A Study of Energy Requirements for Electric and Hybrid Vehicles in Cities

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Abstract – **This paper provides evaluation of driving power and energy requirements for automotive vehicle. A survey of most promising applications of electric and hybrid vehicles in cities with commercial line solutions is given. The simulation of small hybrid car is processed with the aid of Advisor programme, indicating profitable distribution of power sources between fuel cell and ultracapacitor bank.**

1. Introduction

The benefits of cleaner vehicles in crowded cities are particularly valuable to achieve Europe's goals for air quality, fuel savings and security of energy supply. Most promising applications of ecological urban transport concern buses, fleet-rental vehicles (e.g. delivery vans), available for lease small cars and two-wheeler systems [1-2]. Each of these categories can be specified by its own requirements of daily routing range, acceleration and maximal speed, which are defined by a number of driving cycles [6]. Based on these data constraints, rated energy consumptions and power can be analysed. For optimisation of power-train configuration, different options are usually considered: ranging from battery electric vehicles, fuel cell vehicles to hybrids that utilise some ratio of fuel converter and other sources such as ultracapacitor banks. In this paper, the analysis is enhanced by simulating of small car with the aid of ADVISOR software (ADvanced VehIcule SimulatOR), which has been developed by the National Renewable Energy Laboratory in USA and is available on the Internet [3]. Results of this work indicate profitable power sources hybridisation between the fuel cell converter and ultracapacitor storage bank.

2. Power and Energy Evaluation

Based on principles of vehicle mechanics, one can assess both the driving power and energy necessary to ensure vehicle operation, (Fig.1). Power P_v required to drive a vehicle at the speed v has to compensate following counteracting forces

$$P_v = v \cdot \left(F_r + F_w + F_a + F_h\right) \tag{1}$$

The rolling resistance force F_r interacts between the tires and road

$$F_r = GC_r \cos\phi \tag{2}$$

The tire rolling resistance coefficient C_r is a non linearly dependent of vehicle speed, type and pressure of tires and road surface characteristic. Average C_r values are estimated in a range: <0.01…0.1>. The G represents a vehicle weight ($G=mg$).
The viscous resistance force F_w of air acting upon the vehicle is given by

$$F_w = \frac{1}{2}\rho C_d A_f (v + v_w)^2 \tag{3}$$

where ρ is the air density, C_d is the aerodynamic drag coefficient, A_f is the vehicle front area and v_w is the head-wind velocity. The acceleration force of the vehicle F_a

$$F_a = m\delta \frac{dv}{dt} \tag{4}$$

is referred to the equivalent mass inertia δm, consisting of linear and rotational moving vehicles masses [4]. The climbing (positive sign) and downgrade (negative sign) resistance force F_h is dependent of the grade angle ϕ

$$F_h = \pm G \sin\phi \tag{5}$$

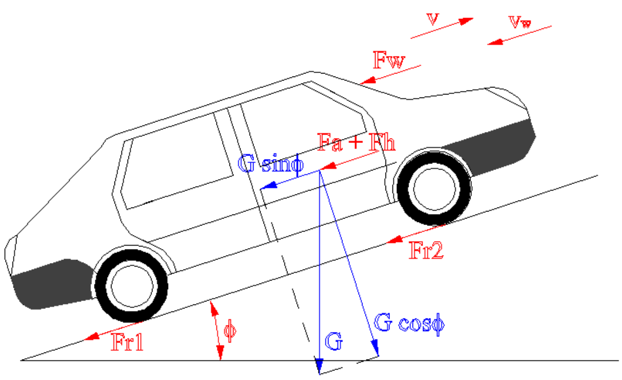

Fig. 1. Elementary forces acting on the vehicle

Total power P_{tot} requirement is extended, by a power components of the accessories P_a (lights, air-conditioning, ect.) and representing looses of mechanical end electrical systems P_l

$$P_{tot} = P_v + P_a + P_l \tag{6}$$

In particular routing conditions, we distinguish the requirements of instantaneous power $P_{tot}(t)$ and the mean value P_{tot_av} over standardized driving cycle. The total energy consumed by a vehicle can be evaluated in terms of time integral function of the P_{tot} and the energy consumed at idle E_{idle} state

$$E_{tot} = \int P_{tot}\, dt + E_{idle} \tag{7}$$

3. State of the art solutions

In order to compare energetic performances of electric and hybrid vehicles in cities we concentrate on most promising applications where existing technical and economic barriers of market development are less significant. The survey is based on transparent demonstration projects and commercially available products.

