EVS25
Shenzhen, China, Nov 5-9, 2010

Influence of powertrain parameters on vehicle performance of a fuel cell / battery city bus

Liangfei Xu, Minggao Ouyang, Jianqiu Li, Jianfeng Hua

State Key Lab of Automotive Safety and Energy, Tsinghua University, Haidian District, Beijing, 100084, P.R.China
E-mail: xuliangfei@tsinghua.edu.cn

Abstract

Proton Exchange Membrane (PEM) fuel cell is favored in automotive applications because it is clean, efficiency and quiet. Performance of a fuel cell-powered vehicle depends on two aspects, the component sizing and the control strategy. The former determines how good a vehicle can be, and the latter decides the degree of exploiting system potential. This paper presents the influence of primary parameters of the hybrid powertrain on vehicle performance. Generally speaking, the performance of a vehicle can be evaluated using following indicators: the maximal speed that can be reached, the accelerating time from zero to a certain speed, the maximal climbing angle, the mileage in a certain condition and the hydrogen consumption in a specific cycle. When the vehicle moves, the fuel cell system fulfills the stationary power requirement, and the battery supplies the accelerating power and recycles brake energy. The vehicle performance is affected by parameters of the hybrid powertrain, e.g. the maximal power of PEM fuel cell system, the PEM fuel cell average efficiency, the battery charging/discharging resistances, the battery open circuit voltage and the vehicle auxiliary power. A theoretical model describing the relationship between these parameters and vehicle performance is firstly proposed. The model is verified by several prototypes of fuel cell city buses developed in past years. Influence of system parameters on vehicle performance is explained in detail. Several suggestions for improving the entire system performance are proposed.

Keywords: PEM fuel cell, battery, component sizing, vehicle performance, model

1. Introduction

In order to cope with energy crisis and environmental pollution, researching on vehicles with an alternative propulsion system has been focused on by automotive manufacturers, research institutes and governments all over the world for decades [1]. Because of the high efficiency and environmental friendly property, PEM fuel cell vehicle is regarded as a possible solution to the environment and energy problems. Transnational automotive corporations, e.g. GM, Ford, Mercedes-Benz, Volkswagen, Toyota, launched their prototypes of fuel cell vehicles several years ago. Vehicles were demonstrated on road, and technologies have been improved greatly. However, many obstacles still remain to the commercial deployment.

China has developed fuel cell vehicles ever since 2000. The first prototype of fuel cell city bus was released by Tsinghua University in 2002 [2]. Several fuel cell vehicles, including buses and passenger cars, appeared in the Beijing Olympic Games of 2008 [3,4]. After that, the buses were demonstrated on Beijing urban roads for one year, and a wealth of experience was accumulated [5]. Currently, a demonstrational program in Shanghai with a larger scale than the program in Beijing is in process. The industry-research-study collaborations are trying their best to improve technologies and reduce entire prices.

From a viewpoint of working life time, the PEM fuel cell system performs better in a steady state condition than in a dynamic condition. Therefore, it is necessary to hybrid the fuel cell system with an ESS (energy storage system, e.g. batteries or super capacitors) so as to drive the vehicle. The ESS doesn't only meet the accelerating power requirement, but also recycles braking energy, which is important to reduce the hydrogen consumption [6].

Performance of a fuel cell-powered vehicle depends on two aspects, the system configuration and component sizing [7,8] and the control strategy [9,10]. The former determines how good a vehicle can be, and the latter decides the degree of exploiting system potential.

Recently there are many literatures about system configuration and component sizing. Jian M. et al. presents an optimizing method basing on multi-objective genetic algorithm for component sizing of a fuel cell plug-in hybrid electric vehicle [7]. Phatiphat T. et al. gave a comparative study of fuel cell hybrid powertrains with two configurations: fuel cell/battery and fuel cell / super capacitor [8]. This paper focuses on the influences of powertrain parameters on vehicle performance. It is organized as follows. Section 2 introduces the theoretical model describing the relationship between system parameters and vehicle performance. In section 3 the model is verified with several fuel cell bus prototypes. Section 4 explains the influences of system parameters on vehicle performance in detail. Section 5 is the conclusions.

2. The theoretical model

2.1 Hybrid powertrain structure

The powertrain structure discussed here is shown as in Fig. 1. A PEM fuel cell system and a Li-ion battery package are the two power sources. The battery and the electric motor are connected directly. The Li-ion battery responses to the electric motor as quickly as possible, depending on its electro-chemistry property. The output power of the fuel cell system is controlled by a dc (direct current) converter.

