International Congress Motor Vehicles & Motors 2014

Kragujevac, October 9th-10th, 2014

MVM2014-046

Vladimir Marjanović[1]
Marko Kitanović[2], Slobodan Popović[3], Nenad Miljić[4]

COMPARATIVE STUDY ON PERFORMANCE OF CONVENTIONAL AND SERIES HYBRID POWER TRAIN FOR PASSENGER CAR IN TAXI SERVICE

ABSTRACT: The main objective of the study presented in this paper was to perform a comparison of a conventional power train system (CPS) with a diesel engine and a series hybrid electric power train system (SHEPS) and analyse the feasibility of the implementation of hybrid power train in taxi service. Development software package AMESim was used to create detailed mathematical models of a passenger car powered by conventional high-tech Common-Rail supercharged CI engine and a SHE power train system based on the same type of CI engine. The vehicle used to perform the comparative numerical study was set as a C-segment passenger car which is intended to be applied as taxi service vehicle. Simulation of both vehicle power train systems has been accomplished on the basis of New European Driving Cycle (NEDC), the custom, purposely extended NEDC for battery configuration and charging system evaluation and real driving cycles, which were obtained experimentally. Simulation models were applied in order to conduct parametric analysis and investigate battery charging strategy and its influence on performance, fuel economy and emission of the SHEPS compared to CPS. The reduction of 20 - 60% of total fuel consumption was observed in case of SHEPS. Accordingly, total exhaust gas emissions are reduced as well.

KEYWORDS: series hybrid electric power train system; simulation; analysis; fuel consumption; exhaust gas emission

INTRODUCTION

Hybrid electric power train system (HEPS) represents a promising approach to reduce vehicle fuel consumption and exhaust gas emission. An additional electric power train including an energy storage device, typically a rechargeable battery or supercapacitors, is combined with an internal combustion engine to provide the desired

[1] *Dipl. Ing. Vladimir Marjanović, Research Assistant, Internal Combustion Engines Department, Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11120 Belgrade 35, Serbia, vmarjanovic84@gmail.com*
[2] *Marko Kitanović, M.Sc., Teaching Assistant, Dr Slobodan Popović, Docent, Dr Nenad Miljić, Docent, Predrag Mrđa, M.Sc., Teaching Assistant, Internal Combustion Engines Department, Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11120 Belgrade 35, Serbia, mkitanovic@mas.bg.ac.rs, spopovic@mas.bg.ac.rs, nmiljic@mas.bg.ac.rs, pmrdja@mas.bg.ac.rs*
[3] *Marko Kitanović, M.Sc., Teaching Assistant, Dr Slobodan Popović, Docent, Dr Nenad Miljić, Docent, Predrag Mrđa, M.Sc., Teaching Assistant, Internal Combustion Engines Department, Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11120 Belgrade 35, Serbia, mkitanovic@mas.bg.ac.rs, spopovic@mas.bg.ac.rs, nmiljic@mas.bg.ac.rs, pmrdja@mas.bg.ac.rs*
[4] *Marko Kitanović, M.Sc., Teaching Assistant, Dr Slobodan Popović, Docent, Dr Nenad Miljić, Docent, Predrag Mrđa, M.Sc., Teaching Assistant, Internal Combustion Engines Department, Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11120 Belgrade 35, Serbia, mkitanovic@mas.bg.ac.rs, spopovic@mas.bg.ac.rs, nmiljic@mas.bg.ac.rs, pmrdja@mas.bg.ac.rs*

overall power output. This configuration makes it possible to employ the internal combustion engine in its most efficient operating conditions and to recuperate kinetic energy of the vehicle during deceleration for further use, which leads to reduced total fuel consumption. HEPSs are typically classified by the division of power between sources. Both sources may operate in parallel to simultaneously provide acceleration (parallel hybrid), or they may operate in series with one source exclusively providing the acceleration and the second being used to augment the first's power reserve (series hybrid). The sources can also be used in both series and parallel as needed, the vehicle being primarily driven by one source but the second capable of providing direct additional power if required (power-split or series-parallel hybrid). They can also be categorized according to their degree of hybridization as a mild hybrid, a full hybrid and plug-in hybrid electric power trains. HEPSs are assumed to pave the way for electricity-based power train solutions, such as full electric (EPS) or fuel cell power train systems (FCPS).

METHODOLOGY

The main objective of this study was to perform a comparison of a CPS with a diesel engine and a SHEPS and analyse the feasibility of implementation of hybrid power train in taxi service vehicle. In order to do so, development software package AMESim was used to create detailed mathematical models of a passenger car powered by conventional high-tech Common-Rail supercharged diesel engine and a SHEPS based on the same type of engine. The vehicle used to perform comparative numerical study was set as a C-segment passenger car which is intended to be applied as taxi service vehicle.

Vehicle power train calculations

Power train calculation of vehicle with a series hybrid electric power train was conducted under the assumption that the hybrid vehicle is made on the basis of Skoda Octavia 1.6 TDI. Calculations will be presented only with the final formulas. The entire course of these calculations can be found in the relevant literature which is given at the end of this paper.

Required engine power for overcoming resistances at maximum slope and maximum driving speed [3]

Calculations were carried out in two driving modes in which the power required to drive the vehicle is reaching a maximum value:

1. Mode at the maximum speed of the vehicle
   u=0 % – road with 0% slope
   v=140 km/h – maximum speed during NEDC increased by 20 km/h
2. Mode when driving a vehicle on the maximum slope
   u=20 % – road with 20% slope
   v=30 km/h – maximum speed at 20% slope

Engine power which is required to overcome the resistance to vehicle motion is calculated as shown below:

$$P_e = \frac{P_f + P_v + P_u}{\eta_p} \quad (1)$$

where P_f is power required to overcome rolling resistance, P_v power required to overcome air resistance, P_u power required to overcome the resistance of the slope and η_p efficiency of transmission. The values of power to overcome resistances at maximum slope and maximum driving speed were calculated based on the characteristics of the Skoda Octavia 1.6 TDI [5, 6] and mass of the components of the hybrid drive:

1. P_e=34816 W
2. P_e=32927 W

Required engine power for overcoming resistances during vehicle acceleration [2]

