PORT HOUSTON℠

2021

Goods Movement Emissions Inventory

PREPARED BY

Kristiansson

STARCREST CONSULTING GROUP, LLC
ENVIRONMENTAL MANAGEMENT • AIR QUALITY • CLIMATE • SUSTAINABILITY

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Authors:
Joyce Kristiansson, CEO, Kristiansson
Guiselle Aldrete, Consultant for Kristiansson
Archana Agrawal, Principal, Starcrest
Joseph Ray, Principal, Starcrest
Rose Muller, Consultant for Starcrest
Jill Morgan, Consultant for Starcrest

Contributors:
Nicole D. Hausler, Principal, Summer Hill Environmental

Cover:
Melissa Anderson, Principal, Starcrest

Photos:
Port Houston, media gallery

Document Preparation:
Denise Anderson, Consultant for Starcrest

ACRONYMS AND ABBREVIATIONS

AIS	automatic identification system
ATB	articulated tug and barge
BSFC	brake specific fuel consumption
CF	control factor
CHE	cargo handling equipment
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
D	distance
DF	deterioration factor
DR	deterioration rate
DWT	deadweight tonnage
E	emissions
ECA	emission control area
EF	emission factor
EI	emissions inventory
EPA	U.S. Environmental Protection Agency
FCF	fuel correction factor
g/bhp-hr	grams per brake horsepower-hour
g/hr	grams per hour
g/kW-hr	grams per kilowatt-hour
g/mi	grams per mile
GIS	geographic information system
GHG	greenhouse gas
GWP	global warming potential
HC	hydrocarbons
HDV	heavy-duty vehicle
HGB	Houston-Galveston-Brazoria ozone nonattainment area
hp	horsepower
hrs	hours
IMO	International Maritime Organization
kW	kilowatt
kW-hr	kilowatt-hour
lbs/day	pounds per day
LF	load factor
LLA	low load adjustment
Lloyd's	Historical name for marine vessel data licensed from IHS Markit
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MCR	maximum continuous rating
MDO	marine diesel oil
MGO	marine gas oil
mph	miles per hour
MMGT	million gross ton
MMSI	maritime mobile service identity
MOVES	Motor Vehicle Emissions Simulator, EPA model
MY	model year
N_2O	nitrous oxide
nm	nautical miles
NO_x	oxides of nitrogen
OGV	ocean-going vessel
PM	particulate matter
PM_{10}	particulate matter less than 10 microns in diameter
$PM_{2.5}$	particulate matter less than 2.5 microns in diameter
PHA	Port of Houston Authority
ppm	parts per million
PTRA	Port Terminal Railroad Association
RoRo	roll-on roll-off vessel
rpm	revolutions per minute
S	sulfur
SFC	specific fuel consumption
SO_x	oxides of sulfur
TCEQ	Texas Commission on Environmental Quality
TEU	twenty-foot equivalent unit
tonnes	metric tons
tpy	tons per year
U.S.	United States
ULSD	ultra-low sulfur diesel
USCG	U.S Coast Guard
VBP	vessel boarding program
VMT	vehicle miles of travel
VOC	volatile organic compound
ZH	zero hour
ZMR	zero-mile rate

EXECUTIVE SUMMARY

The Greater Port of Houston is a 25-mile-long complex of nearly 200 private and public industrial terminals along the 52-mile-long federal waterway that is the Houston Ship Channel (HSC). The Port of Houston Authority, known as Port Houston or PHA, is the owner of the public terminals as well the local sponsor of the HSC. The 2019 Goods Movement Emissions Inventory (2019 GMEI) is the latest GMEI to be undertaken by Port Houston. Consistent with the previous GMEIs, the main objective of this report is to estimate air emissions related to the goods movements that occur at the Port Houston public terminals (PHA). In addition to PHA emissions, the ocean-going vessel and commercial harbor vessel emissions for the private facilities (non-PHA) is provided separately in the report for additional information.

Between 2013 (the year analyzed from the previous GMEI) and 2019, Port Houston terminals saw significant growth in cargo volume. For PHA public terminals alone, cargo throughput increased by 8% in short tons and 53% in container twenty-foot equivalent unit (TEU) throughput over the period. **Despite the increase in cargo volume, overall emissions of all pollutants were lower for PHA terminals, primarily due to fleet turnover and the use of lower sulfur content fuel by ocean- going vessels (OGVs) in 2019 as compared to 2013.**

With respect to ocean-going vessel and commercial harbor vessel emissions from the private facilities (non-PHA) of the Greater Port of Houston area, NO_x and CO_2e emissions increased in 2019 due to the increased activity in the Houston Ship Channel since 2013 mainly due to the repeal of the crude oil export ban at the end of 2015. Below are summary tables presenting the findings. More detail can be found in the respective emission source category sections for 2019 emissions and Section 8 for comparisons.

2019 PHA Emissions Results

The 2019 emissions from maritime-related mobile sources associated with PHA are summarized in Table ES.1. Figure ES.1 illustrates the percent distribution of PHA emissions by source category for activity associated with PHA terminals only.

Table ES.1: 2019 PHA Maritime-related Emissions

	NO_x	PM_{10}	$PM_{2.5}$	VOC	CO	SO_x	CO_2e
	tons	tons	tons	tons	tons	tons	tonnes
Ocean-going vessels	4,120	69	63	132	348	171.3	259,134
Commerical harbor vessels	496	12	12	12	113	0.4	39,805
Cargo handling equipment	370	29	28	39	169	0.3	72,121
Locomotives	587	16	16	27	153	0.6	53,329
Heavy-duty vehicles	1,395	70	64	96	498	0.9	233,867
Total	**6,967**	**195**	**182**	**306**	**1,281**	**173**	**658,256**

Figure ES.1: 2019 PHA Distribution of Emissions by Source Category, %

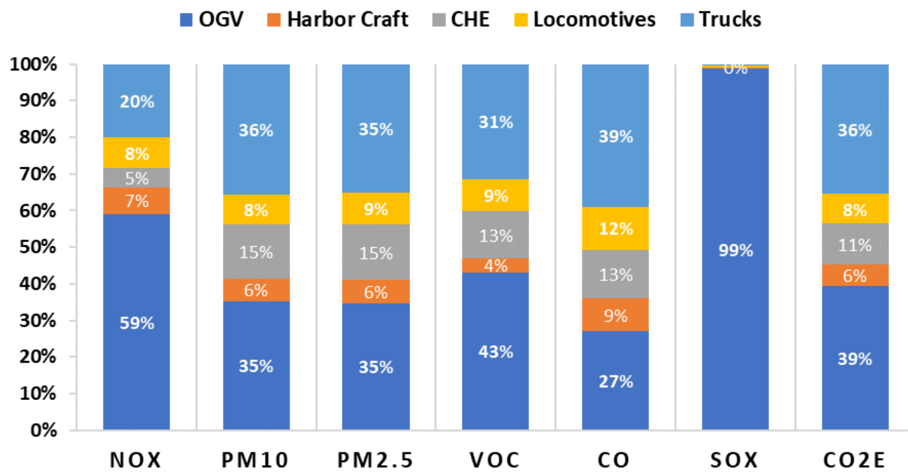


Table ES.2 provides a comparison of cargo volumes in short tons and container throughput for PHA[1] terminals only. The significantly increased container throughput in 2019 since 2013 is due to facility improvements at PHA's Bayport and Barbours Cut Terminals, including increasing container yard capacity, wharf expansions and new post-Panamax ship to shore cranes.

Table ES.2: PHA Cargo Volumes Comparison

Year	Cargo (short tons)	Containers TEU
2019	48,240,858	2,990,175
2013	44,756,323	1,952,122
Change	**8%**	**53%**

Table ES.3 presents the total net change in PHA emissions for all source categories in 2019 compared to 2013. Despite the 53% TEU throughput increase and 8% increase in cargo throughput for PHA, the PHA emissions were lower for all pollutants across the board.

Table ES.3: 2013-2019 PHA Emissions Comparison

Year	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019	6,967	195	182	306	1,281	173	658,256
2013	8,145	511	477	472	1,666	2,666	833,215
Change	**-1,178**	**-316**	**-295**	**-167**	**-385**	**-2,492**	**-174,960**
Change (%)	**-14%**	**-62%**	**-62%**	**-35%**	**-23%**	**-93%**	**-21%**

[1] *Data source: Port of Houston Authority Monthly Cargo Statistical Summary December 2019 and December 2013, both Post Audit files provided by PHA.*

2019 Non-PHA Emissions Comparison

The OGV and commercial harbor vessels emissions for non-PHA entities in the Houston Ship Channel are included in Table ES.4. For non-PHA OGV emissions, the PM and SO_x emissions reductions are due to the use of lower sulfur fuel in 2019. The other pollutants increased in emissions due to increase in vessel activity. The harbor craft emissions are lower for most pollutants due to fleet turnover, while CO and CO_2e emissions increased due to a lack of lower emission standards for these particular pollutants and increased activity.

Table ES.4: 2013-2019 Non-PHA Emissions Comparison by Source Category

	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019							
Ocean-going vessels	7,939	172	159	247	716	448	678,387
Commerical harbor vessels	3,816	88	85	93	847	3	302,443
Total	**11,755**	**261**	**244**	**340**	**1,563**	**451**	**980,831**
2013							
Ocean-going vessels	4,054	288	264	172	409	2,586	388,594
Commerical harbor vessels	4,138	93	90	106	755	3	285,602
Total	**8,192**	**381**	**354**	**278**	**1,164**	**2,589**	**674,195**
Change between 2013 and 2019 (percent)							
Ocean-going vessels	96%	-40%	-40%	44%	75%	-83%	75%
Commerical harbor craft	-8%	-6%	-5%	-13%	12%	5%	6%
Total	**44%**	**-32%**	**-31%**	**22%**	**34%**	**-83%**	**45%**

The 2013 OGV emissions were not re-estimated, but there were major activity impacts to private facilities (non-PHA) emissions in 2019 that should be noted when comparing the 2013-2019 OGV emissions:

- The Houston Ship Channel saw increased activity including a 17% increase in OGV calls which increased OGV emissions overall.
- At the end of 2015, a 40-year ban on exporting oil was lifted allowing the export of U.S. oil to be exported to foreign destinations and increasing liquid bulk activity in the U.S. Gulf Coast.
- For the Houston Ship Channel, tankers are the predominant vessel calling (80%) and tankers have high auxiliary boiler loads at berth while discharging. The high tanker boiler load at berth increased emissions, especially for NO_x and CO_2e emissions.
- The use of lower sulfur fuel (0.1% sulfur) to comply with the North American ECA in 2019 instead of the 1% sulfur fuel used in 2013 significantly lowered the PM and SO_x emissions. The reduction in NO_x emissions for OGV due to the fuel switch was only 6% and was outweighed by the tanker boiler emissions increase and overall increased activity.
- In 2019, there were 33 vessels with Tier III propulsion engines that called non-PHA entities, including 31 tankers, one bulk vessel and one articulated tug barge (ATB). NO_x emissions from Tier III vessels are 75% lower than from Tier II vessels when operating at or above 25% main engine load.
- For commercial harbor craft, the CO, SO_x and GHG emissions increased due to increased activity, but all other emissions are lower due to fleet turnover and newer engines in 2019 as compared to 2013. The NO_x and PM emissions decrease is due to fleet turnover to newer vessels and/or engines.