2.2 The model

The term *vehicle performance* of a fuel cell vehicle covers several topics, e.g. power performance, fuel economy, durability and safety. It is difficult to give a clear definition of the term. Generally speaking, we can use following indicators to evaluate a vehicle: the maximal speed that can be reached, the accelerating time from zero to a certain speed, the maximal climbing angle, the mileage in a certain condition and the hydrogen consumption in a specific cycle.

2.2.1 Basic equations

When the electric motor drives the vehicle, the vehicle dynamic equation can be written as follows.

$$mgfu\cos\alpha + 0.5C_{\mathrm{D}}A\rho u^3 + \delta mu\frac{\mathrm{d}u}{\mathrm{d}t} + mgu\sin\alpha = P_{\mathrm{m}}\eta_{\mathrm{T}}\eta_{\mathrm{md}} \quad (1)$$

where

m: vehicle mass, kg.

g: gravity acceleration, m.s^{-2}.

f: rolling resistance coefficient

u: vehicle velocity, m.s^{-1}.

α: climbing angle, rad.

C_{D}: air drag coefficient.

A: front area, m^2.

ρ: air density, kg.m^{-3}.

δ: mass coefficient.

P_{m}: input electric power of the electric motor when it drives the vehicle, W.

η_{T}: transmission efficiency.

η_{md}: drive efficiency of the electric motor.

Besides, there is a power balance in the hybrid powertrain.

$$P_{\mathrm{m}} + P_{\mathrm{aux}} = P_{\mathrm{fce}}\eta_{\mathrm{dc}} + P_{\mathrm{bat}} \quad (2)$$

where:

P_{aux}: vehicle auxiliary power (e.g. power consumed by air condition), W.

P_{fce}: net output power of fuel cell system, W.

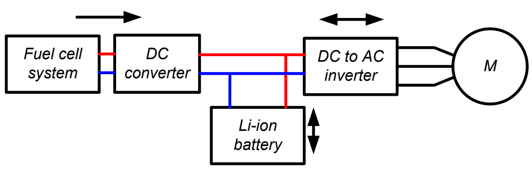


Figure 1: Structure of the PEM fuel cell / Li-ion battery powertrain. Lines with arrow(s) show the direction of energy flow

P_{bat}: output power of battery, W.
η_{dc}: dc converter efficiency.

2.2.2 Maximal speed u_{max}

The maximal speed is evaluated on a flat road, α=0, du_{max}/dt=0. Then, the following equation can be deduced.

$$u_{\max}^3+\frac{2mgf}{C_D A\rho}u_{\max}-\frac{2P_{m\_max}\eta_T\eta_{md}}{C_D A\rho}=0 \qquad (3)$$

It is a standard one element cubic equation. The solution can be written as [11]

$$\begin{cases} u_{\max}=\left[\sqrt{p^2+\frac{8}{27}q^3}+p\right]^{1/3} \\ -\left[\sqrt{p^2+\frac{8}{27}q^3}-p\right]^{1/3} \\ p=\frac{P_{m\_max}\eta_T\eta_{md}}{C_D A\rho} \\ q=\frac{mgf}{C_D A\rho} \end{cases} \qquad (4)$$

where P_{m_max} is the maximal input power of the electric motor, depending on the fuel cell, the battery and the electric motor itself as follows.

$$P_{m\_max}=\min\begin{pmatrix} P_{m\_maxallowed}, P_{fce\_max}\eta_{dc}+ \\ V_{min}\left(V_{ocv}-V_{min}\right)/R_{bat}-P_{aux}\end{pmatrix} \qquad (5)$$

where
$P_{m\_maxallowed}$: the maximal allowed input power of an electric motor, W. It is determined by the property of itself. It is a function of the rotational speed.
P_{fce_max}: the maximal net output power of the fuel cell system, W.
V_{ocv}: the battery open circuit voltage, V. It is mainly decided by the battery SOC (State of Charge) and temperature.
V_{min}: the minimal allowed voltage of the battery, V. It is decided by the electro-chemical property of the battery.
R_{bat}: the discharging resistance of the battery, Ω. It is mainly determined by SOC and temperature.

