Pollution, 6(4): 705-723, Autumn 2020
DOI: 10.22059/poll.2020.300625.778
Print ISSN: 2383-451X Online ISSN: 2383-4501
Web Page: https://jpoll.ut.ac.ir, Email: jpoll@ut.ac.ir

Emissions and Fuel Life Cycle Assessment of Non-passenger Diesel Vehicles in Qatar

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Received: 08.04.2020 Accepted: 01.07.2020

ABSTRACT: The life cycle of diesel fuel in non-passenger vehicles was assessed for all registered vehicles in Qatar as of November 2017. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model was used as a source of normalized data to evaluate diesel fuel emissions for all non-passenger vehicle categories. This work aims at estimating the emissions from all non-passenger diesel vehicles in Qatar and evaluating the impact of the fuel life cycle assessment. The emissions of CO_2, NO_x, CO, SO_2, VOC, black carbon (BC), organic carbon, fine particulates $PM_{2.5}$, and coarse particulates PM_{10} were evaluated. SO_2 emissions were found to be dominant during the well to pump (WTP) stage of the life cycle assessment (LCA) process, while the pump to wheel (PTW) stage was found to be dominated by CO, VOC, PM_{10}, $PM_{2.5}$, and BC emissions. NO_x and organic carbon emissions were virtually the same during both stages. Total greenhouse gas emissions amounted to 5367 kt of CO_2 equivalent (CO_2-eq) in 2017 as compared with that in 2014 (5277 kt), the only reported value in Qatar for transportation emissions. In addition, several mitigation strategies are proposed to ensure sustainability in the transport sector and to minimize the negative impact of diesel fuel emissions in the country.

Keywords: air pollution; LCA; GREET; sustainability; diesel vehicles; Qatar.

INTRODUCTION

The Middle East area (MEA), and in particular, countries in the Arabian Peninsula (AP), has experienced tremendous economic growth in recent decades, which has been accompanied by increased infrastructure development and population growth (McKee et al., 2017). Among them, the State of Qatar is located in the peninsula with an area of 11,000 km^2 and a coastline of 900 km in the eastern coast of the AP. Qatar has been ranked first in the world index of countries that have achieved record economic growth in 20 years from 1997, according to a report carried by CNBC Arabia. These unprecedented developments have been coupled with heavy traffic and industrial activities propelled by their wealth driven from oil/gas resources (Kumar, 2016). The peninsula of Qatar is generally flat with sand dunes dominating the southern part of the country, hence its habitants mostly live in the mid-to north eastern coast within the city of Doha and its neighboring smaller cities; Al-Wakra and Al-Khor (Richer, 2009). Typical of the AP, Qatar is hot and dry, with an annual rainfall of 81mm and

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an average annual maximum temperature of 31°C. The absolute maximum air temperature can exceed 47°C in summer months (Richer, 2009).

According to the Qatar Ministry of Development, Planning, and Statistics (QMDPS), the total population has reached to 2,782,106 as of February 2020 following an exponential growth since 2007 when it was around 800,000. Following such a high rate of population growth, urbanization, construction of buildings, infrastructure, civil works, and vehicle ownership have also increased. Figure 1 shows the total number of vehicles and its annual increase as per the data obtained from the Qatar Ministry of Interior (QMOI) (Ministry of Development Planning and Statistics, 2018).

Among various emerging challenges in the areas of social, cultural, safety, security, economy and energy, environmental sustainability is an underlying challenge due to such population growth and development for Qatar as recognized in Qatar National Vision (QNV 2030) (Ministry of Development Planning and Statistics, 2018). Environmental sustainability demands rapid responses to manage and mitigate several challenges before their consequences are irreversible for an inhabitable environment. The emphasis on the environmental impact of the increased number of vehicles and the extensive use of transportation is clear. Unfortunately, very few data are available regarding recent emissions from transportation in Qatar. According to the Environment Statistics Annual Report published by the Ministry of Development, Planning, and Statistics in 2014, the CO_2 emissions inventory of Qatar from the transport sector was approximately 5,277 kt (Table 1) (Ministry of Development Planning and Statistics, 2015)

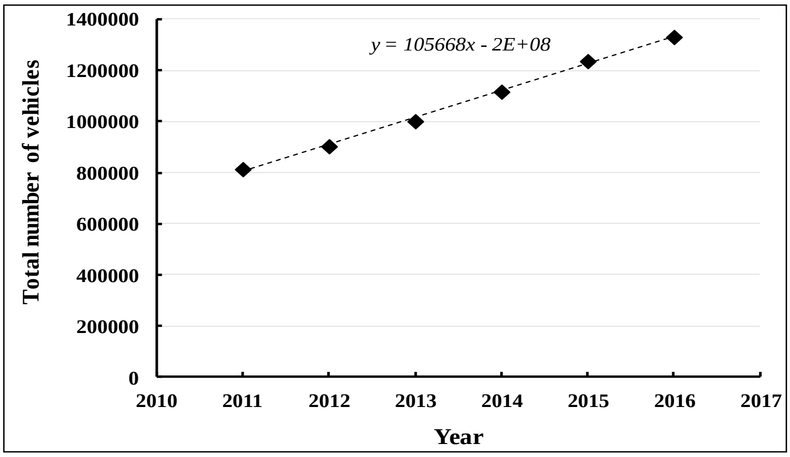

Fig. 1. Total number and annual increase of vehicles. Data from MOI as per (Ministry of Development Planning and Statistics, 2018).

Table 1. Air emission inventory in Qatar as per Qatar's Initial National Communication to UNFCCC (Ministry of Development Planning and Statistics, 2015).

Air emission source categories (1000 metric tons)	CO_2	CH_4	N_2O	NOx	CO	NMVOC	SO_2
Total energy	52924	137	1	162	43	104	127
Fuel combustion activities	46507	68	1	158	24	66	73
Energy industries	38124	66	1	75	22	12	67
Manufacturing industries and construction	3106	1	0	39	1	6	6
Transport	5277	1	0	44	1	48	0
Fugitive emissions from fuels	6417	69	0.22	4	19	38	54
Solid Fuels	0	0	0	0	0	0	0

Considering the total population of Qatar in 2016 (approximately 2.57 million), the average number of vehicles per 1000 capita is 520 which is a relatively high value indicating that there is large dependence on vehicles in Qatar. This value did not change much since it was reported for Qatar in 2014 which was at 532 (Nation Master, 2014). In comparison with other neighboring countries in the Gulf, Kuwait reported a value of 527, Saudi Arabia at 336, United Arab Emirate at 313 and Oman at 215 for the same year (Nation Master, 2014). .

The latest available data on air emissions in Qatar were reported by the World Bank (Economics Trading, 2019). The total CO_2 emissions in Qatar were 107854 kt in 2014 stemming from the burning of fossil fuels and the manufacture of cement. They also include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring, according to the World Bank collection of development indicators, compiled from officially recognized sources (Economics Trading, 2019). CO_2 emissions from transport include emissions from the combustion of fuel for all transport activities, except international marine bunkers and aviation. Hence, these emissions result from domestic aviation, domestic navigation, road, rail, and pipeline transport.

