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IFAC-PapersOnLine 49-11 (2016) 641–648

Energy based method to analyse fuel saving potential of hybrid vehicles for different driving cycles

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Abstract: Fuel saving potential of hybrid electric vehicles (HEVs) depends mainly on driving cycle and on sizing of powertrain components. Since a complete driving cycle, representing the whole life usage of a vehicle, is very long it is time consuming to predict the fuel saving potential, especially if many different types of HEV's should be analyzed. This paper presents an energy based method to quickly screen different types of HEVs for many and long driving cycles, in order to find interesting candidates for deeper and more accurate analysis. The technique used also allows to derive the fuel consumption analytically, and thus it is a very effective tool to explain the main fuel savings mechanisms of different types of HEVs and how they are influenced by the driving cycle. Some of the simplifications will lead to errors, but since the sign of the main errors are known it is still easy to draw several clear conclusions using the method.

Keywords: Driving cycle, Energy, Fuel saving, Hybrid vehicles, Propulsion, Sizing.

1. INTRODUCTION

To find which users should have which type of power train cannot be done by analysing only certification cycles as those do not capture the variability of how vehicles are used. Instead a large set of real driving must be analysed and typically very long cycles in order to capture variability between different ways of using a vehicle (Pourabdollah). Since there are many different ways of using a vehicle as well as many types of powertrains, which also can be sized differently, analysis of the fuel consumption has to be repeated for each way of using the vehicle and for each powertrain configuration and sizing. Another challenge, regarding the proper selection and sizing of powertrain, is that the complexity of the powertrain model and complex control of the hybrid powertrain make it very difficult for a powertrain designer to predict how the fuel consumption will change due to changes in the powertrain or variations in the driving cycle.

This paper describes a simplified energy and power based method to estimate the fuel consumption of different powertrains for different driving cycles. The method is developed as a complement to detailed powertrain simulation, in order to speed up the analysis and to improve the understanding of the main mechanisms that contributes to the changes in fuel consumption for different driving cycles. The method is so simple that it is possible to analytically derive an estimate of the fuel consumption from only a few energy and time values describing the driving cycles. This method will also help in understanding the first order effects of the HEV powertrain design and driving cycle on the fuel consumption, thus making it easier for engineers to predict the consequences on the fuel consumption when making a certain change. The downside of the simplification is that several second order effects combined can still have a significant influence on the results, which the model may miss. Thus the method should mainly be used for quickly screening of powertrain concepts for many different driving cycles, in order to identify few candidates which then should be analysed using one of the existing, more detailed, methods. The control of the powertrain should always be based on a more accurate model and not the simple on used in this paper.

The effectiveness of this method is most valuable when many very long driving cycles shall be analysed for many different powertrain configurations, since the analysis is divided into a pre-processing of the driving cycles, which only have to be done once, and then a simple fuel consumption calculation which is equally simple irrespective of how long the original driving cycle were.

This paper first describes a generalized Willans line fuel consumption model for the powertrain, which is extended to also include the effect of fuel-optimal gear shifting. Thereafter, it is shown how this model can be used to predict the fuel consumption for an arbitrary driving cycle. The method is then used to analyse how different types of hybrid powertrains can reduce the fuel consumption, followed by a discussion of its errors. In the end, it is shown how the generalized Willans line can be derived from an engine fuel consumption map, and what errors is the result of the linearization. The details of the fuel consumption model and its application on a driving cycle will be presented in a coming paper.

10.1016/j.ifacol.2016.08.093

2. FUEL CONSUMPTION MODEL

2.1 Generalised Willans line approximation

A Willans line is a way of describing the fuel mass flow rate to an engine as a function of the mechanical power the engine is producing, and it is widely used for combustion engines (Pachernegg). In the described method, it is assumed that the gearbox is controlled to minimize fuel consumption. This makes it possible to define a more generalized version of the Willans line which is only a function of power, and not depends on the engine speed. The generalized Willans line is somewhat nonlinear, but in this paper approximated as a linear function of power. The linear approximation is necessary for making the rest of the method as simple as possible. In Section 5 the generalized Willans line is explained more thoroughly, and its accuracy is discussed.

