Assessing current vehicle performance and simulating the performance of hydrogen and hybrid cars

Bent Sørensen

Roskilde University
Institute 2, Energy & Environment group
Universitetsvej 1
DK-4000 Roskilde Denmark
fax: +45 4674 3020
boson@ruc.dk
http://mmf.ruc.dk/energy

Abstract:

A measure of the efficiency in transforming energy input into transport work is defined and applied to road vehicles as well as to sea, air and rail vehicles for passenger or freight transportation. The insights obtained with this measure is compared with the results of applying the conventional measure of kilometres per unit of energy for current fleets of vehicles. Then, simulation methods are used to assess the performance of fuel cell vehicles, electric vehicles and hybrids between the two. The latter are found to provide an optimum performance for a small, efficient passenger car.

Keywords: Vehicle efficiency, transport work, hydrogen vehicles, fuel cell hybrid cars

1. Introduction

The on-the-road performance of passenger cars are often discussed in terms of kilometres driven per MJ (or other unit of energy). This does not do justice to the different payloads that different cars are certified to carry, perhaps considering the poor correlation between required, actually used and available passenger and cargo space characterising the vehicle choice of many passenger car owners. Campaigns have occasionally been directed at increasing customer usage of the available payload (better trip planning, pool arrangements), but automobile sales material often mentions only km/MJ overall performance, if anything at all related to energy efficiency (mentioning energy performance is mandatory in some European countries, but mostly not done in North America). Below, I present performance data in terms of transport work carried out, such as kilometres times maximum payload that may be obtained per unit of energy input. In addition to being a prerequisite for encouraging better payload utilisation, this also allows transport modes other than passenger cars to be compared on a equal footing. Such comparisons are made for passenger cars, motorcycles, buses, trucks, rail-based trains, ships and aircraft carriers, with payloads that can comprise different rations of passenger and cargo transportation, as the payload is in all cases expressed in kilograms. This transport work performance measure may be expressed in terms of the maximum certified payload, or it may be expressed in terms of the average actual payload, in order to discuss the role of the payload utilisation fraction (such as seat occupancy for passenger modes).

With the assessment tool described above at hand, a discussion of hydrogen hybrid road vehicles is carried out using simulation techniques. The issue is to determine the optimum battery and fuel cell ratings, with endpoints corresponding to pure electric or pure fuel cell vehicles. The behaviour is non-linear, because the total power requirements for a given driving cycle change as function of vehicle mass, which again – depending on battery type used – is not constant as the ratio between battery and fuel cell ratings are altered. Details of the assumptions will be given in section 4.

2. Performance of passenger cars

Figure 1 gives the conventional performance measure for a number of current passenger car, in km/MJ, but with the payload mentioned along the abscissa. Payloads are the officially permitted maximum loads provided in the certification documents of each vehicle [1], and the fuel efficiencies are the official test results for the New European Union Driving Cycle, as used for taxation purposes in Europe [2]. One notes the wide spread in performance, indicating that properties other than fuel efficiency are important in consumer choices. The top scoring vehicles are the 1999 Audi A2 and VW Lupo common-rail diesel cars with a proprietary high-efficiency automatic transmission (a computer-controlled, driver-independent gear changing device). These cars are no longer in production, but other cars have emerged over the last 2-4 years, with equally efficient diesel engines (and now with particle filters for greatly reducing environmental impacts) but without the automated gearbox (although with efficiency-optimised gear exchange ratios). This trend started in France (Citroën C2, C3 and their Peugeot counterparts, as well as Renault Clio) but has now been taken up by most automakers outside the USA. Other cars making themselves remarked in Fig. 1 are the Toyota Prius gasoline-battery hybrid and the Smart two-seater diesel. At the other end, certain sports cars and utility vehicles (4-wheel driven jeeps or tanks constructed for difficult off-road terrain, but often used as standard cars on paved highways with one person and little luggage in the car).

