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Evaluating impact of electrified vehicles on fuel consumption and CO_2 emissions reduction in Lebanese driving conditions using onboard GPS survey

Charbel Mansour*, Elias Zgheib, Sabine Saba

Center for Energy and Process studies, Mines ParisTech, 60 boulevard Saint-Michel, Paris 75006, France

Abstract

Reviewing past and current mobility assessments for the Lebanese road transport sector, road mobility demand has experienced a real explosion since 1990, and the trend is strongly upward over the decade to come. This growth is mainly attributed to the raise of daily passenger trips and the increase of car ownership. Moreover, this increase in mobility demand results in severe congestion, mostly in Greater Beirut Area (GBA), which leads to chaotic traffic conditions. As a result, Lebanese citizens are suffering from high budget required for transport, high dependence on fossil fuels, in addition to high pollution level particularly in urban areas. Therefore, reducing the fuel consumption and emissions of Lebanese road transport, particularly for passenger cars, has become a must.

Electrification of conventional Internal Combustion Engine Vehicles (ICEV) nowadays appears as an effective solution of paramount importance for car manufacturers, facing the challenge of minimizing the consumption of the road transport. Therefore, the objective of this paper is to present latest technological advancements of hybrid electric vehicles and to assess their impacts in terms of fuel savings in Lebanese urban driving conditions.

The logic of vehicle electrification is outlined first by presenting the technological advantages with respect to conventional vehicles. Then the paper addresses a tank-to-wheel energy consumption comparison and an operating costs comparison between several hybrid electric vehicle types and a reference conventional vehicle, on real world driving cycles, representative of GBA driving conditions. Driving cycles are collected during a survey on real route in GBA using onboard GPS devices equipped with data loggers. Finally, an assessment of fuel consumption and CO_2 emissions of the Lebanese car fleet is presented, in addition to a methodology for creating mitigation scenarios serving to reduce consumption and emissions by 2020.

Keywords: Beirut driving conditions; electrified vehicles; energy consumption; CO_2 emission; operating cost; mitigation scenario.

*Corresponding author. Tel.: +961 70 645 649.
E-mail address of authors: charbel.mansour@mines-paristech.fr; elias.zgheib@mines-paristech.fr; sabine.saba@mines-paristech.fr.

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1. Introduction

Due to lack of organization in land transportation sector at all levels, Greater Beirut Area (GBA) undergoes severe chaotic traffic conditions. GBA, which extends from the Nahr-el-Damour south to Nahr-el-Kalb north, encloses more than 40% of the population of Lebanon, and 1.5 million of daily passenger trips estimated in 1994, expected to reach 5 million in 2015 [1]. Traffic conditions in GBA can be described as mostly congested, with a daily traffic volume of 180 000 vehicles crossing the north coastal highway and 50 000 vehicles the southern highway [2].

The current land transportation system mainly rely on vehicles, particularly private passenger cars that share around 88% from the 1.2 million vehicles of the Lebanese car fleet, in 2005 [2]. The rate of car ownership is estimated to be 3 persons per car in 2002, and the trend is to increase in next decade with an annual rate of 1.5% [1]. With an average speed in GBA around 18 km/h that drops to less than 10 km/h in peak traffic conditions, the efficiency of conventional vehicles drops below 10%, see more when using the air condition system.

In addition, based on the Lebanese inventories for greenhouse gases for the year 1999 [1], the transport sector is the largest contributor to CO_2 equivalent emissions, accounting for 33% of the total emissions. According to recent studies conducted by the International Energy Agency (IEA), the oil consumption of the transport sector constituted more than 60% of the total oil consumption in 2008 [3]. Chaaban et al [4] showed alarming results in terms of air pollution and its health impacts resulting from road transport.

Therefore, chaotic traffic conditions, high rate of passenger cars ownership, poor vehicles efficiency in current GBA driving patterns, and high pollution rates observed: GBA citizens suffer from serious impact at both economic and environmental levels.

In this context, this study aims to analyze the impact of electrified vehicles - a potential solution for reducing fuel consumption and emissions of passenger cars - in GBA driving conditions, taking into consideration particularities of the real traffic situation.

Section 2 outlines the drawbacks of current conventional vehicles through an energy audit within these vehicles on GBA routes. Then the technological advantages of electrified vehicles are highlighted. Next, section 3 presents an onboard GPS survey for building driving cycles emulating the GBA driving conditions, and summarizes the obtained results.

Section 4 explores the fuel consumption savings and the operating costs of electrified vehicles available on the market, comparing to conventional vehicles. Finally, CO_2 emissions and fuel consumption from personal cars are estimated on the national level in section 5. One business as usual and two mitigation scenarios for the year 2020 are then evaluated, based on different figures for engine displacement classes distribution for passenger cars fleet.

