Evaluation of particulate matter emissions from non-passenger diesel vehicles in Qatar

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ABSTRACT

Road traffic is one of the main sources of particulate matter (PM) in the atmosphere. Despite its importance, there are significant challenges in the quantitative evaluation of its contribution to airborne concentrations. In order to propose effective mitigation scenarios, the proportions of PM traffic emissions, whether they are exhaust or non-exhaust emissions, should be evaluated for any given geographical location. In this work, we report on the first study to evaluate particulate matter emissions from all registered heavy duty diesel vehicles in Qatar. The study was applied to an active traffic zone in urban Doha. Dust samples were collected and characterized for their shape and size distribution. It was found that the particle size ranged from few to 600 μm with the dominance of small size fraction (less than 100 μm). In-situ elemental composition analysis was conducted for side and main roads traffic dust, and compared with non-traffic PM. The results were used for the evaluation of the enrichment factor and preliminary source apportionment. The enrichment factor of anthropogenic elements amounted to 350. The traffic source based on sulfur elemental fingerprint was almost 5 times higher in main roads compared with the samples from non-traffic locations. Moreover, PM exhaust and non-exhaust emissions (tyre wear, brake wear and road dust resuspension) were evaluated. It was found that the majority of the dust was generated from tyre wear with 33% followed by road dust resuspension (31%), brake wear (19%) and then exhaust emissions with 17%. The low contribution of exhaust PM emissions was due to the fact that the majority of the registered vehicle models were recently made and equipped with efficient exhaust PM reduction technologies.

Implication: This study reports on the first results related to the evaluation of PM emission from all registered diesel heavy duty vehicles in Qatar. In-situ XRF elemental analysis from main, side roads as well as non-traffic dust samples was conducted. Several characterization techniques were implemented and the results show that the majority of the dust was generated from tyre wear, followed by road dust resuspension and then brake wear; whereas exhaust emissions were tremendously reduced since the majority of the registered vehicle models were recently made and equipped with efficient exhaust PM reduction technologies. This implies that policy makers should place stringent measures on old vehicle license renewals and encourage the use of metro and public transportation.

Introduction

Emissions of air pollutants in urban areas are associated with various sources, both natural and anthropogenic (Teixeira et al. 2018). Nevertheless, mobile sources in main road transportation account for a large fraction of fossil fuel combustion in most countries which emits gaseous and particulate pollutants into the air (Hooftman 2018). These primary pollutants can further react in the atmosphere to form ozone and other secondary pollutants (Hooftman et al. 2016). Moreover, fossil fuel combustion in vehicles produces carbon dioxide which is the main greenhouse gas. The effect of air pollution caused by transport does not only pose a relative damage cost to the crops, farmlands, forests, lakes, materials, building and roads (Al-Thani, Koc, and Isaifan 2018; Isaifan et al. 2017), but it also degrades human health to noticeable extent (Hooftman et al. 2016). Some of the principal pollutants that cause adverse health effect are particulate matter (PM), lead, ozone and nitrogen oxides. Particulate matter (PM) and most specifically PM$_{2.5}$ have been proved to have an association between their concentration and respiratory system diseases. PM$_{2.5}$ can penetrate deeply into the lung,
irritate and corrode the alveolar wall, and consequently impair lung function (Imhof et al. 2005).

Vehicular emissions are one of the main sources of these particulates in urban areas with dense and busy roads. There are two types of vehicular emissions: exhaust and non-exhaust emissions. While most PM$_{2.5}$ are related to exhaust emissions, major PM$_{10}$ contribution is related to both exhaust and non-exhaust sources with the majority being from the later (Boulter 2005). Hence, it is important to understand the sources and types of transportation emissions at certain location in order to propose effective mitigation strategies to control this pollution.

