Electrification Strategy of Hybrid Electric Vehicle as a Solution to Decrease CO_2 Emission in Cities

M. Mourad, K. Mahmoud

Abstract—Recently hybrid vehicles have become a major concern as one alternative vehicles. This type of hybrid vehicle contributes greatly to reducing pollution. Therefore, this work studies the influence of electrification phase of hybrid electric vehicle on emission of vehicle at different road conditions. To accomplish this investigation, a simulation model was used to evaluate the external characteristics of the hybrid electric vehicle according to variant conditions of road resistances. Therefore, this paper reports a methodology to decrease the vehicle emission especially greenhouse gas emission inside cities. The results show the effect of electrification on vehicle performance characteristics. The results show that CO_2 emission of vehicle decreases up to 50.6% according to an urban driving cycle due to applying the electrification strategy for hybrid electric vehicle.

Keywords—Electrification strategy, hybrid electric vehicle, CO_2 emission.

NOMENCLATURE

A	Cross sectional area of vehicle, m^2
C_D	Drag coefficient of vehicle, -
dv/dt	Vehicle acceleration, m/s^2
F_{acc}	Acceleration resistance, N
F_D	Drag aerodynamic, N
F_g	Gradient resistance, N
F_R	Rolling resistance, N
f_r.	Rolling resistance coefficient
g	Gravity acceleration, m/s^2
HEV	Hybrid Electric Vehicle
P	Vehicle power, kW
SOC	State of charge
V	Vehicle speed, m/s
ρ	Air density, kg/m^3
φ	Road inclination, deg.
δ_{rot}	Coefficient of rotating mass, -
sfc	Specific fuel consumption, g/kWh

I. INTRODUCTION

THE large growing of use of fossil fuel in automobiles worldwide can be considered as the main source of the increase of warning up of the surrounding environment due to exhaust emissions of vehicles. The problem of global warming enforced the academic researchers to find unconventional solutions for the fossil energy of vehicles. From the point of view of long term energy security, it is necessary to develop new alternative vehicles and fuels with properties comparable to petrol based fuels [1].

When emission regulations tightened in the last quarter of the 20th century and engineers made breakthroughs in hybrid and electric vehicle technology, automotive researchers began to look more seriously into vehicles with alternative energy sources. In this recent time, the technology of manufacturing electric batteries used in electric vehicles and HEV is still suffering from problems. The development of the battery industry is increasing day by day, but not at the same rate as the internal combustion engines. So researchers are interested in hybrid vehicles to take advantages of both sources of energy (electrical source and conventional source). [2]. Recently, hybrid vehicles have become very important in all their configurations, such as vehicles hybridized with fuel cells, hybridized by compressed natural gas or hybridized by conventional diesel engine. HEV are usually defined as the type of vehicles that operate with power sources (conventional engine and electric batteries) to provide partial or total tractive effort on the wheels of the vehicle. [3]. In a series HEV, only the electric motor drives the wheels and the internal combustion engine is used to give the electrical energy into electric batteries via electric generator. In this case of a parallel type of HEV, the IC engine and electric motor are coupled to the driving wheels and can both drive the vehicle [4].

Hybrid electric drive applications have been tested using gasoline fuel, compressed natural gas (CNG) and biodiesel fuels. It only makes sense that a HEV manufacturer would choose to utilize an engine technology. Several automobile factories have developed the production of HEVs, well beyond the experimental stage [5]. This type of vehicle is characterized by a significant improvement in the economics of fuel and thus less emission of pollutants compared to vehicles powered by gasoline or diesel engine. HEV contribute significantly to reducing pollution and preserving the environment. At the last decades interest in this type of alternative vehicles has increased, such as HEVs, plug-in hybrids, full electric vehicles, and fuel cell vehicles. Therefore, hybrid technology can be considered a stepping stone for increasing the fleets of HEV that contribute significantly to reducing pollution from vehicles, especially CO_2 emission worldwide. [6].

