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A Mid-Tier Approach to Estimating Durban's Port Marine Mobile Emissions: Gauging Air Quality Impacts in South Durban

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Abstract: Durban Port in South Africa is the largest container port and the busiest shipping terminal in sub-Saharan Africa. Approximately 60% of the country's containerised cargo and 40% of break-bulk cargo transit through Durban. The port is near the central business district, which has a positive spin-off in terms of tourism, recreation, and accessibility to transport and other business activities. The juxtaposition of industry, the port, and the community has resulted in sustained public health implications, a relic of the apartheid era. Like most ports in Africa, Durban Port lacks proper quantification of emissions from marine mobile sources. This study is aimed at estimating atmospheric emissions from ocean-going vessels (OGVs) in and around Durban Port for a period of one year from 1 January 2018 to 31 December 2018 using a mid-tier (activity-based) approach to supplement existing understandings of emissions from local industries. Emission estimates were then inputted to the AERMOD atmospheric dispersion model to allow for a comparison between ambient concentrations and national ambient air quality standards to assess potential health impacts. The study is an advancement in understanding the impact of mobile sources, particularly shipping, on air quality and health, and offers an example for other African ports to follow.

Keywords: marine mobile emissions; AERMOD; air quality; post-apartheid South Africa

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1. Introduction

Port emission inventories are necessary to estimate the impact of port activities on ambient air quality in port cities. Emissions from marine mobile sources are often overlooked in the compilation of emission inventories, particularly so in developing countries. This can be because of the lack of data and/or the capacity to conduct such inventories. In South Africa, for instance, marine mobile emissions from Durban Port did not form part of the 2011 study of the city of Durban's carbon footprint [1] and the 2016 study of transport emissions in South Africa [2].

Marine mobile emissions usually result from the exhaust gases generated by diesel engines. These include three different types, viz. 1. the main engines, which are the prime movers, 2. the auxiliary engines for power generation, and 3. boilers, used for domestic heating and fuel oil thinning [3]. The main pollutants produced by marine mobile diesel engines are oxides of nitrogen (NO_X), sulphur dioxide (SO_2), hydrocarbons (HC), particulate matter of less than 10 micrometres in diameter (PM_{10}), and carbon dioxide (CO_2), amongst others [3]. These pollutants are the major causes of respiratory problems and cardiovascular complications, while the latter (carbon dioxide) is a greenhouse gas [4–6].

This paper presents an inventory of four regulated/criteria pollutants (NO_X, SO_2, HC, and PM_{10}) and a greenhouse gas (CO_2), conducted for Durban Port to estimate the impact of ship emissions from 1 January 2018 to 31 December 2018. The mid-tier approach was utilised, where the operational data for individual ships, including speed and time spent per activity, were applied. The technical data involving engine type and engine capacity were averaged per ship type [5,7]. The modes of operation considered were manoeuvring, hotelling, and transiting within the reduced speed zone (RSZ). The study focused only on ocean-going vessels (OGVs) calling into Durban Port. This approach is an advancement of lower-tier, top-down approaches based on fuel usage.

2. Study Site

2.1. South Durban

The city of Durban is located on the east coast of South Africa in the province of KwaZulu-Natal. South of the Port of Durban lies the South Durban Industrial Basin, a dense mixture of industrial, residential, and commercial and heavy transport activities. From the early 1930s, policies of racial segregation in Durban were implemented. In planning for the future of an industrial South Durban, a 1944 racial zoning plan emphasised the need for racially specified zones, comprising a White residential area in the northern Bluff, Indian housing in Merebank, Coloured housing in Wentworth (previously called Austerville) and the African townships of Lamontville and Umlazi. Although legal segregation was abolished over 30 years ago in South Africa, these communities remain racially defined and continue to provide labour for the industrial and port activities nearby. The juxtaposition of community and industry have resulted in an apartheid legacy of chronic air pollution exposure with impacts on public health [8].

2.2. The Port of Durban

More than 90% of Africa's total trade (including imports and exports) pass through seaports [9]. Africa contributes to 4% of the worldwide containerised trade, mainly constituted of imports of manufactured products. The creation of the African Continental Free Trade Agreement (AfCFTA) and a restructuring of the continent's trade network have the potential to boost containerised trade [10,11]. Durban Port is the busiest port in sub-Saharan Africa in terms of the volume of containers passing through the port each year and the third busiest in Africa (after Tanger Med in Morocco and Port Said in Egypt) with a container throughput of approximately 3 million twenty-foot equivalent unit (teu) per annum [12,13].

There are approximately 4000 vessels calling into Durban Port each year [14,15]. This number does not include vessels on an innocent passage passing close to the port within 12NM from the coastline in internal waters. Other vessels stop at the anchorage for refuelling, replenishing, taking up spares, and to conduct repairs whilst at anchor without calling into port. Because of their proximity to the port and the coastline, vessels at anchor and on innocent passage have an impact on the pollution of the city even though they do not enter the port.

Ambient air pollution does not obey clearly defined property boundaries [16]. This is particularly true in the case of emissions from mobile polluters such as ships. The physical boundaries of a study area, however, must be clearly defined to ensure that the study is feasible and clearly contained, and to allow results to be interpreted appropriately.

According to the USEPA [3], the marine boundaries should be set in accordance with the purpose and the scope of inventory so that important activities of OGVs in or near the port are included. The following activities generally form part of the marine mobile emissions inventory:

- Transit areas: areas where ships normally travel at cruising speed.
- Restricted speed zone (RSZ): areas where vessel speed is limited for safety reasons, e.g., within the port limits or in the vicinity of anchorage areas.
- Manoeuvring areas: areas within the port, e.g., after breakwater inbound where vessels are often assisted by tugs.
- Hotelling areas: areas where ships are docking for loading and off-loading operations.
- Anchorage areas: a waiting station for vessels before berth opening [3].

For the purposes of this study, the manoeuvring area was defined to include the port basin, which is the region after the north and south breakwater inbound, up to three nautical miles offshore from the harbour mouth. The activities within the port basin are recorded by the port control as the time of arrival and departure when the ship crosses the breakwater line inbound and outbound, respectively.

An interpolation was then performed within the RSZ, which allowed the study to include ship activities three miles before crossing the breakwater inbound and after crossing the breakwater line outbound. This is an area where the marine pilot will embark or disembark from the vessel that visits the port. This rendezvous point is situated three nautical miles NE of the port entrance [17]. The three nautical miles parameter therefore discards the ships at anchor or on innocent passage from this study, as their movements are not recorded by the port control.

The study area is therefore represented by the below geographical coordinates (Figure 1). The area is approximately 21 square kilometres.