Now the same data are translated into a measure of transport work efficiency, by multiplying the km/MJ figure by the maximum payload in kg. The results are shown in Figure 2, while Figure 3 shows the corresponding quantities for the current average load factor of the vehicles (taken as 1.57 persons per vehicle [3], with an average weight of 100 kg per person, comprising luggage carried). The data shown in Figure 2 shows the perhaps surprising result, that the Skoda Octavia diesel car is the most efficient one, because its high permitted payload outweighs the lower km/MJ-value compared e.g. to the VW Lupo 3L. It is also remarkable, that the order no longer favours the lowest mass car (as seen e.g by the reverse ordering of Citroën C2, C3 and C5 relative to their positions in Fig. 1). However, the advantage of a high maximum payload disappears if it is not used. Replacing the actual maximum payload for each vehicle by the average of 157 kg, the ranking reverts to the conventional km/MJ level, as illustrated in Figure 3.

3. Other transport modes

The payload-weighed measure of performance allows a comparison of passenger cars with other road and non-road vehicles in a reasonably unbiased way. Figure 4 shows the vehicle km/MJ times the average payload for current usage patterns, for land, sea and airborne vehicles. The spread around the average value indicates an estimate of both variations in available technology, and also variations that would emerge with different load factors, i.e. when charter airlines in the vacation business operate completely full aircraft in contrast to the about 70% seat occupancy of many commercial airlines. It is seen that freight transport by sea or train obtain the highest energy performance. The average speed or infrastructure needed to evaluate the cargo delivery time use is not included in this analysis. The lower efficiency of road transport of cargo by lorries is partly due to the decreased energy efficiency associated with current requirements that lorries follow the (passenger car) traffic flows on highways, implying the need for larger engine ratings.

Regarding aircraft efficiency, apart from general aviation, the regular scheduled air travel is seen to be as energy efficient as automobile travel, when measured in relation to transport work, i.e. per person-km or per kg-km travelled. It is only a few decades ago, that air travel was considerable less efficient than road travel [3]. Train transport of passengers is seen to have similar energy performance to road and air travel, inferior only to intercity buses. Decisive for these conclusions are the load factors for each mode. Although seat occupancy may be similar for train and bus travel, the seat arrangement is usually much more condensed in bus design, which accounts for the higher efficiency.

For passenger cars, the spread in data are taken from Fig. 2. The light truck data are from the USA [3] as is the indicated averages for other modes of transportation. This may be the reason that the light truck efficiency is closer to that of an average passenger car than one might have expected. In any case, the scale used in Fig. 3 is logarithmic, so the difference between the best light truck performance within the range given and the best passenger car performance is still a factor of four.

4. Hybrid car simulation setup

The tool used for this part of the study is the modular software-package ADVISOR (Markel *et al.*, 2002), which is well tested and offer a range of simple, parametrised sub-models or more detailed physical models for the fuel cell stack, the batteries, the electric motor, the exhaust control, the transmission and entire power train including controls and control strategies. Each ADVISOR module can be changed or written anew to accommodate particular segments of importance for a given vehicle. The basic vehicle used for studying hybrid fuel cell/battery passenger cars is loosely based upon the Volkswagen Lupo, with a basic mass of 605 kg and total mass ranging from about 1 t (1000 kg) with pure fuel cell propulsion (at a rated power of 30 kW) to nearly 3t with pure battery operation and lead-acid batteries. Even at this weight, it is not possible for the battery version to achieve the average range of 600 km between recharging/refuelling, that the hydrogen vehicle achieves. With advanced lithium ion batteries, the mass of the electric vehicle may be brought down below 2 t, but only the hybrid cars obtain a manageable total weight. The car is in the popular a-class and has a 340 kg maximum load of passengers and/or luggage.

