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On the road performance simulation of hydrogen and hybrid cars

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Abstract

An assessment is made of on-the-road performance, for a pure fuel cell car, a pure battery operated car, and a fuel cell-battery hybrid car. The tool used for this study is the modular software-package ADVISOR [1], 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. The basis configurations of the cars modelled is characterised by high energy efficiency, before adding a fuel cell and electric motor also of high conversion efficiencies. Preceding the presentation of results, the best way to characterise energy efficiency is discussed.

1. Vehicle performance and energy efficiency

The efficiency of driving a road vehicle depends in part on the technical features of the vehicle, such as energy conversion and transmission efficiencies, and partly on factors deriving from driving cycle and driving style. The interface between the road, weather and vehicle factors include air and surface resistance, and driving style exhibits a subtle interaction with the technical design of the vehicle (part load engine efficiencies, assistance say in shutting engine off rather than idling, brake power recovery, etc.) [2].

It is customary to quote the relationship between energy input to the vehicle and a given length of a trip involving a predefined standard driving cycle specified by speed as a function of time and road conditions (slopes, surface types, wind speeds). For licensing purposes (including not only safety but also in many countries car taxation fixation, which increasingly is linked to car efficiency), vehicle performance under idealised driving cycles are been measured and published at annual intervals [3]. Figure 1 gives the 2005 results for selected cars already on the market, as function of payload, showing the great variations in efficiency for a car with a given payload, as well as the general decline of this measure of efficiency with increasing payload.

A better way to characterise the vehicle efficiency is to relate the energy input to the actual work being performed. Traffic work may be defined as the number of kilometres driven (along a given driving cycle) times the payload carried, i.e. km times kg. I use this index defined in terms of the maximum permissible payload for a given vehicle. The maximum payload is the difference between the maximum total mass of the vehicle loaded with passengers and freight, and its proper mass. This number is usually specified in the licensing certificate for the vehicle and is generally available in sales material for cars in Europe [4]. Alternative definitions include a further factor describing the average occupancy over time in terms of payload as a fraction of the maximum permitted, or simplified the occupancy taken as the average number of passengers relative to the maximum that the vehicle is designed to carry. Most of the cars selected for Figures 1 and 2 (see Table 1) are designed for a maximum of 5 passengers, with the exception of the 2-passenger Smart and a few sports cars, as well as the over-5 passenger multipurpose van-type vehicles.

Figure 2 gives the index of transport work produced by a unit of fuel energy (taking into account the different energy densities of gasoline and diesel fuels), for the same vehicles and the same driving cycle as used for the performance index of Figure 1. It is seen that there is still a large spread between the different model vehicles, but now the best performing vehicles are not solely those of small payloads. In fact, the top performer is a fairly large, diesel engine driven Skoda. Clearly, the inclusion of maximum payload in the evaluation is most relevant for customers actually making use of the payload capacity of their vehicle. If the car is driven most of the time with only one or two persons in it, and with modest amounts of freight, then the vehicles topping Figure 1 may be more appropriate.

2. Simulation setup

The simulation uses a mixed driving cycle of total length 89 km and composed of pieces from European and North American standard cycles (shown at the top of Figures 3 and 4). For the hybrid car, surplus power from the fuel cell is used to recharge the batteries, which at the end of the driving cycle are left as well charged as at the cycle start. The hybrid solution needs a fuel cell rated at 20 kW with an average efficiency of 50%, plus a 5 kWh Li-ion battery. Both batteries and fuel cells are emerging technologies, as regards efficiency and durability goals. The battery weight is 113 kg 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. For comparison, the battery solution for the vehicle in question could not reach the required 650 km range, and a pure fuel cell vehicle would need a higher rating of 30 kW [2].

3. Simulation results

Figure 3 shows the simulation results for a small hydrogen fuel cell car with a maximum payload of 340 kg and a 30 kW mature technology fuel cell [2]. The simulated performance shown (for a typical average loading of 136 kg of passengers and freight) corresponds to an efficiency performance of 1.17 km/MJ or an index of transport work performance of 398 kg km/MJ, which is slightly better than the best of current vehicles as seen by comparing with Figure 2. The higher mass of the fuel cell and auxiliary control and battery equipment makes the efficiency advantage over current optimised cars with a common-rail diesel engine and computerised controls very minor.