3.1 City Buses

No other means of public urban transport can offer as many advantages for demonstrating the use of new technologies as buses. In particular, they run on short, regular routs and return to central depot for refueling. Limited availability of supporting infrastructure for recharging, retail supply and maintenance is not a barrier. In addition, public ownership often facilitates the payment of a cost premium in return for a better environment in the city [2].

The New York City Transit, the largest public transportation system in the United States, has tested a pilot fleet of 10 Orion model VI diesel hybrid-electric buses in revenue service since 1998, (Tabl.1). They are equipped with BAE SYSTEMS' HybridDrive™ propulsion system. The diesel engine powers a generator, that provides additional electric energy to the traction motor and recharges the batteries. The range of the bus is limited by the amount of diesel fuel store onboard. Batteries need not to be recharged externally. During acceleration, energy flows from the generator and battery pack to the traction motor. Traditional transmission, is reduced to the gearbox. During cruise mode, energy flows from the generator to recharge the batteries. The regenerative braking system helps slow the vehicle, while producing additional electric power and reducing brake wear. The smaller diesel engine, operating at a more constant speed and with better overall fuel economy, can significantly reduce overall bus emissions and maintenance needs [5,8].

Another example of the Chattanooga Area Transportation Authority USA, due to severe air pollution started a project of free all-electric shuttles to transport passengers in central city between final destination parking places. The shuttle service fleet consists of electric buses AVS-22 (Tab.1), furnished by the Advanced Vehicle Systems Inc. [7]. The lead acid batteries are charged in place inside the bus. A rapid-charge system is being developed, that would charge the battery in 2 hours or less.

Table 1: Series diesel-hybrid and all electric buses (pilot fleets: Manhattan, Chattanooga)

Buses	L×H×W	GVW/ CW*)	traction motor	batteries	economy	batt. weight	top/av speed	range	seats/ standees
type	m×m×m	kg	Type	type	kWh/km	kg	km/h	km	number
Orion VI Diesel-hybrid	12,2×3,18 ×2,59	18.900/ 14.400	AC 187 kW 346 V/500 Hz	Pb-Acid	-	1. 600	-	560	31/32
AVS-22 Electric	6,7×2,59 ×2,59	12.700/ 10.000	AC 140kW -	Pb-Acid (gel)	0,8-1,1	1.360	64/24	100	22/11

* Gross Vehicle Weight / Curb Weight

3.2 Citivans

Citivans of public or municipal fleets utilized as refuse collection vehicles, delivery couriers in Postal Organizations, local taxis and light duty vans are ideal for demanding applications in urban environments. In fleet organization they have the same advantage of returning to a central depot for refueling and maintenance [2].

Small electric citivans like Berlingo/Partner have proved good performance for payloads up to 500kg. Operators however face the need to transport larger weights and volumes, delivered often on pallets, preferably provided with a loading platform. One of the solution tested in the frame of ELCIDIS project [6], was all electric Mercedes Sprint (Tab.2).

Table 2: Light and medium duty electric vans

Vans	L×H×W	GVW	traction motor	batteries	economy	battery weight	top speed	range	payload/ volume
type	m×m×m	kg	type	type	kWh/km	kg	km/h	km	kg/m^3
Berlingo/ Partner**	4,108×1,801×1,719	1950	DC 28kW 180Nm	NiCd 100Ah	0,25-0,55	345	90	80	500/3
Mercedes Sprint	4,215×1,855×1,736	4000	AC 40kW	3xZebra Z5C*)	0,88	630	90	90	1500/16

* sodium nickel chloride (AEG Anglo Batteries)
** 4,215×1,855×1,736 m

3.3 Small cars

Due to incomparable high vehicle cost and lack of public refueling infrastructure, the small cars, regarded as private cars, have still significant economic obstacles. However, in the scheme of rental vehicles they can be again depot-based, which simplifies maintenance and reduce costs of refueling organization [2]. Two commercially available examples given in Tab. 3 indicate power dimensioning and specification of these vehicles.

Table 3: Small electric cars

cars	L×W×H	Curb weight	traction motor	batteries	economy	batt. weight	top speed	range	payload
type	m×m×m	kg	type	Type	Wh/km	kg	km/h	km	kg
Zytek Smart**)	2,5×1,45×1,55	848	DC brushless 60 kW (max)	Zebra*)	-	210	100	100	140
Think Nordic**)	2,99×1,6×1,56	940	AC 27kW	NiCd 100Ah	135	250	90	85	205

* sodium nickel chloride batteries (MES-DEA S.A.)
** Zytek Electric Vehicles Ltd. [12], Think Nordic [9]

3.4 Two-wheelers

Due to the low costs and reduced maintenance recharging periods, electric bikes and scooters can represent an interesting niche application for promoting cleaner vehicle technology. They are offered in the catalogue of major world wide manufacturers e.g. (Tab. 4).