LCA is a tool that can be used to evaluate the environmental impacts of a process or a product from its origin to end of life (Cooney, 2011; Earles & Halog, 2011; Rose et al., 2013; Merchan, 2017). It typically consists of four stages, as shown in Figure 2: (1) extraction of raw material, (2) manufacturing/production, (3) use, and (4) disposal/recycling or end of life (EOL) (International Council of Chemical Associations, n.d.).

LCA related to the transportation sector is gaining more attention due to the energy requirements and the impact of emissions on weather, global warming, human health, and security (Bang et al., 2016). When applied, LCA considers the vehicle, the fuel, and in more detailed studies, road LCA, as shown in Figure 3 (Eriksson & Ahlgren, 2013) (Wu et al., 2006).

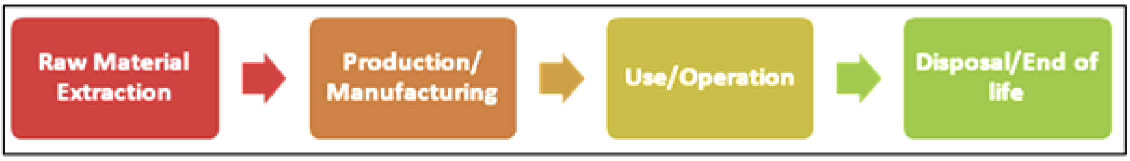

Fig. 2. Life Cycle assessment stages, adopted from Cooney (Cooney, 2011).

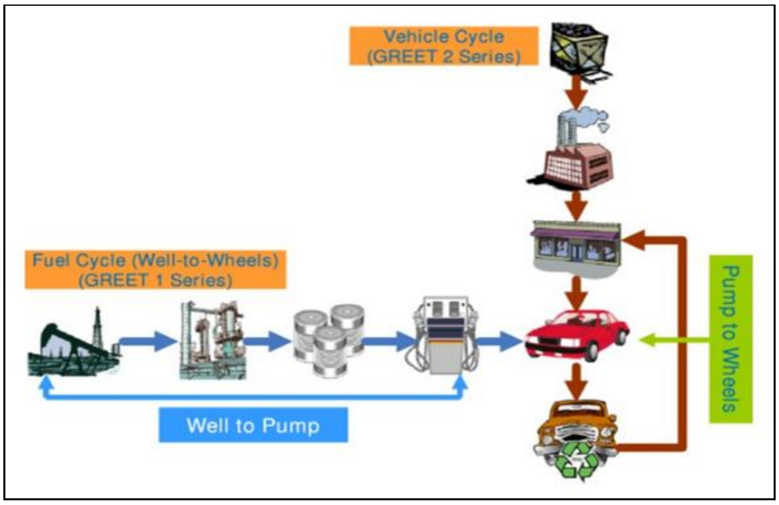

Fig. 3. Well to wheels analysis of vehicle/fuel system that covers activities for fuel production and vehicle use (Wang, 2007).

Lane et al., (Lane, 2006) provided a detailed outline for the life cycle of vehicles, which includes the processes during which energy is consumed and emissions and waste are generated. The first process is related to the production of materials needed to manufacture vehicles. It includes a variety of materials, such as steel, aluminum, rubber, glass, and other composites. The second process is vehicle assembly, where energy is required to assemble the components and operate manufacturing plants. The next stage is vehicle distribution, which involves transporting vehicles from assembly plants to dealerships. It is followed by a longer stage, which is vehicle use and maintenance. The last process is vehicle disposal in which vehicles are shredded and a portion of the materials is recycled for further use. It has been estimated that the energy consumption required for shredding and the further separation processes for the body shell amounts to approximately 66 kWh/t (Messagie et al., 2014)(Hischier, 2007). Moreover, because batteries should be removed and treated separately during the de-pollution step, several studies have reported on different recycling processes to reduce the environmental impact of the materials that make up batteries (Ong et al., 2012).

Vehicle LCA begins with the most important stage, which is the design and development of a vehicle. This stage is critical because it determines the composition of a vehicle in terms of materials used, safety features, and fuel economy, which considerably impacts the rate and type of emissions throughout the vehicle's lifetime. The next step is the extraction and processing of materials from their sources. Then, vehicle manufacturing assembles the final vehicle (Maclean & Lave, 2003). Vehicles are made of diverse materials in various proportions ranging from iron, steel, aluminum in hundreds of kilograms to polymers and ceramics in few kg (Lane, 2006; Bachmann et al., 2015).

The next stage involves the use and operation of the vehicle. This stage is complicated and is comprised of several sub-life cycles. First, the fuel cycle is commonly referred to as "well-to-tank (WTT)" or "well-to-pump (WTP)" in LCA studies (Armanuos et al., 2016). This includes fuel production from recovery or production of the feedstock, its transportation, and conversion of the feedstock to the final fuel, fuel storage, distribution, and delivery to the vehicle fuel tank. The next stage is vehicle operation, which is commonly referred to as "tank to wheel (TTW)" or "pump to wheel (PTW)" in LCA studies (Peng et al., 2017). This stage considers the energy required to move the vehicle, which impacts exhaust and evaporative emissions over the lifetime of the vehicle. It also considers facilities (such as parking lots and roads) and infrastructure to support the vehicles over their lifetimes. The next stage is related to vehicle service, which includes repair and maintenance, during the vehicle's lifetime. In addition, fixed costs for each vehicle, which include vehicle insurance, charges for financing the vehicle, license fees and depreciation rate to be accounted for (Maclean & Lave, 2003).

As mentioned previously, several studies that have conducted LCA split the use stage of vehicles into WTP and PTW. The WTP stage includes the production and distribution of the fuel, while the PTW phase covers the use of this fuel by the vehicle (Messagie et al., 2014).

For the two most common fuels used in transportation, diesel and petrol, all processes in the refinery are taken into consideration in an LCA. This includes process emissions (Figure 4), waste water treatment, and direct discharges into water bodies such as rivers (Messagie et al., 2014; Jungbluth et al., 2007).

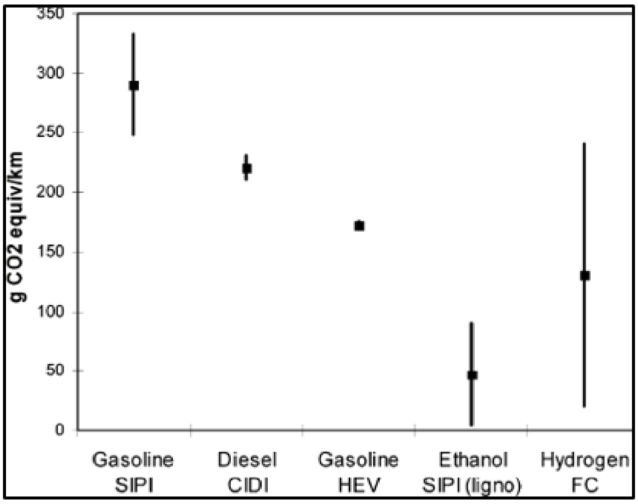

Fig. 4. Greenhouse gas emissions for full life cycle of vehicles which include fuel life cycle and vehicle operation (Well to Wheel). The figure shows mean and range of estimates. Adopted from (Maclean & Lave, 2003).

