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Industrial Electrical Engineering and Automation

The Three Way Catalyst in Hybrid Vehicles

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Abstract

The hybrid car is today one of the most favorable solutions to decrease the fuel consumption and the emissions, including the CO_2, to be able to design more environmental friendly vehicles. As the development progress the hybrids will probably be equipped with stronger electric machines and larger batteries which enable pure electric drive for longer distances.
This constitutes a problem in the exhaust gas after treatment in the three way catalyst which has to be over a certain temperature to reduce the emissions if the internal combustion engine is started by the hybrid control system.

To guarantee drive ability, a hybrid car operating in pure electrical drive, will start the internal combustion engine when the state of charge becomes too low and in addition to this the internal combustion engine may very well start at any time to respond to increased traction power, like in a heavy acceleration.
This may result in higher emission levels than a regular car which somehow diminish the whole idea of hybrid cars.

In this thesis it is investigated what the effect the three way catalyst has in a hybrid car and what is needed to assure that the environmental hybrid car does not become a environmental disaster due to deactivation of the catalyst.

A number of different possible solutions to this problem is presented and evaluated in this thesis. A final conclusion is then drawn of what to be done in the case of a mild hybrid and in the case of a full hybrid respectively.

Table of contents

Preface

This project is done as a master thesis in the school year 2006/2007 at Lund University at the Department of Industrial Electrical Engineering and Automation and represents 20 weeks of work.

The basic idea with this thesis is to illuminate the problems around deactivation of the three way catalyst in a hybrid car.

I would like to thank the following persons for their help during this thesis:

- Mats Alaküla for his expertise in hybrid vehicles.
- Rolf Egnell for his invaluable insights when modeling the catalyst.
- Ingemar Odenbrand for his expertise in the catalytic reactions.
- Bengt Sundén for his expertise in heat transfer.

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Bobbie Frank

Notation

A_i	[m^2]	The inner area of one part of the exhaust pipe or catalyst channel
A_o	[m^2]	The outer area of one part of the exhaust pipe or catalyst channel
C	[-]	Constant
b	[-]	Constant
D_i	[m]	The inner diameter of the exhaust pipe or catalyst channel
D_o	[m]	The outer diameter of the exhaust pipe or catalyst channel
f	[-]	Darcy's friction factor
h_i	[$W/(m^2 K)$]	The heat transfer coefficient inside the exhaust pipe or catalyst channel
h_o	[$W/(m^2 K)$]	The heat transfer coefficient outside the exhaust pipe or catalyst wall
L	[m]	The length of one part of the exhaust pipe or catalyst channel
$\dot{m}$	[kg/s]	The mass flow ratio of the exhaust gas
Nu_i	[-]	Nusselt number inside the exhaust pipe or catalyst channel
Nu_o	[-]	Nusselt number outside the exhaust pipe or catalyst wall
Pr_i	[-]	Prandtl number inside the exhaust pipe or catalyst channel
Pr_o	[-]	Prandtl number outside the exhaust pipe or catalyst wall
Q_{con}	[J]	The energy transferred from the exhaust pipe or catalyst wall to the surrounding ambient by convection
Q_{ins}	[J]	The energy transferred from the exhaust pipe or catalyst wall to the surrounding ambient when insulated
Q_{rad}	[J]	The energy transferred from the exhaust pipe or catalyst wall to the surrounding ambient by radiation
Q_t	[J]	The energy transferred from the exhaust gas to the exhaust pipe or catalyst wall or vice versa
Re_{con}	[-]	Reynolds number outside the exhaust pipe or catalyst wall
Re_i	[-]	Reynolds number inside the exhaust pipe or catalyst channel
r_{crit}	[m]	The critical radius of the insulation
r_i	[m]	The inner radius of the insulation
r_o	[m]	The outer radius of the insulation
T_{amb}	[K]	The ambient temperature
T_{in}	[K]	The temperature of the exhaust gas when entering each part
T_{wall}	[K]	The temperature of the exhaust pipe or catalyst wall of the part
v_{car}	[m/s]	The speed of the car
v_{eg}	[m/s]	The speed of the exhaust gas
Δt	[s]	The time step
λ_{amb}	[$W/(m K)$]	The thermal conductivity for the surrounding air
λ_{eg}	[$W/(m K)$]	The thermal conductivity for the exhaust gas
λ_{ins}	[$W/(m K)$]	The thermal conductivity for the insulation
ν_{amb}	[m^2/s]	The kinematic viscosity for the surrounding air
ν_{eg}	[m^2/s]	The kinematic viscosity for the exhaust gas
ρ_{eg}	[kg/m^3]	The density of the exhaust gas
σ	[$W/(m^2 K^4)$]	Stefan-Boltzmann's constant

1 Introduction

1.1 Background

Hybrid cars have been on the market for a number of years, beginning with Toyota Prius in 1997 [1] followed by Honda Insight in 1999 [2] and then many more. Today most large car manufacturers have realized that at least one of their models has to be a hybrid. This has resulted in cars such as GM´s hybrid trucks which have been on the market since 2004 [3] and Lexus 400h which has been available since 2005 [4].
In the opinion of the author however, all these cars are mild hybrids and the prediction is that in a near future, with the development of better batteries, full hybrids, or plug-in hybrids, will be a must. These are full hybrids that have large enough batteries to make it meaningful to charge via the power grid. The plug-in hybrid has large enough batteries and strong enough electrical machine which enable pure electrical drive, at least for shorter distances to work etcetera. The internal combustion engine is used at heavy accelerations, at high speed and in hybrid drive when the state of charge is low. In such a case it is possible to encounter the problem that the three way catalyst is deactivated due to too low temperature due to cooling, by convection and radiation, when the internal combustion engine is turned off. This means that every time the internal combustion engine starts is potentially equal to a cold start, with the high amount of emission this brings, in a conventional vehicle. This would completely contradict and demolish the purpose of the development of hybrid vehicles as an environmentally friendly alternative to conventional vehicles.

1.2 Purpose of the project

In this rapport the problem with deactivation of the catalyst due to too low temperatures is investigated, this includes how long time it takes to deactivate the catalyst and how to prevent it from happening.
This can be done by:

- Controlling the internal combustion engine to start when the catalyst is reaching its deactivation temperature.
- Maintaining high enough temperature, to prevent deactivation, in the catalyst by electrical heating.
- Instantaneously heating the catalyst when the internal combustion engine is about to start to a catalyst temperature higher than the catalysts lightoff temperature.

The investigation will also look into how location and insulation influences the temperature of the catalyst.
In this project two types of hybrids are used, a mild parallel hybrid with similar properties to the hybrids available on the market today and a full hybrid. In the full hybrid case a plug-in parallel hybrid with strong enough electric machine to drive the car alone and large enough batteries to drive for about 40-50 km is used.

1.3 Content

To be able to investigate the problems that occur in hybrid vehicles when the catalyst is deactivated due to cooling a quite simple thermodynamic model of the exhaust system is implemented in a parallel hybrid model where a set of control algorithms also are implemented, this is presented in chapter 2. Simulations of different scenarios are made, presented in chapter 3, and an analysis of the problem is presented in chapter 4 and 5.

2 The Model

The model consists of an exhaust system model made in Matlab®, presented in chapter 2.1, and a model of a parallel hybrid made in Simulink®, presented in chapter 2.2. The exhaust system model is implemented in the parallel hybrid model and a control algorithm, presented in chapter 2.3, is also written to be able to investigate which of the methods presented in chapter 1.2 that is the most appropriate.

2.1 Exhaust system model

The exhaust system model consist of an exhaust pipe and a catalyst and is primarily a thermodynamic model, this because the main parameter of interest in this project is the temperature. This means that some simplifications have been done in the model. The model works discretely which means that the exhaust pipe and the catalyst are divided into a number of parts, n, and the heat transmission is calculated in each and one of the parts separately.

The principle of the discrete system is shown in Figure 1 where the exhaust pipe is to the left and the catalyst is to the right. In the catalyst a characteristic channel is chosen, the blue-grey channel in Figure 1, and the other channels, the white channels in Figure 1, are approximated to function in the same way in terms of heat transmission. This results in that in a vertical cross-section of the catalyst all the channels will have the same temperature. This because the exhaust gas entering the catalyst from the exhaust pipe is assumed to be equally divided between the catalyst channels. Further on it is assumed that all the catalyst channels share the heat losses, due to radiation and convection, that occur at the outer catalyst wall. This results in that all the channels in a vertical cross-section have the same temperature which actually is the cross-section mean temperature in a physical catalyst where the outer channels are a bit cooler than the inner channels.

An approximation that is made is that there is no heat conduction between the parts, this should however not be a major approximation because of the fact that both the exhaust pipe and the catalyst is divided in such a large number of parts, n=50 for the exhaust pipe and n=100 for the catalyst. The large number of parts results in that the temperature difference between two parts beside one and another is small, and thereby is the heat conduction almost non-existent. Technical data for the exhaust pipe and catalyst used is presented in Appendix 1.

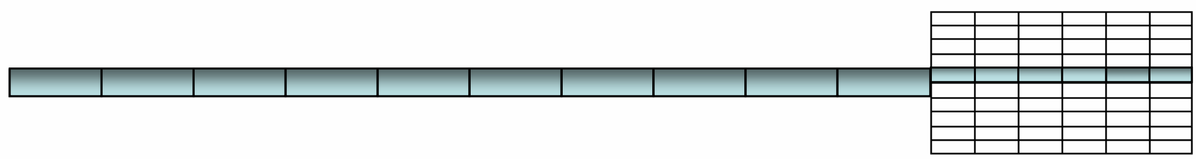

Figure 1, the principle of the discrete system.

Figure 2 shows in a schematic way how the heat transmission in each part works, the grey arrows represent the exhaust gas, with a higher internal energy when ingoing comparing to outgoing, and the red arrows represent the energy dissipated to the pipe or catalyst wall from the exhaust gas. The blue arrows represent energy dissipated from the wall to the surroundings through convection and radiation.

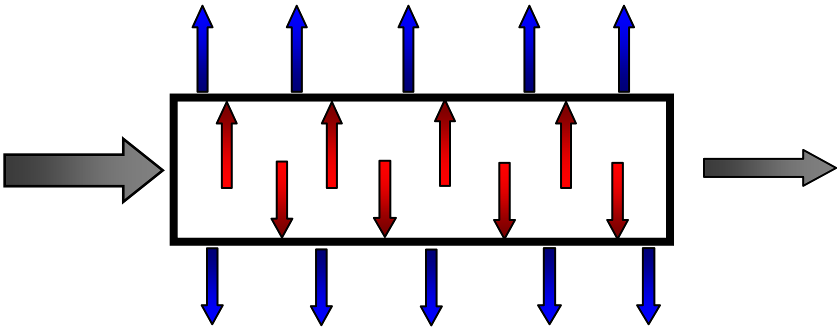

Figure 2, a schematic image of the heat transition in one part of the discrete model.

The reasoning above is valid when the exhaust gas has a higher temperature than the pipe or catalyst wall, in the case when the exhaust gas has a lower temperature than the pipe or catalyst wall the red arrows in Figure 2 will be pointing the other way and the pipe or catalyst wall will dissipate energy to the exhaust gas. This results in that the grey arrows in Figure 2 will change places, that is the exhaust gas has a higher internal energy when outgoing comparing to ingoing.

The red arrows in Figure 2 are modelled by Equation 1, where Q_t is the energy transferred from the exhaust gas to the pipe or catalyst wall.

$$Q_t = (T_{in} - T_{wall}) \cdot h_i \cdot A_i \cdot \Delta t$$ **Equation 1 [5]**

Where T_{in} is the temperature of the exhaust gas when it goes into the part, compare to the bigger grey arrow to the left in Figure 2. T_{wall} is the temperature of the pipe or catalyst wall, A_i is the inner area of the pipe or catalyst channel for one part and Δt is the time step used in the model. The heat transfer coefficient inside the pipe or catalyst channel, h_i, is calculated by Equation 2.

$$h_i = \frac{Nu_i \cdot \lambda_{eg}}{D_i}$$ **Equation 2 [6]**

Where λ_{eg} is the thermal conductivity for the exhaust gas, D_i is the inner diameter of the pipe or catalyst channel. The Nusselt number, Nu_i is calculated by Equation 3.

$$Nu_i = \frac{\frac{f}{8}(\mathrm{Re}_i - 1000) \cdot \mathrm{Pr}_i}{\left(1 + \sqrt{\frac{f}{8}}\right) \cdot \left(\mathrm{Pr}_i^{\frac{2}{3}} - 1\right)}$$ **Equation 3 [7]**

The Darcy´s friction factor, f, is calculated by Equation 4 and Re_i, Reynolds number inside the pipe or catalyst channel, is calculated by Equation 5 and Pr_i is the Prandtl number inside the pipe or catalyst channel. Equation 3 is valid for turbulent flow, for laminar flow Nu_i is set to 2.98 [8].

$$f = (0.79 \cdot \ln(\mathrm{Re}_i) - 1.64)^{-2}$$

Equation 4 [7]

$$\mathrm{Re}_i = \frac{v_{eg} \cdot D_i}{\nu_{eg}}$$

Equation 5 [9]

Where ν_{eg} is the kinematic viscosity for the exhaust gas and v_{eg} is the speed of the exhaust gas and is calculated by Equation 6.

$$v_{eg} = \frac{\frac{\dot{m}}{A_i}}{\rho_{eg}}$$

Equation 6

Where $\dot{m}$ is the mass flow ratio of the exhaust gas and ρ_{eg} is the density of the exhaust gas.

The blue arrows in Figure 2 are the sum of the heat losses to the surroundings through radiation and convection. The radiation losses, Q_{rad}, is modelled by Equation 7 and the convection losses, Q_{con}, is modelled by Equation 8 when no insulation is present. When insulation is added, Equation 12 models the energy losses due to convection, Q_{ins}.
In the model there are no axial heat losses, only radial for both the catalyst and exhaust pipe. The largest approximation with this is in the catalyst inlet between the exhaust pipe and the catalyst, this transition is supposed to be smoothened out to a streamlined inlet, see the red lines in Figure 3, and is not a sharp edge as in the schematic picture in Figure 1.

