# Impact of Particulate Matter Emissions from Ship Power Plants on the Port City Environment

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**Abstract.** The paper deals with one of the methods for assessing anthropogenic impact of the operation of ship power plants in port areas on the environment. The measurement of mass concentration of particulate matters (PM) in the open air was carried out during summer and winter in eight points of the city that were selected depending on the conditions of orographic characteristics of the area. Moreover, vessel traffic in coastal waters was assessed and information on the number and type of vessels was collected. Based on the data obtained, the total PM volume emitted with exhaust gases from ship power plants in the port areas during a year was calculated.

## 1 Introduction

Air pollution level in many cities of the world goes beyond the level recommended by the World Health Organization [1]. In large industrial centers the key sources of PM in atmosphere are industrial and energy enterprises as well as automobile transport [2, 3]. But in port cities water transport is yet another source of PM pollution, and it should be taken into account, especially when monitoring pollution with fine particles [4, 5].

## 2 Literature overview

Air pollution is mainly caused by multiple anthropogenic emission sources, such as industrial activity, populated area as well as marine, railway, air and automobile transport. However, majority of studies in Vladivostok is focused on ground emission sources. The studies of Golokhvast et al. (2017) [6], Kirichenko et al. (2018) [7] and Chernyshev et al. (2019) [8] are good examples. In recent years no studies of the impact of exhaust gases from ship power plants on the environment in the ports of the region have been carried out, although the commercial port of Vladivostok is a large port in the Russian Far East with significant growth rates (about 39%) [9].

Over past two decades the studies of the environmental pollution by emissions of particles from different types of vehicles have been carried out in many parts of the world [10, 11, 12]: on dynamometer stands based on the cycles of their movement [10, 12]; in real traffic conditions on the roads, in motorway tunnels [9, 13] or near such motorways [11]. All studies are based on the method for calculating emission factors of toxic substances in vehicle exhaust gases that can be used to determine their volume based only on the characteristics of their source [11].

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Jones et al. [11] calculated and proposed in their work the emission factors for particulate matters based on their number per one vehicle per kilometer (Table 1).

**Table 1.** Emission factors for PM2.5 and PM10 [11]

| **Pollutant** | **Measurement units** | **Heavy vehicle** | | **Light-duty vehicle** | |
|---|---|---|---|---|---|
| | | **Emission coefficient** | **Standard deviation** | **Emission coefficient** | **Standard deviation** |
| PM2.5 | $g.veh^{-1}.km^{-1}$ | 0.179 | 0.022 | 0.010 | 0.004 |
| PM10 | $g.veh^{-1}.km^{-1}$ | 0.370 | 0.032 | 0.033 | 0.006 |

Assuming that other pollutants dissipate from their point of release to the sampling points in the same way as $NO_x$:

$$f\{E_{0(\text{pollutant})} \rightarrow X_{(\text{pollutant})}\} = f\{E_{0(NO_x)} \rightarrow X_{(NO_x)}\} \quad (1)$$

where

$E_{O(\text{pollutant})}$ – emission per kilometer for the total number of vehicles passing per hour,

$X_{(\text{pollutant})}$ – concentration of every pollutant on the roads,

$E_{O(NOx)}$ – $NO_x$ emission for all vehicles passing the sampling points,

$X_{(NOx)}$ – $NO_x$ concentrations on the roads.

Having set up an equation of linear regression, A.M. Jones et al. [9] determined the relation between $E_{O(NOx)}$ and $X_{(NOx)}$ as follows:

$$E_{O(NOx)} = 12.48(\pm 0.55) * X_{(NOx)} + 69.50(\pm 190.56)\ gkm^{-1} \quad (2)$$

where: $X_{(NOx)}$ (in $mgm^{-3}$) means standard deviations of the factors (given in brackets). So, the connection between total emission of any pollutant and its concentration at the measurement point and at the background section may be determined as follows:

$$E_{O(\text{pollutant})} = 12.48(\pm 0.55) * X_{(\text{pollutant})} + 69.50(\pm 190.56)\ gkm^{-1} \quad (3)$$

Or, if ignoring the influence of other secondary sources –

$$E_{O(\text{pollutant})} = 12.48(\pm 0.55) * X_{(\text{pollutant})} \quad (4)$$

The measurements were taken by a handheld particle counter TSI Aerotrack 9306 V2 (measurement range from 0.3 to 10 μm) during eight summer weeks from July 2 till September 2, 2018 and during eight winter weeks from January 8 till March 4, 2018. On average, 50 measurements were made per day with an interval of 20 min. The time of one measurement was 1 minute and the volume of the measured air sample comprised 2.8 liters.

