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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 CO₂ 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 CO₂ 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.

Keywords: real driving conditions; electrified vehicles; energy consumption; CO₂ emissions; cost analysis; developing countries.

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 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., 2014a). 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., 2014b), 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 CO₂ 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 CO₂ 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 trend is projected to continue for decades to come (MOE/UNDP/GEF, 2016). This is also the case for many developing countries in the Middle East region and is attributed to strong economic and population growth across the region, estimated to be higher than the global average by about 22% (real GDP) and 67% (inhabitants), over a 2008-2035 planning horizon (WEC, 2011). This translates to rising energy consumption in road vehicles and a corresponding increase in harmful emissions to the environment and human health, especially that road transportation in Lebanon and similar developing countries is largely dependent on fossil fuels. In fact, oil consumption in the road transport sector constituted 40% of total oil consumption in 2012, which made it the second biggest emitter of GHG emissions with over 23% of annual emissions in the same year (MOE/UNDP/GEF, 2016). As a result, there is an almost total dependence on fossil fuels (gasoline and diesel are 97.9% of total fuels), with automotive gasoline consumption increasing by a substantial 25% since 2006 (MOE/UNDP/GEF, 2015). This reflects a dominance of gasoline internal combustion engine vehicles (ICEV), with over 60% of the cars having engine displacements exceeding 2.0 liters, while only 8% have engines less than 1.4 liters (MOE/URC/GEF, 2012). Therefore, the midsize conventional engine car can be considered as the most representative vehicle for the present study.

The GBA encompasses more than 40% of the population of Lebanon and is a major business hub which served an estimated 5 million daily passenger trips in 2015 (Ministry of Environment, 2011), with an annual traffic growth rate of 3.25% over the past 5 years (Council for Development & Reconstruction, 2013). Traffic conditions in the GBA are characterized by a high rate of congestion for the majority of the day, way beyond typical morning and evening peak periods (Omran et al., 2015). In addition to local GBA commuters, an estimated daily traffic volume of 315,000 vehicles flow into and out of the GBA through the northern and southern highways. Vehicle occupancy is approximately 1.2 passengers per vehicle, very low compared to the world average. There is approximately 1 passenger vehicle for every 3 persons in Lebanon, almost double the Middle East region average, and the trend is to increase in next decade with an annual rate of 1.5%, especially in the absence of an effective public transportation system or any alternative mass transit modes such as marine ferry or rail service (Ministry of Environment, 2011).

Heavy congestion in GBA is not only due to demographic growth as is the case in many countries, but also to the significant inadequacy of the roadway infrastructure and the absence of proper enforcement of traffic laws. In particular, poor roadway conditions severely restrict flow speeds at all times of the day and night, most notably the lack of lighting on the majority of roads and highways, insufficient traffic signage and roadway markings, in addition to extensive potholes and slippery pavement conditions in winter weather. Highways and major arterials suffer from severe under-capacity as well as constant disruptions of traffic flow, as they are lined up by commercial establishments on both sides with unregulated access to and from city streets. And due to extensive urban sprawl extending far beyond the limits of the GBA, highways now make up a portion of most trips in or through the GBA, but with a severely impaired level of service that puts them way below the highway functional classification. Highways and arterials now serve as mere extensions to internal roads, without dedicated exits or on-ramps, and no breakdown lanes or proper separation from urban construction, such as with frontage roads. This significantly affects traffic flow and compromises driving safety. For example, the daily average speed on the main southern highway
into Beirut is below 35 km/hr. (Council for Development & Reconstruction, 2013), and severe accidents are a common daily occurrence (Choueiri et al., 2010).

The inadequate state of the road network in the GBA is compounded by a chronic failure in traffic law enforcement across the country. As a result, driving patterns in and around the GBA are highly chaotic and unsafe, with drivers constantly breaching road rules, such as routinely breaking the speed limit in off-peak periods, tailgating even at high speeds, passing traffic on the right hand side, abruptly slowing down to stop at roadside businesses, among many other erratic and hazardous driving habits. And since the majority of roads in the GBA are narrow streets with very few public parking spaces, traffic problems are compounded further by such common practices as double parking or parking over sidewalks and in prohibited curbside spaces. This further reduces the roadway clearance and slows down traffic even more. In addition, the absence of traffic signs at minor intersections and the lack of compliance with traffic signals even at major intersections, both lead to frequent blocking of intersections and further traffic jams at all hours of the day, extending the periods of peak traffic and affecting more areas outside the normally busy business districts.

On highways, trucks frequently drive in the fast lane even when carrying a full cargo load, slowing down traffic considerably throughout the day, and forcing faster traffic to weave across to the right lanes in order to pass them. Vehicles in the right lanes must constantly avoid incoming or exiting traffic without the benefit of merging lanes, forcing them to frequently break and accelerate on short notice. Motorists rarely adhere to driving within their own lanes, and it is common to see vehicles taking up portions of other lanes in free flow traffic, or crowding up the same lane without keeping a safe distance when in heavy traffic. Such driving conditions are the norm rather than the exception in the GBA, whether on highways or city streets, leading to more congestion even during off-peak times, in a seemingly endless vicious cycle.

Lack of planning and regulation of bus and taxi transportation also plays a role in increasing traffic congestion through the lack of dedicated lanes and the absence of designated pickup/drop-off locations at specified time intervals, leading to the irregular service patterns of passenger buses. For example, the unrestrained competition between mass transport operators pushes drivers to abruptly switch lanes at any time in order to stop virtually anywhere for passenger pickup or drop-off. Consequently, additional congestion and stop-and-go patterns are generated for the other cars on the road, not to mention the high risks of collisions with these vehicles (a detailed description of the road transport sector in GBA with applicable indicators is provided in (Haddad et al., 2015)).

In summary, the increase in the number of vehicles on the road, the inadequate roadway infrastructure and the lack of proper enforcement of traffic laws, all contribute to excessively congested traffic, aggressive driving behaviors and chaotic driving conditions in the GBA. This sets the GBA context apart from typical cities in developed countries, and makes the present case study representative of challenging real world conditions that vehicle technologies operate in. The resulting low driving speeds, high accelerations and decelerations as well as average trip times and distances will be considered in the vehicle modeling to account for their impact on consumption and emissions performance in GBA conditions, as discussed in the next section.