29°48′52″ S, 31°00′21″ E
29°48′52″ S, 31°07′22″ E
29°54′54″ S, 31°07′22″ E
29°54′54″ S, 31°00′21″ E

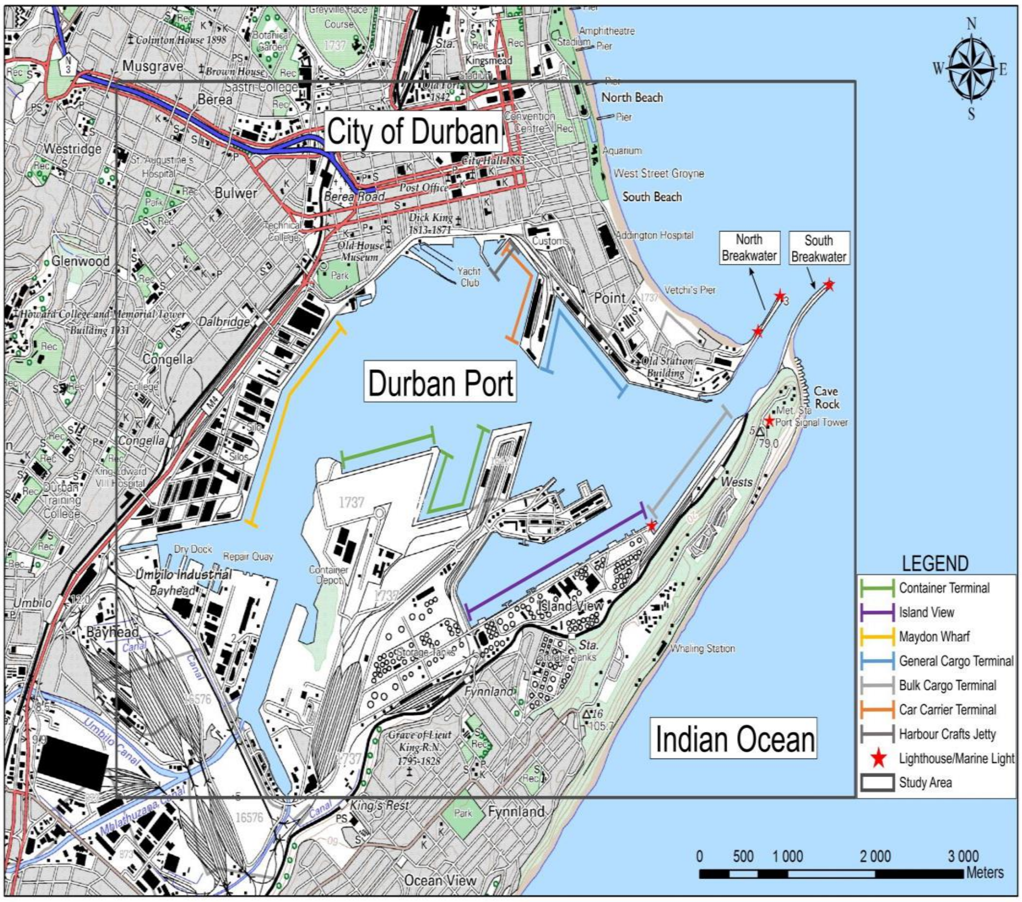

Figure 1. Study area including RSZ, hotelling, and manoeuvring zones.

3. Methodology

3.1. Top-Down versus Bottom-Up Approach

The two main approaches to ship emission inventories are top-down (fuel-based) and bottom-up (activity-based). The former is no longer recommended, as it uses data on marine fuel sales and fuel-related emission factors. The emission factors are multiplied by the sales of fuel for that port where fuel was purchased, and this led to an overestimation of fuel consumption within a small area of purchase. The result is the inflation of emission figures, as ships only burn a fraction of their fuel where the sales occurred [16,18].

The bottom-up activity-based method requires detailed information of ship specifications (e.g., IMO number, ship type, engine characteristics, and fuel type) and operational data (e.g., travel distances, maximum speed, port calls, and operations). In the detailed bottom-up approach, air pollutants emitted by specific ships in a specified spatial context are calculated and summed for the fleet over a specified period of assessment [19,20]. There are also less detailed hybrid methodologies that combine elements of the fuel-based and activity-based methodologies, and these may focus on ship categories with varying assumptions rather than specific ship characteristics.

The bottom-up approach is generally more accurate than the top-down approach, but greater effort is required to reduce data gaps and anomalies, especially for large-scale studies [18]. Even in the more refined bottom-up approach, calculations rely on average parameters for engine load factors, fuel consumption rate, etc., which limits representativity of estimated emissions [16,19,21].

According to the USEPA [16], the approach selected should depend on the following factors:

- The purpose of inventory.
- Financial resources to conduct the inventory.
- The location of the port.
- The geographical size of the port.
- The current and projected number of vessels calling into the port.
- The complexity of the port owner/operator relationship.

In line with the purposes of the inventory and the available budget, a bottom-up (activity-based) approach was applied to the emissions inventory of Durban Port.

3.2. Levels of Detail of the Bottom-Up Approach

The USEPA [16] highlighted three different approaches for performing a marine mobile emission inventory of a port within the bottom-up activity-based method.

The first one is the streamlined approach, with ship emissions estimated from another port's detailed inventory. The calculations for a port with an emissions inventory are used to estimate emissions from another port using the activity ratio between the ports [16].

The second is the mid-tier approach, where the technical data and ship's travel are averaged according to the ship type and tonnage. The mid-tier approach is appropriate for ports that lack the resources for a detailed approach but do have operational data by ship type [22].

The third is the detailed approach, which assesses each ship individually and each trip in and out of the port is quantified. Without information from the vessel traffic system (or automatic identification system), the harbour pilots, and Lloyd's Register of Ships, the detailed approach is not possible [16,22,23].

The mid-tier approach was applied to the emissions inventory of Durban Port, since the operational data for all OGVs visiting the port were obtained from the vessel traffic system. This made it possible to calculate an individual ship's contribution up to three miles from the port based on the ship type. However, the technical data of individual ships were not available during this period and therefore, the detailed approach was not possible. Once this information is available, a comparison of the two approaches will be possible and discrepancies between the two methods can be determined.

3.3. Data Sources

A record of ship movement in the port is compiled by the Transnet National Ports Authority's (TNPA) vessel traffic service (VTS), comprising inter alia, the names of ships, IMO number, and the times of arrival and departure. The period between the time of arrival and departure is called the turnaround time [15]. This is then used to extract the time spent by each vessel on each activity within the port. The three activities of relevance are manoeuvring (movement between the breakwater and the pier), hotelling (time at the pier when main engines are shut) and transiting through the reduced speed zone (between the port entrance and three nautical miles to seaward).

A marine pilot in Durban estimated the time it takes to manoeuvre the vessel from the breakwater to berth as 45 min and from the berth to breakwater as 30 min [24] The time for hotelling is calculated by subtracting the manoeuvring time from the turnaround time. The time spent in the RSZ is obtained by dividing the distance from the breakwater to the pilot pickup station (three nautical miles NE of the port entrance) by the average speed of the vessel (assumed to be 10 knots for bulk carriers and tankers and 12 knots for all other vessels) [15,24,25].