The production process for fuels, including diesel and gasoline, is responsible for large amounts of total emissions, such as VOC, NO_X, and SO_2 (Kawamoto et al., 2019; Cuellar & Herzog, 2015). During this process, SO_2 emissions are mainly due to the use of electricity in refinery plants as well as refinery flaring or off-gassing (Hooftman et al., 2016). For instance, the contribution of SO_2 emissions from petroleum production is as large as tailpipe SO_2 in the case of sedans (Olatunji et al., 2015). Moreover, in the case of pickups and sport utility vehicles (SUV), SO_2 emissions from petroleum or fuel production are seven times larger than tailpipe emissions. NO_X emissions are also another pollutant that results from electricity generation. In addition, VOC emissions can be due to both oil and gas extraction processes and result from direct refinery emissions (Chester & Horvath, 2009).

The PTW stage considers energy or fuel consumption as well as the tailpipe emissions (Messagie et al., 2014). This typically includes the assessment of average CO_2 emissions (g/km) in addition to hydrocarbon (HC), NO_x, SO_2, methane (CH_4), CO, particulate matter (PM), and N_2O emissions (g/km) for each specific type of vehicle (Uihlen, 2008).

Eriksson et al., (Eriksson & Ahlgren, 2013) indicated in their detailed literature review on the LCA of petrol and diesel fuels that there are differences in the PTW part in terms of energy use and greenhouse gas (GHG) emissions (Eriksson & Ahlgren, 2013). This is due to the fact that these emissions are dependent on the type of engine or vehicle that uses the fuel. Hence, studies have reported emission values in two common units: in the per-distance unit and in the per-energy content (Palm, 2011). In all cases, the air to fuel ratio is critical for determining the emission type and level. In an optimal combustion process, the stoichiometric ratio between oxygen and carbon determines the amount of CO_2 and water produced from the burning of HCs. Moreover, the production of NO_x, which is a more potent GHG than CO_2, is determined when oxygen reacts with nitrogen gas in the air. However, if there is not enough oxygen present during the combustion process, there will be more compounds emitted that are not fully combusted, such as CO and CH_4 (Petchers, 2002). Gode et al., (Gode, 2011) also reported that as the vehicle engine size increased, higher emissions of NO_x and CH_4 were observed, while the emissions of N_2O decreased. Another critical factor for the emissions in the PTW stage is the hydrogen to carbon (H:C) ratio. This determines the degree of saturation of HCs, which implies that as the H:C ratio increases, a higher energy content per mass unit of fuel is obtained. Moreover, the emissions of CO_2 per unit of energy decrease as the H:C ratio increases owing to the lower carbon content in the fuel (Edwards et al., 2011). Hence, both of these ratios, the stoichiometric ratio between oxygen and carbon and the hydrogen to carbon ratio, can directly affect the level of greenhouse gas emissions from fuel combustion.

The roadway life cycle can be divided into four stages or categories: roadway construction, roadway lightening, roadway maintenance, and parking construction and maintenance. Roadway construction has major environmental impacts. During this stage, several greenhouse gas emissions and pollutants are produced, such as SO_2, NO_x, VOC, and PM_{10} (Marzouk et al., 2017). It has been reported that emissions of SO_2 during roadway construction are almost as large as SO_2 emissions from sedan cars and are over three times larger for pickup and SUV tailpipe emissions (Chester & Horvath, 2008). In addition, NO_x emissions during road construction are responsible for 160 to 200 mg/passenger miles traveled (PMT) of the 1,000 to 1,300 mg/PMT total emissions for vehicles. The SO_2 and NO_x emissions result from asphalt bitumen transport that is used in the wearing layers of roadways. Additionally, VOC emissions from diluents used in asphalt composition volatilize during placement. These emissions are equivalent to approximately 25% of the total vehicle VOC emissions and approximately 40% of bus emissions. In terms of particulate and fugitive dust emissions during asphalt placement, these emissions are nine times larger than those of PM_{10} from vehicle tailpipes (Chester & Horvath, 2008).

In roadway lighting, SO_2 from the production of fossil fuel-derived electricity is a non-negligible contributor to the automobile inventories. It is more than twice as large as tailpipe SO_2 emissions per PMT for SUVs and pickups (Chester & Horvath, 2008).

During the third stage related to roadway maintenance, SO_2 emissions from the resurfacing of roadways because of damage from urban bus travel overwhelm operational emissions. The origin of the SO_2 emissions is the electricity requirements during the production of hot-mix asphalt in plants. Roadway maintenance SO_2 emissions from buses is 290 mg/PMT compared to the 70 g/PMT released during diesel fuel combustion (Chester & Horvath, 2008).

Finally, the parking construction and maintenance stage, in which the environmental impact is critical, involves SO_2, NO_x, VOC, and PM_{10} emissions. The same causes that are described for roadway construction apply to parking lot construction, but the effects are smaller (Chester & Horvath, 2008).

The goal of this research is to conduct an environmental LCA of diesel fuel during its consumption in conventional internal combustion diesel powered non-passenger vehicles in Qatar. To the best of our knowledge, this is the first study to report on the LCA and actual emissions of all registered non-passenger diesel vehicles in Qatar as per November 2017. The scope includes categorizing the vehicles according to the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (GREET) and estimating greenhouse gas emissions, particulate and carbon emissions to propose applicable mitigation policies for achieving a sustainable transport sector.

The uncertainty of the findings in this study is subject to validation once the actual values are obtained. Recently, our research group has been granted access to the actual travelled distance of the vehicles in Qatar which can be used for recalculating all the emissions annually. Nevertheless, the emission factors shall be obtained experimentally from several type of vehicles or otherwise use modeled or GREET values for approximation. Nevertheless, GREET is used by various industries (including the automotive industry) and has been found to provide results that compare favorably to measured emission data from non-affiliated sources (Almeida & Sousa, 2019)(Frank et al., 2016)(Budsberg, 2013)(Wallington et al., 2016).

The specific objectives of this work are to utilize GREET to evaluate the environmental impacts in terms of gaseous and particulate emissions of all registered non-passenger diesel vehicles in Qatar during the WTP and PTW stages, and provide guidelines for the strategic decision-making process for future transport energy policy and to identify key areas of interest for further technology research and development.

MATERIALS AND METHODS

The life cycle assessment analysis is an attempt to quantify the environmental impacts over the life cycle associated with a material, product, or process involving four main stages, as shown in Table 2 (Lane, 2006).

Table 2. Stages of Life Cycle Assessment. Adopted from Lane (Lane, 2006).

