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Short communication

Emission inventory of key sources of air pollution in Lebanon

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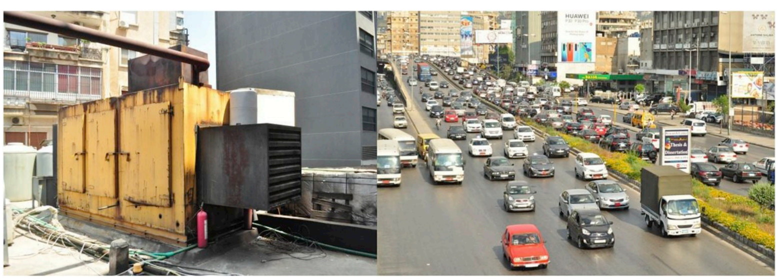
GRAPHICAL ABSTRACT



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ABSTRACT

Exposure to air pollutants has been associated with deleterious health effects that cause premature mortality and a range of morbidities. Air quality in the Mediterranean is of particular interest due to an array of environmental and anthropogenic conditions that make it an air-pollution hotspot. However, the scarcity of data for the region's emission inventories inhibits accurate and holistic assessment. Lebanon, located on the eastern board of the Mediterranean, faces several challenges including an unsustainable transport sector, an unregulated power generation sector, and high urban densities, all of which amplify the air-quality crisis. This paper presents an air pollutant emission inventory for two major emission sources in Lebanon, diesel generators and light duty vehicles (LDVs) of the transport sector, and uncovers trends for over a decade. The exhaust emissions for carbon dioxide, nitrogen oxide, carbon monoxide, sulfur dioxide, and fine particulate matter for diesel generators and for LDVs were estimated by assimilating different approaches and data sources through the use of survey data and national statistics for a higher tier. Our results uncovered that diesel generators consumed almost 1.6 million tons of fuel and emitted about 2 Gg of fine particulate matter in 2016. LDVs doubled in number over a decade and were responsible for approximately 0.20 Gg of fine particulate matter emissions in 2015. While the market for diesel generators appeared to have saturated, ownership of passenger cars per passengers continued to increase, while vehicle age, conditions, and, thus, emissions continued to augment. The results highlight the need for greater government intervention to meet the national electricity demand and promote public transportation and discourage private transportation, especially for energy-inefficient vehicles.

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1. Introduction

Short-term and long-term exposures to outdoor air pollution induce a number of negative health effects, including premature mortality in addition to a range of morbidities. According to the World Health Organization (WHO), the global burden of premature deaths due to outdoor air pollution was 4.2 million in 2016 (World Health Organization, 2019). The most common air pollutants that exceed the regulations in many parts of the world and contribute to health risks are tropospheric ozone (O_3) and its precursors—nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) in addition to particulate matter, such as particles with aerodynamic diameters not above 2.5 µm ($PM_{2.5}$).

An air pollution hotspot, the Mediterranean basin is characterized by high ozone levels during the summer due to the free cloud conditions, high solar radiation intensity, and the region's characteristic location as a crossroads of polluted air masses from Europe, Africa, and Asia (Kallos et al., 2007; Kanakidou et al., 2011; Lelieveld et al., 2002; Millán et al., 2002). The region is also characterized by high PM emissions related to industrial activities and transport sectors in urban areas (Abdallah et al., 2018) and is expected to be severely affected by climate change, including higher ambient temperatures (Ochoa-Hueso et al., 2017; Peñuelas et al., 2017). This calls for continuous tracking of ambient concentrations for common pollutants which is crucial to assess the regional exposure to air pollution (Monks et al., 2015). Due to the challenges of installing, operating, and maintaining air quality monitoring networks (AQMNs) in most developing countries in the region, air quality modeling and climate forcing modeling have become primary alternative solutions. However, an essential requirement for accurate modeling is the availability of a detailed emission inventory. Despite the scarcity of data, there is a growing interest in building local and regional emission inventories in the Middle East and North Africa (MENA) region.

Lebanon, as part of the MENA region, is characterized by an unsustainable road transport sector (Daher et al., 2013; Haddad et al., 2018; Waked et al., 2012), an unregulated private diesel generator sector (Bouri and El Assad, 2016; Ghanem, 2018; Shihadeh et al., 2013), and poor air quality management. As such, Lebanon is witnessing an increase in pollution-related events. The severity of these events is higher in urban neighborhoods due to increasing emissions in these densely populated areas, such as Beirut city (Massoud et al., 2011; Mokalled et al., 2018; Saliba et al., 2007, 2010). An emission inventory (Waked et al., 2012) was established for Lebanon and Beirut for the base year 2010 considering anthropogenic and biogenic sources of CO, NO_x, sulfur dioxides (SO_2), non-methane volatile organic carbons (NMVOC), ammonia (NH_3), as well as $PM_{2.5}$ and PM_{10}. This inventory, which relied on a manual traffic count in Beirut, in addition to the specific origin- and destination-trip information, and a rough estimation of the diesel generator emissions using Tier 1 methodology, was then used by two air quality modeling studies for Lebanon and Beirut. Overestimation of CO and SO_2 concentrations was observed in the first study, while overestimation of O_3 concentrations was observed in the second. These biases have been linked to the boundary conditions and the emission inventory itself (Abdallah et al., 2018; Waked et al., 2013).

This study presents an emission inventory for the major emission sources in Lebanon for light duty vehicles (LDVs) and diesel generators and establishes, for the first time, a variation trend for the past twelve years. It should be noted that only exhaust emissions were calculated and that nonexhaust emissions (e.g., brake, tire, and wear component) were not considered. Therefore, our reported emissions for $PM_{2.5}$ are equal to the emissions of PM_{10}. The bottom-up and top-down methodologies adopted to collect the data concerning the diesel generators and LDV fleet are described, followed by the evaluation of calculated emissions for 2005–2016.