This work aims to decrease the CO_2 emission of HEV inside cities. The paper illustrates the effect of different conditions of road resistances on the emission of vehicle generally. The investigation clears that the emission of CO_2 from the vehicle is at the maximum point during the acceleration phase, where the vehicle consumes a large amount of fuel. Therefore, this

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work reports one method to decrease the emission of vehicle especially CO_2 emission in the city by the electrification strategy of HEV. The results of this paper show the effect of electrification on vehicle emission. The value of CO_2 emission decreases up to 50.6% during urban driving cycle due to the use of electrification strategy for HEV.

II. CONFIGURATION OF HEV

A HEV is configured with two power paths, so that either the internal combustion engine or the electric drive system - or both - can be used to produce the required power to move the vehicle wheels. In one approach, the electric energy of traction batteries can be used for short trips or inside the cities. For highway travel, the internal combustion engine would provide the power to the vehicle, with the electric motor assisting during gradient roads, acceleration phase, and other periods of high power required. This type of HEV gives a chance to reduce the size and weight of the combustion engine, which reduces the vehicle's overall weight. Low vehicle weight means low rolling resistance and thus fuel consumption will be decreased, which clearly contributes to decrease CO_2 emissions [7].

Series configuration of hybrid system is shown in Fig. 1. The schematic diagram illustrates the distribution of all components of series HEV. A series hybrid vehicle is driven with only an electric motor. It can run as an electric vehicle while the batteries energy supply is satisfactory. The engine of hybrid vehicle operates as a generator when the battery energy or SOC is less than 0.5. The mechanical connection between the internal combustion engine and the driving wheels play a significant role to recharge the traction batteries. Series-hybrids have also been referred to electric vehicle with longer range [8]. The traction batteries of a series configuration HEV are usually charged by IC engine but technically a series-hybrid allows for a battery to only act as an accumulator, and for the electric motor's energy to be delivered constantly by the conventional engine [9].

Fig. 2 illustrates a schematic diagram of the configuration of parallel hybrid system. It consists of both an electric motor and a fuel converter that can simultaneously or individually drive the vehicle. The electric motor is operated with the electric energy from traction batteries. The combustion engine in HEV is very important. The batteries are charged through the electric generator operated by the vehicle engine which operates the vehicle if SOC batteries are low. When the SOC of the battery reaches a specified lower limit, the fuel converter operates to recharge the traction batteries of HEV. Series hybrid vehicles operate conveniently within the city where traditional vehicle are less efficient. The vehicle delivers the electric power into the motor with the battery pack only, saving the engine for the difficult operating conditions. It can be said that this type of hybrid vehicle does not need an engine with a large power or size where the required power is limited; batteries pack of series-HEV is usually more powerful than the other parallel-HEV in order to provide the remaining power needs.
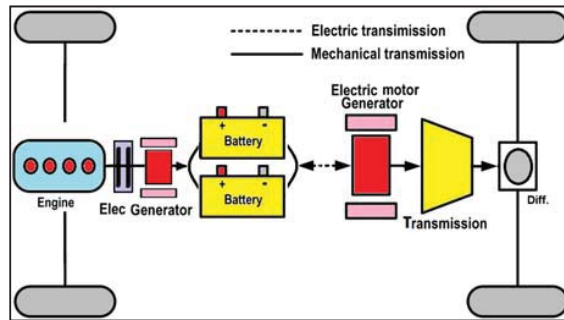

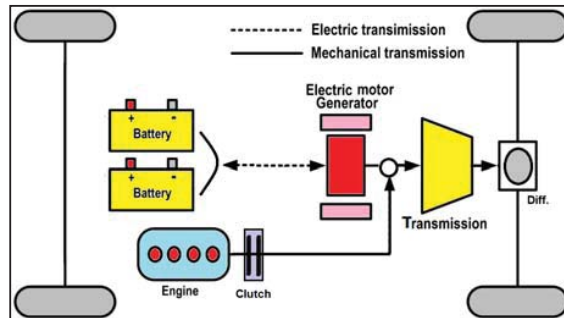Fig. 1 Schematic diagram of series HEV configuration

Fig. 2 Schematic diagram of parallel HEV configuration

III. THEORETICAL STUDY

The simulation program of vehicle will be described in the following part; this simulation model is utilized in order to evaluate the performance of the vehicle. The simulation program used different parameters of vehicle such as: Total weight of vehicle, road resistances, and types of gear ratio, velocity of the vehicle with the time and fuel consumption. The external performance of vehicle and vehicle's emissions has been studied by computer simulation program [10]. The factors that are used in modeling computer are illustrated in Fig. 3.

