ENERGY MANAGEMENT FOR VEHICLE POWER NETS

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ABSTRACT - In the near future a significant increase in electric power consumption in vehicles is to be expected. To limit the associated increase in fuel consumption and exhaust emissions, smart strategies for the generation, storage/retrieval, distribution, and consumption of the electric power can be used.

This paper considers two strategies for energy management: a regenerative braking strategy and a more advanced strategy based on optimization techniques. To explain the energy management potential behind these strategies, typical characteristics of components that are directly related to the energy flow in a vehicle will be discussed.

Although it seems a contradiction, the advanced energy management strategy does not aim at operating the internal combustion engine in the area with the highest efficiency. It will be shown that the method considered here is a better solution to the energy management problem than one that considers the efficiency map of the engine.

Subsequently, engineering rules are presented to estimate the performance that can be expected for each strategy. These rules apply to a vehicle configuration with a conventional drive train. The characteristics of components are included as input parameters to make the method general applicable.

To show the value of the engineering rules, the potential fuel reduction is computed for a specific vehicle configuration and drive cycle and compared with simulation results.

MAIN SECTION

1. INTRODUCTION

Over the last two decades, the electric power consumption in automobiles increased significantly (approximately 4% every year) and in the near future, even higher power demands are expected due to several trends in the market:

- The introduction of the drive-by-wire concept which replaces mechanical and/or hydraulic components by electrical devices.
- Customers expect more safety and comfort from new vehicles. Think for example of features such as active suspension or video entertainment at the back seat.
- Environmental regulations force car manufacturers to develop alternative propulsion systems, in order to reduce the fuel consumption and exhaust gasses.

At this moment, the average electric power consumption in modern vehicles ranges between 750 W and 1 kW, depending on the vehicle and its accessories (4). Considering the fact that a
belt driven 14V alternator typically supplies 1.2 kW at full load, power limitations cannot be neglected in the next years.

Already in the mid-1990’s, several automobile manufacturers realized this problem and started considering new methods to overcome this problem. One of the most promising proposals is to introduce an advanced power net, operating at a nominal voltage of 42V. Under the name “42V PowerNet” (6) several new topologies are defined that should meet tomorrow’s power requirements. Moreover, these topologies make use of high-power components and offer new challenges for energy management to improve the overall energy efficiency in the vehicle.

The 42V power net topology considered in this paper can be seen as a scaled version of a conventional 14V power net. The 42V alternator (power controller) is connected directly to the electric loads as well as the 36V battery.

In (5) and (7), several optimization-based methods are presented to control the energy flow from the alternator to the power net. Based on that work, this paper presents engineering rules that estimate what performance can be expected, regarding the typical characteristics of the components.

This paper is structured as follows: The vehicle is modeled in Section 2. The concept of energy management including regenerative braking will be handled in Section 3. A set of guidelines to predict the performance of an energy management strategy is presented in Section 4. The expected performance will be compared with simulation results in Section 5. Finally, conclusions are given in Section 6.

2. VEHICLE MODEL & CHARACTERISTICS

2.1 Power Flow In A Vehicle

The type of vehicles considered in this paper are conventional vehicles with a manual transmission. The structure of such a vehicle is represented as a power-based model in Figure 1. The drive train block contains all drive train components including clutch, gears, wheels, and inertia. The alternator is connected to the engine with a fixed gear ratio.

The power flow in the vehicle starts with fuel that goes into the combustion engine. The mechanical power that comes out of the engine splits up into two directions: one part goes to the mechanical drive train for vehicle propulsion, whereas the other part goes to the alternator. The alternator provides electric power for the electric loads but also takes care of charging the battery. Contrary to the other components, the power flow of the battery can be positive as well as negative. In the end, the power becomes available for vehicle propulsion and for electric devices connected to the power net.

The goal of energy management is to control the alternator power such that the fuel consumption is reduced, while the drivability remains unaffected, i.e. the driver should not experience different vehicle behavior when the controller is applied. This requirement greatly reduces the problem complexity. It implies that the vehicle speed and thus the drive train torque and engine speed remain unaffected and therefore it is possible to use them as given information.

The remaining components of interest are the engine, the alternator, and the battery. Using a sampling interval of 1 second or larger, their dynamic behavior is neglected, so their
characteristics are represented by static models. The only remaining dynamics in the model is an integrator for the energy storage in the battery.