3. Methodology
Driving patterns are represented by driving cycles which capture the variation of speed for a vehicle over time. OEM’s use regulatory driving cycles to measure fuel consumption and emissions on a chassis dynamometer test bench. This type of driving cycle lacks the ability to capture vehicle performance under real world driving conditions which are unique for every geographical area because of the variation of the road network topography, traffic congestion, car fleet composition and driving behaviour (André, 1998). This is why real driving cycles are needed to more realistically assess consumption and emissions, especially for battery electrified vehicles where actual driving conditions greatly impact performance and electric autonomy (Fiori et al., 2016; Kambly and Bradley, 2014). Real world variations are usually accounted for by considering factors such as road gradient, vehicle stop duration, use of auxiliaries, driver behaviour, trip length, trip composition, and weather conditions, among others (Fontaras et al., 2017).

As an illustration of the difference between regulatory and real world driving cycles, Table 1 shows actual trip characteristics of a typical trip in GBA from the city centre (Hamra) to the outskirts of the city (Jounieh) as compared to regulatory driving cycles adopted in the United States. The trip is one of the most commonly frequented commuter trips during peak-time and consists of an urban and highway portions. The urban portion of the trip is compared to the FTP-72 drive cycle and the highway portion to the HWFET. As the numbers show, regulatory average speeds are roughly 3 times higher than real world urban driving conditions, where stop durations are also 30% higher than the regulatory driving cycle.

<table>
<thead>
<tr>
<th>Trip</th>
<th>Type</th>
<th>Description</th>
<th>Duration [s]</th>
<th>Distance [km]</th>
<th>Max speed [km/h]</th>
<th>Average speed [km/h]</th>
<th>Stop duration [%]</th>
<th>Average acceleration [m/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP-72</td>
<td>Urban</td>
<td>Test Cycle</td>
<td>1,369</td>
<td>12</td>
<td>91.3</td>
<td>31.5</td>
<td>18.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Hamra-Antelias</td>
<td>Urban</td>
<td>Congested</td>
<td>4,676</td>
<td>12.7</td>
<td>68.9</td>
<td>9.8</td>
<td>24.8</td>
<td>0.4</td>
</tr>
<tr>
<td>HWFET</td>
<td>Highway</td>
<td>Test Cycle</td>
<td>765</td>
<td>16.5</td>
<td>96.4</td>
<td>77.6</td>
<td>0</td>
<td>0.19</td>
</tr>
<tr>
<td>Antelias-Jounieh</td>
<td>Highway</td>
<td>Free-flow</td>
<td>723</td>
<td>12.2</td>
<td>78.3</td>
<td>60.7</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Accordingly, specific driving cycles emulating the Lebanese driving conditions in GBA are built for the purpose of this study based on on-road measurements from a travel survey using GPS data loggers. The GPS devices log the vehicle’s on-road position data, recording the latitude, longitude, altitude and velocity of the vehicle, every 1-second time interval. On-road measurements were done by 14 drivers using 14 different midsize class conventional engine vehicles, in attempt to cover all driving typologies in GBA (urban, highway), all traffic conditions (peak, off-peak), and all trip compositions (for example congested urban followed by a free-flow highway). Travel and vehicle data were collected over a period of 12 months, covering a total distance of 10,293 km from 1,278 trips in the GBA during the morning (7:00 am – 10:30 am) and evening (4:00 pm – 8:00 pm) “home-to-work” and “work-to-home” commutes, respectively. These tests were conducted during regular working days, excluding public holidays. Figure 1 illustrates the combination of some of the typical routes recorded in GBA, representing the most frequented main roads serving key entry.
points into the central business district.

Figure 1: Typical routes from the total sample of surveyed routes in GBA

Results of the travel survey in the GBA are illustrated in Figure 2.

Figure 2: (a) Distance range distribution; (b) Stop time distribution
Figure 2: (c) speed range distribution (d) Speed acceleration frequency distribution SAFD

Recorded GBA driving conditions show that 56% of all work commute trips have a total distance less than 6 km with an average trip distance of 8.8 km as depicted in Figure 2.a. It is also noteworthy to mention that trips above 20km, a common electric range limit for many plug-in hybrid electric (PHEV) vehicle models, make up less than 8% of all recorded trips.

The stop duration distribution, presented in Figure 2.b shows that 69% of all stops recorded are below 10 seconds, most of which are found to be related to traffic congestion and particular driver behaviour.

In fact, Figure 2.c shows that 15% of travel time is spent with the vehicle at rest with engine idling, reflecting the high rate of congestion in GBA. The average speed in GBA was found to be approximately 18 km/h reflecting a poor level of service. The average is even lower in peak traffic conditions, dropping to less than 10 km/h. In these conditions, the efficiency of conventional vehicles drops significantly, especially when using the air conditioning system.

Finally, acceleration rates are found to be most significant at very low speeds as shown in Figure 2.d, which is the result of stop-and-go traffic and which translates to high rates of fuel consumption and pollutant emissions for the existing fleet of gasoline and diesel vehicles in GBA.

In summary, the travel survey results revealed that the driving patterns can be characterized by a relatively low driving range with a high rate of congestion and frequent stops at short time intervals. This means there is a significant lack of efficiency in the operation of internal combustion engines and a high rate of fuel consumption and pollutant emissions.