Comparison to Regional Emissions

Part of the scope of this study was to obtain and summarize the regional emissions inventory categories for air quality planning purposes. The emission estimates for the HGB region were compiled from 2019 emissions data provided by TCEQ for point source, area source, on-road and non-road mobile compiled from various data sources. Table 2.6 compares 2019 PHA emissions to the 2019 eight county regional emissions for Houston Galveston Brazoria (HGB) area. The PHA 2019 emissions are 6% of the total regional emissions.

Table ES.5: PHA Emissions Comparison to HGB Regional Emissions

	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons
2019 PHA	6,967	195	182	306	1,281	173
2019 8-County HGB	111,084	26,182	28,828	159,526	426,649	39,222
Percent of PHA-related	**6.3%**	**0.7%**	**0.6%**	**0.2%**	**0.3%**	**0.4%**

Compared to the 5.2% contribution of PHA NO_x emissions published in the 2013 report, the PHA-related NO_x emissions contribution (6.3%) for the region increased in 2019. The increase in PHA contribution to the region is mainly due to lower HGB emissions in 2019 than in past years due to stricter regulations for the regulated sources. Table ES.6 summarizes the contribution of PHA NO_x emissions by source category to the regional emissions provided by TCEQ for the eight-county HGB area in 2019 and for the 2013 report, the 2011 TCEQ HGB emissions. Commercial marine vessels, locomotives and trucks have higher NO_x contributions in 2019 than in 2013.

Table ES.6: Comparison of PHA NOx Contribution to HGB Regional Emissions

	2019 NO_x tpy	2019 NO_x %	2013 NO_x tpy	2013 NO_x %
CMV	4,616	4.2%	5,043	3.2%
CHE	370	0.3%	1,315	0.8%
Locomotive	587	0.5%	640	0.4%
HDDV	1,395	1.3%	1,147	0.7%
Total PHA	**6,967**	**6.3%**	**8,145**	**5.2%**
TCEQ HGB Total	**111,084**		**158,011**	

SECTION 1
INTRODUCTION

This section describes the rationale behind the 2019 Port Houston Goods Movement Emissions Inventory which includes maritime-related emissions associated with the eight public terminals owned, operated, managed or leased by the Port of Houston Authority (PHA), also known as Port Houston. Port Houston is part of the Greater Port of Houston area which is a 25-mile-long complex of nearly 200 private and public facilities centered along the 52-mile-long Houston Ship Channel. The Greater Port of Houston area (private and public facilities) achieved the number one ranking in total waterborne tonnage in the United States (U.S.) in 2019. The port complex is located within the Houston-Galveston-Brazoria (HGB) ozone nonattainment area, which consists of the eight Texas counties of Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties.

1.1 Reason for Study

Port Houston undertook this study to estimate maritime-related mobile source emissions that occurred in 2019 for the public terminals, and to compare those emissions to the 2013 Goods Movement Emissions Inventory. An emissions inventory is a very useful tool to quantify mass emissions and track emission changes over time from a variety of emission sources in a geographic area and to help prioritize those sources for potential emission reduction measures. The high-level comparison of 2019 emissions with 2013 emissions in Section 8 will assist the Port staff in understanding how the Port's continued growth and emission reduction strategies have affected maritime-related emissions and their relationship to emissions in the area as a whole.

The Houston Ship Channel and greater Houston area have experienced some of the highest growth rates in the country in recent years, both economically and by regional population. Energy production, the petrochemical industry, and growth in trade due to the 2015 repeal of crude oil export ban and higher U.S. consumerism have helped drive economic prosperity in the region.

The maritime-related emissions should be viewed in the context of being a part of the region's total air emissions. Other (non-maritime) categories that contribute to area emissions include point sources (refineries, manufacturing facilities, etc.); on-road mobile sources (e.g., cars, trucks, buses and motorcycles); non-road equipment (farming equipment, construction equipment, etc.); and area sources (open burning, auto body shops, etc.). To provide context, maritime-related emissions are compared to the regional emissions (see Section 2.3).

1.2 Scope of Study

The scope of the study is described in terms of the pollutants quantified, the year of operation used as the basis of emission estimates, the emission source categories that are included and excluded, and the geographical extent of activities included in the inventory.

1.2.1 Pollutants
Exhaust emissions of the following pollutants are estimated:

- Criteria pollutants, surrogates, and precursors
  - Oxides of nitrogen (NO_x)
  - Sulfur dioxide (SO_2)
  - Particulate matter (PM) (10-micron, 2.5-micron)
  - Volatile organic compounds (VOCs)
  - Carbon monoxide (CO)

- Greenhouse gases (GHGs)
  - Carbon dioxide (CO_2)
  - Methane (CH_4)
  - Nitrous oxide (N_2O)

Most maritime-related sources of GHG emissions involve fuel combustion, thus the combustion-related emissions of CO_2, CH_4, and N_2O are included in this inventory. Because each greenhouse gas differs in its effect on the atmosphere, estimates of greenhouse gas emissions are presented in units of carbon dioxide equivalents, which weight each gas by its global warming potential (GWP) value. To normalize these values into a single greenhouse gas value, CO_2e, the GHG emission estimates are multiplied by the following GWP values[2] and summed: 1 for CO_2, 25 for CH_4 and 298 for N_2O. The resulting CO_2e emissions are presented in tonnes (metric tons) throughout the report, whereas all other annual emissions are presented as tons (short tons).

1.2.2 Temporal Extent
The activity year for this study is calendar year 2019. To the extent practicable, the emission estimates are based on activities that occurred during this period. If information specific to 2019 was not available, reasonable estimates of operational characteristics were developed. These cases are identified in the text for each source category.

1.2.3 Emission Source Categories
This study includes the following emission source categories:

- Ocean-going vessels
- Commercial harbor craft
- Cargo handling equipment
- Locomotives
- Heavy-duty vehicles

[2] *EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017, April 2015.*

1.3 Geographical Domain

The following PHA facilities located in Harris County and shown in Figure 1.1 are included for all emission source categories.

- Bayport
- Barbours Cut
- Jacintoport
- Care Terminal
- Bulk Materials Handling Plant
- Woodhouse
- Sims Bayou
- Manchester Wharves
- Southside Wharves
- Industrial Park East
- Turning Basin

Figure 1.1: PHA Facilities

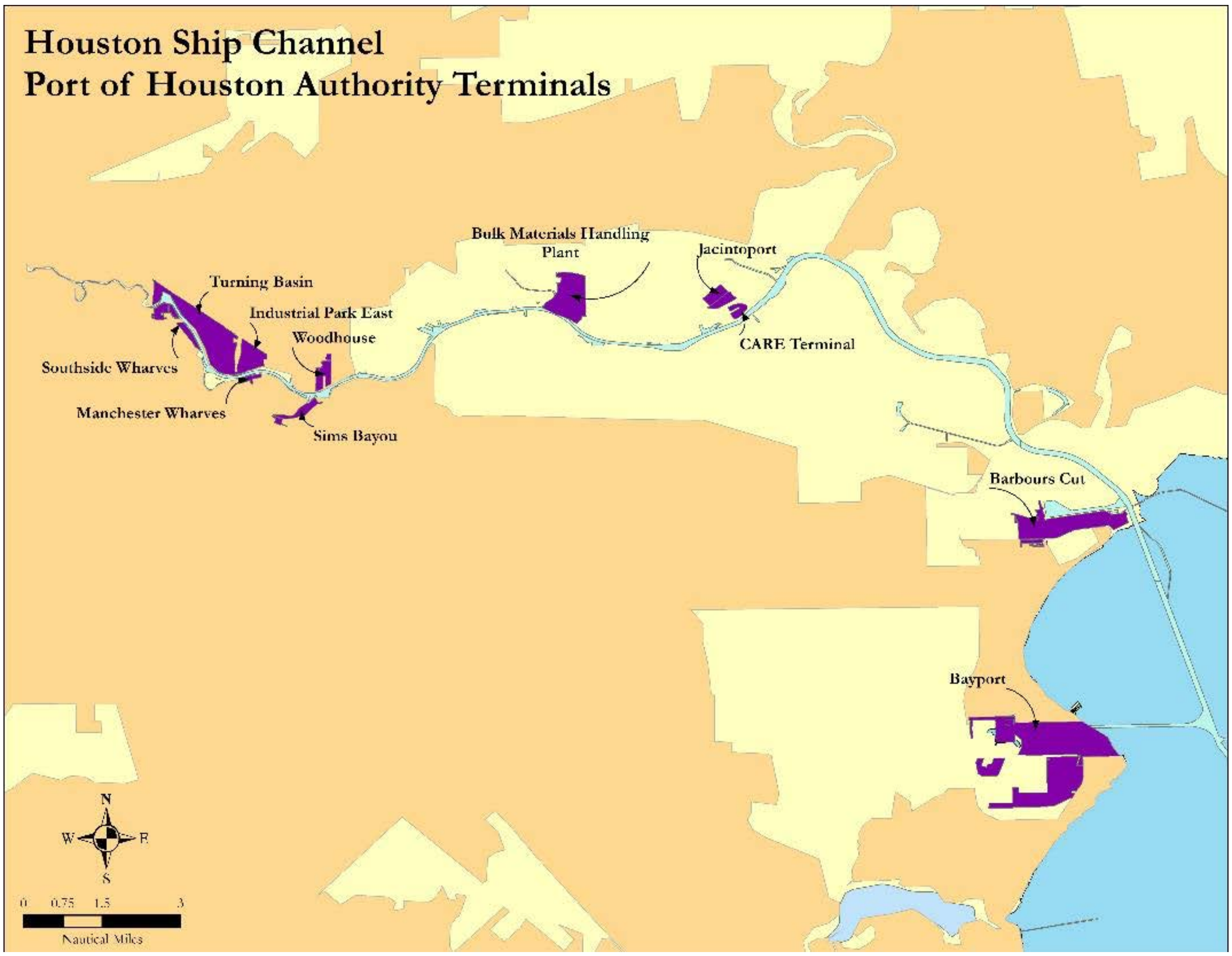
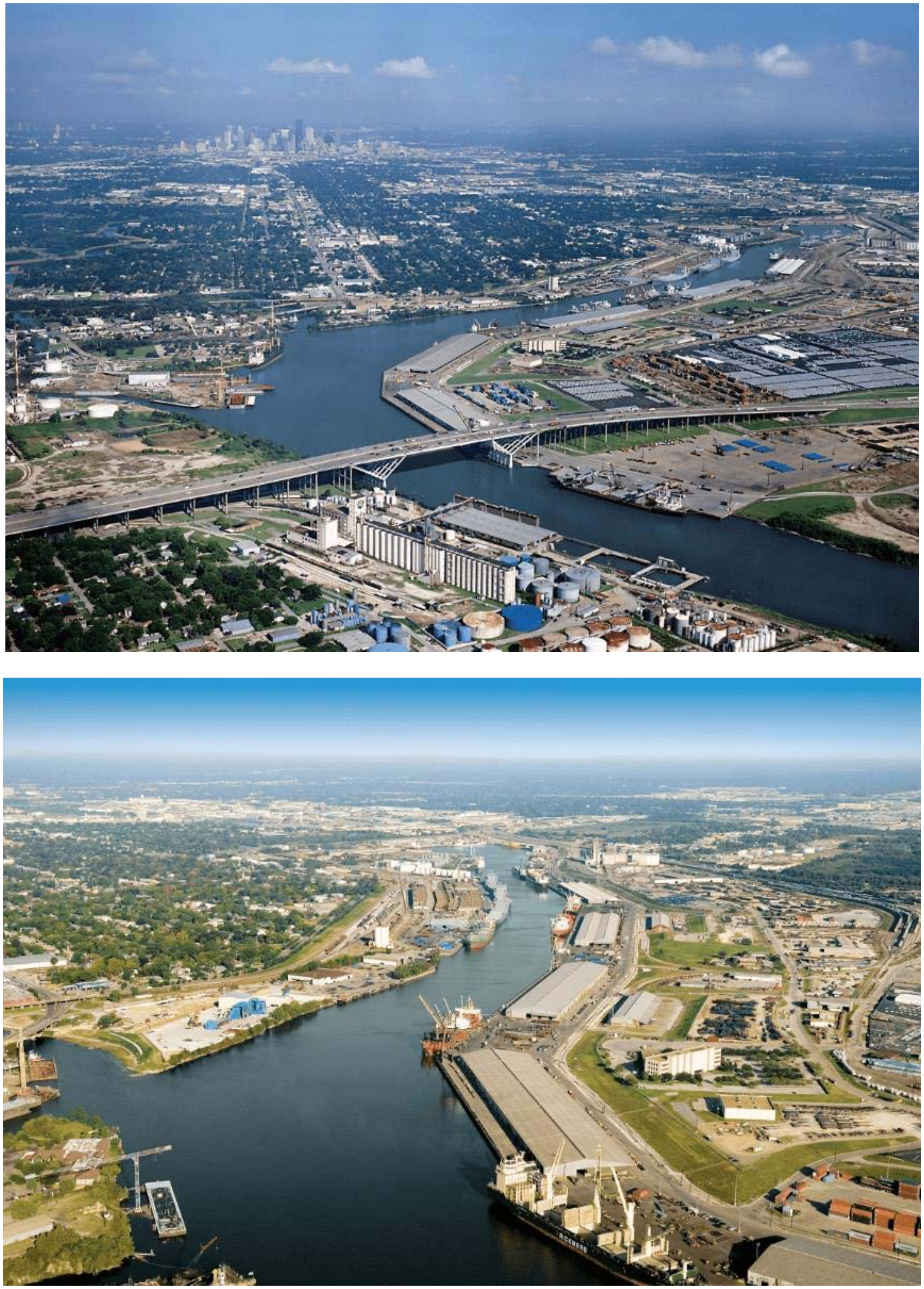