Each mode of activity is associated with a load factor, which is a percentage of the engine's maximum power. Since the ships' movement data were provided by the VTS, the study relied on the vessel trip record approach as opposed to the automatic identification system (AIS) approach [3].

Ships were divided into six different categories or types, including container ships, bulk carriers, tankers, general cargo ships, vehicle carriers, and others, as noted in the study conducted by [26]. The other category included all ships other than the five types mentioned earlier and include, amongst others, fishing vessels, stern trawlers, supply ships, survey ships, dredgers, passenger ships, etc. This six-type classification enabled the interrogation of emissions according to types when the emissions analysis was performed.

3.4. Emission Equation

The propulsion engines, auxiliary engines, and boilers were assessed in this study. The propulsion engine is also known as the main engine of the vessel, while auxiliary engines are electrical generators powering the electrical and electronic equipment onboard the ship. The boilers produce steam and heat onboard the vessel for various purposes. Engine emissions were calculated for each of the three types of engines using the following equation [3]:

$$E = P \times A \times LLAF \times EF \tag{1}$$

where

E = emissions per vessel (g);
P = operating power (kW) as a fraction of maximum continuous rating (MCR);
A = engine operating activity time (hours);
$LLAF$ = low-load activity factor for an engine (always 1 for auxiliary engines and boilers);
EF = emission factor (pollutant- and operation mode-specific, g/kWh).

3.4.1. Operating Power (P)

The US Environmental Protection Agency [3] uses the propeller law (Equation (2)) to estimate the vessel's operating power.

$$P_p = P_{ref} \times \left(\frac{V}{V_{ref}}\right)^3 \times SM \tag{2}$$

where

P_p = propulsion engine operating power (kW);
P_{ref} = vessel's total installed propulsion power (kW);
V = vessel's reported speed (kn);
V_{ref} = vessel's service speed (kn);
SM = sea margin accounting for average weather conditions, assumed to be 1.10 for coastal operations and 1.15 for at-sea operations (unitless).

The admiralty formula, which is regarded as an improvement of the propeller law, includes the impact of drafts and is recommended if the ship's draft is available. If draft is not known, the ship is assumed to be operating at maximum draft, which renders the same result as the propeller law because the propeller law is the upper boundary of the admiralty formula. The maximum limit of the result is the vessel's total installed propulsion power (*Pref*) so that the load factor does not exceed 100% [3].

3.4.2. Engine Operating Activity Time (A)

This is the time spent on each activity including the restricted speed zone, manoeuvring, or hotelling. The vessel traffic control system (VTS) records the time of arrival and the time of departure for each vessel calling into Durban Port. The duration of stay in the port between arrival and departure, namely the turnaround time, was used to determine the time for each activity, referred to as the activity time (A). The activity time for manoeuvring is 45 min and 30 min, which are the times taken for each ship to manoeuvre between the breakwater and the pier during arrival and departure, respectively. The hotelling time was therefore found by subtracting the manoeuvring time from the turnaround time. The activity time for the RSZ depends on the vessel's speed over the distance of 3 nautical miles, which is 10 knots for bulk carriers and tankers and 12 knots for all other ship types [15,24,25].

3.4.3. Load Factors (LF)

The load factor defines the amount of power the engine produces, which is a fraction of its maximum power [3]. This can be used to determine the vessel's mode of operation and whether the low-load adjustment factors can be applied when calculating propulsion engine emissions. For the propulsion engine, the load factor is calculated as

$$LF = \frac{P_p}{P_{ref}} \tag{3}$$

where

LF = load factor for propulsion engine (unitless);
P_p = operating power for propulsion engine (kW);
P_{ref} = vessel's total installed propulsion power (kW).

Unlike propulsion engine loads, the operating loads for boilers and auxiliary engines are not readily available onboard and are generally not included in vessel data sets. The default boiler and auxiliary engine loads, as presented in the Third IMO Greenhouse Gas Study 15, were used as recommended by the [3].

For propulsion engines, the emission factors are for propulsion loads exceeding 20% of the full propulsion power. However, propulsion engine emissions tend to increase as the engine loads decrease because diesel engines are less efficient at low engine loads. Therefore, the LLAF should be applied to Equation (1) when propulsion loads are less than 20% by making use of the LLAF values extracted from the [3] tables.

3.4.4. Emission Factors (EF)

According to Jahangiri et al. [27] the current marine mobile emission inventories need to review the emission factors they currently employ, as they can generally yield an over- or under-estimation of emissions. Emission factors are dependent on the engine type and engine category. The following characteristics are relevant:

- Engine category (C1, C2 or C3);
- Engine stroke;
- Engine bore;
- Engine type (generally slow-, medium-, or high-speed diesel);
- Engine speed (rpm);
- Keel-laid year (used to determine engine tier).

OGVs characteristically have C3 propulsion engines with a cylinder displacement of 30 litres or more. However, some OGVs may have smaller engines (C1 or C2). Nevertheless, this study assumed that all OGVs have C3 propulsion engines and therefore, each engine type had a specific fuel consumption figure [3].

The brake-specific fuel consumption (BSFC) is used for calculating emissions of particulate matter, sulphur dioxide, and carbon dioxide. The BSFC rates vary by engine type, engine group, and fuel type. The BSFC rates for the vessels with C3 propulsion engines are listed in the [3] tables, which also contain emission factors for hydrocarbons and oxides of nitrogen.

The following equations were used in the calculation of emission factors of PM_{10}, SO_2, and CO_2, respectively [3]:

$$EF_{PM_{10}} = PM_{base} + (S_{act} \times BSFC \times FSC \times MWR) \tag{4}$$

$$EF_{SO_2} = BSFC \times S_{act} \times FSC \times MWR \tag{5}$$

$$EF_{CO_2} = BSFC \times CCF \tag{6}$$

where

EF = emission factor adjusted for fuel sulphur (g/kWh);
PM_{base} = base emission factor assuming zero fuel sulphur;
= 0.1545 g/kWh for distillate fuel (MGO and MDO);
= 0.5761 g/kWh for residual fuel (RM and HFO);
S_{act} = actual fuel sulphur level (weight ratio);
= 0.001 for most vessel activity within the ECA in 2015 and beyond;
= 0.027 for all vessel activity outside the ECA before 2020;
= 0.005 for all vessel activity outside the ECA in 2020 and beyond;
$BSFC$ = brake-specific fuel consumption (g/kWh);
FSC = fraction of sulphur in fuel that is converted to direct sulphate PM
= 0.02247;
MWR = molecular weight ratio of sulphate PM to sulphur
= 224/32 = 7;
CCF = carbon content factor, which varies by fuel type (g CO_2/g fuel);
= 3.206 for MGO/MDO;
= 3.114 for RM/HFO;
= 2.75 for LNG.

3.5. Ocean-Going Vessel Operating Modes

The ship's operating mode is determined using the ship's speed and geographical data from the AIS data or VTS data. The operating modes are often associated with the geographic location within the port or outside the breakwater. Determining the operating mode requires each area of interest to be defined, e.g., the area between the breakwater and pier was defined as the manoeuvring area and that between the breakwater and port limit was termed the restricted speed zone [3].