2. Methodology

2.1. Diesel generators

Two approaches were adopted to estimate the fuel consumption of diesel generators in Beirut. The first was a bottom-up approach that starts with calculating the fuel consumption for the diesel generators that were surveyed in a neighborhood region of Beirut, Hamra, and then extrapolating the findings according to the building ratio to the whole city, which suffers from a daily blackout of no less than 3 h. The second was a top-down approach that started with the total fuel consumption of diesel generators in Lebanon and then focused on Beirut, including the area surveyed. In this case, both the socioeconomic factors and the population ratio were also considered in the calculation. The total amount of fuel consumed by diesel generators in Lebanon was derived from two sources: the first was the total amount of fuel imported and reported by the Central Administration of Statistics (CAS, 2016) on behalf of the Ministry of Energy and Water (MoEW), and the second was the distribution by sector as stated by one of the major oil and gas companies, Issa Petrol Trade Energy Center (IPTEC) (Ministry of Environment (MoE), 2017; shared excel data file). Based on the outcome of the two approaches, the diesel generator emissions were calculated according to the European Monitoring and Evaluation Programme/European Environmental Agency (EMEP/EEA) air pollutant emission inventory guidebook using the Tier 2 methodology for reciprocating engine applications (EMEP, 2016b). The difference between Tier 1 and Tier 2 methodologies in EMEP are the emission factors. In Tier 1, the emission factors for a given type of fuel are the same among the different technologies (e.g., boiler, gas turbine, stoves, and reciprocating engines), whereas in Tier 2 the emission factors are dependent on the fuel type and technology used.

2.1.1. Surveying process

The surveyed area in Hamra is bounded by Bliss, Rome, Emile Edde, and Sadat streets. Its surface area is 0.55 km^2 and it contains 588 buildings, including 50 hotels. After securing permission from Beirut Municipality, a survey of the diesel generators in the area was conducted in the summer of 2017. In the survey, the fuel consumption was recorded according to a 3 h daily operation. Additional information, including the stack height and diameter, power rating, age, and maintenance data were also recorded. The collected data was logged into an Excel file and then converted using Earth Point (Earth Point, 2017) into a Keyhole Markup Language (KML) file for visualization on Google Earth.

2.1.2. Emissions

Pollutant emissions (daily for Hamra and Beirut, yearly for Lebanon) of NO_x, CO, SO_2, and $PM_{2.5}$ were estimated using the EMEP/EEA Tier 2 method according to Equation (1):

$$E_i = \dot{v} \times CV_{fuel} \times EF_i \quad (1)$$

where:

$$E_i = \text{Emission of pollutant i} \left(\frac{\text{Gg}}{\text{year}} \text{ or } \frac{\text{Gg}}{\text{3 hours}}\right)$$

$$\dot{v} = \text{Fuel consumption rate} \left(\frac{\text{Tons}}{\text{year}} \text{ or } \frac{\text{Tons}}{\text{3 hours}}\right)$$

$$CV_{Fuel} = \text{Calorific value of burned fuel of} \left(0.04333\frac{\text{TJ}}{\text{Ton}} \text{for diesel oil}\right)$$

$$EF_i = \text{Pollutant emission factor} \left(\frac{\text{Gg}}{\text{TJ}}\right)$$

The average emission factors of the aforementioned pollutants (95% confidence interval [CI]) were taken for reciprocating engines ranging from less than 100 kW to over 20 MW. These emission factors did not depend on generator age and were, therefore, assigned for all generators. $CO_{2,}$ emissions were estimated using Equation (1) and based on the Intergovernmental Panel on Climate Change (IPCC) default emission factors of Tier 1 for stationary diesel combustion (IPCC, 2006) because no CO_2 emission factors were listed in the EMEP/EEA guidebook. The Tier 2 emission factors defined by IPCC could not be used in our case since they are country-specific. The emission factors used for the different pollutants are found in Appendix A in the supplementary material.

Emissions for Lebanon were calculated for 2009–2014 and 2016. Fuel consumption for the 2009–2014 period was based on the assumption that the 80% deficit in the electric power supply was met by private generators and that 1 L of diesel oil generated 3.7 kWh on average, regardless of the age and the power rating of the generator (MoE/UNDP/GEF, 2017). These assumptions were adopted after an intensive consultation process between MoE and the main stakeholders. The fuel consumption for 2016 was estimated using the top-down approach since the information about the deficit in the electric power was missing for 2015 and 2016.

2.2. *Light duty vehicle fleet*

In order to quantify traffic emissions over the decade spanning between 2005 and 2015, we started by identifying the characteristics of the vehicle fleet and their underlying trends. Then, the vehicle characteristics, obtained mainly through the national vehicle registry, were augmented by the manufacturers' specifications and the standards governing their production in order to assign them appropriate emission factors. Finally, the latter were combined with existing data on vehicle fuel consumption at a national level to deduce their activity rate and calculate their total emissions over the aforementioned years. The intricacies of the methodology are further described in the Discussion section.

The national vehicle registry was provided by MoE as a database (Ministry of Interior and Municipalities, 2017). It contains information about the make, model, fuel type, year of manufacture, year of registration, and registration type of each vehicle in Lebanon.