2.2 Fuel Convertor

The internal combustion engine (ICE) can be represented by a nonlinear static map that describes the fuel rate $\dot{m}$ as function of the engine speed $\omega$, and the torque delivered by the engine $\tau_{eng}$. For given engine speed, the mechanical power delivered by the engine $P_{eng}$ can be derived from the engine torque as follows:

$$P_{eng} = \omega \tau_{eng}$$

Using this relation, the fuel map can also be write as a nonlinear function of engine speed and power:

$$\dot{m} = f(P_{eng}, \omega)$$

A typical fuel map of a Spark Ignition engine is displayed in Figure 2. In this figure, fuel consumption curves are drawn for different engine speeds as function of mechanical power. As can be seen, the fuel map can approximately be represented by a linear relation between the mechanical power and the fuel rate for each engine speed.

$$f(P_{eng}, \omega) \approx f_0(\omega) + \frac{k_f}{h_f} P_{eng}$$

The fuel use at zero torque $f_0(\omega)$ is caused by mechanical friction and pumping losses in the engine. It increases with the engine size, the number of cylinders, and the engine speed. The dimensionless factor $k_f$ has a typical value around 2.5, which corresponds with a combustion efficiency of 40%. Parameter $h_f$ is the lower heating value of fuel (i.e., the chemical energy content of fuel), with a typical value of 44 kJ/g for gasoline and 49 kJ/g for diesel.

As is illustrated in the efficiency map in Figure 3, the operating range of the fuel converter is bounded by a drag torque and a maximum torque that are both speed dependent. The drag torque is defined as the engine torque when no fuel is injected. Translated to power this becomes:

$$f_0(\omega) + \frac{k_f}{h_f} P_{eng_{min}} = 0 \quad \Rightarrow \quad P_{eng_{min}}(\omega) = -\frac{h_f}{k_f} f_0(\omega)$$
The fuel map can then also be described as:

\[
\dot{m} = \frac{k_f}{h_f} (P_{\text{eng}} - P_{\text{eng\_min}})
\]

The fuel consumption over a drive cycle can be computed by:

\[
m = \int_0^{t_e} \dot{m} \, dt = \frac{k_f}{h_f} \int_0^{t_e} (P_{\text{eng}} - P_{\text{eng\_min}})
\]

2.3 Alternator

The alternator can be represented by a static nonlinear map that describes the mechanical power as function of the electrical power and the rotational speed. A typical alternator map is shown in Figure 4. Similar to the engine, the alternator can be approximated by a linear relation between electrical power \(P_{\text{el}}\) and mechanical power \(P_{\text{alt}}\) with a constant slope \(k_g\):

\[
P_{\text{alt}} = g(P_{\text{el}}, \omega) \approx g_0(\omega) + k_g P_{\text{el}}
\]
The slope $k_g$ has a typical value around 1.25, which corresponds with an efficiency of 80%. $g_0(\omega)$ is caused by mechanical friction and increases with the speed. The operating range of the alternator is bounded between:

$$0 \leq P_{el} \leq P_{el\, max}(\omega) \Rightarrow P_{alt\, min}(\omega) \leq P_{alt} \leq P_{alt\, max}(\omega)$$

where

$$P_{alt\, min}(\omega) = g_0(\omega) \quad \text{and} \quad P_{alt\, max}(\omega) = g_0(\omega) + k_g P_{el\, max}$$

![Characteristic alternator map](image.png)

**Figure 4: Characteristic alternator map**

### 2.4 Battery

The battery characteristics can be modeled by:

$$P_{bat} = P_s + P_{loss}(P_s, E_s, T)$$

$P_{bat}$ represents the power entering or leaving the battery terminals, and $P_s$ represents the power actually stored in the battery. $P_{loss}$ represents the battery losses that depend on the storage power, the energy level in the battery $E_s$, and the temperature $T$. The energy level in the battery is given by a simple integrator:

$$E_s(t) = E_s(0) + \int_0^t P_s(\tau) \, d\tau$$

The state of charge (SOC) represents the relative energy level in the battery:

$$SOC = \frac{E_s}{E_{s\, max}} \cdot 100\%$$

For simplicity, battery losses are ignored, so the battery can be modeled as:

$$P_{bat} = P_s$$
2.5 Drive Train

The drive train consists of clutch, transmission, final drive, wheels, and inertia. They need not be modeled in detail, only the relation between vehicle speed, engine speed, and drive train torque is of interest.