5. Simulation results

Figure 5 shows the results of a simulation made for a pure fuel cell vehicle. This car would have a range of 675 km with 4 kg of hydrogen stored onboard, under average driving conditions such as the driving cycle shown at the top of Fig. 5 (which is a composite comprising both the EU and the USA regulatory standard driving cycles in a mixed city and highway cycle of total length 89 km). Surplus power from the fuel cell is used to recharge the batteries, which at the end of the driving cycle are required to be as well charged as at the cycle start. The pure fuel cell vehicle in this model has a small-size high-voltage battery, through which all power to the electric motor must pass. A fuel cell rating of 30 kW is found to be sufficient for achieving the performance required by the model driving cycle, with reasonable latitude for the challenges of alternative cycle prescriptions. The fuel cell envisaged is rather the goal cell of current R&D, in terms of efficiency and assumed life of at least 5 years, as further discussed in [4].

The purely electric vehicle shown in Figure 6 is based on a vehicle with 17 kWh of NiMH batteries weighing 1670 kg. Nickel-metal-hydride batteries are common in current electric vehicles, but may in the future be replaced by lighter lithium ion batteries. These batteries have only recently become available for automotive uses, and are (even more than other types of batteries) far from economically viable. The battery weight is 113 kg for Li-ion batteries and would be about 2.5 times more for NiMeH or lead-acid batteries, starting to have a negative effect on performance due to increased overall car weight, in an obviously vicious circle. None of the pure battery solutions for the vehicle in question could fulfil the range requirement (doubling the battery mass in the hope of doubling the range would entail a severe mass penalty on performance and motor rating).

The hybrid solution shown in Figure 7 needs at most a fuel cell rated at 20 kW, plus a modest 5 kWh Li-ion battery. At present, the extra cost of 50% more fuel cells or of a 5 kWH Li ion battery are comparable, and both must come down in order for any of the alternatives to become economically viable. The hybrid solution has a better performance (higher maximum torque and better acceleration characteristics) and even pure fuel cell vehicles are as mentioned above most often equipped with a traction battery of say 1 kWh.

6. Discussion

The key advantage of the car used in the present simulation study is that it has high efficiency in the conventional sense, before adding a fuel cell/electric motor also of high conversion efficiency. Many current fuel cell prototypes puts 60-100 kW of fuel cells into a basic car of poor efficiency, which makes little sense considering that the fuel cell cost is the most difficult obstacle. The assessment technique presented here offers a way of appraising vehicle efficiencies, that can be applied to many different types of vehicles, without bias against variations in the relative passenger and freight-carrying capacity.