Several emission factors have been reported for cities around the world to quantify particulate emissions. The units reported are either fuel-based particle number emission factors (EF) \((\text{particle} \cdot \text{Kg fuel}^{-1})\) (Kirchstetter et al. 1999), or annual traveled distance-based \((\text{particle} \cdot \text{vehicle}^{-1} \cdot \text{Km}^{-1})\) (Imhof et al. 2005). Ban-Weiss et al. (2008) estimated gasoline and diesel on-road vehicle emission factors at a tunnel in San Francisco Bay area and reported that PM$_{2.5}$ emissions were 0.07 and 1.4 g kg$^{-1}$ fuel for light and heavy duty diesel vehicles, respectively. Bukowiecki et al. (2010) have quantified the non-exhaust fraction of traffic-related PM$_{10}$ for two side road locations in Switzerland. The results showed a major contribution from road dust resuspension. Moreover, heavy duty vehicles (HDV) contributed majorly to PM$_{10}$ with 498 mg km$^{-1} \cdot$ vehicle$^{-1}$ compared with 24 mg km$^{-1} \cdot$ vehicle$^{-1}$ for light duty vehicles (LDV) along a street canyon. Moreover, PM$_{10}$ emissions of HDV amounted to 288 mg km$^{-1} \cdot$ vehicle$^{-1}$ compared with 50 mg km$^{-1} \cdot$ vehicle$^{-1}$ for LDV in a freeway location (Bukowiecki et al. 2010). Recently, Johnson, Mi. Bergin, and Hagler (2016) have reported on a mixed fleet PM$_{2.5}$ transport emissions in Atlanta which amounted to 0.39 g kg$^{-1}$ fuel.

In regulations, the measurement of total exhaust particulates is only defined for diesel engines and vehicles. Nevertheless, prior to 1988, there was no requirement to measure particulate mass (Boulter 2005). These emissions consist of coarse particles produced by abrasion from brakes, tyre wear as well as vehicle induced resuspension of deposited road dust. To identify the source of each category from the non-exhaust emissions, several works reported that brake wear has been identified in numerous investigations by ambient mass concentrations of Cu, Mo, Sn, Sb and Ba (Garg et al. 2000; Lough et al. 2005; Świetlik, Strzelecka, and Trojanowska 2013; Weckwerth 2001). In contrast, the experimental identification of other abrasion sources is more difficult and the list of published work is shorter where zinc or black carbon was used as tracer for tyre wear (Adachi and Tainosho 2004; Boulter 2005; Councell et al. 2004). Finally, due to their similar chemical composition, emissions from road wear and resuspended road dust are not easy to distinguish in field data, and thus, were examined with controlled laboratory-type experiments. Nevertheless, quantification of PM$_{10}$ emissions by road wear and/or resuspension of road dust was reported for a number of locations and was distinguished with a high mass fraction of Ca in excess of 10% (Bukowiecki et al. 2010).

Considerable attention is being paid in research toward diesel vehicles since they are the main source of exhaust particulate matter (Boulter 2005). Nevertheless, the year period 2007–2009 is considered a global benchmark with regards to diesel vehicles since it has been reported as the period where diesel vehicle models started to be equipped with after-treatment devices to meet US EPA 2007 standards (Cheung et al. 2010). These devices are based on particle filter technologies and have proved to remove the nonvolatile fraction efficiently but they are less effective in controlling the volatile/semi-volatile portion (Biswas et al. 2009).

In this work, PM emissions from the exhaust and non-exhaust sources of all registered heavy-duty (vehicle with a gross weight of more than 3.5 tonnes) diesel vehicles were assessed and the impact of mitigation policies was discussed. The objectives of this work are (1) to characterize traffic dust in terms of shape, morphology, size distribution, elemental composition and enrichment factor (2) to conduct preliminary source apportionment based on the elemental fingerprint of the particulates, (3) to investigate the diesel traffic contribution to particulate matter pollution annually, (4) to compare emissions of PM from exhaust and non-exhaust diesel traffic and (5) to assess the impact of enforcing the modification of non-compliant vehicles with adding one of the three approved PM filter technologies on the reduction of these emissions.

**Study design and research methodology**

**Sampling and in-situ XRF measurements**

Sampling was performed as dust was deposited on clean glass surfaces and collected as reported in other studies on dust collection methodology (Al-Dousari and Al-Awadhi 2012; Al-Thani, Koc, and Isaifan 2018; Modaihsh et al. 2017). In-situ XRF measurements were also conducted in 20 locations as shown in the detailed maps in Figure S1 in the supplementary material file. Seventeen in-situ measurements were conducted in main streets where heavy duty vehicles were allowed to pass (marked in yellow diamonds), while three in-situ measurements were taken in side road locations where HDV were not permitted.
(marked in white stars). The non-traffic samples were collected as control samples such that the locations were chosen as far as possible (at least 3 km distance) from any possible traffic or industrial pollution.