Nomenclature

E-REV	Extended Range Electric Vehicle
GBA	Greater Beirut Area
ICEV-SS	Internal Combustion Engine Vehicle with Stop/Start
FH-PS	Full Hybrid Power Split
µH-MH	Micro Hybrid - Mild Hybrid
P-inH	Plug-in Hybrid

2. Advantages and topologies of electrified vehicles comparing to conventional vehicles

The ICEV has been imposed worldwide, and particularly in Lebanon, as the most flexible technology of personal mobility. However, despite all efforts for their development, ICEV still remain inefficient in terms of energy consumption and emissions. This section presents the drawbacks of ICEV by analyzing the energy distribution within the vehicle on a common Lebanese driving route. Moreover, it highlights the solutions brought for fuel savings by mean of vehicles electrification, and the current investigated configurations.

2.1. Drawbacks of conventional vehicles in GBA driving conditions

Energy losses within a conventional power train are variable and depend on the mode of use of the vehicle. Considering the Lebanese context, figure 1 illustrates the energy distribution for a common mid-size vehicle (127 kW, 1477 kg, air condition ON, 5 speed automatic transmission) observed on a typical route relating Hamra to Jounieh at traffic peak time. The speed profile is shown in figure 2. The route is divided to two main parts: congested urban and highway with an average speed of 9.8 km/h, and free-flow highway with 80 km/h speed limit and 60.7 km/h average speed (Table 1). The engine idle time observed during this trip is around 25% of the total trip duration.

Table 1: Typology of the route emulating a common driving condition between in GBA

Route section	Driving condition	Description	Per. of total mileage [%]	Max speed [km/h]	Average speed [km/h]	Stop duration [%]	Avg. pos. acceleration [m/s^2]
Hamra-Beirut Port	Urban	Congested	51	68.9	9.8	24.8	0.4
Beirut Port-Antelias	Highway						
Antelias-Jounieh	Highway	Free-flow	49	78.3	60.7	0	0.2

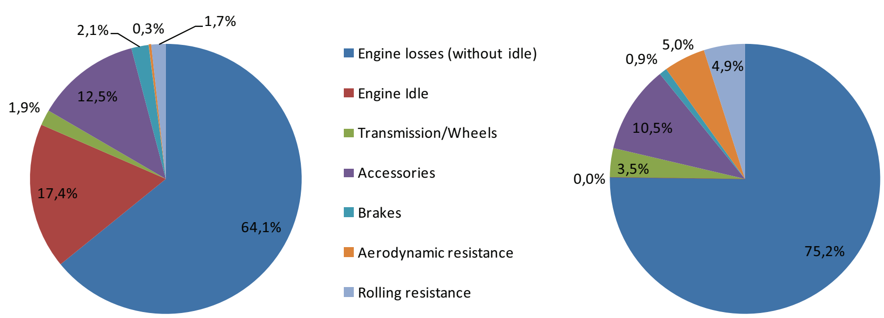


Figure 1: Energy distribution in conventional power train of a 127 kW - 1477 kg passenger car in GBA: (a) Congested urban and highway (Hamra-Antelias); (b) Free-flow highway (Antelias-Jounieh)

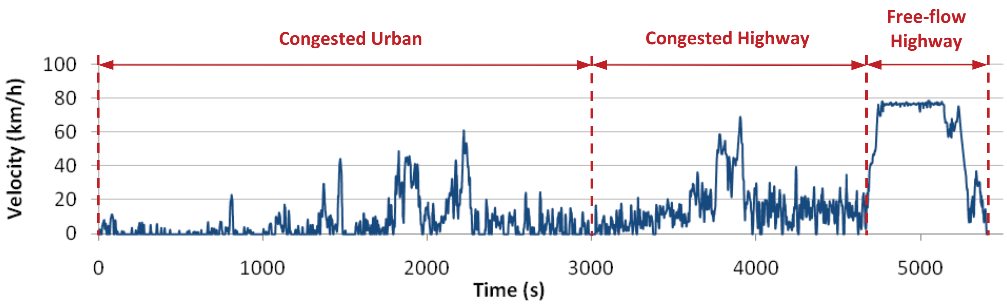


Figure 2: Speed profile of the simulated vehicle in GBA congested and free-flow driving conditions

According to figures 1.a and 1.b, only 2% and 9.9% of the fuel energy have served to drive the vehicle in the urban part and the highway part respectively, the rest have been dissipated within the power train.

The engine shares the lion's part for energy losses with 81.5% and 75.2% respectively in the congested and the free-flow sections. A close examination to the engine operating conditions shows that the engine operates far from optimum (figure 3). Moreover, 17.4% of engine losses are wasted during vehicle stop in the urban section (25% of the total duration), as the engine is idling. Therefore, shifting the engine operating points to higher efficiency range and preventing the engine from idling as the vehicle stops would reduce considerably engine losses on such route.