The hours of engine operation need to be estimated for each vessel call by the various operating modes that a typical vessel call includes. This considers the time of arrival and departure, the estimated time of travel between the pier and breakwater, and the estimated time from the breakwater to port limits on arrival and departure. These translate to the restricted speed zone, manoeuvring, and hotelling times [25].

3.5.1. Restricted Speed Zone (RSZ)

The restricted speed zone has been established by other ports to stipulate the operating speeds in confined waters [25]. This is determined for the safety of navigation or to reduce emissions [3]. However, the estimated hours of operation in this mode can be calculated for ports that lack the RSZ data. This can be achieved by using the ratio of the distance travelled to the maximum speed of the vessel. Durban Port has not established a restricted speed zone and therefore relies on the proper judgement and good seamanship by ships proceeding within the port limits and within the anchorage area and areas with busy shipping traffic [15].

3.5.2. Manoeuvring

The time of manoeuvring commences when the vessel passes the breakwater inbound until the vessel is alongside the pier and from the pier until the vessel passes the breakwater outbound [15]. A marine pilot in Durban Port [24] indicated that different vessels take different times to manoeuvre from the breakwater to the pier depending on the vessel type and the VTS record of the arrival time (passing the breakwater) and the time the ship docks berthed alongside [3,15].

Faster ships like container ships, general cargo, and car carriers proceed at 7 knots from the breakwater until they berth alongside, and slower ships like bulk carriers and tankers proceed at 5 knots. Nevertheless, no ship is permitted to exceed the official speed limit of 8 knots inbound [15]. All vessels are permitted to proceed at 8 knots outbound to counter the tidal streams that normally cause a reduction in speed between the breakwaters and affect the manoeuvrability of the vessel outbound [15,24,25].

3.5.3. Hotelling

The VTS keeps records of the exact times of arrival and departure. These data were used to calculate the duration of stay in the port, which translated to the hours the vessel spent in the hotelling mode when the time of manoeuvring was subtracted from this duration [15]. If the AIS records are used, tables from the [3] are used to determine the mode of operation of a vessel depending on its position, i.e., if it is in the confines of the port, within the port limits, or in open ocean.

During the hotelling mode in the port, a ship may be engaged in loading and off-loading cargo using its cranes and gantries whilst alongside a pier. In Durban Port, for instance, general cargo ships berthed in Pier B, C, D, and E use their own equipment for loading and off-loading cargo. However, this was not factored in, as information on specific vessel berths were not provided in the VTS data set [15].

3.6. Total Emissions Calculation

The algorithm for the calculation of the total ship emissions was made in accordance with the formula approved by the Intergovernmental Panel on Climate Change [5,28,29]:

$$E_i = P_m L_m T_m F_{i,m} + P_a L_a T_a F_{i,a} + P_b L_b T_b F_{i,b} \tag{7}$$

where

E_i = emission of each pollutant;
$P_{m,a,b}$ = maximum power output of main, auxiliary, and boiler engines;
$L_{a,b}$ = load factors for auxiliary and boiler engines;
$T_{m,a,b}$ = time in operation;
$F_{i,m,a,b}$ = emission factors of each engine for each pollutant.

Various operational conditions and navigational statuses determined the value of each function within Equation (7). When the vessel was in transit, the boilers were shut down and $P_b L_b T_b F_{i,b} = 0$ and therefore, emissions were calculated using the modified formula, which included main engines and auxiliary engines $E_i = P_m L_m T_m F_{i,m} + P_a L_a T_a F_{i,a}$. When the vessel was moored or berthed alongside in the port, it meant that the main engines were shut down so that $P_m L_m T_m F_{i,m} = 0$ and emissions were therefore calculated using only the auxiliary engines and boilers; thus, $E_i = P_a L_a T_a F_{i,a} + P_b L_b T_b F_{i,b}$. If the vessel was loading and unloading alongside using its own cargo handling equipment, then the total emissions are based on $E_i = P_a L_a T_a F_{i,a} + P_b L_b T_b F_{i,b} + P_s L_s T_s F_{i,s}$, where s is for ship-borne equipment [29]. This would apply in ports where some terminals are known to have no shore gantries and vessels use their onboard equipment to load and offload cargo. However, for Durban Port, the ship-borne equipment was not factored in due to a lack of berthing details for ships in 2018.

4. Results and Discussion

4.1. Total Emissions

A total of 3939 ships visited Durban Port between 1 January 2018 and 31 December 2018 with an average of 328 ships per month. Bulk carriers were frequent visitors in Durban Port in 2018, followed by container ships and tankers (Figure 2). November had the highest number of ships visits, accounting for 375 ship visits, and April was the least busy month, with 288 ship visits. The total emissions were obtained by adding emissions from all OGV operations up to three miles from the port. The results are presented in the form of the tables and graphs below.

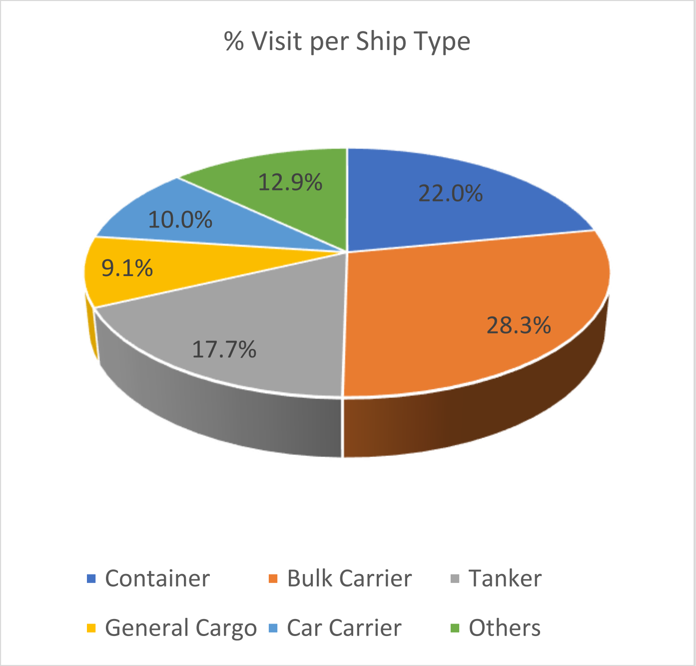

Figure 2. Percentage of ship visits by ship type in Durban Port in 2018.

The results indicate that bulk carriers had the highest emissions of NO_X, SO_2, PM_{10}, and HC, and container ships were responsible for the highest emissions of CO_2 (Table 1 and Figure 3).

Table 1. Emissions per vessel type in Durban Port (tonnes per year) in 2018.