The information about vessels was taken from https://www.marinetraffic.com/ for two periods: from July 29 till August 28 and from November 15 till December 15. Besides the number of ships specified in Tables 2 and 3, the average gross tonnage of each type of vessel was collected and shown in Table 4.

**Table 2.** Information about the number of vessels in the port area of Vladivostok city in 2019.

| **Vessel category** | **Periods** | | **Average value** |
|---|---|---|---|
| | **August 14 – August 27** | **December 1 – December 14** | |
| Passenger | 8.6 | 4.6 | 6.6 |
| Bulk Carriers | - | - | 1.5 |
| Containers | - | - | 2.2 |
| Consolidated cargo | - | - | 4.0 |
| RO-RO vessels | - | - | 1.8 |
| Tankers | 6.1 | 8.0 | 7.1 |
| Tugs | 2.8 | 1.5 | 2.1 |
| Fishing vessels | 2.8 | 1.3 | 2.0 |
| Other | 10.8 | 10.9 | 10.9 |

**Table 3.** Average number of arriving and departing vessels.

| **Event** | **Periods** | | **Average value** |
|---|---|---|---|
| | **July 29 –August 28** | **November 15 – December 15** | |
| Arrivals per day | 45.9 | 35.7 | 40.8 |
| Departures per day | 44.8 | 34.7 | 39.8 |
| Arrivals per hour | 2.06 | 1.49 | 1.8 |
| Departures per hour | 2.0 | 1.45 | 1.7 |

**Table 4.** Relation between engine power and gross tonnage of a vessel.

| **Vessel category** | **Relation between the power of main engine and gross tonnage of a vessel [12]** | **Relation between the power of main and auxiliary engines [12]** | **Average gross tonnage** |
|---|---|---|---|
| Tankers | $14.755*GT^{0.6082}$ | 0.30 | 1,909 |
| Bulk Carriers | $35.912*GT^{0.5276}$ | 0.30 | 19,572 |
| Containers | $2.9165*GT^{0.8719}$ | 0.25 | 6,335 |
| Consolidated cargo | $5.56482*GT^{0.7425}$ | 0.23 | 4,821 |
| RO-RO vessels | $164.578*GT^{0.4350}$ | 0.24 | 14,127 |
| Passenger | $9.55078*GT^{0.7570}$ | 0.16 | 718 |
| Fishing vessels | $9.75891*GT^{0.7527}$ | 0.39 | 1,353 |
| Other | $59.049*GT^{0.5485}$ | 0.35 | 4,636 |
| Tugs | $54.2171*GT^{0.6420}$ | 0.10 | 1,046 |

**Table 5.** Average power of main and auxiliary engines.

| **Vessel category** | **Average power of the main engine (kW)** | **Average power of the auxiliary engine (kW)** |
|---|---|---|
| Tankers | 1,977.1 | 593.1 |
| Bulk Carriers | 7,248.2 | 2,174.5 |
| Containers | 4,571.9 | 1,143.0 |
| Consolidated cargo | 3,255.4 | 748.7 |

| Vessel category | Average power of the main engine (kW) | Average power of the auxiliary engine (kW) |
|---|---|---|
| RO-RO vessels | 9,948.6 | 2,387.7 |
| Passenger | 598.9 | 95.8 |
| Other | 3,875.7 | 1,356.5 |
| Tugs | 3,581.9 | 358.2 |
| Fishing vessels | 1,505.4 | 587.1 |

Estimation of the average power of main and auxiliary engines of the vessels is based upon relation between the power of main engine and gross tonnage of the vessels as well as on the relation between the power of main and auxiliary engines. The results are given in tables 3 and 5.