2.2.3 Accelerating time t_u

The accelerating ability is usually evaluated by the accelerating time, which is defined as the time that a vehicle accelerates from zero to a certain speed u_1. Like the maximal speed, it is tested on flat roads. The discrete velocity in the accelerating process can be calculated as

$$\begin{cases} u(k)=\frac{F(k)}{\delta m}\Delta t+u(k-1) \\ u(0)=0 \\ F(k)=T_{m\_max}(k)i_g i_0\eta_T/r-mgf \\ -0.5C_D A\rho u(k-1)^2 \\ T_{m\_max}(k)=\min\left(T_{m\_max\_allowed}, P_{m\_max}(k)\eta_{md}/\omega(k)\right) \end{cases} \qquad (6)$$

where:
T_{m_max}: maximal torque of an electric motor, N.m.
$T_{m\_max\_allowed}$: maximal torque of an electric motor that can output, N.m.
ω: rotational speed of an electric motor, rad.s^{-1}.
i_g: main transmission ratio.
i_0: transmission ratio of the gear box.
r: tire radius, m.
The accelerating time is the time accumulated from start to the end.

$$t_u=N\Delta t \qquad (7)$$

where N is the index that the vehicle reaches the target velocity u_1, N=min k, $u(k)\geq u_1$.

2.2.4 Maximal climbing angle α_{max}

In case the vehicle reaches its maximal climbing angle α_{max}, the climbing velocity is very small. Thus, du/dt=0, u^3->0. Then,

$$mgfu\cos\alpha+mgu\sin\alpha=P_{m\_max}\eta_T\eta_m \qquad (8)$$

We can deduce that,

$$\alpha_{\max}=\arcsin\frac{T_{m\_max}i_g i_0\eta_T}{mgr\sqrt{f^2+1}} -\arcsin\frac{T_{m\_max}i_g i_0\eta_T f}{mgr\sqrt{f^2+1}} \qquad (9)$$

2.2.5 Maximal mileage D_{max} with constant vehicular speed u_0, α=0

The vehicle mileage is affected by road conditions, driving habits and vehicle control strategies. We use the maximal mileage at a constant velocity u_0 to evaluate vehicle performance. Normally, in a fuel cell / battery powered vehicle, the battery is kept charge sustaining when the fuel cell system works. Therefore, the process can be separated into two stages. 1) The hybrid mode: fuel cell system works and battery is kept charge sustaining. 2) The pure electric mode: after the hydrogen is out, the battery drives the vehicle.
In the hybrid mode, the driving distance L_1 is

$$\begin{cases} L_1 = \dfrac{(1-\sigma_1)E_{\text{fce}}\eta_{\text{dc}}\eta_{\text{T}}\eta_{\text{md}}}{mgf + 0.5C_{\text{D}}A\rho u_0^2} \\ E_{\text{fce}} = m_{\text{hydro}}\text{LHV}\,\eta_{\text{fce}} \\ \sigma_1 = E_{\text{aux}}/(E_{\text{fce}}\eta_{\text{dc}}) \end{cases} \quad (10)$$

where

E_{fce}: the net output energy of fuel cell system, J.

E_{aux}: the energy consumed by vehicle accessorial components, e.g. the air condition, J.

m_{hydro}: hydrogen mass stored in the high-pressed tank, kg.

LHV: low heat value of hydrogen, J.kg^{-1}.

η_{fce}: net efficiency of fuel cell system.

In the pure electric mode, the driving distance L_2 is

$$\begin{cases} L_2 = \dfrac{(1-\sigma_2)E_{\text{bat}}\eta_{\text{bat}}\eta_{\text{T}}\eta_{\text{md}}}{mgf + 0.5C_{\text{D}}A\rho u_0^2} \\ \sigma_2 = E_{\text{aux}}/(E_{\text{bat}}\eta_{\text{bat}}) \end{cases} \quad (11)$$

where

E_{bat}: energy stored in the battery, J.

η_{bat}: battery discharging efficiency.

The mileage in this case is the summary of the two parts.

$$D_{\max} = L_1 + L_2 \quad (12)$$

2.2.6 Hydrogen consumption

In China, we use the hydrogen consumption per 100 km in the "China city bus typical cycle" as the indicator to evaluate the fuel economy. In this cycle and in case of a battery charging sustaining strategy, the hydrogen energy consumption E_{hydro} can be calculated as [6]

$$E_{\text{hydro}} = \frac{E_{\text{md}}/\eta_{\text{md}} + E_{\text{aux}} + E_{\text{batloss}} - E_{\text{mb}}\eta_{\text{mb}}}{\eta_{\text{fce}}\eta_{\text{dc}}} \quad (13)$$

where

E_{md}: mechanical energy of the electric motor for driving the vehicle, J.