The size distribution of the samples was characterized via optical microscope where optical images were taken and the particle size of about 300 particles was measured in each image (Aissa et al. 2016; Heywood 1946; Isaifan et al. 2015; Martin 1923). The elemental composition was determined in-situ using Bruker S1 Titan (Bruker, USA) Handheld energy-dispersive x-ray fluorescence (XRF) spectrometer. The instrument was equipped with an Rh tube working at a maximum voltage of 50 kV. The in-situ measurements were conducted in the marked main and side road locations in zone 51 in Doha following the standard procedures as recommended by The International Atomic Energy Agency (IAEA) as per their document IAEA-TECDOC-950 (The International Atomic Energy Agency 1997), and The Environmental Protection Agency (EPA) as per Compendium Method IO-3.3 (U.S.Environmental Protection Agency 1999). The elemental composition provided the mass concentrations of 30 elements (Mg, Al, Si, S, Cl, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, As, Sr, Zr, Pb, P, Rb, Sn, V, K, Ag, Rh, Tl, Ta, Hf, Ce, Ba and Mo) in each sample. The average concentration of the measurements conducted per each category was reported.

Enrichment factor of chemical elements

The enrichment factor (EF) is widely used as an approach to characterize the chemical composition of airborne particulate matter. It relates the concentration of an element in dust to its average concentration naturally existing in the earth’s continental crust. The EF index of potential contamination is calculated by the normalization of one metal concentration in the PM sample with respect to the concentration of a reference element which is generally aluminum. Aluminum is a conservative element and a major constituent of clay minerals and has been used successfully by several scientists as given in Eq. (1) (Abdulqaderismaeel and Kusag 2015; Barbieri 2016; Sun et al. 2004).

\[
\text{EF} = \frac{\text{X} / \text{Al}_{\text{(aerosol)}}}{\text{X} / \text{Al}_{\text{(crust)}}}
\]

(1)

Hence, an EF of about unity indicates that the dominant source is natural crustal PM and an EF value > 10 indicates an anthropogenic input to the PM. Al was used as the normalizing crustal element in calculating the EFs, assuming that its anthropogenic input was minor and negligible. Generally, an element is assumed to be of natural origin when its enrichment factor is less than 10 (Barbieri 2016; Rushdi et al. 2013; Sun et al. 2004).

Source apportionment

Preliminary source apportionment evaluation of the traffic dust was conducted based on the elemental fingerprint of the dust composition, and in accordance with previous source apportionment work reported by other groups (Al-Thani, Koc, and Isaifan 2018b; Davy et al. 2011, 2012; Katherei, Jallad, and Al Omar 2012; Khodeir et al. 2012; Pant and Harrison 2013; Santoso et al. 2011). This method provides a preliminary insight of the possible sources of the particulate matter when detailed analysis and characterization are not feasible to feed the data into Positive Matrix Factorization or Chemical Mass Balance Analysis methods. Examples on the possible sources for each element are provided in Table S1, S2 and S3.

Particulate emission calculations

Since actual data on the annual traveled distance of each type of vehicle in Qatar or the region are unavailable, the recommended values were adopted from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model. 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. Ideally, values related to the annual traveled distance of each vehicle should be obtained from surveys of statistical data from the traffic department or vehicle insurance/testing 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 and 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 (M.Q. Wang, GREET 1.5 – Transportation Fuel Cycle Model, Vol. 2: Appendices of Data and Results, Argonne National Laboratory, Illinois, 1999). This value was used to evaluate the total annual particulate matter emissions from diesel vehicles and the impact of these diesel vehicles on PM emissions from the exhaust and non-exhaust sources. The non-exhaust sources are basically due to tyre abrasion, brake abrasion and road dust resuspension. Moreover, due to the absence of data on emission factors of vehicles in this region, the universal emission factors were based on the
Table 1. Exhaust PM$_{10}$ emission factors (g·km$^{-1}$·vehicle$^{-1}$) for heavy diesel vehicles (Cai, Burnham, and Wang 2013; Faiz et al. 1996).

| Model year | Exhaust emission | Model year | Exhaust emission |
|------------|------------------|------------|------------------|
| 1944–1989* | 2.4600           | 2004       | 0.5150           |
| 1990       | 0.8029           | 2005       | 0.5139           |
| 1991       | 0.9835           | 2006       | 0.5132           |
| 1992       | 0.9842           | 2007       | 0.0297           |
| 1993       | 0.9594           | 2008       | 0.0249           |
| 1994       | 0.9935           | 2009       | 0.0247           |
| 1995       | 0.9927           | 2010       | 0.0235           |
| 1996       | 0.9512           | 2011       | 0.0234           |
| 1997       | 0.9169           | 2012       | 0.0233           |
| 1998       | 0.5630           | 2013       | 0.0214           |
| 1999       | 0.5569           | 2014       | 0.0213           |
| 2000       | 0.5603           | 2015       | 0.0213           |
| 2001       | 0.5335           | 2016       | 0.0213           |
| 2002       | 0.5502           | 2017       | 0.0213           |
| 2003       | 0.5160           | 2018       | 0.0213           |

*Values from Table 2.4, page 41 by (Faiz et al. 1996).