The simulation of hybrid vehicle was done on the road by *Advisor* software. This HEV program can also calculate performance characteristics for different types of vehicles. It is designed by MATLAB/Simulink, where the program user can change all vehicle technical specifications and the different operating conditions as well as standard driving cycle. This program can determine the fuel consumption of the vehicle and the tractive effort on the driving wheels and pollutants emission resulting from the vehicle according to the driving cycle. It has been used by all of the world's major automobiles manufactures [11].

To implement the vehicle simulation code, all specifications data of the vehicle must be entered into the mathematical model such as specific fuel consumption, engine torque according to engine speed. All technical specification data of vehicle such as projected area of vehicle and aerodynamic drag coefficient, total mass of vehicle, rolling resistance coefficient, tire radius and vehicle dimensions and weight of various components should be supplied to the simulation code. The technical specifications of vehicle are shown in Table I.

TABLE I
SPECIFICATION DATA OF VEHICLE

Description	Data
Maximum vehicle weight	1070 kg
Engine power	41 kW
Batteries power	25 kW
Height of gravity centre	0.50 m
Cross-section area,	1.37 m²
Drag coefficient	0.26
Rolling coefficient	0.018
wheel diameter	0.28 m
Wheel base	1.6 m
Type of Fuel	Gasoline

Vehicle Characteristics:
GVW of vehicle, Aerodynamic drag coefficient
Coefficient of rolling resistance
Tyre radius
Transmission efficiency
Projected area of vehicle

Traction batteries Characteristics:
Maximum capacity
Stat of charge
Efficiency of batteries
Maximum output power

Elec. motor Characteristics:
Torque and power of electric motor
Angular speed
Electrical efficiency

Transmission Characteristics:
Mechanical efficiency, losses, Gear ratios, final ratio

HEV performance:
Vehicle power, torque at driving wheels, fuel consumption of vehicle

Fig. 3 Flow chart of HEV simulation model

Inside the cities, the vehicle can operate with two sources of power (engine and batteries), because the required power to overcome the vehicle resistances is increased; both internal combustion engine and electric batteries supply their powers to the planetary gearbox to the driving wheels. The engine should be controlled to operate in its optimal region for efficiency and emission reasons. The batteries supply the extra power to satisfy the traction power demand [12]. This operation mode can be expressed as $P_{total} = P_{engine} + P_{batteries}$

For the duration of the traction, batteries become the main source of power into driving wheels, only the batteries supply its power to complete the power required. If the engine only gives the traction power; in this operation mode, only the engine gives its power to equal the required power to overcome the resistances of road. The traction batteries are charged from the engine/generator: When the energy in the traction batteries decrease to a minimum line of SOC, the batteries must be charged. This can be done by regenerative braking from the

road or by the generator via engine. Usually, the engine charging is needed, since regenerative braking charging is not sufficient for all different operating conditions. In this case, the engine power is divided into two ways; the first way is used to propel the vehicle and the other way to charge the traction batteries with the necessary electrical energy until the SOC rise to satisfied level [13].

Regenerative braking phase: When the vehicle is experiencing a braking, the traction motor can be used as a generator, converting part of the kinetic energy (inertia of vehicle) of the vehicle into electric power via electric generator to the traction batteries.

The relationship equations, which are used to determine the power ratings of these components, are described as [14]:

$$F_{acc} = m_{veh} . dv/dt . \delta_{rot}$$

where m_{veh} is mass of vehicle with all its components dv/dt is the change of vehicle speed at certain time δ_{rot} is the change of rotating masses.

$$F_{air} = 0.5. \rho_{air}. A. C_D .v^2$$

ρ_{air} is the air density A is the trailer projected area C_D is the coefficient of air resistance "drag coefficient" V is the vehicle speed on road.

$$F_{roll} = m_{veh} . g . f_{roll}$$

F_{Roll} is the rolling resistance at wheel of vehicle. The following equation represents the total power of the traction.

