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Investigation of the energy requirements for the on-board generation of oxy-hydrogen on vehicles

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Abstract

The present study investigates the energy needs for the on-board generation of oxyhydrogen (HHO) used as fuel additive on vehicles. HHO production is performed through the use of an alkaline electrolyzer, directly taking energy from the equipped internal combustion engine. A longitudinal vehicle dynamic model is used to evaluate the driving power to be supplied by the engine for two reference speed profiles, NEDC and WLTC. The performed investigation determines the engine brake thermal efficiency gain required to ensure HHO production without increase in fuel consumption. The results can be used as guidelines for the development of on-board control strategies.

Keywords: *HHO; energetic analysis; brake thermal efficiency; fuel savings; NEDC; WLTC.*

1. Introduction

The use of oxy-hydrogen (HHO) as fuel additive has been disputed for long time due to uncertainty and unclear scientific rationale behind the several solutions proposed in the literature and in the market. It has been demonstrated that some on-board configurations (e.g. micro-hybrid) are feasible and effective energy-wise.

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Some authors investigated the use of HHO as fuel additive in both Diesel [1-3] and Gasoline [4,5] fueled engines, observing an improvement in engine Brake Thermal Efficiency (BTE) and emissions. For instance, Bari et al. [1] reported an increase of about 6% of a Diesel engine BTE with the injection of about 30 l/min of HHO at constant engine power output of 19 kW. Comparable performance variations have been also observed by Yilmaz et al. [2] but with a lower HHO amount (i.e., 5 l/min). From the available literature, it has been observed that there is not a univocal assessment of the benefits achieved by the use of HHO and most of the scientific investigations have been performed at fixed operating points (e.g., given load or engine speed).

The analysis performed in this work aims at assessing the possibility to achieve fuel savings during transient operations, by addressing the use of HHO in vehicle engines while driving through reference speed profiles. Variable load request and transient manoeuvers are taken into account with respect to standard cycles. A vehicle model has been used to evaluate the driving power and an energetic analysis, preliminary performed for steady state operation in a former authors' work [6], has been carried out to extract reference guidelines to prove the capability of fuel saving.

From the investigation of the available literature it has been observed that most of the works focus on the analysis of performance and emissions variation in laboratory environment with engine operating in steady state conditions. Proper experimental campaigns in engine transient conditions have not been carried out yet. Moreover, no experimental analysis of the whole system composed by engine coupled with HHO generation device is as well available in the literature. For this reason, a direct comparison of the simulation results here proposed with literature data was not possible at this stage. Nevertheless, a further advancement in the work can involve the design of a dedicated experimental test bench to overcome this lack of data and to perform a rigorous validation of the results and the guidelines illustrated in the present paper.

2. Speed profile and vehicle model

The energetic analysis carried out in this paper refers to a segment B vehicle equipped with a production Common-Rail Diesel engine. The power required at the engine crankshaft is evaluated through a dedicated vehicle model according to the considered speed profile. The vehicle model is based on a forward scheme including internal combustion engine (ICE), alternator, battery and the overall driveline. A schematic representation of the main components and their interaction is depicted in Fig. 1.

The driving cycle information (i.e., desired speed and gear profiles) are given as inputs to the driver model, which minimize the difference between desired and actual speed by means of Proportional-Integral-Derivative (PID) controller, computing as output the torque demand at engine shaft. The engine in-cylinder processes and friction losses are modeled by a black-box parametric approach, known in literature as Willans line method [7,8]. This approach allows evaluating the mean effective pressure (mep) by the injected fuel amount accounting for the auxiliaries and friction losses (p_{loss}) and pumping losses (p_{pump}) [9]:

$$mep = e \cdot \frac{4\pi \dot{m}_f LHV_f}{\omega V_d} - p_{loss} - p_{pump} \tag{1}$$

The Willans conversion efficiency e is expressed as function of the mean piston speed and mean available pressure, p_{loss} as function of mean piston speed and p_{pump} is evaluated from the intake and exhaust pressures. These latter are achieved by simulating the intake/exhaust manifolds dynamics by means of mass and energy equations, with manifolds pressure and temperature as internal states [10-13].