$E_{batloss}$: energy losses during charging/discharging process, J. Although the battery is kept charging sustaining, there is energy loss due to battery resistance.

E_{mb}: recycled mechanical energy of the electric motor during braking regeneration process, J.

η_{mb}: brake regeneration efficiency of the electric motor.

The hydrogen mass then can be calculated as

$$m_{\text{hydro}} = E_{\text{hydro}}/\text{LHV} \quad (14)$$

3. Model verification

Figure 2: One of the fuel cell city bus to verify the model

The model is verified basing on three PEM fuel cell city buses, named Bus A, Bus B and Bus C. One of them is shown in Fig. 2.

Parameters for the vehicle dynamic equation of the three are almost the same, as in Table 1.

The three buses differ in component sizing, which is shown as in Table 2. Bus A is equipped with a single fuel cell stack with a rated power of 40kW. Bus B and C are installed with two stacks.

The PEM fuel cell stack(s) is(are) hybrid with Li-ion battery packages. The battery capacity in Bus A is larger than Bus B and C. Battery material in Bus B and C are the same, but is different from that in Bus A. Different materials lead to different rated voltages and minimal voltages. Because of some unknown reasons battery resistance of Bus B is much larger than that of Bus C. The increment of resistance doesn't only reduce the charging/discharging efficiency and maximal output power, but also increase the heat quantity generated during operation.

A comparison between simulating and experimental results of the three buses is shown as in Table 3. Because of limitation of road conditions, not each parameter was tested.

The maximal speed referred in Equation (4) can only be reached when the vehicle runs on an enough long road. But actually the testing roads are of limited length. Therefore, the actual maximal speed is always smaller than the

Table 1: Parameters for vehicle dynamic equations

Parameter (Unit)	Value
vehicle mass with loads (ton)	14~16
Length (m)	12
gravity acceleration (m.s^{-2})	9.8
rolling resistance coefficient	0.018~0.021
air drag coefficient	0.7
front area (m^2)	7.5
mass coefficient	1.1~1.3
transmission efficiency (%)	90
driving efficiency of the electric motor (%)	80
air density (kg.m^{-3})	1.29

Table 2: Power-train parameters for three buses

Parameter (Unit)	A	B	C
Fuel cell system maximal net power (kW)	40	80	80
Battery type	Li-ion	Li-ion	Li-ion
Battery capacity (A.h)	180	100	100
Battery rated voltage (V)	360	350	350
Battery minimal voltage (V)	330	280	280
Battery resistance (Ω)	0.07	0.35	0.15

Table 3: Comparison between theoretical and experimental results for three fuel cell buses.

Parameter (Uint)	Bus No.	Model	Actual	Error (%)
u_{max} ($km.h^{-1}$)	A	87.0	>72	-
	B	72.3	>55	-
	C	94.0	>80	-
t_u, u_1=50 $km.h^{-1}$ (s)	A	22.8	23.5	3
	B	33.9	37.5	9.6
	C	18.5	20	7.5
α_{max} (degree)	A	9	>5	-
	B	9	-	-
	C	9	-	-
$D_{max} = L_1 + L_2$ u_0=30 $km.h^{-1}$ (km)	A	145+37	130+40	7.1
	B	137+12	-	-
	C	137+19	-	-
Fuel economy[1] ($kg.100km^{-1}$)	A	10.3	-	-
	B	10.6	-	-
	C	9.8	10.5	6.7

theoretical one. Accelerating time from zero to 50$km.h^{-1}$ is calculated and tested, and relative errors are within 10%. Maximal climbing angles of the three buses are 9 degree. Actually this angle is affected by vehicle suspension system and road conditions. Thus it is also very difficult to be verified in practice, and only Bus A was tested. The mileage at a constant speed of 30$km.h^{-1}$ of Bus A is calculated and tested. In the practical situation the velocity fluctuates around the constant value, and some of the mechanical energy can be recycled. Therefore, the distance of "pure electric mode" in experiment is slightly longer than that in calculating. The relative error of the entire mileage of Bus A is about 7.1%. The mileage of hybrid mode for the three buses is about 140 km. It can be improved by storing more hydrogen in tanks. The fuel cell system in Bus A works almost at its rated load, while the stacks in B and C work at a low load ratio. Therefore, the average efficiency of the fuel cell system in Bus A is higher than that in Bus B and C. Because of the higher efficiency of Bus A, L_1 of Bus A is larger than that of Bus B and C. Fuel economy in "China city bus typical cycle" is calculated and tested for Bus C. The relative error is about 6.7%. In addition, a vehicle dynamic model is necessary to calculate the fuel economy in the specific testing cycle.