Figure 1.2: Aerial Photos of the Houston Ship Channel

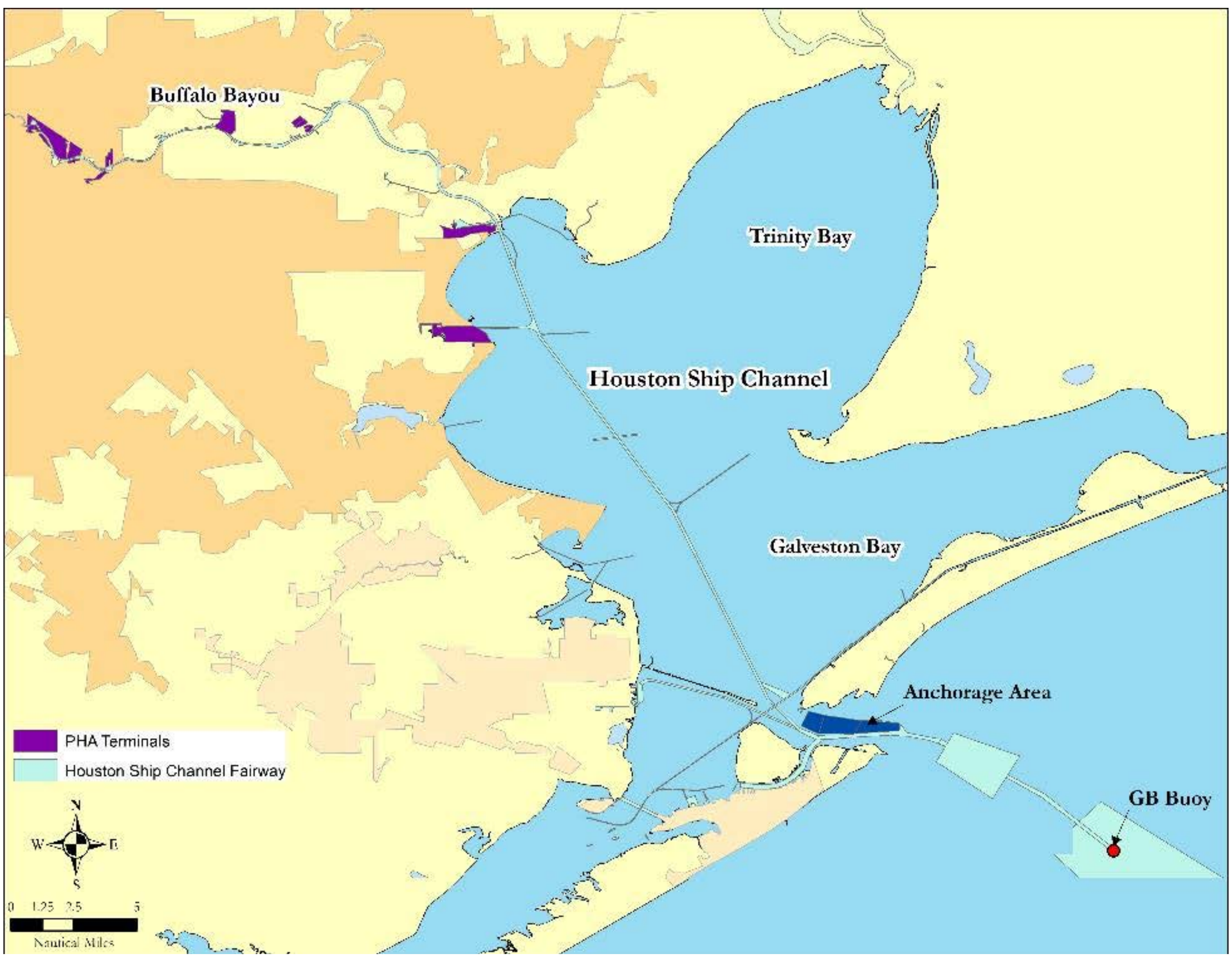


The 2019 GMEI includes the following geographical domains for each source category:

- Ocean-going vessels (OGV) – activity associated with PHA properties and the Houston Ship Channel.
- Harbor vessels - activity associated with PHA properties and the Houston Ship Channel.
- Cargo-handling Equipment (CHE) – activity on PHA properties.
- Railroad activity – yard and line haul operations associated with PHA freight movements within the HGB non-attainment area.
- On-road heavy-duty vehicles (HDV) – drayage and other goods movement operations for heavy-duty trucks that visit the PHA terminals and occur within the HGB non-attainment area.

The marine vessel geographical domain includes the extent of the Port of Houston Authority, in addition to the numerous private industrial companies along the Houston Ship Channel, and the maneuvering and transiting zones extend nine nautical miles (nm) off the coast at the outer sea buoy. Figure 1.3 illustrates the geographic domain for commercial marine vessels including ocean-going vessels and harbor vessels such as towboats/pushboats.

Figure 1.3: Marine Vessels Geographical Domain



SECTION 2
SUMMARY RESULTS AND COMPARISON

The emissions in this section are separated into two sections: PHA emissions for public terminals for five source categories and non-PHA emissions which include OGV and commercial harbor vessel emissions for the private facilities.

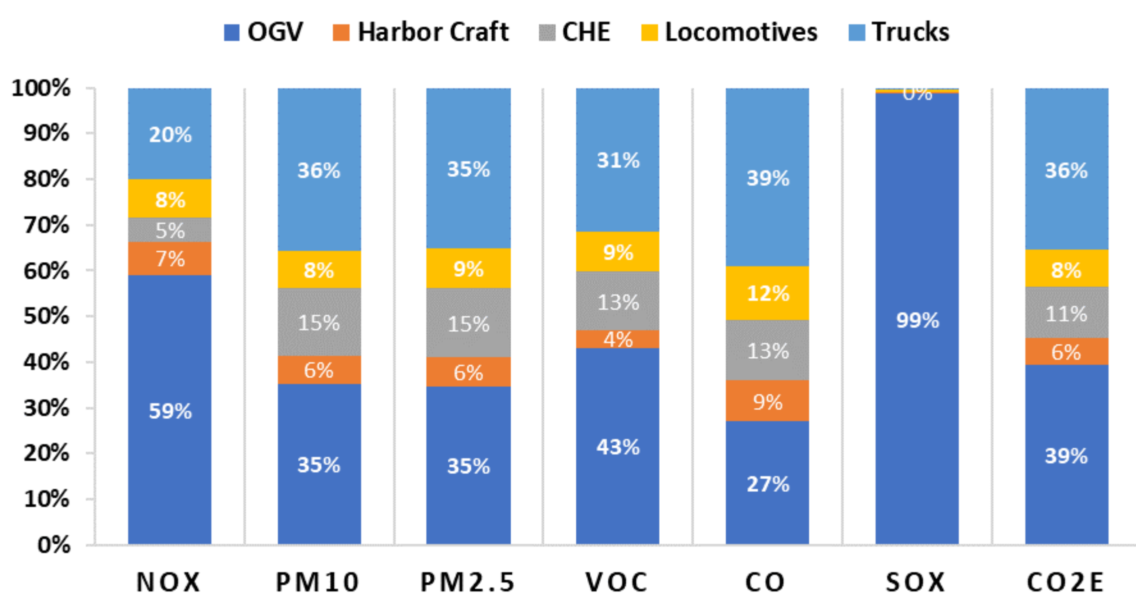
2.1 PHA Emissions

The 2019 emissions from maritime-related mobile sources associated with PHA are summarized in Table 2.1. As discussed in Section 1, the CO_2e emissions are presented in tonnes rather than short tons and have been calculated using the GWP values listed in Section 1. Figure 2.1 illustrates the distribution of PHA NO_x emissions by source category for activity associated with PHA properties only.

Table 2.1: 2019 PHA Maritime-related Emissions

	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
Ocean-going vessels	4,120	69	63	132	348	171.3	259,134
Commerical harbor vessels	496	12	12	12	113	0.4	39,805
Cargo handling equipment	370	29	28	39	169	0.3	72,121
Locomotives	587	16	16	27	153	0.6	53,329
Heavy-duty vehicles	1,395	70	64	96	498	0.9	233,867
Total	**6,967**	**195**	**182**	**306**	**1,281**	**173**	**658,256**

Figure 2.1: 2019 PHA Distribution of Emissions by Source Category, %



Between 2013 and 2019, PHA saw significant growth in cargo volume and moved up in port size rankings. During that period expansion projects were completed at Bayport and Barbours Cut Terminals, and new terminals commenced operations, such as the Bayport Auto Terminal. Cargo throughput, measured in tons, increased 8% while the container throughput, measured in TEU, increased 53% in 2019 as compared to 2013.