Table 2. Non-exhaust PM$_{10}$ emission factors (g·km$^{-1}$·vehicle$^{-1}$) for heavy diesel vehicles (Ntziachristos and Boulter 2016).

| Model Year | Brake wear | Tyre wear | Road resuspension |
|------------|------------|-----------|-------------------|
| All years  | 0.0228     | 0.0400    | 0.0380            |

Values reported in (Cai, Burnham, and Wang 2013; Faiz et al. 1996; Ntziachristos and Boulter 2016) as shown in Tables 1 and 2.

The exhaust PM$_{10}$ emissions were calculated by multiplying the emission factor tabulated for each year (g·km$^{-1}$·vehicle$^{-1}$) in Table 1 by the number of vehicles registered in that year to yield the total emissions in g·km$^{-1}$. The values obtained were then multiplied by the average annual traveled distance to give the final total emissions in g which was converted to kg and hence, plotted.

The same procedure was followed to estimate non-exhaust PM$_{10}$ emissions, but this time, the factors tabulated in Table 2 were initially used.

**Results and discussion**

**Characterization of traffic dust**

Figure 1 shows the optical images of traffic dust. It can be seen that traffic dust varied in shape, color and size. This is due to the fact that traffic dust was exposed to the ambient environment where it could be a combination of different sources including sand, construction dust, road surface abrasion, tyre wear, brake wear particles and sea salts.

Figure 2 presents the particle size distribution of the collected samples of road dust. It can be seen that the particle size ranged from few micrometers to 600 µm. Nevertheless, the majority of dust had sizes of less than 100 µm. The dominance of smaller particle size of road dust is affected by the nature of dust blown by the wind in Doha. Recent studies on the physical and chemical characterization of urban dust in Qatar showed that the average particulate matter size is less than 10 µm (Aïssa et al. 2016; Hanadi Al-Thani, Koc, and Isaifan 2018).

Moreover, it was reported that under normal driving conditions for heavy driving vehicles, non-exhaust particulate emissions are generally coarse (having a diameter size of >2.5 µm) (Ahagon and Kaidou 1990; Boulter 2005). Previous studies reported that coarse fractions of PM can be produced naturally by the mechanical break up of larger solids. These solids may originate from agricultural processes, soil, unpaved roads or mining operations. This is in agreement with the massive construction projects currently being executed in Qatar in preparation for the World Cup 2020. Those construction activities have been contributing to more than half of urban dust generated locally. Moreover, traffic and vehicular emissions produce major portions of PM which can also be re-suspended from road surface or due to tyre and brake wear (Maas 2007). On the other hand, the small fraction of PM which is less than 0.1 µm in size can be produced basically from the condensation of combustion products when fossil fuel burning takes place in high temperatures (Maas 2007; Viana et al. 2008). This is expected as anthropogenic sources of dust have a smaller size than dust originating from natural sources. Adamiec and Jarosz-Kreminska (2016) reported that brake lining dust collected directly from disc and drum brake pads in an automotive repair station has sizes that ranged from 20 to 250 µm. The particle size range was reported in several studies. Rauterberg-Wulff (1999) indicated that tyre wear particles were only present in the coarse fraction and the finding by Moosmuller et al. (1998) confirmed that tyre wear was dominated by particles larger than 10 µm. On the other hand, very little information can be found on the size of road dust wear. Fauser (1999) found that road wear particles can range in size from 0.35 to 2.8 µm.

Figure 3 presents the average elemental composition of the samples collected in Doha showing the elements with mass % >1. It can be seen that most of the samples were formed of calcite (Ca) and quartz (Si) with 77%, 81% and 79% in non-traffic, side and main road samples, respectively, due to the nature of crust/soil in Qatar and the Gulf region (Aïssa et al. 2016; Al-Thani, Koc, and Isaifan 2018; Saraga et al. 2017; Yilbas et al. 2015). The fact that road dust primarily consists of soil-driven minerals has been reported for other locations as well (Adamiec and Jarosz-Kreminska 2016; Gunasekaran, Anbalagan, and Pandi 2006). The remaining amounts were albite (NaAlSi$_3$O$_8$), chlorite...
(ClO$_2^-$), microline (KAlSi$_3$O$_8$) and muscovite (KAl$_2$ (AlSi$_3$O$_10$)(OH)$_2$) (Adamiec and Jarosz-Kreminska 2016; Gunawardana et al. 2012).