After all, because of limitations of practical conditions, e.g. road conditions and safety reasons, only several parameters were tested and compared with theoretical results. Relative errors of these parameters are within 10%, which partly verifies the model in Section 2.

4. Influences of powertrain parameters on vehicle performances

As mentioned in Section 2, vehicle performance is influenced by numbers of variables. The most important parameters among them are those of the PEM fuel cell system and the battery. In the following paragraphs, we focus on these parameters: C_{bat}, R_{bat}, P_{fce_max}, η_{fce} , m_{hydro} and P_{aux}. The basic vehicle prototype is Bus A. Since the maximal climbing angle is not very often used to evaluate a city bus, it is not discussed. Preconditions for the following performance indicators are the same as in Table 3.

4.1 PEM fuel cell parameters: P_{fce_max} , η_{fce} and m_{hydro}

Influence of PEM fuel cell parameters on vehicle performance is shown as in Fig. 3. The vehicle was equipped with a 180 A.h Li-ion battery. The maximal speed can be kept around 83 $km.h^{-1}$, even if the maximal net output power of the fuel cell system decreases to 20 kW. The maximal speed increases with the increment of P_{fce_max}, but it is limited by the driving ability of the electric motor. If the maximal net output power exceeds 65 kW, the maximal speed will keep constant around 94 $km.h^{-1}$. The accelerating time from 0 to

[1] A vehicle dynamic model is necessary to calculate the fuel economy in the specific testing cycle. Battery is kept charge sustaining in the simulation model.

50 km.h^{-1} decreases from 24.3 s to 18.5 s, and then keep constant. The two relationships are almost linear, 0.24 km.(h.kW)$^{-1}$ and -0.13 s.kW^{-1} respectively. The driving distance at 30km.h^{-1} in "hybrid mode" increases linearly with the increment of fuel cell system net efficiency and stored hydrogen, 3.6 km.%$^{-1}$ and 9.6km.kg^{-1} respectively.

Moreover, the fuel cell system efficiency affects the fuel economy. Based on Equation (13), we can deduced that,

$$\frac{\Delta E_{\text{hydro}}}{E_{\text{hydro}}} = -\frac{\Delta \eta_{\text{fce}}}{\eta_{\text{fce}}} \tag{15}$$

Using data in Fig. 8 (a) of [6], if the efficiency of PEM system increases from 48.3% to 55%, the hydrogen consumption will increase by 14%.

4.2 Battery parameters: C_{bat} and R_{bat}

Fig. 4 (a) and (b) illustrate the influences of battery parameters on vehicle performance.

A battery with larger capacity is able to output more power than one with small capacity. Growth of capacity leads to increment of maximal velocity and reduction of accelerating time. As in Fig. 4 (a) along with the growth of capacity, the maximal velocity increases almost linearly with a slope of about 0.3 km.h^{-2}.A^{-1}. The accelerating time decreases nonlinearly with capacity. It is about 50 s when the capacity is 100 A.h. After that, the time decreases gradually. If we want to an accelerating time of about 25 s, the capacity should be more than 160 A.h. The battery with larger capacity is able to keep more energy than a small one. Thus, the driving distance of "pure electric mode" grows with the capacity with a slope of 0.33 km.(A.h)$^{-1}$, as in Fig. 4 (b).