Table 2.2: PHA-associated Cargo Volume Comparison[3]

Year	Cargo (short tons)	Containers TEU
2019	48,240,858	2,990,175
2013	44,756,323	1,952,122
Change (%)	**8%**	**53%**

The 2013 vs 2019 PHA emissions comparison is summarized in Table 2.3. Despite the double digit increase in container throughput (53%), overall emissions are lower for all pollutants in 2019. The particulate matter (PM_{10} and $PM_{2.5}$) and SO_x emissions are significantly lower in 2019 due to the use of lower sulfur content fuel by ocean-going vessels in compliance with the North American Emission Control Area (ECA). The emissions comparison should be viewed at a high level as methodologies have changed since the 2013 emission estimates were published. To the extent it was feasible to do so, the methodology changes were factored into the 2013 PHA emissions shown in this report and therefore may not match the emissions listed in the original 2013 GMEI.

Table 2.3: 2013-2019 PHA Emissions Comparison

Year	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019	6,967	195	182	306	1,281	173	658,256
2013	8,145	511	477	472	1,666	2,666	833,215
Change	**-1,178**	**-316**	**-295**	**-167**	**-385**	**-2,492**	**-174,960**
Change (%)	**-14%**	**-62%**	**-62%**	**-35%**	**-23%**	**-93%**	**-21%**

[3] *Data source: Port of Houston Authority Monthly Cargo Statistical Summary December 2019 and December 2013, both Post Audit files provided by PHA.*

2.2 Non-PHA Emissions

In addition to the emissions associated with PHA properties, emissions were also estimated for ocean- going vessels and commercial harbor vessels that transited through the Houston Ship Channel and/or called on private facilities that are not related to PHA. The non-PHA emissions are listed in Table 2.4.

Table 2.4: 2019 Non-PHA emissions

	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
Ocean-going vessels	7,939	172	159	247	716	448	678,387
Commerical harbor vessels	3,816	88	85	93	847	3	302,443
Total	**11,755**	**261**	**244**	**340**	**1,563**	**451**	**980,831**

The OGV and commercial harbor vessels emissions for non-PHA entities in the Houston Ship Channel are included in Table 2.5. For non-PHA OGV emissions, the PM and SO_x emissions reductions are due to the use of lower sulfur fuel in 2019. The other pollutants increased in emissions due to increase in vessel activity. The harbor craft emissions are lower for most pollutants due to fleet turnover, while CO and CO_2e emissions increased due to a lack of lower emission standards for these particular pollutants and increased activity.

Table 2.5: 2013-2019 Non-PHA Emissions by Source Category

	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019							
Ocean-going vessels	7,939	172	159	247	716	448	678,387
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Commerical harbor vessels	4,138	93	90	106	755	3	285,602
Total	**8,192**	**381**	**354**	**278**	**1,164**	**2,589**	**674,195**
Change between 2013 and 2019 (percent)							
Ocean-going vessels	96%	-40%	-40%	44%	75%	-83%	75%
Commerical harbor craft	-8%	-6%	-5%	-13%	12%	5%	6%
Total	**44%**	**-32%**	**-31%**	**22%**	**34%**	**-83%**	**45%**

2.3 Comparison to Regional Emissions

Part of the scope of this study was to obtain and summarize the regional emissions inventory categories for air quality planning purposes. The emission estimates for the HGB region were compiled from 2019 emissions data provided by TCEQ for point source, area source, on-road and non-road mobile compiled from various data sources. Table 2.6 compares 2019 PHA emissions to the 2019 eight county regional emissions for Houston Galveston Brazoria (HGB) area. This regional comparison is different from the comparison included in the 2013 GMEI in that total PHA emissions are compared to total regional emissions to estimate PHA's contribution of emissions in the region.

Table 2.6: PHA Emissions Comparison to HGB Regional Emissions, tpy

	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons
2019 PHA	6,967	195	182	306	1,281	173
2019 8-County HGB	111,084	26,182	28,828	159,526	426,649	39,222
Percent of PHA-related	**6.3%**	**0.7%**	**0.6%**	**0.2%**	**0.3%**	**0.4%**

Compared to the 5.2% contribution of PHA NO_x emissions published in the 2013 report, the PHA-related NO_x emissions contribution (6.3%) for the region increased in 2019. The increase in PHA contribution to the region is mainly due to lower HGB emissions in 2019 than in past years due to stricter regulations for the regulated sources.

Table 2.7 summarizes the contribution of PHA NO_x emissions by source category to the regional emissions provided by TCEQ for the eight-county HGB area in 2019 and for the 2013 report, the 2011 TCEQ HGB emissions. Commercial marine vessels, locomotives and trucks have higher NO_x contributions in 2019 than in 2013. The Counties included in TECQ's regional emissions are Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery and Waller.

Table 2.7: Comparison of PHA NOx Contribution to HGB Regional Emissions

	2019 NO_x tpy	2019 NO_x %	2013 NO_x tpy	2013 NO_x %
CMV	4,616	4.2%	5,043	3.2%
CHE	370	0.3%	1,315	0.8%
Locomotive	587	0.5%	640	0.4%
HDDV	1,395	1.3%	1,147	0.7%
Total PHA	**6,967**	**6.3%**	**8,145**	**5.2%**
TCEQ HGB Total	**111,084**		**158,011**	

SECTION 3
OCEAN-GOING VESSELS

This section presents emissions estimates for the ocean-going vessels (OGV or vessels) source category is organized into the following subsections: source description (3.1), data and information acquisition (3.2), operational profiles (3.3), emissions estimation methodology (3.4), and OGV emission estimates (3.5).

3.1 Source Description

The OGV activity and emissions included in this section include 1) activity directly associated with PHA properties and 2) activity for the Houston Ship Channel that is not PHA-associated (non-PHA). The Bolivar anchorage area activity is included, with anchorage hoteling emissions apportioned between PHA and non-PHA depending on whether the vessel ultimately called a PHA facility or not. Also, the activity and maneuvering emissions for vessels that called the Port of Galveston and then called a PHA terminal were included with the PHA-associated activity and emissions.

The geographical domain includes the Houston Ship Channel, Galveston Bay, Trinity Bay, and Bolivar anchorage area and extends nine nautical miles (nm) from shore to the GB Buoy. Figure 3.1 illustrates the outer limit of the geographic domain on the ocean side for commercial marine vessels.

Figure 3.1: Geographic Domain

The following vessel types called the PHA in 2019:

- Auto carrier – vehicle carriers that can accommodate vehicles and large wheeled equipment.
- Bulk carrier – vessels with open holds to carry various bulk dry goods, such as grain, salt, sugar, petroleum coke, and other fine-grained commodities.
- Containership – vessels that carry standardized intermodal shipping containers on their decks and in their holds, and transport primarily retail goods.
- General cargo – vessels that are designed to carry a diverse range of cargo in their hold and on their decks, such as bulk metals, machinery, and palletized goods.
- Ocean-going tugboat (ATB) – includes articulated tug barges (ATB) only. These barges have a notch in their stern to enable a special tug to connect to the barge, creating one single vessel.
- Roll-on roll-off vessel (RoRo) – commonly known as RoRos, these vessels can accommodate vehicles and large wheeled equipment.
- Tanker –vessels that transport liquids in bulk, such as oil, chemicals, or other specialty goods such as molasses or asphalt. Tankers are classified based on their size.

Figure 3.2: Photo of Containership

Figure 3.3: Photo of General Cargo Vessel

Figure 3.4: Photo of Tanker

Table 3.1 presents the number of arrivals, departures, and shifts for the whole study area in 2019, including PHA and Houston Ship Channel (non-PHA) movements. A shift is a movement of a vessel from one berth to another within the port complex.

Table 3.1: Total Arrivals, Departures, and Shifts by Vessel Type

Category	Arrivals	Departures	Shifts	Total
Auto Carrier	98	98	3	199
Bulk	655	654	172	1,481
Bulk - Heavy Load	7	6	0	13
Bulk - Self Discharging	41	41	1	83
Container 1000	30	30	2	62
Container 2000	188	187	10	385
Container 3000	112	111	3	226
Container 4000	139	138	3	280
Container 5000	200	199	3	402
Container 6000	196	196	2	394
Container 7000	13	13	0	26
Container 8000	114	115	0	229
Container 9000	12	12	1	25
Container 13000	1	1	0	2
General Cargo	682	682	235	1,599
ATB	256	240	435	931
RoRo	14	15	0	29
Tanker - Chemical	2,584	2,571	2,613	7,768
Tanker - LPG	33	33	0	66
Tanker - Handysize	613	605	219	1,437
Tanker - Panamax	622	607	222	1,451
Tanker - Aframax	660	655	266	1,581
Tanker - Suezmax	114	113	37	264
Total	**7,384**	**7,322**	**4,227**	**18,933**

Table 3.2 presents the number of arrivals, departures, and shifts for vessels that called PHA terminals in 2019.

Table 3.2: PHA Arrivals, Departures, and Shifts by Vessel Type

Vessel Type	Arrivals	Departures	Shifts	Total
Auto Carrier	97	96	3	196
Bulk	373	268	58	699
Bulk - Heavy Load	7	6	0	13
Bulk - Self Discharging	1	24	0	25
Container 1000	30	30	2	62
Container 2000	187	179	10	376
Container 3000	112	110	3	225
Container 4000	139	137	3	279
Container 5000	200	189	3	392
Container 6000	196	196	2	394
Container 7000	13	13	0	26
Container 8000	114	114	0	228
Container 9000	12	12	1	25
Container 13000	1	1	0	2
General Cargo	279	300	83	662
ATB	4	2	1	7
RoRo	14	8	0	22
Tanker - Chemical	461	395	534	1,390
Tanker - LPG	30	30	0	60
Tanker - Handysize	102	81	30	213
Tanker - Panamax	51	47	4	102
Tanker - Aframax	51	51	8	110
Tanker - Suezmax	26	22	3	51
Total	**2,500**	**2,311**	**748**	**5,559**

Figures 3.5 and 3.6 show the percentage of calls by vessel type for PHA-associated vessels and for the Houston Ship Channel (non-PHA), respectively. Most of the calls to non-PHA terminals are predominantly tankers (80%), while the vessels that call PHA terminals are containerships (40%) and tankers (29%), with the balance being various other vessel types.