Stage	Description
Scoping	defines the purpose of the analysis, the boundary parameters within which the analysis occurs, the product/material/process of study, and lists the information sources and assumptions used in the analysis
Inventory analysis	accounts for all the energy, raw materials and emissions used and/or generated throughout the life cycle of the product/material/process under assessment
Impact analysis	identifies and quantifies the impacts on the environment (e.g. eco-systems, human health, natural resources) as defined in the scope of the assessment
Improvement Analysis	a qualitative and quantitative comparison of the options assessed to identify opportunities for a reduction in the environmental impacts within the scope of the assessment

In order to perform an LCA for diesel fuel in non-passenger vehicles in this work, several assumptions have been made due to the absence of specific values in Qatar and the region.

GREET Fleet Footprint Calculator 2012 is the version we used in this study. It is a module of the GREET1 2012 software. Originally, GREET was developed long time ago based on excel spreadsheets which gather data and produces models to calculate life cycle energy and emissions related to the transportation sector. But later, it became harder to maintain and expand theses spreadsheets, so a software was developed using a new platform for life cycle assessment studies and database management. This new platform combines all the previous Excels spreadsheets in a single environment with a single database that is now easier to maintain and manage. The input data in our case was the type of vehicle, fuel type and vehicle count. We adopted the emission factor of diesel from GREET. The main assumption used in our work is the annual kilometer travelled distance as this piece of information is completely absent for Qatar and the region.

The count of all registered non-passenger diesel vehicles (as per 2017) was obtained from the traffic department. The count excluded private passenger cars, military and police vehicles. The vehicle type and count were obtained following the recommended categories from the GREET model, which is a unique analytical tool that simulates the energy use and emission outputs from a variety fuels and vehicle types. This tool was developed by Argonne National Laboratory and is sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy. GREET offers two platforms to use: the GREET.net model and the GREET Excel model. Because of technical issues with downloading and operating the

GREET.net version, which is a common challenge, we used the GREET Excel model. In this type of studies for assessing fuel life cycle emissions and energy consumption, it is necessary to consider “normalized” data (i.e., data that have been made comparable) to allow for meaningful comparisons of the different technologies. Hence, GREET was chosen as the source of the normalized data. For a given fuel/vehicle combination, GREET calculates the fuel life cycle consumption of energy (from all sources) and fossil fuels, and the emissions of CO_2, CH_4, N_2O, CO, NO_x, SO_x, volatile organic compounds, and particulate matter with a diameter of 10 µm or less (Argonne National Laboratory, Illinois, 1999). The accurate emission data and flexibility of the program for accepting a variety of user inputs makes GREET a worthy research tool. For example, a recent study used GREET emission data to compare the fuel life cycle emissions of trucks utilizing compression ignition direct injection (CIDI) engines fueled with liquefied petroleum gas (LPG), compressed natural gas (CNG), and diesel (Daniel & Rosen, 2002).

In the GREET Excel model, the vehicle types are grouped as shown in Table 3. Hence, the vehicle count was considered according to the classification provided. Then, the average annual traveled distance was obtained as suggested by GREET along with the miles traveled per gallon of diesel fuel, which was converted to km per liter of diesel (Table 4). The Internal Combustion Engine Diesel model was adopted for all vehicles, which implies that certain number of tons of CO_2-eq emissions is produced per barrel of diesel.

Since actual data on the annual traveled distance of each type of vehicle in Qatar or the region is not available, the recommended values from the GREET model were adopted. Ideally, such values should be obtained from surveys of statistical data from the traffic department or vehicle insurance companies. This shortcoming will be considered in the recommendation section and will be performed by our research team in future studies. Several other annual traveled distances have been reported in studies for different parts of the world. Ally et al., (Ally & Pryor, 2007) reported that an average bus in Perth/Australia travels 55,000 km annually with a lifetime of 16 years. In this study, the annual average traveled distance for all non-passenger vehicles was based on GREET and is approximately 44,500 km.

Table 3. Type of vehicle and count as per GREET model classification. Data obtained from Traffic Department in Qatar.

Type of Vehicles	Abbreviation	Examples	Count
Bus	Bus	School and transit bus	9407
Waste Hauler	WH	Waste dumber, drainage tanker, trash container	3163
Street Sweeper	SS	Street sweeper	80
Delivery Step Van	DSV	All types of delivery vans	1100
Transport/Freight Truck	TFT	Vehicle carrier, animal carrier, cranes and lorries	9576
Medium/Heavy Duty Pickup Truck	M/HDV	All types of pickups	16105
Maintenance Utility Vehicle	MUV	Asphalt roller, excavator, stone crusher, traffic light lifter, cement mixer, tractor	13977
Other	Other	Paramedic, fire fighters, mobile mosque, mobile workshop	13343
Total			66751

Table 4. Vehicle kilometers Travelled per year (VKT) for each type of vehicles as per GREET (Argonne National Laboratory, 2012).

Type of Vehicles	VKT	km/ liter of diesel
Bus	18,645	1
Waste Hauler	14,543	1
Street Sweeper	7,831	2
Delivery Step Van	10,255	6
Transport/Freight Truck	49,720	3
Medium/Heavy Duty Pickup Truck	7,085	5
Maintenance Utility Vehicle	3,108	11
Other	18,645	1

Other studies have considered the functional unit to be one vehicle-kilometer over a 12-year lifetime, as reported by Cooney et al., (Cooney, 2011). In general, the effect of assuming a prescribed lifetime should have a minimal impact on the results (Cooney, 2011).

For the calculation of well to wheel emissions and energy consumption, GREET follows the standard methodology to predict the emission factor for each pollutant. In the case of diesel fuel for internal combustion engines, the following outlined energy pathways are generally assumed for the purpose of the LCA analysis:

Diesel: Crude oil extraction → production and conditioning → shipping → refining → mixed transport to depot→ 150-km road transport to fuel stations (Lane, 2006).

In the case of Qatar, this pathway can be further modified to become:

Diesel: Crude oil extraction → production and conditioning → refining at Ras Laffan 2 plant in the north→ road transport to fuel stations around Qatar.

RESULTS AND DISCUSSIONS

Figure 5 shows the vehicle count as per the statistics received in November 2017. Medium, heavy duty vehicles, maintenance utility vehicles and other types of vehicles make up approximately 65% of the total count.

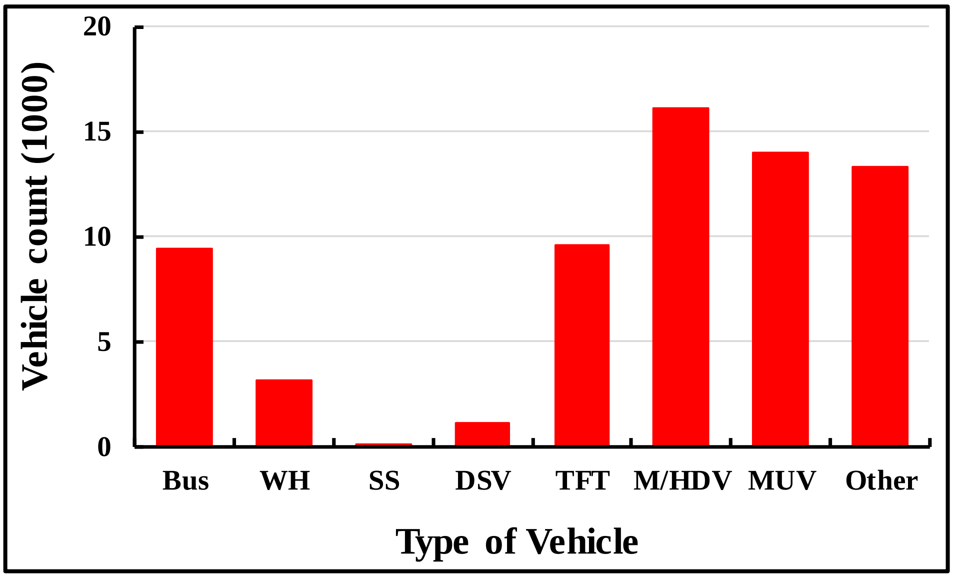

Fig. 5. Total count of vehicle types as received in November 2017. B: bus, WH: waste hauler, SS: street sweeper, DSV: delivery step van, TFT: transport/freight truck, M/HDV: medium/heavy duty pickup transport, MUV: maintenance utility vehicle.