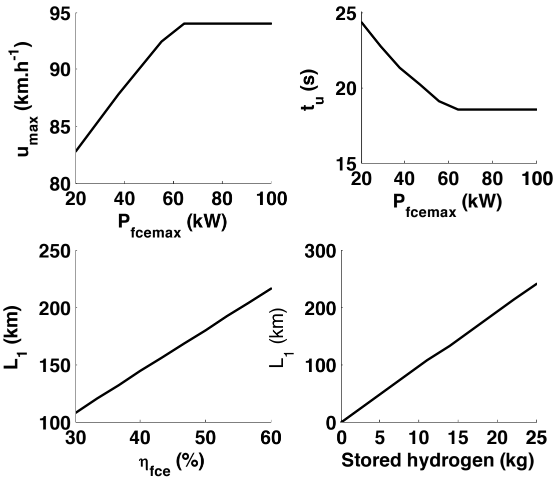


Figure 3: Influences of PEM fuel cell system on vehicle performance

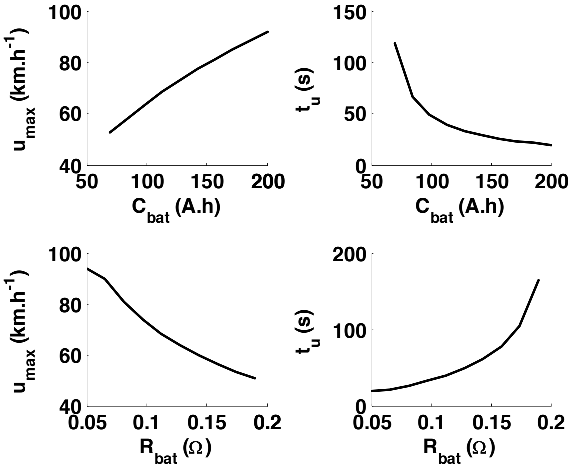
Battery resistance is another sensitive parameter for the vehicle performance. Growth of resistance means reduction in output power and increment of energy loss, which will finally lead to reduction in mileage. As in Fig. 4 (a), the maximal velocity decreases with a slope of -3.6 km.(h.mΩ)$^{-1}$. The accelerating time increases nonlinearly with resistance. Before three times of the original value (0.05Ω), the accelerating time increases almost linearly with a slope of 4 s.mΩ^{-1}. After that, it increases suddenly. The driving distance of pure electric mode reduces with resistance with a slope of -2 km. mΩ^{-1}.

What's more, the increase of battery resistance results in a growth of hydrogen consumption. The formula can be written as

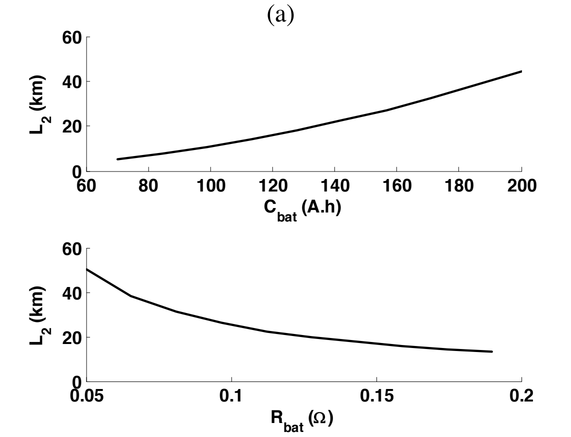
$$\frac{\Delta E_{\text{hydro}}}{E_{\text{hydro}}} = \frac{-NEC}{E_{\text{hydro}}} \frac{\Delta R_{\text{bat}}}{R_{\text{bat}} \eta_{\text{fce}} \eta_{\text{dc}}} \tag{16}$$

where NEC is net electric consumption of the battery. It is an integration of battery input/output energy during operation. Considering data in Fig. 8 (a) of [6], if the battery resistance increases by 50%, the hydrogen consumption will grow by 3.4%.

4.3 Vehicle auxiliary power P_{aux}



(a)



(b)

Figure 4: Influences of battery on vehicle performance

Fig. 5 presents the influence of vehicle auxiliary power on the entire system performance.
In a fuel cell electric vehicle, there are many electric driven auxiliary components, e.g. the air condition and the electric power steering system. The air condition consumes quantity of energy. The input power of an air condition may range from 10 kW to 20 kW, depending on its type. Along with the increase of auxiliary power, the maximal speed and the driving distance reduce, and the accelerating time grows. The relationships are almost linear. And the slopes are -0.3 km.(h.kW)$^{-1}$, 0.15 s.kW^{-1}, -0.88 km.kW^{-1}, -0.22 km.kW^{-1} for the maximal velocity, the accelerating time, the hybrid mode distance and the pure electric mode distance, respectively.