Vehicle acceleration is the most important drivability quantifier. In this text it will be presented as the time necessary to accelerate the vehicle from 0 to 100 km/h. This value is not easy to accurately calculate because it depends on many uncertain factors and includes highly dynamic effects. An approximation of this parameter can be obtained as shown below:

$$t \approx \frac{v^2 \cdot m_v}{P_{max}} \quad (2)$$

where t is time necessary to accelerate the vehicle from 0 to 100 km/h, v=100 km/h, m_v mass of the vehicle and P_{max} maximum rated power. For the purpose of this study it was necessary to estimate the maximum power of the engine that is required to achieve the appropriate acceleration of the vehicle. This was accomplished by the following equation:

$$P_{\max} \approx \frac{v^2 \cdot m_v}{t} \tag{3}$$

Required engine power for vehicle acceleration was calculated under the assumption that series hybrid vehicle has similar acceleration as Skoda Octavia 1.6 TDI:

P_{max}=107,43 kW

The final selection of components of series hybrid electric power train [1, 4]

From the calculations it can be seen that the continuous power, which is necessary to overcome the resistance at the maximum slope and the maximum speed of the vehicle is P_{con}≈35 kW, while the acceleration of vehicle needed to deliver a lot more power (P_{max}≈107,5 kW). This maximum power is needed for short periods of time while the vehicle is accelerating, and in other operating modes, the vehicle will require a much lower power.

Components of the series hybrid power train were chosen based on calculations shown above, and they are shown in Table 1.

Table 1 *Components of the series hybrid electric power train*

Component	Model
Electric motor	BRUSA ASM-6.17.12
Electric generator	BRUSA ASM-6.17.12
Inverter for EM	BRUSA DMC534
Inverter for EG	BRUSA DMC534
Battery	BRUSA EVB1-400-40-HP
Battery charger	BRUSA NLG513
Converter	BRUSA BSC624-12V
Water Pump	BOSCH PA66-GF30

Simulation models and driving cycles

Simulation models of conventional and series hybrid electric vehicle were created by using AMESim software tool. Parameters of used submodels were set to match the selected components of CPS and SHEPS. Figure 1 shows the sketch for the model of series hybrid used in numerical simulations.

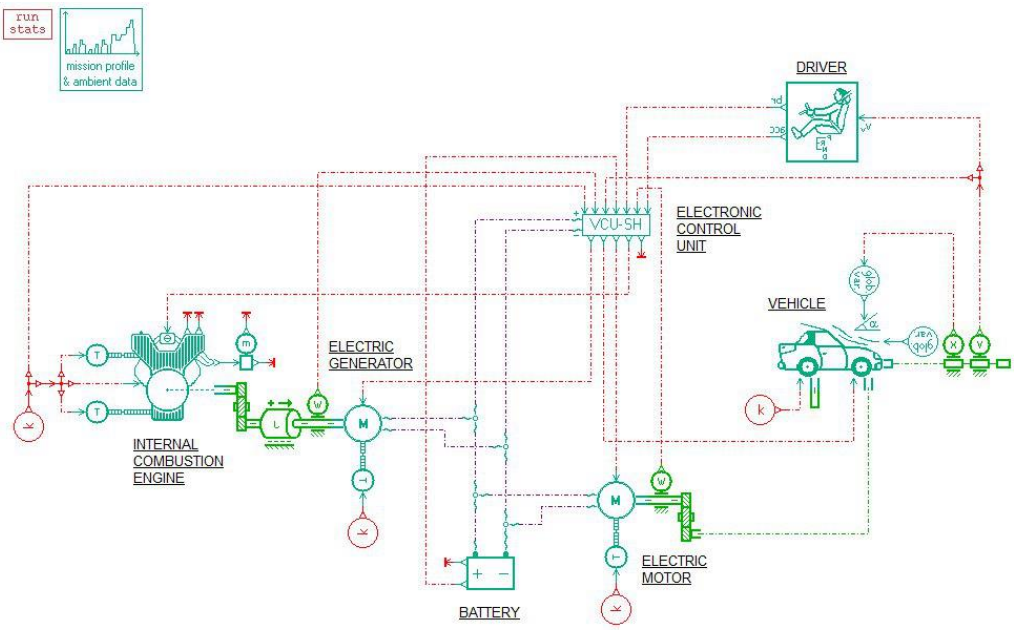

Figure 1 *Sketch for the model of series hybrid electric power train system*

Simulation of these vehicle propulsion systems was done on the basis of New European Driving Cycle (NEDC), extended NEDC and three real driving cycles (200, 201 and 401), which were obtained experimentally. Real driving cycles were recorded on the streets of Belgrade and represent morning cycle (200), morning rush hour (201) and afternoon rush hour (401). Figure 2 shows driving patterns of New European Driving Cycle and real cycles 200, 201 and 401. Main characteristics of these driving cycles are shown in Table 2.