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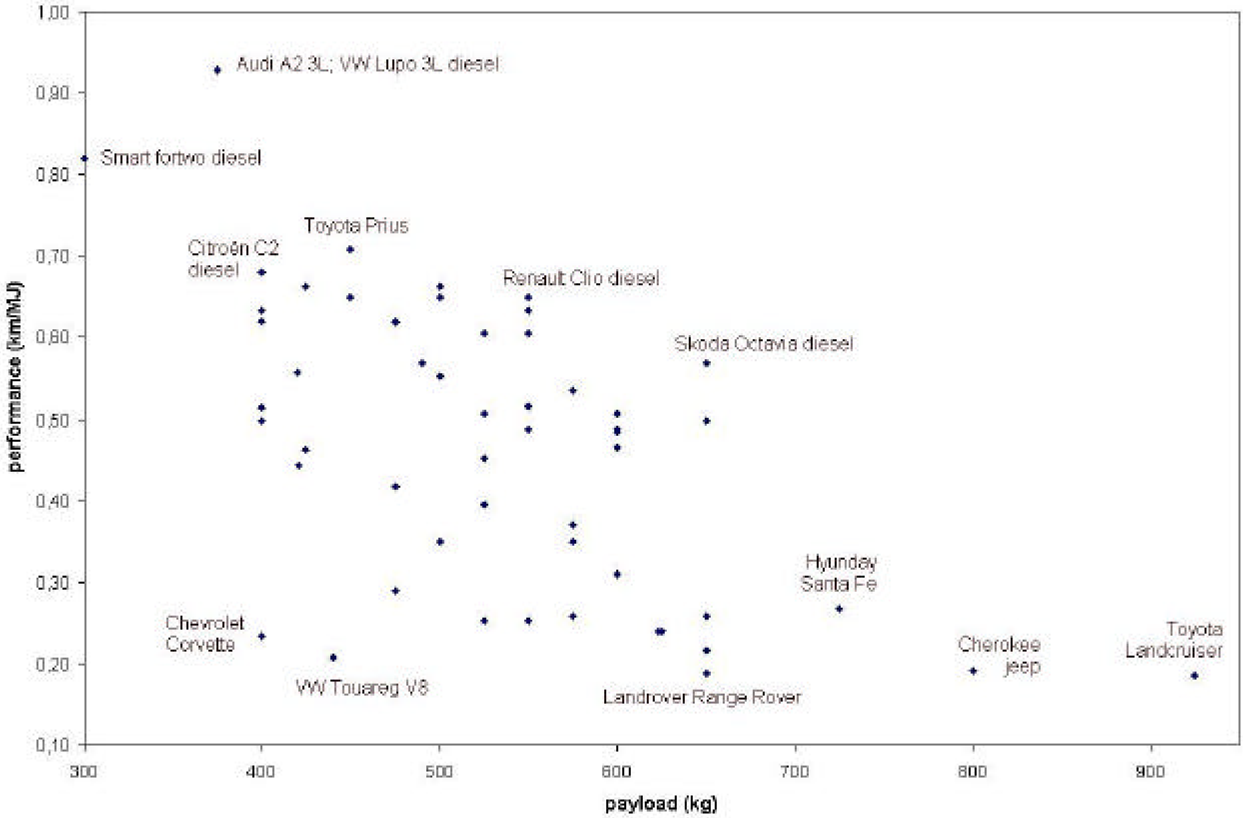