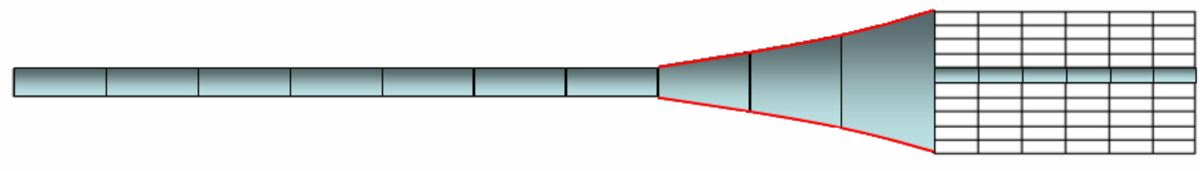

Figure 3, a schematic image of the streamlined catalyst inlet.

A less important approximation is that the sheet metal casing around the honeycomb structured catalyst is assumed to have the same temperature as the honeycomb at all times which results in that the casing is cancelled from the equations for simpler calculation. If the casing would be accounted for in the model, Equation 8 would resemble Equation 12 and Equation 12 would have another term in the denominator.

When calculating the heat losses through radiation the surrounding temperature is approximated to T_{amb}, the air temperature outside the car. This temperature should in reality be higher because the internal combustion engine warms up the area surrounding the exhaust pipe and the catalyst but due to the complexity to approximate this temperature the ambient temperature is used.

$$Q_{rad} = \left(T_{wall}^4 - T_{amb}^4\right) \cdot \sigma \cdot A_o \cdot \Delta t$$ **Equation 7 [10]**

Where σ is the Stefan-Boltzmann's constant and A_o is the outer area of the pipe or catalyst channel for one part.

When calculating the heat losses through convection two important approximations are made. The first is that each and one of the channels in the catalyst in Figure 1 share the heat losses equal among them, this means that a whole vertical cross section of the catalyst will have the same temperature. The second approximation is that the outer cooling air flow is perpendicular to the exhaust pipe and catalyst. This is of course not entirely true but this approximation is made because this represent a worst case scenario, the cooling will not be larger than this when the exhaust pipe or catalyst is parallel, or at an angle less than 90°, with the air flow. Besides the air flow under a car is complex and not easy to model. The same reasoning is used when approximating the exhaust pipe to a completely straight pipe as in Figure 1.

$$Q_{con} = \left(T_{wall} - T_{amb}\right) \cdot h_o \cdot A_o \cdot \Delta t$$ **Equation 8 [5]**

The heat transfer coefficient outside the pipe or catalyst wall, h_o, is calculated by Equation 9.

$$h_o = \frac{Nu_o \cdot \lambda_{amb}}{D_o}$$ **Equation 9 [6]**

Where λ_{amb} is the thermal conductivity for the surrounding air and D_o is the outer diameter of the pipe or catalyst channel. The Nusselt number outside the pipe or catalyst wall, Nu_o is calculated by Equation 10, where C and b are taken from Table 1.

$$Nu_o = C \cdot \mathrm{Re}_{con}^{b} \cdot \mathrm{Pr}_o^{\frac{1}{3}}$$ **Equation 10 [11]**

Re_{con} <4000	C = 0.683	b = 0.466
4000 < Re_{con} < 40000	C = 0.193	b = 0.618
Re_{con} > 4000	C = 0.0.0266	b = 0.805

Table 1, constants in Equation 10 [[12].

Where Re_{con} is Reynolds number outside the pipe or catalyst channel, calculated by Equation 11, and Pr_o is Prandtl number outside the pipe or catalyst wall.

$$\mathrm{Re}_{con} = \frac{v_{car} \cdot D_o}{\nu_{amb}}$$ **Equation 11 [9]**

Where ν_{amb} is the kinematic viscosity for the surrounding air and v_{car} is the speed of the car.

When calculating the heat losses through convection when insulation is present one more approximation is made, that all the heat that goes out to the environment from the insulation is coming into the insulation from the exhaust pipe or catalyst. This not only make the calculations easier but it is also highly reasonable that this is the case.

$$Q_{ins} = \frac{T_{wall} - T_{amb}}{\frac{1}{2 \cdot \pi \cdot \lambda_{ins} \cdot L} \cdot \ln \frac{r_o}{r_i} + \frac{1}{2 \cdot \pi \cdot r_o \cdot L \cdot h_o}} \cdot \Delta t$$ **Equation 12 [5]**

Where λ_{ins} is the thermal conductivity for the insulation, r_i is the inner radius of the insulation, r_o is the outer radius of the insulation and L is the length of each part in the exhaust pipe or the catalyst.

To decide the ultimate insulation thickness the critical insulation thickness, r_{crit}, is calculated by Equation 13. If r_{crit} becomes smaller than r_i the insulation will always have the desired effect, that is a insulating effect. If r_{crit} becomes larger than r_i this is the optimal outer radius of the insulation. If the insulation is thinner the insulation does not have full effect and if the insulation is thicker the cooling becomes so large, due to the fact that the outer area increases in square with the insulation thickness, that the increased heat losses trough convection is larger than the savings due to increased insulation which results in poorer insulation properties.

$$r_{crit} = \frac{\lambda_{ins}}{h_o}$$ **Equation 13 [13]**

Besides the heat transmissions from the exhaust gas to the pipe and catalyst walls and the losses to the surrounding there are three major exothermic catalytic reactions when reducing the emissions. The energy release for each of them is presented in Table 2.

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	801 kJ/mol CH_4
$2CO + O_2 \rightarrow 2CO_2$	283 kJ/mol CO
$2NO \rightarrow N_2 + O_2$	91 kJ/mol NO

Table 2, exothermic catalytic reactions [14].

In reality $2NO \rightarrow N_2 + O_2$ does not happen by itself, only in combination with $2CO + O_2 \rightarrow 2CO_2$ which results in $2NO + 2CO \rightarrow N_2 + 2CO_2$. This is however not a problem in the model because it is the same amount of energy that is released by this reaction as the sum of the heat released by the original two reactions listed in Table 2.

The energy released from these reactions is added to the catalyst wall following the graph in Figure 4. This due to the fact that the reaction speed has a direct dependence of the emission concentration and the temperature, which both reduces along the catalyst horizontal axis in Figure 1. This result in that most of the reactions will take place in the beginning of the catalyst as can be interpreted from Figure 4 [15].

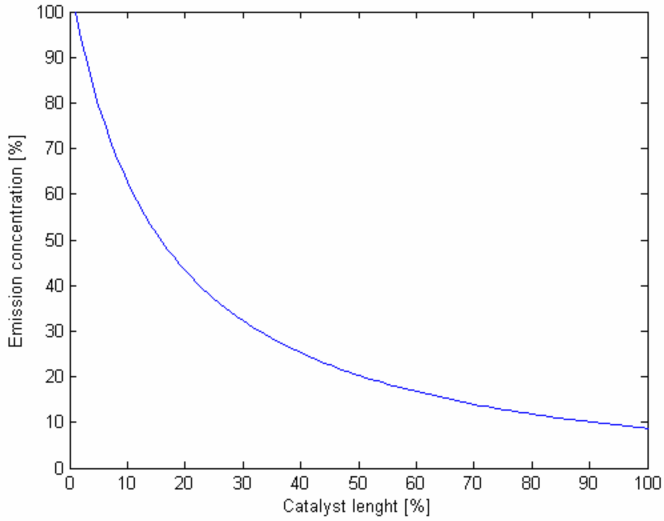

Figure 4, the emission concentration in the catalyst.

As can be seen in Figure 4 the total conversion ratio is set to about 90% [16] when the catalyst has reached the lightoff temperature for the different reactions. The lightoff temperatures used in the model is shown in Table 3.

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	550 K
$2CO + O_2 \rightarrow 2CO_2$	600 K
$2NO \rightarrow N_2 + O_2$	500 K

Table 3, lightoff temperatures [17].

The two major approximations that are made when the exothermic reaction is considered is that the curve in Figure 4 is constructed and that the conversion of emissions goes from zero to full conversion when the lightoff temperature is reached.

2.2 Hybrid model

The hybrid model that is used in this project is a research and educational tool developed by Mats Alaküla et al. and is available at LTH for virtual studies on hybrid cars.
To be able to implement the exhaust system model, presented in chapter 2.1, in the hybrid model additional maps over the internal combustion engine have to be implemented. This results in that, in addition to the existing map over the efficiency, maps over mass flow, exhaust gas temperature when leaving the engine and HC, CO and NOx mass flow maps are implemented in the hybrid models internal combustion engine block. The result after the implementation of the exhaust system model, which is made by using an embedded Matlab function, in the hybrid model is shown in Figure 5.

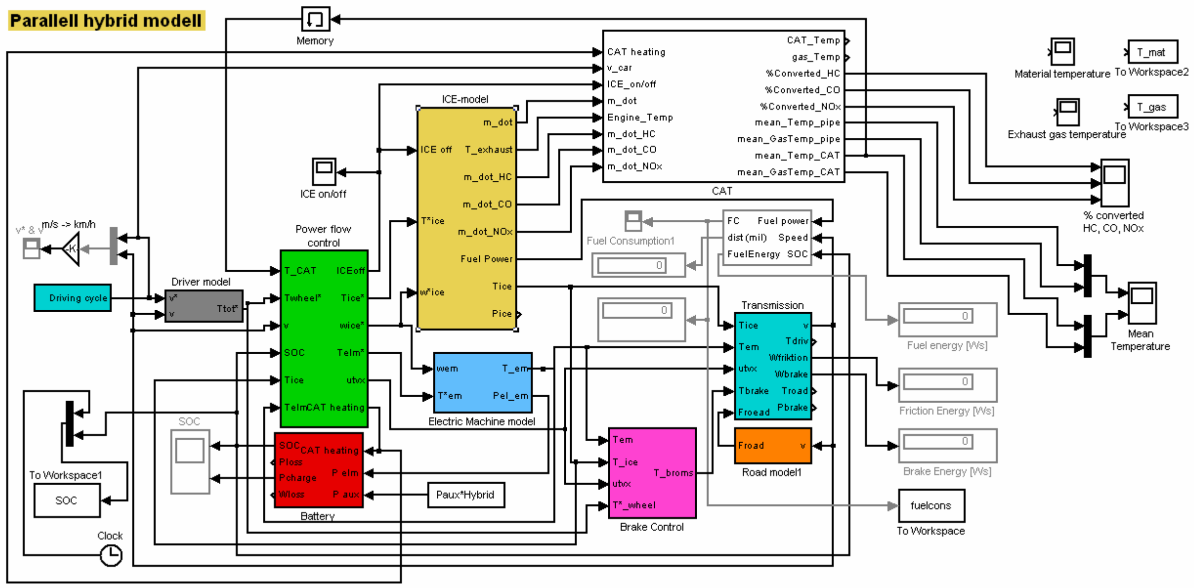

Figure 5, an overview of the parallel hybrid model with the catalyst implemented.

The type of hybrid that is used in this project is a parallel hybrid due to the fact that this system, in the opinion of the author, has the highest potential to have the lowest conversion losses. The parallel hybrid system is also the most cost efficient and has the highest adaptability to existing car platforms of the different hybrid systems on the market today [18].

A parallel hybrid has one internal combustion engine and at least one electrical machine, see Figure 6 that shows a schematic picture of how a parallel hybrid with one electrical machine positioned next to the clutch. It is however possible to have two electrical, or four, machines in the wheels for example. In this project Figure 6 gives a good description of the hybrid model used.

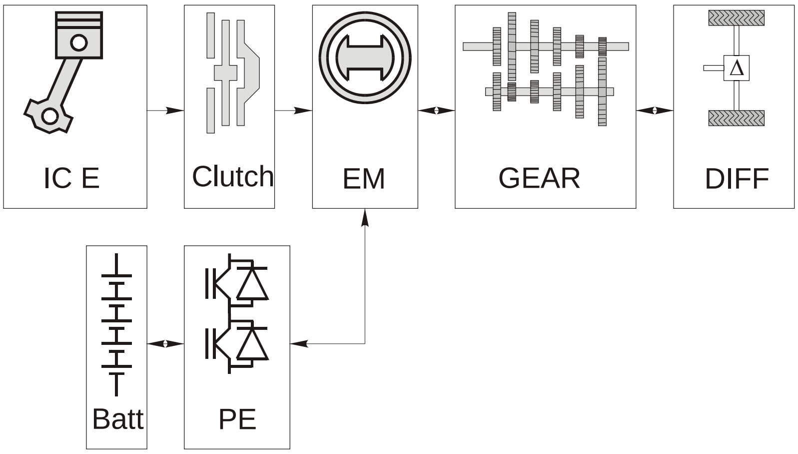

Figure 6, a schematic picture of parallel hybrid [19].

The parallel hybrid works after the principle of always running the internal combustion engine at near optimum efficiency, this means when the power needed to drive the car cannot be delivered with high enough efficiency the internal combustion engine is turned off and the electrical machine fills in. If the state of charge is too low the electrical machine works as a generator either by the internal combustion engine operating at higher power than needed to drive the vehicle or by the dynamic energy of the vehicle when decelerating. The electrical machine also fills in dynamic changes of the traction power to limit the dynamic requirements of the internal combustion engine, thus contributing to lower fuel consumption and lower emissions [20].