2.2.1. *Vehicle categories*

The national vehicle registry classifies the fleet into seven categories: public buses, private buses, public trucks, private trucks, motorcycles, public passenger vehicles, and private passenger vehicles. The model, weight, and use of a vehicle are the factors determining the category under which it falls (DieselNet, 2018). Passenger cars (or "touristic" cars following the literal translation of the Arabic term), "whether public" and "public", overlap with the LDV term adopted by the Global Fuel Economy Initiative (TransportPolicy.net, 2018). In both cases, the concerned parties are referring to vehicles with a weight rating of 3500 kg or less. LDVs constitute the majority of the vehicle fleet, varying between 85% and 90% between 2005 and 2015, as detailed in the results section (Table 1). Hereafter, light duty vehicles are referred to as LDVs or simply vehicles.

2.2.2. *Number of vehicles in circulation*

The total number of vehicles in circulation for each year was obtained by counting the number of vehicles registered each year using the national vehicle inventory. However, the registration date is that of the latest vehicle ownership change. Therefore, the number of vehicles reregistered, obtained from the data reported by CAS (CAS, 2016) for the years 2006 through 2016 were back-propagated to correct the total number of vehicles in circulation. Between this back-propagation and use of the current inventory to look into the past trends of the fleet, it is important to note that vehicles with registration that had been scrapped after the vehicle itself had been scrapped, totaled, unregistered and parked to die, or for any other reason, did not show up in the inventory.

2.2.3. *Emissions*

This study presents the theoretical estimation of Tier 2 emissions (EMEP, 2016a), where the activity rate is the traveled distance (Equation (2)):

$$E_{i,j} = \sum_k (N_{j,k} \times M_{j,k} \times EF_{i,j,k}) \tag{2}$$

where

$E_{i,j}$ = Emission of pollutant i of vehicle type j (Gg)

$N_{j,k}$ = Number of vehicle types in fleet of type j and standard k (veh)

$M_{j,k}$ = Average annual distance traveled per vehicle type j and standard k $\left(\frac{\text{km}}{\text{veh}}\right)$

$EF_{i,j,k}$ = Standard specific emission factor of pollutant i, vehicle type j and standard k $\left(\frac{\text{Gg}}{\text{veh. km}}\right)$

The emissions included in the study are CO_2, CO, NO_x, SO_2, and $PM_{2.5}$. These were determined using Equation (2) separately for diesel and gasoline cars, except for SO_2 which was determined using Equation (3):

$$E_{SO2} = 2 \times k_{S,m} \times FC \tag{3}$$

where

E_{SO2} = Emission of sulfur dioxide (Gg)

$k_{S,m}$ = Weight − related sulfur content in fuel type m $\left(\frac{\text{Gg}}{\text{Tons}_{\text{fuel}}}\right)$

FC = Fuel consumed ($\text{Tons}_{\text{fuel}}$)

2.2.4. *Emission factors*

The discussion of vehicle specifications in this paper is limited to the data used in assigning emission factors to each individual vehicle in the fleet. Thus, we reverted to the emission factor reported by the manufacturers for a given model and year of manufacture for CO_2 emission factors and for applicable standards for CO, NO_x, and $PM_{2.5}$ (DieselNet, 2018). These are based on the maximum allowable emission factors as per regulations in effect in the country of manufacture during the year

Table 1
Vehicle fleet composition (in %) by registration category per year (Ministry of Interior and Municipalities, 2017).

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	10-year average
Private passenger cars	88.39	88.00	87.51	87.23	86.80	86.26	85.81	85.31	84.69	83.79	83.10	86.08
Private trucks	6.58	6.69	6.83	6.82	6.94	7.11	7.13	7.23	7.30	7.37	7.50	7.05
Motorcycles	1.54	1.82	2.20	2.53	2.84	3.20	3.63	4.04	4.63	5.52	6.15	3.46
Public passenger cars	2.00	1.99	1.96	1.96	1.94	1.94	1.94	1.94	1.92	1.87	1.82	1.93
Public trucks	0.68	0.68	0.66	0.64	0.63	0.64	0.64	0.63	0.62	0.61	0.60	0.64
Private buses	0.49	0.50	0.51	0.50	0.51	0.51	0.50	0.50	0.50	0.50	0.51	0.50
Public buses	0.31	0.32	0.33	0.33	0.34	0.34	0.35	0.35	0.34	0.33	0.33	0.33

the vehicle was manufactured. In the process, we mapped each of the vehicles to the applicable standards in the following manner: United States (US), European Union (EU), or Japan (Jap), with Korean cars coming under Japanese standards (DieselNet, 2018). For vehicles produced before the EU came into existence, we used the pre-Euro factors reported in the standards. The country of manufacture was considered to be the country within which the manufacturer headquarters was located. Unlike Tier 1 factors, these differentiate between different fuel types, mass categories, and engine technologies. In the case of vehicles from United States, the emissions varied according to whether the vehicle was less than 5 years old, between 5 and 10 years old, or older than 10 years. These details were also considered in choosing the emission factors.

Due to the fragmentation of the applicable regulations, spanning 3 continents and 50 years, the pollutants they mention varied. For models predating the regulations stating the maximum allowable emission factors of the vehicles, the average emission factors for vehicles having the same model year in the fleet was used. For the sake of brevity, only average emission factors for the fleet for each year are reported in Appendix A in the supplementary material.

As for SO_2, its mass content on the fuel by weight was used in determining the emissions. Thus, SO_2, emissions are based solely on the fuel consumed, falling back to Tier 1 emissions. While reports from a single importer show that the sulfur content decreased from 400 to 40 gpm (grams per million) for diesel and from 165 to 40 gpm for gasoline between 1996 and 200, respectively, and reached as low as 7.3 gpm for diesel and 2.1 gpm for gasoline in 2017, we used the maximum allowable limit set by the government at 350 gpm for diesel and gasoline in 2005 (General Directorate of Oil, 2005), which used to be 500 gpm in 2004 (United Nations, 2005).