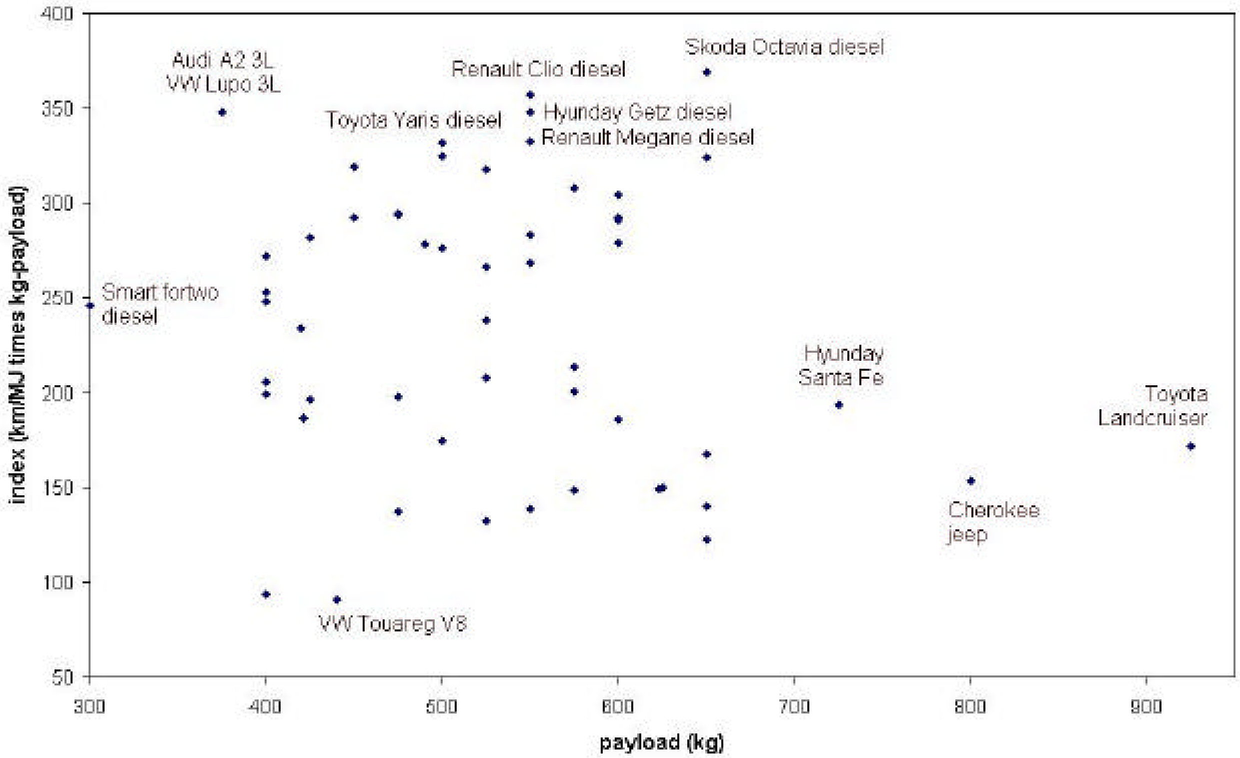
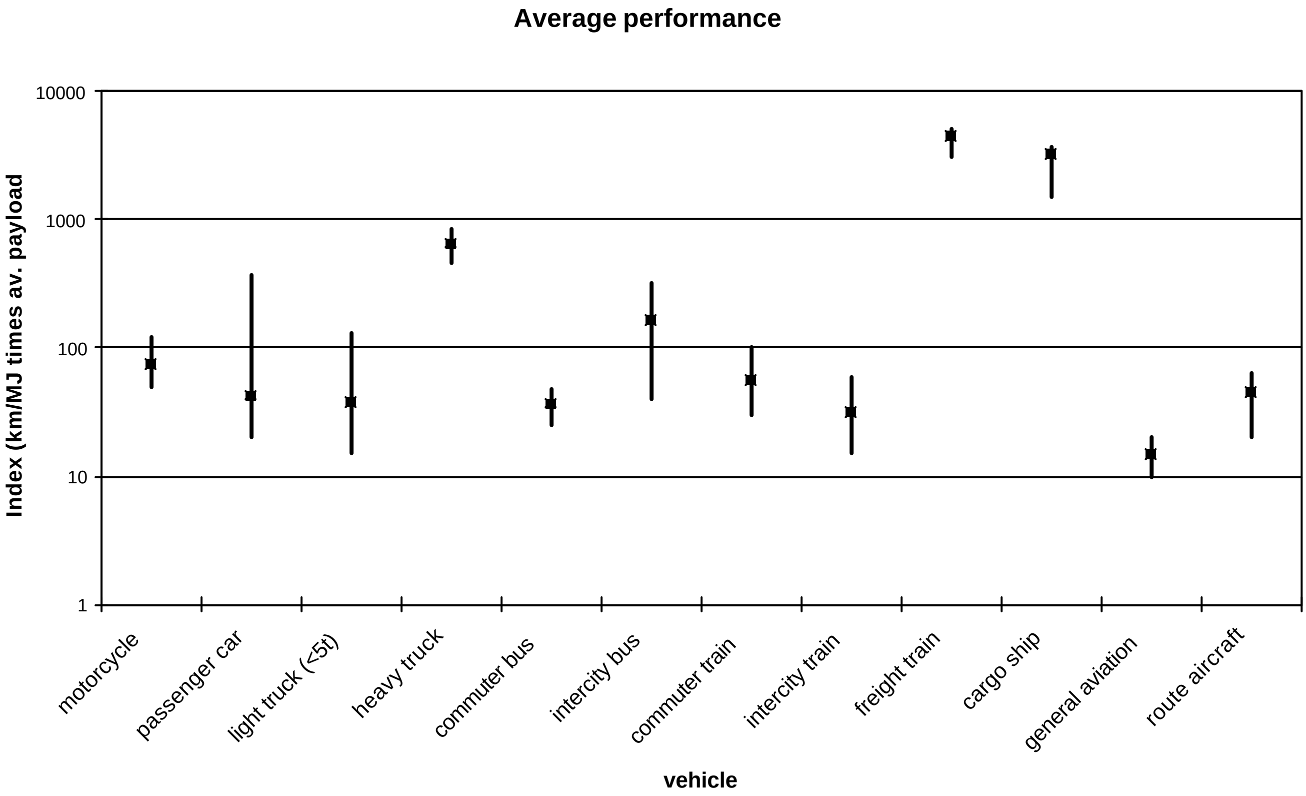