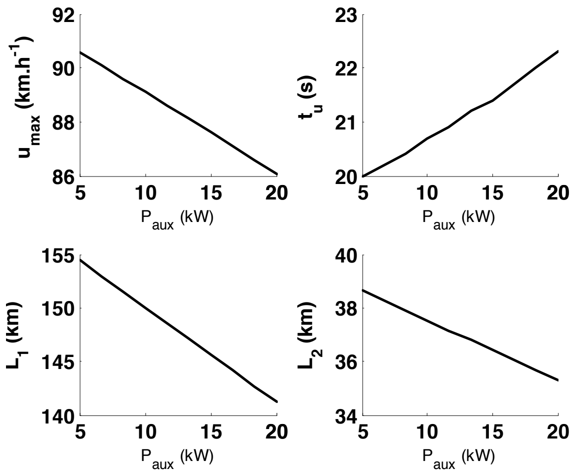


Figure 5: Influences of vehicle auxiliary power on vehicle performance

Besides, the auxiliary power affects the hydrogen consumption greatly. The formula can be written as

$$\frac{\Delta E_{\text{hydro}}}{E_{\text{hydro}}} = \frac{\Delta E_{\text{aux}}}{E_{\text{hydro}}\eta_{\text{fce}}\eta_{\text{dc}}} \qquad (17)$$

Basing on data in Fig. 8 (a) of [6], if the auxiliary power grows from 5 kW (without air condition) to 22 kW (with air condition), the hydrogen consumption will increase by 52%. Another factor that affects hydrogen consumption greatly is the braking energy. The formula can be noted as

$$\frac{\Delta E_{\text{hydro}}}{E_{\text{hydro}}} = \frac{-\Delta E_{\text{mb}}\eta_{\text{mb}}}{E_{\text{hydro}}\eta_{\text{fce}}\eta_{\text{dc}}} \qquad (18)$$

Using data in Fig. 8 (a) of [6], if the braking energy increases from 0 to 6.06MJ, the hydrogen consumption will reduce by 16%.

5. Conclusion

This paper proposes a model describing the relationship between powertrain parameters and vehicle performance of a PEM fuel cell/Li-ion battery city bus. Although parameters are difficult to obtain, the model was verified by several experimental results for three buses with relative errors within 10%. The analysis of influence of powertrain parameters on vehicle performance is carried out basing on Bus A as shown in Fig. 2. Results are as follows.

- Within the working range of the electric motor, the ideal maximal velocity is affected by fuel cell net output power, battery capacity, battery resistance and vehicle auxiliary power linearly, with slopes of 0.24 km.(h.kW)$^{-1}$, 0.3 km.h-2.A^{-1}, -3.6 km.(h.mΩ)$^{-1}$ and -0.3 km.(h.kW)$^{-1}$, respectively.
- Within the working range of the electric motor, the accelerating time from 0 to 50km.h^{-1} is influenced linearly by fuel cell net output power and vehicle auxiliary power, with slopes of -0.13 s.kW^{-1} and 0.15 s.kW^{-1}, respectively. There are nonlinear relationships between the accelerating time and C_{bat}, R_{bat}. Battery resistance is very sensitive for the accelerating time. The time increases three times when the resistance grows three times.
- The driving distance in “hybrid mode” with a velocity of 30km.h^{-1} is primary affected by fuel cell net efficiency, stored hydrogen mass, and vehicle auxiliary power. The relationships are linear, with slopes of 3.6 km.%$^{-1}$, 9.6 km.kg^{-1} and -0.88 km.kW^{-1}, respectively.
- The driving distance in “pure electric mode” with a velocity of 30km.h^{-1} is mainly affected by battery capacity, resistance and vehicle auxiliary power. The relationships are linear, with slopes of 0.33 km.(A.h)$^{-1}$, -2 km.mΩ^{-1} and -0.22 km.kW^{-1}, respectively.
- The hydrogen consumption in a determined cycle is influenced by fuel cell net efficiency, battery resistance, vehicle auxiliary power and braking energy. Comparing to improve fuel efficiency and reduce battery resistance, it is much easier to reduce vehicle auxiliary power consumption and to recover brake energy.

In order to improve the dynamic response property of a fuel cell city bus, we should:

- To increase battery capacity and to reduce battery charging resistance firstly.

- To increase fuel cell output power and to reduce vehicle auxiliary power also helps to improve the dynamic property.

In order to reduce the hydrogen consumption and extend mileage, we should:

- To improve the brake energy regeneration strategy and the air condition system, so as to recover more energy and reduce vehicle auxiliary energy consumption.
- To improve the fuel cell system and battery system also helps to reduce hydrogen consumption. But it is really difficult to be realized.