For a given vehicle speed profile $v(t)$ and selected gear ratio $g_r(t)$, the corresponding engine speed and torque needed for propulsion can be calculated using the following formulas:

\[
\omega(t) = \frac{f_r}{w_r} g_r(t) v(t)
\]

\[
F_{\text{drive}}(t) = M \dot{v}(t) + \frac{1}{2} \rho C_d A_d v(t)^2 + MgC_r
\]

\[
\tau_{\text{drive}}(t) = \frac{w_r}{f_r} \frac{1}{g_r(t)} F_{\text{drive}}(t)
\]

\[
P_{\text{drive}}(t) = \omega(t) \tau_{\text{drive}}(t)
\]

When the engine speed drops below a certain value, the clutch is opened. Then the drive train torque becomes zero and the engine runs at idle speed. The parameters are explained in Table 1.

<table>
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<th>Quantity</th>
<th>Symbol</th>
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<td>$M$</td>
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<td>$f_r$</td>
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<td>Air friction coefficient</td>
<td>$g$</td>
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<tr>
<td>$C_r$</td>
<td>Rolling resistance</td>
<td>$\rho$</td>
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3. ENERGY MANAGEMENT

Energy management strategies are characterized by the fact that they shift the operating points of energy converting components, such that the losses are reduced. In the situation considered in this paper, the operating points of the ICE, the alternator, and the battery can be shifted, although not independently. These actions should lead to a reduction in fuel consumption. This section takes a closer look at the fuel use characteristics of an SI engine and explains how fuel savings can be obtained.

3.1 The Difference Between Efficiency Improvement And Fuel Reduction

In automotive engineering, several different forms are used to represent the characteristic behavior of an ICE. A very intuitive method is to consider the absolute fuel rate of the engine and express it as a function of engine speed $\omega$ and engine torque $\tau_{\text{eng}}$ (measured at the crankshaft).

The absolute fuel consumption can be normalized with respect to the power delivered by the
engine. This so called Brake Specific Fuel Consumption (BSFC) is defined as:

\[ \beta_{\text{eng}} = \frac{\dot{m}}{P_{\text{eng}}} = \frac{\dot{m}}{\omega \tau_{\text{eng}}} \]

By including the lower heating value \( h_f \), the instantaneous efficiency of the engine can be calculated:

\[ \eta_{\text{eng}} = \frac{P_{\text{eng}}}{P_{\text{fuel}}} = \frac{\omega \tau_{\text{eng}}}{h_f \dot{m}} = \frac{1}{h_f \beta_{\text{eng}}} \]

Now consider the fuel rate curves as drawn in Figure 2. The corresponding curves for the BSFC and the efficiency are given in Figure 5 a and b respectively. Apart from a constant factor, they are inverse to each other. Except for the highest power region, the efficiency increases (and consequently, the BSFC decreases) when more power is delivered by the ICE and the engine speed remains constant. This can be explained as follows.

If the mechanical power delivered by the engine is zero, the fuel rate is \( f_0(\omega) \). Consequently, the efficiency of the engine will be zero. If the ICE does provide a small amount of mechanical power, the extra fuel use with respect to the term \( f_0(\omega) \) is relative small. As a result, the efficiency of the engine increases significantly in the lower power region, because it provides relatively much additional power for relatively little additional fuel. For increasing \( P_{\text{eng}} \), the efficiency will further increase. This is due to the fact that the offset term \( f_0(\omega) \) becomes less dominant with respect to the total fuel consumption \( f(P_{\text{eng}}, \omega) \) of the engine. When the engine comes near to its maximum power limitations, the combustion is less optimal, so the efficiency curves start decreasing as indicated in Figure 5 b.

![Figure 5: Engine maps: (a) BSFC map (b) Efficiency map](image-url)

It is easy to assume that increasing the efficiency (or lowering the BSFC) will result in a lower fuel consumption. In some situations this is true, think for example of a gear shifting problem where the requested engine power is predefined and freedom exists in the engine speed by selecting the optimal gear shifting pattern. Because the engine power is fixed at each time instant, a higher efficiency corresponds with a lower fuel rate and results in a lower fuel consumption for a driving cycle. However, it will be shown that the energy management
The problem considered in this paper is not solved simply by bringing the ICE to an area with a higher efficiency (or lower BSFC).