The fuel mass flow rate of the engine is expressed as

$$\dot{m}_{fuel} = \begin{cases} \dot{m}_{idle} & \text{when engine is idling} \\ 0 & \text{engine off OR fuel cutoff} \\ \dot{m}_{active} + k_P\, P_{ICE} & \text{engine is active} \end{cases} \quad (1)$$

The fuel consumption model described in (1) only has three parameters and the values used in this paper are shown in Table 1. The difference between $\dot{m}_{idle}$ and $\dot{m}_{Active}$ is caused by the idling speed of the engine, typically 700-900 rpm, being lower than the lowest speed the engine can use when being connected to the transmission, typically around 1000-1200 rpm.

Table 1. Fuel consumption parameters used in this paper

Engine	$\dot{m}_{idle}$	$\dot{m}_{Active}$	k_P
Petrol 1.5 l	0.15 g/s	0.25 g/s	250 g/kWh

2.2 Fuel consumption for a driving cycle

The fuel consumption model allows calculating the fuel consumption for a driving cycle as the integral of the fuel mass flow rate. For the generalized Willans line (1) the fuel consumption in a driving cycle becomes

$$\begin{aligned} m_{fuel} &= \int_{Idling} \dot{m}_{\text{idle}}\, \mathrm{d}t + \int_{Active} \left(\dot{m}_{active} + k_P\, P_{ICE}\right) \mathrm{d}t = \\ &= \dot{m}_{\text{idle}}\, T_{idle} + \dot{m}_{active}\, T_{active} + k_P\, W_{ICE} \end{aligned} \quad (2)$$

where

$$W_{ICE} = \int_{Active} P_{ICE}\, \mathrm{d}t$$

Note that the power required from the engine can have any time variation, and with a linear Willans line the part of the fuel consumption caused by the power demand will only depend on the total energy required from the engine, W_{ICE}, and not at all on the time variation of the power. Also, the fuel consumption caused by the no-load and idle fuel consumption will only depend on the total time the engine is active or idling and not on when this occur. The no-load consumption is the fuel consumption when the engine is not producing any power, but is not running at idle speed. The simple fuel consumption calculations in (2) allow a quick estimate of the fuel consumption for different driving cycles, without time consuming simulations of the power train.

3. DRIVING CYCLE ANALYSIS METHOD

A driving cycle is normally expressed as speed versus time which is then translated into wheel power versus time, before the fuel consumption is analysed. Example of typical ways of describing a driving cycle are shown in Fig. 1. To calculate the power at the wheels as function of time requires running a vehicle model with the driving cycle as input. In this paper a standard vehicle model is used. It includes rolling resistance, aerodynamic resistance, gradient forces, acceleration and deceleration forces (Guzzella). Notice that the resulting load cycle will be different for different vehicles, even if the driving cycle is the same. Any differences in vehicle mass, aerodynamic drag or rolling resistance will make it necessary to repeat the calculation of the power-time series.

Once the power versus time has been calculated the power values are sorted in descending order. The result is a power-duration vector presented in Fig 2, showing how long time the powertrain is required to produce power of different levels. Note that the power-duration curve also distinguish between the situations in which the propulsion power is zero because of coasting, or because the vehicle is stopped. There are many important properties of the driving cycle which can be read from a power-duration diagram. Figure 2 shows, as examples, the positive and negative peak power, the time the vehicle is operating in different modes as well as the energy used for propulsion and braking. Required energy values are calculated as the time integral of power, i.e. the area between x-axis and the power-duration curve.

In this paper values from the NEDC driving cycle is used as example when calculating fuel consumption. Note, the power duration plots shown in this paper are for illustrative purpose and are not showing the NEDC cycle. The reason to not use the NEDC in the figures is because it is not typical for real world driving cycle, for example, it has too little variability and lacks the coasting part.

From the power-duration diagram, the inputs required for (2) can be determined and thus an estimate of the total fuel consumption can be calculated. For a conventional powertrain, without start/stop system the NEDC cycle give us:

$$T_{\text{Active}} = T_{\text{Prop}} + T_{coast} = 723\ s \quad (3)$$

(3)

The engine is also active most of the braking time, however, due to fuel-cut-off during braking the fuel consumption in this part of the driving cycle is close to zero. The idling time is thus the vehicle stop time, .i.e. when propulsion power is zero.

$$T_{\text{idle}} = T_{stop} = 255\ \text{s} \quad (4)$$