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Energy Management System for a FCHV based on Linear Programming

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Abstract: Challenges facing fuel cell hybrid vehicles is in implementing a control strategy to find the optimal split of power between the different power sources. This paper proposes a mathematical model of power flow in such vehicles taking into consideration power train losses. Linear programming locates the global optimum indicating the finest synchronization among power units in an attempt to lower operational cost and reduce hydrogen fuel consumption of the energy management system for respective driving cycles. The formulation considers the life-cycle cost, limits and ramp rates of the subsystem, hydrogen tank capacity and battery state of charge. Comparison is done between the proposed controller and a controller using rule based techniques. Results indicate a reduction in system cost and up to 29% reduction in hydrogen fuel consumption highlighting the importance of using such controllers in urban driving cycles since reduction in hydrogen consumption is much higher compared to highway cycles.

Keywords: Controllers, Engineering, Batteries, Fuel Cells, Vehicles.

Introduction

Fuel cell hybrid vehicles (FCHV) attract the attention of engineers and researchers due to their promising future as alternatives to the internal combustion engine vehicles [1]. FCHVs decrease greenhouse gas emissions when compared to ICE vehicles, and contribute to the solution of fast growing demand on fuel [2]. FCHVs combine fuel cells (FC) and power peaking sources such as batteries and super capacitors. Such vehicles have proven their advantageous performance in various demonstration programs under all operating conditions including cold-starts, but there is still a room for further improvement in order to reach the target costs in production and operation as well as lifetime requirements. For this reason, research is heading towards improving different components of the FCHV system such as the design of the FC, chemistry of the battery, the technology and efficiency of the converters and the controller of the system. Of importance also is to find the best fit in scaling and managing the different power sources and storage units.

Hydrogen fueled FC with polymer exchange membrane are used in automotive devices [1]. These membranes enable the FC to have a high power density and low operating temperature. Their transient performance when responding to load demand is limited due to the chemical reactions that occur in the FC. High dynamic operations may cause significant negative impacts to the overall lifetime of the cells. Energy storage components aid the FC to overcome transient response effects. They have faster dynamics and thus can respond faster to power fluctuations. Normally, two devices are considered, super capacitors and batteries. Super capacitors have higher power densities up to 10 times more than batteries, while batteries have higher energy densities than super capacitors. Batteries are mainly needed to capture the large amount of kinetic or potential energy that could be recovered by regenerative braking when reducing speed or running downhill. They can also power FC auxiliaries and provide additional power for accelerations. The types of batteries that are used in FCHV are lead acid, NIMH, or lithium ions. Improvements in battery systems in terms of performance as well as building high efficiency charging converters and advanced FC controllers [3], contribute to the growing interest in FCHV [4].

There is a wealth of papers that address the design of the energy management systems (EMS) in FCHV. Two kinds of controllers are addressed, offline controllers and online controllers [5]. Online controllers are real time controllers, which use learning algorithms such as neural networks [6] [7], predictive controllers or rule based controllers. Offline controllers usually use intelligent or non-intelligent approaches in order to find the optimal power split between energy sources in an attempt to minimize hydrogen fuel consumption. Some authors use linear programming [8] techniques to optimize the split of power between an internal combustion engine and a battery system. The problem is formulated as a convex optimization and then approximated as a large linear program. Offline controllers also employ dynamic programming [9], stochastic dynamic programing [10], game theory [11], genetic algorithm [12], load shifting [13] and control theory [14] [15]. The equivalent minimization strategy mechanism is also an optimization method used to find an approximate value for the optimal split. It is based on formulating the problem by setting the battery power as equivalent hydrogen fuel consumption. This method approximates the power needed from the sources and does not depend on the knowledge of the driving cycle as other methods do. In [16], the authors optimized a FC system by minimizing hydrogen consumption. The method is formulated as an NLP aiming at minimizing the stack current subject to non-linear constraints depending on the net power of the fuel cell and the oxygen excess ratio. Xu et al [18], developed a controller based on dynamic programming where the cost of FC and battery are minimized while subjected to limit constraints. The authors introduced a penalty factor on the SOC (state of charge) where the cost increases cubically if SOC is outside the limit margin.

