SIMPLE TANK-TO-WHEELS ANALYSIS TOOL FOR FUTURE VEHICLE POWERTRAINS

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Abstract

The future powertrains have to be properly assessed in early stages of vehicle design using simple and fast but reliable tools. The aim of the paper is to develop a simulation tool suitable for any of current transient cycles for finding of upper limits of tank-to-wheel efficiencies of recent or future vehicle powertrains in different concepts of vehicles to assess their potential, to find gaps between the state-of-the-art and to find ways to bridge them.

The simulation philosophy and procedure may be described in the following steps. The testing cycle power demands on vehicle movement are analyzed and the optimum operation efficiency of a primary mover (engine, fuel cell, electric motor) is assigned to them. Dynamic torques at powertrain are accounted for. Speed, speed slip (driving machine/wheels) and load dependencies of transmission efficiency are simulated by simple models. In the case of a hybrid solution, charging and discharging efficiencies of energy accumulators and additional losses (e.g., in converters and inverters) are considered. The clear modular structure of the simulation tool enables the researcher to amend new features of powertrain components. The links to more detailed simulation tools are prepared.

The simulation tool is described by regression and algebraic models (based on the results of higher level simulation tools) in a way giving immediate response during sensitivity analysis. The examples of tool calibration for different powertrains and results comparing powertrain potential are presented for lower medium class passenger car.

The current simulation tool creates a useful link between detailed and accurate but CPU time demanding 1-D tools, based on partial differential equations, and rules-of-thumb, used sometimes for initial potential assessments. Moreover, the described tool does not require detailed data on the powertrain during early stage of design but it shows its potential for further development.

Keywords: *vehicle powertrain efficiency, internal combustion engine, fuel cells, simulation, driving cycle*

1. Introduction

The aim of this paper consists in stating realistic upper limits for road fuel consumption of different vehicle powertrains to assess the potential of future vehicle powertrains especially hydrogen fuel cell (FC) based ones, in comparison to an internal combustion engine (ICE) as a vehicle prime mover.

The methodology of the described approach consists in simulation of required power, computed by the simplified physical model of vehicle involving all kinds of driving resistances during arbitrary driving cycle, and its coverage by a primary mover, taking transmission efficiency into account. Moreover, the impact of vehicle weight, influenced, e.g., by hybrid concept, can be respected. TTW is substituted by Tank-to-User (TTU) assessment, which is more accurate for these cases.

The efficiencies of a primary mover, a transmission and accessories are determined for operation mode providing the required power. Fuel consumption or heat (chemical energy) consumption is integrated during driving cycle together with the traction work. The averaged efficiency can be than evaluated from their ratio. The slip during take-off is interpolated during characteristic time setting, starting with zero efficiency. Transmission efficiency for electric drive system involves DC/DC convertor and DC/AC invertor efficiency. Joule's, eddy current losses and torque and speed dependent losses are included for a synchronous electric motor.

No transient (unsteady) features of a powertrain are involved by direct simulation except for powertrain inertia. The estimated corrections for other transient losses may be applied in dependence on initial power, speed and demanded power change.

ICE-based powertrains were simulated with the assumption of using fully continuously variable transmission (CVT) that allows engine operation along minimum specific consumption line for the whole power range to achieve the best obtainable fuel consumption. The minimal fuel consumption line of various types of ICEs has been evaluated from real engine performance maps within the whole power range.

The transmission concepts enabled us – especially in the case of ICE - to take into account the expected level of FC future costs. Therefore, rather expensive but perfect concepts of ICE-wheels transmissions with almost continuous gear ratio variation provides for the use of highest ICE efficiency available at required power at wheels. Despite this fact, the cost of an ICE powertrain would be a fraction of a FC powertrain only. It opens additionally further possibilities of enhanced exhaust gas aftertreatment.

Vehicle powertrain with two internal combustion engines of different size in parallel configuration was considered.

Proton exchange membrane fuel cell (PEMFC) based vehicle powertrains were simulated using real polarization curves of a PEMFC, fuel amount unused in a stack and the additional losses, associated with pressure boosting the fuel cell and fuel conversion (if any).

Upper estimate of efficiency gain for fictitious test-tailored, recuperative hybrid system was calculated using braking work assessment. An integrated efficiency of charging/discharging was used to correct the recuperation gain in these cases.

More realistic hybrid configuration with diesel engine has been considered as well. The electric drive covers the whole region of poor engine efficiency according to proposed control strategy. The previously mentioned mechanical and electrical losses have been included into the hybrid vehicle model. The efficiencies of charging/discharging energy accumulator and voltage (DC/DC) convertor have been accounted for as constant values for the first approximation. Additional mass of more sophisticated hybrid powertrain has been accounted for as well.