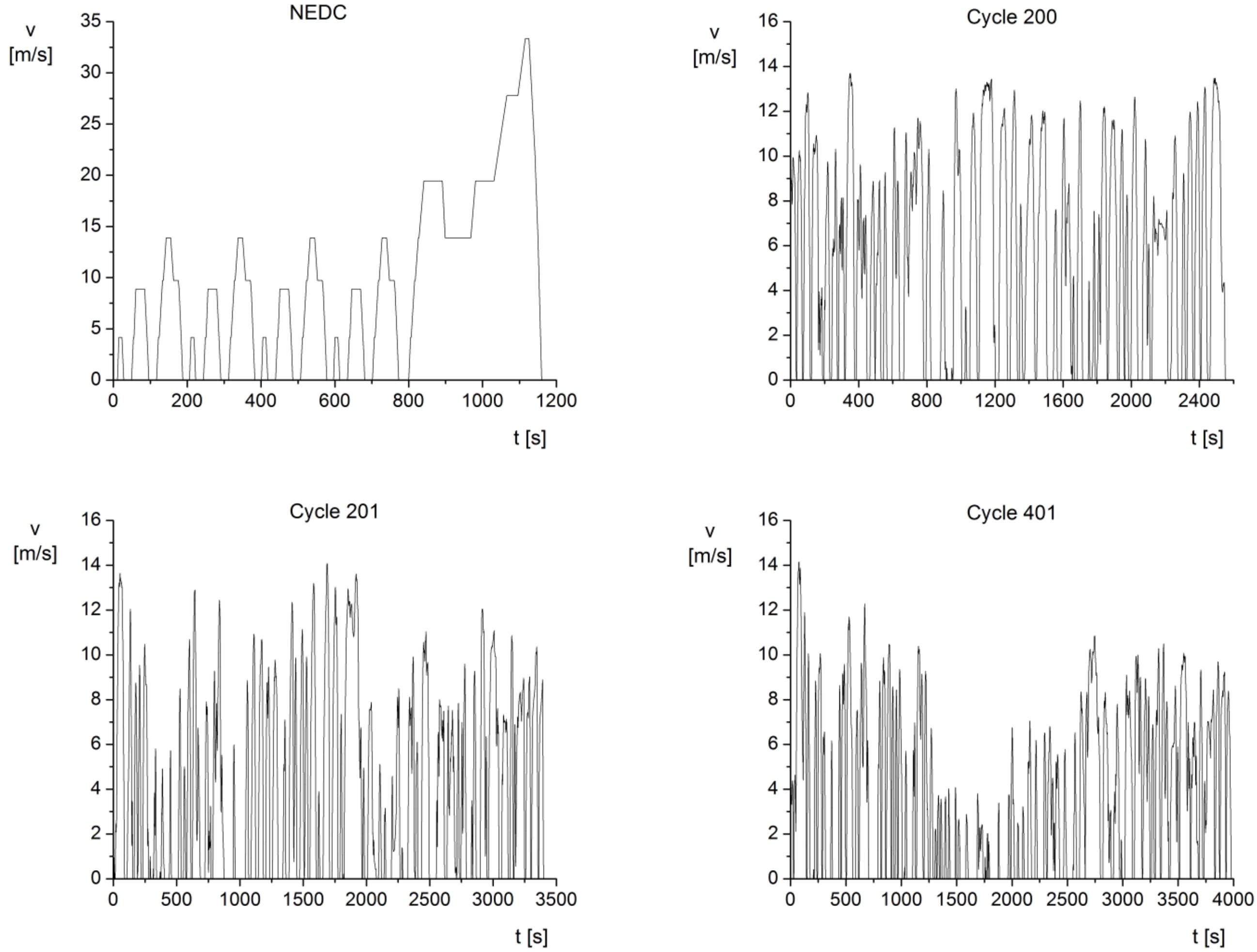

Figure 2 *Driving patterns of NEDC and real driving cycles 200, 201 and 401*

Table 2 *Main characteristics of NEDC and real driving cycles 200, 201 and 401*

Cycle	NEDC	200	201	401
Distance [m]	11006	14048	14061	13844
Duration [s]	1180	2560	3400	3985
Maximum speed [m/s]	33,33	13,71	14,08	14,15
Average speed [m/s]	9,328	5,487	4,135	3,474

RESULTS

Simulations were performed with four different sets of parameters. With each set of simulations there was one parameter which was varied while the other parameters remained unchanged. That was done to analyse how different parameters affect total fuel consumption of SHEPS. Table 3 shows which parameters were varied during these four sets of numerical simulations. Additionally, for one set of parameters (NEDC, SOC=92% and $P_{startHM}$=10 kW) analysis of exhaust gas emission was performed.

__Table 3__ Settings of the variable parameters used in mathematical models

	1	2	3	4
Driving cycle	NEDC	NEDC x 10	200 201 401	401
Battery state of charge (SOC)	90 % 92 % 95 %	40 % 60 % 80 %	92 %	92 %
Requested power to start the hybrid mode ($P_{startHM}$)	10 kW	10 kW	10 kW	10 kW 15 kW 20 kW

Correction of total fuel consumption

If battery state of charge changes at the end of the cycle, correction of total fuel consumption has to be made. This correction is based on differences in the battery state of charge at the end and beginning of the cycle ($\Delta SOC = SOC_E - SOC_B$). In cases where the ΔSOC>0, the hybrid drive has spent additional energy to recharge the battery, which increases total fuel consumption. If the ΔSOC<0, vehicle used electric drive without recharging the batteries to proper level in which case results show improved fuel economy. Mass of the fuel that is equivalent to ΔSOC = 1% can be calculated based on the characteristics of the fuel and the batteries, and energy losses of the system.

The total energy of a battery that can theoretically be used to power the vehicle can be calculated if the battery capacity (C) is multiplied by the voltage (V) and efficiencies of inverter (η_I), electric motor (η_{EM}) and final drive (η_{FD}):

$$E_{BAT} = C \cdot 3600 \cdot V \cdot \eta_I \cdot \eta_{EM} \cdot \eta_{FD} \quad (4)$$

This energy is equal to fully charged battery (ΔSOC = 100%). Energy of battery that is equal to ΔSOC = 1% can be calculated by the following equation:

$$E_{1\%} = \frac{E_{BAT}}{100} \quad (5)$$

Theoretical amount of energy that can be stored in the battery by combustion of 1 kg of fuel can be calculated based on the lower heating value (LHV) of the diesel fuel and efficiencies of the internal combustion engine (η_{ICE}), electric generator (η_{EG}) and inverter (η_I):

$$E_f = LHV \cdot m_f \cdot \eta_{ICE} \cdot \eta_{EG} \cdot \eta_I \quad (6)$$

The mass of fuel that needs to be combusted to obtain the energy which is equivalent to the ΔSOC = 1% is:

$$m = \frac{E_{1\%}}{E_f} \quad (7)$$

Simulation results of total fuel consumption of CPS and SHEPS with almost full battery during NEDC

Figure 3 shows total fuel consumption of CPS and SHEPS with almost full battery at the start of the cycle during NEDC. Total fuel consumption and difference in total fuel consumption compared to CPS are shown in Table 4. In all three cases (SOC = 90%, SOC = 92% and SOC = 95%), total fuel consumption of SHEPS is lower than the one of CPS. Reduction in fuel consumption is lowest in case with SOC = 90%, and fuel economy improves with higher SOC.