This paper formulates the system as an optimization problem with an objective to lower hydrogen consumption and achieve an optimal split of power between sources. The life-cycle cost of system components, as well as the limits and ramp rates of FC and battery are accounted for in the objective function and constraints. Linear programming is used to find the optimal trajectory for known driving cycles. This conceptual approach is selected because it can be easily extended to more complex limitations including for instance those related to temperature, aging, reliability and lifetime. It will be shown that with the same driving cycle, the proposed technique will result in lower fuel consumption and lower cost as compared to a rule based controller. On the other hand, results indicate that higher reduction in terms of cost and hydrogen consumption can be achieved in urban cycles as compared to highway cycles. This is due to rapid stops and starts in urban cycles which make use of the battery system and thus decrease hydrogen fuel consumption.

System Description

The vehicle considered in this paper is a light duty sprinter. It has two energy sources which are the FC and the battery. The drive train is of the series type with a 70 kW induction electric motor. The battery system has a nominal energy of 1.9 kWh. The 70kW FC System is based on hydrogen fuel with an operating voltage range between 250 and 430V. Therefore, the battery system can assist with power during fast dynamics to prolong the life cycle of the FC and to reduce fuel consumption. The system topology is shown in Figure 1. The FC and battery are connected to the bus via a DC/DC converter. The DC bus supplies the vehicle auxiliaries with DC power which will be transformed to AC by inverters. The auxiliary path is split in two branches one with DC/DC to the lower 12V or 24V DC board and the other with DC/AC to the electric drives for the sub-components (water pumps, servo steering, servo brake, air conditioning and heating oil pumps. The controller controls the converters and inverter of the system to supply the needed amount of power by sending signals to adjust the duty cycle. The linear program block, which is the focus of this paper, takes the initial SOC of the battery as well as the initial hydrogen availability in the tank. The system costs and characteristic block (Figure 1) which is also an input to the linear program block represents the vector of fixed input values which are the cost of H2 consumption γ_{FC} in \$/kWh, the initial cost of FC system $\gamma_{SL\text{-}FC}$ in \$/kWh, the cost of BT γ_{BT} in \$/kWh, battery energy capacity E_{BT} , the minimum power provided by the FC system $P_{FC\text{-}min}$, the maximum power provided by the FC system $P_{FC\text{-}max}$, the minimum power provided by the battery system $P_{BT\text{-}min}$, the maximum power provided by the battery system$P_{BT\text{-}max}$, the minimum battery sate of charge SOC_{min} , the maximum state of charge of the battery SOC_{max} , FC ramp down and up rates ($R_{down\text{-}fc}$, $R_{up\text{-}fc}$), the battery ramp down and up rates($R_{down\text{-}bt}$, $R_{up\text{-}bt}$) , the consumption rate of H2 molecules per kW of energy λ , and the initial mass of hydrogen in the tank in grams (MH_o). The linear program will yield the optimal split of power between the FC and the battery for a specific driving cycle. The program feeds the results to the controller to yield optimal power flow management.

