Comparative Study of Petrol- and Diesel Hybrid Topologies vs Directly Diesel Driven Vehicle

Karin Jonasson, PhD Student
Department of Industrial Electrical Engineering and Automation
University of Lund, Box 118, S-221 00 LUND, Sweden
Phone: +46 46 222 74 99, Fax +46 46 14 21 14

Mats Alaküla[1], Professor
Rolf Egnell[2], Assistant Professor
[1] Department of Industrial Electrical Engineering and Automation
University of Lund, Box 118, S-221 00 LUND, Sweden
Phone: +46 46 222 92 84, Fax +46 46 14 21 14
[2] Department of Heat and Power Engineering, Division of Combustion Engines
University of Lund, Box 118, S-221 00 LUND, Sweden
Phone: +46 46 222 45 64 Fax +46 46 222 47 17

Abstract

The over all aim with this survey has been to realize a comparative study of a limited number of hybrid topologies, to a pure diesel driven vehicle, all given as similar performance requirements as possible. For this purpose a gasoline and a diesel engine, with a higher maximum efficiency than a gasoline engine, have been added into comparable simulation models of different hybrid topologies.

As reference vehicle for the simulations the Toyota Prius (generation I) is chosen. It is a power split hybrid electric vehicle run by a gasoline internal combustion engine and it is available on the market today. A simulation model, which is equal to the Toyota Prius, has therefore been developed.

The comparison in this paper contains three further vehicle simulation models of which the first is a parallel hybrid electric vehicle with a gasoline engine and the second is a parallel hybrid electric vehicle but with a diesel engine. Finally, the same model is used for a comparison with a directly diesel driven vehicle.

The simulation models have thereafter been tested a city cycle (ECE 15) and a highway cycle (US06).

Keywords: HEV (hybrid electric vehicle), Hybrid Strategy, Simulation, ICE (internal combustion engine), Diesel Hybrid

Introduction

The increasing difficulties with air pollution, their influences on the green house effect and the limitations of the oil resources in the world contributes to the needs of an alternative to the conventional fossil fuel driven vehicle. The shortcomings of the batteries make the pure electric vehicle yet not ready to conquer the market of conventional vehicles. There is simply not enough energy supply for longer trips. The HEV (Hybrid Electric Vehicles), however, combines the extended range of a conventional vehicle with the environmental benefits of an electrical vehicle due to its possibilities to adjust its working point of the engine, i.e. its torque and speed combination. The control law of the HEV forces the vehicle traction system to choose an operation point that yields the highest efficiency possible and/or the lowest emissions. The result is a vehicle with improved fuel economy and lowered, but not zero, emissions.

The numbers of HEVs available on the market are constantly increasing. The used engineering practice, topologies and control strategies represents a great variety of solutions. The varying range of applications of HEVs also results in a broad diversity of target vehicles, for example city vehicles, grand tourismos, light maintenance vehicles and SUVs.

The over all aim with this survey has been to realize a comparative study of a limited number of hybrid topologies to a pure diesel driven vehicle, which all are given as similar performance requirements as possible. As an additional comparable vehicle a directly driven diesel vehicle has been modelled too, given the same conditions as the other models as far as possible. As reference vehicle for the simulations the Toyota Prius (generation I) has been chosen. It is a power split hybrid electric vehicle run by a gasoline internal combustion engine (ICE) and it is available on the market today.

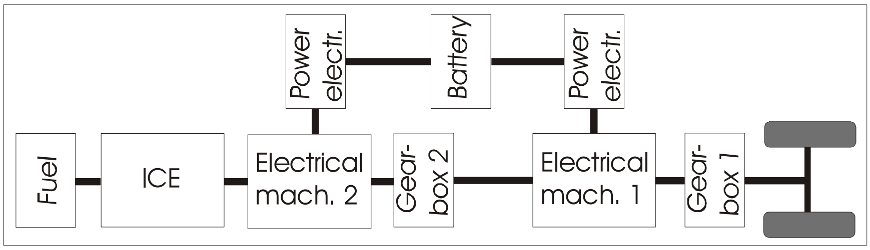
A simulation model, which is equal to the Toyota Prius, has therefore been developed. The comparison in this paper contains three further vehicle simulation models of which the first is a parallel hybrid electric vehicle with a gasoline engine and the second is a parallel hybrid electric vehicle but with a diesel engine. Finally, the same model is used for a comparison with a directly diesel driven vehicle.