2.2.5. Activity rate

Tier 2 emission calculation relies on the distance traveled as an activity rate. This distance was obtained from the total fuel consumed by the vehicles and the average fuel efficiency for each year, as detailed below. The fuel efficiency of each vehicle was obtained from the manufacturer specifications for each vehicle. The national fuel efficiency is reported as the average of the above value for all the vehicles in circulation for a specific year. The total distance traveled by the fleet per year and the average distance traveled per vehicle per year were calculated based on the national fuel consumption reported by CAS (2016) and IPTEC (Equations (4) and (5)). It is worthy to note that the calculation was done separately for diesel and gasoline fuels.

$$\textit{Total Distance Traveled}\left(\frac{km}{year}\right) = \textit{Total Fuel Consumed}\left(\frac{L}{year}\right) \times \textit{Average Fuel Efficiency}\left(\frac{km}{L}\right) \tag{4}$$

$$\textit{Total Distance Traveled per Vehicle}\left(\frac{km}{year}\right) = \textit{Total Fuel Consumed}\left(\frac{L}{year}\right) \times \frac{\textit{Average Fuel Efficiency}\left(\frac{km}{L}\right)}{\textit{Number of Vehicles in Circulation}} \tag{5}$$

The fuel efficiency of a vehicle was considered constant and equal to the value provided by the manufacturer when the vehicle is brand new. Emission factors were also taken as a constant, and neither of the two standards accounted for ageing effects. However, we calculated the distance traveled form the fuel consumed rather than relying on odometer readings. This approach is more effective as a distance metric as it includes idling and accounts for an empirical mean ageing effect inherent in the fuel consumption of the fleet.

3. Results

For both generators and vehicles, the results below attempt to quantify the emission sources, present the trend lines for their characteristics, over a decade, and estimate their emissions.

3.1. Diesel generators

3.1.1. Hamra and Beirut

3.1.1.1. Distribution and characteristics. The total number of surveyed buildings in Hamra was 588. Out of these, 310 buildings had one or more diesel generators that were placed either on the roof, at street level, or underground level. The distribution of the generators overlaid over the buildings in a Google Earth satellite map is displayed in Fig. 1. The collected data include the number of diesel generators per building, the capacity, stack height, and other operational information. The 258 diesel generators located in 168 buildings (marked in blue in Fig. 1) consume 21.3 metric tons (MT) of fuel per 3 h per day. Notably, 60% of the fuel was consumed by generators that were not regulated by Lebanese law (Decision 8/1, addendum 2–9, 2001) since their engine power was less than 500 KVA. It was also found that 66% of the buildings have one generator, 23% have two, 7% have three, and 4% have more than three generators, with 25% of the total number of generators being at least 10 years of age. Most of the generators were placed at ground level, and their stacks were extended above roof level. The average stack height and engine power of the surveyed generators were 33 m (measured from ground level) and 200 KVA, respectively.

Fig. 1. The Hamra area showing the 588 buildings that were surveyed. 258 generators were identified in 168 buildings (blue circles) and missing information is for the remaining 142 buildings (yellow circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1.1.2. Total fuel consumption and emission inventory. The missing data for the 142 buildings was extrapolated from the data that was collected for the 168 buildings. It was discovered that around 469 generators in total were installed in the area. Their total fuel consumption was then determined as 38 MT/3 h/day (Appendix B in the supplementary material) assuming that all the generators were in operation. However, the survey revealed that 26% of the generators operated only when the electricity-outage period exceeded 3 h per day. Hence, the total fuel consumption was better estimated at 28 MT/3 h/day. Using Equation (1) and assuming that all diesel generators operate 3 h daily, the pollutant emissions of NO_x, CO, SO_2, and $PM_{2.5}$ from the diesel generators were estimated to be 1551 kg, 214 kg, 79 kg, and 49 kg, respectively. It is important to note that the density of diesel generators per building was similar to that determined back in 2010 by Shihadeh et al. (2013) in a study that covered 25% of Hamra. Extrapolating the data collected in Hamra to Beirut, while taking into consideration the building density, we discovered that the total fuel consumption of the diesel generators in Beirut city was 879 MT/3 h/day.

To complement the bottom-up approach just presented, a top-down approach based on 1,566,768 MT of fuel consumed by diesel generators in Lebanon in 2016 was also adopted. The fuel consumption in Beirut city and Hamra neighborhood were then estimated as 615 MT/3 h/day and 20 MT/3 h/day, respectively (refer to Appendix C in the supplementary material for the calculations). Assuming that the diesel generators operated for 3 h daily, the average value of the fuel consumption in Beirut (747 MT/day) produced daily emissions of 0.03 Gg of NO_x, 0.004 Gg of CO, 0.0015 of SO_2, and 0.00097 Gg of $PM_{2.5}$. As for Lebanon, the yearly emissions were estimated as 64.0 Gg of NO_x, 8.83 Gg of CO, 3.3 Gg of SO_2, and 2.0 Gg of $PM_{2.5}$.