Table 4: Two-wheelers examples: Scooter [10] and moped [11]

Two-wheelers	L×H×W	Curb weight	traction motor	batteries	economy	batt. weight	top speed	range	payload
type	m×m×m	kg	Type	Type	Wh/km	kg	km/h	km	kg
EVT 4000e	1,692×1,1×0,64	127	DC 1,5 kW	4 × 12 V Pb-Acid	37	60	48	65	150
eGO Cycle 2	1,67×1,11×0,66	54	AC 27kW	2 × 12V Pb-Acid	22	-	37	40	113

4. Fuel Cell small car simulation

The simulation is based on mini-car data, referred to the Daimler Chrysler Smart, (Tab. 5). Firstly from eq. (1), is assessed a power P_v required to drive a vehicle as function of vehicle speed, wind speed and acceleration (Fig. 2). The influence of moderate head-wind velocity (10m/s) at normal city cruising (70km/h) claims at least for 10kW driving net power. Adding vehicle acceleration of the order 1.38m/s^2 (Fig. 3: initial start-up to 70km/h in 14s) increases to 30kW net power requirement, which is usually offered in this class of small city vehicles.

Table 5: Small car simulation data

Vehicle type	Smart
Gross vehicle weight	860 kg
C_r	0.01
A_f	2 m^2
C_d	0.37
Cargo mass	136 kg

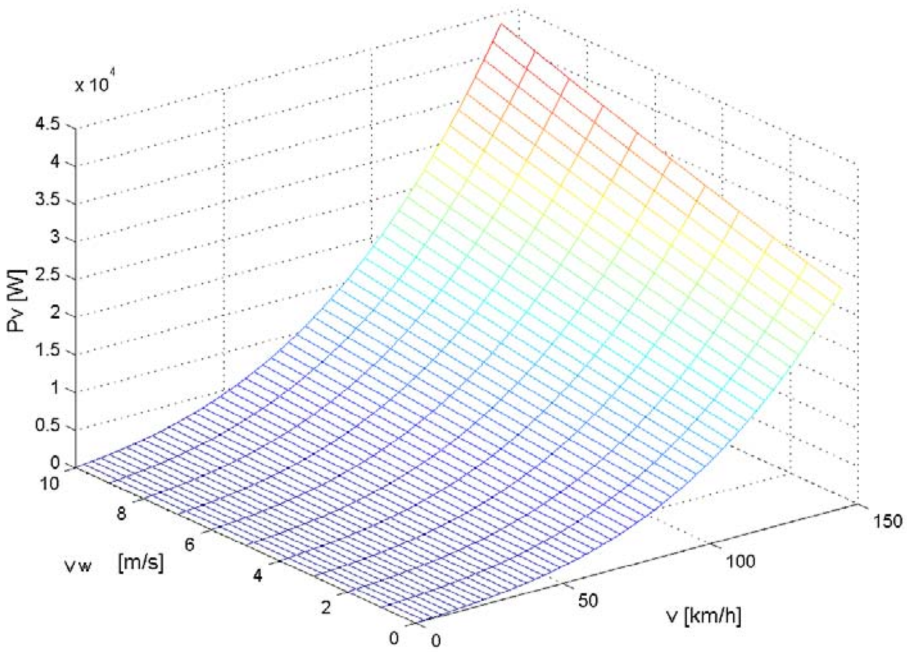

Fig. 2. Driving power P_v as function of vehicle v and head-wind v_w velocity

Simulated vehicle has a series hybrid electric structure. The propulsion power is delivered from the fuel converter and from the energy storage system. As a fuel converter and an energy storage system are used respectively: hydrogen fuel cell system (FC) and supercapacitor bank (SC). These basic fuel converter and electric components have been defined in terms of Advisor text files for use with Matlab and Simulink simulation platform, (Tab. 6). In order to fulfil driving power requirements, the FC system is scaled for 20 kW and the SC is rated for 10 kW high dynamic operation. Propulsion of the vehicle front axle is modelled by 30 kW inverter-fed induction drive.

