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Improving the performance of a hybrid electric vehicle by utilization regenerative braking energy of vehicle

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Abstract
Environmentally friendly vehicles with range and performance capabilities surpassing those of conventional ones require a careful balance among competing goals for fuel efficiency, performance and emissions. It can be recuperated the energy of deceleration case of the vehicle to reuse it to recharge the storage energy of hybrid electric vehicle and increase the state of charge of batteries under the new conditions of vehicle operating in braking phase. Hybrid electric vehicle has energy storage which allows decreasing required peak value of power from prime mover, which is the internal combustion engine. The paper investigates the relationships between the driving cycle phases and the recuperation energy to the batteries system of hybrid electric vehicle. This work describes also a methodology for integrating this type of hybrid electric vehicle in a simulation program. A design optimization framework is then used to find the best position that we can utilize the recuperation energy to recharge the storage batteries of hybrid electric vehicle.

Keywords: Hybrid electric vehicle, Regenerative braking energy, Driving cycle.

1. Introduction
Automotive engine emissions are recognized as a major source of concentrated pollution, particularly in urban areas. Although the internal combustion engine remains the dominant prime mover for technological and cost reasons, Furthermore the growing dependence on fossil oil, along with a heightened concern over the environmental impact of personal transportation, has led worldwide the country's governments to investigate and sponsor research into alternative vehicle to save the consumed energy. One of these future technologies is the hybrid electric vehicle (HEV), typically featuring both an internal combustion engine and an electric motor, with the goal of producing lower emissions while obtaining superior fuel economy. Figure 1 below lists the typical components found in an HEV [1].
Hybrid electric vehicles combine the benefits of several propulsion subsystems in an attempt to produce a more efficient vehicle. A common approach to hybrid vehicle design takes a conventional vehicle drivetrain and combines it with subsystems commonly found in an electric vehicle. In this type of vehicle, a gasoline engine might be augmented by an electric motor. In a hybrid that uses a fuel cell, a different approach must be taken to harness the electrochemical energy of hydrogen.
A hybrid electric vehicle (HEV) is a vehicle that has at least two sources of propulsion or energy conversion, one of them being electric [2]. The most popular designs have an electric motor, energy storage and/or peaking device, and a power controller in combination with one or more of the following power units: diesel engine, spark-ignition engine, sterling engine or fuel cell. Once the components have

been chosen, they can be arranged according to several configurations. These arrangements are classified as being either series or parallel, as shown in Figure 1 for engine-based hybrids. A parallel HEV allows the engine and the motor to drive the wheels simultaneously or independently. In the latter configuration, the engine can also recharge the batteries depending on the control strategy implemented [3]. The design process requires a system engineering approach, where the design of each component must be evaluated through the component's contribution to the overall system performance. The design process typically starts with evaluation of trade-offs associated with component sizes for a targeted fuel economy and performance. Successful optimization depends on the quality and flexibility of the system simulation, as well as on an effective optimization algorithm.