	NO_x	SO_2	PM_{10}	HC	CO_2
Container ship	83.85	113.01	11.28	4.31	11,773.90
Bulk carrier	154.29	145.88	17.31	6.41	9407.92
Tanker	96.63	98.25	11.15	4.15	6372.66
General cargo	21.05	24.45	2.59	0.96	1555.50
Vehicle carrier	48.38	42.04	5.11	2.02	3630.69
Other ships	54.42	63.93	7.02	2.35	4198.76
Total	458.62	487.57	54.45	20.20	36,939.43

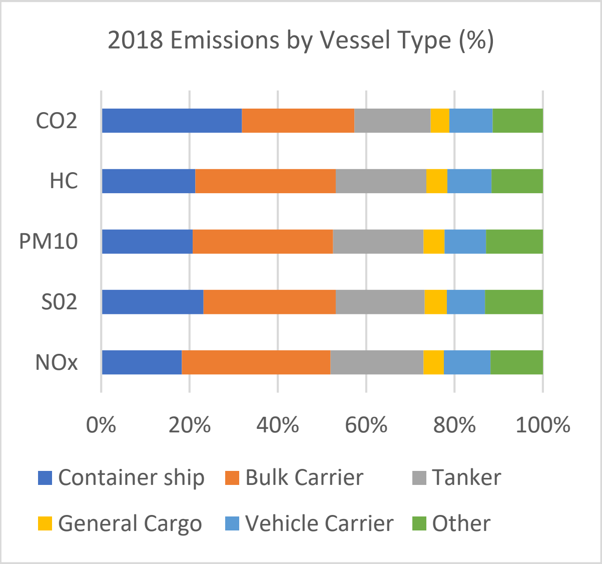

Figure 3. Emissions by vessel type in Durban Port (%) in 2018.

The main propulsion engines accounted for the highest emissions of all categories of pollutants despite remaining shut down during hotelling (Figure 4). This is because the main engines have higher load factors during transit within the reduced speed zone and during manoeuvring in ports. Such load factors combined with high emission factors and the size of the main engines compared to auxiliary engines and boilers increase the fuel consumption of the main engines and in turn result in higher pollutant emissions.

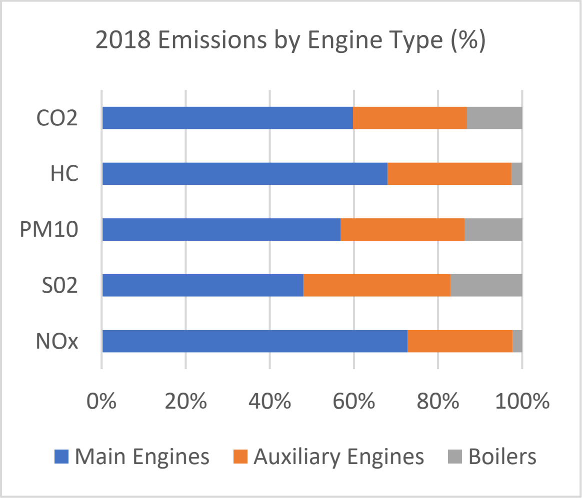

Figure 4. Emissions by engine type (%) in 2018.

Most of the pollution occurs within the reduced speed zone outside the port (Figure 5). This zone is assumed to exist within three nautical miles from the harbour entrance, as all OGVs found within this distance are either embarking or disembarking the pilot when entering or leaving the port, respectively. Ships have a higher usage of main propulsion engines within this zone and propulsion engines had higher emissions than auxiliary engines and boilers; therefore, the reduced speed zone had higher emissions than the manoeuvring and hotelling modes.

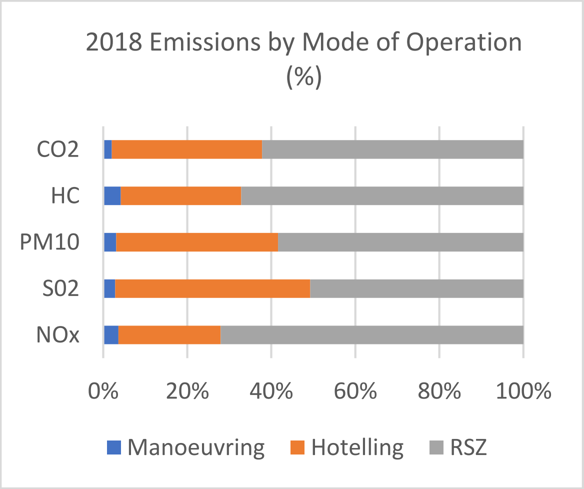

Figure 5. Emissions by mode of operation (%) in 2018.

4.2. Ambient Pollution from Ship Emissions

The AERMOD air dispersion model was used to map the ambient concentration and spatial distribution of pollutants of NO_2, SO_2, PM_{10}, and HC. The AERMOD uses meteorological data, emissions data, and terrain data to map the density and spatial concentration of pollutants in space. A CALPUFF-ready PSU/NCAR MM5 (prognostic mesoscale weather model) meteorological file from Lakes Environmental was used to produce meteorology inputs for AERMOD for the GPS coordinates at the centre of Durban Port for the year in focus, 2018.

The meteorological data used in AERMOD can be obtained from Lakes Environmental [30]. The stack height inserted in AERMOD was 30 metres above sea level and the flue gas emission rate was estimated to be 30 m per second (m/s) with a temperature of 350 °C for all ships. The roughness parameters were set at 0.3 metres and were mostly urban [31].

The results from AERMOD were then compared with the South African ambient standards for these priority pollutants and were all (except the 24-hourly SO_2) found to be below the maximum allowed annual, daily, and hourly average concentrations [32].

The annual maximum NO_2 concentration resulting from ships calculated across the study domain was 21.8 $\mu g/m^3$ and thus remained below the permissible annual National Ambient Air Quality Standards (NAAQS) of 40 $\mu g/m^3$ [32]. The epicentre of maximum NO_2 concentration is along the track approaching the port entrance where the ships are in the reduced speed zone (Figure 6).

The annual maximum SO_2 concentration resulting from ships was 17 $\mu g/m^3$ (Figure 7) and remained below the NAAQS of 50 $\mu g/m^3$ [32].

However, the maximum 24-hourly SO_2 concentration resulting from ship emissions, taking the worst-case scenario for the day with the highest emissions, was found to be 228 $\mu g/m^3$ (Figure 8) and was above the current 24 h NAAQS of 125 $\mu g/m^3$. This exceedance of the NAAQS occurred outside the port entrance within the reduced speed zone, thus away from sensitive receptors.

The annual maximum PM_{10} concentration resulting from ships across the study domain was 2.22 $\mu g/m^3$ (Figure 9), remaining well below the annual NAAQS of 40 $\mu g/m^3$ [32]. The highest concentration of 24-hourly P100 resulting from ships across the study domain was 25.3 $\mu g/m^3$ and was below the 24-hourly NAAQS concentration of 75 $\mu g/m^3$, as revised from 120 $\mu g/m^3$ in 2015 [32,33].