In a vehicle with a conventional drive train and manual transmission, the driver defines directly the speed of the engine, so there is no freedom left in changing the engine speed. The availability of an energy storage device (here the battery) introduces freedom to the energy management strategy when to generate electric power. By changing the power set point of the alternator, the engine moves to a new operating point, following one of the curves in Figure 5.

Suppose that the vehicle drives at a constant speed and requires a fixed amount of mechanical power $P_{\text{drive}}$ for vehicle propulsion. Repeating the fuel map of Figure 2 for this particular speed leads to the schematic fuel curve as given in Figure 6. According to the requested alternator power $\Delta P_{\text{alt}}$, the ICE moves to a new operating point. The corresponding change in fuel consumption $\Delta \dot{m}$ depends directly on the slope of the fuel map, leading to the definition of the incremental fuel rate $\lambda$ in [g/J]:

$$\lambda = \frac{\Delta \dot{m}}{\Delta P_{\text{alt}}}$$

An effective strategy should compare the additional costs for delivering additional power at each time instant and generate electric energy when the incremental fuel rate is typically small. In general, these areas do not correspond to the operating range where the ICE achieves maximum efficiency (or minimal BSFC). In Figure 6, the operating point where the engine achieves maximum efficiency is indicated by $P_{\eta_{\text{max}}}$. Since the slope of the curve slightly increases when the engine moves towards $P_{\eta_{\text{max}}}$, requesting additional power becomes less profitable at higher power levels.

![Figure 6: Explanation of incremental fuel rate](image)

To answer the question whether it is profitable or not to generate electric power and hence, push the ICE to a higher power level, one can consider the slope of the nonlinear fuel map with respect to the present operating point of the engine:

$$\phi(P_{\text{eng}}, \omega) = \frac{\partial f(P_{\text{eng}}, \omega)}{\partial P_{\text{eng}}}$$
In principle, the idea of saving fuel comes down to producing electric energy at moments that the costs are relatively low. So comparing the value of $\phi$ at different moments, will tell the energy management strategy when to use the alternator and when to use the battery for supplying the electric loads.

For modern engines, the deviations in $\phi$ are rather small, which limits the fuel reduction that can be obtained with an electric energy management system. When battery losses are taken into account, the savings on the fuel map must be larger than the additional losses of storing and retrieving energy, which further reduces the potential.

This analysis also applies to mild hybrid electric vehicles with an integrated starter generator (ISG) that is mounted directly on the crank shaft, such as the Honda Insight (2). There the engine and the ISG are always operating simultaneously and there is no freedom in the engine speed. Fuel reduction is then obtained mostly by the fact that a smaller engine can be used, because the ISG can be used for boosting to obtain a similar performance as a larger engine. A smaller engine has smaller friction and pumping losses, and thus a smaller drag torque. This results in less fuel consumption during propulsion, and also leaves more energy available for regenerative braking.

Full hybrid electric vehicles, such as the Toyota Prius (3), have both freedom in the engine speed and torque, and the engine and the electric motor can be operated independently. This makes the energy management problem more complex and lies beyond the scope of this paper.

### 3.2 Regenerative Braking

When a vehicle is decelerating, kinetic energy becomes available, causing a negative drive train torque. As long as the clutch is closed, a part of this energy is absorbed by the engine (which has a negative drag torque). The remaining part can be absorbed by the brakes that convert it into useless heat and wear, but it can also be used by the alternator to convert it into useful electric energy. When the clutch is engaged, the kinetic energy can no longer be used by the engine or the alternator, so it will all be absorbed by the brakes.

Because regenerative braking delivers electrical power with no extra fuel use, it should be used as much as possible. The brakes should only be used when the desired deceleration torque is larger than the maximum negative torque that can be delivered by the engine and the alternator.

The potential of regenerative braking can be increased by altering the drive train configuration such that the alternator is connected directly to the drive train instead of to the engine. In this case, generating can be continued when the clutch is open and the vehicle is still decelerating. A drawback is that when the vehicle is standing still, no power can be generated, so electricity is drawn from the battery. This configuration is not further investigated in this paper.

### 4. PERFORMANCE ANALYSIS

This section presents some engineering rules to predict what fuel reduction can be obtained for a given configuration with regenerative braking and with a more advanced energy management strategy compared to a baseline strategy.