Figure 3.5: 2019 PHA Distribution of Calls by Vessel Type

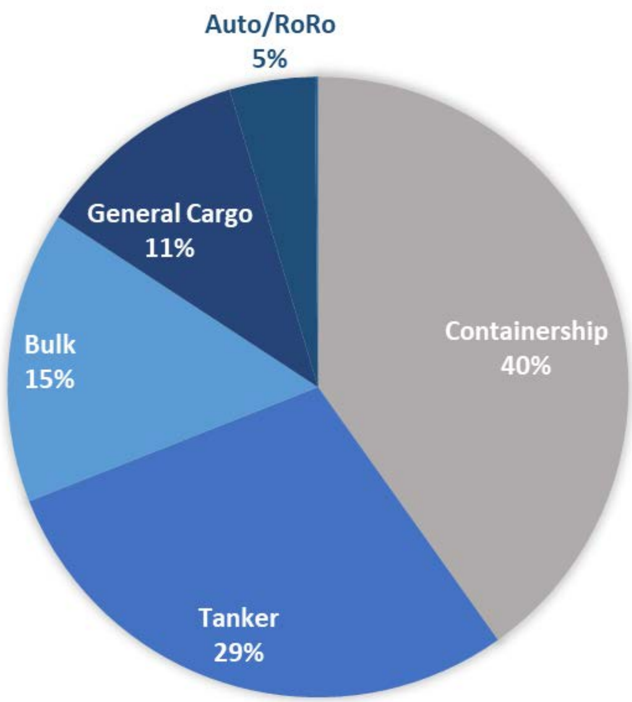
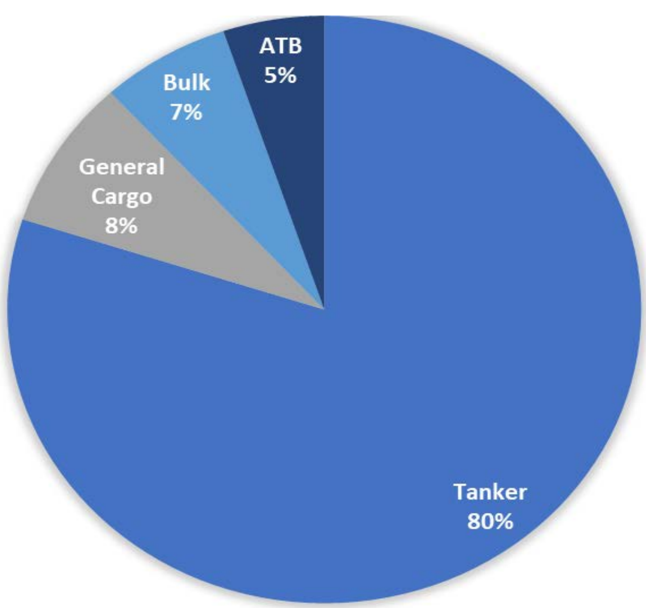


Figure 3.6: 2019 Houston Ship Channel (Non-PHA) Distribution of Calls by Vessel Type



3.2 Data and Information Acquisition

The OGV emission estimates presented in this report are primarily based on vessel activity data, vessel operational data, and vessel parameter data. Activity data sources include automatic information system (AIS) data. The AIS data was used for identifying vessels operating within the geographical domain and processed to determine discrete vessel activity parameters including speed over water and time in mode. This data was collected through the AIS receiver network administered by the U.S. Coast Guard (USCG) and compiled into files comprised of unique AIS records. AIS data points contain vessel specific geographical and temporal information including, but not limited to: International Maritime Organization (IMO) number, maritime mobile service identity (MMSI) number, geographic coordinates, speed over water, heading, date, and time. The AIS data was processed into vessel call activity through a combination of database processing and Geographic Information System (GIS) analysis. The processed AIS data provides vessel specific speed profiles and time spent operating in the approach and maneuvering zones, as well as hotelling time at a PHA terminal. Table 3.3 summarizes the hotelling times at berth for vessels that called PHA.

Table 3.3: PHA Hotelling Times at Berth, hours

Vessel Type	Min Hrs	Max Hrs	Avg Hrs	Vessel Count
Auto Carrier	3.8	76.9	22.6	27
Bulk	0.0	430.5	85.1	323
Bulk - Heavy Load	24.1	171.0	77.1	5
Bulk - Self Discharging	15.2	15.2	15.2	1
Container 1000	13.1	146.7	38.3	4
Container 2000	2.0	372.4	26.7	25
Container 3000	12.6	98.4	31.3	22
Container 4000	10.6	151.0	34.7	34
Container 5000	1.6	276.6	33.4	39
Container 6000	16.7	97.7	40.2	55
Container 7000	21.7	45.4	35.4	3
Container 8000	1.2	96.3	39.7	36
Container 9000	28.8	57.8	41.7	5
Container 13000	27.3	27.3	27.3	1
General Cargo	0.0	4,523.2	81.3	198
ATB	13.8	82.4	41.1	3
RoRo	27.8	140.0	78.0	6
Tanker - Chemical	0.0	304.3	46.8	328
Tanker - LPG	20.3	95.7	54.8	8
Tanker - Handysize	1.4	557.2	55.1	45
Tanker - Panamax	5.4	214.1	89.4	20
Tanker - Aframax	4.0	136.3	37.8	39
Tanker - Suezmax	0.0	254.3	52.1	15

Actual time at berth is used for each vessel and the times presented in Table 3.3 only show minimum, maximum and average. Each year, there may be one or two outliers in the data that show vessels staying longer than normal due to maintenance or other issues.

Vessel operational data includes auxiliary engine and boiler loads from the Starcrest Vessel Boarding Program (VBP) which includes data collected from ships engineers at various ports to determine auxiliary engine and boiler loads, by the various operational modes. If VBP data for the vessels was not available, appropriate defaults used for other ports EIs were used. The vessel specific parameter data is obtained under license from IHS Markit and includes vessel type, engine type, propulsion engine horsepower, keel laid date, and other parameters.

In 2019, there were a total of 37 vessels with Tier III propulsion engines that called PHA and non-PHA entities:

- 31 tankers, one bulk vessel and one ATB called non-PHA terminals.
- four tankers called PHA terminals.

NO_x emissions for Tier III vessels are 75% cleaner than Tier II vessels when operating above 25% main engine load. Table 3.4 presents the percent propulsion engine Tier by vessel type. It shows that 56% of the vessels had Tier I engines and 37% had Tier II engines.

Table 3.4: OGV Propulsion Engine Tier by Vessel Type, %

Vessel Type	Tier 0	Tier I	Tier II	Tier III
ATB	30%	51%	16%	2.7%
Auto Carrier/RoRo	13%	41%	46%	0.0%
Bulk	2%	50%	48%	0.1%
Containership	5%	83%	12%	0.0%
General Cargo	9%	70%	21%	0.0%
Tanker	6%	53%	40%	1.7%
Total	**6%**	**56%**	**37%**	**1.1%**

3.3 Operational Profiles

Emission estimates have been developed for the three combustion emission source types associated with marine vessels: main (or propulsion) engines, auxiliary engines, and, for OGVs, auxiliary boilers.
Fuel sulfur content plays an important role in marine vessel emissions. The 2019 emission estimates are calculated based on the assumption that vessels were operated using marine fuel with an average sulfur content (S) of 0.1% per IMO's requirement for the North American ECA. Based on the geographical domain and operational information, the following vessel operational modes define the characteristics of a vessel's operation within the emission inventory domain:

1. Maneuvering - Vessel movements inside the EI geographical boundary, after the vessel enters the EI geographic domain or before the vessel departs the EI geographical boundary. Additional power is typically brought online since the vessel is preparing to travel to or is traveling in restricted waters.
2. At-Berth - When a ship is stationary at the dock/berth/anchorage.
3. Shift - When a ship moves from one berth to another within the geographical boundary.

3.4 Emission Estimation Methodology

In general, emissions are estimated as a function of vessel energy demand expressed in kW-hr multiplied by an emission factor, where the emission factor is expressed in terms of grams per kilowatt-hour (g/kW-hr). Emission factors are adjusted for different fuel usage if the fuel used to develop the factors differs from the fuel that the vessel used. For the purposes of this report, no fuel correction factors were utilized. Emission factor adjustments for different propulsion engine load (see section 3.4.5), or emissions controls (see section 3.4.10) are also accounted when estimating OGV emissions.

Equations 3.1 and 3.2 are the basic equations used in estimating emissions by mode.
Equation 3.1

$$\mathbf{E_i = Energy_i \times EF \times FCF \times CF}$$

Where:

E_i = Emissions by mode
$Energy_i$ = Energy demand by mode, calculated using Equation 3.2 below as the energy output of the engine(s) or boiler(s) over the period of time, kW-hr
EF = Emission Factor, expressed in terms of g/kW-hr
FCF = Fuel Correction Factor(s) are used in the equation if the fuel used to develop the EF is different than the actual fuel used, dimensionless
CF = Control Factor(s) are used to adjust baseline emissions for emission reduction technologies, dimensionless

The ‘Energy’ term of the equation is where most of the location-specific information is used. Energy by mode is calculated using Equation 3.2:
Equation 3.2

$$\mathbf{Energy_i = Load \times Act}$$

Where:
$Energy_i$ = Energy demand by mode, kW-hr
Load = maximum continuous rated Power (MCR) times load factor (LF) for propulsion engine power (kW); reported operational load of the auxiliary engine(s), by mode (kW); or reported operational load of the auxiliary boiler, by mode (kW)
Act = activity, hours

The emissions estimation methodology for propulsion engines can be found in subsections 3.4.1 to 3.4.6, for auxiliary engines subsections 3.4.7 and 3.4.8, and for auxiliary boilers subsection 3.4.9. Propulsion engines are also referred to as main engines. Incinerators are not included in the emissions estimates because interviews with the vessel operators and marine industry indicate that vessels do not use their incinerators while at-berth or near coastal waters.

3.4.1 Propulsion Engine Maximum Continuous Rated Power (MCR)

MCR power is defined as the manufacturer’s tested maximum engine power and is used to determine propulsion engine load by mode. The international convention is to document MCR in kilowatts, and it is the highest power available from a ship engine during average cargo and sea conditions. For this study, it is assumed that the ‘Power’ value in the IHS data is the best proxy for MCR power. For diesel-electric configured ships, MCR is the combined rated electric propulsion motor(s) rating, in kW for all diesel generators.

3.4.2 Propulsion Engine Load Factor

Load factor for propulsion engines is estimated using the ratio of actual speed compared to the ship’s maximum rated speed. Propulsion engine load factor is estimated using the Propeller Law, which shows that propulsion engine load, varies with the cube ratio of vessel speed and maximum rated speed. Therefore, propulsion engine load at a given speed is estimated using the following equation.

Equation 3.3

$$\mathbf{LF = (Speed_{Actual} \,/\, Speed_{Maximum})^3}$$

Where:
LF = load factor, dimensionless
$Speed_{Actual}$ = actual speed, knots
$Speed_{Maximum}$ = maximum speed, knots

For the purpose of estimating emissions, the load factor has been capped to 1.0 so that there are no calculated propulsion engine load factors greater than 100% (i.e., calculated load factors above 1.0 are assigned a load factor of 1.0).

OGVs traveling in confined channels, such as the Houston Ship Channel, encounter additional resistance known as the phenomenon of "squat". Discussions with pilots operating in similar waterways have approximated those vessels traveling at or above 5 knots in restricted waterways would need an additional average main engine load of 10% (squat factor). Therefore, Equation 3.4 was used in the maneuvering zone for vessels traveling at or greater than 5 knots.

Equation 3.4

$$\mathbf{LFx} = \mathbf{LF} + \mathbf{10\%}$$

Where:

LFx = calculated load factor for maneuvering zone in the channel at or greater than 5 knots
LF = load factor as calculated using Equation 3.3

3.4.3 Propulsion Engine Activity

Activity is measured in hours of operation within the geographical boundary. At-berth times are determined from the date and time stamps in the AIS data when a vessel is determined to be at a terminal. The maneuvering time within the geographical boundary is estimated using equation 3.5, which divides the segment distance traveled by ship at its over water speed.