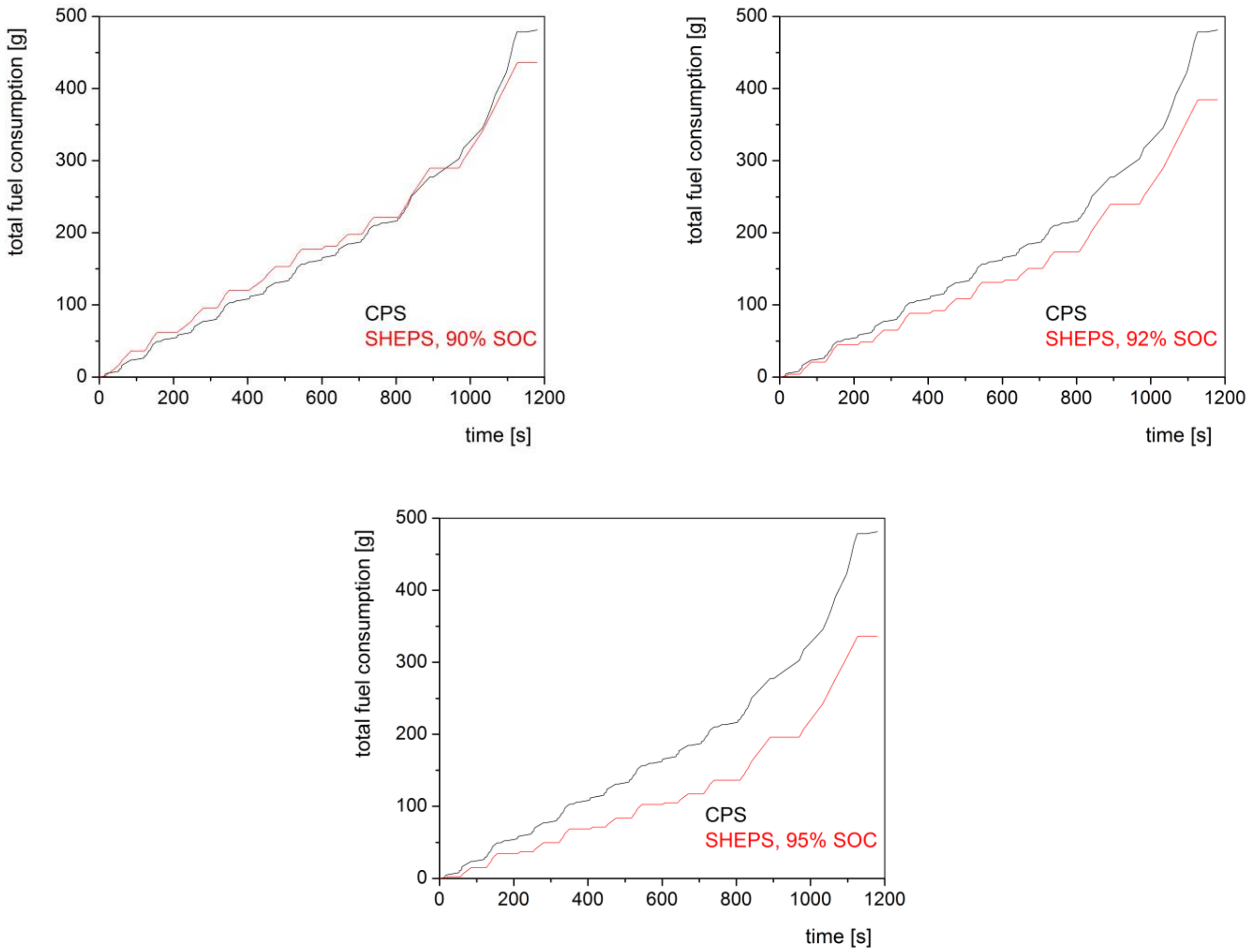

***Figure 3** Total fuel consumption of CPS and SHEPS with almost full battery during NEDC*

***Table 4** Total fuel consumption and difference in fuel consumption compared to CPS during NEDC*

	ΔSOC [%]	Total fuel consumption [g]	Difference in fuel consumption [%]
CPS		481,2	0
SHEPS, SOC = 90%	+ 1,85	436,1	– 9,37
SHEPS, SOC = 90%	Corrected values	371,7	– 22,75
SHEPS, SOC = 92%	+0,64	384,5	– 20,09
SHEPS, SOC = 92%	Corrected values	362,2	– 24,73
SHEPS, SOC = 95%	– 0,58	336,3	– 30,12
SHEPS, SOC = 95%	Corrected values	356,7	– 25,87

Simulation results of total fuel consumption of CPS and SHEPS with partially depleted battery during extended NEDC

Total fuel consumptions of CPS and SHEPS with partially depleted battery at the beginning of the cycle during extended NEDC are shown in Figure 4. Table 5 presents the numerical values of the total fuel consumption of CPS and SHEPS during NEDC x 10, for the cases when the battery is partially depleted and differences in fuel economy compared to a CPS.

