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Combining DMDF and Hybrid Powertrains: A Look on the Effects of Different Battery Modelling Approaches

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Abstract

Fleet electrification has been demonstrated as a feasible solution to decarbonize the heavy-duty transportation sector. The combination of hybridization and advanced combustion concepts may provide further advantages by also introducing reductions on criteria pollutants such as nitrogen oxides and soot. In this scenario, the interplay among the different energy paths must be understood and quantified to extract the full potential of the powertrain. One of the key devices in such powertrains is the battery, which involves different aspects regarding operation, safety, and degradation. Despite this complexity, most of the models still rely on resistance-capacity models to describe the battery operation. These models may lead to unpractical results since the current flow is governed by limiters rather than physical laws. Additionally, phenomena related with battery degradation, which decreases the nominal capacity and enhances the heat generation are also not considered in this approach. In this sense, this work investigates the potential of powertrain hybridization coupled with the dual-mode dual-fuel combustion concept while considering the use of electrochemical models for battery modelling. To do this, a commercial truck model was built in GT-Drive and validated with respect to experimental driving cycle results. Next, electric components such as battery and electric motors were included in the powertrain. The former is modelled by means of GT-Autolion, which allows detailed modelling of the electrochemical reactions and current flow by means of Butler-Volmer, Tafel and Fick's equations. This allows to consider the limitations of power requests and the battery aging on the final energy consumption of the powertrain. The results have demonstrated an increased demand on the energy request of the combustion engine as the battery ages, as well as limitations on the maximum current transfer in the battery. Finally, the battery aging can reach limiting conditions where the driving cycle profile cannot be fulfilled, concluding that the realistic modelling of this device must be sought during the powertrain design phase.

Introduction

The recent political moves in some of the most economical representative nations around the world points Battery Electric Vehicles (BEVs) as the solution for the greenhouse gases emissions problem in the transportation sector [1]. The use of taglines such as zero emission vehicles and ultra-efficient powertrain compared to Internal Combustion Engines (ICEs) are commonly used to justify the preference for BEVs [2]. It is well known that the former is a biased view of the technology, since it uses the current legislation based on tank-to-wheel emission to move the carbon dioxide emission upstream in the chain (well-to-thank) [3]. Considering the legislation gap it is argued that the assessment on life cycle basis may offer a much fair comparison of the technologies [4, 5]. On the other hand, different investigations have demonstrated that the use of holistic approaches to compare the efficiency of the technologies results in a similar scenario in terms of efficiency [6]. The concept of full-load-hours of operation for renewable energy facilities indicates that the production of synthetic fuels in Medium East, North Africa (MENA) region and its use on ICEs in other locations as Europe or USA can be as efficient as a BEV powered by electricity generated in Germany [7]. This scenario evidence that ICEs fueled by synthetic fuels will be part of the solution for decarbonize the transportation in different parts of the world.

This outlook reinforces the importance of continuous development of combustion concepts and powertrains aimed at delivering better efficiency and lower pollutants [8]. Among of the recent introduced combustion concepts, those based on low temperature combustion (LTC) excels due to their capability of reducing soot and NOx emissions while providing higher efficiency at the same time [9-11]. Dual-Mode Dual-Fuel combustion (DMDF), formerly described by Benajes et al. [12], has been demonstrated in different Technology Readiness Levels (TRLs), from 1 to 6 [13-15]. Moreover, DMDF has been validated with a wide range of conventional and synthetic fuels, still low enough to fulfill EUVI constraints without a particulate filter. It should be remarked that this affirmation regards only the total mass of soot and not the particulate number.

Figure 16 summarizes the vehicle energy consumption by electrification type for fresh and aged cells. The BEV allows a drastic reduction of the energy consumption thanks to the high efficiency of the electric motor compared to the ICE. The increase on battery losses due to the aging is marginal compared to the benefits of the pure electric powertrain. The main restriction of the aging is in terms of driving range as shown in previous graphs. Nonetheless, as previously discussed, additional restrictions regarding the heat generation of the cell may also play a dominant role on the powertrain performance, requiring a properly sized cooling system. In addition, the heat generated may also lead to undesirable phenomena such as thermal runaway that could impact the vehicle safety.