The driveline sub-model describes the longitudinal vehicle dynamics reduced to the engine crankshaft [14,15]:

$$I_{tot} \frac{d\omega}{dt} = T_{ICE} - T_{aero} - T_{roll} - T_{slope} - T_{acc/aux} \tag{2}$$

where the engine torque T_{ICE} is the output of the ICE sub-model (fed to transmission and vehicle sub-models, as shown through the blue arrow from the Engine box in Fig. 1), ω is the engine angular speed and I_{tot} is the total vehicle inertia reduced to the engine crankshaft. The vehicle dynamics is influenced by aerodynamic drag force T_{aero}, rolling resistance T_{roll}, slope T_{slope} and alternator load $T_{acc/aux}$. The transmission model accurately simulate the losses due to clutch, gearbox and transmission of the vehicle. The alternator resistance torque takes into account the auxiliaries and accessories electrical loads.

Model simulations are performed according to the forward scheme presented in Fig. 1 with the objective of evaluating the required speed and torque at engine crankshaft along the whole speed profile, to define the power need for vehicle propulsion. Such values are then used as reference power for the assessment of fuel saving with the use of HHO as fuel additive.

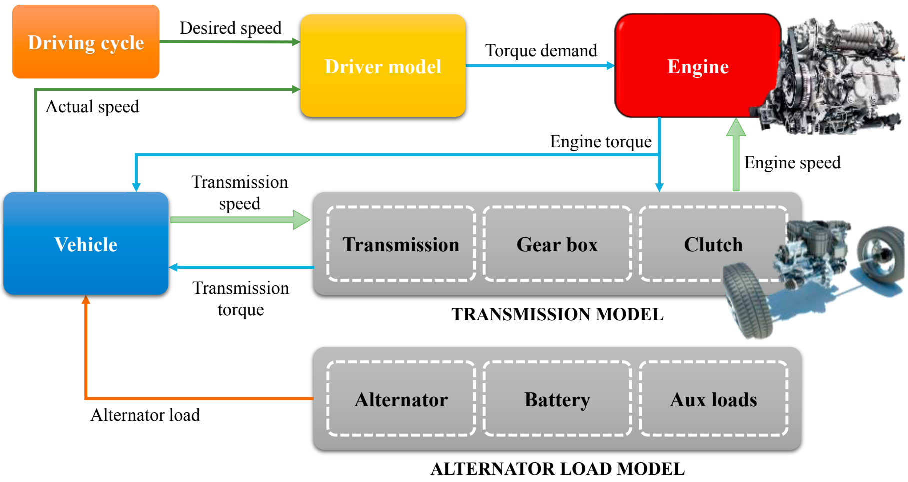

Fig. 1. Schematic representation of the overall forward vehicle-powertrain model including alternator and energy storage devices.

The simulations have been carried out considering two reference driving cycles, that are the New European Driving Cycle (NEDC) and the World-wide harmonized Light duty Test Cycle (WLTC). The results in terms of engine torque, speed and power output along the chosen profiles are presented in Fig. 2 and Fig. 3 for NEDC and WLTC, respectively. With respect to the use of HHO in the literature, due to the lack of data in engine transient conditions, the authors preferred to focus the current analysis on driving cycles that are highly diffused among the community, in order to help the interpretation of the proposed results. Moreover, the vehicle/engine model introduced in this section was already experimentally validate against the NEDC and WLTC cycles, and to keep a coherent evaluation of the energetic analysis results illustrated in next section, the same cycles have been accounted as well in this paper.

The results presented in Fig. 2 and Fig. 3 show the driving torque and power needed to accomplish the NEDC and WLTC cycles (i.e., the velocity profiles), respectively, for the reference vehicle with a given mass, geometrical and transmission data. The engine angular speed depends on the gearbox and the gear shift profile along the transients. These results have been achieved without the use of any HHO production system and are then taken, in the energetic analysis presented in Section 3, as inputs/reference targets (i.e., boundary conditions) to be satisfied also with the addition of HHO production.