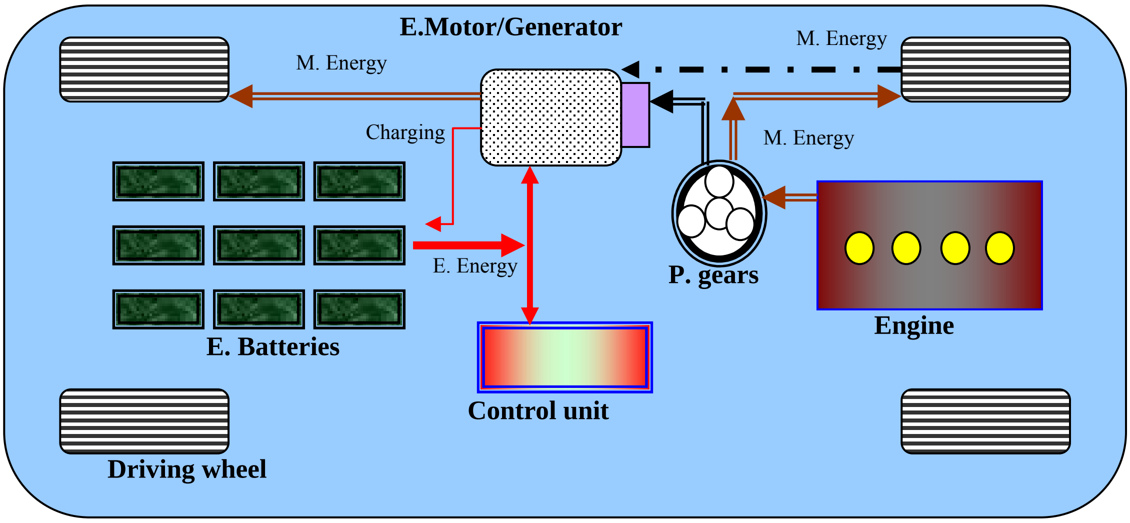

Figure 1. Main mechanical and electric components of hybrid electric vehicle

The main advantages of this drive train are [4]:

- traction torque provided directly by the ICE and by the electrical drive at the same time, like in parallel powertrains;
- a slight increase of system's weight due to the presence of a planetary gear train;
- the vehicle can operate with electrical traction.

Design optimization studies found in the open literature focus mostly on conventional powertrains. Work on hybrid powertrains has been directed mainly to parametric studies to assess component sizes and energy management strategies using a variety of models and simulations. Moore (1996) uses a set of five linked spreadsheets to size powertrain components based on continuous and peak demand for power and torque. He concludes that component sizes are mostly determined by starting and cruising gradeability, acceleration, and regenerative braking requirements. Cumulative energy throughputs over torque and speed plots are suggested to match an electric motor to a given combination of vehicle characteristics and driving cycle. It was employed a direct search technique to obtain a minimum energy path through the driving cycle. The control variables are the torque split (between IC engine and electric motor) and gear ratio. This process leads to the definition of an energy management control algorithm. Parametric studies are then conducted to optimize component size and further improve vehicle performance.

In this work we present a methodology for hybrid electric vehicle design that can be used to study and optimize a variety of vehicle and powertrain configurations. Since practical experience with such configurations is limited and hardware prototypes are expensive, the methodology uses mathematical models and simulations to represent components and subsystems considered in the preliminary design stage. Optimization algorithms are used to drive design iterations in search of the best possible design according to specified design criteria and constraints [5]. The vehicle simulation program *advisor* [6], developed at the national renewable energy laboratory, was selected as the hybrid-electric system simulation model. *Advisor* allows easy reconfiguration of the vehicle and integration of new component modules.

The braking performance of a vehicle is undoubtedly one of the important factors to affect vehicle safety. A successfully designed braking system for a vehicle must always meet two distinct demands. Firstly, in emergency braking, it must bring the vehicle to rest in the shortest possible distance. Secondly, it must maintain control over the vehicle's direction. The former requires that the braking system be able to supply sufficient braking torque on all the wheels. The latter requires braking force to be distributed on all the wheels equally.
This research will be gone to utilize the dissipation energy during braking phase along the driving cycle. It could use it as feedback energy to the storage system of batteries and the deceleration of the vehicle on the road at different operating conditions of vehicle.

2. Configuration description of HEV

In addition to design studies of overall hybrid powertrain systems that tend to use relatively simple models for vehicle components, we have looked into the integration of system simulations with high-fidelity subsystem and component models, such as models of engines, transmissions, and batteries. Inclusion of detailed component models extends the set of design variables to subsystems and components. Higher fidelity can be so introduced and decisions can be made at an increased level of detail. Also, a component may be studied in great detail while tracking the impact of local design decisions on the overall system which is included in the study with much less detail.
A parallel HEV is configured with two power paths, so that either the heat engine or the electric propulsion system - or both - can be used to produce the motive power to turn the wheels. In one approach, the electric-only mode can be used for short trips. For longer trips, the engine would provide primary power to the vehicle, with the electric motor assisting during hill climbs, fast acceleration, and other periods of high power demand. In such a vehicle, the engine can be downsized in relation to a similar-sized conventional vehicle, reducing weight and providing greater relative fuel economy [7].
Figure 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 receiving power from an onboard battery pack. This is essentially the configuration used in a battery-driven electric vehicle. The hybrid addition is in the form of a fuel converter, which is usually a small internal combustion engine whose main function is to extend vehicle range. When the state of charge of the battery reaches a specified lower limit, the fuel converter engages to recharge the batteries.