2.3 Control algorithm

To be able to investigate the different scenarios presented in chapter 1.2 a set of control algorithms are implemented, an electrical heater for the catalyst is also implemented.
All the control algorithms are hysteresis regulators which regulates on the state of charge in the batteries and the mean temperature in the catalyst.
The implemented control algorithms are:

- The original control algorithm, which starts the internal combustion engine when the state of charge reaches 20% and charge the batteries until the state of charge reaches 70%. This algorithm is designed without any consideration to the catalyst temperature or operation. The original control algorithm is kept for comparison.
- The control algorithm which heats the catalyst, with an electrical heater, continuously which means that when the catalyst gets close to extinction temperature the electrical heater turns on and heats the catalyst.
- The control algorithm which heats the catalyst, with an electrical heater of 5 kW, to its lightoff temperature right before the internal combustion engine starts. This is done by predicting when the state of charge in the batteries reaches its minimum level which means that the internal combustion engine has to be started. This control algorithm does not account for the need of have to start the internal combustion engine before the state of charge in the batteries reaches its minimum, for example due to high power needed at heavy acceleration.
- The control algorithm which keeps the catalyst over its extinction temperature by starting the internal combustion engine when the catalyst gets close to the extinction temperature which heats the catalyst. When the internal combustion engine is started it will be run in the same way as in the original control algorithm, that is in normal hybrid drive mode. If the temperature does not get low enough the internal combustion engine will start when the state of charge reaches 20% anyway just as in the original control algorithm.
- The last control algorithm works just as the third with the exception that when the internal combustion engine is on, it keep on running until the state of charge has reached 70%.

3 Simulations

Two types of simulations are performed, the first, presented in chapter 3.1, is performed to show the characteristics of the exhaust system model and the second, presented in chapter 3.2, are showing how the system works when inserted in two types of hybrid vehicles.

3.1 Exhaust system model characteristics

To be able to show the characteristics of the exhaust system model a simple drive cycle is designed, the vehicle accelerate the first 120 seconds to 108 km/h then maintain this speed, using only the internal combustion engine. After 240 seconds, that is 120 seconds after the acceleration stops, the internal combustion engine is turned off to simulate electrical drive in a hybrid vehicle. The driving cycle is showed in Figure 7.

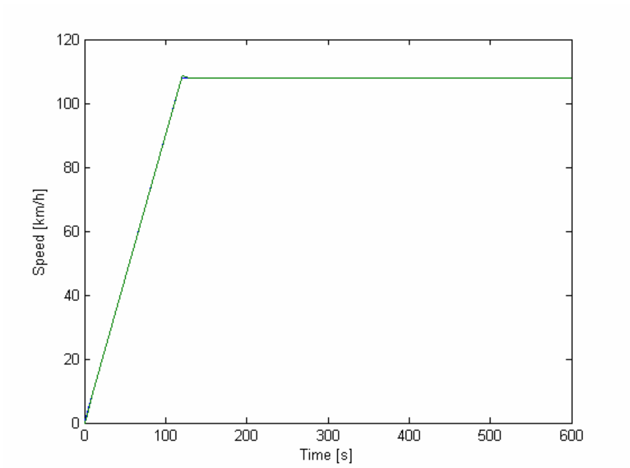

Figure 7, the speed of the drive cycle used when showing the characteristics of the exhaust system model.

The simulation is done with, see Figure 8, and without insulation, see Figure 9. Technical data for the insulation of the exhaust pipe and catalyst is presented in Appendix 1. Due to the fact that the critical insulation thickness calculated according Equation 13 becomes smaller than the inner diameter of the exhaust pipe and catalyst channel respectively the insulation can be chosen to a certain thickness according to chapter 2.1, in this case 10 mm.

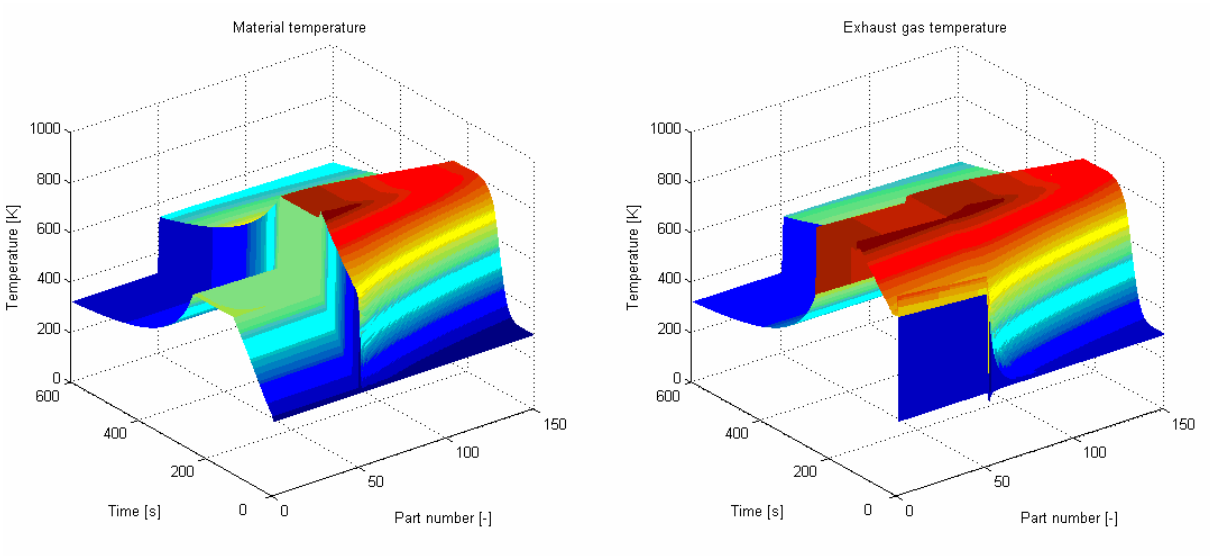

Figure 8, Exhaust system with insulation characteristics.

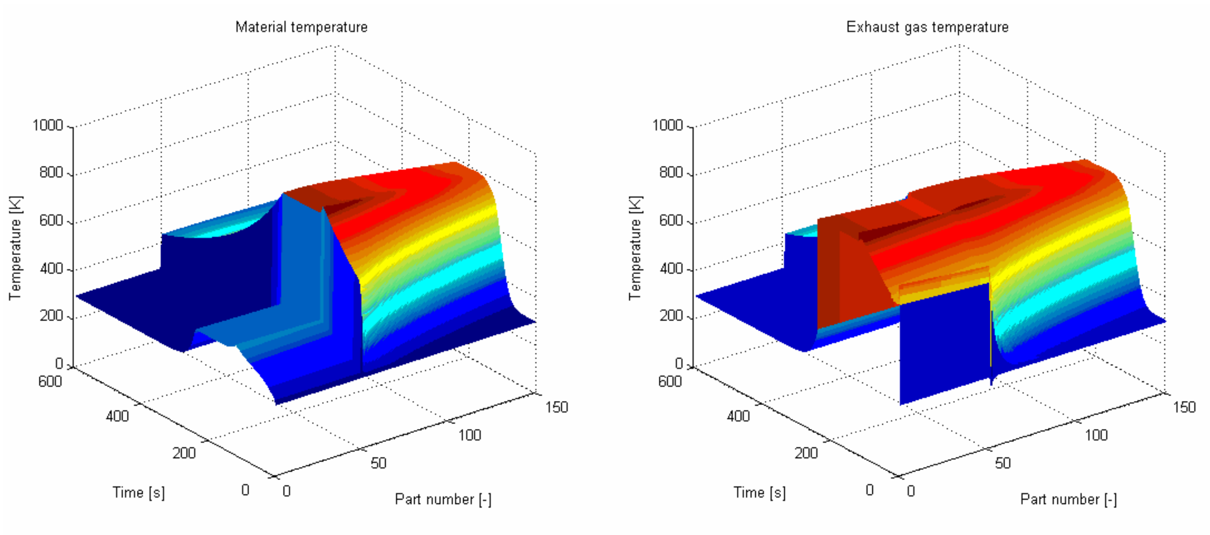

Figure 9, Exhaust system without insulation characteristics.

In Figure 8 and Figure 9 the 50 first parts is the exhaust pipe and the following 100 parts is the catalyst as mentioned in chapter 2.1 and illustrated in Figure 1.
The little notch that is visible right before the temperature becomes constant appear because the mass flow is higher when the car accelerate comparing to when it keeps the final constant velocity, see Figure 7.
What is an interesting phenomenon that can be seen in Figure 8 and Figure 9 is that the maximum heat is not at the edge in the beginning of the catalyst but a little bit in. This is because of the exothermic catalytic reactions which actually heats the exhaust gas resulting in that the walls gets warmer than the exhaust gas where the reactions occurs, or slightly after, which is mainly in the beginning of the catalyst as mentioned in chapter 2.1.

3.1.1 Results

Evidently the insulated exhaust system cools off in a slower pace which is better in this case, at least if the catalyst is to be kept warm electrically, because then the catalyst does not have to be heated so much.

3.2 Hybrid vehicle simulations

Two types of vehicles are simulated, the full hybrid where it is anticipated that the deactivation of the catalyst is a problem, see chapter 1, and the mild hybrid where it is expected that the deactivation of the catalyst is not a significant problem since the internal combustion engine is not turned off for any longer periods of time due to the very short periods of pure electric drive due to the relatively small batteries installed in the mild hybrid.

Here it is important to realize that even though both the full and the mild hybrid are driven in depletion mode here, usually the mild hybrid is not driven in depletion mode. The reason why the mild hybrid is driven in depletion mode here is to simulate a worst case scenario. This because the mild hybrid can not drive pure electrical for a longer distance in ordinary mode than in depletion mode, which means that the catalyst will always have a higher temperature in ordinary hybrid mode comparing to depletion mode.

The simulation parameters for the hybrid cars is chosen in respect to the most cost efficient way to design a hybrid car [18], the parameters is shown in Table 4.

	Mild Hybrid	Full Hybrid
ICE Power	66 kW	66 kW
EM Power	15 kW	40 kW
Battery	20 kg	125 kg

Table 4, simulation parameter for the two vehicles simulated [18].

The internal combustion engine used to create the maps, see chapter 2.2, is a 2.3 l turbo Otto engine which seems a bit big, especially for the full hybrid. This was however the only engine available with complete maps, besides the internal combustion engine power is limited as shown in Table 4 anyway. This can also be seen in the third plot from the left in Figure 10 where the upper red line is the maximum torque and the blue lower line is the optimum torque work point for the internal combustion engine.

The properties of the internal combustion engine used are illustrated in Figure 10.

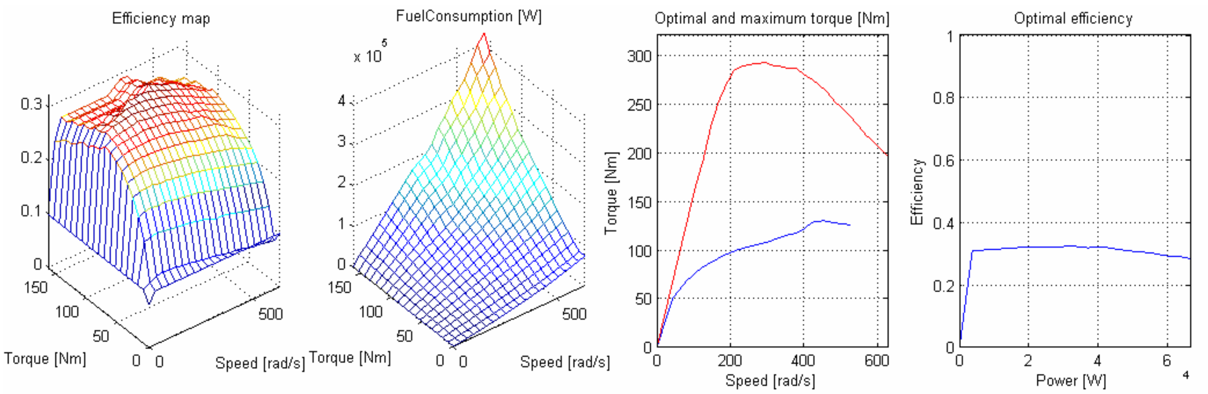

Figure 10, internal combustion engine properties.

The properties of the electrical machines used, the 15 kW to the left and the 40 kW to the right, are illustrated in Figure 11.

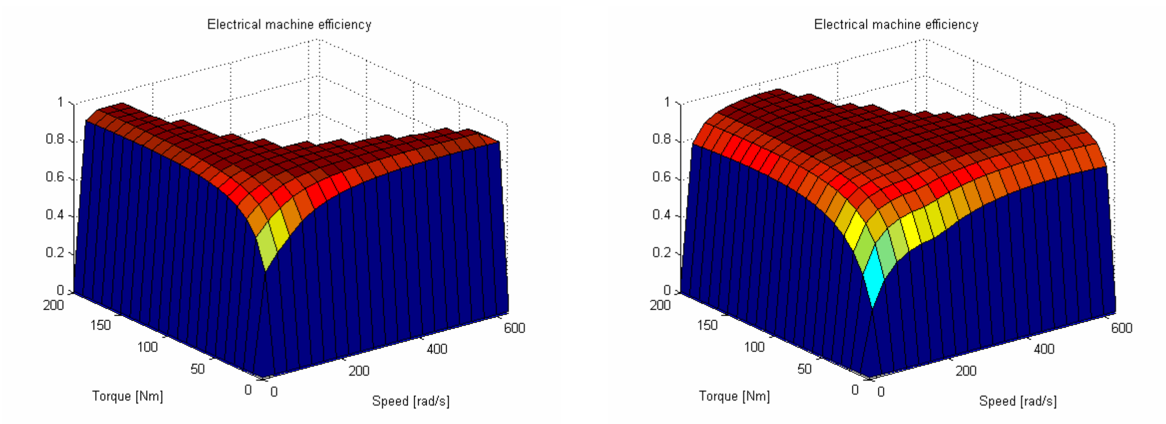

Figure 11, electrical machines properties.

To be able to get a repetitive behavior in the simulation data longer driving cycles is constructed by adding ten eudc, which simulate urban driving, respectively ten us06, which simulate highway driving, to create ten times longer driving cycles, see Figure 12. These two will further on only be referred to as eudc respectively us06 because the ordinary single driving cycles will not be used henceforth.