The tool was developed in MS Excel spreadsheet and has been currently used for New European Driving Cycle (NEDC) simulations.

2. Passenger Car Evaluation

The methodology has been initially developed and tested on lower-medium class passenger car with various types of powertrains, as presented in Table 1. The first two columns show the car parameters powered by gasoline engines, the first one naturally aspirated spark ignition (SI) gasoline engine *1.6FSI* (displacement volume of 1.6 dm3 with the power output of 70 kW). The second gasoline engine is a downsized turbocharged engine *1.2T* (displacement volume of 1.2 dm^3 with the same nominal power).

The third and the fourth columns show parameters of vehicle with diesel turbocharged engines, the first one state of the art (SOTA) *1.9TDI* 66 kW and the second one *TDIPx* down-sized to maximum power demand by NEDC. The latter virtual engine can be used for comparison to a FC hybridized powertrain with the same averaged power requirements. Of course, these virtual powertrains may be used in the case of NEDC for comparison only because the power demands of NEDC are much smaller than those of real engine use.

The fifth column describes parameters of car hydrogen powered naturally aspirated engine *H2ICE*. The next two columns show parameters of *PEMFC* powered vehicles. The first one with the power output of 57 kW, suitable to cover all power demands and the second one *PEMFCPx*, tailored to maximum power needed in NEDC. The last column describes the parameters of hybrid vehicle *TDIHyb* with diesel prime mover coupled with electric energy storage (battery or ultra-capacitor) and electric motor/generator with voltage convertor.

Tab. 1. Main parameters of a car used in model

	1	2	3	4	5	6	7	8
	1.6FSI	1.2T	1.9TDI	TDIPx	H2ICE	PEMFC	PEMFCPx	HybICE
Vehicle type	Skoda Octavia Combi							
Vehicle Weight [kg]	1450				1600			
Frontal Area [m^2]	2.1							
Air drag coeff [1]	0.34							
Wheel radius dyn. [m]	0.308							
Rolling resistance coef [1]	0.016							
Iaxle incl.wheels [kgm^2]	0.95							
No of axles	2							
Air density [kg/m^3]	1.2							
Fuel density [kg/m^3]	760		790		0.084			790
Fuel LHV [MJ/kg]	44		43.2		120			43.2

The total weight of hydrogen powered and hybrid cars have been increased in comparison to combustion engine powered ones due to estimated heavier fuel storage system and more complex FC and hybrid electric storage system, taking TTU concept into consideration instead of TTW one.

3. Optimal fuel consumption line evaluation

ICE-based powertrains were simulated with the assumption of using CVT allowing engine operation along minimum specific consumption line for the whole power range. Built-in Matlab interpolation functions were utilized for evaluation of the minimum fuel consumption line from engine maps for all evaluated engines. SI ICE performance maps were obtained from [1], data for diesel 1.9TDI Diesel ICE were obtained from measurements carried out at the authors' laboratory and hydrogen SI engine performance were obtained from [2]. The performance maps and the lines of optimal consumption for all types of combustion engines are presented in Fig. 1.

As far as the authors know, any turbocharged hydrogen engine performance maps has not been published yet. The real hydrogen turbocharged engine performance map will lie close to lean burn natural gas engines. The contribution of faster combustion of hydrogen will be apparently compensated by limits of compression ratio and spark advance due to knocking and higher demands on boost pressure due to low volume-specific calorific value of hydrogen ultra-lean mixture.

4. Fuel Cell Characteristics

PEMFC characteristics have been evaluated by means of a physical model based on FC polarization data obtained from [3]. For these data fuel and air flows have been evaluated according to [4]. FC polarization curve *Ballard Mk900,* power output P_e and efficiency eta_{FC} lines over current density are displayed in Fig. 2. Incomplete fuel utilization together with FC compressor power have been included in power output estimation. Resulting curve P_e-P_c has been applied in vehicle model as traction power input.

5. Comparison of optimal lines of specific heat consumption

Comparison of optimal brake specific heat consumption *bshc* lines over power output for various power converters is shown in Fig. 3. The worst consumption is shown by the two gasoline SI engines. H_2 fuelled engine achieves better values due to qualitative (i.e., mixture strength) power control. At low loads it is comparable to diesel engines. Diesel engines show better efficiency than the FC systems at high load operation. This feature is, however, almost insignificant if the engine is not downsized. If it is downsized and kept permanently at higher power level by hybridization, this feature can be of advantage at sufficiently high charging/discharging efficiency.