3.2 Construction of real driving cycles for the GBA

In further analysis of the travel survey data, speed and road gradient profiles, i.e. driving cycles, are extracted in order to compute the fuel consumption of the studied vehicles in GBA driving conditions. There are several methods for constructing representative drive cycles from large amounts of on-road data, with the common objective of having the summary statistics of the constructed cycle matching those of the collected data as closely as possible. The methods differ by the types of statistics considered and the type of screening approach chosen to compare them against the real driving data (a detailed description is found in (Tong and Hung, 2010)). For
example, (Kruse and Huls, 1973) used average and maximum speeds, idle time and stops per trip statistics from each trip in the travel survey to define a speed-time profile that most closely captures the real world idling, accelerating, cruising and decelerating patterns. (Kent et al., 1978) used the same approach but chose average speed, root mean square acceleration and percentage idle time as the most impactful statistics when using the constructed driving cycle to estimate vehicle exhaust emissions. (Watson et al., 1982) considered additional statistics from the survey data, namely positive acceleration kinetic energy per unit distance (PKE) and relative time duration in various speed ranges, to define drive cycles based on matching a random selection of micro-trips forming an entire route to the target statistics. Other variations on the original approach have involved the use of advanced statistical techniques to minimize the uncertainties inherent in drive cycle construction, such as the use of Markov theory to divide a driving cycle into a chain of interdependent modal events grouping similar speed and acceleration profiles, and rearranging them into an appropriate drive cycle (Shi et al., 2011). Recently, travel survey techniques for improving the precision of collected data have been employed, such as the chase-car technique which involves the use of an instrumented car (equipped with infrared and video equipment) that follows randomly chosen vehicles in traffic, recording their speed profiles over their routes (Kamble et al., 2009; Schifter et al., 2005), but the general principles of drive cycle construction remain largely the same. This study emulates the approach used in the construction of the FTP72 regulatory drive cycle, which is based on (Kruse and Huls, 1973) and on the consideration of home-to-work trips, by choosing from the entire set of on-road measurements those trips with the most representative speed-time profile based on the idle time, average speed, maximum speed and number of stops per trip. As a result, 12 representative GBA driving cycles were generated for the peak-period and 8 for off-peak, according to a best fit of the peak and off-peak survey data, such that criteria statistics for the constructed drive cycles are within ±5% variation from those of the travel survey, as presented in Table 2.

Table 2: Statistics for the overall travel survey in GBA

<table>
<thead>
<tr>
<th>Statistic</th>
<th>GBA peak</th>
<th>GBA off-peak</th>
<th>NEDC</th>
<th>FTP72</th>
<th>HWFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average trip distance (km)</td>
<td>8.6</td>
<td>10.5</td>
<td>17.7</td>
<td>11.97</td>
<td>16.52</td>
</tr>
<tr>
<td>Max. velocity (km/hr)</td>
<td>76.1</td>
<td>87</td>
<td>120</td>
<td>91.23</td>
<td>96.38</td>
</tr>
<tr>
<td>Avg. velocity (km/hr)</td>
<td>16.1</td>
<td>38.7</td>
<td>33.6</td>
<td>31.5</td>
<td>77.68</td>
</tr>
<tr>
<td>Avg. acceleration (m/s²)</td>
<td>0.29</td>
<td>0.25</td>
<td>1.04</td>
<td>0.5</td>
<td>0.19</td>
</tr>
<tr>
<td>Avg. deceleration (m/s²)</td>
<td>0.36</td>
<td>0.36</td>
<td>1.39</td>
<td>0.58</td>
<td>0.22</td>
</tr>
<tr>
<td>Idle time %</td>
<td>23.7</td>
<td>7.8</td>
<td>23.1</td>
<td>18.92</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Note that the majority of GBA trips have similar compositions due to the structure of the roadway network where the connection between any two main locations involves a portion of city streets and highway driving. This is why no distinction is made between GBA downtown and suburban geographical areas, such that the representative GBA work commute is inclusive of both. Typical peak and off-peak drive cycles generated for the GBA are shown in Figure 3. Note that there are different methods for constructing drive cycles using variations of the basic approach which involves the selection of assessment criteria and a systematic drive cycle construction method (an overview is provided in (Hung et al., 2007)).
The typical peak cycle has the lowest average speed of 16.1 km/h along with the longest idle time, amounting to 23.7% of the total trip time. This cycle represents the worst driving conditions in the GBA during peak hours.

In the off-peak hours, idle time decreases to 7.8% of total trip time, and the average speed increases by more than 2.4 times (38.7 km/h) compared to the peak cycle. Note that the off-peak period is much smaller than peak which spans most of the day, such that traffic volumes observed during peak hours continue at nearly the same levels throughout the day (Waked et al., 2012).

The constructed GBA driving cycles are compared against regulatory test cycles, namely the NEDC, FTP-72 and HWFET shown in Table 2, in order to highlight any differences in vehicle operating conditions. The comparison shows that the average speeds of the test cycles are much higher than peak speeds which are the most common in GBA, meaning the test cycles overestimate average flow speeds in this context.

3.3 Vehicle modeling assumptions and parameters
This section details the vehicle characteristics, powertrain control strategies, and auxiliary power loads used in the modeling and simulation of vehicle fuel consumption and emissions in GBA driving conditions.

3.3.1 Characteristics of the modeled vehicles

In order to assess the fuel consumption of vehicles in GBA driving conditions, a reference midsize ICEV (segment C) is chosen, with all vehicle, engine and component characteristics (efficiency maps, battery and motor specifications, and auxiliaries) similar to those of the Toyota Prius as representative of the average passenger car in Lebanon. The reference characteristics, obtained from (Zgheib and Clodic, 2009) are summarized in Table 3. The modeling was done using Argonne National Laboratory’s simulation tool Autonomie (Halbach et al., 2010).

Table 3: Characteristics of the reference ICEV

<table>
<thead>
<tr>
<th>Glider Mass (kg)</th>
<th>Aerodynamic Drag Coefficient (-)</th>
<th>Frontal Area (m²)</th>
<th>Rolling Resistance Coefficient (-)</th>
<th>Accessories Load (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>995</td>
<td>0.254</td>
<td>2.289</td>
<td>0.009</td>
<td>800</td>
</tr>
</tbody>
</table>

To further assess the energy savings of electrified vehicles relative to the reference ICEV, the modeling included a micro-hybrid (mHEV), a full-hybrid (HEV) as the electrified vehicle types considered applicable in Lebanon over the near-to-medium term, as well as a plug-in hybrid (PHEV) and a battery electric vehicle (BEV) which are potentially viable in the long term.