Figure 4 shows the results of calculations made for a hybrid fuel cell/battery vehicle, again in the popular a-class with a 340 kg maximum but 136 kg actual average load of passengers and/or luggage. This car would have a range of 675 km with 4 kg of hydrogen stored onboard, under average driving conditions specified by the driving cycle shown at the top of Figure 4 (as compared to 600 km range for the pure fuel cell car of Figure 3, with the same amount of stored hydrogen). Surplus power from the fuel cell is used to recharge the batteries, which at the end of the driving cycle are left as well charged as at the cycle start. The simulated performance is 1.32 km/MJ, corresponding to a transport work efficiency index of 448 kg km/MJ, which is substantially higher that what can be achieved by the current car concepts shown in Figure 2 or Table 1.

The hybrid solution needs a fuel cell rated at 20 kW, assuming an average efficiency of 50%, plus a 5 kWh Li-ion battery. These batteries have only recently become available for automotive uses, and 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. 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 presently most often equipped with a traction-type battery (of say 1 kWh).

4. Conclusions

The key advantage of the car concept described in Figures 3 and 4 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 prototype cars put 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 transport work per unit of energy concept proposed in this paper for appraising vehicle efficiencies has the advantage, that it can be applied to both passenger cars, buses and freight trucks, and for looking at the current distribution of efficiencies for various vehicles on the market, in order to form a basis that does not bias against cars with increased passenger- or freight-carrying capacity.

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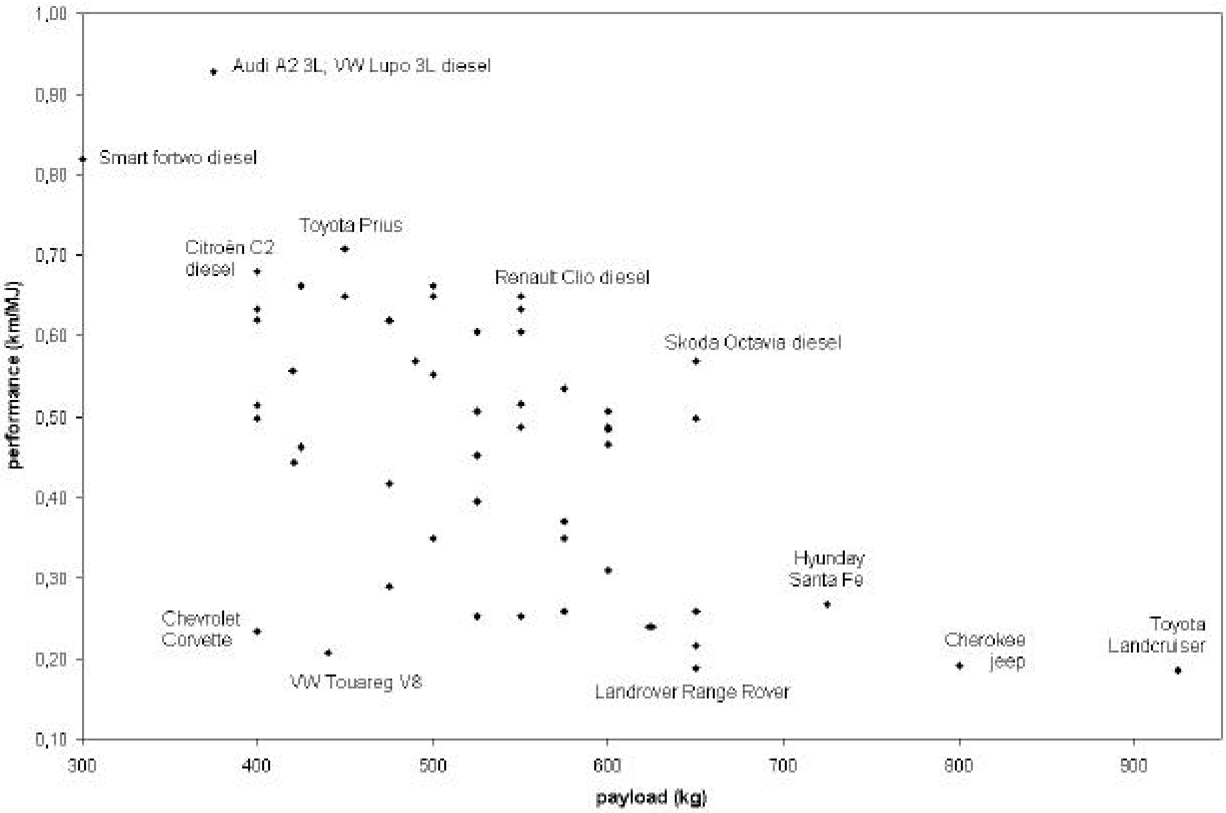