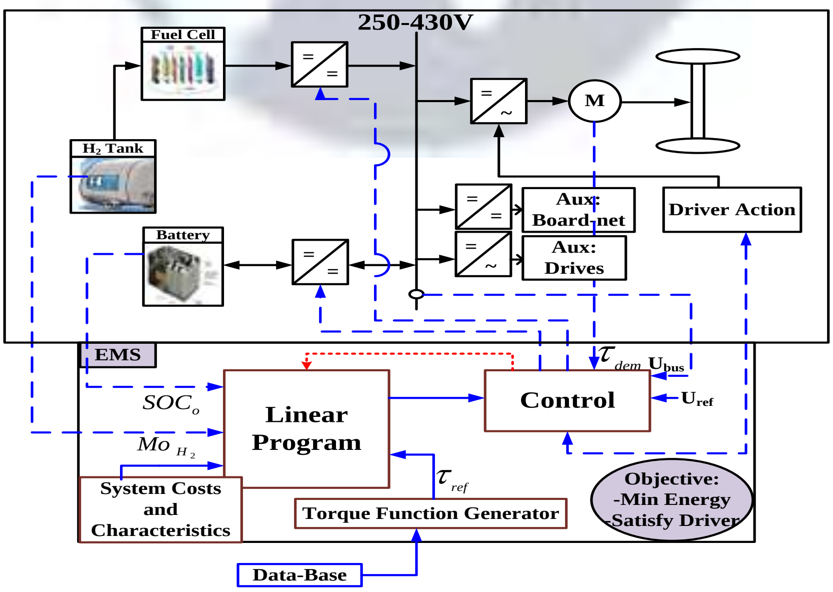

Figure 1: System Topology

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Power Train Model

The power train of the FCHV is composed of several components as indicted in Figure 2. It is required to approximate the power demanded from the sources by the electric motor taking into account the efficiencies of the system components. For this purpose, a reformulation of the power equation is shown in equation (1), where the electric motor power (P_L) is the power at the wheels (P_{wheels}) divided by the efficiencies of the transmission system (η_{tran}), the motor system (η_{mot}) and inverter (η_{inv}). The respective values of the efficiencies of the transmission system, motor system and inverter are 0.9, 0.95 and 0.94 [19].

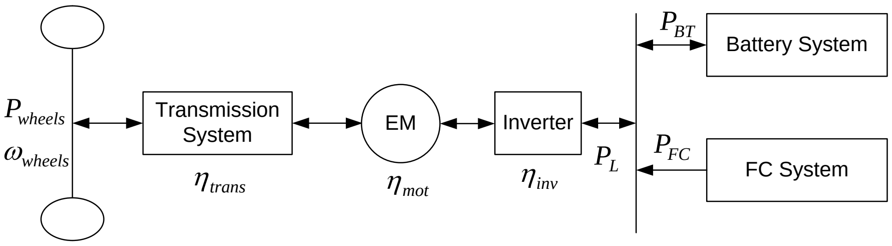

Figure 2: Power Train Model

$$P_L = \frac{P_{wheels}}{\eta_{trans}\eta_{mot}\eta_{inv}} \tag{1}$$

A. Problem Formulation

The problem is formulated as a constrained optimization problem with linear constraints. The main aim is to find the optimal split of power between the components of the FCHV, thus to find the power required from the FC (P_{FC}) and the power required from the battery (P_{BT}). The cost function is depicted in equation (2).

$$\min\left[\sum_{k=1}^{N}\left[(\gamma_{FC}+\gamma_{SL-FC})P_{FC}(k)+(\gamma_{BT})P_{BT}(k)+\gamma_{FC}P_{br}(k)\right]d(k)\right] \tag{2}$$

The cost minimization function calculates the cost of energy from the FC. It also considers the braking energy (P_{br}) as equivalent to the FC energy. This is due to the fact that this dissipated energy originally came from the FC. The cost of the FC includes the hydrogen consumption cost as well as a penalty factor. The latter is a fraction of the life of the fuel cell. In this manner, the cost function will consider the life cycle of the FC. The cost of the battery is considered during charging and discharging phases. This cost comprises the depletion of the battery towards its end life.

B. System Constraints

The system constraints are described in equations (3) till (10) respectively.