Topologies

The tractive system of a hybrid electric vehicle contains a combustion engine (or muscle power, e.g. Twike [1]) and at least one electric motor as well as transmission. The numbers of combinations of the included components are many and this comparison contains four different simulation models, but only three topologies.

The parallel topology, as well as the series topology, constitutes the two primary hybrid topologies. The series hybrid topology involves many energy conversions, thus less suitable except in city traffic [2]. The series hybrid topology is therefore not the target for this survey.

The other primary topology, the parallel hybrid electric topology, is however a part of this survey. It has been simulated with both a gasoline as well as a diesel engine. The parallel hybrid is a combination of drive systems and the engine is mechanically connected to the wheels via a gearbox (see Figure 1).



Figur 1. Parallel hybrid topology. The figure shows the topology with an optional electrical machine.

The working point of the engine can be chosen freely with the help of electrical machines. The rate of hybridisation can be varied from purely engine driven to purely electric vehicle and any combinations thereof.

The power split hybrid electric vehicle is a blurred combination of a series and a parallel hybrid electric vehicle. It can also be mentioned as a complex, combined or a dual hybrid vehicle [3]. The two electric machines and the ICE are connected via a planetary gear, which is equipped with three output shafts. See Figure 2.

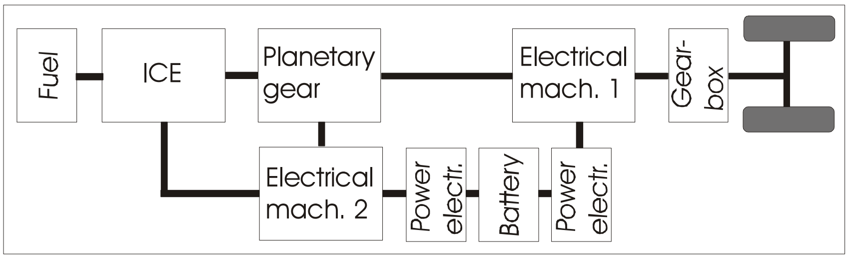


Figure 2. Power split hybrid topology.

Diesel engine

Efficiency is a definition of the relation of the capability to transform input to output, such as fuel to kinetic energy. The theoretical maximum efficiency of a spark ignition engine (Otto) is around 33%, while the corresponding value for the diesel engine is 45%. This makes the diesel engine to the most efficient power plant among all known types of internal combustion engines [4]. The high efficiency of the diesel engine is due to the higher compression ratio.

With a good choice of control algorithm in the HEV, the engine is possible to run near its maximum efficiency value and the batteries will then be used for power adjustments. The engine efficiency at optimum choice of requested traction power as a function of requested torque is shown in Figure 3 for a gasoline and diesel engine respectively.

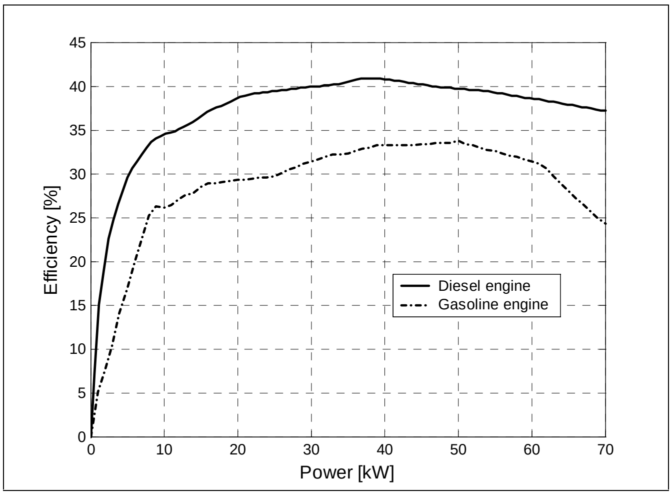


Figure 3. The maximum efficiency for a gasoline and a diesel engine respectively.

Diesel vs gasoline engine

The overall purpose with the two engines is the same, i.e. by combustion of fuel achieve kinetic energy. Nevertheless there are small differences between the two types of engines. To start with the diesel fuel has a higher energy density than gasoline and the combustion itself differs between the two engines.

