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Assessing consumption, emissions and costs of electrified vehicles under real driving conditions in a developing country with an inadequate road transport system

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ABSTRACT

This study assesses the tank-to-wheel savings in fuel consumption and CO_2 emissions as well as vehicle ownership and operating costs of electrified versus conventional midsize passenger vehicles in real-world driving conditions of the greater area of Beirut, Lebanon. This was done by developing representative driving cycles for typical home-to-work commutes during peak and off-peak traffic conditions based on an on-road travel survey. Results show that micro-hybrids are beneficial only in peak times, reducing consumption by 18.3%. Electrified vehicles provide substantial savings of 38.7% for hybrids and 88.6% for plug-in hybrids. However, plug-in and battery electric vehicles are found to contribute significant well-to-tank CO_2 and pollutant emissions due to the dirty electricity mix in Lebanon. In addition, we find that the use of thermal comfort auxiliaries in congested traffic significantly reduces performance of electrified vehicles. Finally, an analysis of vehicle ownership and operating costs is done for the case of Lebanon and results show that hybrid electric vehicles are the preferred technology at low gasoline prices, while plug-in hybrids with a low electric range capability of 20 km become the most competitive at medium to high gasoline prices.

1. Introduction

The adverse impacts of road transportation globally on fuel consumption, greenhouse gas (GHG) and pollutant emissions as well as mobility costs have been well-established worldwide. Successful strategies for mitigating such impacts involve shifting to more fuel-efficient and less polluting transport modes, such as mass transit and alternative fuel vehicles (Chavez-Baeza and Sheinbaum-Pardo, 2014; Ong et al., 2011; Vafa-Arani et al., 2014). Many studies found that electrified vehicles including hybrid electric vehicles (HEVs), plug in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) are particularly effective in tank-to-wheel fuel and emissions savings despite their relatively higher ownership and operating costs to date (Dimitrova and Maréchal, 2015; Nanaki and Koroneos, 2013). For example, The Hyundai Ioniq, which is available in PHEV and BEV models, is 54% and 77% more fuel efficient than its gasoline counterpart, respectively (USEPA, 2018).

Original equipment manufacturers (OEM) assess the fuel consumption and environmental performance of their road vehicles using regulatory drive cycles, such as the Federal Test Procedure (FTP-72) and the Highway Fuel Economy Driving Schedule (HWFET) for US city and highway driving conditions respectively, the New European Driving Cycle (NEDC) in Europe or the Japanese Cycle of 2008 (JC08) in Japan. However it has been shown that real driving conditions, which are specific to every

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geographical region, are important to consider when assessing the real fuel consumption of road vehicles (Saxena et al., 2014; Wang et al., 2015) as well as their environmental impacts (Rodríguez et al., 2016; Zhang et al., 2014) and operating costs (Karabasoglu and Michalek, 2013; Sharma et al., 2012). Driving conditions include driving speed, acceleration, and idling time, among other trip parameters.

In addition, there is recent evidence that OEM vehicle testing on regulatory test cycles substantially under-estimates performance with respect to real world driving conditions due to additional loads on the vehicle in real driving mode (Demuynck et al., 2012; Sileghem et al., 2014). In particular, auxiliaries such as air conditioning and heating, which are not accounted for in regulatory cycles, are significant contributors to energy consumption. This is especially relevant for BEV and PHEV where the additional consumption can significantly affect the electric driving range (Raykin et al., 2012). The focus of previous studies has been on showing the differences between real-world fuel consumption and test cycles when it comes to traction needs, but no studies have comprehensively estimated the additional impacts from the seasonal use of heating and cooling auxiliaries on fuel consumption and emissions (Sileghem et al., 2014), as is done in this study.

In Lebanon where this study is performed, the road transport system is one of the most unsustainable in the middle east region, due in large part to a chronic lack of enforcement of traffic laws and a severely underdeveloped and poorly maintained road infrastructure, leading to highly unregulated driving patterns, and aggressive driving behaviors on the whole (Haddad et al., 2015). This makes the context of this study quite different than that of developed countries where traffic is typically highly regulated. The difference is especially pronounced in the greatly congested Greater Beirut Area (GBA) where most traffic is concentrated, 55% of which is for work commutes during peak periods, leading to high fuel consumption and the highest levels of air pollution. In addition, Lebanon is one of the few countries in the region with a climate covering all four seasons, including significant temperature differences between summer and winter times. This makes it possible to assess the additional impact of using heating and cooling auxiliaries on real world fuel consumption and emissions in this demanding context.