#### 4.1 Baseline Strategy

The baseline strategy is defined such that the alternator always generates exactly what is
For a given speed and gear profile, the corresponding engine speed \( \omega \) and propulsion power \( P_{\text{drive}} \) can be computed as shown in Section 2. By adding the alternator power, the total mechanical power becomes:

\[
P_{\text{mech}} = P_{\text{drive}} + P_{\text{alt}}
\]

The power delivered by the engine is then given by:

\[
P_{\text{eng}} = \max(P_{\text{mech}}, P_{\text{eng min}})
\]

During deceleration periods where \( P_{\text{drive}} < P_{\text{eng min}} \), the electrical power is generated without using fuel. This means that the baseline strategy already does some regenerative braking. This is illustrated in Figure 7a, where the mechanical energy that can be obtained for free is indicated by the solid areas. The amount of mechanical energy can be calculated as follows:

\[
P_{\text{regen bl}} = -\min(\max(P_{\text{eng min}} - P_{\text{alt}}, P_{\text{drive}}), P_{\text{eng min}} - P_{\text{alt min}}) + P_{\text{eng min}} - P_{\text{alt min}}
\]

The corresponding electric power is then given by:

\[
P_{\text{el regen bl}} = \frac{1}{k_g} P_{\text{regen bl}}
\]

Using the linear approximation of the fuel map, the amount of fuel that is saved with respect to a fictive baseline strategy that does not exploit regenerative braking is then given by:

\[
\Delta m_{\text{regen bl}} = \frac{k_f}{h_f} \int_{0}^{t_e} P_{\text{regen bl}} \, dt
\]

The amount of energy that can be obtained for free increases with \( P_{\text{alt}} \) and thus with the requested load.

4.2 Regenerative Braking Strategy

The regenerative braking strategy as will be considered in this paper is defined as follows. During normal operation, the alternator generates exactly what is requested. During deceleration phases, it generates the maximum amount of electrical power that does not cost fuel. If this is more than what is requested at that moment, the surplus of electrical energy is stored in the battery. After the braking period, the load request is supplied by the battery, till it reaches the original SOC level. From that point on, the loads are provided by the alternator again.
During normal operation, the additional fuel use is more or less proportional with the electric energy provided, so the fuel saving that can be obtained with regenerative braking, depends on the amount of electric energy that can be generated for free during braking periods.

The mechanical power that can be used for free during braking is the part between the engine drag power minus the alternator drag power, and the engine drag power minus the maximum alternator power. This is illustrated by the solid areas in Figure 7b. The amount of power can be calculated as follows:

\[ P_{\text{regen}} = \min(\max(P_{\text{eng min}} - P_{\text{alt max}}, P_{\text{drive}}), P_{\text{eng min}} - P_{\text{alt min}}) + P_{\text{eng min}} - P_{\text{alt min}}) \]

The corresponding electric power is then given by:

\[ P_{\text{el regen}} = \frac{1}{k_g} P_{\text{regen}} \]

The corresponding fuel consumption that can be saved is given by:

\[ \Delta m_{\text{regen}} = \frac{k_f}{k_f} \int_0^{t_e} P_{\text{regen}} \, dt \]

The amount of electrical energy that can be obtained for free with regenerative braking does not depend on the requested electric load, but only on the power needed for propulsion. How much of the electric energy is stored for later usage, does depend on the load.

The amount of electrical energy that is already obtained for free with the baseline increases with the requested load. This means that the higher the load is, the smaller the additional improvement of a real regenerative braking strategy.

4.3 Advanced Energy Management Strategy

On top of regenerative braking, additional fuel reduction can be obtained by using a more advanced energy management strategy, that exploits differences in the incremental fuel cost and only generates when these costs are low. Its potential depends on the differences between
the nonlinear fuel map and the linear approximation, in other words, the deviation of \( \phi(P_{\text{eng}}, \omega) \) from the linear approximation \( k_f \).

The fuel reduction also depends on the amount of the requested electric load and the maximum alternator power. When the amount of the electric load is small compared to the maximum alternator power, most of the electricity can be generated in the cheapest area. Since the load is small, the fuel use needed for it is also small and the fuel reduction will also be small. When the load is higher, it causes more fuel use, so the fuel that can be saved by generating only at cheap moments also increases. When the requested load is close to the maximum alternator power, there is not much freedom anymore when to generate, so the fuel reduction will decrease again.