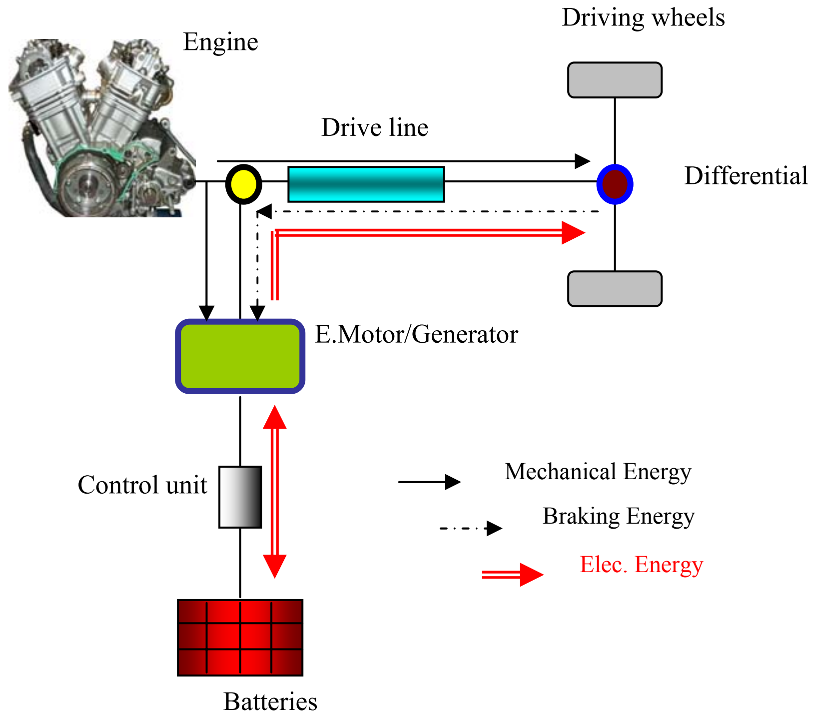

Figure 2. Schematic diagram of HEV configuration

However, the development of these vehicles within the next ten years will require accurate, flexible simulation tools. Such a simulation program is necessary in order to quickly narrow the technology focus of the PNGV to those HEV configurations and components which are best suited for these goals [8]. Therefore, the simulation must be flexible enough to encompass the wide variety of components which could possibly be utilized. Finally, it must be able to assist vehicle designers in making specific decisions in building and testing prototype automobiles.
Parallel HEVs are configured such that both the electric motor and the ICE are mechanically coupled to the drive wheels of the vehicle as shown in Figure 2. This design offers the advantage of drive system redundancy. If either of the drive systems should fail, the other system would still be available to move the vehicle for service. A parallel hybrid usually provides better highway fuel economy, due to its efficient engine loading at steady highway speeds, and less mass than its series counterpart. It also provides the ability to withstand long uphill grades. The design often allows for a pure electric vehicle, or zero emissions vehicle (ZEV), mode. However, the parallel design does not allow for full vehicle power when operating in ZEV mode [9]. The mechanical coupling of the motor, engine, and wheels can also be complex, often requiring a multi-speed transmission. The direct mechanical connection between the engine and the wheels also makes engine tuning more difficult, since the engine must operate over a range of speeds and loads.