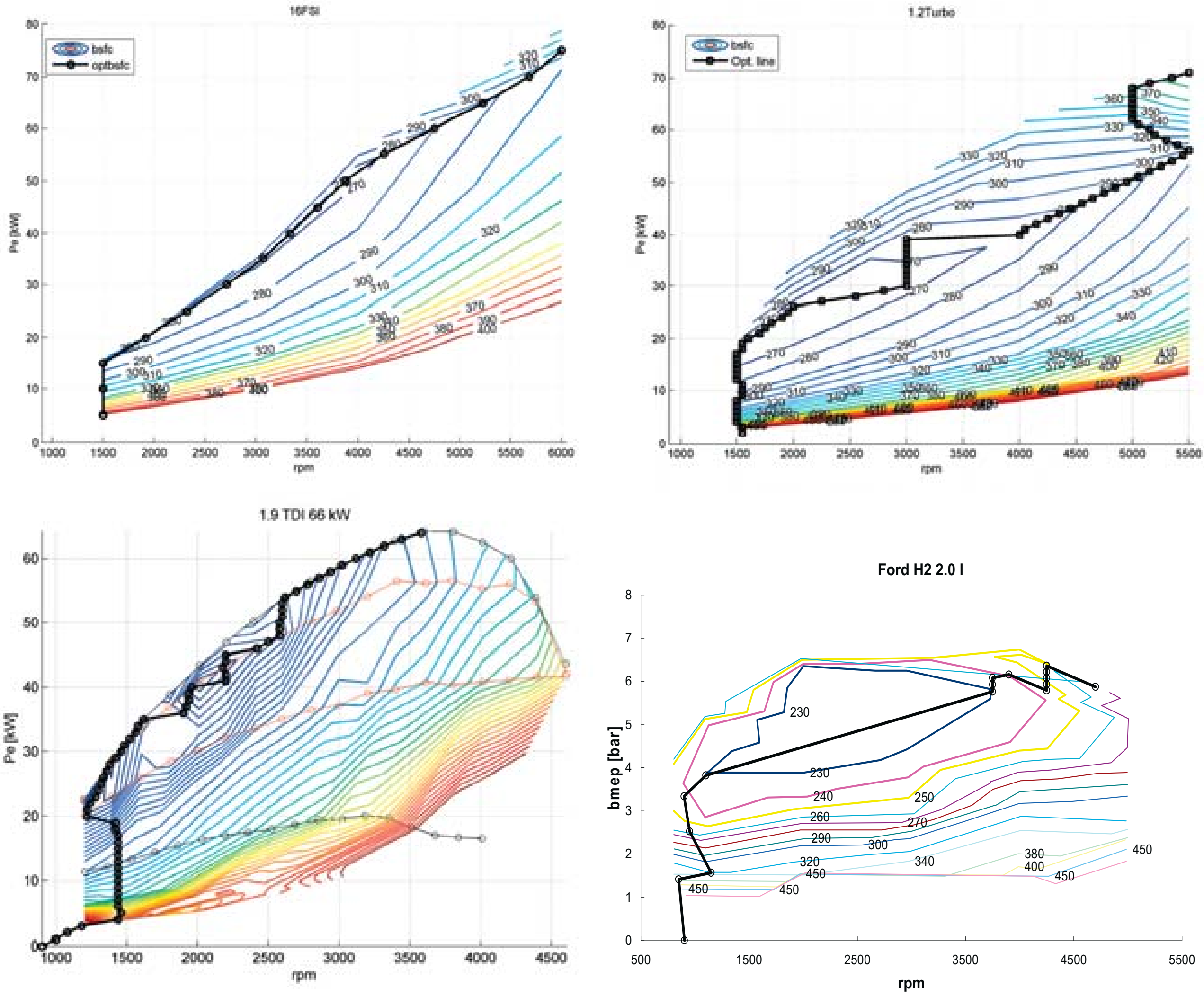

Fig. 1. ICE performance maps and minimum fuel consumption lines for 1.6FSI, 1.2T gasoline engines, 1.9 TDI diesel and 2.0 Ford hydrogen engine