It has been reported that five contamination categories are recognized on the basis of the enrichment factor: EF < 2: depletion to mineral enrichment; 2 ≤ EF < 5: moderate enrichment; 5 ≤ EF < 20, significant enrichment; 20 ≤ EF < 40: very high enrichment; and EF > 40: extremely high enrichment (Barbieri 2016 and Abdulqaderismael and Kusag 2015). Table S4 in the supporting information shows the screening results of the level of contamination of each element as per the enrichment factors in Figure 4 and Fig. S2.

The significant variability in the chemical composition of road dust adds to the complexity of identifying the sources of each element. Nevertheless, the results of EF indicate that there was an extreme high enrichment of elements that were considered as transportation emission indicators such as sulfur. Vanadium and nickel are also considered the two main trace elements

Figure 1. Optical microscope images of traffic dust collected in Doha in April 2018.
that indicate road dust resuspension since they are the main constituents of asphalt (Kennedy and Gadd 2003; Oelofse 2009). Moreover, recent studies with a focus on tyre wear have linked significant enrichment of Zn, Cd, Co, Cr, Cu, Hg, Mo, Ni and Pb with tyre abrasion (Adamiec and Jarosz-Kreminska 2016; Shauer et al.

**Figure 2.** Particle size distribution of traffic dust collected in Doha, April 2018.

**Figure 3.** The elemental composition of the samples collected from (a) non-traffic area, (b) side road and (c) main road in Doha. The figure represents only the main elements with mass % >1.
Zn has been identified as the most abundant heavy metal that is associated with tyre wear (Table 3). Table 3 shows the results we obtained of Zn concentration of dust attached to several wheels in Doha.

On the other hand, Adachi and Tainosho (2004) and Hjortenkrans, Bergbäck, and Häggerud (2007) have reported that brake dust mainly contained Fe with significant amounts of Ba, Sb, Cu, Si, S, Ti, Ni, Zn, Cr and Pb, in addition to small amounts of Cd. Road dust generated from asphalt abrasion are significant sources of Ni, V and As (Adamiec and Jarosz-Kreminska 2016; Österle et al. 2001). Our results showed that Ni and Cr have a much higher enrichment factor (4.6–5.4) compared with 1.5 in the traffics and non-traffic locations, respectively. Moreover, V had never been detected in non-traffic locations compared with its relatively low concentration in traffic areas. Table 3 and Fig. S2 also show that there was a huge difference in the scale between non-traffic and traffic-related dust. The maximum enrichment factor in non-traffic samples is less than 40, while it exceeded 160 and 350 for side and main road samples, respectively. The individual enrichment factor plots for each category are shown in Fig. S2 in the supporting information file which showed significant variation in the anthropogenic elements when the three sample categories were compared. Sulfur was significantly in extreme high enrichment category in the side and main road samples only. Silver was in extremely high enrichment in the road samples while it is not found in non-traffic samples. Silver is a rare but naturally occurring metal, often found deposited as a mineral ore in association with other elements. Nevertheless, several anthropogenic sources of silver in the biosphere have been reported such as emissions from smelting operations, manufacture and disposal of certain photographic and electrical supplies, coal combustion, and cloud seeding (Howe and Dobson 2002). In addition to the several industrial sources of silver, it has been reported in a pilot study examining four brake pads that silver, chromium, nickel and cadmium are found in those samples (Armstrong 1994; Kennedy and Gadd 2003). Figure S2 also shows that Ba was present in the samples collected from the side and main roads which is a characteristic metal for brake wear (Adamiec and Jarosz-Kreminska 2016; Österle et al. 2001). It is worth noting that the enrichment of Ba in side road was slightly higher than that in the main road sample since drivers tend to slow down and use brakes more frequently in side roads compared to main roads and highways. It has also been reported that brake lining consists of 48% barite (BaSO₄) and that Ba can be considered the trace element distinguished for brake wear (Adamiec and Jarosz-Kreminska 2016; Adachi

### Table 3. Concentration levels of Zn in tyre wear dust.

| Reference | Zn concentration (ppm) |
|-----------|-------------------------|
| Christensen and Guinn (1979) | 7300 |
| Brewer (1997) | 8378–13,494 |
| Kennedy et al. (Gadd and Kennedy 2000) | 5650–9640 (group of tyres) 13,800–18,300 in another group of tyres |
| Six in-situ XRF measurements of different wheels in our study | 5869–14,000 |