The gasoline engine generally uses either carburetion, for mixing air and fuel, or port fuel injection. In both cases the fuel will be supplied before entering the cylinder. The intake of a gasoline engine is therefore a mixture of gas and air, which is then being compressed and ignited by a spark. The diesel engine on its part has an intake of only air, which is compressed. The fuel is then injected direct into the cylinder, into the compressed air. The fuel will then spontaneously ignite by the heat developed while compressing the air.

There are also differences of the compression ratio. The gasoline compresses at a ratio between 8:1 to 12:1 and the diesel, on its hand compress at a ratio of 14:1 to 25:1 [5]. Hence follows the higher efficiency for the diesel engine.

Emissions

The above all, not negligible, draw back with especially the diesel engine is the NO_X emission and particulates. The emissions and particulates are depending on the chosen control strategy and are hereby possible to affect to some extent. There is however some environmental benefits of diesels, such as low greenhouse gas emissions.

Formation of NO_X is strongly depending on the temperature in the combustion chamber. By diluting the reaction mixture the temperature can be reduced and the forming of NO_X will decrease. This is done with an inert gas and since engine exhaust essentially is inert, it is being used for this purpose. Some of the heat in the chamber will then be used to heat the inert gas, and the result is a lowered maximum temperature in the combustion chamber. This procedure is called Exhaust Gas Recirculation (EGR) and circulates exhaust gas back to the air intake manifold. This is being done with a small loss of power. Figure 4 below shows a) NO_X formation, b) EGR injection and c) NO_X formation when taking EGR into consideration.

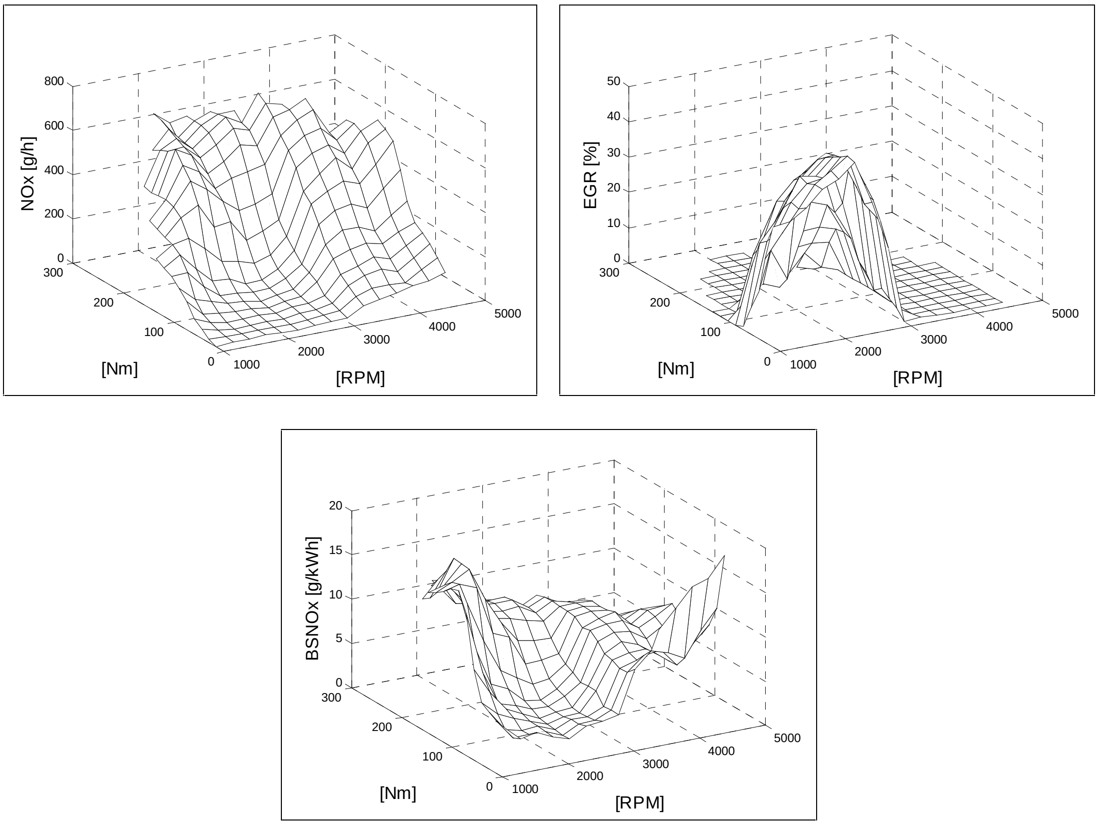


Figure 4: The graphs shows static data for a passenger car diesel, linearly interpolated. a) NOx flow (g/h) vs. engine speed and torque. b) EGR vs. engine speed and torque. c) Specific NOx emissions (g/kWh) vs engine speed and torque.