Figure 1. Official 2005 performance data (based on European driving cycle and licensing procedures) for selected passenger cars as function of maximum permitted payload [3, 4].

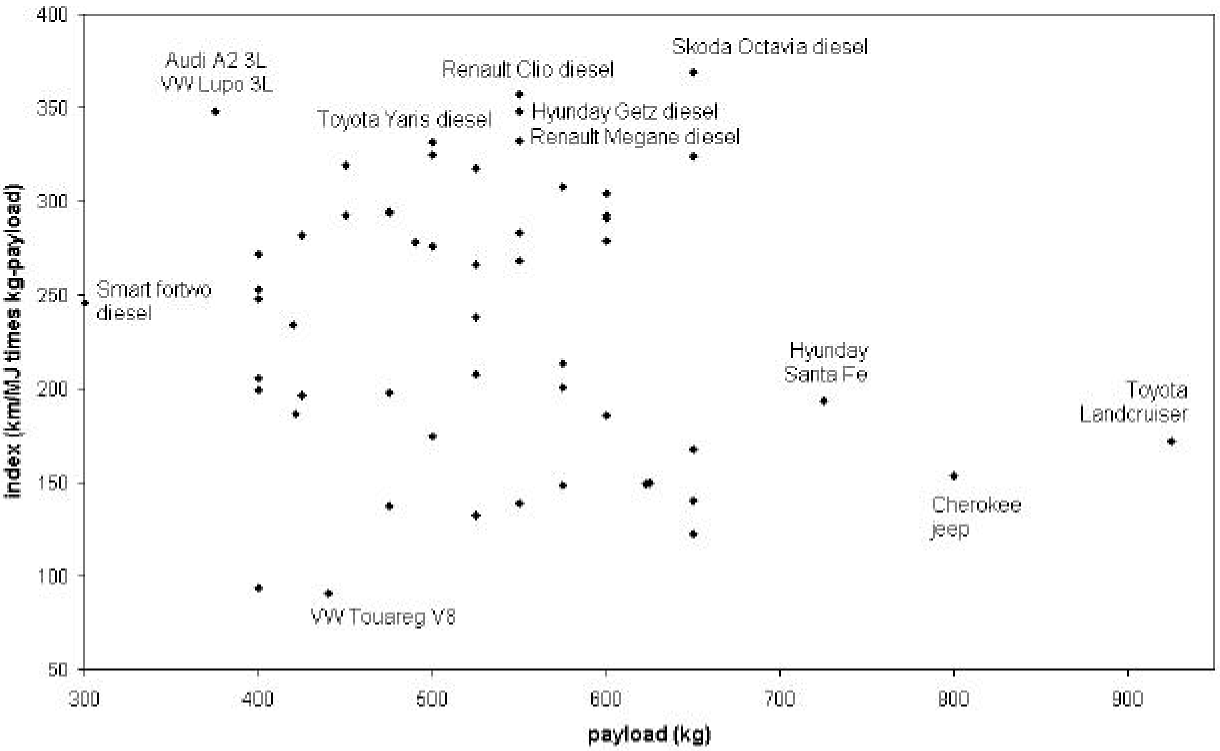

Figure 2. Calculation of transport work efficiency index based upon official 2005 performance data for selected passenger cars as function of maximum permitted payload [3, 4].