SOC Period Coupling Constraint

$$SOC_{BT}(k) = SOC_{BT}(k-1) - \left(P_{BT}(k)d(k)\right)/\left(\eta_{BT}E_{BT}\right) \tag{3}$$

Power Balance Constraint

$$P_{FC}(k) + P_{BT}(k) - P_{br}(k) = P_L(k) \tag{4}$$

Fuel Cell Power Limits

$$P_{FC-\min} \le P_{FC}(k) \le P_{FC-\max} \tag{5}$$

Battery Power Limits

$$P_{BT-\min} \le P_{BT}(k) \le P_{BT-\max} \tag{6}$$

Battery State of Charge Limit

$$SOC_{BT-\min} \le SOC_{BT}(k) \le SOC_{BT-\max} \tag{7}$$

FC Ramp Rate Constraint

$$R_{down-fc}d(k) \le P_{FC}(k) - P_{FC}(k-1) \le R_{up-fc}d(k) \quad (8)$$

BT Ramp Rate Constraint

$$R_{down-bt}d(k) \le P_{BT}(k) - P_{BT}(k-1) \le R_{up-bt}d(k) \quad (9)$$

Hydrogen Tank Capacity Constraint

$$\sum_{k=1}^{N} \lambda P_{FC}(k)d(k) \le MH_o \quad (10)$$

The SOC period coupling constraint calculates the available state of charge of the battery after each discharge in a given time step d(k). The subtracted value represents the fraction of energy from the total energy available in the battery spent at time t. The power balance constraint ensures that the load is served at each step k. The system dumps any available extra power via Pbr, which is usually the case when the battery is fully charged and the load demand is generative. Constraints shown in equation (5), equation (6) and equation (7) are limitation constraints for the power that can be provided by the FCHV components. The ramp rate constraints limit the ramp rate of both the FC and the battery. This is very important to prevent a phenomenon known as oxygen starvation of the FC system. The latter occurs when a high instantaneous power is required from the FC. Due to the stoichiometry of the chemicals present, the FC does not respond fast to the requirement yielding oxygen starvation causing FC degradation. Similarly the battery needs a certain amount of time to be able to deliver the required power. The storage capacity constraint ensures that the hydrogen tank is able to cover the entire desired trip [15]. The calculation of the initial available hydrogen consumption is done using the ideal gas equation.

C. Battery Storage System Characteristsics

The selected battery is a lithium-ion cell battery [20] suitable for vehicular applications. The test-bench based datasheet shown in Table I indicate the relation between the DOD and the cycles that the battery can withstand till the end of its life.

Table 1: Battery Datasheet

DOD (%)	Number of Cycles	Energy Delivered during Battery Life (kWh)
100	1000	1824
90	1100	1862
80	1200	1824
70	1400	1805
60	1600	1748
50	1900	1824
40	2300	1824
30	3200	1824
20	4800	1862

It can be fairly assumed that the amount of energy that is delivered by the battery system during its lifetime is constant depending on the DOD. From Table I, the average energy delivered by the battery system over its life is 1,816 kWh. The current cost of the battery is 700 $/kWh [21] [22]. Therefore, the cost of the battery for its service life is shown in equation (11).

$$\gamma_{BT} = 700 \times 1.9 / 1816 = 0.73\,\$/KWh \quad (11)$$

D. Fuel Cell System Characteristsics

Life cycle analysis of the FC system is considered in this paper. The current service life of FC that is embedded in automotive systems is 5,000 hours under cycling conditions, which is equivalent to 242,000 km [23]. The current cost of the system is $5000/kW [23]. Therefore, a cost measure for the service life γ_{SL-FC} of a FC is indicated in equation (12).

$$\gamma_{SL-FC} = 1\,\$/KWh \quad (12)$$

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There are three important parameters that need to be approximated in-order to run the linear program. These are: the rate of consumption of hydrogen molecules per kW of energy in g/kWh, the cost of energy from hydrogen consumption in $/kWh, and the initial mass of hydrogen molecules available in the tank in grams.