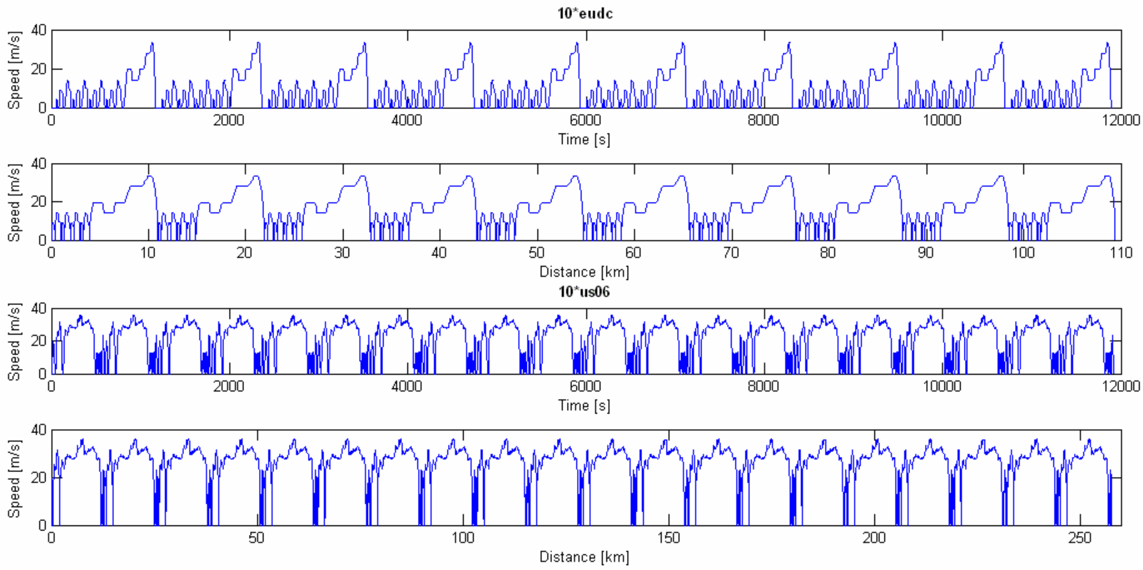

Figure 12, the driving cycles used when simulating vehicles.

In Figure 12 the speed is plotted as a function of both time and distance to be able to do an easy translation between distance covered and elapsed time henceforth.

3.2.1 Mild Hybrid

An overview of the simulations done with the mild hybrid vehicle is shown in Table 5 which also show the average fuel consumption in the different simulations. Each and one of the simulations will be explained more closely in connection with the plots, see Figure 13 to Figure 22.

Driving cycle / Control algorithm	eudc, no insulation	eudc, with insulation	us06, no insulation	us06, with insulation
Original	6.524	6.524	7.083	7.083
Continuously electrically heated	7.180	6.567	7.160	7.110
Instantaneously electrically heated	6.725	6.692	7.178	7.093
Continuously heated by the ICE	7.042	6.623	7.102	7.089
Continuously heated by the ICE up to 70% SOC	*5.371*	*6.137*	7.123	7.075

Table 5, fuel consumption (l/100 km) in the different simulations of a mild hybrid.

Because the simulation graphs when the exhaust system is insulated and when it is not looks very similar only the plots with insulation will be presented here, see Figure 13 to Figure 22.

In each simulation five graphs is presented;

- The amount of emissions converted.
- If the electrical heating is on or off (on=1 and off=0).
- If the internal combustion engine is on or off (on=1 and off=0).
- The state of charge of the batteries.
- The mean temperature in the catalyst.

Figure 13 and Figure 14 show graphs from the simulation with the original control algorithm. The most important thing to realize in this simulation is that in the conversion graph dips are shown every time the internal combustion engine starts, at least in the eudc case. This means that deactivation due to too low temperature in the catalyst occurs.

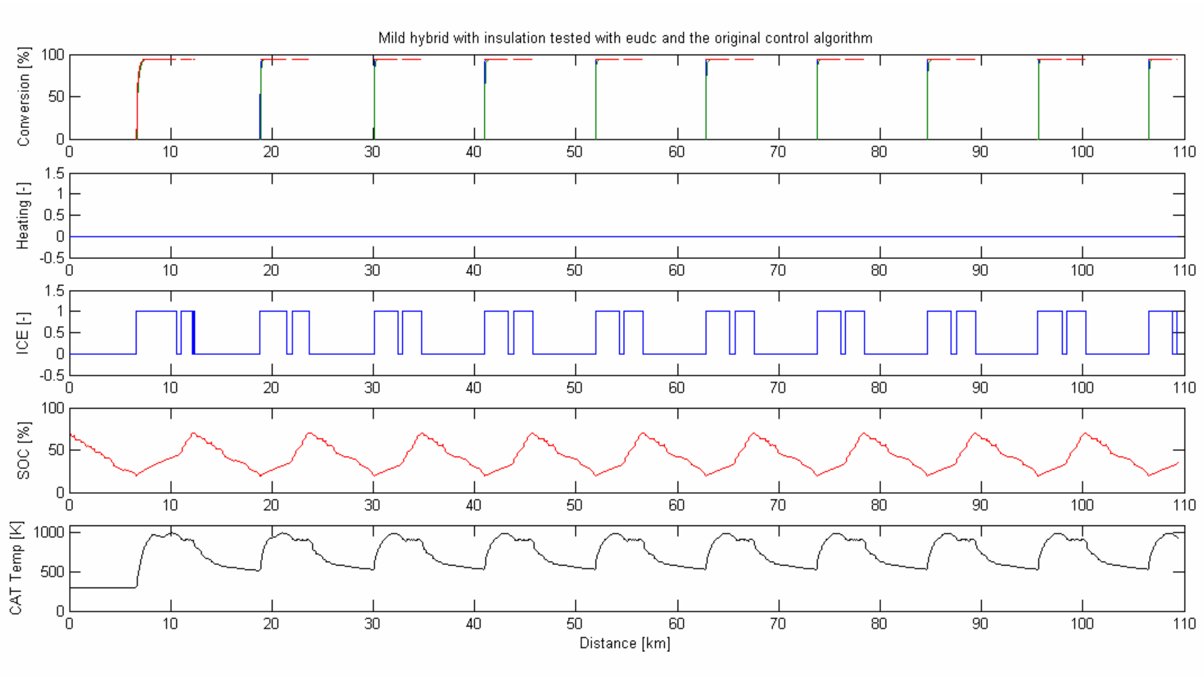

Figure 13, simulation of a mild hybrid with insulation tested with eudc and the original control algorithm.

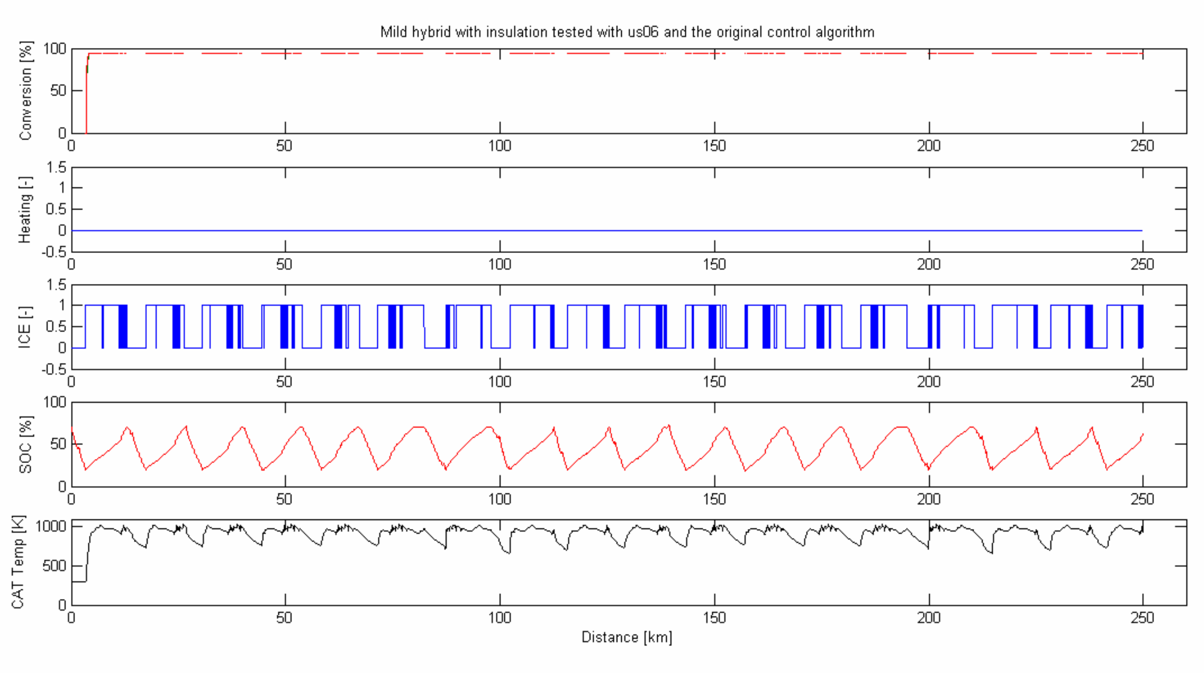

Figure 14, simulation of a mild hybrid with insulation tested with us06 and the original control algorithm.

Figure 15 and Figure 16 show graphs from simulations with the algorithm where the electrical heater continuously heating the catalyst to prevent deactivation due to too low temperature. The most important thing to notice in these graphs is that the temperature always stays over the lightoff temperature and that the electrical heater turns on at even intervals.

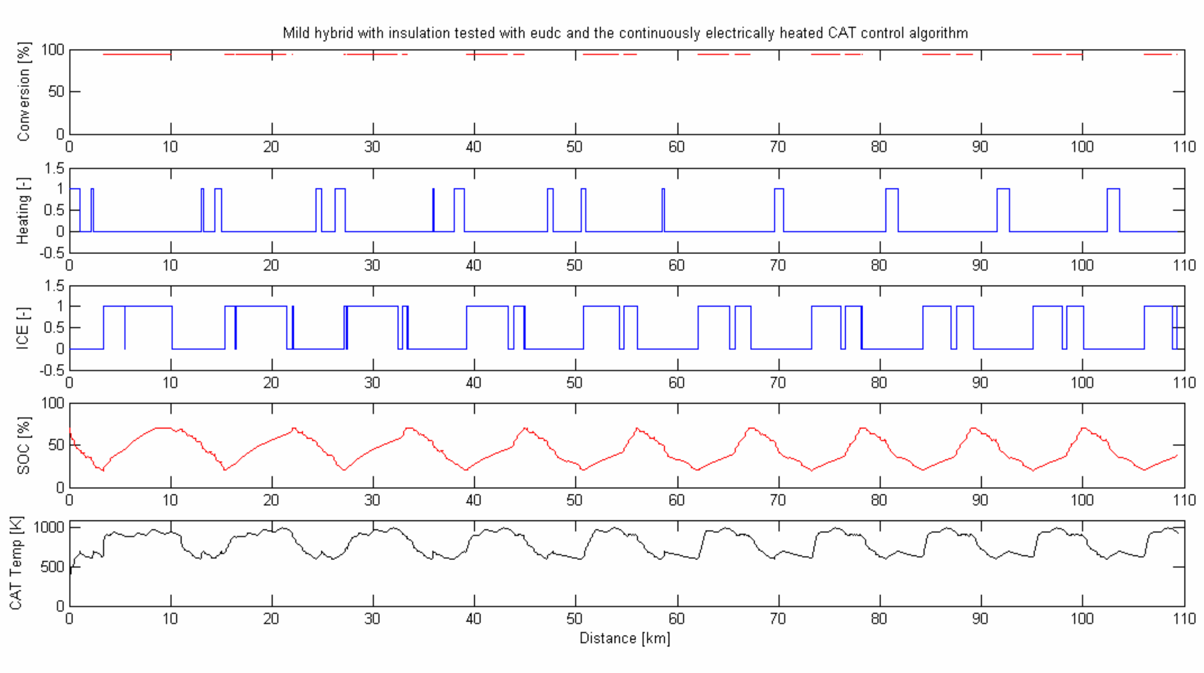

Figure 15, simulation of a mild hybrid with insulation tested with eudc and the continuously electrically heated catalyst control algorithm.

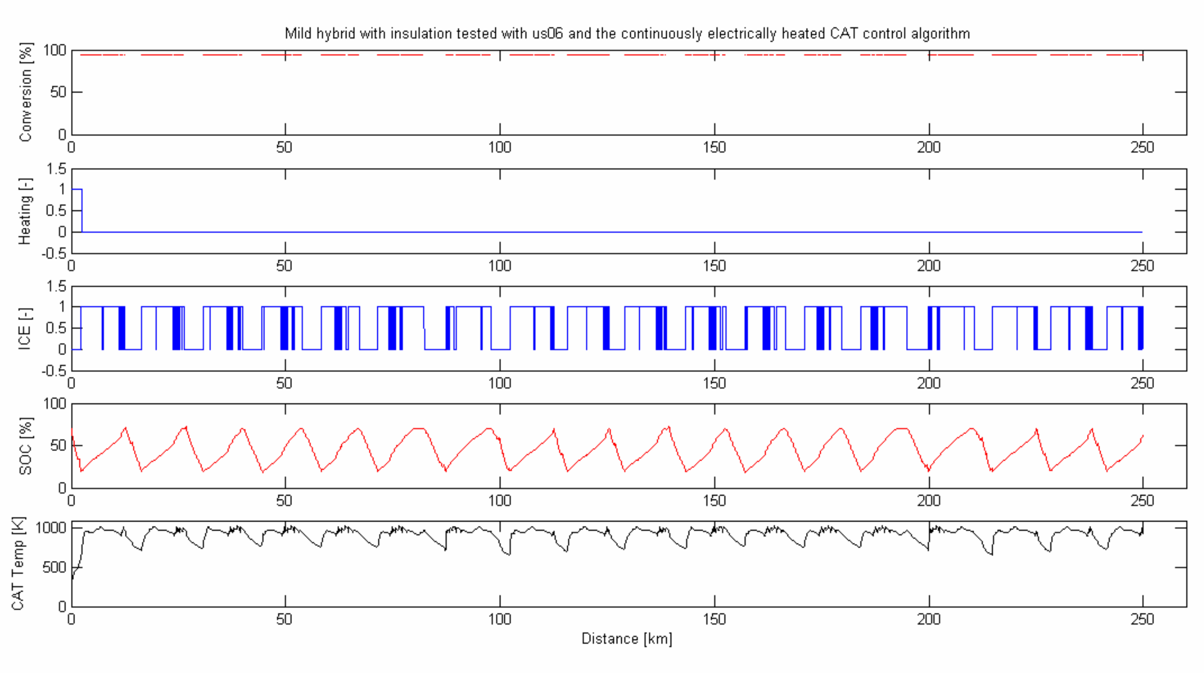

Figure 16, simulation of a mild hybrid with insulation tested with us06 and the continuously electrically heated catalyst control algorithm.