All vehicles are assumed to have the same glider mass as the reference ICEV, following the standard comparative approach as detailed in (Zgheib and Clodic, 2010). The glider mass is defined as the mass of the vehicle without the powertrain components. Accordingly, the mass of the other assessed vehicles is computed by adding the mass of each component to the glider mass as shown in Table 4.

Table 4: Vehicles curb mass

<table>
<thead>
<tr>
<th>Components mass [kg]</th>
<th>ICEV</th>
<th>mHEV</th>
<th>HEV</th>
<th>PHEV</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider mass</td>
<td>995</td>
<td>995</td>
<td>995</td>
<td>995</td>
<td>995</td>
</tr>
<tr>
<td>Battery pack</td>
<td>-</td>
<td>-</td>
<td>35</td>
<td>105</td>
<td>200</td>
</tr>
<tr>
<td>Engine + Fuel tank</td>
<td>220</td>
<td>220</td>
<td>170</td>
<td>170</td>
<td>-</td>
</tr>
<tr>
<td>Transmission</td>
<td>100</td>
<td>100</td>
<td>60</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>MG1 (30 kW motor)</td>
<td>-</td>
<td>-</td>
<td>25</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>MG2 (50 kW motor)</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>Curb mass</td>
<td>1315</td>
<td>1315</td>
<td>1325</td>
<td>1395</td>
<td>1305</td>
</tr>
</tbody>
</table>

The four vehicle types differ in their powertrain architectures, which dictates the hybrid functionalities available on-board, the battery weight and capacity, and the electric power fraction. The mHEV is an ICEV using gasoline engine and a five-speed manual transmission with a stop-start functionality in order to cut on idling consumption. The HEV model considered is based on
the power-split drivetrain of the second generation Toyota Prius which offers a host of functionalities including stop-start, brake-energy recovery, downsized engine with electric power boosting and a short-electric drive mode (Mansour and Clodic, 2010). The PHEV model is based on the Prius HEV model with an oversized battery in order to provide 30 km of electric drive range (Mansour, 2016). This level of electric autonomy was chosen on the basis of covering the majority of home-to-work commutes in GBA in electric mode for the least vehicle cost. The BEV model is a standard 30 kWh battery employed to ensure a 160 km electric range.

Since the modeled vehicles have different curb masses, a fair comparative assessment of their consumptions requires identical performance specifications; therefore, the modeled vehicles are assumed to have the same vehicle characteristics of the reference ICEV as presented in table 3, and the components are sized in a way to ensure comparable power performance, represented in this study by accelerations of 0-100 km/h in 9.7 ± 0.5 seconds, and 48-80 km/h in 4.4 ± 0.5 seconds.

The engine maps of the ICEV and mHEV were chosen from the available components library in Autonomie. The Ford 1.8 L (99 kW) was chosen and its maximum power was downsized to 81 kW in order to meet the required acceleration performances. The transmission of the reference ICEV is assumed to be manual with the default gear-shifting program in Autonomie.

The main specifications of HEV and PHEV components are assumed identical, chosen to match those of the second generation Toyota Prius, except for battery capacity and type, where the HEV battery is a NiMH 1.3 kWh and the PHEV battery is a Li-ion 5.5 kWh. The BEV electric machine is a permanent magnet synchronous motor with maximum power of 80 kW.

In summary, the modeled vehicle specifications and applicable hybrid functionalities are presented in Table 5.

Table 5: Vehicle configuration characteristics

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Curb Mass (kg)</th>
<th>Battery Capacity (kWh)</th>
<th>Total Power (kW)</th>
<th>Hybrid functionalities*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICEV</td>
<td>1315</td>
<td>-</td>
<td>81</td>
<td>-</td>
</tr>
<tr>
<td>mHEV</td>
<td>1315</td>
<td>-</td>
<td>81</td>
<td>SS</td>
</tr>
<tr>
<td>HEV</td>
<td>1325</td>
<td>1.3</td>
<td>81</td>
<td>SS+BER+EB+EM</td>
</tr>
<tr>
<td>PHEV</td>
<td>1395</td>
<td>5.5</td>
<td>100</td>
<td>SS+BER+EB+ER30</td>
</tr>
<tr>
<td>BEV</td>
<td>1305</td>
<td>30</td>
<td>80</td>
<td>ER</td>
</tr>
</tbody>
</table>

* SS: stop/start; BER: brake energy recovery; EB: electric boost; EM: electric mode; ER30: electric range 30km

3.3.2 Control strategies for the modelled powertrains

The ICEV and BEV do not require the development of any advanced control strategy to manage the energy on-board, since these vehicles hold one type of energy source, a fuel tank for the ICEV and a battery for the BEV. In this case, a typical control strategy is considered, where the driver generates acceleration and braking commands to follow the drive cycle traction requirements.

The control strategy of the modeled HEV emulates the Prius energy management strategies for the use of the fuel and the electric energy stored in the battery. The details of the control strategy are reverse engineered from on-road testing on a second generation Toyota Prius, as detailed in
The PHEV control strategy consists of a charge depleting (CD) followed by a charge sustaining (CS) strategy that maximizes the use of electric energy from the battery. The specifics of the adopted strategy are given in (Zgheib and Clodic, 2012).

3.3.3 Power loads of cabin thermal comfort auxiliaries

The impact of thermal comfort of the PHEV and BEV was included in the fuel assessment, due to the electric range sensitivity of these vehicles to auxiliary consumption and in particular the auxiliaries used for thermal comfort. Therefore, heating and cooling of the cabin were considered in the modeling, using an electric heat pump system powered by the battery. Therefore, using the heat pump will decrease the electric drive range of both vehicles, and increase the fuel consumption of PHEV for its additional reliance on the engine to cover the requested trips.

A heat pump with a constant coefficient of performance (COP) of 1.5 is used in the modeling (note that COP is dependent on ambient temperature but maintaining it constant is a reasonable estimation). Typical summer and winter conditions for the GBA are considered, with initial cabin temperatures of 48 °C and 10 °C respectively, and a relative humidity of 80%. The reference comfort temperature is 21 °C at a relative humidity of 50%. Cabin heating and cooling loads are calculated using a dynamic cabin thermal model, as developed in (Brèque and Nemer, 2017), under steady state and as a function of ambient temperature and the amount of airflow recirculation. The required heating and cooling loads are shown in Figure 4, and are used with the COP to determine the electric power consumption from the heat pump compressor.