Figure 4. The enrichment factor in the samples collected from non-traffic area, side road and main road in Doha.
and Tainosho 2004; Österle et al. 2001). Moreover, the results show extreme high enrichment in Cl which was not probably related to sea salt (Roshan et al. 2019) entirely since sodium levels were not detected in all the samples. Sea salt is characterized with the molar ratio of Cl-/Na+ of 1.16 (Lazarcik and Dibb 2017). This is in agreement with the study conducted in Saudi Arabia where the authors found that the concentration of chlorine varied from one particle to another in the dust samples collected in the Arabian Gulf when EDS (Energy Dispersive X-ray Spectroscopy) data did not satisfy the molar ratio for NaCl which indicated that NaCl is dissolved in the compound form rather than being present as salt crystals (Al-Thani, Koc, and Isaifan 2018b). Hence, the significant high enrichment of chloride in the road samples might be due to the asphalt composition. Ferric chloride and/or ferrous chloride are added to the asphalt mixture in order to reduce hydrogen chloride emissions during blowing process. The asphalt is subjected to a blowing process which produces hydrogen chloride emissions. Hence, a chemical modifier is added to reduce the hydrogen chloride emissions by at least 25% compared to the same process without the addition of the chemical modifier. The addition of the ferric chloride and/or ferrous chloride provides beneficial effects such as increased blowing rate and increased final penetration of the asphalt (Marzari et al. 1998; Quddus, Khan, and Sarwar 2003). Moreover, most chloride aerosols emitted in industrial smoke are mixed with transition/heavy metals, and a coating of organics and/or sulfates appear on aged particles. In addition, some secondary chlorides are produced by the reactions of HCl with alkaline substances, and can mix with mineral dusts, nitrates, and sulfates (Wang et al. 2017).

Figure S3 in the supporting information shows the source apportionment of the samples based on the in-situ XRF analysis. The sources were approximated based on the elemental fingerprint in this region as reported earlier in Table S1 (Al-Thani, Koc, and Isaifan 2018b) and as summarized by other studies as in Table S2 (Pant and Harrison 2013) and Table S3. It can be seen that non-traffic sites were highly affected by dust generated from construction activities as well as naturally occurring calcite at 46% (Aïssa et al. 2016; Al-Thani, Koc, and Isaifan 2018b; Saraga et al. 2017). Moreover, the non-traffic samples (Fig S3. a) had the highest fraction of natural crustal matter compounds at 22% compared with 16% in side and road dust samples. Moreover, construction and desert dust together made more than 77% in all samples. The main difference in the three samples was the percentage of dust due to traffic emissions as summarized in Figure 5. The impact of traffic was clearly seen with the increase in sulfur content from 1% in a non-traffic sample to almost 5% in the samples collected from a main road. In addition, it was reported that sulfur is among the main elements in asphalt (Oelofse 2009).

Vanadium and nickel are also considered the two main trace elements that indicate road dust resuspension since they are the main constituents of asphalt (Kennedy and Gadd 2003; Oelofse 2009). Figure 5

![Figure 5](image-url)  
Figure 5. Traffic source in the samples collected from non-traffic area, side road and main road in Doha.
shows that main road samples had more than 4% of its composition related to traffic dust. Traffic dust has been segregated as diesel emission, petrol emission, catalytic convertor emissions, road dust, tyre and brake wear. The side road had around 2.3% of dust related to traffic emissions while non-traffic sites had the least composition due to traffic activities.

**Traffic particulate matter emissions**

The count of all registered non-passenger heavy diesel vehicles as per 2017 was obtained from the traffic department in Qatar and classified per vehicle model year as shown in Figure 6.

Since all diesel vehicles of model 2009 forward were equipped with PM filters, the mitigation scenario will consider all vehicles of older models to evaluate the impact of the utilization of PM filters adjusted to these vehicles to reduce PM exhaust emissions. On the other hand, all the cars contribute to non-exhaust PM sources related to brake wear, tyre wear and road dust resuspension, hence only exhaust emissions vary between old and new vehicles.