Figure 6 shows the total annual traveled distance in 1000 km. Although the number of transport/freight trucks (TFT) was not major compared with other types of vehicles, such as medium/heavy duty pickups or maintenance utility vehicles, TFT had the longest annual traveled distance (approximately 50,000 km per vehicle), followed by the distance traveled by other type of vehicles. The annual traveled distance is a critical parameter to estimate fuel consumption in LCA studies because it affects fuel consumption, and hence, energy and emission rates. As mentioned in the Methods section, because of the unavailability of such data for the Middle Eastern region, data suggested by the GREET database were adopted.

Figure 7 shows the total greenhouse gas emissions in CO_2-eq (kt) for each type of vehicle. We observe that some types of vehicles produce more GHG CO_2-eq than others because their internal combustion process is relatively inefficient. This is reflected by the emission factor reported by GREET for these types of vehicles. For instance, the distance traveled for each liter of diesel is 1 km for these vehicles, whereas it is 6 km for a delivery step van and 3 km for a transport/freight truck. Hence, the further distance these vehicles travel, the more fuel they require; consequently, more GHG CO_2-eq is produced.

Moreover, the data from the count of vehicles in 2017 is in agreement with the results reported earlier for 2014 as the projection in vehicle number growth was considered to increase from that year (2014). The total CO_2-eq emissions from all transport sectors (all fuels and vehicles, including diesel and others) were approximately 5277 kt in 2014. The total CO_2-eq emissions from non-passenger diesel vehicles according to this study for registered vehicles in 2017 were approximately 5367 kt, as shown in Figures 7 and 8. Both figures show the same order of magnitude, which sets a reasonable baseline for future mitigation measures to avoid continuous growth in diesel fuel emissions from transportation.

Figure 8 shows the share of GHG CO_2-eq emissions over the total annual traveled distance for each type of diesel non-passenger vehicle. As shown, the majority of emissions was due to TFT, buses, and other types of vehicles.

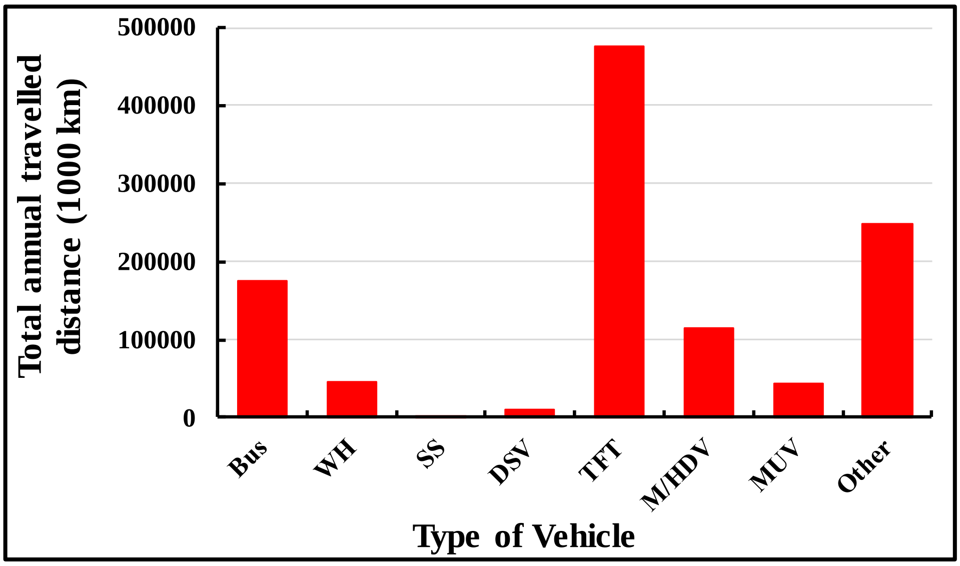

Fig. 6. Total annual travelled distance of all vehicle types as received in November 2017. B: bus, WH: waste hauler, SS: street sweeper, DSV: delivery step van, TFT: transport/freight truck, M/HDV: medium/heavy duty pickup transport, MUV: maintenance utility vehicle.

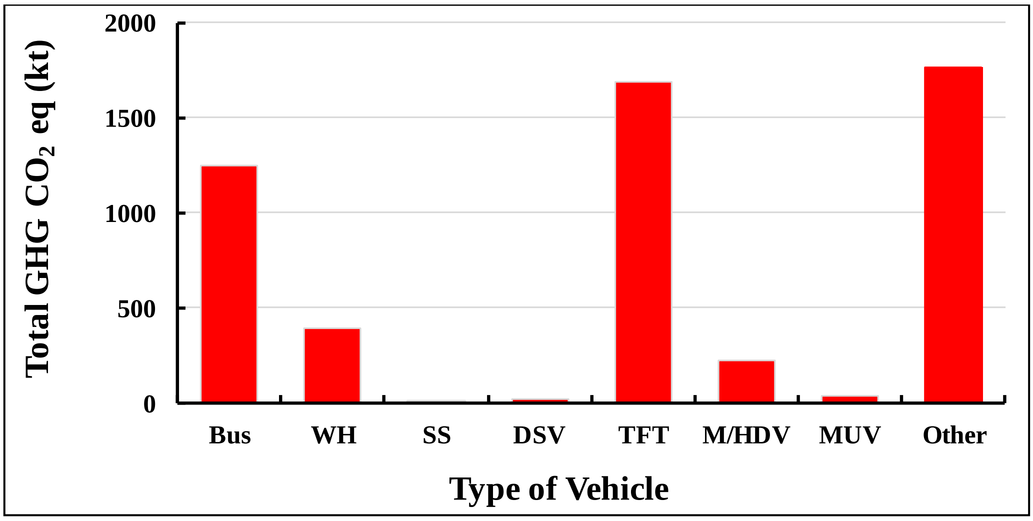

Fig. 7. Total GHG CO_2-eq emissions. B: bus, WH: waste hauler, SS: street sweeper, DSV: delivery step van, TFT: transport/freight truck, M/HDV: medium/heavy duty pickup transport, MUV: maintenance utility vehicle.