Figure 17 and Figure 18 show graphs from simulations with the algorithm where the electrical heater heats the catalyst to its lightoff temperature right before the internal combustion engine starts. It can be noticed that some dips are present in the conversion graph but is not a problem because they are so small. In a real car this could simply be fixed by saying that the internal combustion engine is not allowed to start before the catalyst have reached its lightoff temperature, which would delay the start a couple of seconds in the cases where a dip in the conversion graph is shown and maybe bring the start forward a couple of second in the case where the dips is not present. An important thing to notice in this simulation is that the electrical heater is only on right before the start of the internal combustion engine and in between, when the internal combustion engine is off, the catalyst is allowed to cool off below its lightoff temperature.

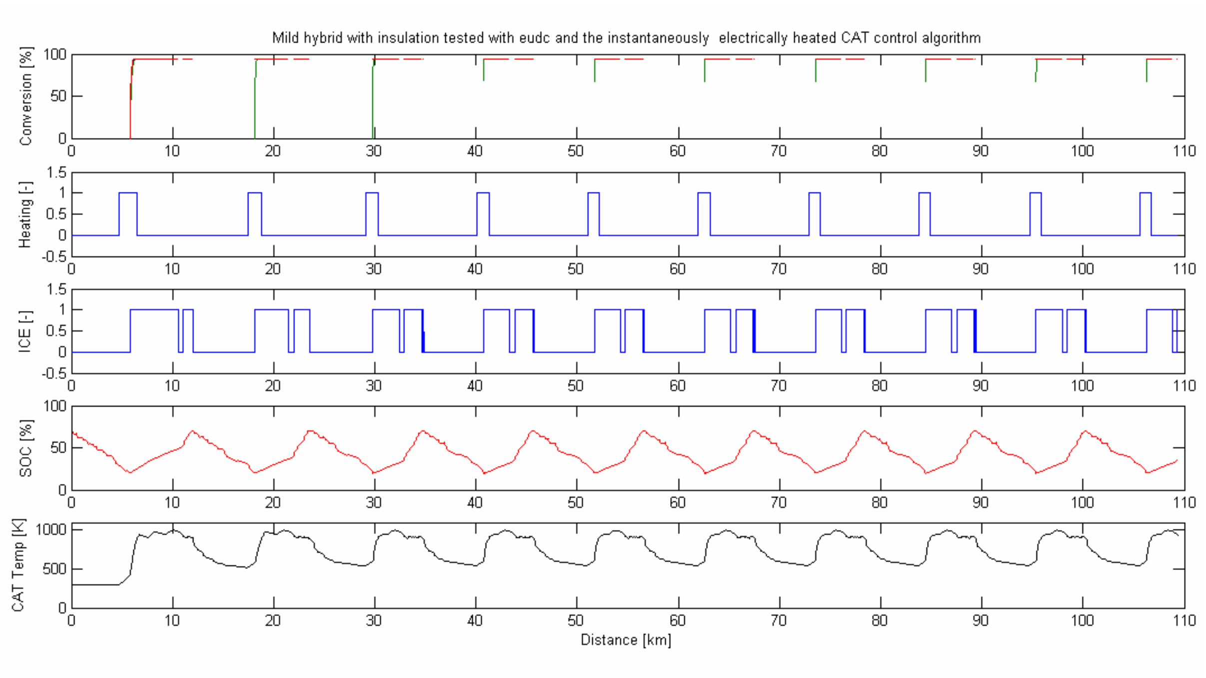

Figure 17, simulation of a mild hybrid with insulation tested with eudc and the instantaneously electrically heated catalyst control algorithm.

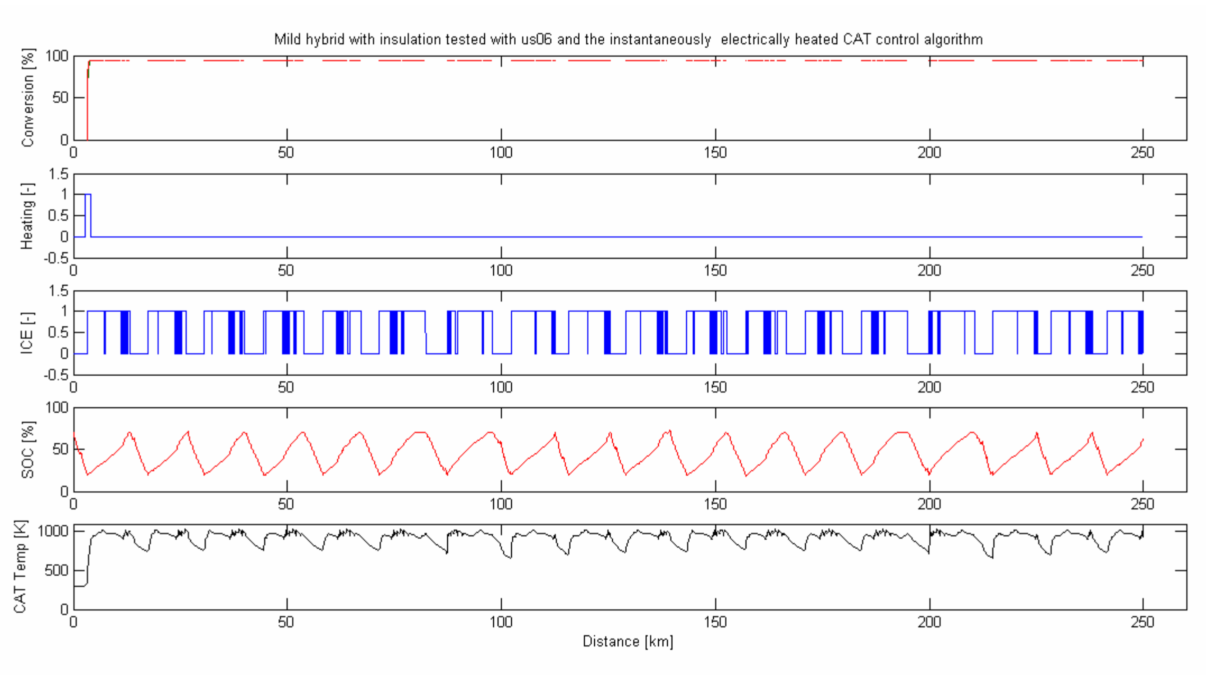

Figure 18, simulation of a mild hybrid with insulation tested with us06 and the instantaneously electrically heated catalyst control algorithm.

Figure 19 and Figure 20 show graphs from simulations with the algorithm where the internal combustion engine continuously heating the catalyst to prevent deactivation due to too low temperature. The most important thing to notice in these graphs is that the temperature always stays over the lightoff temperature and that the internal combustion engine turns on at even intervals.

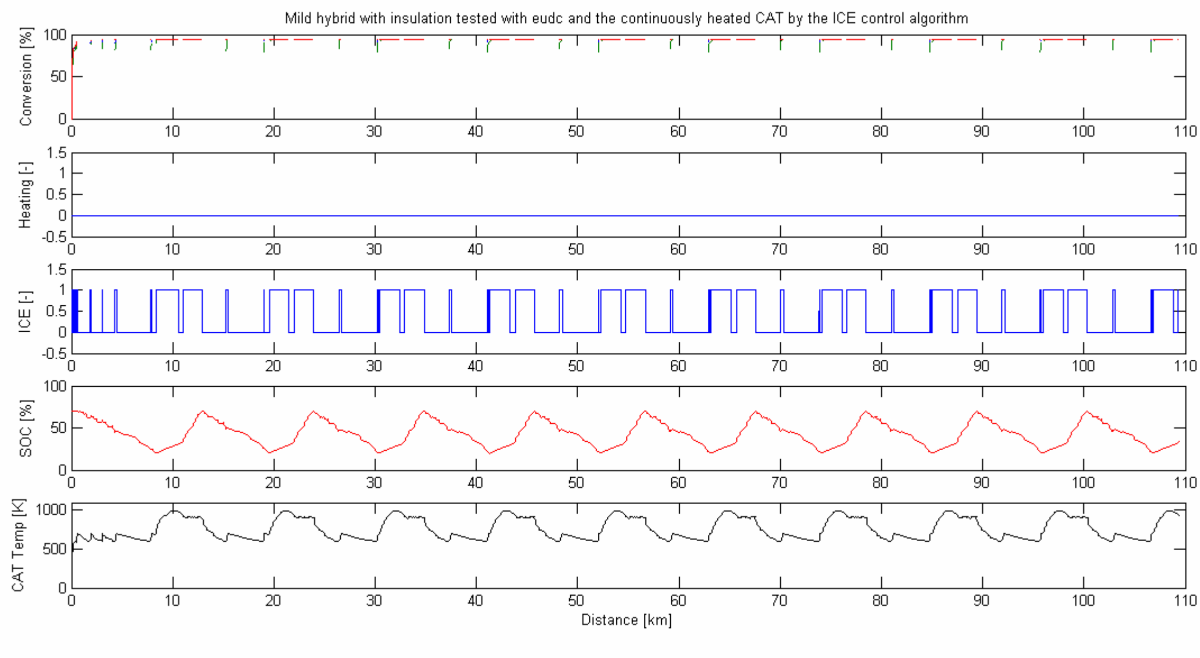

Figure 19, simulation of a mild hybrid with insulation tested with eudc and the continuously heated catalyst by the internal combustion engine control algorithm.

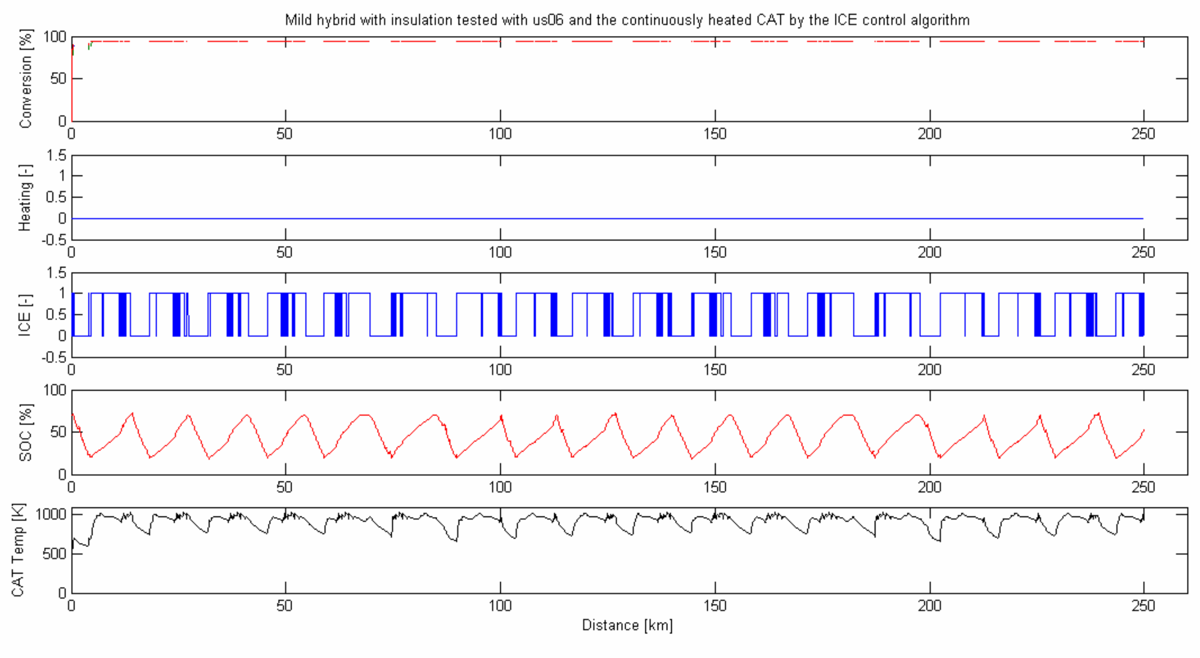

Figure 20, simulation of a mild hybrid with insulation tested with us06 and the continuously heated catalyst by the internal combustion engine control algorithm.

Figure 21 and Figure 22 show graphs from simulations with the algorithm where the internal combustion engine continuously heating the catalyst to prevent deactivation due to too low temperature. The difference from the previous control algorithm is that when the internal combustion engine starts it keeps on running until the state of charge is 70 % which can be seen in the SOC graphs when comparing Figure 19 and Figure 20 with Figure 21 and Figure 22. Also in this simulation the temperature always stays over the lightoff temperature. The internal combustion engine get a behavior intermediary the previous control algorithm and the original control algorithm.