On the other hand, 10 to 12% of energy has been used to drive the accessories, particularly the air condition system where the compressor is powered mechanically by the engine; and 1 to 2% of energy is dissipated in the hydraulic brakes without any recovery (note that this value can be up to 6% in free-flow urban driving conditions). Therefore, electrification strategies for powering accessories and recovering brake energy present real potential for reducing fuel consumption.

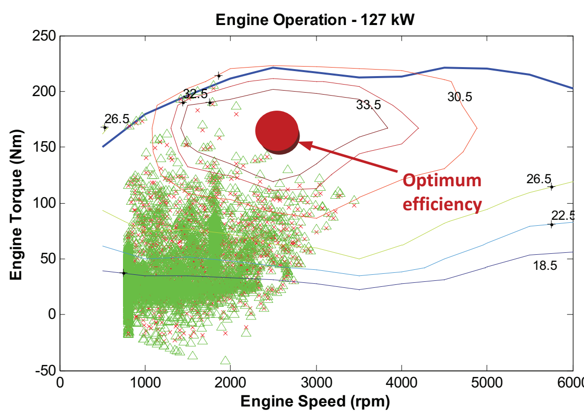


Figure 3: Engine operating points observed on the Hamra-Jounieh route

As a result, significant amount of energy losses are identified in conventional power trains while driven in GBA, and opportunities for energy savings and increasing the efficiency of ICEV are possible. However this needs rethinking the operation mode of the power train, to be adapted to the mode of use of the vehicle (idling, accelerating, braking, cruising, etc.). Accordingly, car manufacturers are developing diverse alternatives to the ICEV, by means of electrification of their conventional power trains.

2.2. Logic of vehicle electrification

The logic of electrification is to bring a specific solution – called hybrid functionality – to each source of energy savings of conventional power trains. The concept relies on adapting the power train to meet the load requirement with an optimal overall efficiency, by applying the proper hybrid functionality for each particular operating condition. The proposed hybrid functionalities for electrified vehicles are represented on the engine performance map in figure 4.a:

- Engine stop/start to prevent from burning idle fuel
- Brake energy recovery during vehicle decelerations
- Engine downsizing assisted by electric boosting during accelerations
- Electric launch
- Driving in electric mode (eDrive)
- Shifting the engine operating points to the high range efficiency by mean of power-split

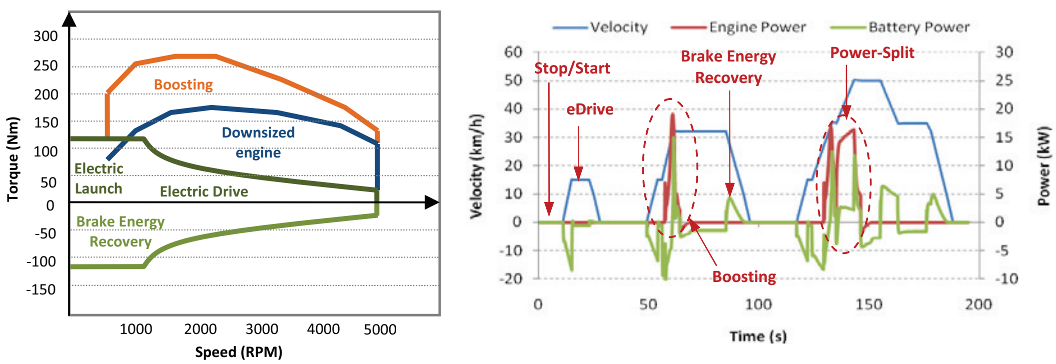


Figure 4: (a) Engine map associated to hybrid functionalities; (b) Hybrid functionalities on UDC

Figure 4.b illustrates these functionalities occurring on the UDC cycle, according to each type of driving condition (acceleration, cruising, deceleration and idle).

2.3. Classifications of electrified power trains

The roadmap of vehicles electrification can be described as illustrated in figure 5 as a succession of continuous technological steps going from “only conventional drive” to “full electric drive”. As a result, several power train configurations have been investigated by the automotive industry. They are sorted according to two common classifications: power and configuration.

From the power point of view, electrified power trains are classified into three categories: micro hybrid (μH), mild hybrid (MH) and full hybrid (FH). The three categories are differentiated by the fraction of electric power added onboard; consequently, the ability to achieve more hybrid functions as summarized in figure 5. Note that the more electric energy is available onboard, the more fuel reduction will result, at the expense of additional control complexity.