Equation 3.5

$$\mathbf{Activity} = \mathbf{D/Speed_{Actual}}$$

Where:

Activity = activity, hours
D = distance, nautical miles
$Speed_{Actual}$ = actual ship speed, knots

Distance and actual speeds are derived from AIS data point locations and associated over the water speed.

3.4.4 Engine Emission Factors

IMO has established NO_x emission standards for marine diesel engines.[4] NO_x emission factors are based on the IMO Tier of the vessel engines, which is based on the keel laid data provided in the IHS data. For regulatory purposes, all diesel cycle fuel oil/marine distillate fueled engines are categorized as Tier 0 to Tier III as per the NO_x standards and by engine rated speed, in revolutions per minute or rpm, as listed below:

- Slow speed engines: less than 130 rpm
- Medium speed engines: between 130 and 2,000 rpm
- High speed engines: greater than or equal to 2,000 rpm

Emission factors for all engine types used in this study were obtained from equations or values included in EPA's document entitled "Port Emissions Inventory Guidance: Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions," dated September 2020[5]. For the remainder of this report this document will be referred to as EPA Ports EI Guidance document.

All vessels in 2019 were assumed to be compliant with the IMO North American ECA requirement to use 0.1% sulfur content fuel. Table 3.5 list the emission factors for propulsion engines using 0.1% sulfur.

[4] *www.dieselnet.com/standards/inter/imo.php*
[5] *www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance*

Table 3.5: OGV Emission Factors for Diesel Propulsion, Steam (Boiler) Propulsion and Gas Turbine Engines, g/kW-hr

Engine Category	Tier	Model Year Range	NO_x	PM_{10}	$PM_{2.5}$	HC	CO	SO_x	CO_2	N_2O	CH_4
Slow Speed Main	0	1999 and older	17.0	0.18	0.17	0.60	1.40	0.36	593	0.029	0.012
Slow Speed Main	I	2000 to 2010	16.0	0.18	0.17	0.60	1.40	0.36	593	0.029	0.012
Slow Speed Main	II	2011 to 2015	14.4	0.18	0.17	0.60	1.40	0.36	593	0.029	0.012
Slow Speed Main	III	2016 and newer	3.4	0.18	0.17	0.60	1.40	0.36	593	0.029	0.012
Medium Speed Main	0	1999 and older	13.2	0.19	0.17	0.50	1.10	0.40	657	0.029	0.012
Medium Speed Main	I	2000 to 2010	12.2	0.19	0.17	0.50	1.10	0.40	657	0.029	0.012
Medium Speed Main	II	2011 to 2015	10.5	0.19	0.17	0.50	1.10	0.40	657	0.029	0.012
Medium Speed Main	III	2016 and newer	2.6	0.19	0.17	0.50	1.10	0.40	657	0.029	0.012
Gas Turbine		All	5.7	0.01	0.01	0.10	0.20	0.59	962	0.075	0.002
Steamship Main		All	2.0	0.20	0.19	0.10	0.20	0.59	962	0.075	0.002

Evidence from engine manufacturers[6] and classification societies[7] suggests that Tier III propulsion engines will not meet Tier III emission standards when operating below 25% load because the exhaust heat does not reach the necessary temperature for selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) systems to effectively reduce emissions. As such, when Tier III main engines operated below 25% within the emissions inventory domain, the default Tier II NO_x emission factors were used in emission calculations.

Table 3.6 list the emission factors for auxiliary engines using 0.1% sulfur.

Table 3.6: Emission Factors for Auxiliary Engines using 0.1% S, g/kW-hr

Engine Category	Tier	Model Year Range	NO_x	PM_{10}	$PM_{2.5}$	HC	CO	SO_x	CO_2	N_2O	CH_4
Medium Auxiliary	0	1999 and older	13.8	0.19	0.17	0.40	1.10	0.42	696	0.029	0.008
Medium Auxiliary	I	2000 to 2010	12.2	0.19	0.17	0.40	1.10	0.42	696	0.029	0.008
Medium Auxiliary	II	2011 to 2015	10.5	0.19	0.17	0.40	1.10	0.42	696	0.029	0.008
Medium Speed Main	III	2016 and newer	2.6	0.19	0.17	0.40	1.10	0.42	696	0.029	0.008
High Auxiliary	0	1999 and older	10.9	0.19	0.17	0.40	0.90	0.42	696	0.029	0.008
High Auxiliary	I	2000 to 2010	9.8	0.19	0.17	0.40	0.90	0.42	696	0.029	0.008
High Auxiliary	II	2011 to 2015	7.7	0.19	0.17	0.40	0.90	0.42	696	0.029	0.008
High Auxiliary	III	2016 and newer	2.0	0.19	0.17	0.40	0.90	0.42	696	0.029	0.008

In addition to the auxiliary engines that are used to generate electricity for on-board uses, most OGVs have one or more boilers used for fuel heating and for producing hot water and steam. Table 3.7 shows the emission factors used for the auxiliary boilers.

[6] *MAN Diesel & Turbo, "Tier III Two-Stroke Technology."*
[7] *DNV-GL, "NO_x Tier III Update: Choices and challenges for on-time compliance," November 2017.*

Table 3.7: Emission Factors for OGV Auxiliary Boilers using 0.1% S, g/kW-hr

Engine Category	Model Year Range	NO_x	PM_{10}	$PM_{2.5}$	HC	CO	SO_x	CO_2	N_2O	CH_4
Auxiliary Boiler	All	2.0	0.20	0.19	0.10	0.20	0.59	962	0.075	0.002

3.4.5 Propulsion Engine Load Emission Factor Adjustments

Studies conducted by EPA and San Pedro Bay Ports (SPBP) have shown that slow speed main engine emissions vary by engine load. Based on these studies, pollutant specific load adjustment multipliers as a function of main engine load have been established and are used in conjunction with the base emission factors shown in Table 3.5 to estimate OGV emissions. Emissions test results of the SPBP study of engines produced by MAN also observed significant difference in magnitude from the base emission factors for HC and CO. Based on the SPBP study, in addition to load adjustment factors that are applied to all pollutants, emission factor adjustments (EFA) are applied to the base HC and CO emission factors of slow speed MAN engines. Please refer to Appendix A for the equations and tables that show the values used.

3.4.6 Auxiliary Engine Load Defaults

The IHS Markit database contains limited auxiliary engine installed power information and information on use by mode, because neither the IMO nor the classification societies require vessel owners to provide this information. The primary data source for the Ports' EI related auxiliary load data is the Starcrest VBP implemented at several ports. Under VBP, vessels are boarded during their visits to ports and information is collected for the vessel and sister vessels. Specifically, during VBP, interviews with the vessel engineer is conducted to obtain data on auxiliary engine and boiler loads at various modes. Actual VBP data by vessel type, by emissions source and by mode, if available, is used when estimating auxiliary engine emissions. If actual VBP data is not available, average auxiliary engine load defaults derived from VBP data for vessels calling the Port were used by vessel type and mode. If average auxiliary engine load defaults specific to the Port is not available, an average of the 2019 published defaults for the Port of Los Angeles[8] and Port of Long Beach[9] by vessel type and mode is used.

[8] *www.kentico.portoflosangeles.org/getmedia/4696ff1a-a441-4ee8-95ad-abe1d4cddf5e/2019_Air_Emissions_Inventory*
[9] *www.polb.com/environment/air#emissions-inventory*

Table 3.8 summarizes the auxiliary engine load defaults by mode used for this study by vessel subtype.

Table 3.8: Average Auxiliary Engine Load Defaults, kW

Vessel Type	Maneuvering	Berth Hotelling	Anchorage Hotelling
Auto Carrier	1,815	1,072	622
Bulk	749	180	253
Bulk - Heavy Load	949	211	253
Bulk - Self Discharging	807	179	305
Container 1000	1,652	575	1,000
Container 2000	2,144	1,003	977
Container 3000	2,293	584	621
Container 4000	1,958	1,200	1,108
Container 5000	2,267	1,110	1,000
Container 6000	2,504	985	1,515
Container 7000	2,694	946	942
Container 8000	2,763	934	1,000
Container 9000	2,700	900	1,020
Container 13000	3,027	1,274	1,120
General Cargo	1,297	816	180
ATB	205	101	78
RoRo	849	490	283
Tanker - Chemical	833	967	402
Tanker - LPG	750	500	500
Tanker - Handysize	768	605	560
Tanker - Panamax	801	679	379
Tanker - Aframax	559	894	400
Tanker - Suezmax	678	816	606

3.4.7 Auxiliary Boiler Load Defaults

Similar to auxiliary engine loads, the primary data source for the Ports' EI related auxiliary load data is VBP. If actual VBP data is not available, average auxiliary boiler engine load defaults derived from VBP data or an average of defaults for other ports by vessel type is used.[10] The auxiliary boiler load defaults in kilowatts used for each vessel type are presented in Table 3.9. Tankers have much higher auxiliary boiler usage rates than the other vessel types. Tankers' boilers produce steam for steam-powered liquid cargo pumps when discharging, steam powered inert gas fans, and to heat fuel for pumping. Less steam is needed when liquid cargo is being loaded. Berth hoteling loads shown in Table 3.9 represent tanker boiler load during discharging. Specific loading and discharging data were not available for the tankers for each call, but enough information[11] was found to apply a 60% loading and 40% discharging assumption for boiler loads. For tanker loading, except chemical tankers, a lower berth hoteling default (875 kW) was used for boiler load than what is listed in Table 3.9.

Articulated tug barges (ATBs) do not use boilers for pumping cargo; therefore, their boiler energy default is zero. Auxiliary boilers are not typically used when the main engine load is greater than 20% due to heat recovery systems that are used to produce steam while the ship is underway. If the main engine load is less than or equal to 20%, the maneuvering boiler load defaults are used.

Table 3.9: Auxiliary Boiler Load Defaults, kW

Vessel Type	Maneuvering	Berth Hotelling	Anchorage Hotelling
Auto Carrier	184	314	305
Bulk	94	125	125
Bulk - Heavy Load	94	125	125
Bulk - Self Discharging	103	132	132
Container 1000	213	273	270
Container 2000	283	357	354
Container 3000	319	412	408
Container 4000	320	410	406
Container 5000	390	469	465
Container 6000	532	620	618
Container 7000	432	554	549
Container 8000	423	542	537
Container 9000	672	862	853
Container 13000	332	569	554
General Cargo	175	224	224
ATB	0	0	0
RoRo	148	259	251
Tanker - Chemical	136	568	255
Tanker - LPG	200	1,000	200
Tanker - Handysize	144	2,586	144
Tanker - Panamax	351	3,421	451
Tanker - Aframax	184	5,837	410
Tanker - Suezmax	171	5,880	482

[10] See port references for auxiliary engine load defaults.
[11] US Army Corps of Engineers Waterborne Commerce Statistics Center (WCSC) is responsible for capturing information on vessels, tonnage, commodity, origin, and destination from vessel operating companies.

3.5 OGV Emission Estimates

Table 3.10 shows that containerships and tankers have the highest emissions for PHA while tankers have the highest emissions for the private Houston Ship Channel entities (non-PHA). It also shows that in general, PHA OGV emissions account for nearly a third of the total emissions, which is in line with the kilowatt-hours shown on Table 3.11.