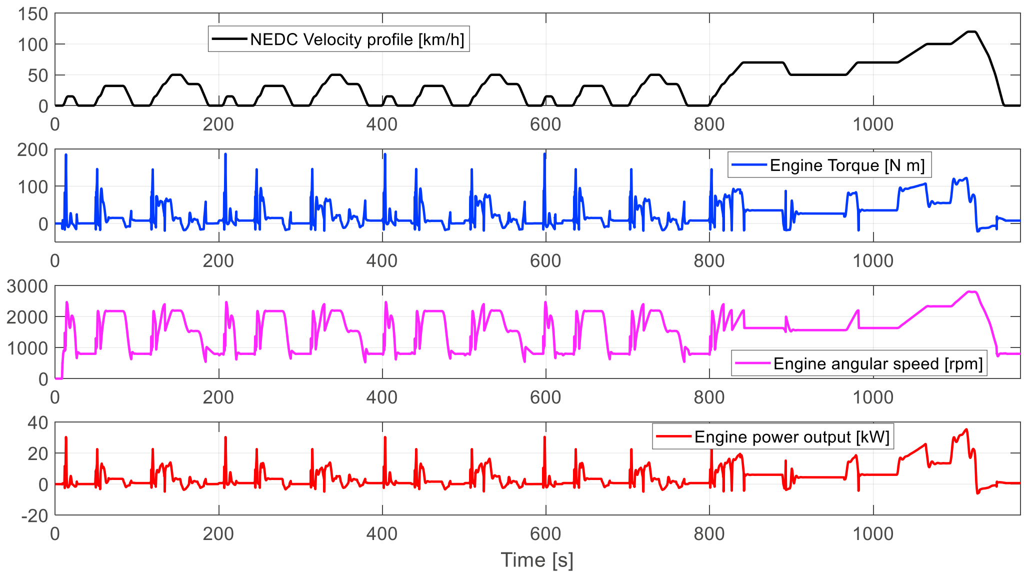

Fig. 2. Engine torque, speed and power output referred to the NEDC speed profile.

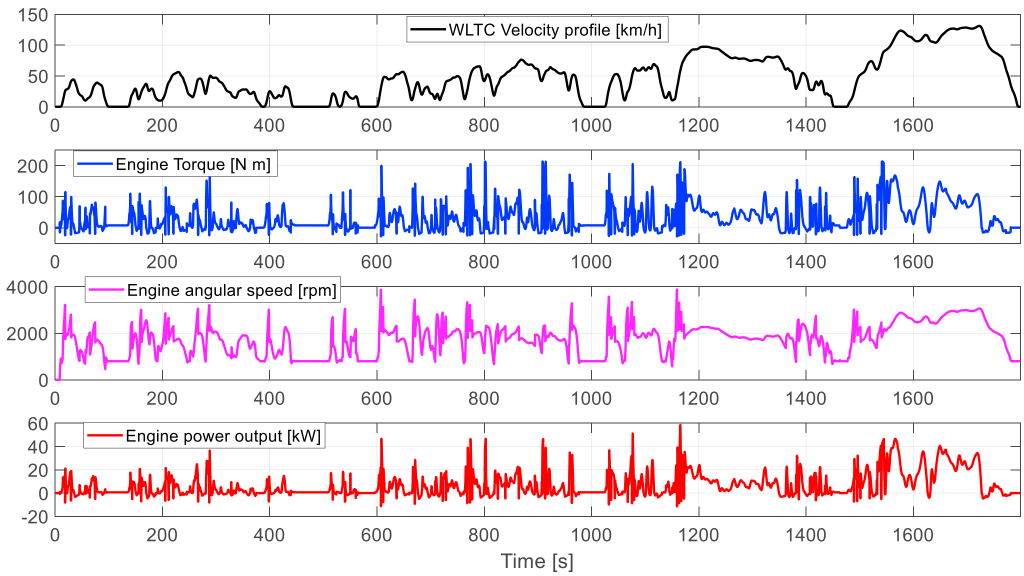

Fig. 3. Engine torque, speed and power output referred to the WLTC speed profile.

3. Energetic study

The engine is considered as unique power generator to cover the energy needs for vehicle operation and for on-board HHO production. The net power request at engine output has been computed in the previous section according to the reference speed profile and here represents the overall useful power P_U taken at engine shaft. The gross power provided by the engine P_{ICE} covers the P_U amount and the power required for HHO production, performed through and alkaline electrolyzer. The energy flow from the engine to the electrolyzer involves other two devices, i.e., an electric motor generator (EMG) and a battery. The configuration proposed in [6] is here accounted as well and represented in Fig. 4.

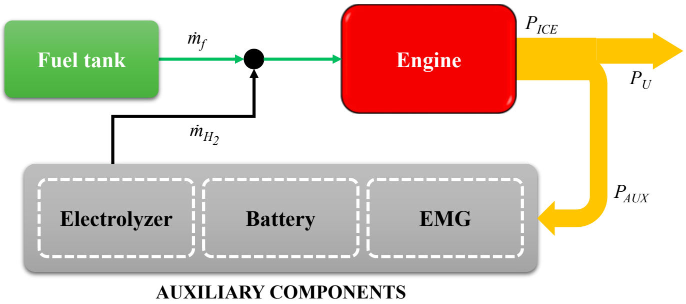

Fig. 4. Schematic representation of system layout with the HHO (i.e., hydrogen H_2) addition to the engine, with electrolyzer, battery and EMG as auxiliary components.