Table 1. Selected 2005 passenger vehicles ranked by fuel efficiency (km/MJ) times maximum payload (kg)

model *(d = diesel, o = otto engine)*		***kg km/MJ***	***payl. kg***	***km/MJ***	***kW***	***weight kg***	***km/l***
Skoda Octavia 1.9 TDI	d	369,36	650	0,57	77	1250	20,4
Renault Clio 1.5 dCI	d	356,96	550	0,65	48	975	23,3
Audi A2 3L 1.2TDI aut	d	347,84	375	0,93	45	825	33,3
Volkswagen Lupo 1.2 TDI 3L	d	347,84	375	0,93	45	825	33,3
Hyundai Getz 1.5 CRDI	d	347,77	550	0,63	60	1050	22,7
Renault Megane 1.5 dCI Touring	d	332,45	550	0,60	60	1250	21,7
Toyota Yaris 1.4 4D Terra	d	331,48	500	0,66	55	925	23,8
Opel Corsa 1.3 CDTI aut	d	324,51	500	0,65	51	1025	23,3
Jaguar X-type 2.0 Diesel	d	324,09	650	0,50	96	1375	17,9
Toyota Prius 1.5 aut	o	318,69	450	0,71	57	1275	23,3
Nissan Micra 1.5 d CI	d	317,34	525	0,60	48	975	21,7
Mercedes-Benz A180 CDI	d	307,52	575	0,53	80	1225	19,2
Peugeot 407 1.6 HDI part. filter	d	304,18	600	0,51	80	1425	18,2
Kia Picanto 1.1	o	294,53	475	0,62	48	875	20,4
Mazda 2 1.4 Diesel	d	293,73	475	0,62	74	1050	22,2

Audi A4 1.9 TDI avant	d	292.48	600	0.49	85	1425	17.5
Opel Vectra 1.9 CDTI part.filter	d	292,48	600	0,49	88	1425	17,5
Fiat Panda 1.3 JTD	d	292,06	450	0,65	51	925	23,3
Ford Mondeo 2.0 TDCRi	d	290,81	600	0,48	85	1400	17,4
Citroën C5 1.6HDI part.filter	d	283,43	550	0,52	80	1400	18,5
Citroën C3 1.4HDI	d	281,75	425	0,66	52	1025	23,8
Toyota Avensis 2.0 Diesel D-4D STW	d	279,11	600	0,47	85	1400	16,7
Volvo S40 1.6D part. Filter	d	278,44	490	0,57	81	1275	20,4
Seat Ibiza 1.9 TDI	d	275,77	500	0,55	96	1175	19,8
Citroën C2 1.4HDI	d	271,87	400	0,68	50	1000	24,4
BMW 120d	d	268,11	550	0,49	120	1300	17,5
BMW 320d sedan	d	266,16	525	0,51	320	1375	18,2
Peugeot 1007 1.4 HDI	d	252,92	400	0,63	50	1172	22,7
Suzuki Alto 1.1	o	248,02	400	0,62	46	775	20,4
Smart fortwo coupé 0.8 CDI	d	245,68	300	0,82	30	700	29,4
Toyota Corolla 1.4	o	237,77	525	0,45	71	1100	14,9
Volkswagen Fox diesel	d	233,98	420	0,56	51	1100	20
Subaru Legacy 2.0 AWD	o	213,22	575	0,37	121	1325	12,2
Honda 2.0i Accord Sedan	o	207,45	525	0,40	114	1300	13
Ford Ka 1.3	o	205,47	400	0,51	51	875	16,9
Nissan Primera 2.0	o	200,99	575	0,35	103	1325	11,5
Volkswagen Fox gasoline	o	199,39	400	0,50	40	1000	16,4
Lada 112 1.5 Easy	o	197,80	475	0,42	56	1000	13,7
Chevrolet Matiz 1.0	o	196,35	425	0,46	47	800	15,2
Hyundai Sante Fe 2.4 4WD aut	o	193,92	725	0,27	127	1700	8,8
Volkswagen Golf 1.4	o	186,83	421	0,44	55	1150	14,6
BMW 520i aut	o	186,02	600	0,31	125	1475	10,2
Mazda Premacy 2.0	o	174,77	500	0,35	96	1300	11,5
Mitsubishi Lancer 2.0 STW	o	174,77	500	0,35	99	1275	11,5
Toyota Landcruiser 100 4.7 aut	o	171,50	925	0,19	175	2300	6,1
Mercedes-Benz E500 T aut	o	167,93	650	0,26	225	1750	8,5
Cherokee jeep Grand 4.7 aut	o	153,19	800	0,19	167	1900	6,3
Kia Sorento 3.5 V6 aut	o	150,08	625	0,24	143	1925	7,9
Volvo XC90 T6 aut cross country	o	149,60	623	0,24	200	2025	7,9
Suzuki Grand Vitara 2.5 aut	o	148,56	575	0,26	135	1675	8,5
Cadillac SRX 4.6 V8 4x5 aut	o	140,27	650	0,22	239	2025	7,1
Lexus LS 430 aut	o	138,75	550	0,25	207	1800	8,3
Crysler PT Cruiser 2.4 aut	o	137,16	475	0,29	105	1450	9,5
Alfa Romeo 147 GTA 3.2	o	132,45	525	0,25	184	1325	8,3
Landrover Range Rover 4.4 aut	o	122,49	650	0,19	210	2400	6,2
Chevrolet Corvette 6L V8 Coupé	o	93,62	400	0,23	297	1425	7,7
Volkswagen Touareg 4.2 V8 aut	o	90,94	440	0,21	228	2317	6,8
Porsche Carrera GT 5.7 10 cyl.	o	43,40	255	0,17	450	1300	5,6