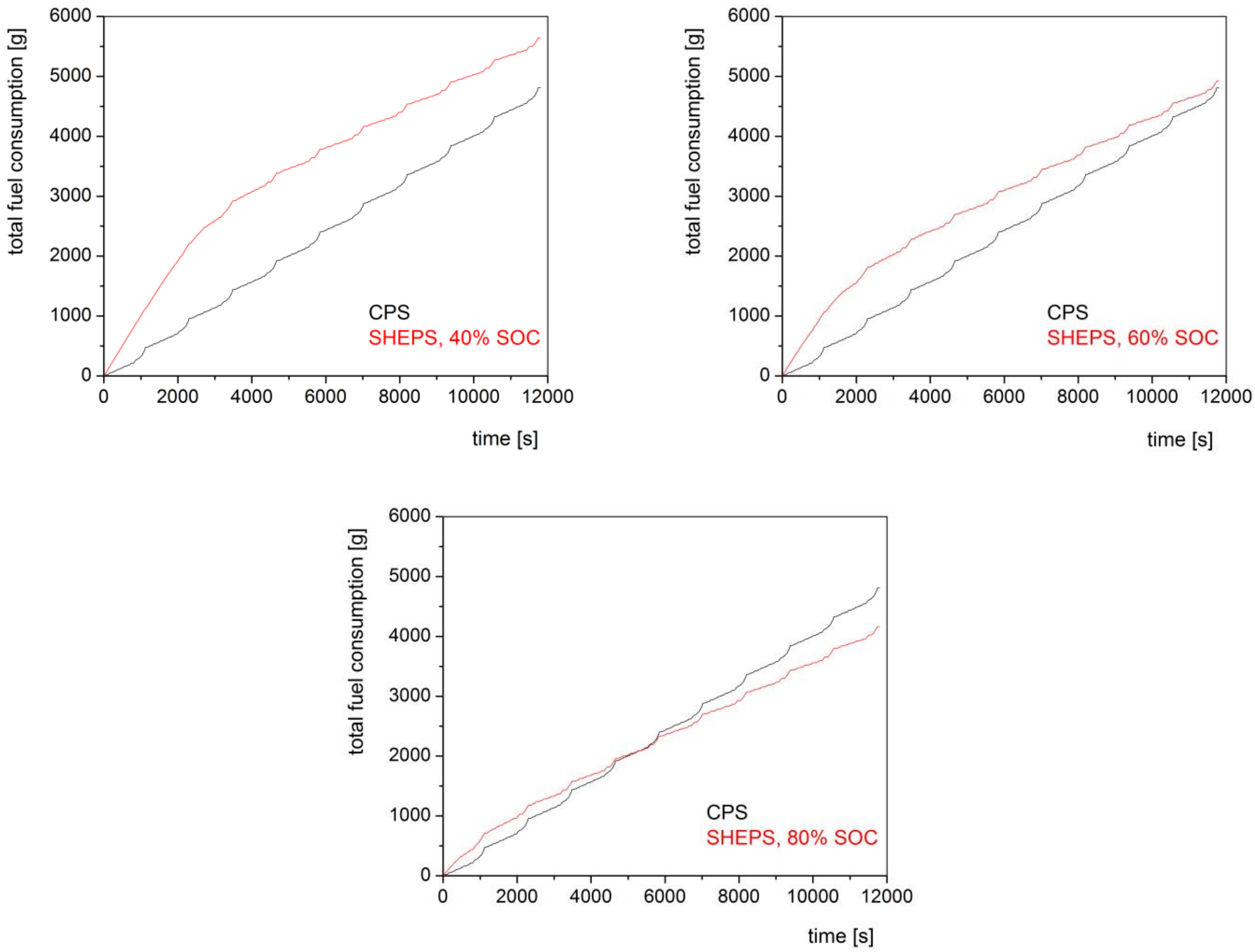

Figure 4 *Total fuel consumption of CPS and SHEPS with partially depleted battery during extended NEDC*

Table 5 *Total fuel consumption and difference in fuel consumption compared to CPS during extended NEDC*

	ΔSOC [%]	Total fuel consumption [g]	Difference in fuel consumption [%]
CPS		4812,5	0
SHEPS, SOC = 40%	+ 53,77	5642,6	+ 17,25
SHEPS, SOC = 40%	Corrected values	3771,4	– 21,63
SHEPS, SOC = 60%	+ 33,86	4920,5	+ 2,24
SHEPS, SOC = 60%	Corrected values	3742,2	– 22,24
SHEPS, SOC = 80%	+ 13,91	4163,5	– 13,48
SHEPS, SOC = 80%	Corrected values	3679,4	– 23,54

It can be seen that the total fuel consumption of SHEPS in cases with SOC=40% and SOC=60% is higher than the one of CPS. This increase in consumption is due to the fact that the cycle started with a partially depleted battery, so that internal combustion engine needs to invest additional energy to recharge the batteries. A similar effect occurs in the first t≈5000s in the case of SOC=80%. In this part of the cycle the total fuel consumption of a SHEPS is higher than the one of CPS due to the additional charging of batteries. However, because this additional charging of the battery is lower than the one in cases with SOC=40% and SOC=60% by the end of the cycle reduction in fuel consumption of 13.48% is achieved. Corrected fuel consumption in cases when the battery is partially discharged shows lower total fuel consumption of SHEPS by 21.63% to 23.54%. Fuel economy of SHEPS improves as the battery state of charge at the beginning of the cycle increases.

Simulation results of total fuel consumption of CPS and SHEPS with almost full battery during real cycles 200, 201 and 401

Figure 5 shows total fuel consumption of CPS and SHEPS with almost full battery at the start of the cycle during real cycles 200, 201 and 401. Table 6 presents numerical values of total fuel consumption and differences in fuel consumption compared to a CPS for simulations with settings from the third set of parameters.