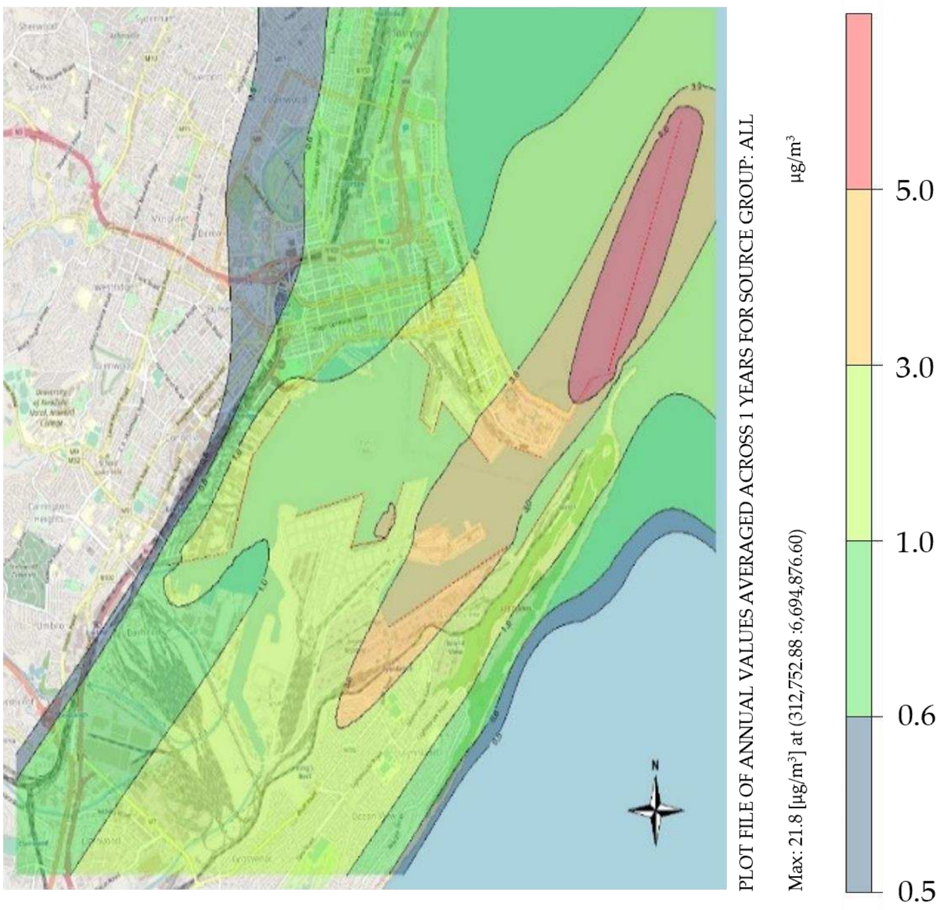

Figure 6. Annual NO_2 concentration.

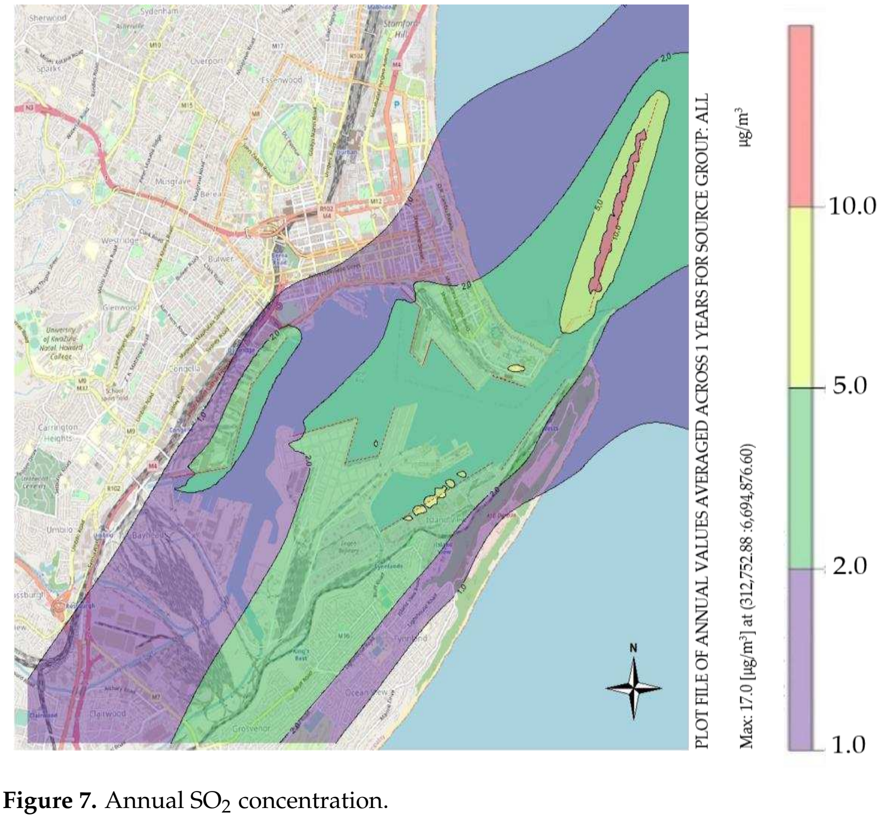

Figure 7. Annual SO_2 concentration.

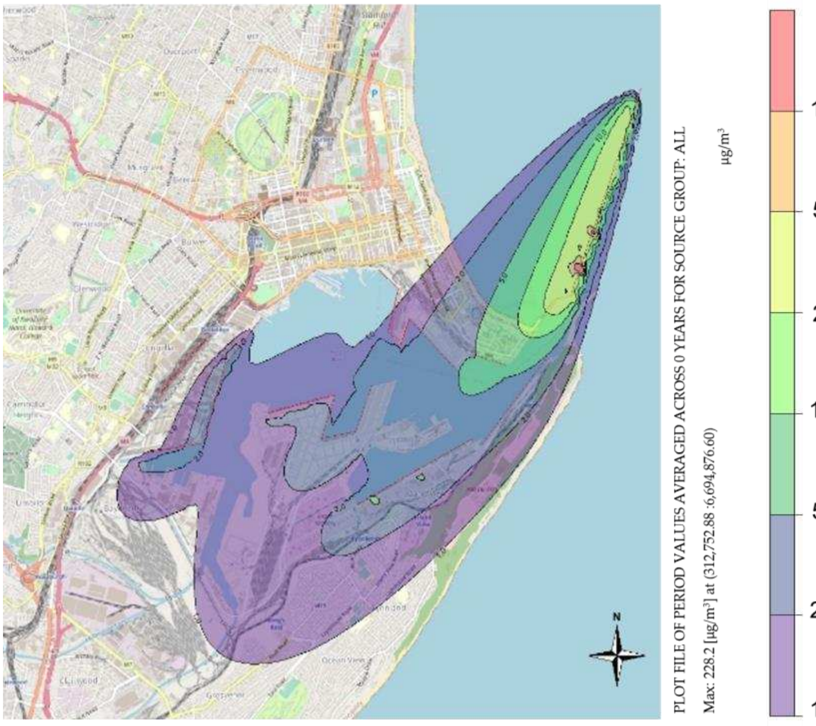

Figure 8. 24-hourly SO_2 concentration.

