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Assessing additional fuel consumption from cabin thermal comfort and auxiliary needs on the worldwide harmonized light vehicles test cycle

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ABSTRACT

Standards for fuel consumption and carbon dioxide emissions are implemented worldwide in most light-duty vehicle markets. Regulatory drive cycles, defined as specific time-speed patterns, are used to measure levels of fuel consumption and emissions. These measurements should realistically reflect real world driving performance, however there is increasing concern about their adequacy due to the discrepancies observed between certified and real world consumption and emissions values. One of the main reasons for the discrepancy is that current testing protocols do not account for non-mechanical vehicle energy needs, such as passengers' thermal comfort needs and the use of electric auxiliaries on-board. Cabin heating and cooling can especially lead to considerable increase in vehicle energy consumption. This paper presents a simulation-based assessment framework to account for the additional fuel consumption related to the cabin thermal energy and auxiliary needs under the worldwide-harmonized light vehicles test procedure (WLTP). A vehicle cabin model is developed and the thermal comfort energy needs are derived for cooling and heating, depending on ambient external temperature under cold, moderate and warm climates. A modification to the WLTP is proposed by including the generated power profiles for thermal comfort and auxiliary needs. Dynamic programming is used to compute the fuel consumption on the modified WLTP for a rechargeable series hybrid electric vehicle (SHEV) architecture. Results show consumption increases of 20% to 96% compared to the currently adopted WLTP, depending on the considered climate.

1. Introduction

There has been ever growing interest over the past few years for improved estimation procedures of vehicle fuel consumption and emissions, especially in light of recent controversy regarding the under-estimating of performance between original equipment manufacturers (OEM) tests and real world driving conditions. This has pushed the United Nations Economic Commission for Europe (UNECE) to define a new Worldwide harmonized Light vehicles Test Procedure (WLTP) as a new global standard for assessing fuel consumption and emissions, starting in September 2017 (Marotta et al., 2015). The WLTP consists of a number of procedures for testing a vehicle on driving cycles, known as WLTC (Worldwide harmonized Light vehicles Test Cycles) which are designed to be

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more representative of real world driving behaviors compared to the outdated NEDC (1997). This is done by incorporating low, medium, high and extra-high loads on the vehicle (Tsokolis et al., 2016) which will reflect higher average real world fuel consumption and emissions from vehicle propulsion needs (Mock et al., 2014; Sileghem et al., 2014; Demuynck et al., 2012; Tsokolis et al., 2017).

However, the WLTP still doesn't consider non-mechanical vehicle energy needs which impact fuel consumption and emissions, such as those for ensuring passenger thermal comfort by cabin heating and cooling, as well as the need to power auxiliary systems. It is well established that thermal comfort and electric needs account for a substantial share of overall vehicle energy needs, which can have a significant impact on the electric autonomy of hybrid and electric powertrains, especially under extreme climate conditions. In fact, thermal comfort needs vary considerably depending on factors such as cabin internal temperature, external temperature, type of vehicle, trip length, among several others (Farrington et al., 1999; Carlson et al., 2010). Therefore, in order to bring regulatory drive cycle test results closer to real world consumption, thermal comfort and electric needs in real world conditions should be accounted for. So far, only an optional U.S. test for assessing energy consumption and emissions, the SC03 Supplemental Federal Test Procedure (SFTP) (Farrington and Rugh, 2000), addresses some of these non-mechanical energy needs by considering the air conditioning only. Farrington et al. (1999) shows that 3500 W peak A/C load reduces the driving range of a sedan EV by 36% on the SC03, while it increases the consumption of an HEV by 57%.

Several studies have demonstrated the impacts of cabin heating on energy consumption. For example, EV energy consumption has been shown to increase by up to 32% with the decrease in ambient temperature, and a reduction in electric driving range of up to 24% has been measured when a heating system is operated (Fiori et al., 2016).