Figure 5: Classification by power of existing electrified vehicles

Two additional categories are recently under development, the Plug-in hybrid (P-inH) and the extended-range electric vehicle (E-REV). The P-inH vehicle is based on the configuration of the FH, with an additional battery capacity extending the pure electric drive mode. As an example, the Toyota Prius Plug-in offers 20 km of electric drive against 2 km with the equivalent FH Prius 3.

The E-REV is based on a pure battery electric power train configuration, with an engine and a generator added as range extenders onboard, and the possibility of mechanical connection of the engine to the wheels to drive the vehicle in particular conditions. Therefore, the difference results in the size of the electric motor and the battery capacity as shown in figure 6.

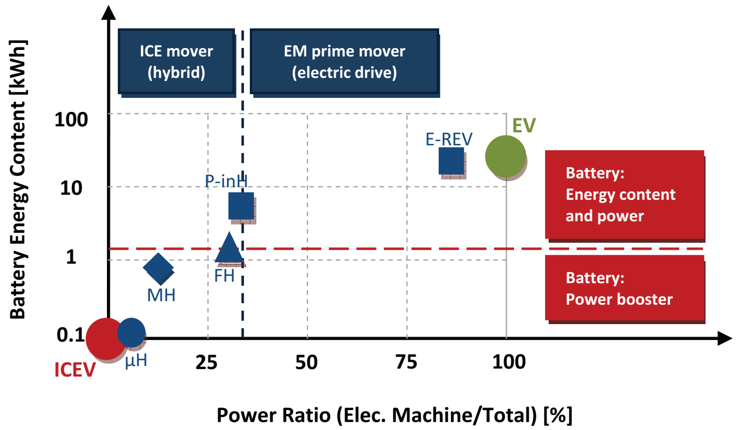


Figure 6: Steps of drive train electrification

Classified by configuration, independently from the degree of electrification, three different topologies are observed: series, parallel, and power-split configurations, summarized in figure 7. Many papers in the literature present a clear and detailed description for each of these topologies [5-7]. For the scope of this study, only the power-split configuration is considered and compared to a conventional and a stop/start vehicle, as such configuration is available on the Lebanese market with the current Toyota Prius.

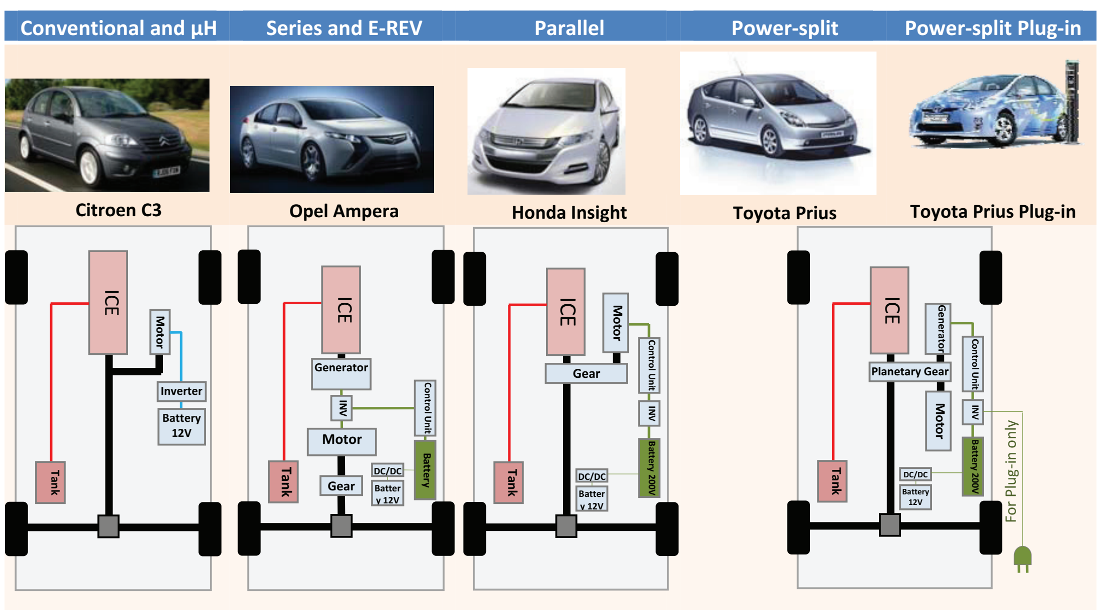


Figure 7: Classification by configuration of existing electrified vehicles

3. On-road measured driving routes simulating GBA driving conditions

In the context of assessing fuel consumption of passenger cars in Lebanon, the ANL's simulation tool PSAT is used, in order to bypass the complexity of real world measurements. Current existing driving cycles lack the ability to capture all the variants observed in real world, such as road gradient, stop duration, use of accessories, driver behavior, routes length, driving situation chronology, weather condition, etc.; thus, they could not be realistic in assessing the fuel consumption of electrified vehicles as in real driving conditions [8]. Moreover, the variants in driving conditions are unique for every geographical area because of the variation of the road network topography, traffic congestion, car fleet composition and driving behavior in the underlying region [9, 10]. Accordingly, specific driving cycles emulating the Lebanese driving conditions in GBA are built for the purpose of this study, based on on-road measurements.