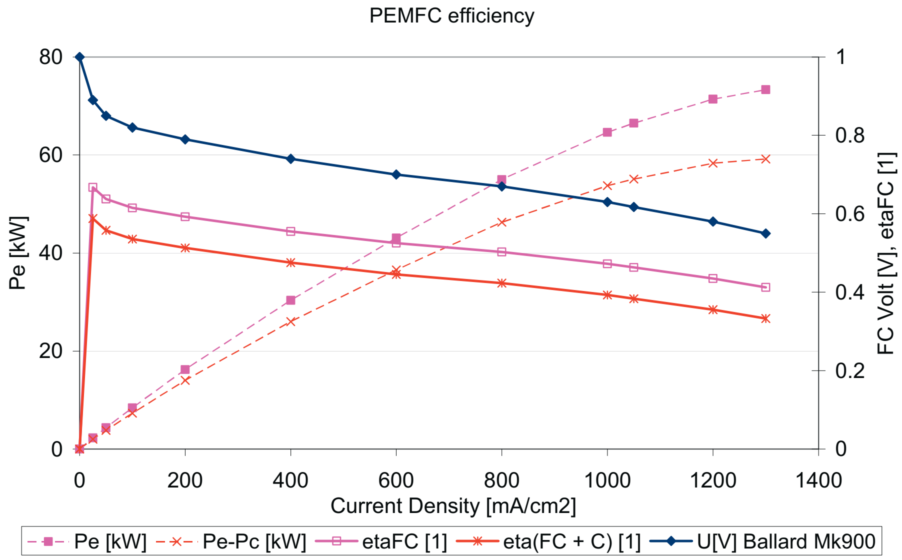

Fig. 2. Fuel cell performance characteristic for passenger car

Low load efficiency of PEMFC is much better than that of any ICE. This conclusion may be changed provided that all accessories are perfectly controlled and unused ones are switched off.

This idea has already been realized several times even taking the whole engine into account by means of switching off the cylinders. Extending this idea further, it led the authors to using two engines of different size and power and switching them on or off according to power demand. As an illustration, two TDI engines of total power of original 66 kW divided in the ratio 1/3 were tested. The control strategy may be the following: during low power demand the smaller engine works alone until it reaches its optimum point. From this power the larger engine is switched on and both engines work in parallel. The smaller one is kept by its „CVT" (e.g., electric power transmission) in optimum point as long as possible. At the highest power demand both engines work at their maximum power. The result of this implementation is significant improvement in consumption during low loads as shown in Fig. 3.

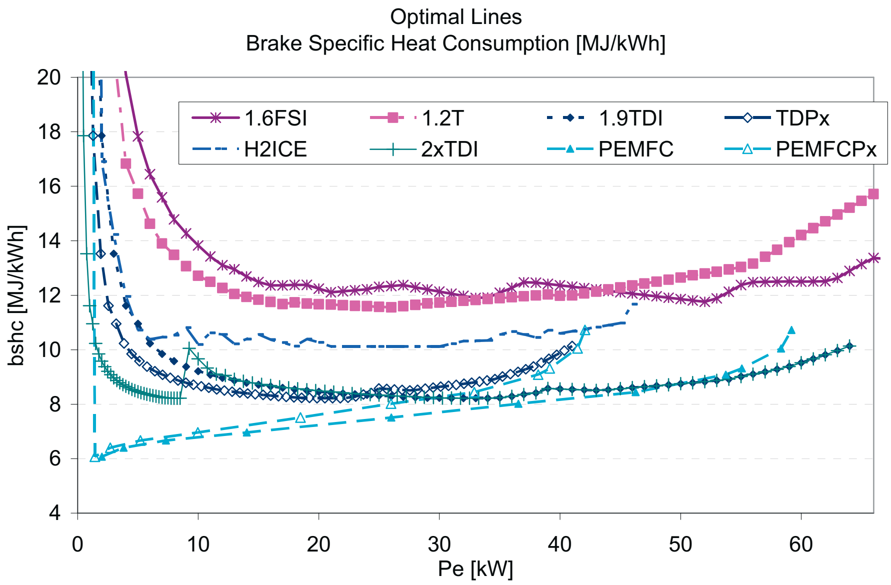

Fig. 3 Comparison of minimum specific heat consumption (bshc) over power output of combustion engines and hydrogen fuel cells

6. Hybrid ICE car model

The next development stage of simulation tool evaluates energy demands for charging of electric energy accumulators aiming to cover certain part of acceleration work (or any other extra work, e.g., for climbing a slope with unreduced velocity). The charging will occur at any time if accumulators are not charged to cover the preset work margin and the power requirement will enable prime mover to use the remaining power. On the other hand, the accumulators are used at any time of high power demand, exceeding the maximum power or power at the best efficiency. The hybrid efficiency will depend significantly on the prime mover power assignment.