3. Energy storage system

Batteries are used for storage of electrical energy in hybrid electric vehicles. Batteries store and deliver electrical energy chemically by initiating and reversing chemical reactions respectively. One energy storage system (ESS) option is the conventional lead-acid battery. Lead-acid technology is mature and economical. In addition to the lead-acid battery, there are newer options such as nickel metal hydride (Ni-MH) and lithium-ion (Li-ion) batteries [10]. The ESS is normally comprised of a bank of batteries in series. Of all the sub-systems constituting a hybrid electric vehicle, the energy storage system is probably the most difficult to understand and model. Although a battery is a simple electrical energy storage device that delivers and accepts energy, the highly nonlinear nature of its electrochemical processes makes it difficult to model.

4. Modeling principle of HEV

Inter the city can be operated the hybrid Traction, when great power is required; 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 [11]. This operation mode can be expressed as $P_{total} = P_{engine}+P_{batteries}$
When the traction power consumed from the electric batteries only, in this operation mode, only the batteries supplies its power to fulfill the power required. The last phase of operation of HEV, if the engine only gives the traction power; in this operation mode, only the engine supplies its power to meet 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 state of charge (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 state of charge rise to satisfied level.
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 mass into electric energy and could be used it as a charging power to electric traction batteries.
The relationship equations, which are used to determine the power ratings of these components, are described as the following

$$F_{acc}=m_{veh}.dv/dt.\delta_{rot} \tag{1}$$

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.

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

where 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

$$F_{roll}=m_{veh}.g.f_{roll} \quad (3)$$

where F_{roll} is the rolling resistance at wheel of vehicle

The power rating of the traction motor can be represented as

$$F_{total}=m_{veh}.dv/dt.\delta_{rot}+0.5.\rho_{air}.A.C_D.v^2+m_{veh}.g.f_{roll} \quad (4)$$

Energy is power integrated over time. If the total distance traveled is long enough, the initial acceleration and final deceleration have negligible effect on the total energy calculation. Also, since this is a steady state analysis the aerodynamic drag is constant. Noting that *V = dv/dt*, At constant speed and on level road, the power output from the power source can be calculated as:

$$P_{average}=(1/t)\ \int_0^t (\ dv/dt\ .\ \delta_{rot} + 0.5.\ \rho_{air}.\ A.\ C_D\ .v^2 + m_{veh}\ .\ g\ .\ f_{roll})\ v\ dt \quad (5)$$

State of charge (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. The energy capacity of the battery Ec can be determined as follows:

$$E_c=\Delta E_{max}/(SOC)_{max}-(SOC)_{min} \quad (6)$$

5. Scope on simulation program

The tool used for this part of the study is the modular software-package *advisor*, which is well tested and offers a range of simple, parameterized 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. Each *advisor* module can be changed or written anew to accommodate particular segments of importance for a given vehicle [12].

Simulation program is designed by MATLAB/SIMULINK-based, feed-backward simulation of hybrid electric power trains. *Advisor* allows quick analysis of the performance, emissions, and fuel economy of conventional, electric, and hybrid vehicles. The component models in *advisor* are empirical, relying on input/output relations measured in the laboratory, and quasi-static, using data collected in steady state tests and correcting them for transient effects such as the rotational inertia of drivetrain components.

Hybrid power trains are complex electromechanical systems that can be configured in a variety of ways. To examine design scenarios prior to building physical prototypes requires a sophisticated simulation and computing environment. Such a design environment should allow for easy integration of engineering models and simulations, along with the capabilities to perform visualization and optimization studies. In our efforts to build a design environment for hybrid electric vehicles, we have developed two practical approaches for analysis and design tool integration: the first one uses distributed object technology whereas the second is based on the commercial MATLAB-SIMULINK computing environment.

The Technical specification and data of hybrid electric vehicle which used in simulation program was illustrated in Table1.

6. Evaluation of results

Vehicle testing was performed at an emissions test facility equipped with roller dynamometers capable of performing a range of tests including the city driving cycle in Germany (Figures 3 and 4).