3.1. On-road measurements methodology

Two GPS are used for the geolocation of the vehicle driven along several routes in GBA. These GPS serve as a position data logger, recording the latitude, longitude, altitude and velocity of the vehicle, each 1 second time interval of the on-road measurements.

On-road measurements are done by several drivers, in attempt to cover all driving typologies in GBA (urban and highway), all traffic conditions (congested, free-flow), and all driving situation chronologies (for example congested urban followed by a free-flow highway). Over 200 measurements have been recorded. Figure 8 illustrates the combination of some routes recorded in GBA. These routes have been translated into a speed and road gradient profiles, i.e. driving cycles, serving for computing the fuel consumption of the studied vehicles in GBA driving conditions.

Figure 8: Typical routes recorded in GBA

3.2. Measurement statistics

This survey includes only 8 different drivers so it could not be totally representative of driving patterns in Lebanon. However, it gives a partial description of driving behaviors in GBA. Collected data during the survey show that 50% of total trips have a total distance lower than 5 km with an average trip distance of 8.8 km as depicted in Figure 9.a. In parallel, stop duration distribution presented in Figure 9.b shows that capacity onboard. They are respectively equipped with 2, 3 and 4 Li-ion battery packs, 1.9 kWh each. Note that increasing battery capacity results in an extended electric mileage.

Table 2: Common characteristics of the modeled vehicles

Glider Mass (kg)	Aerodynamic Drag Coefficient (-)	Frontal Area (m^2)	Rolling Resistance Coefficient (-)	Default Minimum Accessories Load (W)
1000	0.254	2.289	0.009	800

Table 3: Vehicle configuration characteristics

Vehicle type	Weight (kg)	Battery Capacity (kWh)	Power (W)	Hybrid functionalities
ICEV	1315	-	81	-
ICEV-SS	1315	-	81	SS
FH-PS	1325	1.3	81	SS+BER+B+EV
P-inH 3.8	1400	3.8	81	SS+BER+B+EM
P-inH 5.7	1450	5.7	81	SS+BER+B+EM
P-inH 7.6	1500	7.6	81	SS+BER+B+EM

SS: stop/start; BER: brake energy recovery; B: boost; EV: electric drive; EM: electric mileage

4.2. Energy and fuel consumption results

The modeled vehicles are simulated on 23 driving routes recorded in GBA in January 2011, as described in section 3.1. These routes represent typical daily trips: "home-to-work" and "work-to-home" commutes, collected from six different drivers at different times of the day. Figures 11.a and 11.b summarize the distance and velocity distribution of these routes. Results show that 83% of the trips do not exceed 10 km, with 80% of the trips duration the vehicle speed is less than 30 km/h, and 27% for speed less than 5 km/h.

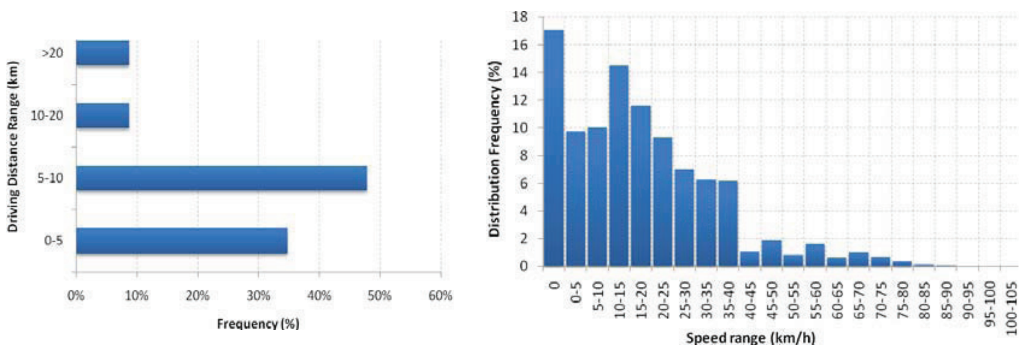


Figure 11: (a) Distance distribution; (b) Velocity distribution of the recorded routes