EGR has a reducing effect on NO_X. EGR is applied in the diesel engine used in these calculations, however as the load points in a hybrid application differs from the load points in a conventional passenger car, the full benefit of EGR is not reached in this application.

There are also alternative solutions available for reducing the NO_X emissions, for example Selective Catalytic Reduction (SCR). A reducing nitrogen compound, such as urea or ammonium, is injected to the exhaust gas. This is done in proportion of present NO_X [6]. Research has also been done of injecting diesel into the exhaust gases and using a catalyst, which results in decreased NO_X, but also increased fuel consumption [7].

Simulation model

The comparison presented in this paper is based on simulation models made in Matlab/Simulink environment and fed with input parameters via Matlab. The models can be diversified from a private car to a heavy vehicle, be given different size of battery, motor, generator, ICE and charging strategies etc. Even the driver’s behaviour is possible to adjust. Since the result is strongly depending on the chosen driving cycle, the simulated HEVs is tested in different driving cycles. The simulation models include both recorded driving cycles and artificial driving cycles from Europe, USA and Japan. In Figure 5 is the topmost level of the diesel electric hybrid shown. The power split hybrid simulation model differs slightly from Figure 5 due to it is equipped with a planetary gear.

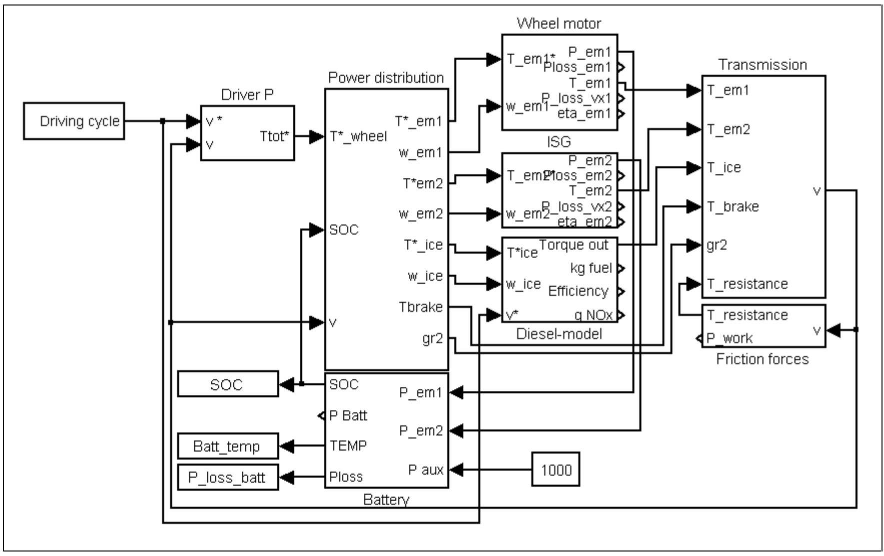


Figure 5: The top level of the HEV simulation model with a diesel engine.

The engine input data are measured values from a SAAB naturally aspirated gasoline engine and a state of the art turbo diesel from another manufacturer.

Case study

In this study there is not only an interest in comparing the different topologies. The simulations provide also an opportunity for stressing a selected number of parameters.

The simulations made will compare the vehicle under different conditions, i.e. driving cycles. The interest will be pointed at the fuel consumptions and the emissions, though the emission input data are not quit comparable due to their design for an other application then the used on, as mentioned above.

The simulated vehicles are given the same total power as the reference vehicle has, as far as possible. This means that the pure diesel driven vehicle is equipped with an engine of 86 kW and the parallel hybrids, both the gasoline and diesel ones, are equipped as the reference vehicle.

Last, but certainly not least, the importance of regenerative feedback will be investigated in this survey. The diesel parallel electric vehicle model will be simulated both with and without regenerative feedback.