A significant amount from the total energy of the vehicle is consumed in braking phase on roads. When the vehicle is driving with a stop-and-go pattern in cities streets, a significant amount of energy is consumed by frequent braking, which results driven wheels, energies consumed by road resistances such as rolling resistance and aerodynamic speed, average speed, total traction energy on driven wheels, and total energies consumed by drags and braking during the traveling distance of the passenger car. The

braking energy in city urban field may reach up to more than 20% of the total traction energy. In large cities, such as Stuttgart or Nuremberg in Germany, it may reach up to 50% [13]. It is concluded that effective regenerative can significantly improve the fuel economy of HEV.
Figures 5, 6 and 7 indicate that a mild hybrid electric drive train with a small motor cannot significantly improve engine operating efficiency because most of the time, the engine still operates in a low load region. However, because of the elimination of engine idling and an inefficient torque converter, and the utilization of regenerative braking, the fuel economy in urban driving is significantly improved.
The engine in a parallel hybrid drive is used to supply the steady-state power to the driving wheels and also in order to prevent the traction batteries from being discharged completely or reaching the SOC of batteries to the level under 0.5. We can observe in the Figure 7 that SOC of batteries raise when the vehicle decelerates at the braking phase and the generator will feed the batteries with the charging current.
Figure 8 shows a comparison between the consumed energy by traction batteries and IC engine. The consumed energy from the batteries is 0.05 kWh and energy from engine is 0.17 kWh.
HEV emissions are dramatically lower than those of ICE vehicles for all pollutants which emitted from the vehicle. It can be observed in Figure 9 that the different values of exhaust emission element CO, HC and NO_x are poor. The emission levels are reduced by half, due to small engine sizes, and peak efficiency usage.
During the city driving cycle the combustion process is lean-burn driving, NO_x is directly absorbed; it is later reduced to harmless nitrogen in stoichiometric driving conditions.
Figure 10 shows the specific fuel consumption of IC engine and motor efficiency map and operating points of HEV during the driving cycle. They indicate that the electric motor operates as a generator more than a traction motor, to support the electric load of auxiliaries and maintain the battery SOC balance.
The electric motor is used during city driving and slow traffic. The IC Engine is used some time to recharge the batteries during the actual running. Regenerative braking is possible, to recover valuable energy.

Table 1. Technical specification of hybrid electric vehicle

parameter	**Data**	**Parameter**	**Data**
Wheel base, m	2.6	Max. power, kW @ rpm	41 @ 5700
Height of gravity centre, m	0.5	Max. torque, Nm @ rpm	81 @ 3500
Rolling radius of tyre, m	0.282	Engine displacement, l	1.0
The first gear ratio	3.46	Idle engine speed, rpm	750 ± 50
The second gear ratio	1.1	Fuel type	Gasoline, 92
The third gear ratio	1.34	Firing order	1-3-4-2
The fourth gear ratio	0.86	Ignition system	electronic
The fifth gear ratio	0.71	Traction batteries eff., %	90
Final drive ratio	3.88	Electrical motor, AC, kW	75 Induction motor
Cross-section area, m^2	2.0	Max. current of batteries, A	25
Drag coefficient	0.30	Curb weight, kg	1220
Maximum vehicle weight, kg	1400	Pay load, kg	180

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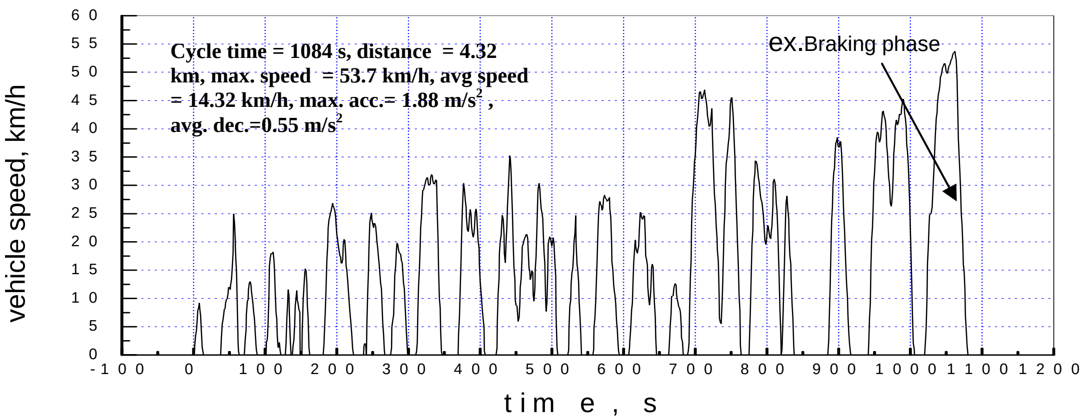