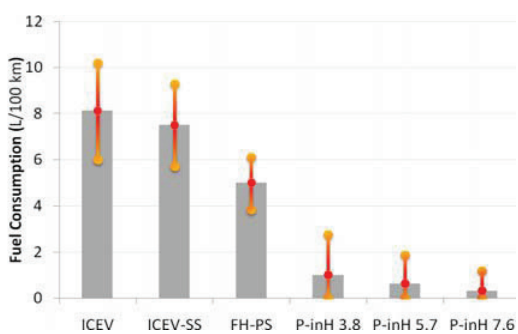
The average fuel and energy consumption for these trips are computed according to equations 1 and 2, by weighting with the distance distribution of figure 11.a. Figures 12.a and 12.b illustrate the average fuel and energy consumption observed for the 23 routes for each vehicle, in addition to the minimum and maximum consumptions obtained.

$$FC = \Sigma FC_i \, d_i / \Sigma d_i \quad (1)$$
$$EC = \Sigma EC_i \, d_i / \Sigma d_i \quad (2)$$

where

d_i	: Trip distance	km
FC_i	: Fuel consumption for the trip d_i	L/100km
EC_i	: Electric energy consumption for the trip d_i	Wh/100km

7.6% of fuel savings are observed with the stop/start vehicle, and 38.3% of fuel savings with the FH power-split vehicle. Note that, the fuel consumption of FH calculation is performed using the linear regression method, which consists on determining the fuel consumption for the trip with nil battery SOC variation.



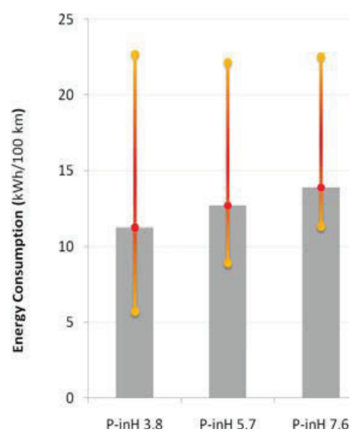


Figure 12: (a) Average, minimum and maximum fuel consumption for the different vehicles over the recorded routes; (b) Average, minimum and maximum energy consumption for the P-inH vehicles

Regarding the P-inH, for the same traveled distances, the energy and fuel consumption illustrated in figures 12.a and 12.b varies as function of the battery capacity. In fact, the more electric energy is available in the battery, the more the vehicle can go in electric drive mode and consequently less the engine turns on. This is due to the control strategy behind, where the engine turns on as the required power exceeds a defined power threshold, which decreases with battery SOC. Therefore, with large battery capacity, the SOC decreases slowly and the power threshold is less exceeded, resulting in less turn on of the engine.

On the other hand, the minimum and maximum values of both figures show that P-inH vehicles are sensitive to the travelled distance. For short distance trips (with max speed less than 100 km/h), the vehicle is driven all the way in electric drive. Therefore, since 83% of the trips were less than 10 km, the three P-inH vehicles have behaved mostly as an electric vehicle, as illustrated in figure 13.

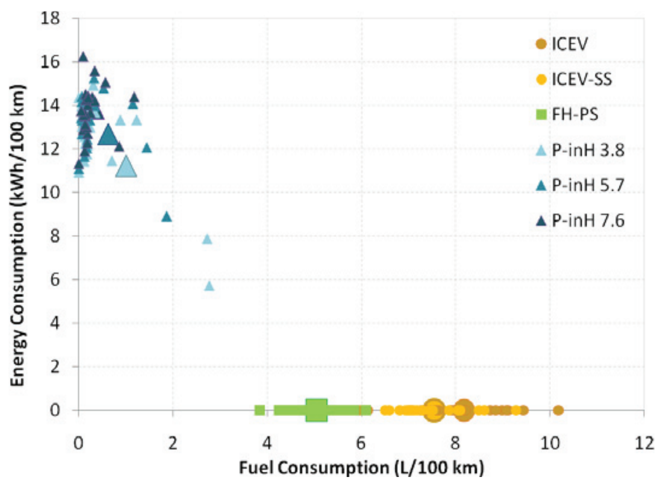


Figure 13: Energy and fuel consumption of electrified vehicles in GBA driving patterns

4.3. Operating costs of electrified vehicles

The annual operating costs for the studied electrified vehicles in section 4.2 are assessed, compared to the reference conventional vehicle. The cost of each vehicle is computed by using equation 3, based on the average fuel and energy consumption. Note that these average consumptions are obtained for the simulated routes in GBA without considering the accessories consumption. The assumed total annual mileage is 15 000 km.

$$C = FC_{avg} \,.\, ATD \,.\, C_f + EC_{avg} \,.\, ATD \,.\, C_e \qquad (3)$$

where

C	: Annual operating cost	USD
FC_{avg}	: Average fuel consumption	L/km
EC_{avg}	: Average electric energy consumption	kWh/km
ATD	: Annual travelled distance	Km
C_f	: Fuel price	USD/L
C_e	: Electricity tariff	USD/kWh