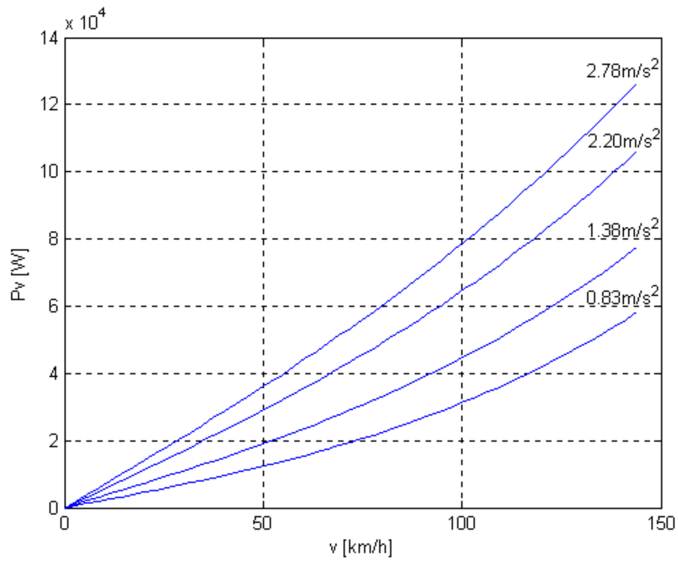

Fig. 3. Driving power P_v at acceleration conditions, as function of vehicle speed v

Table 6: Fuel converter and electric component files

Component	ADVISOR filename	Description
Fuel cell system	FC_ANL50H2.m	Hydrogen fuel cell scaled to 20kW net
Supercapacitors	ESS_ULTCAP_EPCOS.m	EPCOS SC bank 50×2×2700F/2.5V
Motor/Controller	MC_AC30.m	Siemens AC 30kW ind. motor / inverter
Accessory load	ACC_HYBRID.m	Accessory 700W constant electric load

Control strategy of hysteresis type, determines the FC power demand depending on the state of charge (SOC) of the SC bank, additional power required to correct the SC bank SOC and previous state of the fuel converter. The rule applied to start FC, is 5 second period of average power command greater then 120% of minimal FC output power level (cs_min_pwr). The SOC correction system tends to stabilize the SOC of SC bank in the middle of recommended range (sc_lo_soc, sc_hi_soc) by recharging additional power from the FC system (Fig. 4).

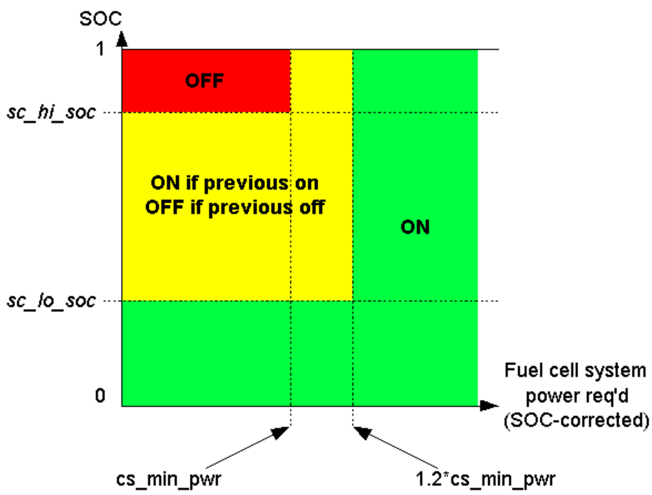

Fig. 4. Hysteresis-state control of the Fuel Cell; SOC - state of charge, cs_min_pwr - minimal output power

Simulation tests illustrate vehicle operation following the ECE urban driving cycle (Fig. 5). The cycle is used for emission certification of light duty vehicles in Europe. It is characterized by low vehicle speed (avg. speed: 18.3 km/h, max speed: 50 km/h) and low engine load (max accel: 1.06 m/s^2). It was devised to represent city driving conditions e.g. in Paris or Rome. Total duration of the double ECE cycle was 390 s, with overdriven distance of 1.98 km. Results of simulation depict distribution and exchange of power between fuel cell converter and ultracapacitor bank energy storage system. Over the entire vehicle trajectory, the average total energy consumption, taking into account regenerative mode and stored energy, results in 220 Wh/km. The following time intervals are distinguished in detail:

A. At the beginning of operation cycle, induction drive is supplied exclusively by the supercapacitor bank. Average power consumption is lower then 120% of minimal FC power and the energy stored of the SC bank is high enough to sustain vehicle motion.