![Figure 4: Cabin heating and cooling loads in steady state](image)

3.4 Calculation of vehicle fuel consumption, emissions and costs in GBA driving conditions

The average fuel consumption $FC_{avg}$ ($L/100km$), and average energy consumption $EC_{avg}$ ($Wh/100km$) for the representative GBA drive cycles are computed according to equations 1 and 2, by weighting each with the corresponding trip distance $d_i$ ($km$).

$$FC_{avg} = \frac{\sum FC_i \ d_i}{\sum d_i}$$ \hspace{1cm} (1)
The average TTW CO₂ emissions $E_{CO₂} (g/km)$ are calculated for each vehicle type using equation 3, where $EF_{CO₂} (g/L)$ is the corresponding emission factor (Intergovernmental Panel on Climate Change and Houghton, 1997).

$$E_{CO₂} = \frac{\sum [F_{Ci}, EF_{CO₂}] \cdot d_i}{\sum d_i} \quad (3)$$

The fixed cost components considered include the vehicle ownership costs $C_{ow} (USD/km)$ defined as the vehicle purchase cost $C_{v}$ minus its salvage value $S (USD)$ depreciated over $t_{d}$ of 10 years, the value-added tax $VAT (USD)$, the cost of the charging station $C_{ch} (USD)$, custom and excise fees $C_{c} (USD)$, registration fees $C_{r} (USD)$, as well as additional fees calculated for the service life of the vehicle $t_{d}$ such as insurance fees $C_{i} (USD)$, road-usage fees $C_{ru} (USD)$ and loan financing charges $I (USD)$.

The variable cost components considered include the vehicle operating costs $C_{op} (USD/km)$ defined as the cost of consumed fuel $C_{f} (USD/L)$ and electricity $C_{e} (USD/kWh)$, maintenance and repairs cost $C_{m} (USD/km)$ and tires; note that for the HEV, PHEV and BEV, the custom and excise fees are waived to represent potential government financial subsidy for incentivizing the market adoption of these technologies.

The costs of the studied electrified vehicles are assessed as compared to the reference conventional vehicle for a total annual mileage $ATD$ of 15,000 km. The cost of each vehicle is computed by using equations 4 and 5.

$$C_{op} = F_{Ca} \times C_{f} + EC_{av} \times C_{e} + C_{m} \quad (4)$$

$$C_{ow} = \frac{C_{v} - S + VAT + C_{ch} + C_{i} + C_{c} + C_{r} + C_{ru} + I}{ATD \times t_{d}} \quad (5)$$

Vehicle purchase costs for the ICEV, mHEV and HEV were estimated from a market survey in Lebanon, and from international industry data adapted to the Lebanese market for the PHEV and BEV not yet deployed in Lebanon. Battery costs were estimated from 2015 industry data at 450 USD/kWh every 8 years or 240,000 km, with one battery replacement considered over the 10 year service life of the vehicle. Vehicle maintenance and repair costs were estimated from worldwide professional databases in 2016 as no local data is available. Other fees were computed according to official formulas used locally (Ministry of Finance, 2011), as summarized in Table 6.

An annual mileage estimated at 15,000 km and an appropriate average fuel cost for each fuel type (1.0 USD/liter for gasoline and 0.13 USD/kWh for electricity).

Table 6: Assumptions used in computing different cost components for the local context
<table>
<thead>
<tr>
<th>Cost components</th>
<th>Local data and assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle salvage value</td>
<td>$S$ 20% for the first year and 12% for the following years over a vehicle service life of 10 years</td>
</tr>
<tr>
<td>Loan interest and period</td>
<td>$I$ 4% over a 5-year loan period</td>
</tr>
<tr>
<td>Insurance fees</td>
<td>$C_i$ 14.5% of the vehicle purchase cost for the 5-year loan period, plus an average of 150 USD/year for the remaining life of the vehicle</td>
</tr>
<tr>
<td>Customs and Excise fees</td>
<td>$C_c$ Customs: 5% of the vehicle purchase cost</td>
</tr>
<tr>
<td></td>
<td>Excise: 15% on the first 13,333 USD of the vehicle purchase cost, plus 45% of the vehicle’s value above the initial value</td>
</tr>
<tr>
<td>Car registration fees</td>
<td>$C_r$ 4% of the vehicle purchase cost</td>
</tr>
<tr>
<td>Value-added tax</td>
<td>$VAT$ 10% of the vehicle purchase cost</td>
</tr>
<tr>
<td>Road-usage fees</td>
<td>$C_{ru}$ estimated at 159 USD/year, computed based on the fees required from the 11-20 horsepower vehicle category</td>
</tr>
<tr>
<td>Charging station cost</td>
<td>$C_{ch}$ estimated at 1,000 USD</td>
</tr>
</tbody>
</table>

### 4. Modeling Results and Discussion

#### 4.1 Fuel and electric consumption results in GBA

The modeled vehicles are simulated on the 20 representative driving cycles for the GBA. Figures 5 and 6 illustrate the maximum, minimum and average fuel and electric consumptions estimated for each vehicle type for peak and off-peak periods. Parts (a) and (b) of each figure illustrate separately the corresponding fuel consumptions for each vehicle type (gasoline in part (a) and electricity in part (b), noting that PHEV consumes both fuel types since it is capable of both gasoline and electric drive modes).

![Figure 5](image_url)
As shown in the comparison of the pair of (a) figures, as well as the comparison of the pair of (b) figures, peak period average consumption in GBA is higher than off-peak for all vehicle types. This is because congested conditions reduce overall engine efficiency as a result of frequent stops, longer idling times, higher accelerations and lower overall speeds, as captured in the GBA driving cycle. In addition, the differences between average peak and off-peak fuel consumptions become significantly smaller as the level of electric drive range increases, with only 4.8% difference for PHEVs versus 33.7% for HEVs, showing that vehicle electrification reduces the impact of driving patterns on vehicle efficiency. In other words, electric powertrains are more efficient, especially in congested city driving, and therefore the fuel savings from these technologies can be most significant in cities similar to the GBA. This is a significant finding for developing countries considering the typically high cost of mobility relative to Gross Domestic Product (GDP) per capita in such contexts.