Figure 3. Vehicle speed against time of city cycle

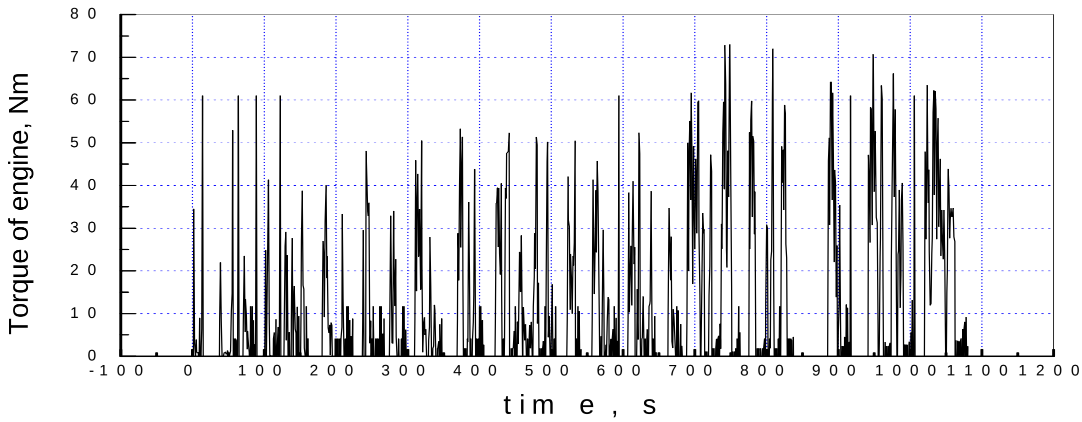

Figure 4. Torque of IC engine during the city driving cycle

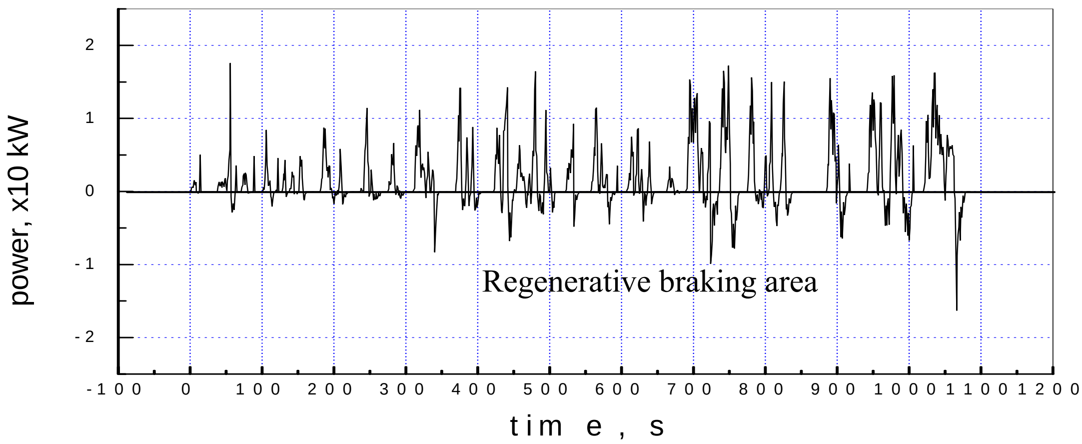

Figure 5. Power of electric controller during the city driving cycle

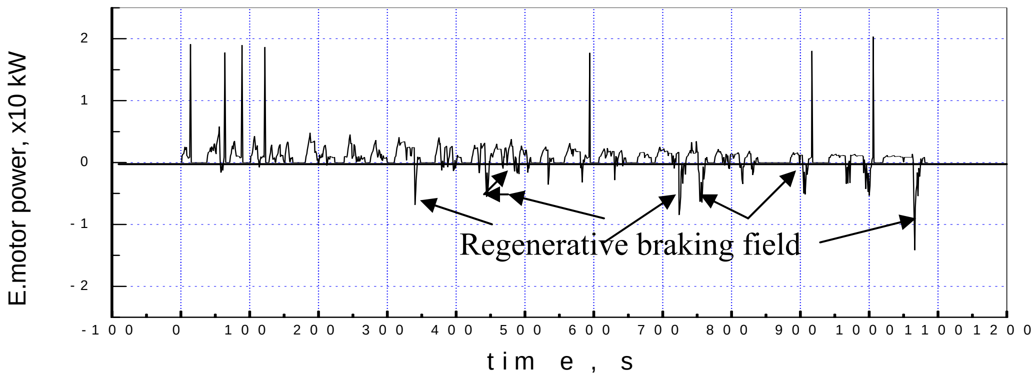

Figure 6. Power of electric motor during the city driving cycle

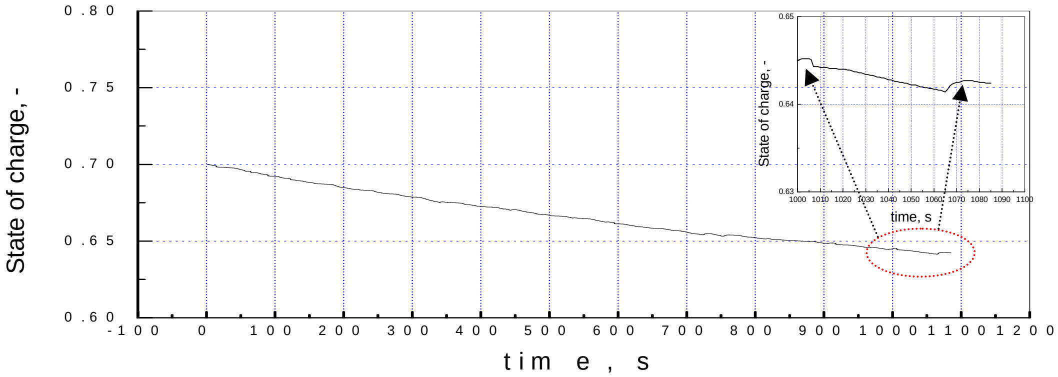

Figure 7. State of charge of traction batteries

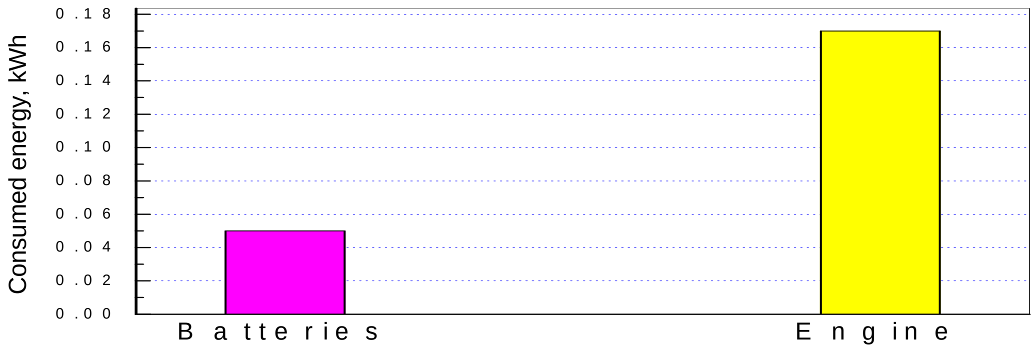

Figure 8. Consumed energy of the traction batteries and the IC engine

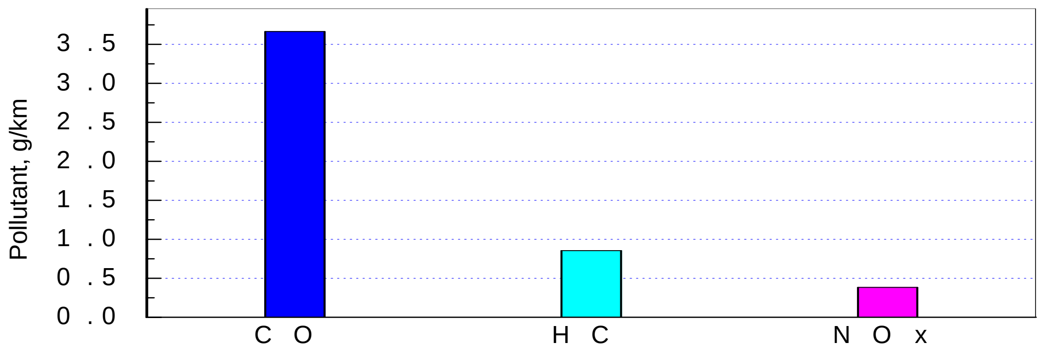