E. The Rate of Consumption of Hydrogen Molecules per kW of Energy

The consumption rate of hydrogen molecules per kW of energy depends on the type of fuel cell used and on the manufacturer's datasheet. Table II shows the experimental data recorded from running a FC under certain conditions. Our goal is to find a constant relation between the hydrogen fuel consumption rate and the power capacity of the fuel cell. The derivation is shown in equation (13) and equation (14).

$$P_{FC} = I_{net} V_{FC} \tag{13}$$

$$\dot{m} = M_{H2} \dot{n} \tag{14}$$

Table 2: FC Experimental Data

Net-Current (A)	ṅ(/sec)	V_{FC} (V)
1.49	0.003	360
3.06	0.005	359
7.82	0.015	358
13.48	0.025	356
25	0.05	352
46.51	0.1	344
68.45	0.15	336
94.51	0.2	328
118.75	0.258	320
190	0.4	300
285.71	0.5952	280

Figure 3 shows the plot of versus PFC. The rate of consumption of hydrogen molecules per kW of energy λ is the slope of the graph which is 0.015 g/kWs. It is obtained by using a basic linear curve fit of the available data. Therefore, λ=54$ g/kWh.

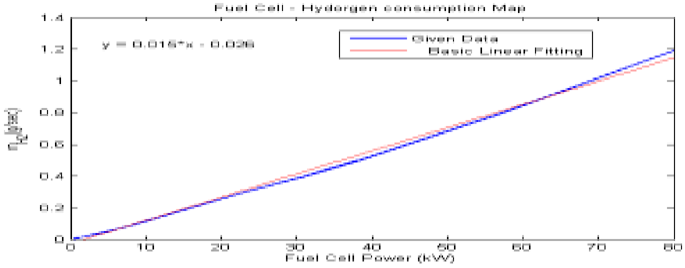

Figure 3: FC Power-Hydrogen Consumption Relation

Simulation Results

The system simulation is performed under the MatLab environment. Two driving cycles are considered, the highway driving cycle and the FUDS driving cycle which represents a typical urban driving cycle. Small test cycles consisting of ten driving speeds were used to capture the essence of the system variables. The addition of the braking power is essential for the feasibility of the system. Without it the linear program will not converge to a feasible optimal point. Moreover, the test cycles indicate that the cost imposed on the braking power in the cost function, serves to limit power dissipation through the brake. This is due to the fact that this power originates from the fuel cell system. These tests also indicate that the wider the SOC range is, the less hydrogen is consumed and hence lower system cost. Moreover, the service life cost that is imposed of the FC affects the overall performance of the system. For instance, if this cost is masked, the system exploits the FC more than the battery since the latter has a higher cost coefficient.

The vehicle component parameters that are considered in the simulation are shown in Table III.

Table 3: Vehicle Component Parameters.

FC Power Limits (kW)	[0 70]
BT Power Limits (kW)	[-40 40]
SOC Limits	[0.5 0.9]
Initial SOC	0.8
Final SOC	0.8
FC Ramp Rates (kW/s)	[-10 5]
BT Ramp Rates (kW/s)	[-15 8]

A. Highway Driving Cycle

The highway driving cycle (HDC) represents slow dynamics and high speed points. Figure 4 shows the speed and power values for such a cycle. Figure 5 shows the power curves of the load demanded at the vehicle wheels and at the electric motor system. It indicates the losses in the system. Figure 6 indicates the behavior of the vehicle during the trip. According to the LP, the highway driving cycle used the FC more than the battery. This is due to the fact that the dynamics in the highway cycles are slow and there isn't much switching. Table IV reveals the results of the LP in terms of the energy share between the sources. Figure 7 shows one episode of the load share between components. The battery aids the FC in supplying the load all during the trip. It is noticed that at approximately 640 seconds, the load is generative and the system could not charge the battery due to the ramp rate and limitation constraints so the brake power is nonzero. As to hydrogen consumption, the 13 minute trip used approximately 13% of the initial hydrogen fuel available in the tank at a cost of $5.44. Finally, to check the performance of the battery along the trip, Figure 8 shows that the battery is being discharged throughout the cycle in an attempt to lower fuel consumption. The SOC is kept between limits that are defined by the user.

Table 4:LP Results for Highway Driving Cycle.