In peak periods, the mHEV shows 18.3% fuel savings over the ICEV. This highlights the contribution to fuel economy of this vehicle type in highly congested cities of developing countries like Lebanon. The HEV and PHEV provide even more substantial fuel savings of 38.7% and 88.6%, respectively. Note that for the HEV, the total fuel consumption includes the fuel consumed to recharge the battery and restore the energy used during the trip. For the PHEV, the additional fuel savings are due to vehicle operation relying more on electric driving mode where vehicle efficiency is highest. Therefore, while the fuel savings are very beneficial, there is electric consumption being sourced from the grid to operate these vehicles and that must be considered when assessing the total impact of electrified vehicle technology on emissions and operating costs, as discussed in the following subsections.

The minimum and maximum fuel consumptions for each vehicle type in the peak period show that the ICEV is the most affected by variations in driving conditions, with a standard deviation of 2.54 L/100km compared to only 1.20 L/100km for the mHEV. This is in contrast to the much smaller variations in fuel consumptions during off-peak periods for all vehicle types (the largest standard deviation is for ICEV at 0.65 L/100km), as driving patterns are relatively more steady. Note that while PHEVs and BEVs have similar variability in their electric consumptions, this however does not affect vehicle efficiency since the electric motor operates at high efficiency over a wide range of torques and speeds.
In Lebanon, there are no officially adopted emissions and fuel economy standards or regulatory test cycles, however it is informative to compare the consumption results in GBA against commonly adopted regulatory drive cycles, namely the FTP-72, HWFET and NEDC discussed previously. Table 7 shows the fuel and electric consumption results for the modeled vehicles on the standard drive cycles.

Table 7: Fuel and electric consumption results by vehicle type on regulatory driving cycles

<table>
<thead>
<tr>
<th>Regulatory Cycle</th>
<th>ICEV</th>
<th>mHEV</th>
<th>HEV</th>
<th>PHEV</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel Consumption [L/100km]</td>
<td>Fuel Consumption [L/100km]</td>
<td>Electric Consumption [Wh/km]</td>
<td>Electric Consumption [Wh/km]</td>
<td></td>
</tr>
<tr>
<td>NEDC</td>
<td>7.2</td>
<td>6.9</td>
<td>5.4</td>
<td>1.22</td>
<td>129.1</td>
</tr>
<tr>
<td>FTP72</td>
<td>7.4</td>
<td>7</td>
<td>5.6</td>
<td>1.29</td>
<td>137.3</td>
</tr>
<tr>
<td>HWFET</td>
<td>5.4</td>
<td>5.3</td>
<td>4</td>
<td>1.10</td>
<td>109.7</td>
</tr>
</tbody>
</table>

The ICEV average fuel consumption in GBA peak period is 10.9 L/100 km, which is 47% to 51% higher than FTP-72 and NEDC respectively, and 102% higher than HWFET. This means that for the majority of home-to-work trips that are spent in GBA peak conditions, fuel consumption is much higher than estimated under regulatory test cycles. In other words, the OEM fuel economy ratings shown to consumers on vehicle labels significantly overestimate the real vehicle efficiency in GBA conditions. This is in line with trends from other comparative studies (Burke and Zhao, 2012; Wang et al., 2015; Zhang et al., 2014).

The difference becomes much bigger when taking the additional consumption of auxiliaries into consideration, particularly air conditioning in summer and heating in winter. This is especially relevant for electrified vehicles where additional consumption affects the electric driving range, namely for PHEV and BEV. The additional seasonal consumption from auxiliaries compared to the average consumption in GBA conditions was considered in the modeling, and results are given in Table 8.

Table 8: Additional seasonal consumptions for PHEV and BEV in GBA relative to average without auxiliaries

<table>
<thead>
<tr>
<th>Additional Consumption</th>
<th>PHEV</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel (%)</td>
<td>Electric (%)</td>
</tr>
<tr>
<td>Air conditioning</td>
<td>+84.6</td>
<td>+2.6</td>
</tr>
<tr>
<td>Heating</td>
<td>+53.8</td>
<td>+0.5</td>
</tr>
</tbody>
</table>

As shown in the table above, the use of auxiliaries can significantly affect fuel efficiency in PHEVs, especially air conditioning in summer, incurring an additional consumption nearly equivalent to energy consumed for vehicle traction. For the BEV, additional electric consumption is significant enough to affect electric autonomy. This result is in line with findings in similar studies (Mansour et al., 2018), and means that the impact of using heating and cooling auxiliaries on fuel efficiency and electric autonomy must be assessed by OEMs to properly inform end users of the real world performance of their electric vehicle models. In GBA where average trips are of
relatively short distance as previously discussed in subsection 3.1, range anxiety would not be a concern for most commuters, but fuel efficiency would have significant financial implications for the majority of drivers.

4.2 CO\textsubscript{2} emissions results in GBA

The tank-to-wheel (TTW) CO\textsubscript{2} emissions for the modeled vehicles in GBA driving conditions are presented for peak and off-peak periods in Figure 7.

![Figure 7: Emissions in GBA driving patterns by vehicle type for peak and off-peak periods](image)

When comparing against the ICEV, mHEV shows tangible emissions savings in peak periods (over 18%), but the emissions reduction in off-peak driving conditions is less than half the peak levels (8%). This reflects the fuel savings potential of these vehicles as shown in the previous subsection, so that mHEVs become attractive from a fuel consumption and emissions perspective when operated in driving conditions of developing countries like Lebanon where the majority of home-to-work commutes are spent in highly congested traffic.