Figure 14.a illustrates the impact of variation of the gasoline price on the annual operating costs savings of the studied electrified vehicles, compared to the reference ICEV. 7.6% and 38.3% of annual savings are observed respectively for the stop/start and the FH vehicles, independently from fuel price increase. Concerning the P-inH vehicles, their annual operating costs depend on the sum of the electric and fuel consumption. As they mostly operate in electric drive mode in GBA and the electricity tariff is fixed to 0.13 USD/kWh, the P-inH savings increase with fuel price. 55 to 80% of savings are observed. However, sensitivity of operating cost on electricity tariffs (figure 14.b) demonstrates that P-inH are less beneficial than FH vehicles beyond 0.33 USD/kWh for a fixed gasoline price of 20 USD/20 Liters.

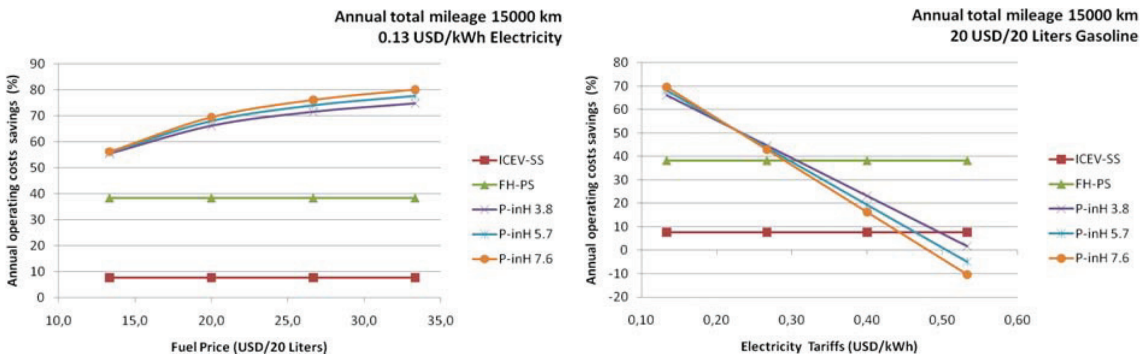


Figure 14: Annual operating costs sensitivity: (a) to gasoline prices; (b) to electricity tariffs

Combining both sensitivity studies, figure 15 summarizes the most beneficial electrified technology as function of the variation of the fuel and electricity prices.

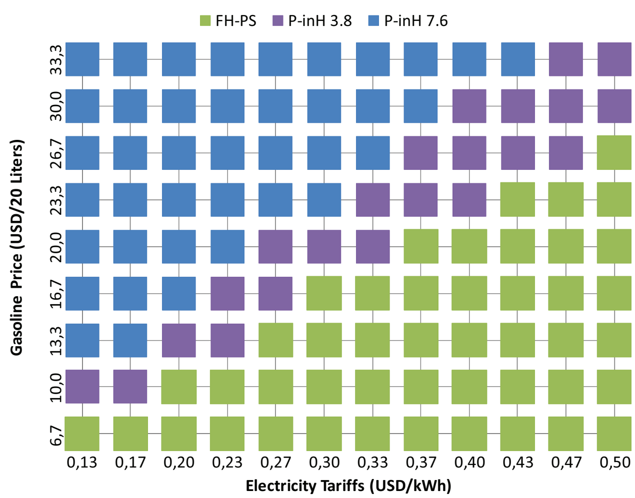


Figure 15: Optimal electrified vehicle technology as function of electricity and fuel prices variation

5. Evaluation of CO2 emissions from the transport sector in Lebanon: mitigation scenarios for consumption and emissions reduction

The 2006 IPCC guidelines provide three methods for greenhouse gases emissions estimates [11]. These methods are either based on fuel consumption (Tier1 and Tier2) or on technology related data (Tier3). The choice of method depends on the level of data availability. Tier1 is given by equation 4.

$$Emission = \Sigma(Fuel_a * EF_a) \quad (4)$$

Where,

Emission	: Emissions (kg)
$Fuel_a$	: Fuel sold (TJ)
EF_a	: Emission factor (kg/TJ)
a	: Type of fuel (e.g. petrol, diesel, natural gas, LPG etc)

This method requires the knowledge of two parameters: the fuel consumption per type of fuel and the emission factors.

Numbers on fuel consumption for the transport sector are provided by the International Energy Agency (IEA). Statistics are detailed per type of fuel. For the year 2008, Lebanon has consumed 1.401 Mtonnes of motor gasoline and 11 ktonnes of Gas/Diesel oil within the transport sector. It should be noted that based on numbers from the Lebanese Ministry of Environment (MOE) [12] "the overall import of transport-related fuels in 1999 was around 1 611 157 tons, with a 12.7% increase over the 1994 figure of 1 429 619 tons".