Table 3.10: PHA and Non-PHA OGV Emissions of Criteria Pollutants by Vessel Type

Entity	Vessel Type	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	HC tons	CO tons	SO_x tons	CO_2e tonnes
PHA	Auto Carrier	112	1.5	1.3	3	9	4	5,467
PHA	Bulk	337	4.9	4.5	9	29	12	18,837
PHA	Containership	1,822	23.6	21.7	57	141	58	88,283
PHA	General Cargo	526	9.0	8.3	18	47	21	31,946
PHA	ATB	1	0.0	0.0	0	0	0	73
PHA	RoRo	16	0.3	0.3	1	2	1	1,055
PHA	Tanker	1,305	29.4	27.1	44	119	75	113,474
PHA		**4,120**	**69**	**63**	**132**	**348**	**171**	**259,134**
Non-PHA	Auto Carrier	1	0.0	0.0	0	0	0	40
Non-PHA	Bulk	341	5.0	4.6	9	30	13	19,175
Non-PHA	Containership	12	0.1	0.1	0	1	0	471
Non-PHA	General Cargo	655	11.4	10.5	22	59	27	40,656
Non-PHA	ATB	136	2.4	2.2	6	14	5	7,772
Non-PHA	RoRo	3	0.0	0.0	0	0	0	123
Non-PHA	Tanker	6,791	153.4	141.2	209	611	402	610,149
Non-PHA		**7,939**	**172**	**159**	**247**	**716**	**448**	**678,387**
Total		**12,059**	**241**	**222**	**379**	**1,064**	**619**	**937,521**
Percent PHA		**34%**	**29%**	**29%**	**35%**	**33%**	**28%**	**28%**
Percent Non-PHA		**66%**	**71%**	**71%**	**65%**	**67%**	**72%**	**72%**

Table 3.11: OGV Kilowatt-hours by Emission Source

Entity	Total kWh	Main Engine kWh	Aux Engine kWh	Boiler kWh
PHA	342,250,594	97,420,731	157,159,821	87,670,043
Non-PHA	846,684,005	183,474,366	318,285,544	344,924,096
Total	**1,188,934,600**	**280,895,097**	**475,445,365**	**432,594,139**
Percent PHA	**29%**	**35%**	**33%**	**20%**
Percent Non-PHA	**71%**	**65%**	**67%**	**80%**

Figures 3.7 and 3.8 show the distribution of NO_x emissions by vessel type for PHA-associated vessels and for the Houston Ship Channel (non-PHA), respectively. The distribution of NO_x emissions by vessel type follows the vessel call distribution closely.

Figure 3.7: 2019 PHA Distribution of NO_x Emissions by Vessel Type

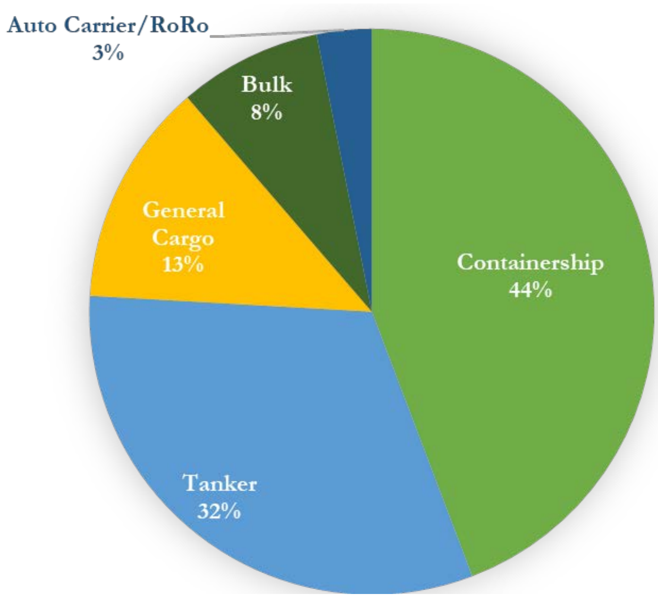


Figure 3.8: 2019 Houston Ship Channel Distribution of NO_x Emissions Vessel Type

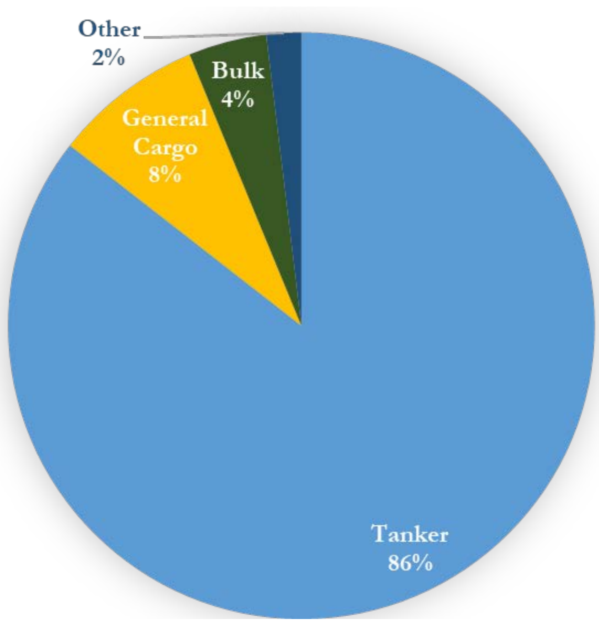


Table 3.12 presents the total PHA vessel emissions by terminal which shows that Bayport and Barbours Cut Terminals have the highest emissions. Figure 3.9 shows the distribution by terminal for NO_x emissions.

Table 3.12: PHA Total OGV Emissions by Terminal

Terminal	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	HC tons	CO tons	SO_x tons	CO_2e tonnes
Bayport Terminal	1,470	22.7	20.8	48.0	121.7	55.7	84,287
Barbours Cut Terminal	1,009	15.9	14.6	31.6	80.3	40.5	61,298
Turning Basin	562	9.7	8.9	18.3	49.9	23.6	35,703
Care Terminal	249	5.6	5.1	7.6	21.8	14.7	22,249
Jacintoport Terminal	177	2.8	2.6	6.0	15.5	6.5	9,825
Southside Wharves	167	3.6	3.3	5.7	15.3	9.0	13,594
Manchester Wharves	141	2.8	2.6	4.9	13.0	6.9	10,368
Woodhouse	130	2.1	1.9	3.7	11.4	5.2	7,821
Bulk Materials Handling	88	1.3	1.2	2.3	7.8	3.2	4,795
Sims Bayou	60	1.4	1.3	1.9	5.6	3.7	5,534
Industrial Park East	47	0.7	0.7	1.4	4.2	1.8	2,758
Other	18	0.2	0.2	0.5	1.5	0.6	902
Total	**4,120**	**68.7**	**63.2**	**131.9**	**348.0**	**171.3**	**259,134**

Figure 3.9: 2019 PHA Distribution of Total NO_x Emissions by Terminal

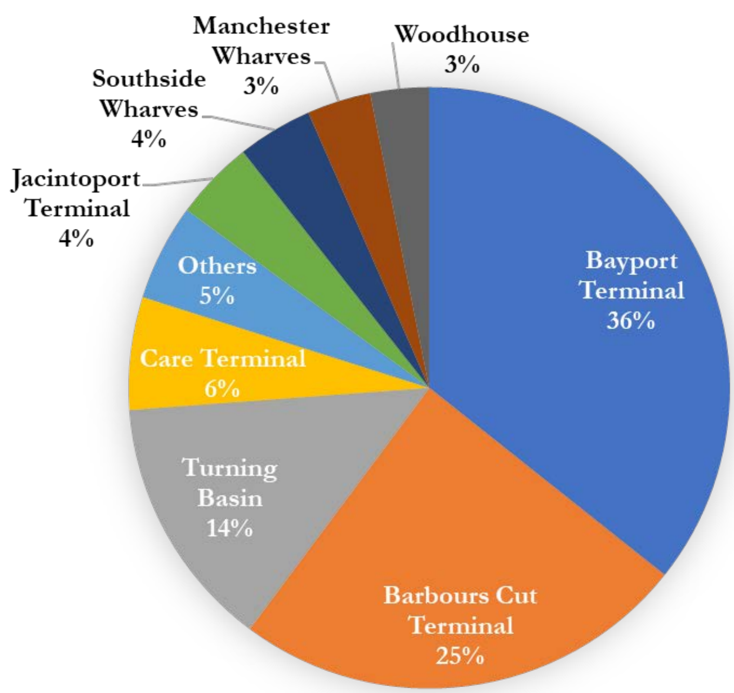
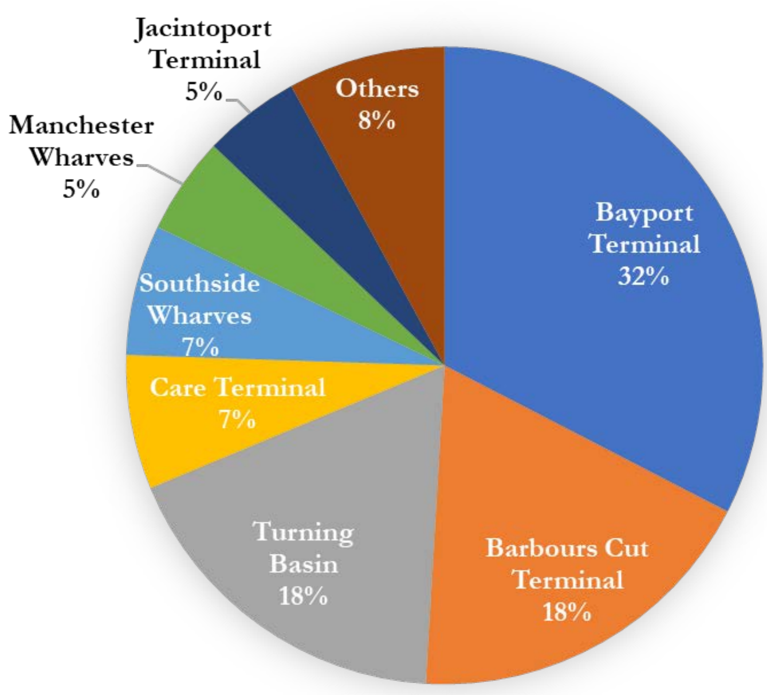


Table 3.13 presents the PHA at-berth vessel emissions by terminal which only includes the hotelling emissions. It excludes the maneuvering and transit emissions. Figure 3.10 shows the distribution with others including Woodhouse, Sims Bayou, Bulk Materials Terminals and Industrial Park East.