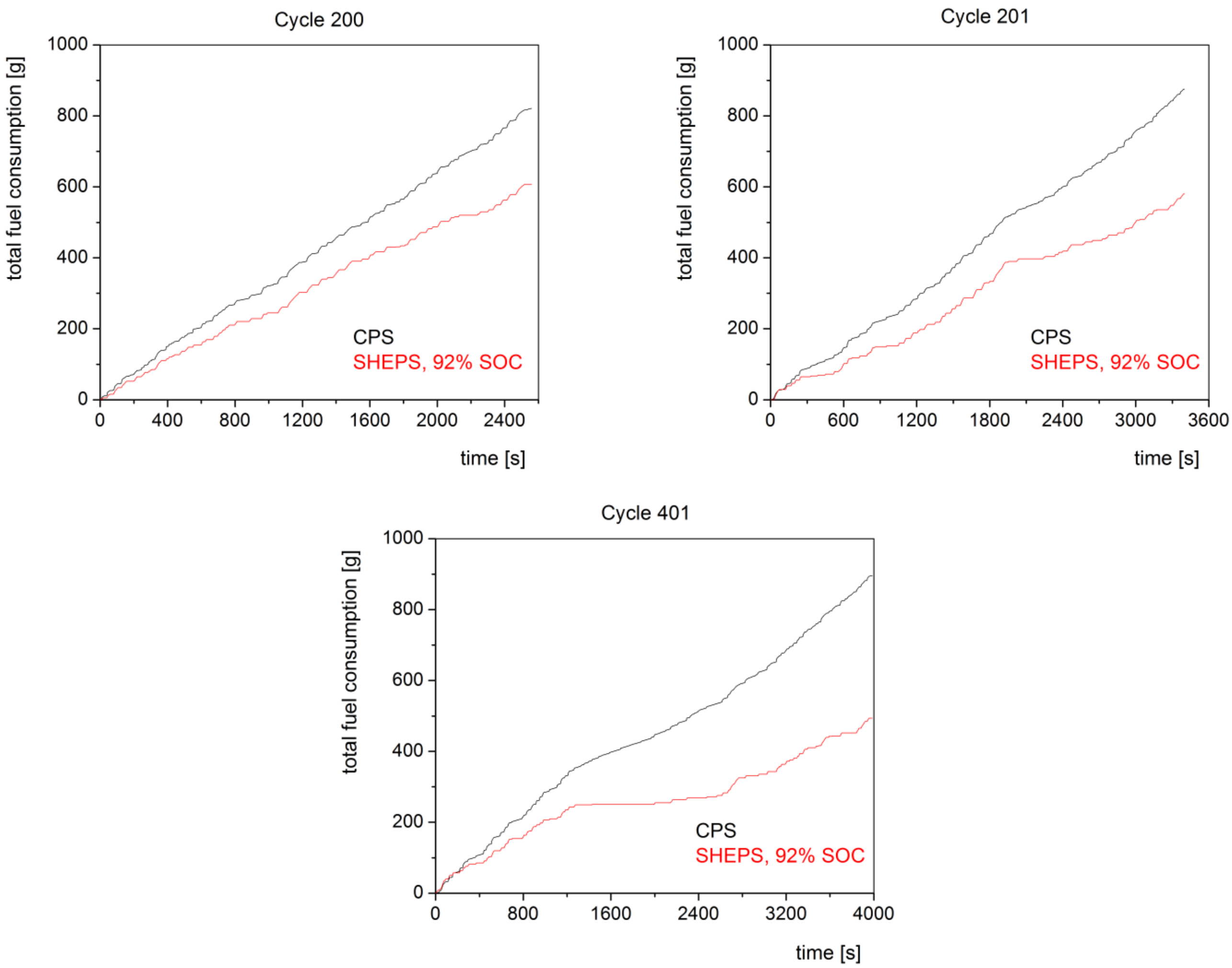

***Figure 5** Total fuel consumption of CPS and SHEPS with almost full battery during cycles 200, 201 and 401*

***Table 6** Total fuel consumption of CPS and SHEPS and difference in fuel consumption compared to CPS during real cycles 200, 201 and 401*

Cycle		ΔSOC [%]	Total fuel consumption [g]	Difference in fuel consumption [%]
200	CPS		821,3	0
	SHEPS, SOC = 92%	+ 3,39	607,7	– 26,01
	SHEPS, SOC = 92%	Corrected values	489,7	– 40,37
201	CPS		875,4	0
	SHEPS, SOC = 92%	+ 2,95	580,0	– 33,74
	SHEPS, SOC = 92%	Corrected values	477,3	– 45,48
401	CPS		896,1	0
	SHEPS, SOC = 92%	+ 2,29	494,1	– 44,86
	SHEPS, SOC = 92%	Corrected values	414,4	– 53,75

Total fuel consumption of SHEPS is considerably lower than that of CPS. The maximum fuel savings are during the afternoon rush hour (44.86%) and are lower with fewer traffic jams. Corrected values show similar features, but with improved fuel economy for all three cycles.

Simulation results of total fuel consumption of CPS and SHEPS with SOC=92% and different settings of $P_{startHM}$ during cycle 401

Figure 6 shows total fuel consumption of CPS and SHEPS with SOC=92% on cycle 401. During this set of simulations, the requested power to start the hybrid mode was varied. Numerical values of total fuel consumption and differences in fuel consumption compared to a CPS are shown in Table 7.