Figure 9. Exhaust emission of HEV during the driving cycle

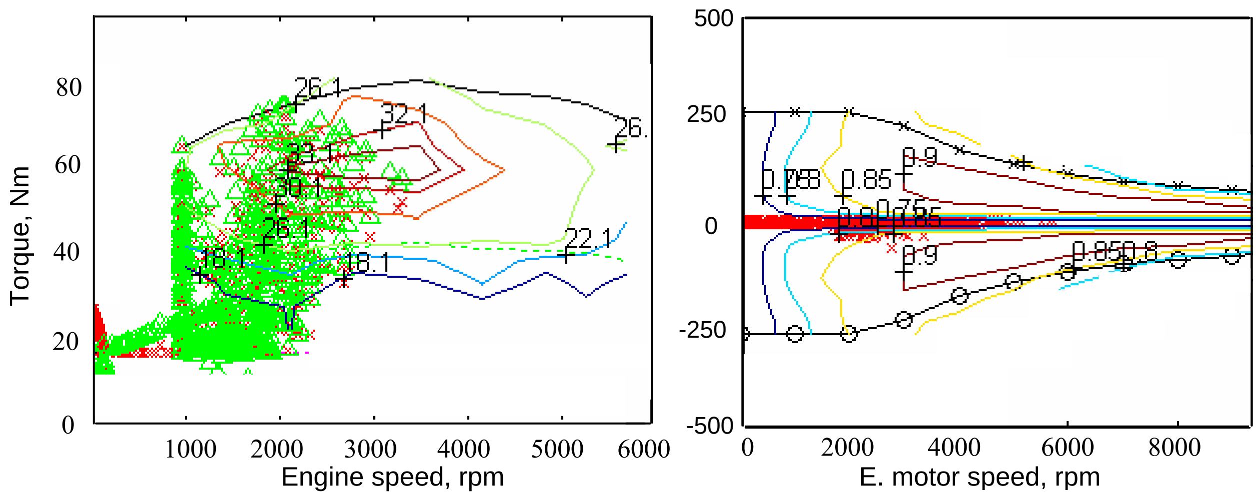

Figure 10. Operating points of hybrid electric vehicle on Engine and Electric motor map

7. Conclusion

The aim of the work is to demonstrate the effectiveness of a parallel Hybrid Electric Vehicle in city road conditions, by displaying different fields of regenerative braking energy during the driving cycle. The IC Engine is used to recharge the batteries during the actual running. Regenerative braking is possible, to recover valuable energy. Furthermore it could be decreased the fuel consumption of vehicle, reducing pollution of air.

It uses both an Internal Combustion Engine and an Electric motor to propel the vehicle in a synergetic effect.

Regenerative braking capability, which helps minimize the energy lost when driving. The braking energy in city urban field may reach up to more than 20% of the total traction energy. In large cities, such as Stuttgart or Nuremberg in Germany, it may reach up to 50%. It is concluded that effective regenerative can significantly improve the batteries energy economy of HEV.

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