Reference vehicle

In this comparison a vehicle is chosen which is as alike the Toyota Prius (generation I) as possible. It is an ordinary family car and is available in the European market. Due to it is equipped with a planetary gear there are two electric machines. Table 1 shows the most important data of the Prius [8]:

Table 1: Data for Toyota Prius, used as input in the simulation models.

Property	**Value**
Vehicle mass (total) [kg]	1645
Front area [m^2]	2.52
Max power EM1 [kW]	33
Max torque EM1 [Nm]	304
Max speed EM1 [rad/s]	585
Max power EM2 [kW]	33
Max torque EM2 [Nm]	68
Max speed EM2 [rad/s]	471
Max power ICE [kW]	53
Max torque ICE [Nm]	140
Gear ratio ring wheel/wheel axis	3.5
Battery type	NiMH
Maximum charge [kWh]	1.7

Driving cycles

The simulations made have been carried out with the US06 and the ECE 15 cycles [9]. US06 describes a demanding highway driving including aggressive accelerations and high speed driving. The cycle is 12.8 km long and has a mean speed of 77.8 km/h, maximum speed of 130 km/h and a maximum acceleration of 3.24 m/s^2 (See Figure 6).

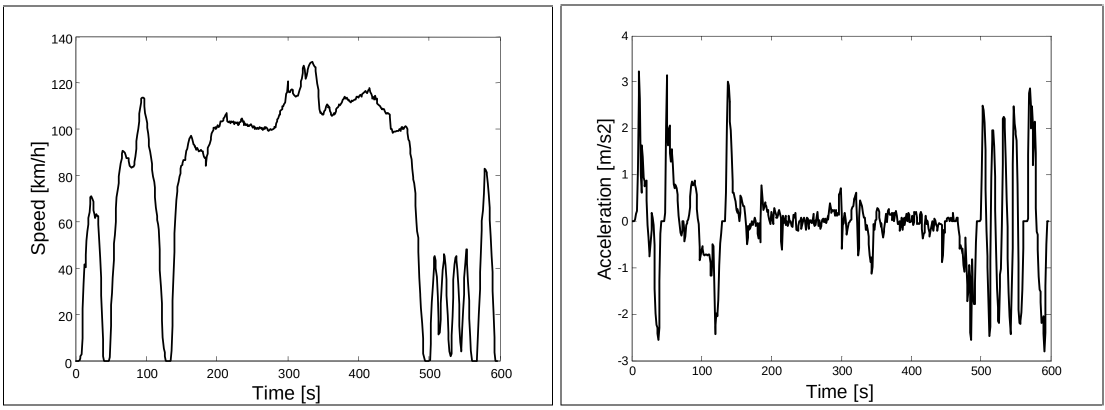


Figure 6: Drive cycle US06, velocity and acceleration.

The US06 Supplemental Federal Test Procedure (SFTP) is developed to address the shortcomings with the FTP-75 test cycle in the representation of aggressive, high speed and/or high acceleration driving behavior, rapid speed fluctuations and driving behavior following start up. The reason to include the US06 cycle in the survey is that its demanding accelerations expose the transient behavior in fuel consumption and emission.

The ECE cycle is an urban driving cycle, also known as UDC. It was devised to represent city driving conditions. It is characterized by low vehicle speed, low engine load, and low exhaust gas temperature. The ECE 15 drive cycle is not as demanding as the US06 cycle. Car manufacturers that aim to measure fuel consumption use the ECE 15 cycle. The cycle is theoretical and includes relatively low accelerations. For light duty vehicle the speed limit is 90 km/h. The cycle is 10.8

km long and its average speed is 31.7 km/h. The accelerations are considerably lower than the US06 with 1.04 m/s^2 (see Figure 7).