Assuming that the whole power required by the auxiliary components (i.e., electrolyzer, battery and EMG) corresponds to P_{AUX}, the power link among engine, auxiliaries and the vehicle is:

$$P_{ICE} = P_U + P_{AUX} \tag{3}$$

It is worth observing that the main energy carrier within the HHO flow is the hydrogen, since the HHO is usually referred to as a stoichiometric mixture of 2/3 of H_2 and 1/3 of O_2 [1]. Therefore, for a specific HHO volumetric flow, the related hydrogen mass flow can be evaluated as:

$$\dot{m}_{H_2} = \frac{2}{3} M_{H_2} \frac{p}{RT} \dot{V}_{HHO} = \gamma \dot{V}_{HHO} \tag{4}$$

The coefficient γ assumes the value of $9.24 \cdot 10^{-7}$ kg/l considering normal pressure and temperature (i.e., 1 atm and 20°C) and the HHO volumetric flow in l/min. The hydrogen gross chemical power available at the electrolyzer output $P^g_{H_2}$ represents the maximum amount of energy that can be theoretically released by the hydrogen mass flow, assuming water output in liquid state and thus referring to hydrogen Higher Heating Value (HHV):

$$P^g_{H_2} = \dot{m}_{H_2} HHV_{H_2} \tag{5}$$

This power amount can be related to the auxiliary components power P_{AUX} through their efficiency η_{AUX} as follows:

$$P^g_{H_2} = P_{AUX} \eta_{AUX} \tag{6}$$

The net power release by hydrogen combustion in the engine is related to hydrogen Lower Heating Value (LHV):

$$P_{H_2} = \dot{m}_{H_2} LHV_{H_2} \tag{7}$$

and the generated engine power is then:

$$P_{ICE} = \left(\dot{m}_{H_2} LHV_{H_2} + \dot{m}_f LHV_f \right) \eta_{ICE} \tag{8}$$

where η_{ICE} is the engine BTE, while $\dot{m}_f$ and LHV_f are the fuel mass flow and LHV, respectively. The overall fuel consumption can be then related to the provided hydrogen flow by combining equations (3) through (8):

$$\dot{m}_f = \frac{1}{LHV_f \eta_{ICE}} \left[P_U + \dot{m}_{H_2} \left(\frac{HHV_{H_2}}{\eta_{AUX}} + LHV_{H_2} \eta_{ICE} \right) \right] \quad (9)$$

Considering that the fuel consumption without hydrogen injection with the same power request P_U is:

$$\dot{m}_f^0 = \frac{P_U}{LHV_f \eta_{ICE}^0} \quad (10)$$

the fuel saving condition is achieved if:

$$\dot{m}_f < \dot{m}_f^0 \quad (11)$$

Introducing equations (9) and (10) in equation (11), the fuel saving condition can be expressed in terms of engine BTEs as follows:

$$\eta_{ICE} > \frac{\eta_{ICE}^0}{\eta_{AUX}} \left(\frac{P_U \eta_{AUX} + \dot{m}_{H_2} HHV_{H_2}}{P_U + \eta_{ICE}^0 \dot{m}_{H_2} LHV_{H_2}} \right) \quad (12)$$

The percentage change in BTE is defined as:

$$\%\Delta\eta_{ICE} = \frac{\eta_{ICE} - \eta_{ICE}^0}{\eta_{ICE}^0} 100 \quad (13)$$

and equation (13) can be rearranged as follows:

$$\%\Delta\eta_{ICE} > 100 \frac{\dot{m}_{H_2}}{\eta_{AUX}} \left(\frac{HHV_{H_2} - \eta_{AUX} \eta_{ICE}^0 LHV_{H_2}}{P_U + \eta_{ICE}^0 \dot{m}_{H_2} LHV_{H_2}} \right) \quad (14)$$

Equation (14) describes the increase in engine BTE above which fuel saving is achieved with on-board hydrogen production, at given power output and hydrogen flow. Since the objective of the present work is to assess the theoretical feasibility of using hydrogen as fuel additive with variable load profile and transient manoeuvers, the auxiliary components performance is here assumed ideal (i.e., η_{AUX}= 1), thus changing equation (14) into:

$$\%\Delta\eta_{ICE} > 100 \cdot \dot{m}_{H_2} \left(\frac{HHV_{H_2} - \eta_{ICE}^0 LHV_{H_2}}{P_U + \eta_{ICE}^0 \dot{m}_{H_2} LHV_{H_2}} \right) \quad (15)$$

This condition represents a first indicator that can prove the feasibility of using HHO for vehicle propulsion to reduce fuel consumption. In the following section, the index expressed through equation (15) is evaluated for the two different speed profiles presented in Section 2, under various HHO injected amounts.