3.1.2. Emission trend over time

A trend line of the fuel consumption for diesel generators in Lebanon spanning the period 2009–2016 is shown in Fig. 2. Emissions ranges were 2071.5–5032.0 Gg for CO_2, 26.3–64.0 Gg for NO_x, 3.63–8.83 Gg for CO, 1.3–3.3 Gg for SO_2, and 0.84–2.0 Gg for $PM_{2.5}$ as shown in Table 2. Upon inspecting the trend over time presented in Fig. 2 and Table 2 for the fuel consumption and pollutant emissions respectively, we note the following: (i) the sharp rise in both quantites during the period 2010–2012 is explained by the population increase and the influx of Syrian refugees, (ii) the decrease in 2013 and 2014 followed the installation of two powerships feeding the grid and thereby decreasing the deficit (The Guardian, 2013), (iii) the sharp increase from 2014 to 2016 with levels in 2016 exceeding those in 2012 may be explained as follows. Beyond breaking the 2.5 years of presidential vacancy, 2016 was a noteworthy year for Lebanon and for the power sector in particular. It marked the end of term for both the first national energy efficiency plan 2011–2015 (LCEC, 2011) and the lease of the Turkish powerships helping close the gap between electricity supply and demand (The Guardian, 2013). The United Nations-supported crisis response plan also steeply increased the budget for energy and heating to serve refugees, which was estimated to have reached 2 million in 2016 (United Nations, 2016), alongside host communities. Moreover, 2016 witnessed a harsher winter (Timeanddate.com, 2016), increasing electricity demand for heating.

Table 2
Annual Emissions of CO_2, NO_x, CO, SO_2 and $PM_{2.5}$ in Gg from diesel generators.

	2009	2010	2011	2012	2013	2014	2016	7-year average
CO_2	2136.1	2071.5	3013.6	4837.5	4322.6	3273.2	5032.0	3526.6
NO_x	27.2	26.3	38.3	61.5	55.0	41.6	64.0	44.8
CO	3.75	3.63	5.29	8.49	7.58	5.74	8.83	6.19
SO_2	1.4	1.3	2.0	3.1	2.8	2.1	3.3	2.3
$PM_{2.5}$	0.87	0.84	1.2	2.0	1.8	1.3	2.0	1.4

3.2. Vehicle fleet

3.2.1. Registered vehicles

Passenger cars and public trucks were the only registration categories which, overall, lost shares over the course of the decade, while the number of motorcycles quadrupled. Nevertheless, LDVs continued to dominate the vehicle landscape, making up 88% of the fleet on average as illustrated in Table 1. The number of LDVs almost doubled from 760,000 to 1,491,000 between 2005 and 2015. The data also reveal that the number of yearly registered vehicles, with an average of approximately 70,000, doubled between 2005 and 2008 and peaked in the 2009–2010 period (Table 3). It should be noted that vehicles whose owners removed them from circulation for any reason (export, fatal accidents, and so on) before 2015 did not appear in the database.

3.2.2. Vehicle characteristics

As shown in Table 4, German and Japanese-made vehicles continued to make up almost three quarters of the fleet over the decade 2005–2015. South Korean-made vehicles displayed the largest increase in their share, reaching 8% in 2015. This is contrasted by the 5% increase in the average vehicle mass, bypassing the 1350 kg mark, which is usually indicative of larger and more luxurious vehicles entering the fleet. Traditional internal combustion engines or microhybrids constituted nearly the entire fleet, with negligible numbers of hybrids, plug-in hybrids, and electric vehicles. Among the former, diesel-

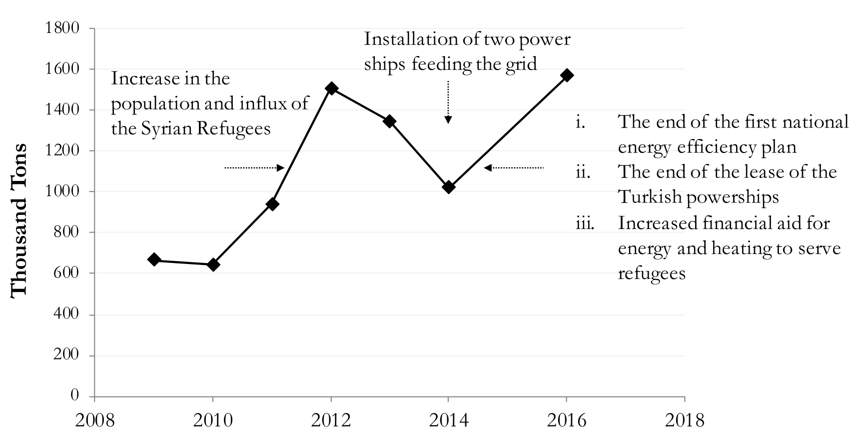

Fig. 2. Fuel consumption in thousand tons for diesel generators in Lebanon over the period between 2009 and 2016. Marked are the justifications for the trend changes.

Table 3
Number of light duty vehicles per year (CAS, 2016; Ministry of Interior and Municipalities, 2017).

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	10-year average
In circulation	763756	801610	847053	924786	1023153	1117973	1195475	1271046	1341881	1413248	1490509	1108226
Registered per year	38803	37854	45443	77733	98367	94820	77502	75571	70835	71367	77261	69596

powered vehicles in fact jumped from 7% to 12%, as illustrated in Table 5. The average model year over the decade is 1994, equal to its value in 2010.

3.2.3. Vehicle age

While model year is indicative of vehicle technology, the vehicle age is a measure of the vehicle condition. Fig. 3 shows a heat map of the yearly number of cars in circulation belonging to a certain model year. As can be inferred from the Figure, the average age increased by 50% from 13 years to 19 years, marking an alarming deterioration.

3.2.4. Fuel consumption

The average fuel efficiency deteriorated only slightly, from 10.91 to 10.80 km/l, remaining close to an average of 10.84 km/l. Estimated values of the average annual distance travelled per vehicle are shown in Table 6. The trend over time is that of a general decrease for both gasoline and diesel vehicles, with a peak around 2008–2009 and slight increase towards the end of the decade .