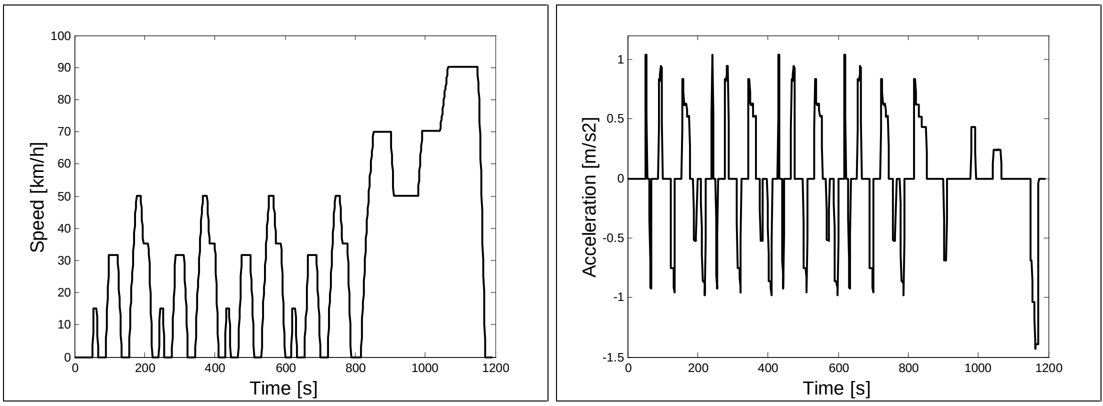


Figure 7: Drive cycle ECE 15, velocity and acceleration.

There is a possible variation of the cycle. For heavy-duty vehicles the top speed is limited to 70 km/h. This affects also cycle distance and average speed.

Results and conclusions

The four different vehicle models have been run through the two driving cycles. Some of the results are shown in Figure 8 and 9, corresponding to the city cycle (ECE 15) and the highway cycle (US06). The ICE-efficiency, the system efficiency, the fuel consumption and the NO_X emissions are indicated in the diagrams. Note that the average ICE-efficiency of the pure diesel is close to the corresponding gasoline hybrids, but that the diesel hybrid is significantly more efficient in the city cycle. Note also that the advantage of hybridisation of the diesel motor is lost when running the highway cycle.

The higher NO_X emissions of the diesel hybrid is due to the use of a diesel motor that is optimised for low emissions when run in a conventional vehicle, not as a hybrid. If it had been optimised for a hybrid vehicle application, the NO_X emissions would have been considerably lower.

From the examples simulated, it is evident that a diesel hybrid probably is the best hybrid drive train possible with conventional technology at the moment. The performance in the city cycle could have been even better if the diesel engine was reduced in size, but then the vehicle would not have been able to cope with highway traffic.

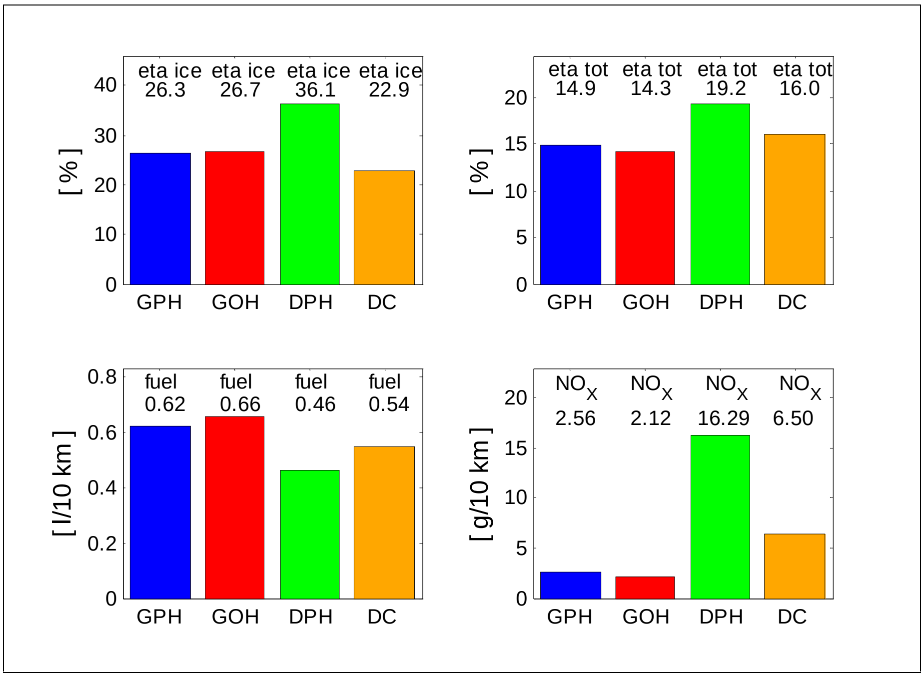


Figure 8: Results from the ECE 15 driving cycle. The figure shows the efficiency for the ICE and the total efficiency (the two uppermost plots), the fuel consumption and the NO_X production (the two plots at the very bottom) respectively. GPH = gasoline parallel hybrid electric vehicle, GOH = gasoline power split hybrid electric vehicle (i.e. Toyota Prius), DPH = diesel parallel hybrid electric vehicle and DC = conventional diesel vehicle.