Other studies have addressed the impacts of cabin cooling on energy consumption, where in hot climates vehicle air conditioning (A/C) loads can become significant enough to even outweigh rolling resistance loads (Johnson, 2002). It has also been established that cooling energy consumption in plug-in hybrid electric vehicles (PHEV) is strongly dependent on climate, varying considerably among different regions of the US (Kiran et al., 2014). The energy required for cabin cooling has been shown to reduce the range of PHEV between 35% and 50% depending on outside weather conditions (Farrington and Rugh, 2000). Farrington et al. (1999) shows that a 1000 W steady-state A/C load in a small sedan EV reduces the SC03 range by 16%, and increases the fuel consumption by 16% in an HEV. For EVs, the A/C is used also to heat up the vehicle, which in winter can reduce electric autonomy by 8–24% depending on the external temperature (Clodic et al., 2011).

Some studies assessed the impacts of both cabin heating and cooling on vehicle energy consumption. Fiori et al. (2016) estimated an 850 W cooling, 1200 W cooling and 2200 W heating of thermal power needs when outside temperatures are respectively 25 °C, 35 °C and −5°C. Results show an EV range reduction on NEDC between 3% and 9% under the cooling scenarios and 22% under the heating scenario when compared to the baseline scenario of 700 W auxiliary load consumption. Similarly, Zhang et al. (2017) presents the simulation results of an EV performance on NEDC with cooling and heating needs. Results show 17.2–37.1% range reduction due to cooling load in summer, and a 17.1–54% range reduction when using a PTC heater in winter. Testing of a Ford Focus EV on the Urban Dynamometer Driving Schedule (UDDS) drive cycle showed a reduction in range of 53.7% due to air conditioning and 59.3% due to heating (Rask, 2014). Cooling and heating have also been shown to reduce the UDDS driving range of a Nissan Leaf by 18% and 48%, respectively (Slezak, 2012).

Few studies have considered the impact of auxiliaries on vehicle energy consumption. Farrington et al. (1999) shows that an increase in the accessory load from 500 W to 3500 W will cause the EV range on repeated FUDS cycle to decrease by 38%, and by 36% on SC03 cycle.

Across all the assessments surveyed above, there was no common framework for assessing the impacts of thermal comfort and electric needs on vehicle energy consumption, such as a drive cycle which incorporates cabin heating, cooling and auxiliary needs in a way to reflect real world driving conditions.

On the industry side, OEMs work continuously to reduce the amount of energy used for cabin environment control through a variety of techniques, such as advanced window glazing, individual cooling control, heated/cooled seats, parked car ventilation (Jeffers et al., 2015), recirculation strategies and air cleaning (Farrington et al., 1999). But despite these advances, OEMs continue to face significant challenges in meeting cabin energy consumption needs, especially with electric vehicles (EVs) where cabin thermal comfort has to be ensured from relatively inefficient technologies which reduce electric autonomy, such as electric heaters. In this respect, manufacturers might be well served to accurately assess the real world consumption of their electrified vehicles in order to better fulfill cabin thermal energy needs with the appropriate technologies. For example, depending on cabin heating needs in different climates, the choice of heating technologies might be different and the design of the vehicle architecture might be optimized to deliver those particular needs.

Hence, in order to better inform future assessments of fuel consumption in real world conditions, this study proposes a modification to the WLTP that includes cabin thermal comfort and electric auxiliary needs in addition to vehicle propulsion needs. The resulting amended WLTP will be denoted in the rest of the study as “modified WLTP”. The study starts with a framework for redefining the vehicle energy needs, as presented in Section 2. This includes a methodology for defining the heating and cooling power profiles under different climates. To that end, a vehicle cabin thermal model is developed and presented in the same section. The resulting heating and cooling power profiles, in addition to the auxiliary power needs are used to propose a modified WLTP that is more representative of real world conditions under three climate categories (hot, moderate and cold). Section 3 presents the modelling of the powertrain for a rechargeable SHEV, which uses dynamic programming in order to assess the additional fuel consumption from heating, cooling and electrical power needs under the three climate categories. The corresponding results are discussed in Section 4, and compared to the consumption results of a baseline scenario where only mechanical traction needs are considered.