$$F_{total} = m_{veh} . dv/dt . \delta_{rot} + 0.5. \rho_{air}. A. C_D .v^2 + m_{veh} . g . f_{roll}$$

Energy is the power produced by the vehicle multiplied by the consumed time of trip. If the traveled distance by vehicle is relatively long, the impact of acceleration resistance can be neglected. The acceleration resistance in this case is small if compared to air resistance or rolling resistance. At constant speed and on level road, the power output from the power source can be calculated as:

$$P_{ave} = F_{total} * v = [m_{veh} . dv/dt . \delta_{rot} + 0.5. \rho_{air}. A. C_D .v^2 + m_{veh} . g . f_{roll}] * v$$

SOC and charging characteristics are the most important factors affecting the state and performance of traction batteries of HEV. These SOC parameters as well as the input/output power are calculated by a mathematical model that takes into account the internal resistance of the batteries. The internal resistance of the batteries is determined during experiments on SOC on the batteries. SOC of a battery is the ratio of the present charge of a battery to the maximum charge that can be possibly stored in the battery [14]. The energy capacity of the battery E_c can be determined as:

$$E_c = \Delta E_{max} / (SOC)_{max} - (SOC)_{min}$$

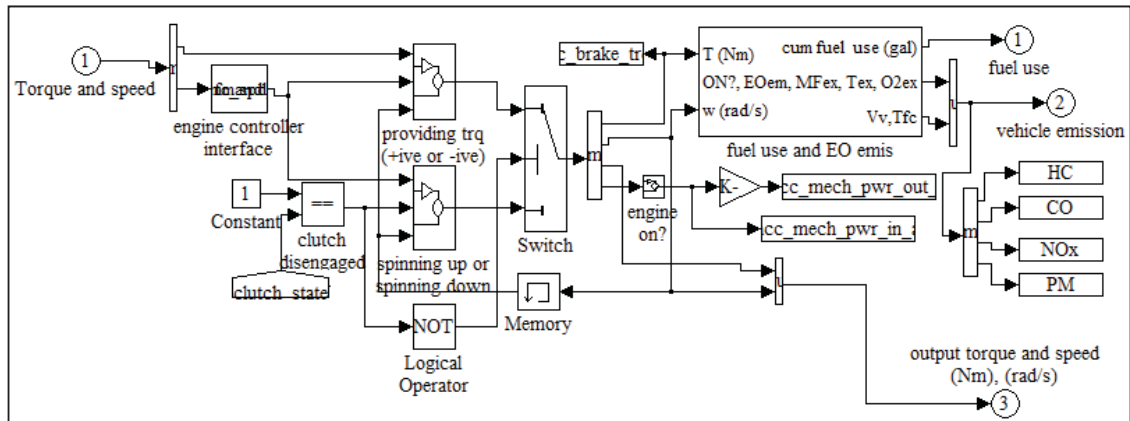The simulation block diagram of series HEV is as shown in Fig. 4.

Fig. 4 Simulink block diagram of series HEV

IV. RESULTS AND DISCUSSION

Fig. 5 shows the emission of vehicles with an internal combustion engine, where the CO_2 emission level is below or close to the value of 95 g/km at the range of economic vehicle speed. At the high vehicle speed, the CO_2 emissions increase considerably. Another interesting observation is that for very low average speeds, such as in urban environments with intensive traffic in the cities and crowded roads, the CO_2 emissions have a tendency to increase dramatically by a factor of different vehicle technologies. The two parallel lines illustrate the region of low speed of vehicle inter the city, it can be observed that the value of CO_2 increase in-between the two vertical outline to reach up to 300 g/km [15].
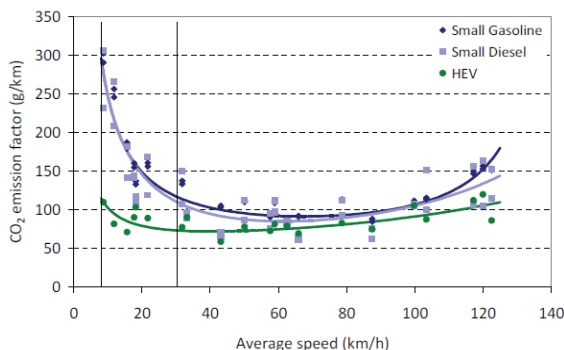
Fig. 5 CO_2 emission results of the various technologies as function of average speed

Fig. 6 is a torque and speed map of engine efficiency for the conventional engine of hybrid vehicle. This fuel consumption map of engine shows that these engine characteristics are similar across many internal combustion engines. The engine is least specific fuel consumption (sfc) at low torques, and gets somewhat less "sfc" with higher speeds. Highest engine specific fuel consumption comes at reasonably low speeds and higher torques, around the center of the 262 g/kWh zone shown in light pink.