## 3 The method for estimation of particle emissions by vessels

Average emission from main and auxiliary engines is calculated according to the following formula [14].

$$E = MCR \times LF \times EF \times FCF \times LLA \qquad (5)$$

where
E - speed of emission from the engine (g/h);
MCR - maximum continuous rating (kW) (given in table 4);
LF - load factors (without units) (given in table 5, 6);
EF - emission coefficient (g/kWh),
FCF - fuel correction factor (without measurement units);
LLA - low load adjustment (without measurement units);

**Table 6.** Auxiliary engine load factor allowances [15]

| Vessel category | Cruising mode | Maneuver mode | Hotel mode |
|---|---|---|---|
| Bulk Carriers | 0.17 | 0.45 | 0.10 |
| Containers | 0.13 | 0.48 | 0.19 |
| Passenger | 0.80 | 0.80 | 0.64 |
| Consolidated cargo | 0.17 | 0.45 | 0.22 |
| Tugs | 0.17 | 0.45 | 0.22 |
| RO-RO vessels | 0.15 | 0.45 | 0.26 |
| Refrigerators | 0.20 | 0.67 | 0.32 |
| Tankers | 0.24 | 0.33 | 0.26 |
| Other | 0.17 | 0.45 | 0.22 |

**Table 7.** Main engine load factor allowances [16]

| Operation mode | Main engine load |
|---|---|
| Cruising mode | 80 |
| Maneuver mode | 20 |
| Hotel mode | 20 |

Emission factors for engines on heavy diesel fuel with average sulfur content of 2.7% comprise 1.2 g/kWh for PM2.5 and 1.5 g/kWh for PM10 [14].

When vessels navigate in port areas, the main engines are usually operated under very low load. In general, diesel engines are not as efficient when operating under low loads. For main engines operating under load not exceeding 20 percent, decrease in engine efficiency and increase of emission factors are taken into account by using correction factors as a load function (given in table 7). Adjustment for auxiliary engines under low load is not carried out as far as they always operate under optimum loads [16].

**Table 8.** Low load adjustment for emission coefficients

| **Load (%)** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|
| PM | 7.29 | 4.33 | 3.09 | 2.44 | 2.04 | 1.79 | 1.61 | 1.48 | 1.38 |

| **Load (%)** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
|---|---|---|---|---|---|---|---|---|---|---|
| PM | 1.30 | 1.24 | 1.19 | 1.15 | 1.11 | 1.08 | 1.06 | 1.04 | 1.02 | 1 |

Sulfur content in fuel affects particles emissions from engines. That's why fuel correction factors are used for calculating emissions when the actual fuel used differes from 2.7% S fuel. Such fuel correction factors are represented in Table 9.

**Table 9.** Fuel correction factors (FCR)

| **Actual fuel** | **HFO** | **MDO** | **MDO/MGO** | **MDO/MGO** | **MDO/MGO** |
|---|---|---|---|---|---|
| Sulfur content (%) | 1.5 | 1.5 | 0.50 | 0.2 | 0.1 |
| FCF (PM) | 0.82 | 0.47 | 0.25 | 0.19 | 0.17 |

Calculation of total annual emission of PM2.5 and PM10 is based on the following formula:

$$TE = \left[a_1 \times (ER_1 + ER_2) + \textstyle\sum_{i=1}^{b}(a_2 \times ER_3)\right] \times 24 \times 365 \times 10^6 \quad (6)$$

where:

TE - total volume of particle emissions per year (t/y);

$a_1$=3.5: average number of vessels arriving and departing per hour. This parameter is obtained from table 2b;

$ER_1$ - average rate of emissions from main engines when vessels operate in maneuvering mode (g/h). This parameter is calculated according to formula 3;

$ER_2$ - average rate of emissions from auxiliary engines when vessels operate in maneuvering mode (g/h). This parameter is calculated according to formula 4;

b=8 - number of types of vessels;

$a_2$ average number of vessels of each type. This parameter can be found in table 2a

$ER_3$ - average rate of particle emissions from auxiliary engines when vessels operate in hotel mode (g/h). This parameter can be found in table 9.

Parameters $ER_1$ and $ER_2$ are calculated according to the following formula:

$$ER_1 = \frac{\sum_{i=1}^{b}(a_2 \times ER_4)}{\sum_{i=1}^{b} a_2} \quad (7)$$

$$ER_2 = \frac{\sum_{i=1}^{b}(a_2 \times ER_5)}{\sum_{i=1}^{b} a_2} \quad (8)$$

where:

$ER_4$: average rate of emissions from main engines when vessels operate in maneuvering mode (g/h). This parameter is given in Table 10;

$ER_5$: average rate of emissions from auxiliary engines when vessels operate in maneuvering mode (g/h). This parameter is given in Table 10.