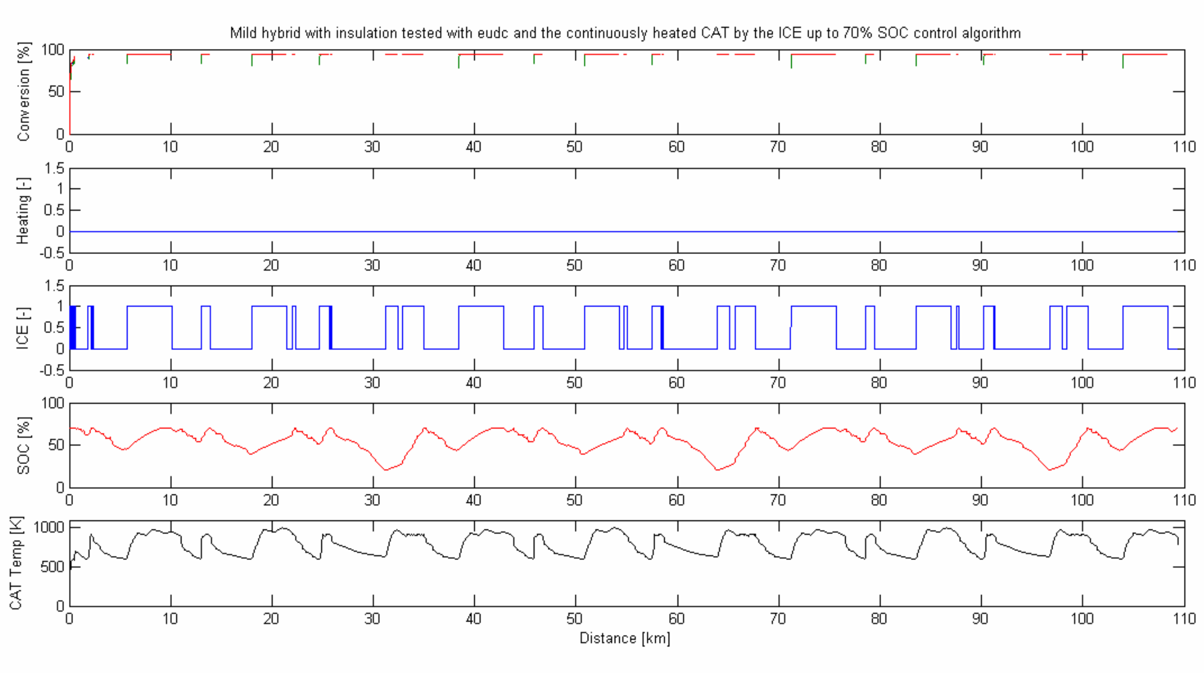

Figure 21, simulation of a mild hybrid with insulation tested with eudc and the continuously heated catalyst by the internal combustion engine up to 70% state of charge control algorithm.

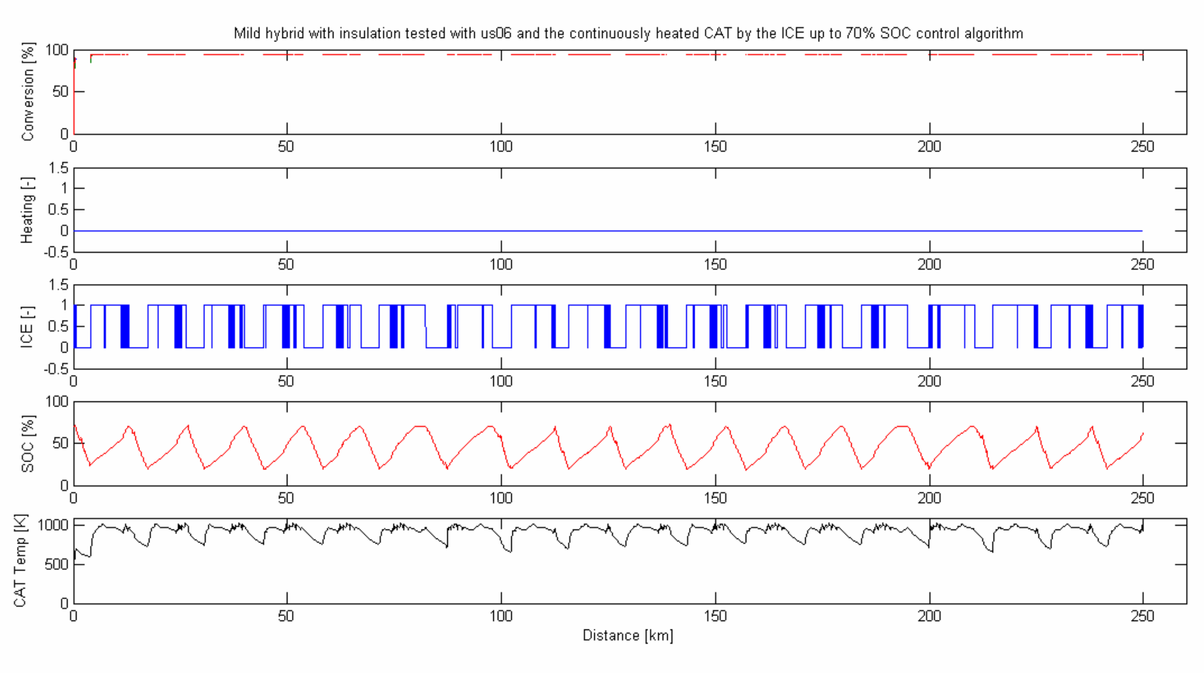

Figure 22, simulation of a mild hybrid with insulation tested with us06 and the continuously heated

3.2.1.1 Results

Figure 13 and Figure 14 clearly show that deactivation due to too low temperature in the catalyst is a problem in a mild hybrid. Table 5 clearly shows that the best control algorithm is when the internal combustion engine starts when the temperature get close to extinction temperature and then run until the state of charge of the batteries is 70%. From Figure 21 and Figure 22 the interpretation is that the function of the hybrid in untouched when this control algorithm is used. The reason why the fuel consumption is lower for the eudc cycle with no insulation in this case is because the efficiency in the driveline becomes higher when the mean value of the state of charge is higher. This effect however the distance the hybrid can travel in electrical drive only and therefore it is better to have insulation present anyway.

3.2.2 Full Hybrid

An overview of the simulations done with the full hybrid vehicle is shown in Table 6 which also show the average fuel consumption in the different simulations. Each and one of the simulations will be explained more closely in connection with the plots, see Figure 23 to Figure 32.

Driving cycle / Control algorithm	eudc, no insulation	eudc, with insulation	us06, no insulation	us06, with insulation
Original	6.657	6.657	7.894	7.894
Continuously electrically heated	8.723	7.638	8.759	8.282
Instantaneously electrically heated	7.033	7.015	8.197	8.185
Continuously heated by the ICE	*6.465*	*6.796*	7.931	7.895
Continuously heated by the ICE up to 70% SOC	6.452	6.422	*7.785*	*7.905*

Table 6, fuel consumption (l/100 km) in the different simulations of a full hybrid.

Because the simulation graphs when the exhaust system is insulated and when it is not looks very similar only the plots with insulation will be presented here, see Figure 23 to Figure 32.

In each simulation five graphs is presented;

- The amount of emissions converted.
- If the electrical heating is on or off (on=1 and off=0).
- If the internal combustion engine is on or off (on=1 and off=0).
- The state of charge of the batteries.
- The mean temperature in the catalyst.

Figure 23 and Figure 24 show graphs from the simulation with the original control algorithm. The most important thing to realize in this simulation is that in the conversion graph dips are shown every time the internal combustion engine starts. This means that deactivation due to too low temperature in the catalyst occurs.

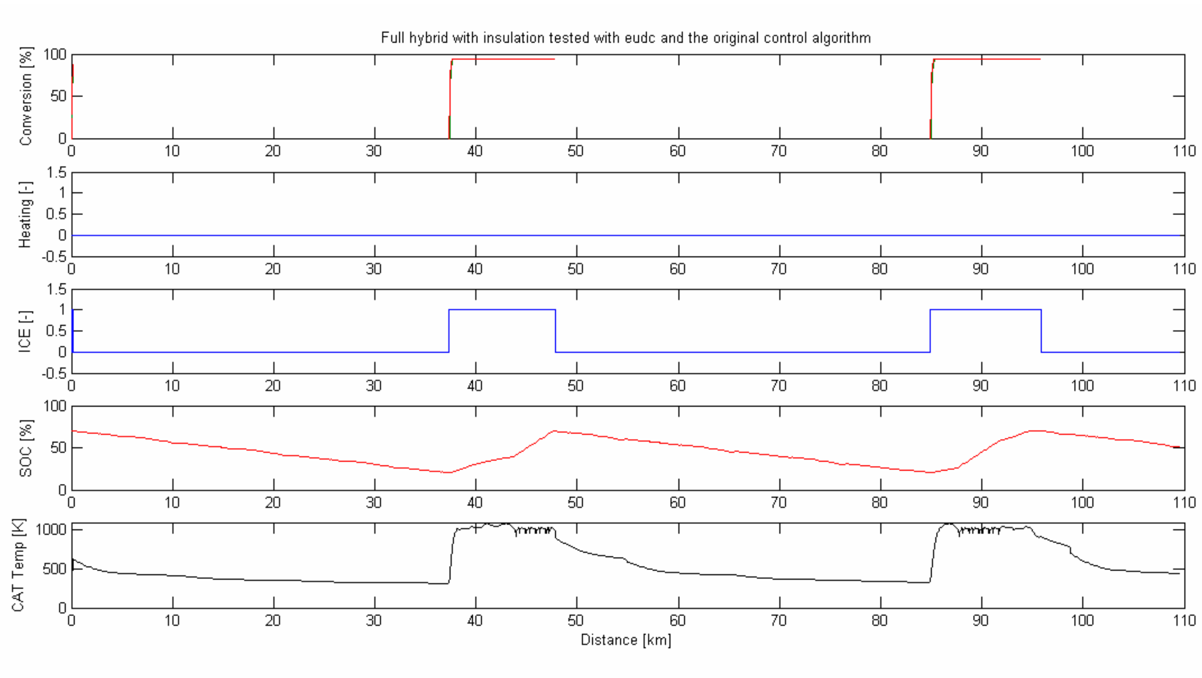

Figure 23, simulation of a full hybrid with insulation tested with eudc and the original control algorithm.

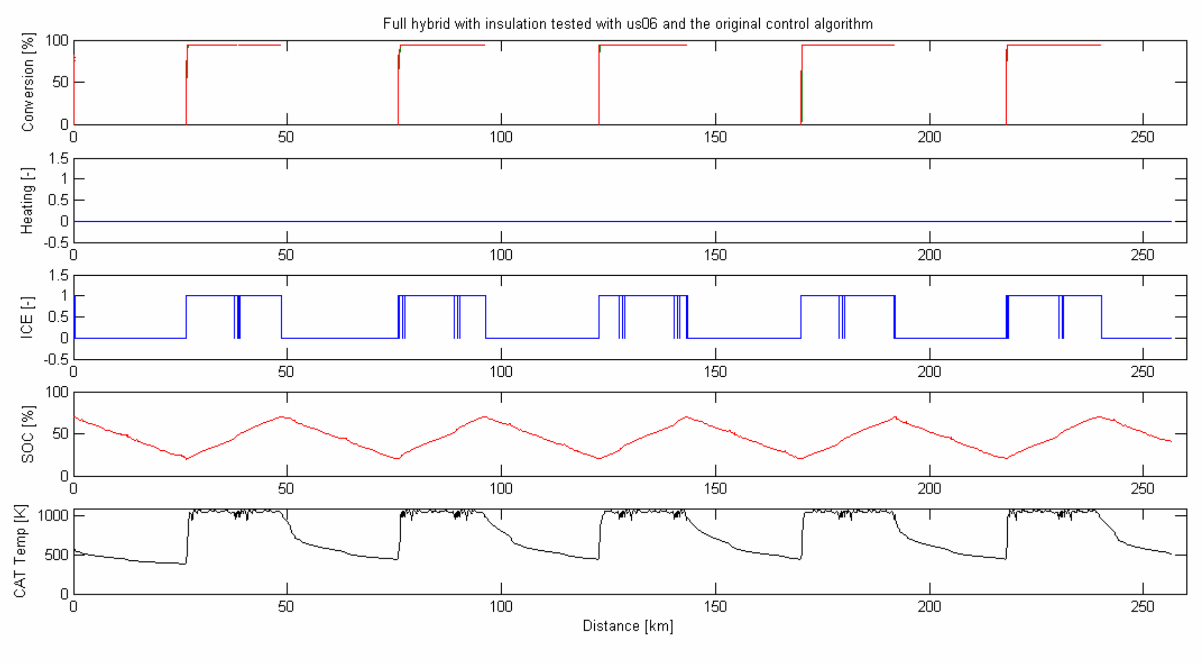

Figure 24, simulation of a full hybrid with insulation tested with us06 and the original control algorithm.

Figure 25 and Figure 26 show graphs from simulations with the algorithm where the electrical heater continuously heating the catalyst to prevent deactivation due to too low temperature. The most important thing to notice in these graphs is that the temperature always stays over the lightoff temperature and that the electrical heater turns on at even intervals.

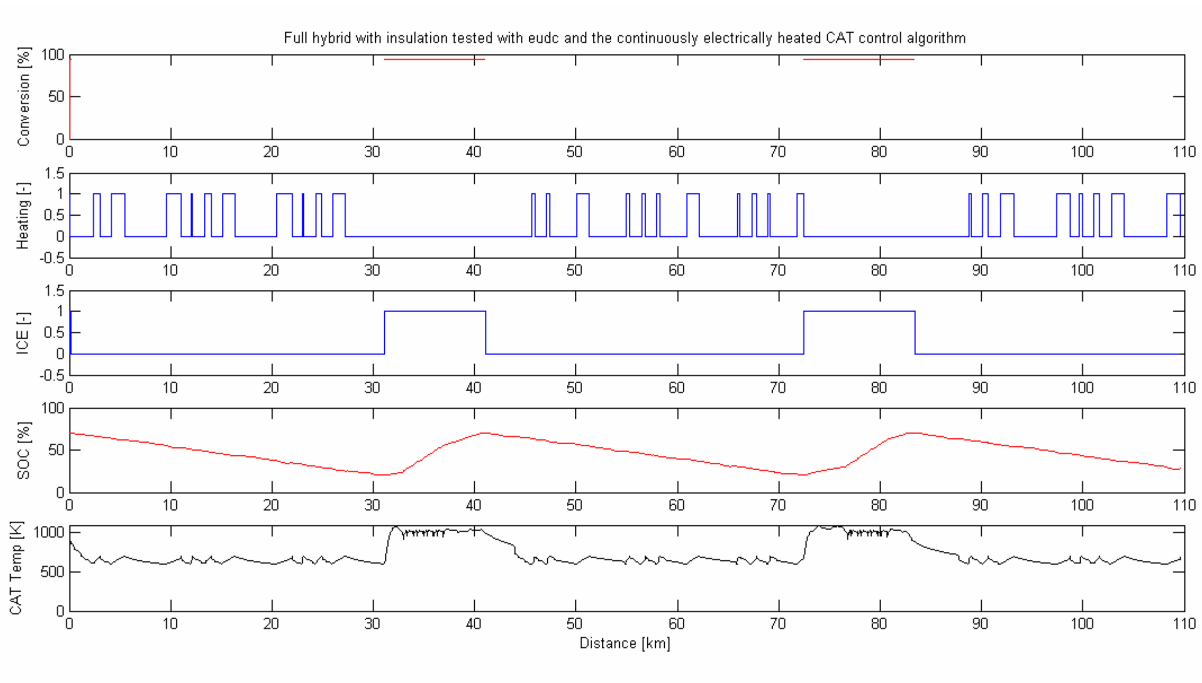

Figure 25, simulation of a full hybrid with insulation tested with eudc and the continuously electrically heated catalyst control algorithm.