Additional savings are achieved by all electrified vehicles which offer significant reductions in both peak and off-peak conditions. In particular, BEVs have zero TTW emissions since only battery energy is used, and PHEVs are close behind since electric driving is the dominant mode. A noteworthy observation from the figure above is that PHEVs are not sensitive to driving conditions as shown by the nearly equal TTW performances in peak and off peak conditions. This demonstrates the strong potential of BEVs and PHEVs in helping Lebanon to meet its INDC climate change reduction targets. However, this largely depends on their well-to-tank (WTT) emissions at the level of electricity production. Therefore, and in order to better assess the overall emissions reduction potential of the modeled vehicles in GBA, the WTT CO\textsubscript{2} emissions are estimated in this study using the same methodology detailed in a previous well-to-wheel (WTW) emissions assessment of alternative fuel vehicles for the case of Lebanon (Mansour and Haddad, 2017). Figure 8 presents the estimated WTT CO\textsubscript{2} emissions for the case of Lebanon under the current electricity mix which relies almost exclusively on highly polluting fossil fuels, specifically 31.3% heavy fuel oil, 64% diesel oil and only 4.7% renewable sources (Ministry of Energy and Water, 2010).
Figure 8: Well-to-Tank CO₂ emissions by vehicle type for Lebanon

As the figure shows, PHEV and BEV are significant contributors of CO₂ emissions on the energy production side (i.e. from a WTT perspective), by up to 45 times the ICEV level for BEV, since the electricity mix in Lebanon is not clean, as is the case in many developing countries. Therefore, while these vehicle types can be some of the cleanest technologies on the road (i.e. from a TTW perspective) of even the most congested cities, they can displace CO₂ emissions to the power plants if they are recharged with dirty electricity, and their overall contribution to the mitigation of global warming is reduced as a result. Potential solutions in this context are to improve power plant efficiency, use cleaner fuels for electricity generation such as natural gas instead of fossil fuels, and increase the share of renewable resources applicable in the country, particularly solar and hydropower.

A related challenge is that power plants in Lebanon are located inside or very close to major cities, so that the adoption of electrified vehicles under a dirty mix poses additional problems from a local air quality perspective. While air quality consideration is beyond the scope of this study, an assessment of criteria pollutants was done in order to illustrate the potential adverse impacts to air quality of the modeled vehicle technologies for the case of Lebanon. As such, TTW for peak-period and WTT pollutant emissions were calculated using the same methodology detailed in (Mansour and Haddad, 2017), adapted to the modeled vehicles in this study, as shown in Figure 9.

Figure 9: (a) Peak TTW pollutant emissions for VOC, CO, NOx, SOx and PM per vehicle type in GBA; (b) WTT pollutant emissions for VOC, CO, NOx, SOx and PM per vehicle type in Lebanon;

As can be seen in the figures above, vehicle electrification can substantially mitigate TTW pollutant emissions despite the inefficient driving patterns in GBA, but this comes at the expense of
generating significant emissions at the level of the power plant where additional electricity generation for these vehicles would be needed. The most significant increases in WTT emissions were calculated for BEV in terms of CO, NOx and SOx (18, 48 and 53 times the corresponding ICEV levels, respectively).

Potential solutions in this context, in addition to those proposed for CO2 above, are to employ emissions control techniques at the power plants, or to source additional electricity for recharging electrified vehicles from plants outside the cities.

4.3 Ownership and Operating costs of modeled vehicles in GBA

The annual ownership and operating costs for the modeled vehicles are assessed compared to the reference conventional vehicle. The corresponding costs per vehicle kilometer (veh.km) are shown in Table 9 using the assumptions detailed in Section 3.4 (15,000 km annual mileage, 1.0 USD/liter for gasoline, 0.13 USD/kWh for electricity, reflecting the current average prices to consumers in Lebanon).

Table 9: Evaluated vehicle technologies ownership costs, operating costs and government subsidy.

<table>
<thead>
<tr>
<th>Vehicle Technology</th>
<th>Ownership cost (USD/km)</th>
<th>Operating cost (USD/km)</th>
<th>Subsidy (USD/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICEV</td>
<td>0.338</td>
<td>0.142</td>
<td>-</td>
</tr>
<tr>
<td>mHEV</td>
<td>0.338</td>
<td>0.122</td>
<td>-</td>
</tr>
<tr>
<td>HEV</td>
<td>0.449</td>
<td>0.102</td>
<td>0.151</td>
</tr>
<tr>
<td>PHEV</td>
<td>0.580</td>
<td>0.039</td>
<td>0.202</td>
</tr>
<tr>
<td>BEV</td>
<td>0.543</td>
<td>0.029</td>
<td>0.187</td>
</tr>
</tbody>
</table>

A sensitivity analysis is conducted over a range of gasoline and electricity prices to determine the real world operating cost-effectiveness of the modeled vehicles for the case of Lebanon. Figure 10.a illustrates the impact of variation of the gasoline price on the annual operating costs savings of each vehicle type compared to the reference ICEV, for a fixed electricity tariff (0.13 USD/KWh). Similarly, Figure 10.b shows the sensitivity of electrified vehicle technologies to electricity cost for a fixed gasoline price (1 USD/Liter).

Annual savings of 11.3% and 37.2% are estimated for the mHEV and the HEV vehicles, respectively, independently from fuel price increase. For the PHEV, annual operating costs depend on both electric and fuel consumptions. However, since these vehicles would operate mostly in electric drive mode in GBA, and since the cost of electricity in Lebanon is subsidized by the government and fixed at a relatively low tariff of 0.13 USD/kWh, the PHEV savings relative to ICEV increase substantially with fuel price, from 45.6% at a fuel price of 0.35 USD/Liter to 71.2% at 1.5 USD/Liter. The same is true for the BEV, with even higher savings relative to ICEV at high fuel prices (up to 80% at a fuel price of 1.5 USD/Liter). However, sensitivity of operating cost on electricity tariffs (Figure 10.b) demonstrates that PHEV are less beneficial than HEV beyond 0.32 USD/kWh for a fixed gasoline price of 1 USD/ Liter. EV stops being cost-effective beyond 0.45 USD/kWh, and is less competitive than PHEV beyond 0.2 USD/kWh.
In summary, the sensitivity analysis suggests that BEV is most competitive from an operating cost perspective as long as the electricity tariff in Lebanon is low due to being subsidized by the government, or in case of future policy to source cleaner and cheaper electricity from solar photovoltaic plants under a controlled charging scenario as detailed in (Jochem et al., 2015). If electricity tariffs increase beyond 0.2 USD/kWh, PHEV becomes more attractive until the tariff reaches approximately 0.32 USD/kWh, when HEV becomes the most cost-effective technology.