In 2016, Lebanon signed the Paris agreement of the United Nations Framework Convention on Climate Change (UNFCCC) for the mitigation of GHG emissions. Under this agreement's Intended Nationally Determined Contribution (INDC), Lebanon committed to reducing GHG emissions by a minimum of 15% in 2030 compared to the business-as-usual (BAU) scenario in 2010 (Ministry of Energy, 2015). In the transport sector, this would be done by renewing the vehicle fleet with fuel-efficient and alternative fuel vehicles, especially for passenger cars which are the highest polluters in this sector, contributing nearly 76% of total road CO_2 emissions in 2010. This is because passenger cars and light duty vehicles constitute the vast majority of road vehicles operating in Lebanon (92.3% of the total fleet of 1.58 million vehicles in 2012), and are dominated by older model years (MOE/URC/GEF, 2012).

The mitigation potential in terms of fuel consumption and CO_2 emissions reduction for a number of alternative fuel vehicle types has been assessed for the Lebanese case, with electric powertrains prioritized as having the most promise over the long-term if an appropriate infrastructure is made ready, and hybrid electric vehicles (HEV) being the most beneficial in the near term since they provide substantial savings without the need for new infrastructure (Mansour and Haddad, 2017). It has also been shown that increasing the market share of fuel-efficient vehicles in Lebanon to 35% by 2040 has the potential to stop the increase in fuel consumption and emissions despite the increasing demand for mobility (Haddad et al., 2017). Therefore, this study assesses the real world energy and emissions reduction potential as well as the corresponding ownership and operating costs of the top prioritized electrified passenger vehicles (mHEV, HEV, PHEV and BEV) relative to a reference midsize conventional vehicle (ICEV) in GBA driving patterns. The use of cabin cooling and heating auxiliaries is also considered in the modeling.

This study makes unique contributions in the following ways: First, it is the first environmental assessment of alternative fuel vehicles using real driving conditions in a city of the Middle East region. This is significant since it is important to have representative studies for different regional contexts. It is also useful for informing OEM's of the real-world performance of their vehicles in urban contexts with similarly inadequate road transportation infrastructure and aggressive driving conditions, especially that the majority of published studies have been done in cities of developed countries, such as Winnipeg (Ashtari et al., 2014), Athens (Tzirakis et al., 2006), or Celje (Knez et al., 2014), among others. Second, it provides a comprehensive comparative analysis which covers energy consumption, emissions and economic costs, that have not all been previously combined in one study using real driving conditions and accounting for thermal comfort auxiliaries.

The rest of the paper is structured as follows: Section 2 provides a detailed description of the current state of road passenger transport in the GBA, which is essential for understanding real driving conditions in this context. Section 3 presents the study methodology, including an onboard GPS survey for building driving cycles emulating the GBA driving conditions. Section 4 provides the modeling results along with a discussion of the performance of alternative fuel vehicles in terms of fuel consumption and emissions savings as well as additional ownership and operating costs compared to conventional vehicles. Concluding remarks are given in Section 5.

2. Overview of road passenger transport in the GBA

In order to properly assess the relative performance of electrified vehicles in the GBA, it is first necessary to understand the current state of mobility in Lebanon, which will serve as the baseline scenario for the study. This section presents an overview of the vehicle fleet and fuel characteristics, the road transport infrastructure and the driving conditions in Lebanon and the GBA, where such data are severely lacking due to the absence of any governmental or non-governmental agency for transport statistics. This serves to illustrate the realities of vehicle performance and driver behavior in this context, and that will be captured in this study by the construction of representative driving cycles for the GBA, as detailed in the methodology section.

The road transport sector in Lebanon has seen a large and rapid increase in demand for mobility in recent years, and the upward