The model includes estimated efficiencies of electric motor, pulse convertor and invertor. Efficiencies were estimated by the following formulas.

$$\eta_{motor} = \frac{P}{P + \Delta P}, \tag{1}$$

$$P = \left(\frac{M}{M_n}\right) \cdot \left(\frac{\omega}{\omega_n}\right), \tag{2}$$

$$\Delta P = 0.0525\, P_n \left(\frac{M}{M_n}\right)^2 + 0.0175\, P_n \left(\frac{\omega}{\omega_n}\right)^{1.8}, \tag{3}$$

where:

η_{motor} - electric motor efficiency,

P, P_n - relative and nominal power,

ΔP - losses due to variable load and speed,

$\frac{M}{M_n}$ - relative motor torque,

$\frac{\omega}{\omega_n}$ - relative angular speed.

Pulse converter and electric invertor efficiencies were estimated according to following formulas:

$$\eta_{PulseConverter} = \frac{P}{1.02\,P + 0.005} \tag{4}$$

and

$$\eta_{Invertor} = \frac{P}{1.025\,P + 0.005}\,. \tag{5}$$

A total efficiency of electric drive is expressed as a product of these efficiencies. Fig. 4. displays the resulting efficiency of electric drive over the relative power *P*. The electric drive of hybrid car was also simulated with the assumption of using CVT allowing its operation along optimum efficiency line for the whole power range, as in the case of the ICE. The CVT efficiency equal to 90% has been taken into account.

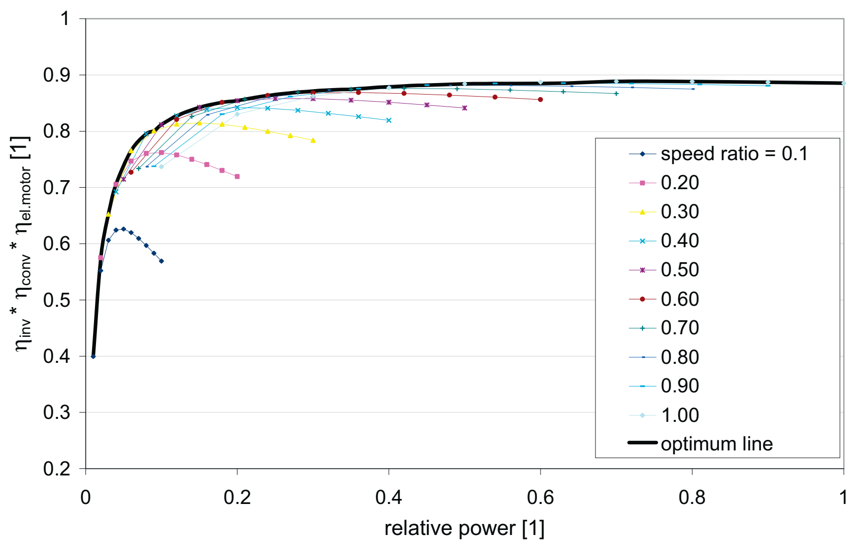

Fig. 4. A total efficiency of electric drive over power output

Values of charging and discharging efficiencies of energy accumulator were kept constant during this development step. The values were following:

$$\eta_{charging} = 0.9 \text{ and } \eta_{discharging} = 0.8. \tag{6}$$

7. NEDC Results for Passenger Car

Fig. 5 shows speed (demanded and actual), wheel power *Pact* and engine speed *RPMdem* during NEDC driving schedule of a car powered by *1.6FSI* gasoline engine.