3.2.5. Emission trend

Annual LDV emissions for Lebanon are reported in Table 7 for the period 2005–2015. Emission ranges for the various elements were recorded as follows: 4045–7180 Gg for CO_2, 40.0–57.4 for CO, 2.6–4.6 Gg for NO_x, 1.81–3.27 Gg for SO_2, and 0.55–0.75 Gg for $PM_{2.5}$.

4. Sources of uncertainty

A qualitative approach was used to assess the uncertainty due to the lack of data for our quantitative approach. The two main determinants for emission uncertainty estimation were the source activity rate (i.e., fuel consumption) and emission factors. A moderate uncertainty was associated with the diesel generators' emission estimation since the calculation was based on an extrapolation from a surveyed number of diesel generators in a representative neighborhood and the fuel consumption that was averaged between a bottom-up and a top-down approach. Along the same line, a high uncertainty was attributed for car emissions because the manufacturer specifications were considered for new vehicles, regardless of terrain, age, national driving conditions, and temperature.

5. Discussion and conclusions

The emission inventory that we presented covered the two major emission sources in Lebanon: the undocumented diesel generators for electricity production and the LDVs of the transport sector.

The inability of the government to meet the demand for electricity in the country has made the diesel generator sector ‘s subsidy a stable business, with a consistent coverage area of 1172 m^2/generator in Beirut since 2010 (Shihadeh et al., 2013). With an increase of 133.5% in the total fuel consumption for the installed diesel generators in Lebanon between 2010 and 2012 explained by an increase in electricity demand due to the influx of refugees during that period. The ratio of NO_x emissions from diesel generators to LDVs more than doubled (6.9 for 2010 and 15.7 for 2012), which transformed the diesel generator sector into the major contributor of NO_x emissions in the country. Diesel generators have been shown to have consumed almost 1.6 million tons of fuel and emitted about 2 Gg of $PM_{2.5}$ in 2016. The CO_2 emissions/year/km^2 from the diesel generators calculated for Lebanon are 1.14 times higher than those reported in Nigeria (Somorin et al., 2017), a country that also relies heavily on diesel generators to meet power demand. On the other hand, a comparison with the Waked et al. inventory (Waked et al., 2012) for the diesel generator emissions was not possible since they did not report these emissions explicitly in their work. For future studies, age and maintenance data should be taken into account in terms of methodology to refine the diesel generator emissions estimate.

Vehicular emissions worsened over the years, in spite of the decreasing trend in annual distance traveled per vehicle. This could be attributed to the explosive growth in the number of vehicles in the fleet, and the deterioration of the vehicle running conditions. The share of buses has remained fairly constant over the decade, during which growth of modes of individual transportation continued to dominate. The share lost by the private passenger car category appeared to be taken up by motorcycles. However, the most popular public transportation option, registered as public passenger cars, suffered a 10% loss of fleet share. The reign of LDVs over the transportation fleet is indicative of the scale of emission reduction that could be achieved with policies that target public transport. However, the consistent share of public buses is a sign that the Lebanese population is willing to adopt them as a form of mass transit as they continue to expand.

The explosive growth of the LDV fleet, two-fold over a decade, could be partially explained by the accompanying population growth. It also suggests that the inadequacy of public policy guiding the transport sector, with the vehicle fleet reflecting the prioritization of individual convenience over social benefit. Controlling fleet characteristics and emissions could not only curb the emission hazards but also improve the nation's fuel economy and trade deficit. With an annual effective distance of 28.3 billion km covered by LDVs alone, the need for reforming the fleet characteristics and transportation schemes remains considerable and should be further investigated by other studies. The

Table 4
Vehicle fleet composition (in %) by country of manufacture per year (Ministry of Interior and Municipalities, 2017).

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	10-year average
Germany	42.6	42.4	42.1	41.4	41.0	40.6	40.2	39.6	39.0	38.4	37.8	40.5
Japan	31.0	31.2	31.5	31.9	32.6	32.8	32.8	32.7	32.7	32.8	33.0	32.3
France	10.4	10.2	10.0	9.5	8.9	8.4	8.1	7.8	7.5	7.3	7.1	8.7
United States of America	5.9	6.0	6.2	6.6	7.0	7.2	7.2	7.2	7.2	7.2	7.2	6.8
South Korea	2.5	2.6	2.9	3.3	3.6	4.3	5.1	6.1	6.9	7.7	8.2	4.8
Sweden	3.2	3.1	3.0	2.8	2.5	2.4	2.2	2.1	2.0	1.9	1.9	2.5
United Kingdom	2.2	2.2	2.2	2.2	2.2	2.3	2.4	2.5	2.6	2.8	2.9	2.4
Italy	1.6	1.5	1.5	1.4	1.2	1.2	1.1	1.1	1.0	1.0	1.0	1.2
Others	0.6	0.8	0.6	0.9	1.0	0.8	0.9	0.9	1.1	0.9	0.9	0.8

Table 5
Vehicle fleet composition (in %) per fuel type per year (Ministry of Interior and Municipalities, 2017).