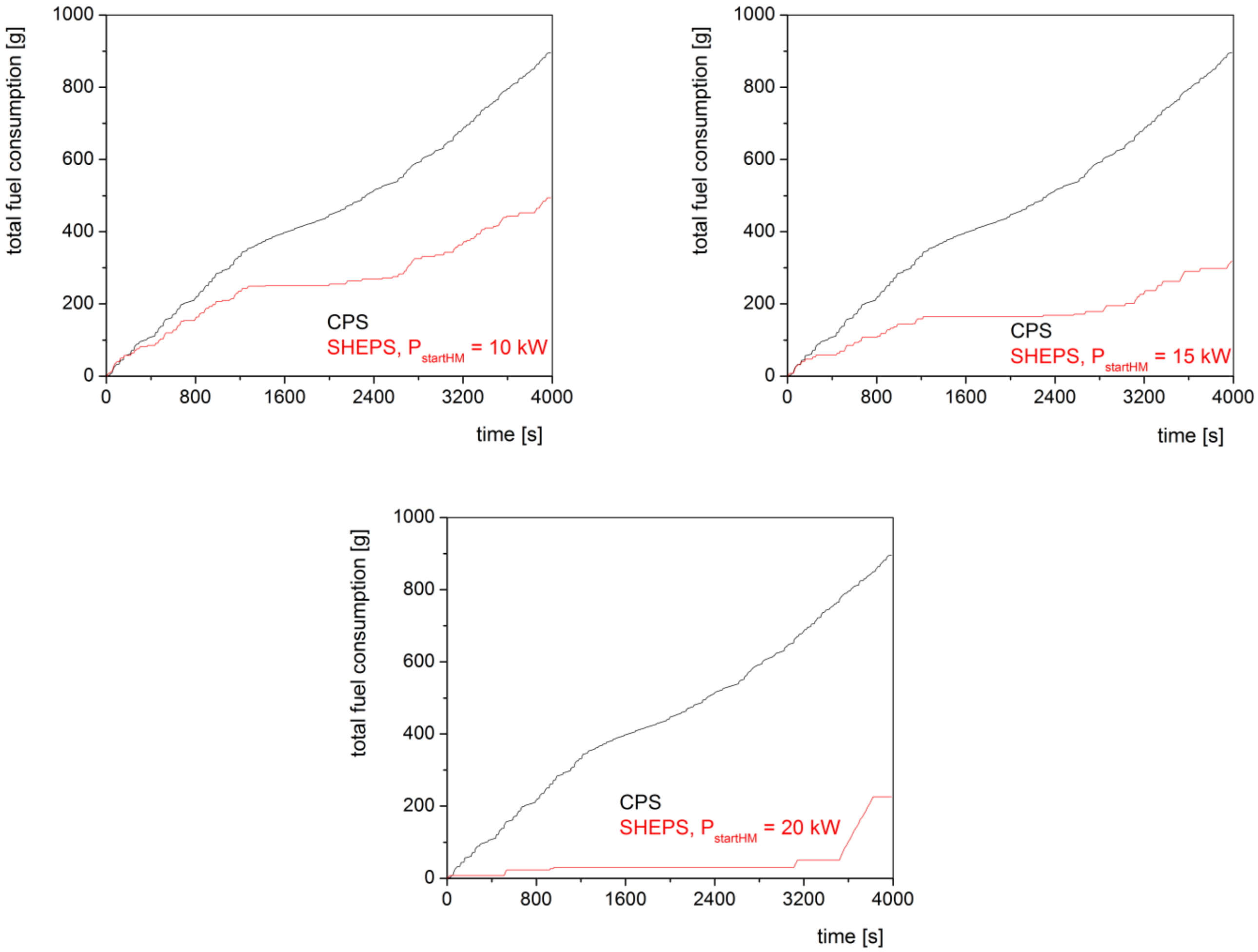

Figure 6 *Total fuel consumption of CPS and SHEPS with variable $P_{startHM}$ during cycle 401*

Table 7 *Total fuel consumption of CPS and SHEPS with variable $P_{startHM}$ and difference in fuel consumption compared to CPS during cycle 401*

	ΔSOC [%]	Total fuel consumption [g]	Difference in fuel consumption [%]
CPS		896,1	0
SHEPS, $P_{startHM}$ = 10 kW	+ 2,29	494,1	– 44,86
SHEPS, $P_{startHM}$ = 10 kW	Corrected values	414,4	– 53,75
SHEPS, $P_{startHM}$ = 15 kW	– 1,95	318,6	– 64,44
SHEPS, $P_{startHM}$ = 15 kW	Corrected values	386,5	– 56,87
SHEPS, $P_{startHM}$ = 20 kW	– 3,48	225,8	– 84,80
SHEPS, $P_{startHM}$ = 20 kW	Corrected values	346,9	– 61,29

Total fuel consumption of SHEPS is considerably lower than that of CPS. As power to start the hybrid mode increases, longer will be periods of driving in all electric mode and batteries will recharge fewer times. Simulated values of total fuel consumption during cycle 401 decreased by increasing the power required to start the hybrid mode and for $P_{startHM}$ = 20 kW is as high as 84.8%. After correction of values obtained by simulations, the differences in total fuel consumption are decreased.

Simulation results of exhaust gas emissions of CPS and SHEPS with SOC=92% and $P_{startHM}$=10 kW during NEDC

Figure 7 shows cumulated CO_2 emissions of CPS and SHEPS during NEDC. In submodel that represents the IC engine, CO_2 emissions are estimated assuming they are proportional to the fuel consumption as mentioned in the following equation:

$$CO_2\ emissions = fuel\ consumption \cdot CO_2\ \ factor \tag{8}$$

where CO_2 factor is the parameter called "fuel to CO_2 conversion factor [g CO_2/g fuel]". The cumulated CO_2 mass is calculated by making the integral of the CO_2 emission. That is why this parameter shows similar curve as total fuel consumption (Figure 3, CPS and SHEPS (92% SOC)). Cumulated CO_2 emissions of SHEPS are reduced by 20.09% compared to CPS.

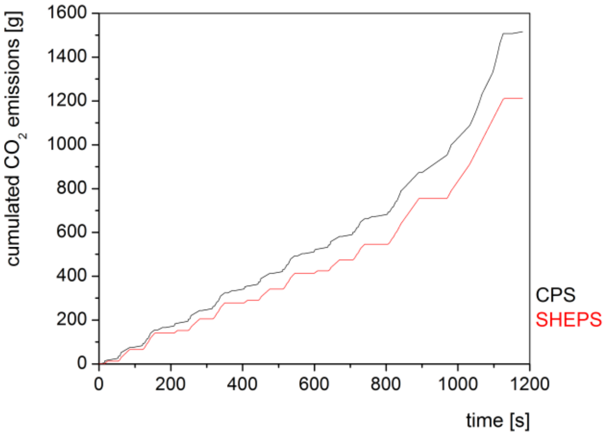

Figure 7 *Cumulated CO_2 emissions of CPS and SHEPS with SOC=92% and $P_{startHM}$=10 kW during NEDC*