B. Due to increase of driving power demand, the FC system is turn on. Fuel cell system and ultracapacitor bank deliver output power parallel.4

C. Low power value is required for vehicle operation but SC state of charge decreased below limit (sc_hi_soc). As previously, the fuel cell was switched on, it continues operation, partly recharging SC bank.

D. While the vehicle rest in idle, some auxiliary load are fed by the fuel cell converter. Moreover, the FC is still recharging SC bank.

E. The ultracapacitor bank is recharged, above the SOC upper limit (sc_hi_soc). As the vehicle is again in idle, the fuel cell is turn off.

F. The FC converter is turn off. Due to vehicle deceleration and regenerative braking, kinetic energy is transformed into electric recharging the SC bank.

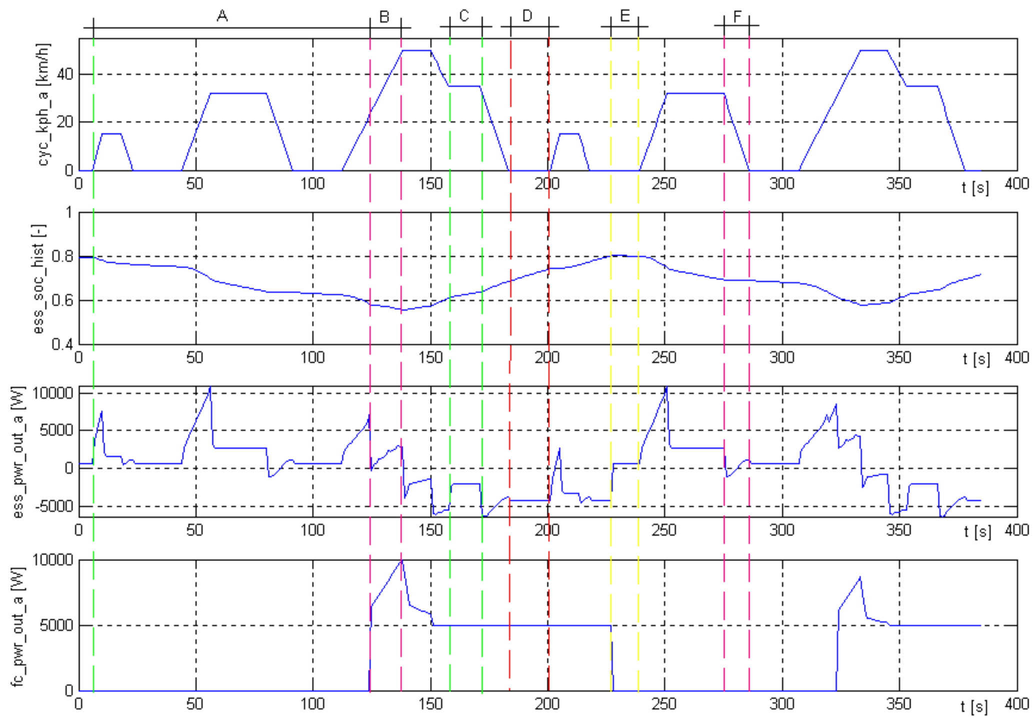

Fig. 5. Simulation transients at the double ECE cycle; cyc_kph_a - vehicle speed, ess_soc_hist - SC SOC, ess_pwr_out_a – output power of SC bank, fc_pwr_out_a – power available from the fuel cell converter

5. Conclusions

It has been recognized by number of demonstration projects, that electric and hybrid vehicles in cities became part of the solutions to the poor air quality, traffic congestion, urban decay and even loss of revenue. These vehicles are ideally suited for short urban journeys and are particularly suitable for historical or tourist parts of cities, where their quiet, smooth and clean operation is highly valued. Among most promising all electric and hybrid electric urban solutions appear listed below vehicle categories, that have been classified by the decreasing order of power/energy rated consumptions (Tab. 1-4):

- Diesel hybrid-electric buses,
- Electric citivans of municipal fleets,
- Fleet-rental small electric cars,
- Electric scooters, mopeds and bikes

Evaluation of vehicle's energy, when is referred to urban driving cycles, reflects an important diversification of the average and maximal power requirements. Optimal electric propulsion should be characterized by hybrid power sources, in terms of fuel converter and energy storage system. Simulation results of a small car equipped with advanced fuel cell converter and supercapacitor storage bank have indicated the power flow between these sources at normalized urban driving conditions. The scaling (hybridization) ratio of the fuel cell system and the supercapacitor bank should result from prospective optimization procedures.

6. References

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