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	10-year average
Gasoline	91.5	91.3	90.9	90.1	89.1	88.8	88.5	88.2	88.1	87.8	87.6	89.3
Diesel	7.3	7.6	8.0	8.9	10.0	10.3	10.6	10.9	11.1	11.4	11.6	9.8

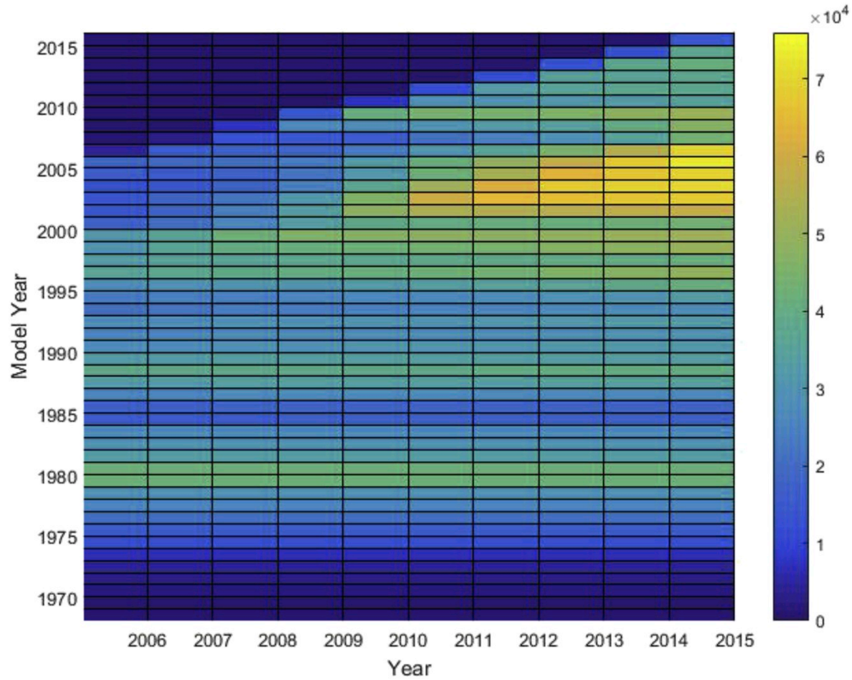

Fig. 3. Heatmap showing the evolution of the vehicle fleet by model year (Ministry of Interior and Municipalities, 2017) between 2005 and 2015.

popularity of vehicles from certain regions, namely, the European Union and Japan, facilitates the process of enforcing vehicle characteristics. It could be expanded beyond imports at the level of Lebanese customs. Bilateral agreements with the European Union and Japan could ensure that the vehicles that are allowed to be exported to the country not only meet Lebanese regulations but also fulfill the updated requirements of the countries of manufacture.

The ageing fleet is not only losing its efficiency but is also gradually shifting towards higher emission factors. The average age of the vehicle fleet was 19 years as of 2015, and it has been increasing steadily at a rate of 0.66 vehicle age years per calendar year. This situation creates a lag in adopting enhanced vehicle technology. For example, at the current rate, the average vehicle model would not reach the standards of 2015 until 2063. A major concentration of vehicle models from 2000 to 2005 entered the fleet after 2010, around the same time Euro 5 came into effect. The Euro 5 legislation drastically cut the maximum allowable carbon monoxide and nitrous oxide emission factors for gasoline vehicles and particulate matter and nitrous oxide emission factors for diesel vehicles. It appears that Lebanon might be importing dated technology that are banned elsewhere. This situation was exacerbated by the increase in diesel vehicles from 7% to 12% in clear violation of a 2001 law prohibiting their further import.

The peak in emissions in the 2009–2010 period could be understood in light of the relative political stability the country experienced then. This same peak was observed in the number of vehicles registered and the average distance traveled per vehicle. The varying trends in emissions were the result of all the combined factors discussed previously. On the one hand, the relatively newer vehicle models, 2000–2005, were introduced to the fleet between 2009 and 2015, the bulk of which entered the fleet after 2010. On the other hand, the country experienced a rise in diesel and Korean-made vehicles. The former tend to have higher particulate matter and nitrous oxide emission factors, while the latter exhibit the lowest emission factors and highest fuel efficiency. The emissions are subject to competing factors resulting in non-monotonous variations over the years. The key factors are the population, the traveled distance affected by the socio-economic conditions of the country, and the fleet characteristics.

LDV emissions were compared to those of the entire Greek fleet in 2010 (Fameli and Assimakopoulos, 2015) despite Greece having an area approximately 13 times larger and Lebanon having 7 times the population density. In terms of per capita emissions, Lebanon fares better such that its emissions are 0.5, 0.4, 0.07 and 0.3 times those of Greece with respect to CO_2, CO, NO_x and $PM_{2.5}$. These results are expected given the difference in population density of the two countries. However, when compared per unit area, Lebanese emissions are respectively 4, 3, 0.5, and 2 times higher.

Table 6
Total distance and average distance traveled by vehicle fuel type per year.

		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	10-year average
Distance by fuel type (1000km/vehicle/year)	Gasoline	27.0	24.3	24.5	25.0	26.5	24.2	22.8	20.7	19.4	19.7	22.2	23.3
	Diesel	70.4	55.5	40.6	46.6	55.5	42.2	42.4	43.1	44.9	43.8	43.7	48.1
Total distance (10^{10} km/year)		2.28	2.12	2.16	2.47	2.98	2.89	2.95	2.92	2.96	3.15	3.65	2.83

Table 7
Annual emissions of CO_2, CO, NO_x, SO_2, and $PM_{2.5}$ in Gg from light duty vehicles.