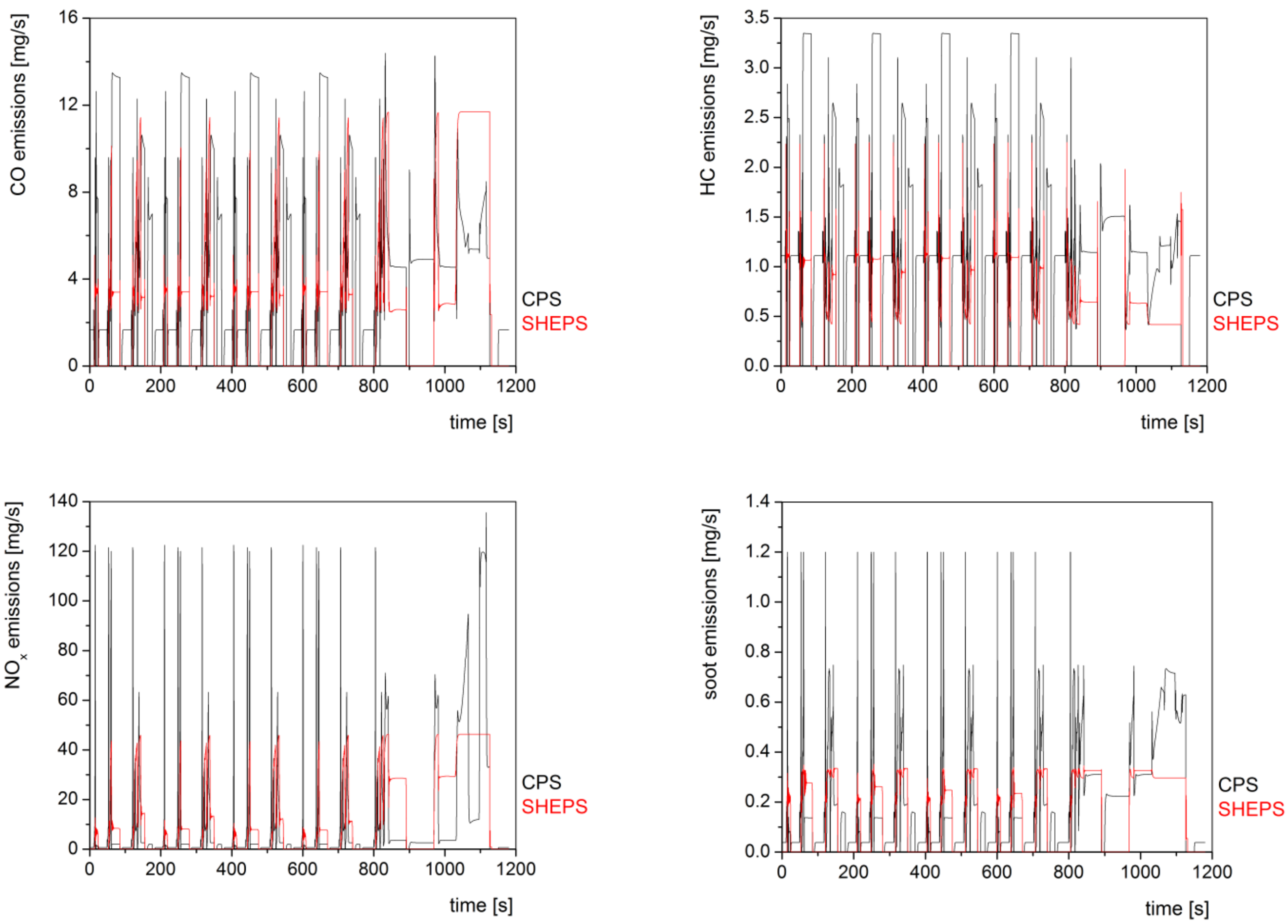

Figure 8 *CO, HC, NO_X and soot emissions of CPS and SHEPS with SOC=92% and $P_{startHM}$=10 kW during NEDC*

Table 8 *Cumulated CO, HC, NO_X and soot emissions of CPS and SHEPS with SOC=92% and $P_{startHM}$=10 kW at the end of NEDC*

	CO [mg]	HC [mg]	NO_x [mg]	soot [mg]
CPS	5145,8	1499,2	11657,7	232,2
SHEPS	3063,1	428,5	13945,6	159,6

CO, HC, NO_X and soot emissions during NEDC are shown in Figure 8. Exhaust emissions of these components depends on the operating conditions of the IC engine in CPS and SHEPS. In some parts of the cycle better performances are shown by CPS and in others by SHEPS. The cumulated emissions of these gases are calculated by making the integral of their emissions. Calculated values of cumulated CO, HC, NO_X and soot emissions at the end of NEDC are shown in Table 8. Cumulated CO, HC and soot emissions are decreased in SHEPS by 40.5% (CO), 71.4% (HC) and 31.3% (soot), while the NOx emission is increased by about 19.6%. This increased NO_X emission is the result of settings of SHEPS. When the IC engine accelerates and reaches the desired operating conditions, it continues to run in this mode until requested power to stop the hybrid mode reaches pre-set value (in this case P_{stopHM}=2 kW). Diesel engines produce high levels of NO_X at high loads, which occur at the end of the NEDC (at approximately 800-1200s).

CONCLUSIONS

Analysis of simulation results shows that the series hybrid electric power train provides a number of advantages over conventional power train in taxi vehicles. The most important feature of the series hybrid power train is that the work of IC engine does not depend on the vehicle load, which always enables it to work approximately at maximum efficiency. By increasing the efficiency of the IC engine, which is possible in the series hybrid power train, its fuel consumption is reduced. Depending on the choice of driving cycle and adjustment of components of hybrid drive total fuel consumption of the series hybrid electric power train systems can be reduced by 20 - 60%. Also, the cumulated exhaust gas emission of internal combustion engine in a SHEPS is lower than the one of CPS. Series hybrid electric power train system have increased NO_X emission during high loads, but these driving conditions are not very frequent during city driving where taxi service vehicle usually operates.

ACKNOWLEDGMENTS

The results presented in this paper have been obtained through the research project TR-35042, which is realized under the financial support by the Serbian Ministry of Education and Science within the National Energy Efficiency Program.

REFERENCES

[1] “BRUSA Elektronik AG”, Web. September 19. 2014. http://www.brusa.eu/index.php?L=1,
[2] Guzzella L., Sciarretta A.: “Vehicle Propulsion Systems, Introduction to Modeling and Optimization”, ISBN 978-3-540-74691-1, 2007, Springer, Berlin, Germany,
[3] Janković D., Todorović J., Ivanović G., Rakićević B.: “Teorija kretanja motornih vozila”, 2001, Faculty of Mechanical Engineering, University of Belgrade, Serbia,
[4] “Metric Mind Corporation”, Web. September 19. 2014. http://www.metricmind.com/,
[5] “Skoda Octavia 1.6 TDI Ambition 2009 – 2010”, Cars-Data, Web. September 19. 2014, http://www.cars-data.com/en/skoda-octavia-1.6-tdi-ambition-specs/45247#sthash.ulsZ4X3A.dpbs,
[6] “Vehicle Coefficient of Drag List”, EcoModder Wiki, Web. September 19. 2014, http://ecomodder.com/wiki/index.php/Vehicle_Coefficient_of_Drag_List.