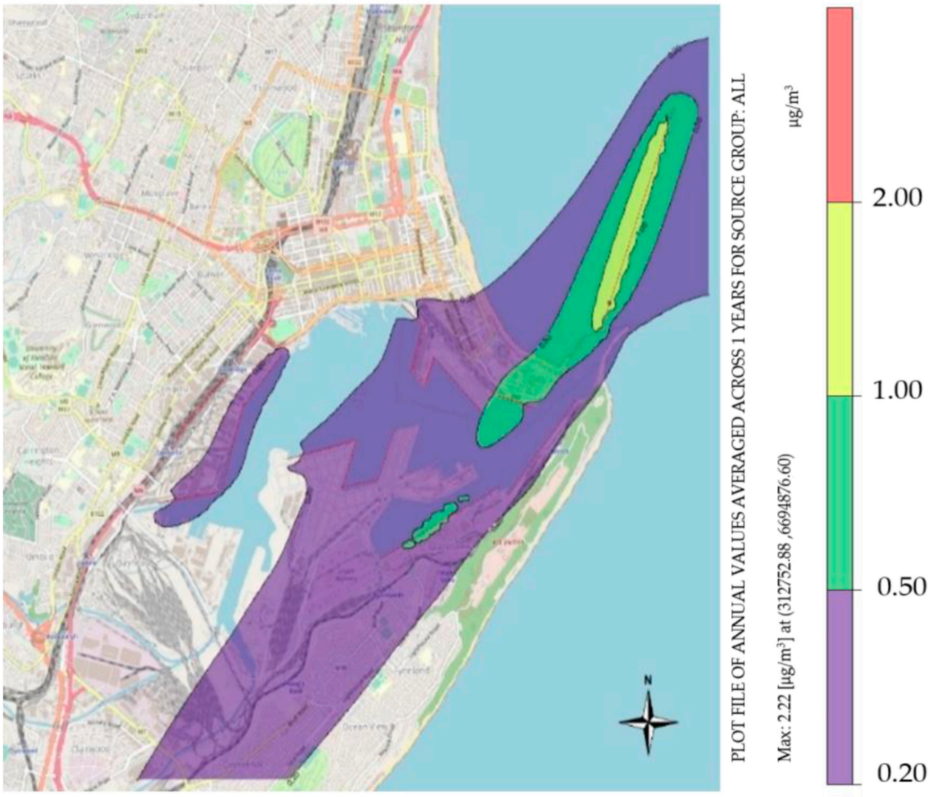

Figure 9. Annual PM_{10} concentration.

The annual HC concentration resulting from ships was 0.90 µg/m^3 (Figure 10) and remained below the benzene NAAQS of 5 µg/m^3 [32].

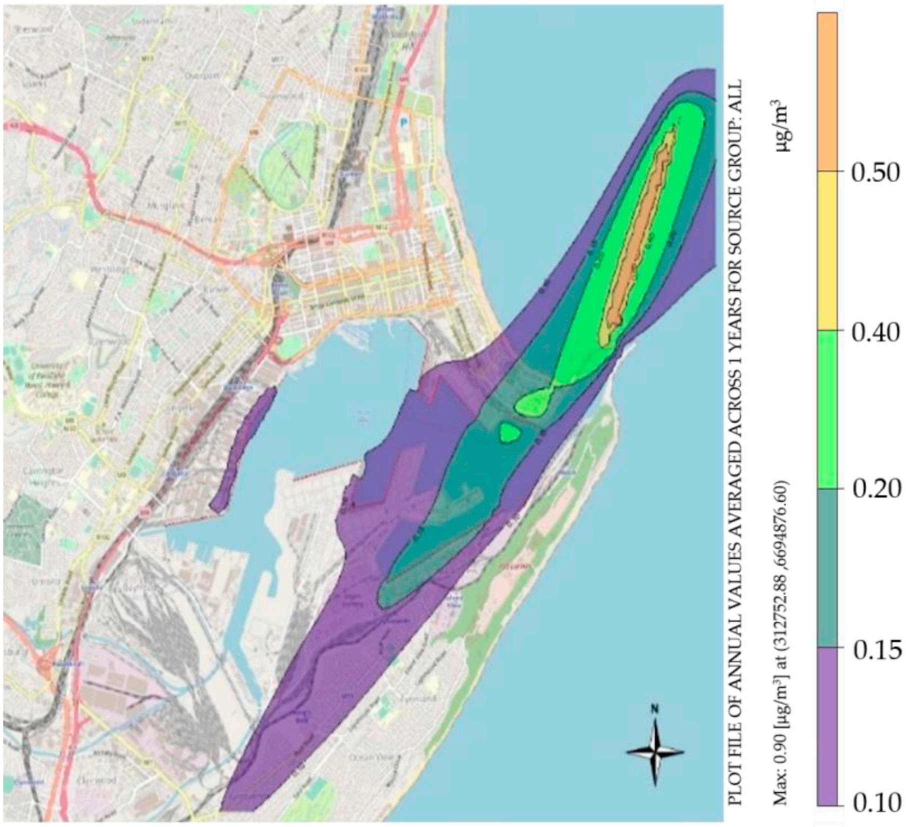

Figure 10. Annual HC concentration.

It is therefore apparent that the annual ambient concentration of OGV emissions do not result in ambient levels that exceed the NAAQS for all four priority pollutants of NO_2, SO_2, PM_{10}, and HC. However, the 24-hourly concentration of SO_2 on the 25 of November 2018 (when highest emissions were experienced) was well above the maximum allowed NAAQS concentration of 125 $\mu g/m^3$. The daily SO_2 concentration reached 228 $\mu g/m^3$, a significant exceedance of 103 $\mu g/m^3$ (82.4%).

Evidently, the contribution of OGVs to the ambient concentration of pollutants is significant and should therefore not be overlooked in cumulative assessments of urban ambient air quality, as has been the case in South Africa to date [1,2].

4.3. Impacts on Proximate Communities

Specified receptors were simulated in AERMOD to assess the local impact. Results indicate low ambient levels of hydrocarbons from shipping emissions. However, baseline levels of BTEX (benzene, toluene, ethylbenzene, and xylene) in Wentworth and Merebank are of concern because of poorly managed oil refinery infrastructure in this area [8]. Shipping emissions will supplement existing levels and potentially exacerbate health impacts.

PM_{10} levels from shipping also are significantly below the NAAQS in these communities (Table 2), but once again, this supplements significant traffic-related pollution in the region, associated particularly with large trucks travelling to and from the port.