Audi A2 3L; VW Lupo 3L diesel
Smart fortwo diesel
Toyota Prius
Citroën C2 diesel
Renault Clio diesel
Skoda Octavia diesel
Hyunday Santa Fe
Chevrolet Corvette
VW Touareg V8
Cherokee jeep
Toyota Landcruiser
Landrover Range Rover
performance (km/MJ)
payload (kg)


Audi A2 3L VW Lupo 3L
Renault Clio diesel
Skoda Octavia diesel
Toyota Yaris diesel
Hyunday Getz diesel
Renault Megane diesel
Smart fortwo diesel
Hyunday Santa Fe
Toyota Landcruiser
Cherokee jeep
VW Touareg V8
index (km/MJ times kg-payload)
payload (kg)



Average performance
Index (km/MJ times av. payload
10000
1000
100
10
1
motorcycle
passenger car
light truck (<5t)
heavy truck
commuter bus
intercity bus
commuter train
intercity train
freight train
cargo ship
general aviation
route aircraft
vehicle

Index (km/MJ times kg of average payloa
150,00
124,00
98,00
72,00
46,00
20,00
0
60
Audi A2 3L 1.2TDI aut
Volkswagen Lupo 1.2 TDI 3L
Smart fortwo coupé 0.8 CDI
Toyota Prius 1.5 aut
Citroën C2 1.4HDI
Toyota Yaris 1.4 4D Terra
Citroën C3 1.4HDI
Renault Clio 1.5 dCi
Opel Corsa 1.3 CDTI aut
Fiat Panda 1.3 JTD
Hyundai Getz 1.5 CRDI
Peugeot 1007 1.4 HDI
Kia Picanto 1.1
Suzuki Alto 1.1
Mazda 2 1.4 Diesel
Renault Megane 1.5 dCi Touring
Nissan Micra 1.5 d Ci
Skoda Octavia 1.9 TDI
Volvo S40 1.6D part. Filter
Volkswagen Fox diesel
Seat Ibiza 1.9 TDI
Mercedes-Benz A180 CDI
Citroën C5 1.6HDI part.filter
Ford Ka 1.3
Peugeot 407 1.6 HDI partæ filter
BMW 320d sedan
Jaguar X-type 2.0 Diesel
Volkswagen Fox gasoline
Audi A4 1.9 TDI avant
Opel Vectra 1.9 CDTI part.filter
BMW 120d
Ford Mondeo 2.0 TDCRi
Toyota Avensis 2.0 Diesel D-4D STW
Chevrolet Matiz 1.0
Toyota Corolla 1.4
Volkswagen Golf 1.4
Lada 112 1.5 Easy
Honda 2.0i Accord Sedan
Subaru Legacy 2.0 AWD
Nissan Primera 2.0
Mazda Premacy 2.0
Mitsubishi Lancer 2.0 STW
BMW 520i aut
Crysler PT Cruiser 2.4 aut
Hyundai Sante Fe 2.4 4WD aut
Mercedes-Benz E500 T aut
Suzuki Grand Vitara 2.5 aut
Lexus LS 430 aut
Alfa Romeo 147 GTA 3.2
Kia Sorento 3.5 V6 aut
Volvo XC90 T6 aut cross country
Chevrolet Corvette 6L V8 Coupé
Cadillac SRX 4.6 V8 4x5 aut
Volkswagen Touareg 4.2 V8 aut
Cherokee jeep Grand 4.7 aut
Landrover Range Rover 4.4 aut
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Porsche Carrera GT 5.7 10 cyl.