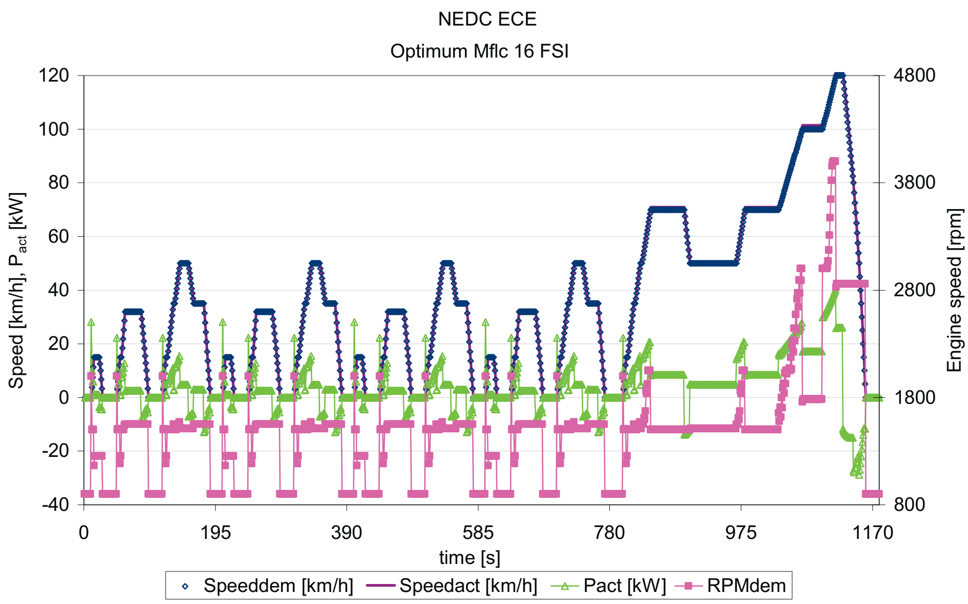

Fig. 5 NEDC driving schedule

Fig. 6. shows comparison of specific energy consumption for UDC, EUDC and NEDC driving schedules. Both fuel cell powered systems show lower energy consumption in UDC cycle than in EUDC part, which is natural due to better near-to-idling efficiency of a FC. Energy consumption of Hydrogen fuelled internal combustion engine in UDC reaches almost the value for naturally aspirated gasoline ICE, during EUDC part it surpasses downsized gasoline engine.

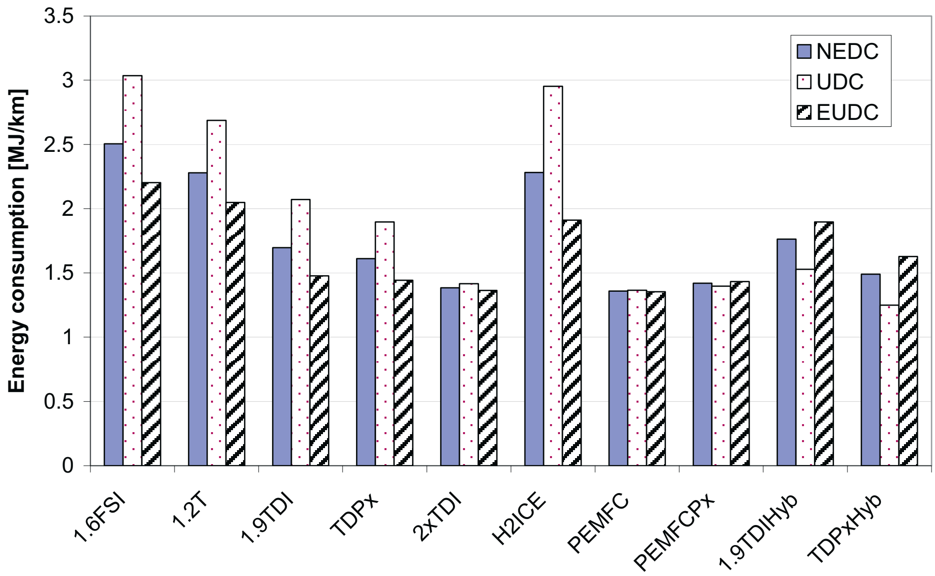

Fig. 6 Specific energy consumption for NEDC, UDC and EUDC for car powered by various powertrains

A FC H_2 system shows the lowest specific energy consumption despite the higher vehicle mass compared to other powertrain systems. However, minimizing size of FC system just for fulfilling NEDC power demand, which is very reasonable from the cost point-of-view, decreases its efficiency due to the FC efficiency drop towards higher power outputs. On the other hand, IC engine downsizing improves efficiency, especially that of a turbocharged diesel. These two features show possible gaps in today's engine and FC design for a specific vehicle matching.

A hydrogen ICE shows much better fuel consumption than gasoline engines, but due to higher vehicle mass and absence of turbocharging the results are worse than those of a diesel ICE system. According to [5] and the authors' experience, turbocharging of a H_2 ICE is feasible and can asset better efficiency despite some limits set to avoid knocking.