**Table 10.** Average level of emissions from main and auxiliary engines with MDO 1.5.

| Vessel category | Main engine emissions level (g/h) under 20% load. | | Speed of emission from auxiliary engines under maneuvering load (g/h) | | Speed of emission from auxiliary engines under hotel load (g/h) | |
|---|---|---|---|---|---|---|
| | **PM2.5** | **PM10** | **PM2.5** | **PM10** | **PM2.5** | **PM10** |
| Tankers | 223.0 | 278.8 | 110.4 | 138.0 | 87.0 | 108.7 |
| Bulk Carriers | 817.6 | 1,022.0 | 551.9 | 689.8 | 122.6 | 153.3 |
| Containers | 515.7 | 644.6 | 290.1 | 362.6 | 122.5 | 153.1 |
| Consolidated cargo | 367.2 | 459.0 | 190.0 | 237.5 | 92.9 | 116.1 |
| RO-RO vessels | 1,122.2 | 1,402.8 | 606.0 | 757.5 | 350.1 | 437.7 |
| Passenger | 67.6 | 84.4 | 43.2 | 54.0 | 34.6 | 43.2 |
| Other | 437.2 | 546.5 | 512.6 | 640.7 | 244.8 | 306.0 |
| Tugs | 404.0 | 505.0 | 90.9 | 113.6 | 44.4 | 55.6 |

Emission factors for marine engines are represented in table 9. There is a considerable difference in emission factors of main engines. Main engine of a Ro-Ro vessel has the highest emission factor: 1,122 g/h and 1,403 g/h for PM2.5 and PM10 respectively. In contrast, main engine of a passenger vessel has the lowest emission factor of 68 g/h for PM2.5 and 84 g/h for PM10. A similar tendency is observed in the rate of emissions from auxiliary engines both in maneuvering and hotel modes. Emission factor greatly depends on the type of engine, fuel, operation mode of the engines. Emission factor for engines operating on 0.5 and 0.1% sulfur fuel were calculated in a similar way, but the results are not given in this paper.

The total mass of particulate matters emitted from marine engines in the port area of Vladivostok city is represented in figure 1. When all vessels operated on 1.5% S MDO, the total mass of PM2.5 and PM10 emitted per year comprised 66.2 and 82.7 tons per year respectively. However, when sulfur content in fuel decreased from 1.5% to 0.5% and 0.1%, the total mass of particles decreased by 47% and 67% respectively. It is obvious that particle emission greatly depends on sulfur content in fuel.

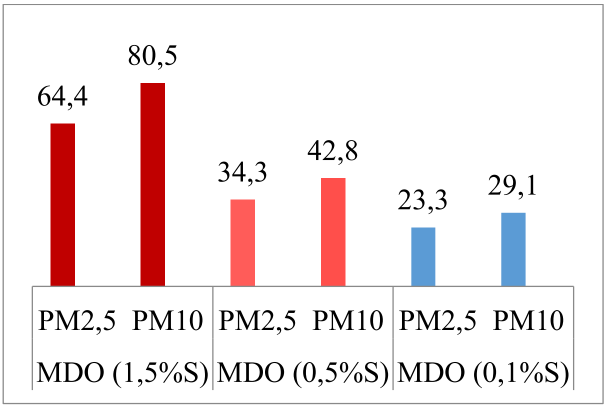

**Fig. 1.** Total mass of PM2.5 and PM10 emitted from marine engine in the area of Vladivostok city, tons per year.

Average concentration of PM2.5 in all measurement points is within the limits of the WHO and Russia standards (as shown in tables 10, 11). In contrast, an average concentration of PM10 in majority of measurement points is approximately 1.5 times greater than the WHO permissible level. In particular, concentration in the area of funicular is almost three times larger. However, PM10 concentration is still within permissible limits for Russia, except for

PM10 concentration in the funicular area. Airborne particulate matters have such negative effects on public health as an increased risk of untimely death from heart and lung diseases and acute exacerbation of respiratory diseases. It was demonstrated that the death rate connected with a short-term exposure of fine particles will be increased by 0.6 - 1% for adults and by 1.66% for children, if the concentration of particles in the environment is increased by10 µg/m3 [16]. Lozovskaya et al. pointed out that between 2000 and 2016 air pollution caused an increase in the primary incidence with respiratory diseases among adult population by 8.5% in the Primorsky region and by 20% in Vladivostok. Average long-term (2000–2016) disease incidence among adult population in Vladivostok city is 14,4% higher than that in the region and comprises 12,111.3 cases per 100 th. of adults as compares to 9,759.8 cases for 100 th. of adults in the Primorsky region [17].