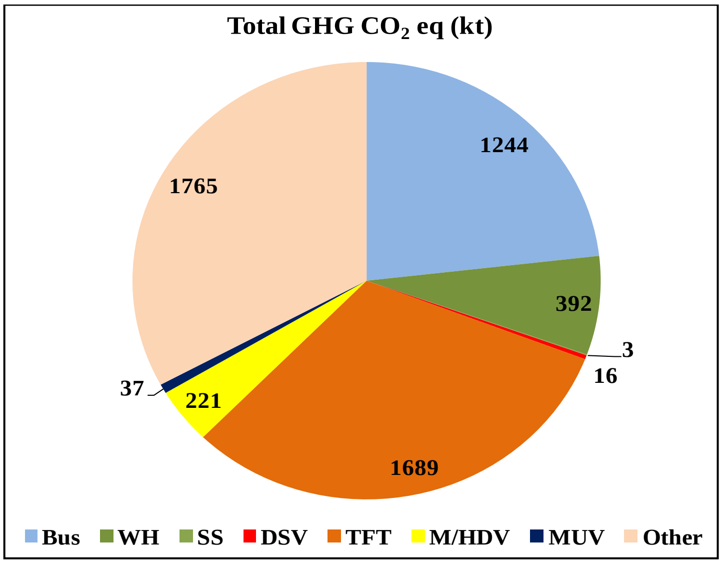

Fig. 8. The share of total GHG CO_2-eq emissions by each type group of vehicles. B: bus, WH: waste hauler, SS: street sweeper, DSV: delivery step van, TFT: transport/freight truck, M/HDV: medium/heavy duty pickup transport, MUV: maintenance utility vehicle.

LIFE CYCLE ASSESSMENT FOR ENVIRONMENTAL IMPACT

The second part of this study utilized the GREET well-to-wheel (WTW) model to evaluate several emissions, including volatile organic carbons, particulate matter (coarse and fine), NO_x, CO, sulfur oxides, and black and organic carbon from diesel fuel vehicles. Table 5 shows the life cycle impact categories of these emissions to indicate the critical importance of their evaluation.

The well to wheel fuel cycle has two stages as mentioned earlier: the WTP, which is the upstream production of the vehicle fuel and includes resource exploitation and transportation, fuel production, transmission, distribution and storage, and the fuel filling process (Peng et al., 2017), and the PTW stage, which incorporates emissions resulting from fuel combustion associated with the actual use of fuel by the vehicle.

Figure 9 shows that the contribution of

CO emissions is heavily dominated by the PTW phase related to the fuel use during vehicle operation. This is in agreement with what has been reported earlier in previous studies, in which conventional spark ignition engines produce the highest amount of CO during operation (Chester & Horvath, 2009)(Lane, 2006).

Table 5. Life Cycle Impact Categories as adopted from Ally et al. (Ally & Pryor, 2007).

Impact Category	Short description	Examples
Global Warming Potential (GWP)	Emissions that contribute to global warming	CO_2, CH_4
Acidification Potential (AP)	Emissions that cause acidification of rain, soil and water	SO_2
Eutophication Potential (EP)	Emissions that change nutrient concentration in lakes, rivers and soil	P and N compounds
Photochemical Ozone Creation Potential (POCP)	Emissions that increase the production of tropospheric ozone	Hydrocarbons

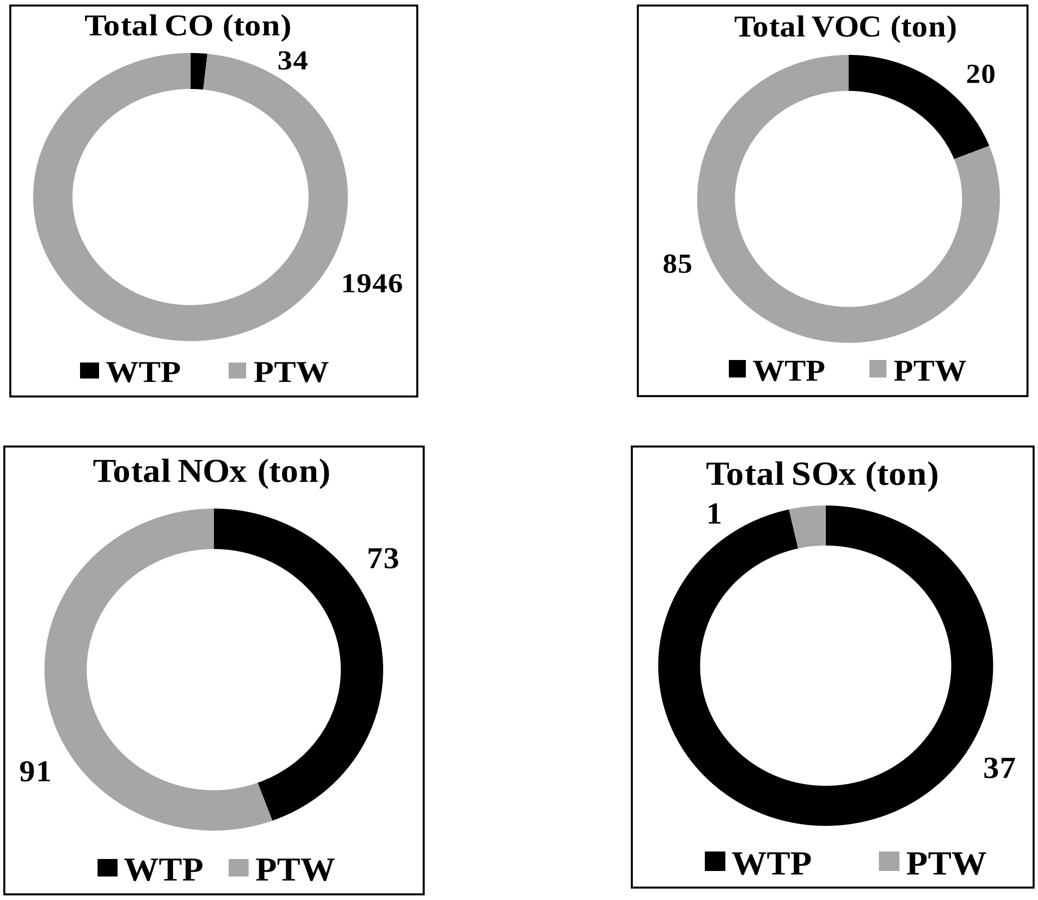

Fig. 9. Criteria air pollution emissions during Well to Pump (WTP) and Pump to Wheel (PTW) of the total annual travelled distance by all types of vehicles in this study assuming internal combustion engine using diesel fuel: total CO emitted, total VOC, total NO_x and total SO_x.

Although CO emissions from diesel vehicles are less that those emitted by gasoline because the latter burn at closer to stoichiometric conditions, diesel engines are lean with excess air (Fornaro & Ynoue, 2014). Nevertheless, it has been reported that CO formation in diesel vehicles is a function of the available amount of unburned fuel and the mixture temperature, which both control fuel decomposition and oxidation. Hence, the CO concentration from diesel exhaust ranges from 10 to 500 ppm (Egusquiza et al., 2009). Table 1 shows that the total CO emissions from the transport sector in 2014 was approximately 1 kt in Qatar. In our study, the total CO emissions from diesel fuel in 2017 are approximately 1.9 kt. The growth in the number of registered vehicles mainly affected this increase during the past few years.