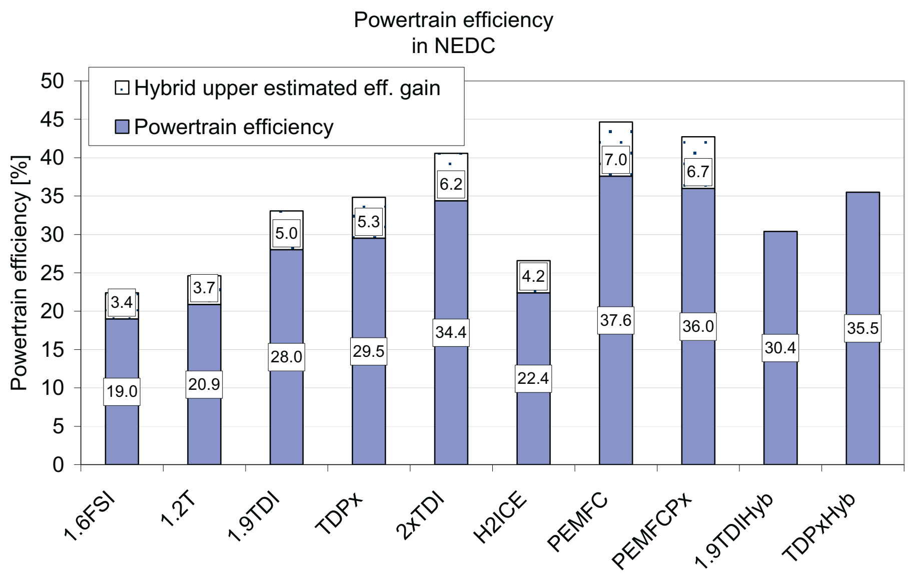

Fig. 7. Total powertrain efficiency and upper estimated hybrid efficiency in NEDC and more realistic hybrid calculations

In Fig. 7. the potential of recuperation is shown for each powertrain except for real hybrid, where this effect has already been included. In the presented estimation the efficiency of recuperation was equal to 70%. The theoretical energy gain due to recuperation has been 7% in the best case (PEMFC) and 3.4% in the worst case (gasoline naturaly aspirated engine) as can be seen from Fig. 7. The best achievable efficiency of a car in NEDC reaches 37.6% with a PEMFC without energy recuperation.

Energy balance of a real hybrid (the last two bars in Fig. 6-7) has been investigated, as well. The first tested hybrid contains 66 kW diesel engine completed by electric drive that covers the power range between zero and engine optimum point i.e. 35 kW. The second one features the engine power of 38 kW and 20 kW electric power.

The smaller diesel hybrid indicates the lowest energy consumption in urban conditions from all investigated powertrains.

Fig. 8. shows speed, demanded wheel power *(P_dem)*, engine effective power *(Pe)* and accumulator state of charge *(SOC)* over time in *NEDC* driving schedule. The engine operation varies between off-state, optimum and maximum power. The *SOC* at the end is higher than that at the cycle start in this case.

The level of hybridization has been investigated within the range of downsizing the engine from original 66 kW to 12 kW. Fig. 9 shows the results in the fuel consumption for the UDC, EUDC and total NEDC. The fuel consumption decreases with the size of diesel engine. In the range of engine power lower than 30 kW the maximum NEDC speed *wmax* cannot be achieved. The difference between battery state of charge *delSOC* at the end and start of test cycle is positive for the engine power higher than 30 kW.

8. Future Development of Simulation Tool

The corrections for transient response will be implemented to the simulation. Their estimate depends on the SOTA of detailed dynamic simulation. Today, this issue is mastered for ICE only.

One of the possible next development steps is a combination of FC and electric accumulator.

However in this case it has to be taken into account that the load of fuel cell in real hybrid will be significantly higher due to the need for recharging an accumulator or a supercapacitor. The FC efficiency will be then lower depending on average power demand, especially high for motorway operation (see FC characteristics at higher loads).