**Table 11.** Maximum allowable concentration of airborne particles.

| **Description** | **Allowable limit as per WHO standards [17]** | | **Allowable limit as per Russian standards [18]** | |
|---|---|---|---|---|
| | **average daily** | **average annual** | **average daily** | **average annual** |
| PM2.5 µg/m$^3$ | 25 | 10 | 35 | 25 |
| PM10 µg/m$^3$ | 50 | 20 | 60 | 40 |

Particulate emissions with exhaust gases from ship power plants in port areas can be one of the main causes for high PM10 concentration in the air as well as for the increase in the number of respiratory diseases in Vladivostok as copmpared with the other regions. Increase in freight turnover by 40% over the past three years is a good sign for the region's economy, but it also has a significant impact on the environment. The total volume of particulate emissions with exhaust gases from ship power plants in the area of the port of Vladivostok over one year is estimated as much as 64.4 tons for PM2.5 and 80.5 for PM10 under the condition that the vessels operate on 1.5% S MDO fuel. Such emissions will be significuntly reduced when the IMO regulation on the use of 0.5% S fuel for vessels comes into force on January 1, 2020. According to estimates, the use of 0.5% S fuel will be reduced by 47% for PM2.5 and by 64% for PM10, which corresponds to 30 tons/year for PM2.5 and almost 40 tons/year for PM10 in the port area of Vladivostok city.

The negative impact of emissions from ship power plants on the port environment is reflected not only in the contribution of the mass of particles from ships to the total mass concentration of particles in the region's atmosphere (up to 15% [19]), but also in the toxicity of particles emitted by ship power plants. Heavy fuel oil, the main fuel for marine engines, contains V, Ni, S ions, which makes particles in the exhaust gases of ship power plants potentially more harmful than those produced from other sources that operate on lighter hydrocarbon fuels such as gasoline or natural gas [20]. In 2007, Kuokka et al. conducted a chemical analysis of atmospheric aerosols between Moscow and Vladivostok. The result showed that the concentrations of V, Ni and $SO_4^{2-}$ ion in PM2.5 were rather high within 500 km from Vladivostok as compared to the other regions. As of October 10, 2005, the concentration of V, Ni and $SO_4^{2-}$ ion comprised 3 ng/m$^3$, 8 ng/m$^3$, 1.87 µg/m$^3$, respectively. On October 11, 2005, these concentrations of V and Ni were about 1 ng/m$^3$, but the concentration of $SO_4^{2-}$ ion in PM2.5 reached 10.719 µg/m$^3$, which was the highest value among the measurement results [21]. Based on a simple model developed by Agrawal et al. in 2009 [22], the contribution of ship emissions to primary PM2.5 in the area of Vladivostok was estimated as 0.377 µg/m$^3$ as of October 10, 2005 and as 0.126 µg/m$^3$ as of October 11, 2005.

## 4 Conclusions

The above results and analysis show that the mass concentration of PM10 at eight measurement points exceeds the allowable limit as per WHO standards (by more than 1.5 times). Concentration of particles varied depending on the season of the year. In five out of eight points the concentration of particles in winter was higher, about 1.2 - 2.2 times for PM2.5 and 1.7 - 3.8 times for PM10, as compared with the concentration in summer. The total mass of particles emitted from vessels in the port area depends on sulfur content in fuel. When all vessels operated on 1.5% S MDO, the total mass of particles comprised about 80.4 tons/year for PM10 and 60.5 tons/year for PM 2.5. The total mass of particles will decrease by 47% or 30 tons/year for PM2.5 and by 64% or 40 tons/year for PM10 with IMO regulation on sulfur content in fuel (0.5%) that will become effective as of January 1, 2020. The contribution of primary PM2.5 particles emitted from ships in the area of Vladivostok was estimated to be higher than 0.126 $\mu g/m^3$. The negative impact of exhaust gases from ships on the environment of the region may be one of the main reasons that the disease incidence among adult population of Vladivostok city is 14.4% higher than the regional value.

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