Sources : www.hvorlangtpaaliteren.dk; www.biltorvet.dk/nyebiler/fabrikat.asp

Table 1: continued.

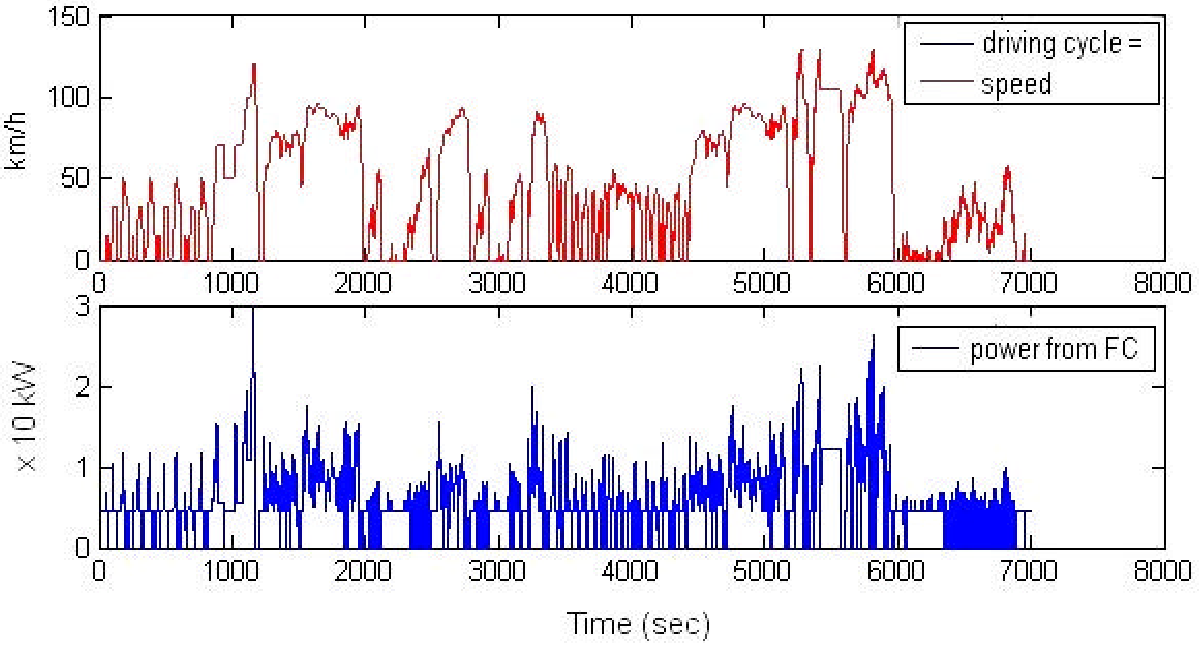

Figure 3. **Simulation results for a 30 kW fuel cell car under the mixed driving cycle shown at top and matching the achieved speed as function of time. The average performance efficiency is 1.17 km/MJ and the transport work efficiency is 398 kg km/MJ [2].**