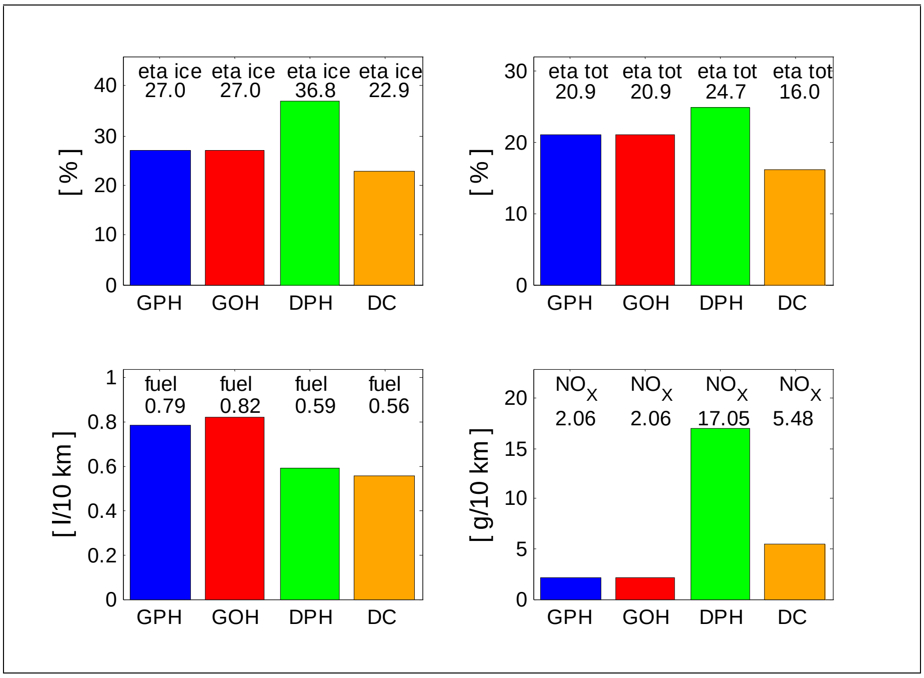


Figure 9: Results from the US06 driving cycle. The figure shows the efficiency for the ICE and the total efficiency (the two uppermost plots), the fuel consumption and the NO_X production (the two plots at the very bottom) respectively. GPH = gasoline parallel hybrid electric vehicle, GOH = gasoline power split hybrid electric vehicle (i.e. Toyota Prius), DPH = diesel parallel hybrid electric vehicle and DC = conventional diesel vehicle.

It should be noted that the engine in the pure diesel driven vehicle (DC above) is larger (86 kW) than the engine in the diesel hybrid (DPH, that is 33 kW). The smaller engine in the hybrid must use the electric machine to manage to deliver the requested torque. This procedure causes losses and results in higher fuel consumption for the diesel hybrid than the conventional diesel vehicle in the demanding US06 cycle.

The hybrid topology includes energy storage possibility, i.e. battery, and it facilitates regenerative feedback of power when braking. To investigate the impact of the regenerative feedback the parallel diesel hybrid simulation model has been simulated with and without regenerative braking. The model has been simulated in both the city cycle (ECE 15) and the highway cycle (US06). The results are shown in figure 10.