Electric Energy Demand (kWh)	4.88
Electric Energy Supplied by FC (kWh)	4.67
Electric Energy Supplied by BT (kWh)	0.32
Electric Energy Dissipated through brake (kWh)	0.11
Final State of Charge of BT	0.59
Cost of Operation ($)	5.44

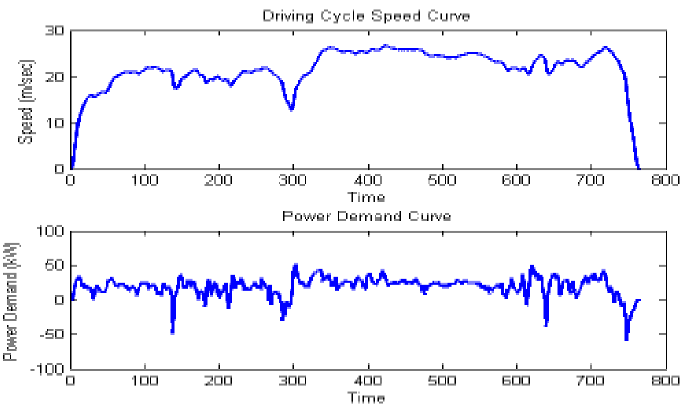

Figure 4. Highway Driving Cycle Characteristics.

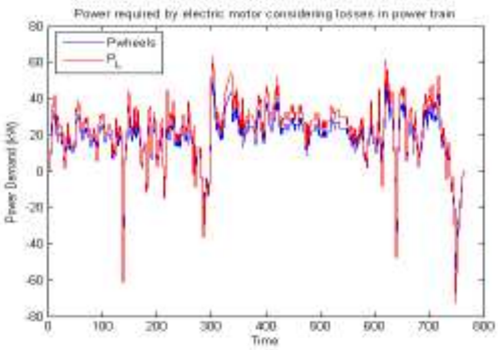

Figure 5. Load Power Considering System Losses

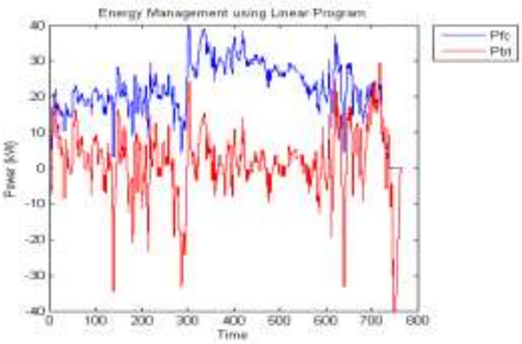

Figure 6.HDC Power Sources Curves.

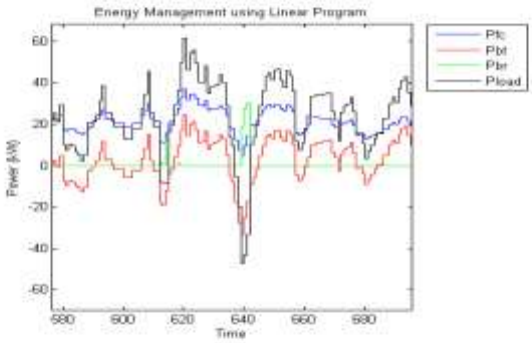

Figure 7.HDC One Episode of Driving Cycle Load Share.

Figure 8.HDC Battery SOC

B. FUDS Driving Cycle

The FUDS driving cycle consists of urban cycles with fast dynamics. Figure 9 shows the FUDS driving cycle characteristic curves. Table V reveals the results of the LP in terms of the energy share between sources. Figure 10 shows the power curves of the load demand at the vehicle wheels and by the electric motor system. Figure 11 scans a certain episode of the driving cycle when the FC and battery are optimally supplying the load according to the LP results. During the trip when the battery could not be charged due to system constraints and the load is generative, power is being dissipated through brake. At other instances, the battery is gradually discharged to help the FC in meeting the power demand. The hydrogen fuel consumption for this trip which is shown in Figure 12, is about 126g which is about 6% of the initial available hydrogen fuel. The respective cost for this fuel is $2.73. Finally, Figure 13 shows the SOC of the battery along the trip. It is noted that the battery is being discharged throughout the cycle in an attempt to lower fuel consumption. The SOC is kept between limits that are defined by the user.