Numbers from IEA are then converted into calorific values using conversion factors provided by the 2006 IPCC guidelines (44.3 TJ/Gg for Motor Gasoline and 43.0 TJ/Gg for Gas/Diesel oil) [13].

Considering the default CO_2 emission factors for Motor Gasoline (69 300 kg/TJ), and Gas/Diesel oil (74 100 kg/TJ), total emissions can therefore be estimated to 4 336 Gg of CO2 emissions for the year 2008.

Higher Tier levels require access to more detailed data, which can be a complicated task in a country like Lebanon. However, such disaggregated level of information is necessary in order to establish forecast scenarios for emissions estimations based on the knowledge of the actual fleet description and propose mitigation scenarios for emissions and oil consumption reduction.

A database was used in order to establish a description of the 2007 fleet of vehicles. A sample constituting 60% of the passenger vehicles fleet was studied. Vehicles were classified in four categories depending on their displacement class. Results are shown in table 4.

Table 4: Distribution of 60% of the engine displacement of the 2007 Lebanese car fleet

	<1.4	**1.4-2.0**	**2.1-3.0**	**>3.0**
Engine displacement classes distribution	8%	32%	48%	12%

This distribution is applied to the total fleet of passenger vehicles. Total consumption of motor gasoline is then computed based on average fuel consumption numbers per class of vehicles. These values are obtained by simulation of typical vehicles for each displacement class, with different engine displacements, on the 23 routes recorded in GBA. The average fuel consumption of each class is considered, taking into consideration the improvements of engine efficiencies according to vehicle age [14]. The annual distance travelled is assumed constant equal to 16 000 km [1].

For the year 2007, 1.648 Mtonnes is obtained for passenger cars, which is higher than numbers provided by IEA and MOE. A more precise evaluation of fuel consumption requires additional surveys for urban, rural and highway driving modes not only in GBA but allover Lebanon.

Three simplified forecast scenarios are considered. For all scenarios, an annual increase of 1.5% for personal cars is assumed. In the business as usual scenario, the distribution amongst types of vehicles shown in table 4 is considered for the year 2020 as well. For the mitigation scenarios, a reduction in high displacement classes vehicles is proposed for the year 2020, as shown in table 5.

Table 5: Business as usual and mitigation scenarios for reducing fuel and CO_2 emissions by 2020

Displacement classes distribution	<1.4	1.4-2.0	2.1-3.0	>3.0	Hybrid
BAU	8%	32%	48%	12%	0%
Mitigation 1	10%	40%	45%	5%	0%
Mitigation 2	20%	35%	35%	5%	5%

For Mitigation 1 scenario, a reduction of 5% in CO_2 emissions and fuel consumption is observed reaching 10% for Mitigation 2 scenario. This is mainly due to increasing the share of fuel efficient vehicles such as electrified vehicles and vehicles with engine displacement lower than 2 liters (particularly less than 1.4).

Although such scenarios could be considered as “non exhaustive”, the authors meant to show the importance of higher Tier levels for inventories establishment, not only for current emissions estimation but also for emissions and oil consumption forecast and policies implementation. The methodology can be obviously applied to the transport sector in Lebanon, and it is indispensable for decision makers to set the Lebanese national strategy for sustainable mobility. Additional field surveys are required and cooperation with relevant authorities is needed.

6. Conclusion

In current competitive context for road transport sector in Lebanon, electrification of vehicles could be one of the adaptive solutions to displace transportation reliance on fossil fuel. This solution requires an interaction between road transport stakeholders.

Public authorities should set a strategic clear and well-defined road map for the implementation of efficient and clean vehicles in the car fleet. Accordingly, public authorities should particularly define adapted incentives on new vehicle technologies, develop efficient infrastructure built to meet the road map and increase rates of renewable and green energy in the electric mix.

Planning of an adapted infrastructure, especially road traffic management in GBA would change significantly driving patterns. A synchronized web of stop signs in urban areas could reduce drastically the frequency of stops and extends the duration of stops increasing by that the potential of Stop and Start systems in lowering fuel consumption and emissions. In addition traffic management could increase the average speed in urban areas and reduce acceleration rates which reduces the transient operating points of the engine and reduces the fuel consumption as a result.

Many actions should be achieved in order to make electrified vehicles competitive in the market. The major controller of the cost-effectiveness of electrified vehicles still the fuel prices which are fluctuating, a small rise in fuel prices make P-inH vehicles on the top list of competitiveness.

In parallel, drivers should adapt and accept to change their use and driving patterns of the vehicle in order to minimize fuel consumption and to reduce green house gases emissions through organized car sharing based on web application social networks.

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