Acknowledgements

Support by the project of National Science Fund for Young Scholars (61004075), the project of National High-tech R&D Program of China - (2011AA11A269) and the Program for New Century Excellent Talents in University (NCET, 2010-2012) is greatly acknowledged.

References

[1] C. C. Chan. The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles. Proceedings of the IEEE, 2007, 95(4): 704-718.

[2] Minggao Ouyang, Liangfei Xu, Jianqiu Li, Dawei Gao, Qicheng Xie. Performance comparison of two fuel cell hybrid buses with different powertrain and energy management strategies. Journal of Power Sources, 2006, 163: 467-479.

[3] Dawei Gao, Zhenhua Jin, Qingchun Lu. Energy management strategy based on fuzzy logic for a fuel cell hybrid bus. Journal of Power Sources, 2009, 185: 311-317.

[4] Liangfei Xu, Jianqiu Li, Jianfeng Hua, Xiangjun Li, Minggao Ouyang. Adaptive supervisory control strategy of a fuel cell/battery-powered city bus. Journal of Power Sources, 2009, 194 : 360-368.

[5] X. Li, J. Li, L. Xu, F. Yang, J. Hua, M. Ouyang. Performance analysis of proton-exchange membrane fuel cell stacks used in Beijing urban-route buses trial project. International Journal of Hydrogen Energy, 2010, 35(8): 3841-3847.

[6] L. Xu, J. Li, J. Hua, X. Li, M. Ouyang. Optimal vehicle control strategy of a fuel cell/battery hybrid city bus. International Journal of Hydrogen Energy, 2009, 34: 7323-7333.

[7] M. Jain, C. Desai, N. Kharma, S.S.Williamson. Optimal powertrain component sizing of a fuel cell plug-in hybrid electric vehicle using multi-objective genetic algorithm. Industrial Electronics, 2009, 3741-3746.

[8] P. Thounthong, V. Chunkag, P. Sethakul,B. Davat, M. Hinaje. Comparative Study of Fuel Cell Vehicle Hybridization with Battery or Supercapacitor Storage Device. IEEE transactions on vehicular technology, 2009.

[9] P. Rodatz, G. Paganelli, A. Sciarretta, L. Guzzella. Optimal power management of an experimental fuel cell/supercapacitor-powered hybrid vehicle. Control Engineering Practice, 13(2005)41-53.

[10] C.C. Lin, H. Peng, J.W. Grizzle, J. Kang. Power managment strategy for a parallel hybrid electric truck. IEEE Transactions on Control Systems Technology, 11(2003)839-849.

[11] Cubic equation. http://www.statemaster.com/encyclopedia/Cubic-equation.

Authors

Dr. Liangfei Xu

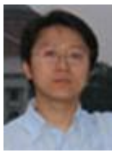
Dr. Liangfei Xu obtained his bachelor’s degree and Ph.D degree in 2003 and 2009 respectively, both from Tsinghua University. Between 2004 and 2005 he studied in RWTH Aachen Germany as a master exchange student. His research interests include fuel cell hybrid powertrain and automotive electronics. He is now an assistant professor of Tsinghua University.

Prof. Minggao Ouyang

Prof. Ouyang Minggao obtained his Ph.D degree in 1993 from Technical University of Denmark. He is the Yangtz Scholar Distinguished Professor, the deputy director of Tsinghua Academic Committee, the director of State Key Lab of Automotive Safety and Energy and the director of Tsinghua New Energy Vehicle Center. His research interests include modeling and control of internal combustion engine systems, hybrid powertrain systems, electrified driven systems and energy policy.

Prof. Jianqiu Li

Prof. Jianqiu Li obtained his Ph.D degree in 2000 from Department of Automotive Engineering, Tsinghua University. His research interests include automotive electronics and all kinds of control systems for advanced gasoline/diesel engines, fuel cell systems, battery packages, electric motors and hybrid powertrains.



Dr. Jianfeng Hua

Dr. Jianfeng Hua obtained his bachelor’s degree and Ph.D degree in 2004 and 2010 respectively, both from Tsinghua University. Between 2005 and 2006 he studied in RWTH Aachen Germany as a master exchange student. His research interests include fuel cell systems, battery management systems and automotive electronics. His is now a postdoc of Tsinghua, and the CTO of KeyPower Ltd..