Carbon dioxide emission of engine is illustrated in Fig. 7. It can be observed that the values of CO_2 range from high concentration at low engine torque along the engine speed. The lowest values of CO_2 at the lighter region of diagram; it reaches to 795 g/kWh.
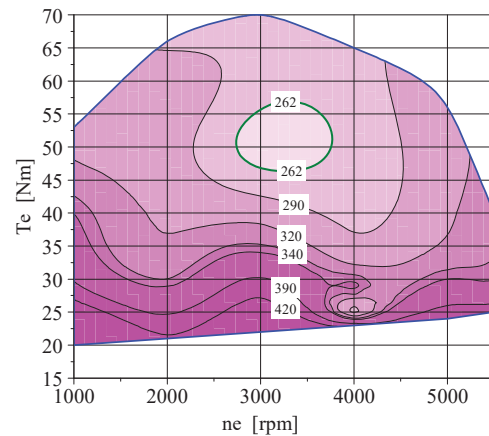

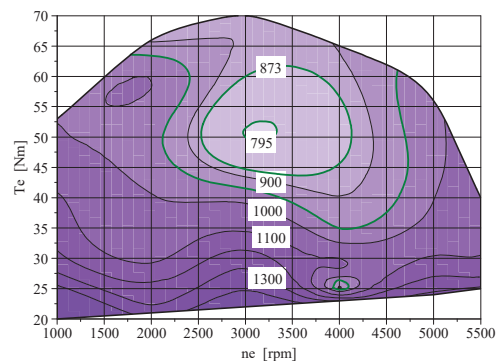Fig. 6 Fuel consumption engine map

Fig. 7 Carbon dioxide emission map of engine

Fig. 8 shows the urban driving cycle. It is therefore a fixed schedule of vehicle operation which allows an emission test to be conducted under real conditions. Driving cycle is usually defined in terms of vehicle speed against the consumed time [16]. The simulation program negotiates the driving cycle as an

input for the calculation of simulation to determine the operating points of vehicle. The maximum vehicle speed is 70.49 km/h, the maximum acceleration is 1.16 m/s^2, the total distance of this driving cycle is 10.81 km. This driving cycle characterizes with repeatability of acceleration phase.
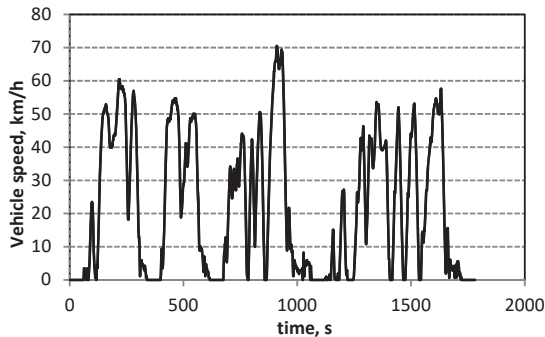

Fig. 8 Urban driving cycle vehicle speed against time

HEV has a different behavior whenever the decelerating conditions are applied. Road torque can be converted by electric generators into useful electric energy which charges the traction batteries, within SOC limits and power limitations on the drive motor. This can decrease vehicle fuel consumption because this regenerated energy can be utilized later for vehicle traction, or to operate vehicle auxiliaries system [17]. Stopping the flow of gasoline fuel into the combustion chamber during braking phase can also improve fuel economy, but drivability and emissions are concerns. Fig. 9 shows that the value of SOC of series HEV (with electrification strategy) decreases to reach the value of 0.45. The conventional engine supplies the electric generator the energy to recharge the batteries.
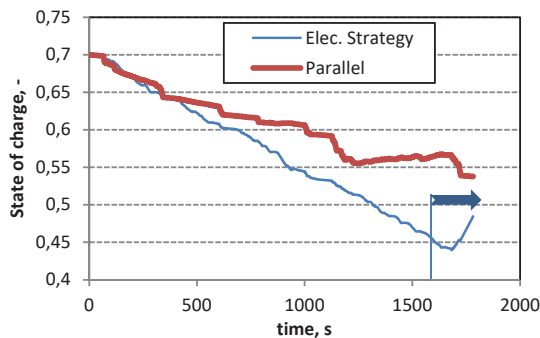