Suppose that the drive train loads are such that the corresponding \( \phi \) is uniformly distributed between:

\[
1 - \sigma_f < \frac{\phi}{k_f} < 1 + \sigma_f
\]

If the requested electrical load equals the maximum alternator power, it is generated within the interval \([1 - \sigma_f, 1 + \sigma_f]\), with an average of 1. If the requested load is half of the maximum alternator power, it can be generated within the interval \([1 - \sigma_f, 1]\), so with an average of \(1 - \frac{1}{2} \sigma_f\). If the requested load is a quarter of the maximum alternator power, it can be generated within the interval \([1 - \sigma_f, 1 - \frac{1}{4} \sigma_f]\), so with an average of \(1 - \frac{1}{4} \sigma_f\).

Defining \( \alpha \) as the relation between the average requested load over a drive cycle and the maximum electric alternator power:

\[
\alpha = \frac{\bar{P}_{\text{load}}}{P_{\text{el max}}}
\]

The load can be generated within the interval \([1 - \sigma_f, 1 - (1 - 2 \alpha) \sigma_f]\), with an average of \(1 - (1 - \alpha) \sigma_f\).

The fuel that can be saved on top of regenerative braking is then given by:

\[
\Delta m_{\text{em}} = (1 - \alpha) \sigma_f \frac{k_f}{k_g} \int_{t_e}^{t_e} (P_{\text{load}} - P_{\text{el regen}}) \, dt
\]

5. COMPARISON

In this section, the fuel reduction that can be obtained with regenerative braking and advanced electric energy management for a specific vehicle and drive cycle will be estimated with the rules presented in the previous sections, and will be compared with simulation results.

Analytical and simulation results are obtained for 4 strategies:

1. The fictive baseline strategy that does not use regenerative braking at all.
2. The realistic baseline strategy that uses regenerative braking to some extent.
3. The regenerative braking strategy that fully exploits the regenerative braking potential.

4. The advanced energy management strategy.

The advanced energy management strategy is a Dynamic Programming routine that minimizes the fuel consumption over the entire drive cycle with the constraint that the energy level of the battery at the end is the same as at the beginning. The fuel consumption is calculated using the original nonlinear fuel map and alternator map. This method is described in more detail in (5).

5.1 Simulation Parameters

Simulations are done for a conventional vehicle equipped with a 100 kW 2.0 liter SI engine and a manual transmission with 5 gears. A 42V 5 kW alternator and a 36V 30Ah lead-acid battery make up the alternator and storage components of the 42V power net. The parameter values for the simulation model are given in Table 2. The slope $\phi$ of the engine map varies roughly between 2.4 and 2.6, leading to a value for $\sigma$ of 0.05.

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</table>

Simulations are done for the New European Driving Cycle (NEDC) (1), of which the vehicle speed and the corresponding engine speed, torque and power are shown in Figure 8. For the electric power request, constant loads between 0 and 5000 W are used.

5.2 Results & Evaluation

The results are presented in Figure 9. As could be expected, the total fuel consumption increases almost proportionally with the requested electric load.

The fuel reduction of regenerative braking is predicted rather well. The benefits of regenerative braking over a normal baseline strategy are large for low electric loads and decrease for higher loads. A load of 200 W can be provided solely by regenerative braking.

The additional fuel reduction of advanced energy management shows larger differences between analysis and simulation. According to the analysis, the highest additional fuel reduction is obtained with a load that is half of the maximum alternator power. In the simulations, the fuel reduction deviates for loads between 1000 and 4000 W, because the distribution of the slope of the fuel map is not uniform, so the savings depend largely on which operating points of the fuel map are visited.
Figure 8: NEDC

Figure 9: Results
6. CONCLUSIONS

Some engineering rules are presented to estimate the fuel reduction that can be obtained with regenerative braking and with more advanced electric energy management strategies in conventional vehicles.

An explanation is given why in the field of energy management, shifting the engine to an operating point with a higher efficiency will not automatically lead to a lower fuel consumption.

For a specific vehicle configuration and drive cycle, the estimated fuel consumption is compared with simulations, with reasonable results, showing the value of this method.

With regenerative braking a fixed amount of electrical energy can be obtained for free. This amount does not depend on the requested load. The baseline strategy already does some regenerative braking, where the amount increases with the requested load. This means that for higher electric loads, the additional fuel reduction of a real regenerative braking strategy becomes smaller.

The fuel use of an internal combustion engine increases almost proportional to the delivered mechanical power. The additional fuel reduction that can be obtained with an advanced electric energy management system depends on nonlinearities in the fuel map. For the engine used in this analysis, these deviations are rather small, which limits the additional fuel reduction.

REFERENCES