The contribution of NO_x emissions is often dominated by tailpipe components (Chester & Horvath, 2009). As shown in Figure 9, approximately 91 tons of NO_x are emitted annually by vehicles, according to our study during the PTW phase. Nevertheless, the emissions of NO_x during the WTP phase are not negligible and were estimated to be around 73 tons/year in this study. These emissions are mainly due to direct electricity use, indirect electricity use for material production, and processes for fuel refinery and production. This trend in the emissions is in agreement with previous studies that showed that the emission factors for NO_x and PM_{10} are particularly higher for heavy drive vehicles (HDVs) compared to light drive vehicles (LDVs) (Pérez-martínez et al., 2014). Moreover, Lane (Lane, 2006) reported that biofuels, such as bioethanol and biodiesel, have the largest life cycle NO_x emissions due to emissions generated during fuel production with an estimated 25–75% of life cycle NO_x emissions. In the case of biodiesel, additional emissions are usually generated during vehicle operation. However, life cycle of NO_x for petrol is approximately 60% of the level for conventional diesel (Lane, 2006).

Although sulfur oxides refer to the group in which sulfur and oxygen are bonded together in the lower atmosphere, such as SO, SO_2, and SO_3, they are generally dominated by SO_2. The contribution of sulfur oxides is the highest during the WTP phase. This is evident because SO_2 is heavily emitted during electricity generation in power plants and in operations for oil excavation and production. However, the low sulfur levels in the fuels currently used in most parts of the world result in low SO_x emissions during vehicle operations (Chester & Horvath, 2009). It has also been reported that SO_2 emissions resulting from vehicle manufacturing and maintenance, roadway construction and operation (such as lighting), construction of parking areas and fuel production are 19-26 times larger than the emissions due to fuel combustion during vehicle operation (Chester & Horvath, 2009). To compare with the results previously reported for Qatar in 2014, as shown in Table 1, the SO_2 emissions were approximated to be zero, while our results show that the total SO_x (SO, SO_2 and SO_3) emissions from diesel fuel were 0.038 kt in 2017.

Figure 10 shows that particulate emissions dominate in the PTW phase, indicating that a high level of particulates is emitted during vehicle operation (Al-Thani et al., 2020), which mainly depends on the fuel economy (the emissions associated with fuel and vehicle production).

Moreover, it has been reported that particulates are also emitted during vehicle manufacture, which may vary depending on the type of vehicle that is manufactured. For instance, vehicles that use two road fuel gases, petrol hybrids and battery electrics using renewable electricity have been reported to produce the lowest levels of life cycle particulates (Lane, 2006). In the case of diesel vehicle operation, approximately 50% of life cycle particulates are emitted during vehicle use (Lane, 2006). In India, Sloss (Sloss, 2012) reported that, in 1998, the total particulate emissions from gasoline amounted to 10 kt, whereas emissions from diesel consumption were almost an order of magnitude greater at 86 kt. Emissions of particulate matter from the transport sector almost doubled between 1990 and 1998, and this increase is likely to continue well into the 21^{st} century (Sloss, 2012). In a recent report on the air pollution inventory in Massachusetts, it was reported that the total annual fine and course PM emissions from on road diesel vehicles in 2016 have amounted to 0.497 and 0.540 kt, respectively (Massachusetts Department of Environmental Protection Bureau, 2018). Hence, the mitigation for PM emissions is of paramount importance because of its negative effect on the climate, environment, materials, and human health (H. Al-Thani et al., 2018; Hanadi Al-Thani et al., 2018).

Black carbon has been reported to have a direct impact on ground level air pollution and global warming. It is emitted due to inefficient combustion and has a short atmospheric lifetime (approximately a few days to a few weeks) (IEA Clean Coal Center, 2012). Hence, unlike CO_2, black carbon (BC) offers the potential for effective and relatively quick mitigation measures for minimizing its negative environmental impacts. If proper action to reduce BC emissions is taken, the world can avoid over 1.6 million premature deaths from inhalation of smoke from indoor cooking and potentially reduce warming on a short time-scale (Rehman et al., 2011).

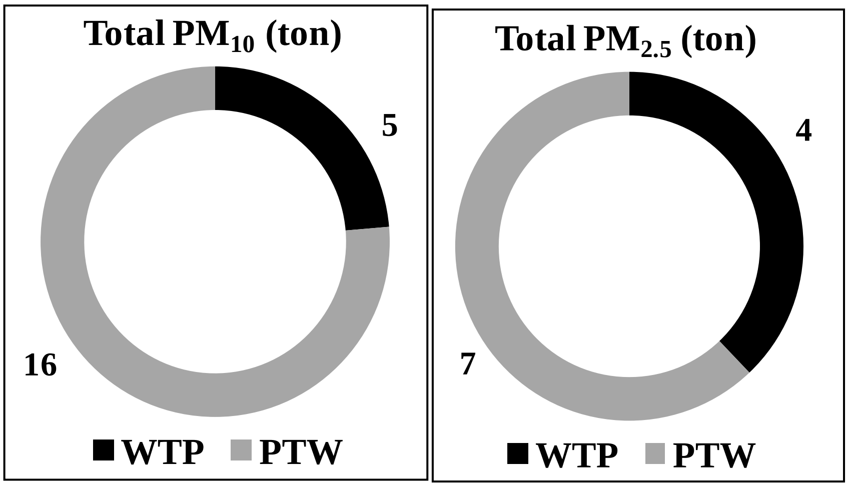

Fig. 10. Total PM_{10} and $PM_{2.5}$ emissions during Well to Pump (WTP) and Pump to Wheel (PTW) of the total annual travelled distance by all types of vehicles in this study assuming internal combustion engine using diesel fuel.

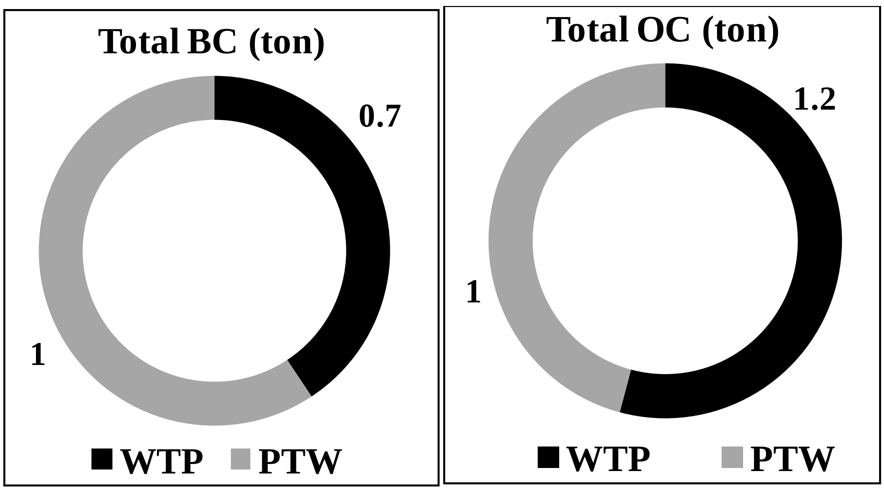

Fig. 11. Total black carbon (a) and organic carbon (b) from Well to Pump (WTP) and Pump to Wheel (PTW) of the total annual travelled distance by all types of vehicles in this study assuming internal combustion engine using diesel fuel.