Fig. 9 SOC of electric batteries for series and parallel HEV

The function of an energy batteries system on a HEV is to provide a technique to regular the loads applied on the engine. In the case of vehicle resistances are high, such as for a fast acceleration, the traction batteries can deliver electric power to the electric motors; this reduces the load affected engine by providing more torque from the traction batteries in extreme conditions. At low vehicle loads such as constant vehicle speed, the engine can use the electric motor as a generator and charge the traction batteries [17].
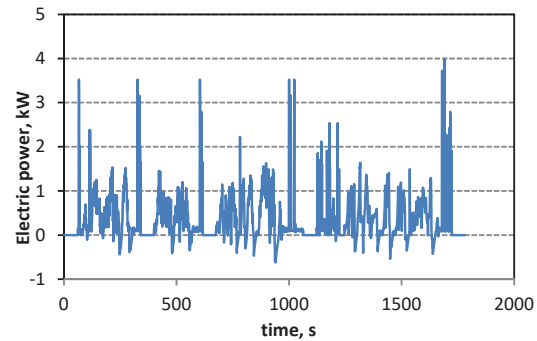

Fig. 10 Electric power of motor during driving cycle for series configuration

Fig. 10 shows the electric power of motor during driving cycle for series configuration. The energy batteries system of series HEV provides the electric power to overcome the vehicle loads inter cities. When the vehicle resistances are high, such as for a quick acceleration, the battery can provide power to the electric motors until SOC reaches to the allowable minimum level. The values of electric power can reach to 4 kW.

Fig. 10 illustrates the wheel torque along the driving cycle time. The value of wheel torque increases with the increase of vehicle resistances such as acceleration resistance.
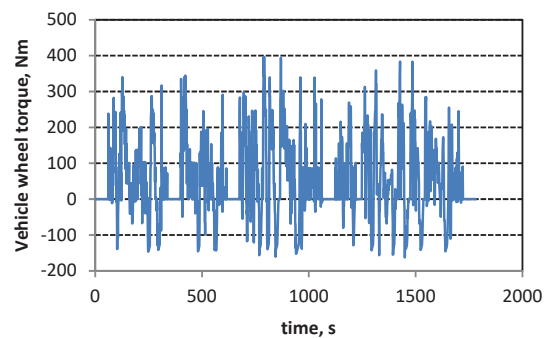

Fig. 11 Vehicle wheel torque during driving cycle for series configuration

Figs. 12-14 show the vehicle emission such as HC, CO and NOx that emits from the conventional engine of HEV during the urban driving cycle. The different emission pollutants of IC engine of parallel HEV outlet from the tailpipe in g/s. It can be observed that the values of pollutant are high at the beginning of driving cycle where the engine is relatively cold.