The analysis of the results for the HEV also depicts a marginal increase on energy consumption with respect to the battery aging. However, for this case, the driving range is not a problem since the ICE can provide the required energy to the powertrain as needed. Despite the lower global efficiency of the powertrain, the HEV still shows a 15% on energy consumption considering the WHVC 50% (homologation case), which can be translated to a 15% of reduction of the CO_2 tailpipe emissions. Such reduction allows the proposed HEV platform to achieve the 2025 CO_2 target. It is interesting to remark that additional benefits can be obtained if the HEV is considered. First, the use of smaller battery and the possibility of decoupling the battery size and vehicle driving range allows for a reduction in the requirements of the battery. This reduces not only the heat generation on the battery but also the probability of having thermal degradation issues and the consequent occurrence of thermal runaway. Moreover, the HEV enables the use of synthetic and renewable fuels. Both fuels have a much lower carbon intensity factor than the current electric energy in the grid. In this sense, the combination of the HEV platform with these fuels may offer a much direct and fast decarbonization path compared to the full electrification.

Summary/Conclusions

This paper has investigated the combination of DMDF combustion concept with a P2 hybrid platform, focusing not only on the performance of the powertrain, but also investigating the effect of the battery aging properties on it. In addition, a full electric vehicle was simulated to understand the impact of the battery aging on the electric properties. The analysis and discussion of the results for each powertrain allowed to conclude important aspects:

- Towing capacity is highly dependent on the battery sizing and consequently the driving range. This trade-off impacts the capability of having a higher capacity truck with the recommend driving range for long-haul applications.
- Battery aging has a significant effect on the driving range of the BEV, showing decreases from 4% to 32%, depending on the aging temperature, driving cycle and payload.
- The increase in the truck payload magnifies all the downsides of the battery aging, increasing the heat generated due to the battery operation, reducing its driving range, and increasing the efficiency losses of the powertrain (both HEV and BEV).
- The HEV provides a way of minimizing the effect of battery aging, since part of the energy is provided by the ICE.
- The combination of DMDF and HEV offers a path to attain an ultra-low NOx and soot emission concept able to achieve the 2025 targets in terms of CO_2 emissions.
- The battery aging has a minimal effect on the emissions of the HEV/DMDF powertrain, since the emission maps presents similar calibration targets for these emissions, independently on the engine speed and load.

In this sense, it can be concluded that the battery aging has a significant role on the performance of both BEV and HEV powertrains, reducing the driving range and the global efficiency. Nonetheless, from the particular conclusions, it can be affirmed that HEV has an edge on the BEV application, since it allows to share the energy demand and, consequently, the losses that may be attained during the aging. It is also suggested considering literature results that the benefits on energy consumption from the BEV can be compensated by using synthetic or renewable fuels. Nonetheless, further investigations are needed to validate this result.

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Definitions/Abbreviations

ATS - After-treatment system
BAS - Belt Starter Assistance
CAD - Crank Angle Degree
CDC - Conventional diesel combustion
DMDF - Dual-mode dual-fuel
DOC - Diesel Oxidation Catalyst
DPF - Diesel Particle Filter
EGR - Exhaust gas recirculation
EM - Electric machine
EUVI - European Union emission limit six for heavy duty engines
HEV - Hybrid Electric Vehicle
HRF - High reactivity fuel
ICE - Internal Combustion Engine
LCA - Life cycle analysis
LHV - Low heating value
LI-Ion - Litium Ion batteries
LRF - Low reactivity fuel
LTC - Low temperature combustion
MHEV - Mild hybrid electric vehicle
NHV - Noise, vibration, and harshness
NOx - Nitrogen Oxides
OEM - Original equiment manufacturer
OMEx - Oxymethylene dimethyl ether
PFI - Port fuel injection
PHEV - Plug in electric vehicle
RCCI - Reactivity Controlled Compression Ignition
REV - Range extender vehicle
SCR - Selective catalytic reduction
SI - Spark Ignition
SOC - State of the charge of the battery
TM - Traction motor
TTW - Tank to wheel
WTT - Well to tank
WTW - Well to wheel