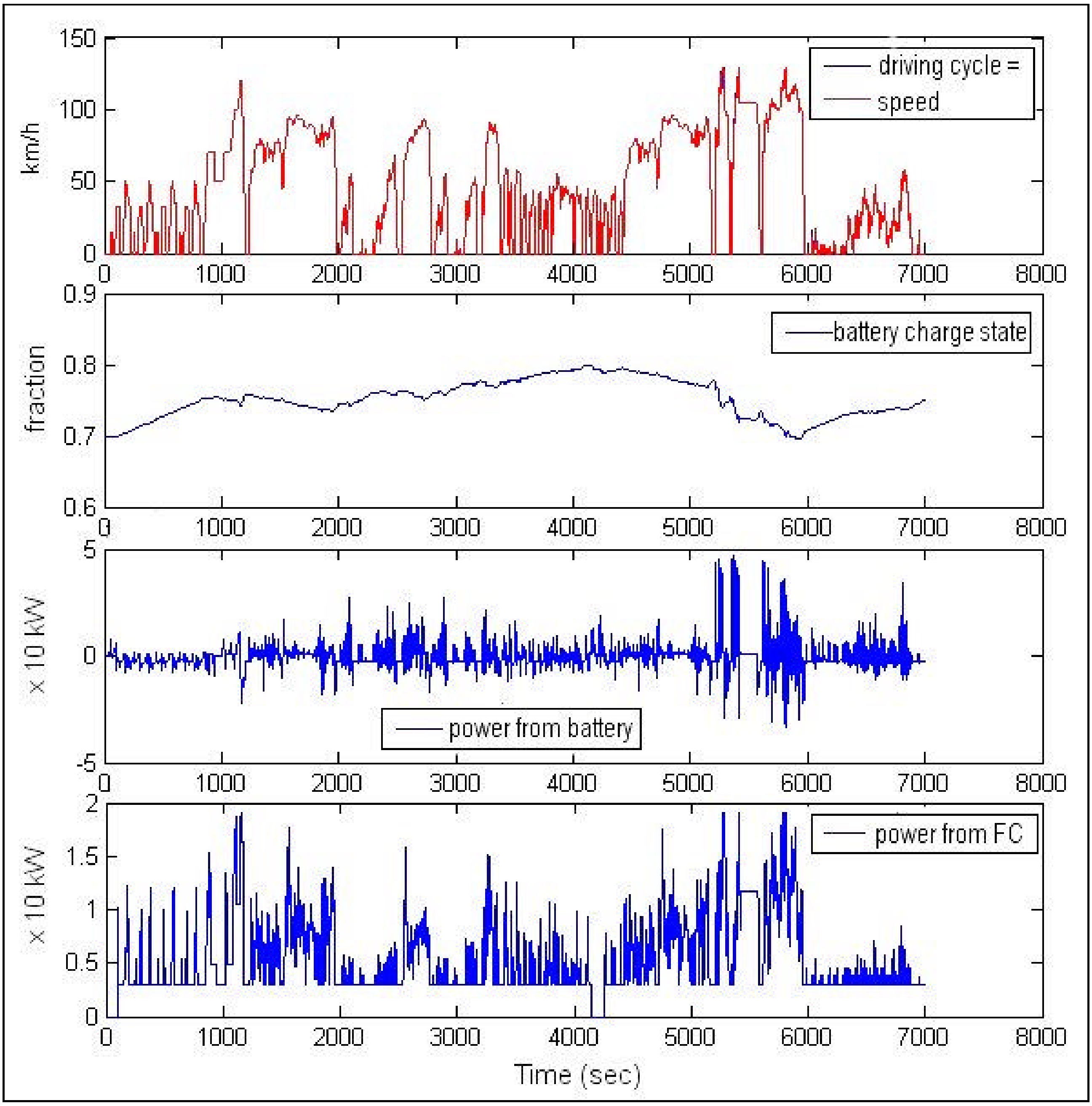

Figure 1. Performance of PEMFC/Li ion battery hybrid car under mixed urban/highway driving cycle shown at top.