When the value of the vehicle resistances increases, the IC engine is given a high power to overcome these resistances. The simulation program determines the appropriate torque and speed to face the road resistances on the specific fuel consumption map as well as the pollutant emission map. Therefore, the value of fuel consumption and emission of pollutants can be determined at all operating points during the driving cycle. Due to high loads and road resistances there is a significant increase in nitrogen oxides emissions during the peak points of loads [16].
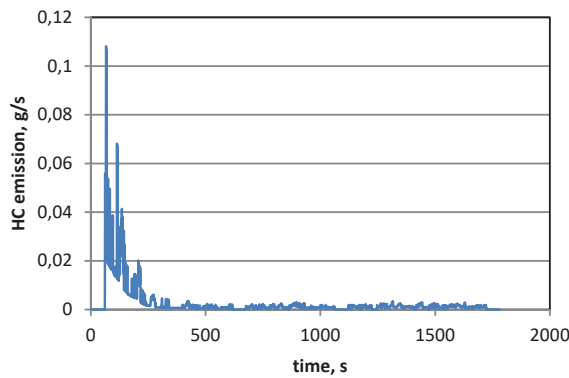
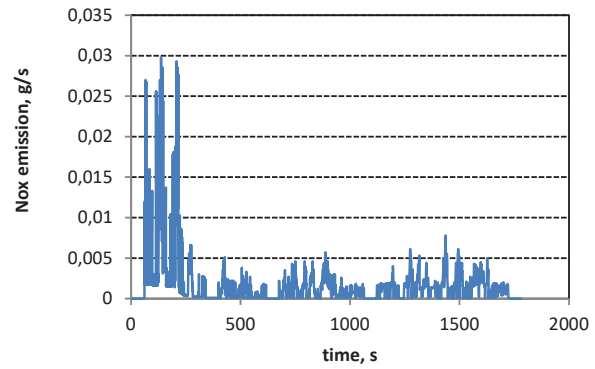Fig. 12 HC emission of HEV during urban driving cycle

Fig. 14 NOx emission of HEV during urban driving cycle

Fig. 15 explains a comparison between series HEV vehicle with electrification strategy and parallel HEV during the urban driving cycle. The fuel consumption in l/100 km improves mainly during driving cycle for series electric hybrid vehicle. The difference between two cases of HEV for variant emission pollutants is less in case of electrification strategy [18].
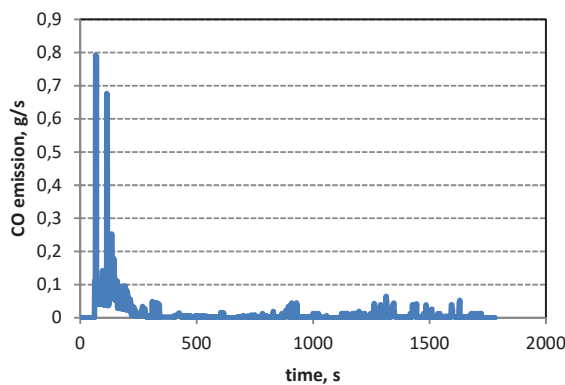

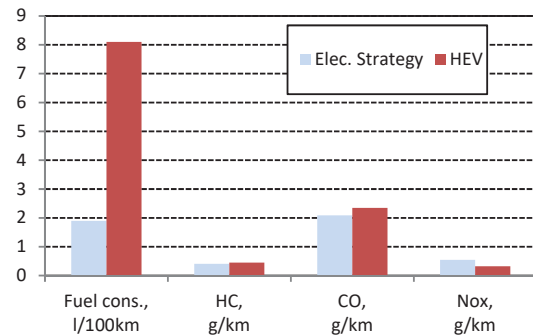Fig. 15 Comparison of two types of HEV during urban driving cycle

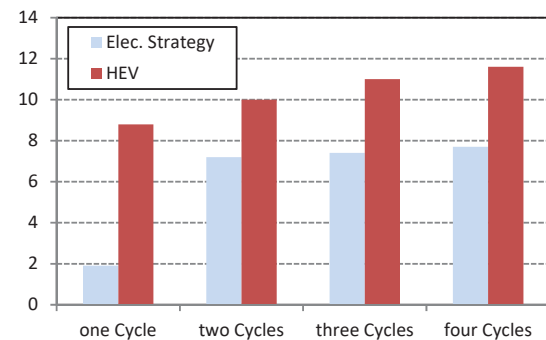Fig. 13 CO emission of HEV during urban driving cycle

Fig. 16 shows the comparison of CO_2 emission of series HEV and parallel HEV. The simulation test was carried out during one urban cycle and another time when the urban cycle was repeated for two, three and four times [19]. The results illustrate that the decrease between two types of HEV reaches to more than 50% for series HEV with electrification strategy.

Fig. 16 CO_2 emission in g/km of vehicle of two types of HEV

V. SUMMARY AND CONCLUSIONS

HEVs are particularly effective for urban driving cycle, significantly lowering CO_2 emissions in series HEV with electrification strategy.