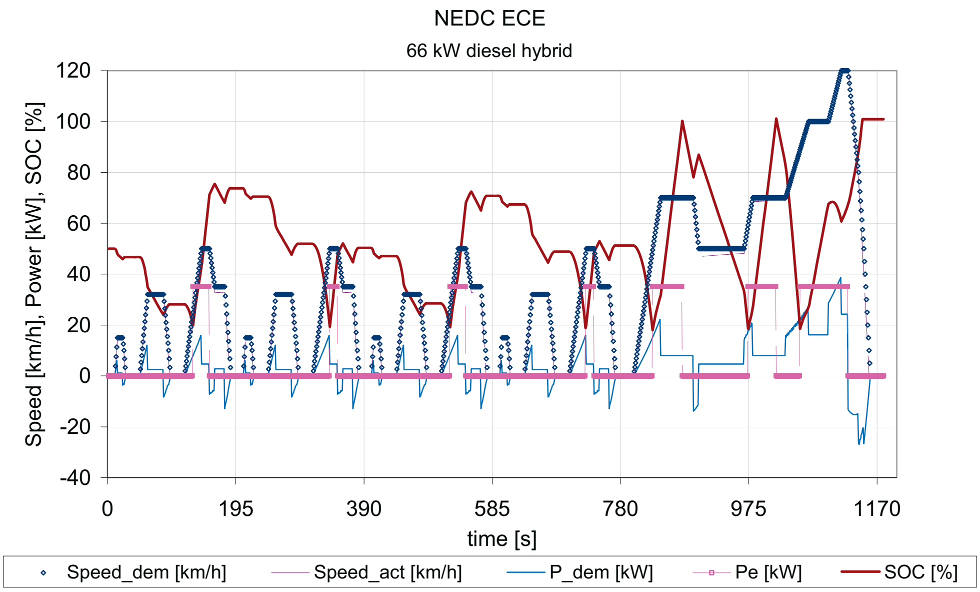

Fig. 8. NEDC simulation of hybrid car with diesel engine of power 66 kW

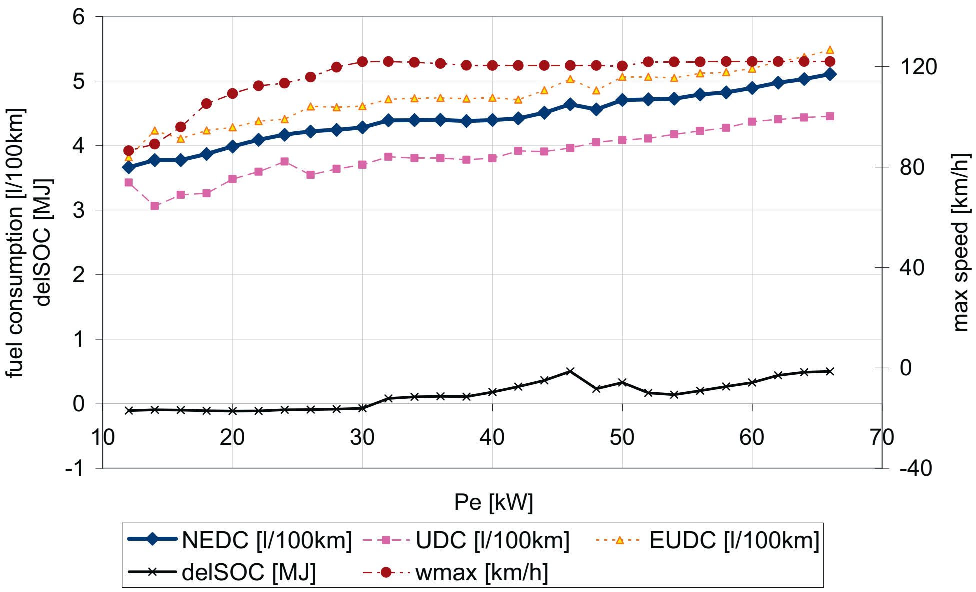

Fig. 9 Diesel-hybrid car fuel consumption in UDC, EUDC and NEDC as a function of the prime mover size

9. Conclusions

Transparent, simplified MS Excel-based software tool for evaluation of efficiency of various powertrain systems has been developed. The tool has been utilized for comparing upper but still realistic estimates of efficiency of gasoline, diesel, diesel hybrid and hydrogen fuelled internal combustion engines and hydrogen proton exchange membrane fuel cell vehicles achieved in NEDC driving schedule.

Upper estimated efficiency for hybrid system has been evaluated for all powertrain systems. More correct hybrid solution for diesel engine has been evaluated as well. The best efficiency of car was achieved by PEMFC in NEDC driving schedule. The total powertrain efficiency nearly reaches 37.6% without recuperative braking. In the case of optimally sized hybrid with recuperation and optimum point engine operation it is 35.5%. The same vehicle driven by two diesel engines could reach 34.4%.

The real hybrid system with fuel cell is expected to be less efficient, nevertheless, due to permanent higher loading of FC. This issue is opened for the further research.

The simulation tool developed for these purposes, compares SOTA of different powertrain efficiencies and extrapolates them to the future level assuming the cost level set by predicted FC price in the future. In such a manner, it keeps sound realistic base for upper estimates of overall efficiency under real driving cycles but predicts at least the limits of future possibilities. Using this way, it finds gaps opened for the future bridging by a consequently focussed R&D.

10. List of Abbreviations

AC	Alternating Current
BSHC	Brake Specific Heat Consumption
CI	Compression Ignition
CVT	Continuously Variable Transmission
DC	Direct Current
EUDC	Extra Urban Driving Cycle
FC	Fuel Cell
FSI	Gasoline Direct Injection
ICE	Internal Combustion Engine
NEDC	New European Driving Cycle
PEMFC	Proton Exchange Fuel Cell
SI	Spark Ignition
SOTA	State of the Art Analysis
T	Turbocharged
TDI	Turbocharged Direct Injection engine
TDIPx	Cycle Tailored Turbocharged Direct Injection engine
TTU	Tank to User
TTW	Tank to Weels
UDC	Urban Driving Cycle

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