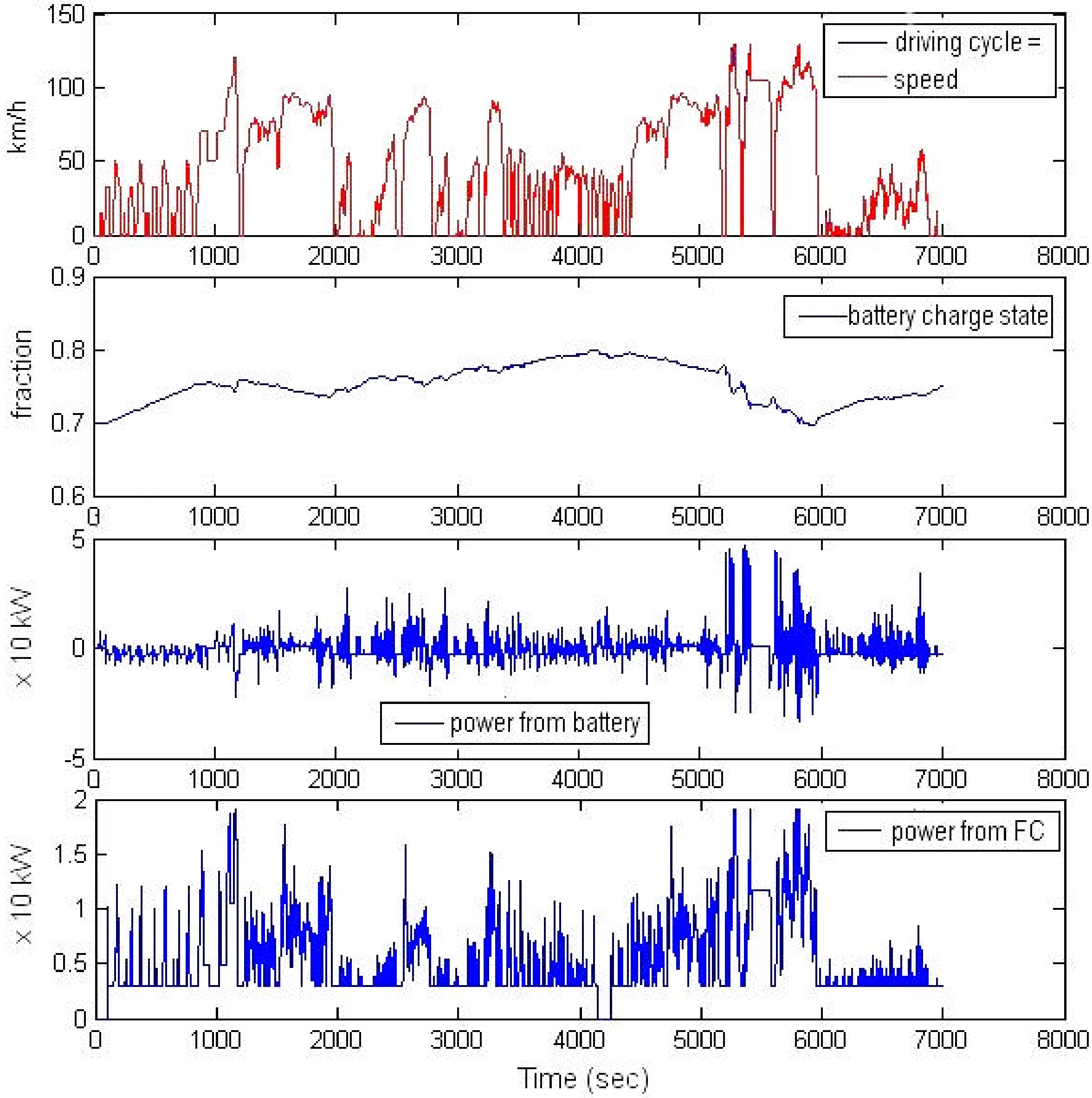

Figure 4. Simulation results for a hybrid car with a 20 kW fuel cell and a 5 kWh Li-ion battery, under the same driving cycle as used in Figure 3. The average performance efficiency is now 1.32 km/MJ and the transport work efficiency is 448 kg km/MJ [2].