In an extensive literature review conducted by TRL (Boulter 2005) on non-exhaust PM$_{10}$ emission factors for road vehicles, it was summarized that for tyres, the wear factor was estimated to be around 100 mg $\cdot$ km$^{-1}$·vehicle$^{-1}$ (0.1 mg $\cdot$ km$^{-1}$·vehicle$^{-1}$) for light-duty vehicles under normal driving conditions. This value was estimated to be likely an order of magnitude higher for heavy-duty vehicles (Ahagon and Kaidou 1990; Boulter 2005). In addition, it was found that for light-duty vehicles, the brake wear was around 10–20 mg km$^{-1}$·vehicle$^{-1}$ (0.01–0.02 g·km$^{-1}$·vehicle$^{-1}$) while can range from 50 to 80 mg·km$^{-1}$·vehicle$^{-1}$ (0.050–0.080 g·km$^{-1}$·vehicle$^{-1}$) for heavy-duty ones (Ahlbom and Duus 1994; Boulter 2005). In terms of road resuspension dust, a wide range of emission factors were reported from 4 to 400 mg·km$^{-1}$·vehicle$^{-1}$, especially where studded tyres and winter road maintenance were frequently used. Studded tyres can damage the road since they contain metal studs embedded within the thread to provide added traction on the driving surface. It is worth noting that the evaluation of PM$_{10}$ is critical for road dust as it makes up 0.6, 0.98 and 0.5 mass fraction of the total suspended particles in tyre wear, brake wear and road dust resuspension, respectively (Boulter 2005).

In addition, it should be noted that there are fundamental differences in some non-exhaust emission factors between the US and EU with those reported for the former to be higher due to the drier and dustier conditions that prevail in the US compared to EU (Boulter 2005).

From Table 1, it can be seen that the PM exhaust emissions started at 2.460 (g·km$^{-1}$·vehicle$^{-1}$) for heavy diesel vehicles manufactured up to the year model 1989. This value has declined annually till it reached 0.5132 g·km$^{-1}$·vehicle$^{-1}$ in 2006 and then it dropped sharply in 2007 to about 0.0297 g·km$^{-1}$·vehicle$^{-1}$. This sharp drop in exhaust emissions was due to the fact that around that period, all new diesel vehicle models have been modified to be equipped with after-treatment devices to meet US EPA 2007 standards (Cheung et al.

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**Figure 6.** Growth in the number of diesel heavy vehicles in Qatar.
These devices were based on particle filter technologies and have proved to remove the nonvolatile fraction efficiently (Biswas et al. 2009). On the other hand, Table 2 shows that for all model years, the PM non-exhaust emission factors were taken around the same value as developments of brake and tyre materials have not changed much to reduce PM emissions from those sources with time.

Figure 7 and Table S5 show the annual PM$_{10}$ exhaust and non-exhaust emissions in (kg/year) of all registered non-passenger heavy diesel vehicles based on the count of model year group.

The non-exhaust emissions are shown in categories as brake wear, tyre wear and road resuspension. It can be seen that the emissions increased consistently with time since the number of registered vehicles has recently grown sharply. More specifically, the exhaust emissions have increased up to 2010 and then declined significantly for the recent vehicle model years due to the implementation of the new PM filter technologies as mentioned earlier. Hence, mitigation policies should strictly emphasize on the importance of using public transport or carpooling to reduce the emissions due to the intensive use of each individual vehicle.

It has been reported that in addition to the above non-exhaust emissions, clutch wear and corrosion may also contribute to direct PM emissions, but these cannot be easily quantified given the current limited level of understanding (Boulter 2005). The results in Figure 8 show that tyre wear dust dominated the emissions with 33%, followed by road dust resuspension. The results also show that exhaust emissions contributed to 17% of the total PM$_{10}$ emissions while the rest was related to non-exhaust sources during the operation of diesel vehicles.

Concerning the non-regulated exhaust emissions, little or no real-world data are available (Hooftman et al. 2016). It must be emphasized that road wear causing dust resuspension is not penalized since the pavement quality is the most determining factor rather than the weight of vehicles or tyre characteristics. On the other hand, the other non-exhaust sources related to the brake and tyre abrasion are more related to the type of the vehicle. The green cars option can be controversial in this case. The electric vehicle, for example, is penalized by 10% in tyre wear (due to increased weight of vehicles together with their specific tyres) while benefited by 66% (less) on brake pad wear (Hooftman et al. 2016). On the other hand, an analysis on the service times of brake pads on Teslas, BMW i3s and Nissan Leafs demonstrates that on average, the brake pads last roughly two-thirds longer than on diesel/petrol vehicles (Hooftman et al. 2016). Although electric vehicles generally have a higher mass, the presence of regenerative braking systems outweigh the mass penalty. Hence, electric vehicles can be considered clean compared with diesel ones.

For PM exhaust emissions, effective filters should be fitted in older cars as a condition to renew the registration of these vehicles. There are three approved

![Figure 7](image-url)
technologies that have been developed to reduce PM emissions from diesel engines; wall flow filters (WFF), partial flow filters (PFF) and diesel oxidant catalyst filter (DOCF). The PM reduction potential is >95%, 30–60% and <25% for WFF, partial flow filters PFF and DOCF, respectively (Association for Emission Control by Catalyst 2018; DCL 2018; Jacobs et al. 2006).