4. Results and discussion

The right hand term in equation (15) represents the BTE percentage variation at which no increase or decrease in fuel consumption is fulfilled with the addition of HHO production device to the vehicle. Therefore, a possible benefit could be achieved only if the BTE percentage increase is higher than this term. A proper simulation analysis is performed to verify what is the variation of the right term in equation (15) with respect to the driving cycles and injected amount of HHO. The driving power request PU (only positive values) is taken from the vehicle simulation results presented in Fig. 2 and Fig. 3 (bottom plots in both figures) for the NEDC and WLTC, respectively, and assuming an engine BTE without HHO injection (i.e., η0ICE) equal to 32%. Hydrogen HHV and LHV were set 142 MJ/kg and 120 MJ/kg, respectively, and the injected H2 mass flow has been computed through equation (4) by considering three different HHO volumetric flows of 1 l/min, 5 l/min and 30 l/min.

The simulation results are resumed in Fig. 5: the proposed curves represent the BTE percentage variation limit above which fuel saving could be achieved at given driving power and HHO flow. The blue, red and yellow curves refer to the three considered HHO flows. The maximum power requests for the NEDC and WLTC speed profiles, respectively, have been highlighted with vertical black lines. According to the experimental activities described in the literature (although related to laboratory environment and steady state conditions), a reference 6% BTE increase (horizontal dashed red line in Fig. 5) is chosen as reference for the discussion of the results.

From the curves proposed in Fig. 5, it can be observed that the BTE limit (i.e., the right hand term in equation (5)) decreases with increasing power demand, whereas increases with higher HHO flows. Assuming that the engine BTE increases, for instance, of about 6% with the addition of HHO at any operating condition, if the power request goes below 2 kW, the reference BTE limit is not exceeded with any HHO flow, thus suggesting that fuel savings could not be achieved at these conditions. However, fuel saving could be achieved at higher power demands, for example above 2 kW with 1 l/min of HHO and 9 kW with 5 l/min of HHO. Only with 30 l/min of HHO injection the reported BTE limit is never exceed in both NEDC and WLTC cycles.

In conclusions, it can be stated that it is more plausible to reach fuel savings with small HHO amounts. Moreover, the lower the HHO, the lower is the power request at which this BTE limit is exceeded. A further observation can be made according to the different speed profiles: since the WLTC shows higher power request with respect to the NEDC, a wider power range is available for HHO usage.

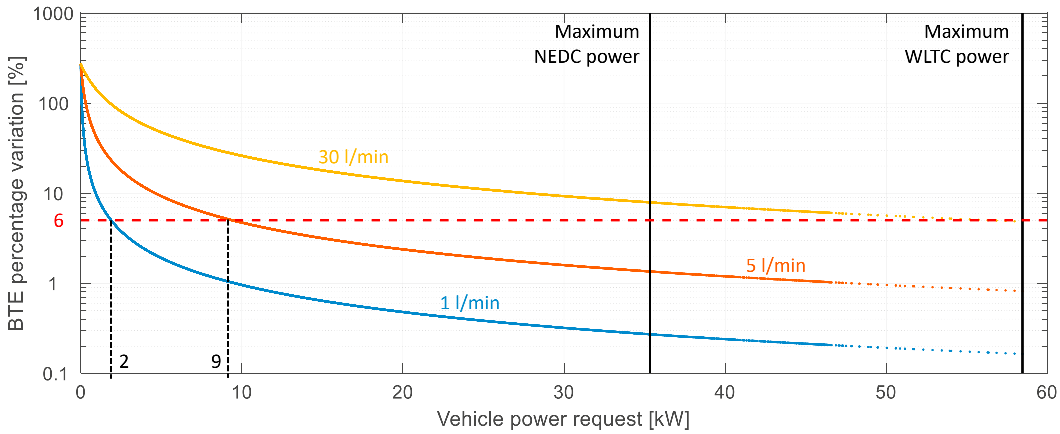

Fig. 5. Engine BTE percentage variation above which fuel saving is achieved at a given power request and HHO amount injection.

5. Conclusions

The present work offered a theoretical assessment of the possibility to achieve fuel savings with HHO injection in internal combustion engines, under variable power request related to NEDC and WLTC speed profiles. The achieved results show that small HHO amounts may lead to fuel savings within a certain power range, which is greater for

WLTC rather than the NEDC. These results can be helpful in defining advanced control strategies for power management and on-board HHO injection, for on-board vehicles uses.

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