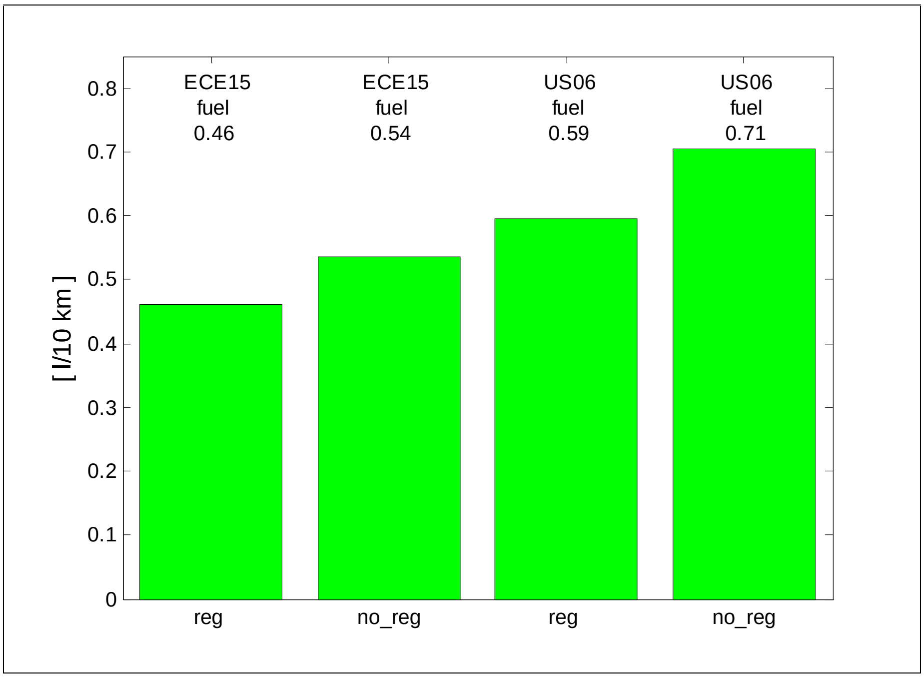


Figure 10: Fuel consumption when simulating the parallel diesel hybrid simulation model in ECE 15 and US06 driving cycle. The figure shows the fuel consumption when regenerative power is used (reg) and when it is not used (no_reg). Without the regeneration of power the fuel consumption is increased with approximately 20%.

When regeneration of braking power was excluded in the simulation model the fuel consumptions increased with approximately 20% for both cycles. For the city cycle the hybrid receives consumptions equal to the conventional diesel vehicle. In the highway cycle the diesel engine in the hybrid does not fulfil to deliver the peak power demand. The electric machine is therefore used to deliver some of the demanded traction power and this causes losses. When, on top of this, the regenerative feedback is excluded, the conventional diesel vehicle turns to be an even better solution in a demanding cycle.

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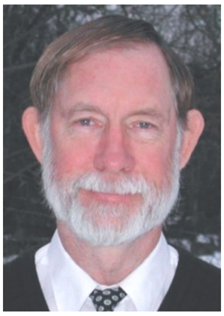
Authors

Karin Jonasson, PhD-Student
K. Jonasson got her BSc (Conservation) degree at Gothenburg University, the BSc (Civil Engineering) degree at Lund University and received her the Licentiate degree in Industrial Electrical Engineering at Lund University 2002. From 1995 to 1996 she was at Göteborg Energi AB, from 1996-1997 at Melcom Electronik and from 1997 to 1998 at Jonasson Agency Consulting. Since 1998 she is a PhD student at Lund University, Department of Electrical Engineering and Automation.

Mats Alaküla, Professor
M. Alaküla got his engineering education at Chalmers University of Technology, Göteborg, where he graduated in Electrical Engineering in 1986. From 1986 to 1989 he was a Ph.D student at the Department of Electrical Machines and Power Electronics and received his Licentiate degree at the same Department in 1989. From 1989 on he has been working in the field of electrical drives at the Department of Industrial Electrical Engineering and Automation (IEA) at the Lund Institute of Technology. In 1993 he received his Ph.D. degree and he is since April 1994 appointed as full professor in Industrial Electrical Engineering at IEA. His main field of interest is various aspects of electrical drives and applications with combustion engines.



Rolf Egnell, Assistant Professor
R.Egnell got his engineering education at Chalmers University of Technology, Göteborg, where he graduated in Mechanical Engineering in 1971. After 20 years in the industry involved with alternative engines and alternative fuels, he got a position as research engineer at Lund University (LU) working with natural gas engines and exhaust cleaning technology for diesel engines. R. Egnell received his Licentiate degree in 1994 and PhD in 2001 at the department of Heat and Power Engineering, Combustion Engines, LU. Since September 2001 Dr Egnell has a position as assistant professor and is presently involved with diesel engine research and hybrid systems.