Figure 11 shows the total black and organic carbon for all types of vehicles over the total annual distance travelled. It can be seen that the amount emitted is relatively low compared with other pollutants estimated in this study. This might be due to the advanced technology implemented in new model vehicles which are implemented to minimize black and organic emissions. A recent report (Evans et al., 2015) reported that, e.g., in Russia, on-road diesel vehicles emitted 21 Gg of BC in 2014. The majority was due to heavy-duty truck emissions, which accounted for 60%, while cars represented only 5% of BC emissions. The remainder of BC emissions was due to light commercial vehicles and buses. Their results were in agreement with previous reports where diesel combustion accounted for 25–30% of BC emissions at the global scale (Evans et al., 2015). The transport sector is not only a major BC emitter in Russia. In India, Sloss (Sloss, 2012) reported that BC emissions are the greatest source of pollution for all Indian cities. In addition, it was reported that transportation and mobile equipment sources are by far the most important sources of black carbon in Canada, accounting for 20 kt (54%) of total emissions in 2017. An important source in this category is mobile diesel engines, which includes on-road and off-road diesel vehicles, and accounted for 38% (14 kt) of total emissions (Government of Canada, 2019).

CONCLUSIONS

A diesel fuel LCA of non-passenger vehicles in Qatar was conducted using the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model to evaluate the environmental impacts in terms of gaseous and particulate emissions of all registered non-passenger diesel vehicles in Qatar for the year 2017. Due to the absence of specific values related to the annual traveled distance by the vehicles in Qatar, a value of 44,500 km/yr was adopted from GREET. It is of critical importance that actual values shall be obtained for each category and LCA analysis is conducted accordingly. The high ratio of vehicles per 1000 capita in Qatar indicates that traffic pollution is a challenge. Nevertheless, the government has started to implement several changes that shall have positive impact on reducing air pollution from transport sector. Two of the main changes are the introduction of electric vehicles and better road transportation management. According to Qatar National Vision 2030, the first electric car will roll out of the assembly line in 2022 with the aim to ensure that at least 10 percent of all cars in Qatar will operate on electricity by 2030 which will significantly reduce carbon emissions. The other option that Qatar is considering is road transportation management by developing many infrastructure projects around the country. These projects once executed, there will be an increase of fluidity and traffic congestion reduction which will have an impact on emission control.

The two phases in the fuel cycle assessment included the WTP and the PTW. The results are also presented as total emissions per vehicle type to help decision makers prioritize the most applicable policies based on the highest polluting vehicles.

Future research can include examples of the most common brands or types of vehicles in Qatar. The LCA can include raw materials and vehicle manufacture based on the composition of each vehicle. The environmental impacts due to material extraction, transportation, production, and ability to recycle shall be assessed.

One of the issues that should be addressed is the absence of local data related to the annual traveled distance. This task can be accomplished with the cooperation of vehicle insurance companies, which gather annual traveled distances to issue insurance policies and assess vehicle consumption.

Moreover, several mitigation or technical improvements can be suggested to reduce transportation emissions, such as the use of specialized materials to achieve specific performance goals in the transportation sector. Examples of technical advancements that have elevated the performance of vehicles include the use of platinum group metal nanoparticles to improve catalyst efficiency and the removal of air pollutants with a high efficiency at low temperatures. Another example is the use of lightweight materials in manufacturing of vehicles to minimize fuel consumption. Other more straightforward mitigation steps can include choosing smaller vehicles and driving less kilometers by using public transport more frequently (Maclean & Lave, 2003). In addition, clean fuel or fuel with an improved standard of composition can be used to reduce exhaust and evaporative emissions. For instance, in the United States, although there has been a tremendous increase in the number of vehicle registrations and vehicle kilometers traveled per year, air pollutant concentrations have been improving in the majority of urban areas. This is due to several improvements in light drive vehicle emissions of conventional gasoline/diesel and associated improvements in fuel quality (Maclean & Lave, 2003).

Several mitigation measures have been recommended to reduce CO_2 emissions from the transport sector in addition to adopting carbon sequestration measures. These include reducing vehicle kilometers traveled and carpooling. In addition, the fuel consumption of vehicles can be lowered by improvements in vehicle design. These changes could directly impact vehicle economics, performance, and consumer attractiveness. Another improvement to reduce CO_2 emissions is to lower the carbon content of fuel by moving from gasoline and petrol fuels to renewable fuels, such as ethanol. Other fuel options that may reduce emissions are compressed natural gas (CNG) or the use of electricity or hydrogen vehicles (Arteconi et al., 2013). In urban environments, carbon reduction from anthropogenic activities have been also achieved by green structures and planting trees in the streets (Isaifan et al., 2018)(Isaifan & Baldauf, 2020).

ACKNOWLEDGEMENT

We acknowledge the Traffic Department at the Ministry of Interior in Qatar for providing the vehicle count data.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

Nomenclature

AP	Acidification Potential
BioE	Bioethanol
EP	Eutrophication Potential
EPA	U.S. Environmental Protection Agency
CIDI	Compressed Ignition Direct Injection
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CH_4	Methane
CNG	Compressed Natural Gas
DSL	Diesel
DOE	Department of Energy
DSV	Delivery Step Van
ELV	End of Life Vehicle
EOL	End of Life
H:C	Hydrogen to Carbon ratio

GHG	Greenhouse gases
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWP	Global Warming Potential
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kt	Kilo ton
kWh/t	kilowatt hour per ton
LCA	Life Cycle Assessment
LDV	Light Duty Vehicle
LPG	Liquefied Petroleum Gas
HDT	Heavy Duty Vehicle
M/HDV	Medium/ Heavy Duty Vehicle
NMVOC	Non methane volatile organic carbon
MUV	Maintenance Utility Vehicle
PET	Petrol
PM	Particulate Matter
$PM_{2.5}$	Particulate matter of diameter equal to or less than 2.5 µm
PM_{10}	Particulate matter of diameter equal to or less than 10 µm
PMT	Passenger Miles Travelled
POCP	Photochemical Ozone Creation Potential
NG	Natural Gas
N_2O	Nitrogen Oxide
SO_x	Sulfur Oxides
SO_2	Sulfur Dioxide
SS	Street Sweeper
TFT	Transport/Freight Truck
TTW	Tank to Wheel
UNFCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compounds
VKT	Vehicle kilometers travelled
VMT	Vehicles miles travelled
WH	Waste Hauler
WTP	Well to Pump
WTT	Well to Tank
WTW	Well to Wheels

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