Figure 9 shows the projected PM emissions after the use of each filter compared with the no filter case annually. It can be seen that further reduction in PM emissions can be obtained if old vehicles adopted any of the approved filter technologies. The vehicles, if continued to operate without any filter will continue to emit around 300 kg of PM annually. The wall flow filter has been approved to reduce the PM emission tremendously. The mode of

Figure 8. The PM$_{10}$ emission percentage based on mass emissions (g/year) of non-passenger heavy diesel vehicles in Qatar for models 2011–2020 by source.

Figure 9. Projected PM emissions (kg/year) from heavy diesel vehicles in Qatar with approved filter abatement technologies for all vehicle models 2009 and older. Abbreviations WFF: Wall Flow Filter, PFF: Partial Flow Filter, DOCF: Diesel Oxidant Catalyst Filter.
operation of WFF is straightforward. The exhaust gas is forced to flow through the walls between the channels of ceramic honeycomb material. These materials are usually cordierite, silicon carbide or aluminum titanate. The particulate matter is deposited as a soot cake on the walls and is mostly ultra-fine particles (Association of Emission Control by Catalysts 2019). Hence, filter regeneration (removal of soot deposits of the filter walls) is a necessary process to maintain continuous operation when the filter is fully loaded. Regeneration is performed through the oxidation of soot particles to reduce the pressure drop across the filter at high temperature which can occur passively through reactions involving \( \text{O}_2 \) already present in diesel exhaust at high temperatures. Nevertheless, sometimes it is often necessary to actively initiate the regeneration through hydrocarbon dosing or through electrical heating of the filter elements (Eastwood 2000; Liu, Berg, and Schauer 2008).

**Conclusions and recommendations**

Exhaust emissions have been extensively studied, monitored and regulated around the world. Nevertheless, non-exhaust emissions still need more research to increase the level of understanding and encourage policy makers to regulate this type of emissions which have impacted our health and the environment. For example, although several countries have banned the use of studded tyres, there are still no regulations specifically designed to control non-exhaust emissions, especially in Europe and the Middle East. Moreover, although exhaust emission technologies are continuously improving decreasing the amount of exhaust emissions, non-exhaust emission sources are continuously increasing. This has been also accompanied by lack of research on the emission rates, physical and chemical properties as well as the health impact of non-exhaust particles.

This work has reported on the first study to evaluate particulate matter emissions from heavy duty diesel vehicles in Qatar. Traffic dust was investigated in zone 51 in Doha. In-situ elemental analysis was conducted for main road locations and compared with side road and non-traffic locations. The results showed a significant impact of heavy duty diesel vehicles on the dust composition and source apportionment compared with the dust studied in side roads where heavy duty vehicles are not permitted to pass. In general, traffic dust varied in size from few micrometers to 600 \( \mu \text{m} \) with the dominance of <100 \( \mu \text{m} \) size range. Moreover, the impact of traffic was evident with the increase of sulfur content from 1% in a non-traffic sample to 4% in the samples collected from main roads. The average elemental composition of the samples shows that most of the samples are formed of calcite (Ca) and quartz (Si) with 77%, 81% and 79% in non-traffic, side and main road samples, respectively, due to the nature of crust/soil in Qatar and the Gulf region. Moreover, the contamination level of the elements in the dust samples as per the enrichment factor values was identified. Ag, S and Cl were found with extremely high enrichment in side and main road samples which were correlated with different traffic emissions. High levels of Zn were obtained via in-situ XRF analysis of dust on different wheels in this study which was in agreement with previous reported Zn concentration levels in tyres. In general, the source apportionment of traffic vs. non-traffic samples showed that traffic emission sources were the highest in main road samples, followed by side road and then non-traffic samples. Non-exhaust PM emission results showed that tyre wear dust dominated with 33%, followed by road dust resuspension and then brake wear.

To this end, when the impact of the implementation of one of the three approved filter technologies in vehicles that do not comply with the standards was evaluated, it was found that the annual \( \text{PM}_{10} \) emissions can be reduced from around 300 kg to less than 20 kg every year.

Although this study had adopted the annual average traveled distance for all non-passenger diesel heavy duty vehicles from GREET as the basis of emission calculations, it is recommended that an actual value should be obtained under the local driving conditions and used for the estimation. Moreover, the short and long-term impact of PM on human health and the environment should be investigated and understood in the future work.

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**Disclosure statement**

The authors declare no conflict of interest.

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