		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	10-year average
CO_2	Gasoline	3560	3400	3630	4050	4750	4760	4800	4630	4570	4890	5780	4438
	Diesel	743	645	532	747	1120	968	1060	1160	1280	1320	1400	998
	Total	4303	4045	4162	4797	5870	5728	5860	5790	5850	6210	7180	5436
CO	Gasoline	38	35	37	40	46	45	44	42	41	43	50	42
	Diesel	5.9	5.0	3.9	5.0	6.8	5.6	6.0	6.4	6.9	7.1	7.4	6.0
	Total	43.9	40.0	40.9	45.0	52.8	50.6	50.0	48.4	47.9	50.1	57.4	47.9
NO_x	Gasoline	1.8	1.7	1.8	2.0	2.3	2.3	2.3	2.2	2.1	2.2	2.6	2.1
	Diesel	1.2	1.0	0.80	1.2	1.8	1.5	1.6	1.7	1.9	1.9	2.0	1.5
	Total	3.0	2.7	2.6	3.2	4.1	3.8	3.9	3.9	4.0	4.1	4.6	3.6
SO_2	Gasoline	1.27	1.20	1.27	1.40	1.62	1.60	1.60	1.53	1.51	1.60	1.88	1.50
	Diesel	0.675	0.660	0.540	0.750	1.11	0.960	1.05	1.15	1.27	1.31	1.39	0.988
	Total	1.95	1.86	1.81	2.15	2.73	2.56	2.65	2.68	2.78	2.91	3.27	2.49
$PM_{2.5}$	Gasoline	0.37	0.35	0.36	0.38	0.42	0.40	0.39	0.37	0.35	0.36	0.42	0.38
	Diesel	0.29	0.24	0.19	0.25	0.34	0.28	0.29	0.30	0.32	0.32	0.33	0.29
	Total	0.66	0.59	0.55	0.63	0.76	0.68	0.68	0.67	0.67	0.68	0.75	0.66

Our LDV emissions for 2010 were compared with the transport sector emissions reported by Waked et al. for the same year (Waked and Afif, 2012; Waked et al., 2012). It was discovered that for CO and NO_x, Waked's values were 10 times larger than ours. In fact, Waked's bottom-up approach for estimating the number of LDVs resulted in an over-estimate when compared to our number, which we obtained by counting the vehicles in the registry given to us by the MoE. Given that the actual number is larger due to the presence of nonregistered vehicles, it still does not justify Waked's estimate, which is 100% larger than ours. This is a classic example of a bottom-up approach incurring large errors because it relies on shaky statistical grounds without being constrained by observed integral values (i.e., the total number of vehicles). In addition, Waked adopted EEA guidelines, which assumed that all the vehicles were European models. In reality, a majority of the vehicles were non-European. Our calculations took the vehicle-make of each individual vehicle into account. As a result, the emission factors used by Waked were also overestimated by a factor of two, when compared to ours. Waked's Tier 3 model requires estimations of the vehicle speeds and travel distances. Unless the estimates of these parameters are accurate, using the Tier 3 emission calculation could lead to significant errors. Under Waked's assumptions and given the age of the fleet with an average model year of 1994.4 in 2010, it becomes equivalent to adopting Tier 1, which replaces vehicle speeds with a range into Tier 3 equations and assumes the characteristics of the 1995 European fleet (EMEP, 2016a). Our calculation is simpler as it uses a Tier 2 calculation where the effective annual travel distance was estimated using vehicle count, fuel efficiency, and total fuel consumed. The total annual fuel consumption and the number of vehicles in circulation for the year were estimated with a high degree of certainty from tables and databases given to us. The only uncertain parameter is the fuel efficiency of the vehicle (km/L), which we obtained from the manufacturer (for each vehicle). We note also that the effective distance should be actually lager than the actual distance because it takes into account the idling conditions. If we use the emission factors from the MoE report (MoE, 2015), HDVs emit as much as LDVs even though they make up only 10% of the fleet. In short, Waked's estimate for the number of vehicles, his chosen emission factors, and inclusion of heavy duty vehicles, each at least doubled the emission estimates, explaining a large part of the stark difference observed.

The towering interest with short-lived climate forces; namely, black carbon (BC), organic carbon, $PM_{2.5}$, NO_X, CO, NMVOC, SO_2 and NH_3, requires emission inventories to promote their scientific understanding and assessment of their impact (IPCC, 2018). We cover only a subset of these components; namely, $PM_{2.5}$, NO_X, CO and SO_2. This approach is due to the variation and shortcomings of the existing methodologies, especially when assessing emissions of nontraditional sources (IPCC, 2018). Black carbon emissions prove to be particularly problematic (IPCC, 2018), and thus, have been completely omitted from this paper.

Beyond the variations inherent in the methodologies, we highlight the sensitivity of existing standard procedures for emission quantification to the availability of data or lack thereof, especially in countries with limited inventory efforts. We have been fortunate to access the national vehicle registry for the purpose of the study. While it contains a basic listing of the vehicles in circulation, their model and technology are sometimes erroneous, leading us to refer back to manufacturer specifications. The latter has been a tedious task for the team with over a 100,000 unique vehicle models, some of which have been transliterated into Arabic and others misspelled. Moreover, we have supplanted the lack of odometer readings with a top-down approach of using the total fuel consumed annually. The former could simply be incorporated into the annual control procedure for the vehicles. In addition, data from the control procedure for the fleet in 2013 were made available to us in the course of the study. While all aspects of a vehicle were examined during the process, including catalytic converters and brakes, the data only included emission factors which were suspiciously identical. The adoption of foreign emission standards for the emission factors could be excluded in future work with the proper reporting of emission factors in the control process. Tracking the characteristics of the vehicles over the years would also allow for more accurate characterization of vehicle condition and age.

With only 46 countries reporting their emission inventories to the United Nations Framework Convention on Climate Change (UNFCC, 2019), this study sets a precedence in a data-scarce region, aiding in the future development of nation-wide policies and interventions. In addition to tracking progress towards environmental commitments, this inventory feeds into air quality models that usually require a fine spatiotemporal resolution, particularly in the Mediterranean basin.

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Appendix A. Supplementary data

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