Table 5: LP Results for FUDS Driving Cycle.

Electric Energy Demand (kWh)	2.63
Electric Energy Supplied by FC (kWh)	2.33
Electric Energy Supplied by BT (kWh)	0.43
Electric Energy Dissipated through brake (kWh)	0.13
Final State of Charge of BT	0.52
Cost of Operation ($)	2.73

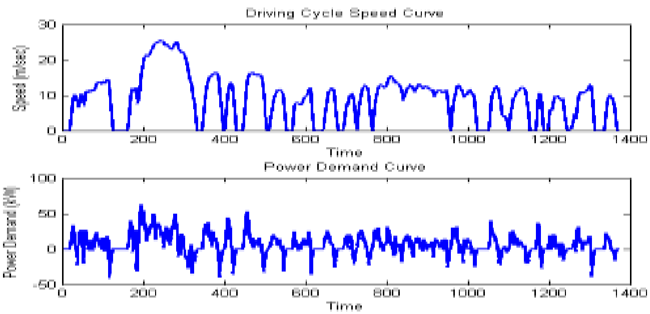

Figure 9.FUDS Driving Cycle Characteristics

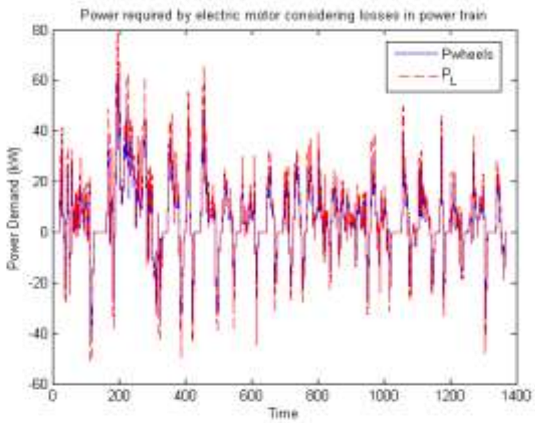

Figure 10. Load Power Considering System Losses

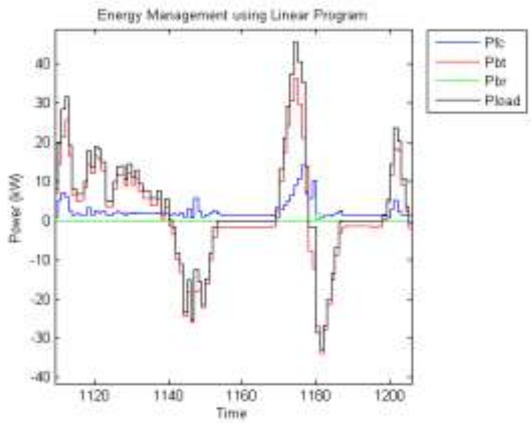

Figure 11. FUDS One Episode of Driving Cycle Load Share

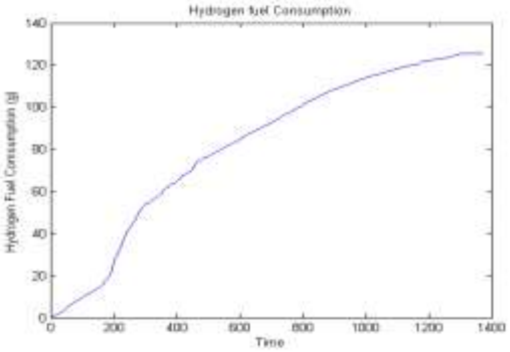

Figure 12. FUDS Hydrogen fuel Consumption

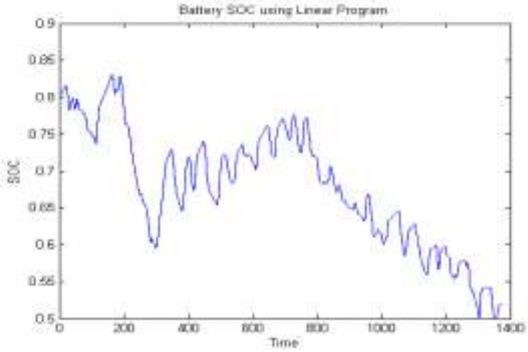

Figure 13. FUDS Battery SOC

C. Effect of increasing the battery capacity

The effect of increasing the battery capacity is also considered. It is known as a rule of thumb that by increasing the battery capacity, the mass of the battery will increase and thus the weight of the vehicle will increase. This will affect the forces acting on the vehicle and will therefore increase the total demanded load. For this reason, the battery capacity is usually bounded. However, it will be assumed that when the battery capacity increases by 1 kWh then the size will increase by 10 kg. By doubling the 1.9 kWh battery to 3.8 kWh, the vehicle mass will increase by 20 kg. Table VI indicates the results of such an increase for both driving cycles considered. It is noted in both driving cycles that by increasing the battery size, lower hydrogen consumption and thus lower operational cost are achieved. Urban driving cycles use the battery more than highway driving cycles. This is due to the increased use of brake through stopping and starting in urban cycles. Thus a 17% cost reduction is observed in the FUDS driving cycle when the battery capacity was doubled; while only a 9% cost reduction occurred in the Highway driving cycle.

Table 6:Doubling battery size.

	Highway Driving Cycle		FUDS Driving Cycle	
	1.9 kWh BT	3.8 kWh BT	1.9 kWh BT	3.8 kWh BT
Electric Energy Demand (kWh)	4.88	4.89	2.63	2.64
Electric Energy Supplied by FC (kWh)	4.67	4.23	2.33	1.89
Electric Energy Supplied by BT (kWh)	0.32	0.77	0.43	0.89
Electric Energy Dissipated through brake (kWh)	0.11	0.11	0.13	0.13
Final State of Charge of BT	0.59	0.55	0.52	0.51
Cost of Operation ($)	5.44	4.95	2.73	2.26

D. Comparison between LP Results and Rule based Method

