34 Wh
Size	Diam: 18 mm, Length: 65 mm
Weight	42 g
Energy Density	
Gravimetric	160 W*h/kg
Volumetric	300 W*h/l
Charge duration	2-4 h (100%)
Operating specifications	
Operating voltage	4.2-3.0 V
Charge voltage	4.2 V ± 50 mV
Cut-off voltage	3.0 V
Temp. range	-20 to 60ºC

Table 3: Specification of an 18650 Li-ion cell [19-21].

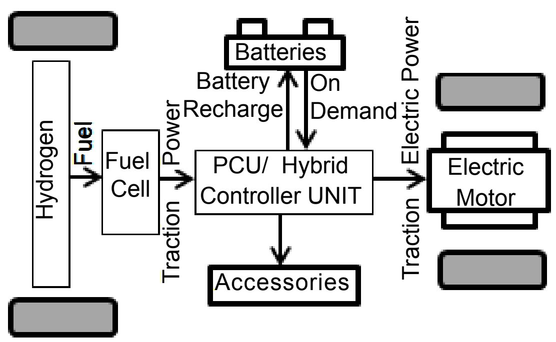

Figure 11: Packaging of the electrified power train components on the vehicle.

Hydrogen Cylinder=3,468.71 in^3. So, the total space required=4,781.68 in^3. The space on the trunk bed is equal to flat bed space area x height of flatbed = 70×48×12=40,320 in^3. Luggage space left= 40,320–4,781.68=35538.32 in^3. Thus, the calculations show that there will be sufficient space for the proposed powertrain without compromising

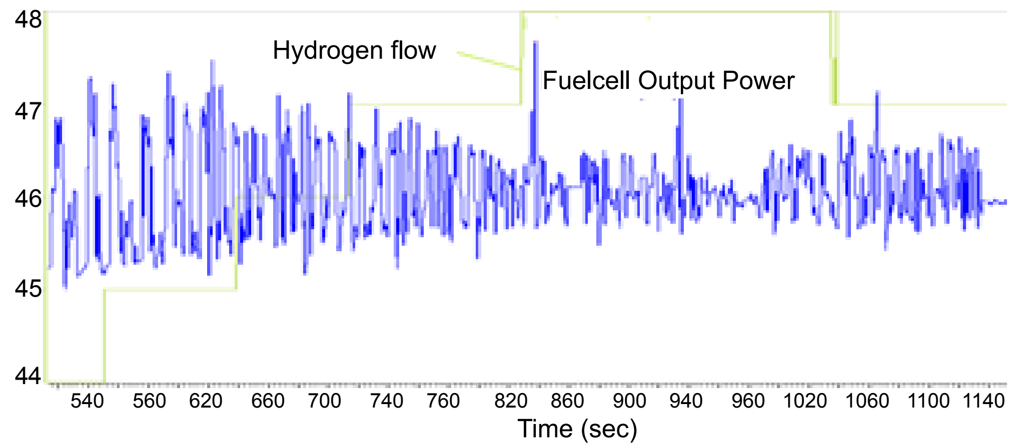

Figure 12: Hydrogen flow vs Fuel cell output Power.

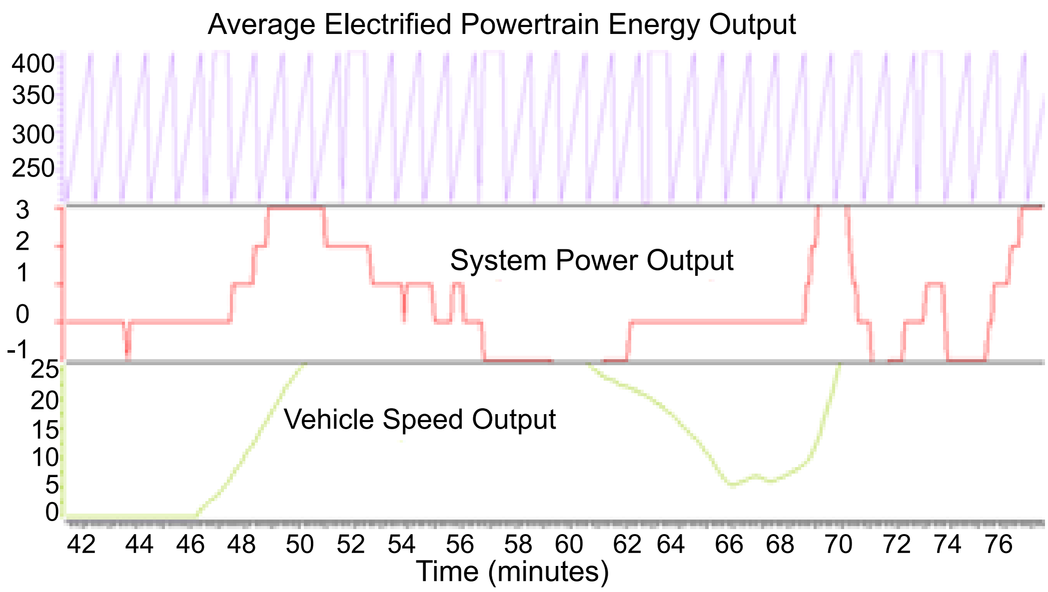

Figure 13: Average energy output and system power output in coherence with vehicle speed demand.

the baggage capacity. Furthermore, to conceptualize the drive cycle feasibility, sample test drives were performed and data is collected to support the pragmatism of the proposed powertrain.

Test drives with prototype FCV powertrain

Sample testdrives are peformed for neighbourhood drive cycles and the example data is compiled to illustrate model results. (Figure 12) shows the hydrogen flow vs the Fuel cell output power .

Figure 13 shows that the average energy output and system power output is enabe to meet the vehicle speed demand for the test neigbourhood drive cycle.

Figure 14 shows that the traction power demand is being met by fuel cell output power for steady state conditions and transient conditions are supervened by battery output power for the test neigbourhood drive cycle.

Conclusion and practical considerations

The basic research shows that there is much promise in developing a hybrid fuel cell electrified powertrain, in respect to the performance, reliability, environment and cost subject to commercial production. The neighborhood fuel cell vehicle (NFCV) electrified powertrain based golf car provides a solution to environmental and energy security challenges for neighborhood transportation applications. The simulation, packaging estimation and hardware in the loop validation of the proposed design for the conversion of the current 2012 GEM eL golf car into a neighborhood hybrid fuel cell-driven automobile is feasible. The proposed NFCV drivetrain addressees the preliminary investigation, design features and sample results as an evidence for realizing the concept into product development and profitable launch.

This conceptual design can be taken to commercialization subject to market demand. Challenges include safety protocols for on-board

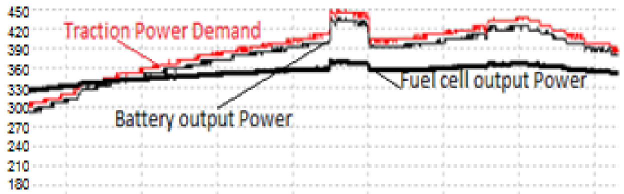

Figure 14: Fuel cell output power and battery output power in uniformity with traction power demand.

hydrogen storage and hydrogen refueling infrastructure, and initial high cost of fuel cell stacks [23].

Conflict of Interest

This manuscript is based on author's individual research interest. This manuscript does not represent directly or indirectly the opinion of any business including author's employer.

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