When vehicle ownership costs are added to the operating costs, the results show that HEV and BEV are the most attractive technologies on the whole. HEV is preferred at lower gasoline prices, and remains the most competitive in this case even if electricity tariffs are very low. BEV becomes preferred at higher fuel cost when electricity tariffs are at or below 0.3 USD/kWh. The PHEV starts out at a disadvantage due to its higher purchase cost, but becomes attractive at high fuel and electricity costs. Figure 11 presents the most cost-effective vehicle technology as function of the variation of the fuel and electricity prices in GBA conditions, accounting for ownership and operating costs.

Therefore, as long as the gasoline price in Lebanon remains lower than 1 USD/Liter, HEV is most competitive from a cost perspective regardless of electricity tariff. EV becomes more attractive at
gasoline prices higher than 1 USD/Liter and normal electricity tariffs, whereas PHEV is only cost-effective if gasoline prices are at or higher than 1.75 USD/Liter and when electricity is very expensive (at 0.3 USD/kWh or higher) at the same time. Note that PHEV models with more limited electric range capability (i.e. less than the 30 km electric autonomy chosen in this study) can be more cost-effective due to the large impact of battery cost on vehicle purchase price. In fact, a PHEV with 20km electric range, which still covers the vast majority of home-to-work trips in GBA, was found to be the most cost-effective of all vehicle technologies at a fuel cost above 1 USD/Liter and an electricity tariff above 0.1 USD/kWh. This is illustrated in Figure 12.

![Figure 12: Expanded cost-effectiveness of PHEV at lower electric range capability](image)

But in addition to an affordable electricity tariff, it is again important to note that for electrified powertrains to be attractive in Lebanon and similar developing countries in the future, the electricity network must use a clean energy mix and must be capable of handling the additional load needed for recharging a large fleet of these vehicles at the same time, while providing convenient access to recharging stations.

5. Conclusion

This study provided an assessment of the energy use and CO$_2$ emissions of midsize passenger cars with conventional and electrified vehicle technologies under real driving conditions in Lebanon. An on-road travel survey was done using GPS data loggers over a period of one year covering 10,293 km from 1,278 work commutes, and was used to construct representative driving cycles during peak and off-peak traffic conditions. The constructed cycles reflected the congested and aggressive driving patterns in the surveyed Greater Beirut Area (GBA), which are characterized by low speeds and high acceleration and deceleration, over mostly short trip distances.

The modeling tool Autonomie was used to represent the powertrains of conventional internal combustion engine (ICEV), micro-hybrid electric (mHEV), hybrid electric (HEV), plug-in hybrid electric (PHEV) and battery electric vehicles (BEV). Modeling results showed that tank-to-wheel fuel consumption is reduced by 38.7% for HEV and 88.6% for PHEV compared to ICEV, which
means that electrified vehicles are fuel-efficient regardless of the aggressive and congested driving patterns in GBA. However, PHEV and BEV were found to contribute significant well-to-tank CO₂ and pollutant emissions due to the dirty electricity mix in Lebanon, particularly for CO, NOₓ and SOₓ. The implication of this result for policy makers is to start shifting electricity production towards cleaner energy sources in the near-term, such as natural gas as existing power plants in Lebanon are already capable of burning this fuel, in order to be ready for the deployment of electrified vehicle technologies over the medium-to-long term.

An analysis of vehicle ownership and operating costs was done for the modeled vehicles using local data and assumptions, and results showed that HEV are the preferred technology as long as gasoline prices remain relatively low (below 1 USD/Liter), while PHEV models that are affordable (i.e. with lower electric range capability of 20 km and therefore smaller battery size) become the most competitive at medium to high gasoline prices. However, it is found that the use of heating and cooling auxiliaries in congested traffic significantly reduces performance of these electrified vehicles, by up to 84.6% when using air conditioning in PHEV. This serves to inform OEM’s of the real-world performance of their vehicles in Lebanon and other countries in the region with comparable climates and similarly congested road traffic conditions.

Another noteworthy finding is that fuel consumption savings from mHEV was only significant in peak times (with an 18.3% reduction compared to off-peak). The implication from this result is that the performance of mHEV can be further maximized if basic traffic management techniques are introduced in GBA, such as the synchronization of traffic signals in urban areas to replace frequent short-stops with fewer but longer-duration stops, thereby maximizing the efficiency potential of mHEV Stop-and-Start technologies.

Overall, in developing countries like Lebanon, mHEV and HEV remain more viable than PHEV and BEV over the near to medium-terms since these vehicles do not require new charging stations and other costly infrastructure that is not available or currently under development in many developing countries. This is reinforced by the fact that the purchase costs of PHEV and BEV remain high due to the high cost of the battery. In this respect, relevant future work out of this study would be to determine an optimal reduced battery size for developing markets, in a way to minimize vehicle cost for such markets while ensuring that the battery capacity can still meet local driving needs.

In conclusion, this study has shown that electrified vehicles powered by clean electricity are needed to face the serious sustainability challenges facing the road transport sector in congested cities such as the GBA. Consequently, public authorities should incentivize new vehicle technologies in order to make them competitive in the market, and to embark on developing the electricity infrastructure in order to meet future requirements for clean mobility. In parallel, road traffic management and proper enforcement of traffic laws are imminent needed to improve driving patterns in Lebanon, helping to reduce fuel consumption especially in conventional vehicles. The integration of these complementary strategies with fuel-efficient vehicles and the development of a reliable public transport system can help the road transportation sector in Lebanon to evolve into a sustainable system in the long-term. This can also be a beneficial conclusion for similar developing countries in the Middle East region where there is inadequate roadway infrastructure and a culture of high
reliance on personal vehicle use.

Acknowledgment

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