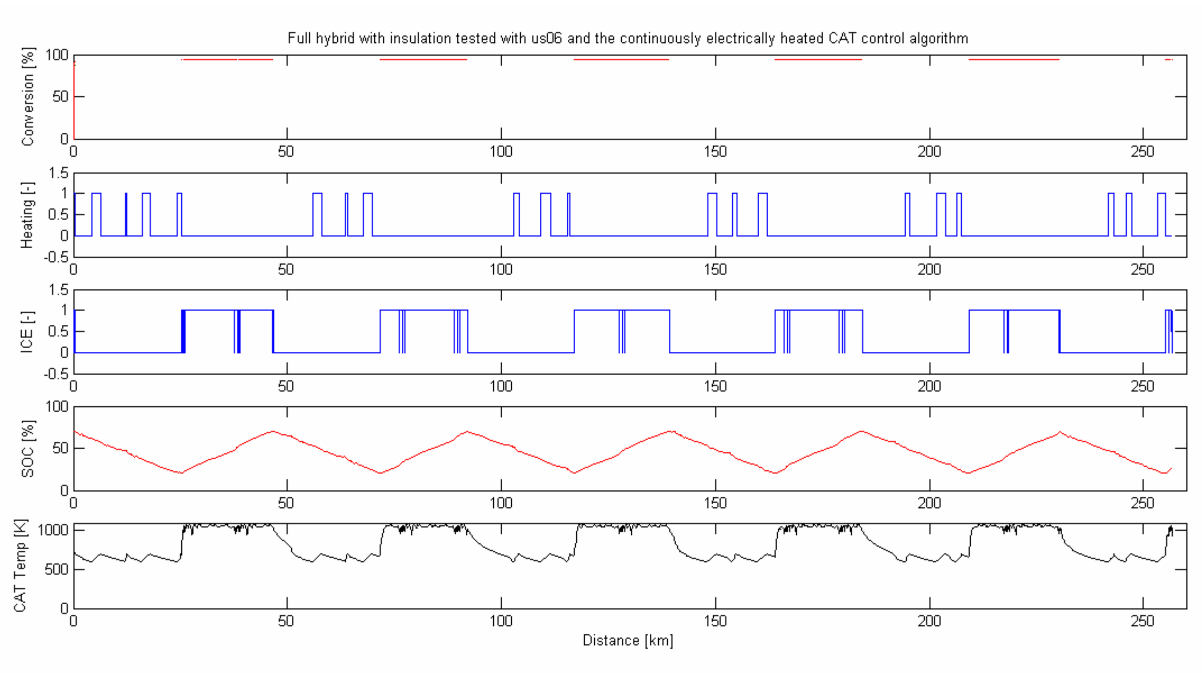

Figure 26, simulation of a full hybrid with insulation tested with us06 and the continuously electrically heated catalyst control algorithm.

Figure 27 and Figure 28 show graphs from simulations with the algorithm where the electrical heater heats the catalyst to its lightoff temperature right before the internal combustion engine starts. The most important thing to notice in this simulation is that the electrical heater is only on right before the start of the internal combustion engine and in between, when the internal combustion engine is off, the catalyst is allowed to cool off below its lightoff temperature.

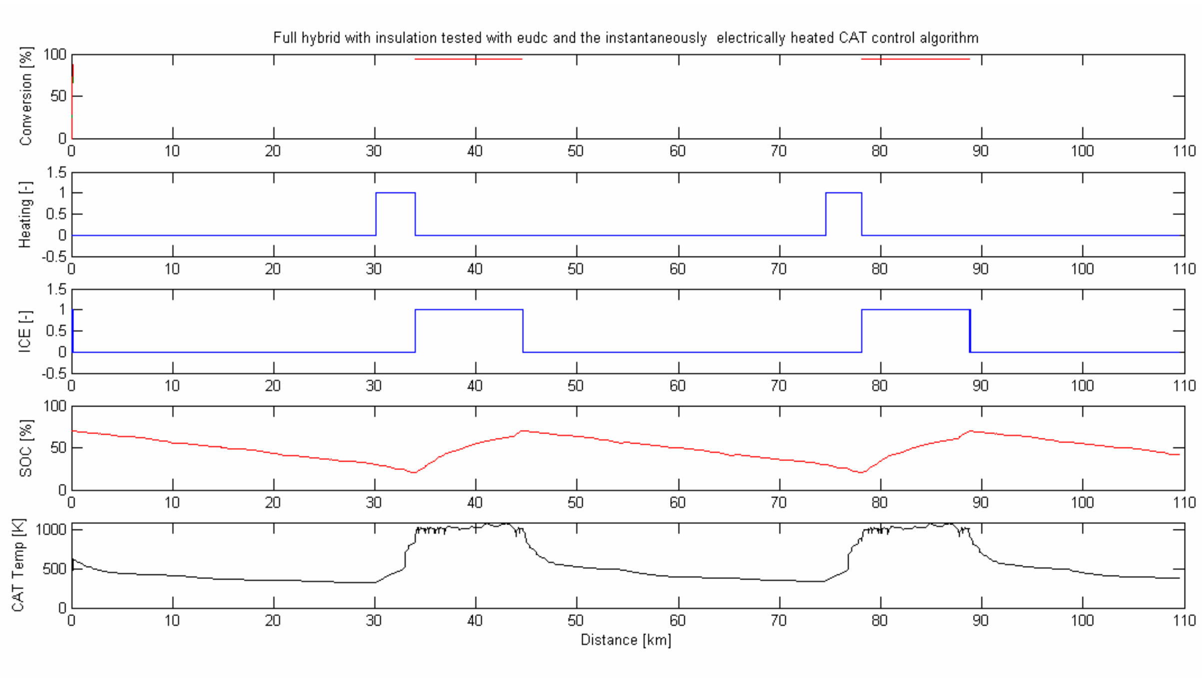

Figure 27, simulation of a full hybrid with insulation tested with eudc and the instantaneously electrically heated catalyst control algorithm.

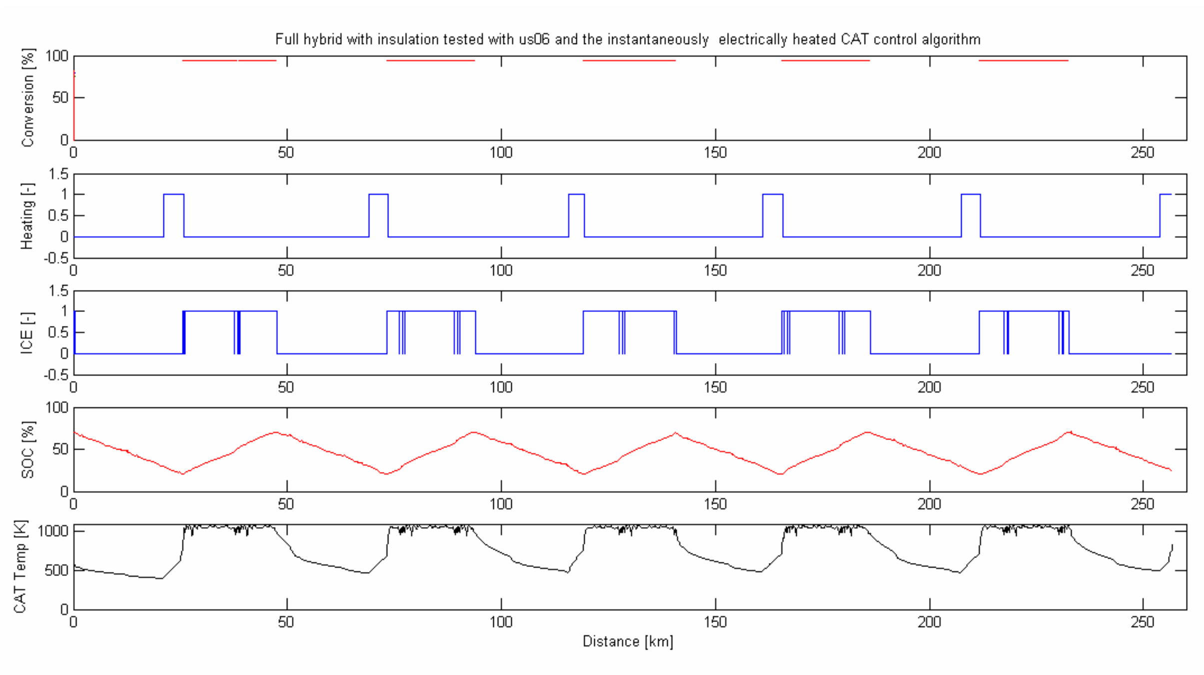

Figure 28, simulation of a full hybrid with insulation tested with us06 and the instantaneously electrically heated catalyst control algorithm.

Figure 29 and Figure 30 show graphs from simulations with the algorithm where the internal combustion engine continuously heating the catalyst to prevent deactivation due to too low temperature. The most important thing to notice in these graphs is that the temperature always stays over the lightoff temperature and that the internal combustion engine turns on at even intervals.

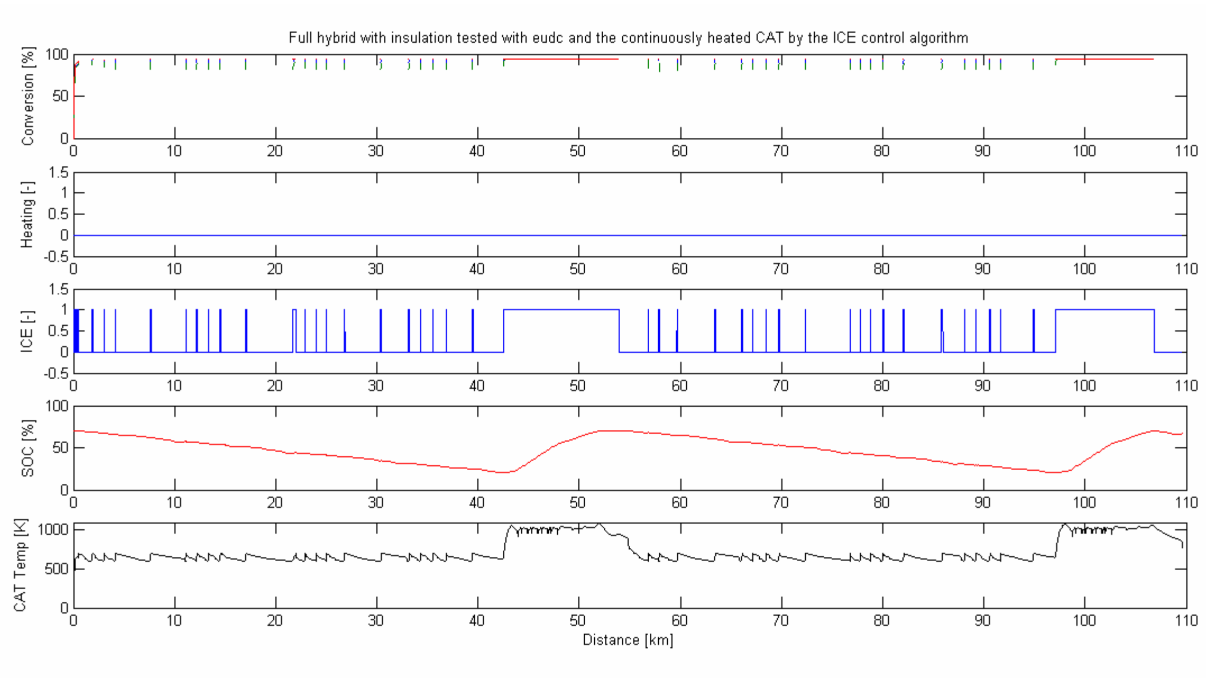

Figure 29, simulation of a full hybrid with insulation tested with eudc and the continuously heated catalyst by the internal combustion engine control algorithm.