Electrification strategy is considered the best solution to decrease the greenhouse gas CO_2. There is linear dependence between the emission of CO_2 and fuel consumption of HEV. The electrification strategies have a noticeable impact on the CO_2 emission intensity from HEV. Average fuel consumption and CO_2 emission of automobiles using electrification strategy is lower than parallel HEV by 50.6%.

REFERENCES

[1] International Energy Agency. CO_2 Emissions from Fuel Combustion, 2011; IEA Publications: Paris, France, 2011.
[2] NREL Vehicle Drive Cycle Tool, User Guide. Copyright © 2009 Alliance for Sustainable Energy, LLC. All Rights Reserved.
[3] Eckerle, W., et al. "Effects of Methyl Ester Biodiesel Blends on NOx Emissions." SAE Publication 2008-01-0078. SAE International Journal of Fuels and Lubricants.
[4] AEA (2009). Assessment of options for the legislation of CO_2 emissions from light commercial vehicles. Final report to European Commission. Framework contract No. NV/C.5/FRA/2006/0071.
[5] Ott, T.; Zurbriggen, F.; Onder, C.; Guzzella, L. Cycle-averaged efficiency of hybrid electric vehicles. Inst. Mechan. Eng. Part D J. Automob. Eng. 2012, 227, 78–86.
[6] T. Ott , C. Onder and L. Guzzella "Hybrid-Electric Vehicle with Natural

Gas-Diesel Engine" Energies 2013, 6, 3571-3592; doi:10.3390/en6073571

[7] L. Göransson, S. Karlsson, F. Johnsson" Plug-in hybrid electric vehicles as a mean to reduce CO_2 emissions from electricity production" EVS24 Stavanger, Norway, May 13-16, 2009

[8] X. Zhang , J. Xie, R. Rao and Y. Liang "Policy Incentives for the Adoption of Electric Vehicles across Countries" Sustainability 2014, 6, 8056-8078; doi:10.3390/su6118056

[9] Gass, V.; Schmidt, J.; Schmid, E. Analysis of alternative policy instruments to promote electricvehicles in Austria. Renew. Energy 2014, 61, 96–101.

[10] D. Ryan " Performance and energy efficiency testing of a lightweight FCEV Hybrid Vehicle" European Electric Vehicle Congress Brussels, Belgium, 3– 5 December 2014

[11] EPA 'Greenhouse Gas Emissions from the U.S. Transportation Sector, 1990-2003' March 2009.

[12] M. Mourad 'Improving the performance of a hybrid electric vehicle by utilization regenerative braking energy of vehicle' International Journal of Energy And Environment, Vol. 2, Issue 1, pp.161-170, 2011

[13] K. B. Wipke, M. R. Cuddy, and S. D. Burch, "ADVISOR 2.1: A User-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach," NREL/JA-540-26839, September 1999

[14] M. Mourad, F. Mohamed, K. Mahmoud and A. Nouh, Influence of Biodiesel Fuel on Performance Characteristics of Hybrid Electric Vehicle According to Urban Driving Cycle. The International Renewable Energy Congress IREC, Tunisia. March 25-27, 2014.

[15] C. Carvalho, W. Lamas, The use of hybrid vehicles as a proposal for reducing CO_2 emissions and its contribution to reducing greenhouse gas emissions. Engenharia Térmica (Thermal Engineering), Vol. 8, No 01, p. 07-11, June, 2009.

[16] J. K. AHN et al "analysis of a regenerative braking system for hybrid electric vehicles using an electro-mechanical brake" International Journal of Automotive Technology, Vol. 10, No. 2, pp. 229−234 (2009)

[17] S. Boyd "Hybrid Electric Vehicle Control Strategy Based on Power Loss Calculations" M. Sc. Mechanical Engineering, Blacksburg, Virginia, August 2006.

[18] G. Mellios "Projection of CO_2 emissions from road transport " Report No.: 10.RE.0034.V4Thessaloniki February 2011

[19] M. Mourad " A proposed fuel cell vehicle for reducing CO_2 emissions and its contribution to reducing greenhouse gas emissions" International Journal of Engineering & Technology, 3 (2) (2014) 252-261