Although no exceedances of SO_2 and NO_2 of the NAAQS were calculated at these community receptors, the high values (particularly of peak 10 h NO_2) calculated for Wentworth, Grosvenor, Fynnlands, and Merebank (Table 2) would supplement industrial- and traffic-related emissions, likely contributing to cumulative exceedances in the region, impacting the health of proximate communities. Further investigation of cumulative impacts is necessary. However, results indicate the importance of shipping emissions in assessing potential health and economic impacts of air pollution in the region.

Table 2. Comparison of pollutant concentration from AERMOD results (per receptor) and NAAQS limits.

		RECEPTORS						
		Wentworth	**Grosvenor**	**Fynnlands**	**Merebank**	**Montclair**	**Lamontville**	**Glenwood**
HC	Annual NAAQS (benzene)				5 μg/m^3			
	Annual (μg/m^3)	0.08	0.07	0.06	0.05	0.02	0.01	0.00
PM_{10}	Annual NAAQS				40 μg/m^3			
	Annual (μg/m^3)	0.22	0.19	0.15	0.14	0.06	0.04	0.01
	24 h NAAQS				75 μg/m^3			
	24 h peak (μg/m^3)	2.50	2.04	1.51	1.66	0.81	0.78	0.16
SO_2	Annual NAAQS				50 μg/m^3			
	Annual (μg/m^3)	1.95	1.67	1.34	1.30	0.53	0.40	0.12
	24 h NAAQS				125 μg/m^3			
	24 h peak (μg/m^3)	21.50	17.97	13.83	15.10	7.46	7.22	1.55
NO_2	Annual NAAQS				40 μg/m^3			
	Annual (μg/m^3)	1.95	1.73	1.29	1.14	0.36	0.28	0.09

4.4. Comparison with Other Studies

A comparison was made with other 2018 studies of ports in other regions including Denmark, the USA, and Italy (Table 3). The results differ in various ports, owing to the differences in study area sizes and the number and types of ships visiting each port.

Table 3. Comparison of 2018 port emissions from different regions [18,34,35].

Port	**Year of Study**	**Number of OGVs**	**NO_2**	**SO_2**	**PM_{10}**	**HC**	**CO_2**
			Tonnes Per Year				
Durban (South Africa)	2018	3939	459	488	54	20	36,939
Copenhagen (Denmark)	2018	2938	565				
Los Angeles (USA)	2018	1737	2909	110	57	119	205,486
Naples (Italy)	2018	900	5418	193	602		

The comparison between the Durban and Copenhagen studies shows that there were 1001 more ships that visited Durban in 2018 than Copenhagen. However, the annual NO_2 emissions reported for Copenhagen (565 tonnes) were higher than Durban (459 tonnes). The approach speed inside Durban Port is strictly restricted to eight knots, whereas in Copenhagen, the speed limit is not specified, and pilotage is only compulsory for certain classes of vessels and for a towing vessel or vessel under tow [15,36]. According to Equation (2) above, a slight increase in the vessel's speed leads to an exponential increase in emissions due to the increased propulsion engine operating power. Ships in Copenhagen may be operating at higher speeds than ships in Durban due to the larger operational area (27.6 km^2 for Copenhagen and approx. 21 km^2 for Durban). Another difference could result from the sizes and types of ships visiting each port. The study in Copenhagen reported cruise ships making up about 12% of the ship visits in 2018, whereas in Durban, cruise ships make up less than 1% of ship visits [35]. Nevertheless, the annual NO_2 concentrations for both Durban and Copenhagen did not exceed the national ambient air quality standard limits of 40 μg/m^3 in both countries [32,35].

Despite having fewer ship visits (Los Angeles had 1737 compared to Durban, with 3939 ship visits), the Port of Los Angeles study reported higher emissions (NO_2, HC, and CO_2 were all five times higher). This discrepancy is likely due to study boundaries; the study in Los Angeles calculated the ship emissions up to 40 kilometres from the harbour mouth, while our Durban port study only considered emissions up to three kilometres from the harbour mouth offshore. Interestingly, the shipping emissions of SO_2 were higher in Durban than in Los Angeles. South Africa is a non-sulphur emission control area (non-SECA), whereas the United States of America is a sulphur emission control area (SECA) [34]. In 2018, the sulphur content of fuel in SECA regions was limited to 0.1%, whilst in non-SECA regions, it was 3.5% [37].

The PM_{10} emissions for the Port of Los Angeles were significantly lower than the Port of Durban emissions when considering the size difference between the two study areas. SO_2 gas forms secondary particulate matter ($PM_{2.5}$) when it oxidises to sulphuric acid (H_2SO_4) by combining with water vapour [38]. It is therefore surmised that the lower SO_2 emissions also contributed to a lower PM_{10} at the Port of Los Angeles.

The Port of Naples is the third busiest port in Italy, priding itself with a high number of ship visits, passengers, and handled cargo. It accounts for approximately 63,000 ship visits, 8 million passengers, and 20 million goods per year [39]. Naples also prides itself on high large cruise ship traffic and ferry activities with dedicated berths for these passenger vessels to and from various places around Italy and abroad. Ferry travelling is a popular means of transport in Italy as it is an efficient and cost-effective service. Passengers commute to and from the mainland, Italian islands, and neighbouring countries of Slovenia, Croatia, Morocco, etc. [40]. Italy is a member of the European Union (EU) under Directive (EU) 2016/802, which requires 0.1% of sulphur fuel to be used in ports [18,41]. Therefore, the SO_2 emissions in the Port of Naples were lower than Durban port SO_2 emissions. However, the NO_2 and PM_{10} emissions were both eleven times higher in Naples, likely due to significantly more shipping activity in the Port of Naples and the different ships considered. Toscano et al. [18] mentioned that the results for the NO_2, SO_2, and PM_{10} emissions significantly exceeded those recorded by Murena et al. [42] for the same year due to the different ships considered.

5. Conclusions and Recommendations

The assessment of the ambient impacts of ship emissions using AERMOD showed that while annual ambient concentrations of NO_2, SO_2, PM_{10}, and HC from ships did not exceed the NAAQS limits, contributions were significant and could contribute to other exceedances, for example, peak short-term NO_2. The contribution of OGVs can therefore be significant when considered with other sources and therefore cannot be ignored in a cumulative assessment, as has happened in previous studies [1,2].

It is noted that the methodology used in this study, namely the mid-tier approach, is not considered as the most accurate method for marine mobile port emission inventories [18]. This is because it does not consider each vessel individually, but it averages the vessels' characteristic data of engine capacity, fuel type, maximum speed, and time in operation according to vessel type [3]. However, it is an improvement on top-down fuel-based assessments.

As a recommendation, the next logical step for an assessment of shipping emissions from the Port of Durban would be the detailed approach. The detailed approach considers emissions from individual ships by detailing the engine capacity, fuel type, and maximum speed of each ship. In this approach, ships are identified by their name, IMO number, and ship type, which facilitates the extraction of technical data and operational data for individual ships [3]. The detailed approach is recommended for further studies of Durban Port if all resources and the required data become available.

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