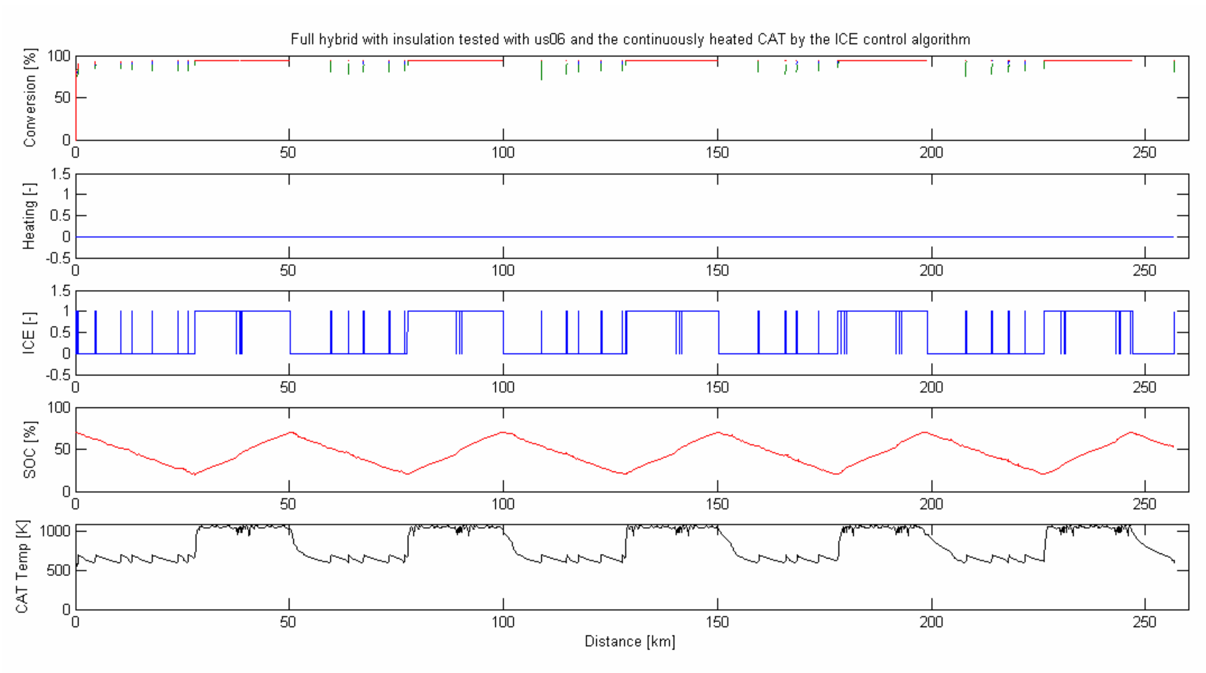

Figure 30, simulation of a full hybrid with insulation tested with us06 and the continuously heated catalyst by the internal combustion engine control algorithm.

Figure 31 and Figure 32 show graphs from simulations with the algorithm where the internal combustion engine continuously heating the catalyst to prevent deactivation due to too low temperature. The difference from the previous control algorithm is that when the internal combustion engine starts it keeps on running until the state of charge is 70 % which can be seen in the SOC graphs when comparing Figure 29 and Figure 30 with Figure 31 and Figure 32. Also in this simulation the temperature always stays over the lightoff temperature. The internal combustion engine get a behavior intermediary the previous control algorithm and the original control algorithm.

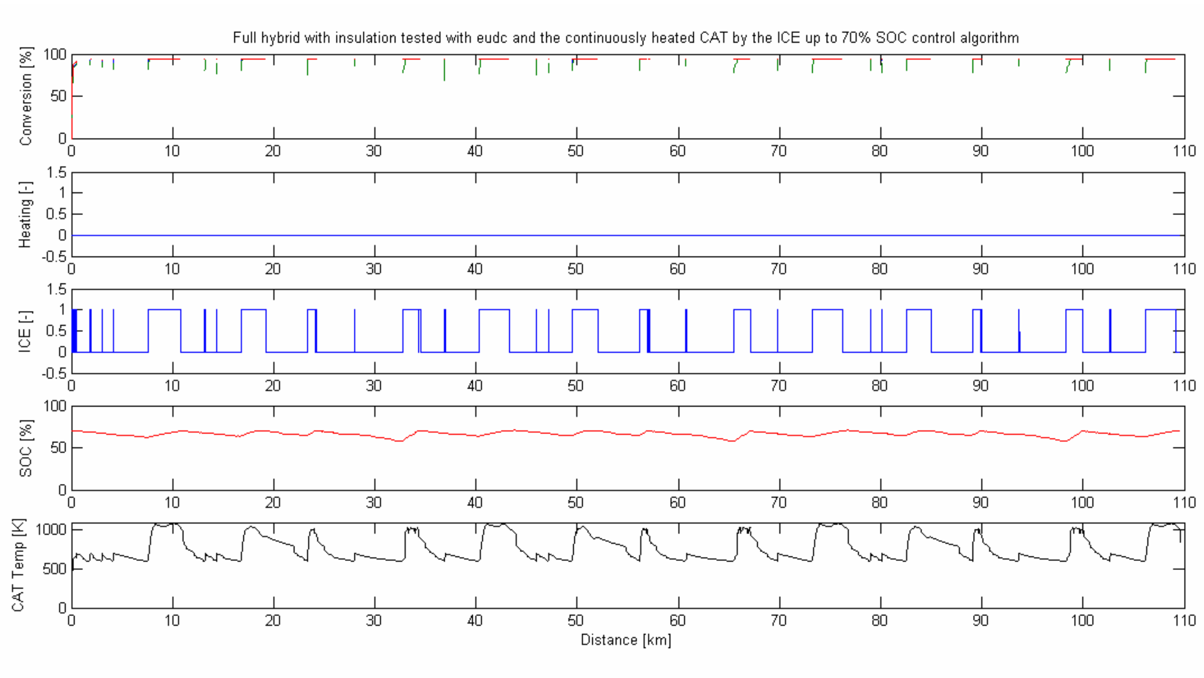

Figure 31, simulation of a full hybrid with insulation tested with eudc and the continuously heated catalyst by the internal combustion engine up to 70% state of charge control algorithm.

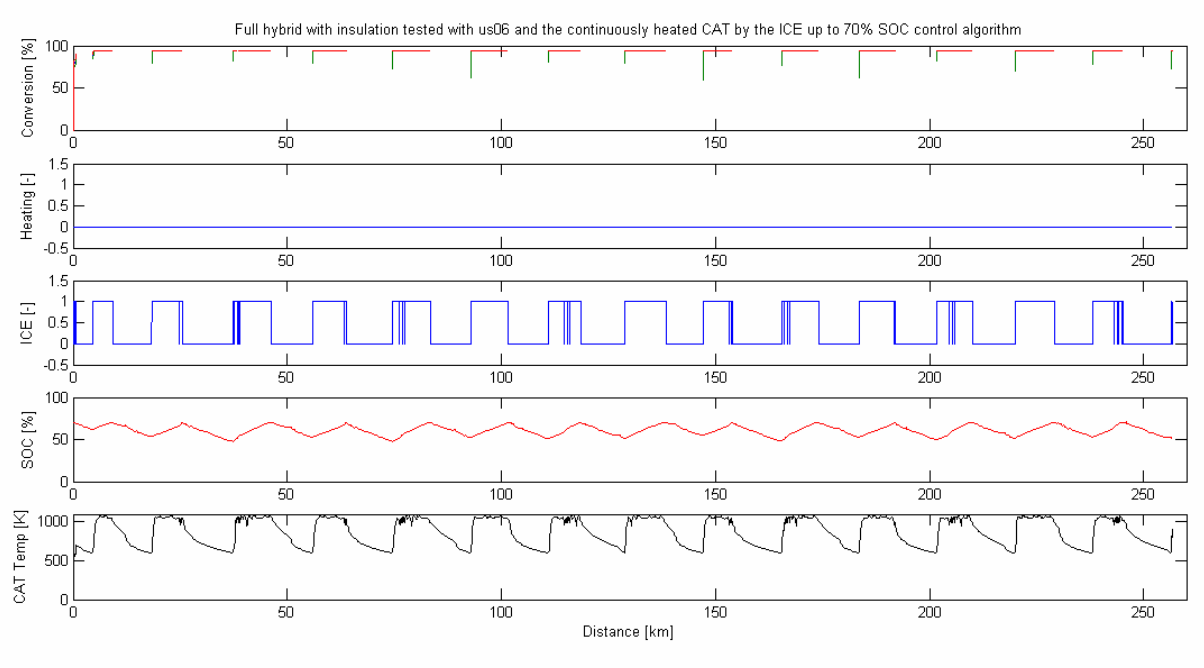

Figure 32, simulation of a full hybrid with insulation tested with us06 and the continuously heated catalyst by the internal combustion engine up to 70% state of charge control algorithm.

3.2.2.1 Results

As for the mild hybrid also Table 6 clearly shows that for the full hybrid the best control algorithm is when the internal combustion engine starts when the temperature get close to extinction temperature and then run until the state of charge of the batteries is 70%. However from Figure 31 and Figure 32 the interpretation that the function of the hybrid is untouched when this control algorithm is used is not true because of the fact that in a full hybrid, especially a plug-in hybrid, it is desirable to drive as much as possible in electrical drive only, so if this control algorithm is used the hole idea with the plug-in hybrid is destroyed. The reason why some driving cycles with control algorithms involving the internal combustion engine have lower fuel consumption when not insulated is because the efficiency in the driveline becomes higher when the mean value of the state of charge is higher.
It is more reasonable to use the instantaneously electrically heated catalyst control algorithm and Table 6 clearly shows that this control algorithm is the most favourable when the internal combustion engine should be turned off as much as possible. From Figure 27 and Figure 28 the interpretation that the functionality of the full hybrid is untouched is made for this control algorithm.
The result of the simulation lean however at that it does not matter if insulation is present or not which is not a surprise since the control algorithm allow the catalyst to cool down below its lightoff temperature and since both the catalyst with insulation and the catalyst without insulation is cooled to ambient temperature in between when the internal combustion engine is off the insulation does not make a great difference. The recommendation is however to have some insulation present due to the fact that the driving cycles used is rather kind to the hybrids car and does not have any heavy accelerations where the internal combustion engine goes in and helps the electrical machine. In such a case the insulation can make a bigger difference due to the fact that it takes longer to cool the catalyst, see chapter 3.1, which results in that the catalyst does not have to be heated as much to reach its lightoff temperature.

4 Discussion

The position of the catalyst, that is the length of the exhaust pipe, was also investigated but the conclusion was drawn quite early that this mainly influenced the lightoff time when starting the internal combustion engine and because the desire in this project is to never be under the lightoff temperature when starting the internal combustion engine this was not investigated further.

In the simulations the exhaust pipe were insulated but further simulations showed that this does not do any significant different for the result so the insulation of the exhaust pipe can be omitted due to economical factors.

An important aspect to mention is that the control algorithms used in this project is stock examples and is only representative which means that in a real hybrid a combination and clarification of the control algorithms is to needed.
An example is that when using the instantaneously electrically heated catalyst it can be controlled so that the heating begin at a certain state of charge and then when the temperature is high enough the internal combustion engine starts never mind the state of charge, this will save energy.
Another example is if the continuously heated catalyst is used, then an adjustable heater, that only heats the catalyst with the amount of heat that is lost through convection and radiation, can be used instead of the hysteresis regulator implemented in this project, this will save energy.

If the control algorithm that use the internal combustion engine to heat the catalyst is used an consideration should be done if the battery can be synchronized so that the batteries need to be charged and the catalyst need to be heated coincide with each other.

In this project the control algorithms regulate regarding to the highest lightoff temperature in Table 3 which is not necessary because the extinction temperature is lower than the lightoff temperature due to hysteresis properties of the catalyst [21]. This hysteresis is however very dependent on the catalyst properties and is not very well known as far as the author could find out. Lowering the temperature on which the control algorithms regulate would of course lower the energy consumption needed to avoid extinction of the catalyst.

Even though the control algorithm with the instantaneously electrically heated catalyst does not account for the need of have to start the internal combustion engine before the state of charge in the batteries reaches its minimum, for example due to high power needed at heavy acceleration, it is a great help to decrease the lightoff time essentially when the internal combustion engine is started.

An interesting idea is that if the control algorithm with the instantaneously electrically heated catalyst is used it may be enough to heat the first 20-30% of the catalyst and let the exothermic reactions heat the rest of the catalyst, because it is in the first 20-30% most of the reactions occur which is shown in Figure 4, in this way 70-80% energy can be saved when heating the catalyst.

Something that is very important not only in this project but also for the whole development of hybrid vehicles is the batteries. In this project the batteries is assumed to have an energy content of 0.1 kWh/kg and to be able to deliver power of 1-2 kW/kg but in pace with continuously developing of better batteries the quality of the hybrid vehicles will improve dramatically.

4.1 Future work

There are several opportunities to future work on this area, a few examples are:

- Optimize insulation thickness of the catalyst due to cooling properties and economics.
- Optimize an advanced control algorithm that work in all types of hybrid cars for all types of driving.
- Investigate the hysteresis between lightoff temperature and extinction temperature in a three way catalyst for the major reactions including HC, CO and NOx.
- Investigate how the smartest heating of a catalyst should be done. Should only the first 20 % be heated or should the ingoing air be heated instead or can waste heat from for example the power electronics be used to heat the catalyst?
- An investigation of the batteries is always interesting in this area and how to optimize the drive range of especially a plug-in hybrid without ignoring the economical aspects is a highly relevant question.
- The most optimal further work would be to be able to do simulation and measuring on a real vehicle to test the conclusions in this thesis.

5 Conclusions

The main, and most important, conclusion that can be drawn from this project is that this is a real problem, not only for the full hybrids but it is also for the mild hybrids. This is of course a major concern if the car manufactures have ignored this potential environmental disaster which means that the hybrid cars is potentially even more damaging for the environment than the conventional cars.

Furthermore the conclusion that different kinds of hybrid cars demands different kinds of control algorithms is of course important to think of when designing hybrid cars in the future.

In a mild hybrid the best way to avoid catalyst extinction is to start the internal combustion engine when the temperature in the catalyst gets close to extinction temperature or if the state of charge in the batteries gets to low and then charge the batteries at the same time as the catalyst heats up until the batteries are full.

In a full hybrid it is better to let the catalyst extinguish and then electrically heat the catalyst to its lightoff temperature right before the internal combustion engine starts. One of the best things with this method is that this can be done before all cold starts of the internal combustion engine which completely takes away the high emissions when cold starting before the catalyst reach its lightoff temperature in conventional vehicles.

Appendix 1

Exhaust pipe	
Length	0.6 m
n, the number of parts the exhaust pipe is divided into in the discrete model	50
Outer diameter	0.055 m
Wall thickness	0.001 m
Specific heat capacity	460 J/(Kg K) [22]
Density	7800 Kg/m^3 [22]

Catalyst	
Length	0.3 m
n, the number of parts the catalyst channel is divided into in the discrete model	100
Diameter	0.1 m
Cell density	620000 cells/m^2 [23]
Channel diameter	0.0014 m [23]
Channel wall thickness	13.6 % of the channel diameter [24]
Specific heat capacity	1200 J/(Kg K) [23]
Density	2000 Kg/m^3 [23]

Insulation	
Thickness	0.01 m
Thermal conductivity	0.104 W/(m K) [25]

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