The literature review highlighted that the rule based method is one of the methods that is adopted in the controllers of EMS for FCHV. For this reason, the linear programing method is compared against the rule based (RB) method proposed in [25]. The RB method sets the split of power between the FC and the battery according to the demanded load, the FC power limits and ramp rates, and the battery power limits and SOC ranges. Results indicate that the method proposed in this paper yields lower hydrogen consumption levels as well as reduced cost values as revealed in Table VII. The hydrogen fuel consumed during the FUDS driving cycle is reduced by 29% using LP based EMS and that for the highway driving cycle is lowered by 7%. The cost for the FUDS and highway driving cycles is reduced by 28% and 5% respectively using the LP based EMS as opposed to the rule based EMS. As noticed, the LP based EMS is achieving lower hydrogen consumption for the same driving cycle. This is reflected on the reduced system cost of operation. However, it will also positively affect the design of the vehicle components yielding a smaller size of the hydrogen tank and thus a lower vehicle weight.

Table 7: Comparison between LP and RB EMS.

Driving Cycle	H_2 Consumed (g)		Trip Cost ($)	
	LP	RB	LP	RB
FUDS	126	177	2.73	3.81
Highway	252	267	5.44	5.75

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Conclusion/Results

This paper presented a methodology to optimize the controller of FCHV based on linear programming. It highlights the improvements achieved with respect to fuel economy and operational cost. The problem formulation which takes into account the life-cycle cost of the system components considered minimizing hydrogen usage along with operational cost. The life-cycle cost of the battery is modeled by imposing a cost on the number of discharging cycles, while the life-cycle cost of the FC is represented by a penalty factor which is a fraction of the FC initial cost. Test simulations were performed on two driving cycles, and a comparison against a rule based EMS revealed that the system cost could be reduced by factor ranging from 5% to 28% depending on the driving cycle. Moreover, up to 29 % reduction in hydrogen fuel consumption was noted. The research also endorses the importance of the battery as an efficient storage in urban driving characterized by numerous stops.

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