Table 3.13: PHA At-Berth OGV Emissions by Terminal

Terminal	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	HC tons	CO tons	SO_x tons	CO_2e tonnes
Bayport Terminal	570	13.1	12.1	19.7	52.3	32.9	49,810
Barbours Cut Terminal	321	9.1	8.4	11.8	30.7	23.5	35,572
Turning Basin	311	6.8	6.2	10.8	28.9	16.7	25,256
Care Terminal	119	4.2	3.8	4.4	11.1	11.1	16,924
Jacintoport Terminal	86	1.7	1.6	2.9	7.8	4.1	6,201
Southside Wharves	116	2.9	2.7	4.2	11.0	7.4	11,260
Manchester Wharves	86	2.0	1.9	3.1	8.1	5.1	7,709
Woodhouse	56	1.3	1.2	2.0	5.3	3.2	4,886
Bulk Materials Handling	29	0.6	0.6	1.0	2.6	1.6	2,426
Sims Bayou	33	1.1	1.0	1.3	3.3	2.9	4,398
Industrial Park East	22	0.5	0.4	0.8	2.1	1.1	1,725
Total	**1,749**	**43**	**40**	**62**	**163**	**110**	**166,168**

Figure 3.10: 2019 PHA Distribution of NO_x At-Berth Emissions by Terminal



SECTION 4
HARBOR VESSELS

This section presents emission estimates for the harbor vessels source category and is organized into the following subsections: source description (4.1), data and information acquisition (4.2), emissions estimation methodology (4.3), and commercial harbor craft emission estimates (4.4).

4.1 Source Description

Emissions from the following types of diesel-fueled commercial harbor craft were quantified:

- Crew and supply vessels – These supply vessels make numerous trips back and forth from a terminal or home berth to the offshore platforms.
- Harbor ferry and excursion vessels – the Sam Houston vessel is included in this category, along with other harbor vessels that move passengers.
- Government vessels – The government vessels include the pilot boats and workboats.
- Tugboats – The tugboats include vessels that assist and escort the ocean-going vessels calling at the Port, in addition to tugboats that do various types of work.
- Towboats – Towboats include self-propelled ocean tugs, pushboats, and towboats that tow/push barges, moving cargo such as bunker fuels and grains. Pushboats are similar to towboats, except as the name implies, they push barges rather than tow them. They can be used to move bulk liquids, scrap metal, bulk materials, rock, sand, and other materials.

Figure 4.1: Photo of Excursion Vessel

Figure 4.2: Photo of Towboat

4.2 Data and Information Acquisition

For towboats/push boats/tugboats, AIS data was used to identify activity (operating hours) in three zones by MMSI numbers. The zones are at berth, maneuvering, and in the transit (approach) zone.

- At berth - Hours in this zone were assumed for one auxiliary engine.
- Maneuvering - Hours in this zone were assumed for one auxiliary engine and two main engines.
- Transit - Hours in this zone were assumed for one auxiliary engine and two main engines.

IMO and MMSI numbers were joined with IHS and U.S. Waterways data to determine number of propulsion engines, model year and horsepower rating. The horsepower provided by U.S. Waterways is total propulsion horsepower for the vessel. Information on several vessels via various tow boat operators' websites was used to determine average number of main engines. Therefore, total propulsion horsepower was divided by known number of engines or averages estimated based on data. The auxiliary engine horsepower was not available through U.S. Waterways data. This information was obtained for several vessels via various towboat operator's websites and the average horsepower based on the collected data was used. The default for auxiliary engines power when unknown is 71 kW for this inventory.

Table 4.1 summarizes the average activity in hours, main engine kilowatt, and engine model year.

Table 4.1: 2019 Vessel Averages by Commercial Harbor Craft Type

Vessel Type	PHA Vessel Count	Average Berth Hours	Average Maneuvering Hours	Average Transit Hours	Average Total Hours	Propulsion Engine kW	Average Engine Year
Crew and supply	68	231	14	4	250	1,623	2009
Government	7	412	2	3	417	1,833	1992
Harbor Ferry	15	373	53	13	438	1,559	1997
Miscellaneous	123	323	36	17	376	935	2006
Pilot	5	737	101	439	1,277	745	2017
Towboat/Pushboat	149	131	34	2	167	992	1993
Tugboat	669	226	31	12	268	1,663	1995
Work Boat	4	329	8	0	337	280	1995

Table 4.2 summarizes the percent of main engine tiers by vessel type. The percentages are based on both actual data and defaults used as not all the CHC engine data was available, and defaults were used based on the known engine data available.

Table 4.2: 2019 Main Engine Tier by Commercial Harbor Craft Type

Vessel Type	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Crew and supply	3%	0%	91%	3%	3%
Ferry and excursion	93%	0%	7%	0%	0%
Gov/Pilot/Misc/Workboat	13%	76%	9%	1%	0%
Tugboat	91%	3%	6%	0%	0%
Towboat and pushboat	72%	2%	7%	2%	17%
Total	**63%**	**12%**	**13%**	**2%**	**11%**

4.3 Emission Estimation Methodology

The basic equation used to estimate harbor vessels emissions is:
Equation 4.1

$$\mathbf{E} = \mathbf{Power} \times \mathbf{Activity} \times \mathbf{LF} \times \mathbf{EF} \times \mathbf{Fuel\ Adjustment}$$

Where:

E = emissions, g/year
Power = rated power of the engine, hp or KW
Activity = engine operating hours, hours/year
LF = load factor (ratio of average load used during normal operations compared to full load at maximum rated horsepower), dimensionless
EF = emission factor, g/kW-hr
Fuel adjustment = EF is adjusted if the EF used is based on fuel that is different than the actual fuel used.

If available, vessel-specific rated horsepower of the engine and hours were used otherwise averages by vessel type as shown in Table 4.1 were used. The calculated emissions were converted to tons per year by dividing the emissions by 2,000 lb/ton x 453.59 g/lb. The emission factors units listed in the following emission factor tables are in grams per kilowatt-hour. These emissions factors were obtained from EPA's Ports EI Guidance Document.[12]

Fuel adjustment was applied to estimate NO_x emissions. Since the harbor craft emission factors are based on ULSD fuel and in 2019 all harbor craft in PHA and the non-PHA region complied with the Texas Low Emission Diesel (TxLED) Program which has lower aromatic content and a high cetane value, an NO_x reduction of 6.2% was applied.

The emission factors used for harbor craft are listed in Tables 4.3 and 4.4 for fueled propulsion and auxiliary engines, respectively.

Table 4.3: Harbor Craft Emission Factors for Propulsion Engines using ULSD, g/kW-hr

kW Range	Year Range	NO_x	PM_{10}	$PM_{2.5}$	VOC	CO	SO_x	CO_2	N_2O	CH_4
Tier 0 Engines										
37 < kW ≤ 600	≤2003	10.08	0.24	0.23	0.29	1.62	0.01	679	0.03	0.01
600 < kW ≤ 1000	≤2003	10.25	0.21	0.20	0.28	1.65	0.01	679	0.03	0.01
1000 < kW ≤ 1400	≤2003	10.45	0.22	0.21	0.27	1.71	0.01	679	0.03	0.01
1400 < kW ≤ 2000	≤2003	11.80	0.20	0.19	0.24	2.03	0.01	679	0.03	0.01
2000 < kW ≤ 3700	≤2003	13.36	0.21	0.20	0.14	2.48	0.01	679	0.03	0.01
2000 < kW ≤ 3700	2004-2006	10.55	0.21	0.20	0.14	2.48	0.01	679	0.03	0.01
3,701+	≤2003	13.36	0.21	0.20	0.14	2.48	0.01	679	0.03	0.01
3,701+	2004-2006	10.55	0.21	0.20	0.14	2.48	0.01	679	0.03	0.01
Tier 1 Engines										
37 < kW ≤ 600	2004-2006	6.50	0.13	0.12	0.23	1.17	0.01	679	0.03	0.01
600 < kW ≤ 1000	2004-2006	7.83	0.16	0.16	0.24	1.44	0.01	679	0.03	0.01
1000 < kW ≤ 1400	2004-2006	7.28	0.15	0.14	0.22	1.39	0.01	679	0.03	0.01
1400 < kW ≤ 2000	2004-2006	9.66	0.20	0.19	0.24	2.03	0.01	679	0.03	0.01
Tier 2 Engines										
37 < kW ≤ 600	2007-2012	6.06	0.12	0.12	0.22	1.10	0.01	679	0.03	0.01
600 < kW ≤ 1000	2007-2012	6.06	0.12	0.12	0.20	1.12	0.01	679	0.03	0.01
1000 < kW ≤ 1400	2007-2011	6.22	0.14	0.13	0.19	1.18	0.01	679	0.03	0.01
1400 < kW ≤ 2000	2007-2011	6.79	0.18	0.18	0.18	1.40	0.01	679	0.03	0.01
2000 < kW ≤ 3700	2007-2015	8.33	0.31	0.30	0.14	2.00	0.01	679	0.03	0.01
3,701+	2007-2015	8.33	0.31	0.30	0.14	2.00	0.01	679	0.03	0.01
Tier 3 Engines										
37 < kW ≤ 600	2013	5.67	0.11	0.10	0.18	1.10	0.01	679	0.03	0.01
37 < kW ≤ 600	2014-2021	4.69	0.07	0.07	0.11	1.10	0.01	679	0.03	0.01
600 < kW ≤ 1000	2013	5.30	0.09	0.09	0.15	1.12	0.01	679	0.03	0.01
600 < kW ≤ 1000	2014-2021	4.74	0.07	0.07	0.10	1.12	0.01	679	0.03	0.01
1000 < kW ≤ 1400	2013	5.66	0.10	0.10	0.16	1.18	0.01	679	0.03	0.01
1000 < kW ≤ 1400	2014-2016	4.83	0.07	0.07	0.10	1.18	0.01	679	0.03	0.01
1400 < kW ≤ 2000	2013	5.40	0.10	0.10	0.10	1.40	0.01	679	0.03	0.01
1400 < kW ≤ 2000	2014-2015	5.27	0.10	0.10	0.10	1.40	0.01	679	0.03	0.01
Tier 4 Engines										
600 < kW ≤ 1000	2017+	1.3	0.03	0.03	0.04	1.1	0.01	679	0.031	0.01
1000 < kW ≤ 1400	2017+	1.3	0.03	0.03	0.04	1.2	0.01	679	0.031	0.01
1400 < kW ≤ 2000	2016+	1.3	0.03	0.03	0.03	1.40	0.01	679	0.03	0.01
2000 < kW ≤ 3700	2016+	1.3	0.03	0.03	0.02	2.00	0.01	679	0.03	0.01
3,701+	2016+	1.3	0.03	0.03	0.02	2.00	0.01	679	0.03	0.01

[12] *www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance*

Table 4.4: Harbor Craft Emission Factors for Auxiliary Engines using ULSD, g/kW-hr

kW Range	Year Range	NO_x	PM_{10}	$PM_{2.5}$	VOC	CO	SO_x	CO_2	N_2O	CH_4
Tier 0 Engines										
37 < kW ≤ 600	≤2003	10.08	0.29	0.28	0.30	1.57	0.01	679	0.03	0.01
600 < kW ≤ 1000	≤2003	10.41	0.21	0.21	0.28	1.62	0.01	679	0.03	0.01
1000 < kW ≤ 1400	≤2003	10.95	0.19	0.19	0.28	1.78	0.01	679	0.03	0.01
1400 < kW ≤ 2000	≤2003	10.08	0.24	0.23	0.28	1.80	0.01	679	0.03	0.01
Tier 1 Engines										
37 < kW ≤ 600	2005-2006	6.10	0.16	0.15	0.26	0.96	0.01	679	0.03	0.01
600 < kW ≤ 1000	2004-2006	7.62	0.17	0.16	0.25	1.32	0.01	679	0.03	0.01
1000 < kW ≤ 1400	2004-2006	9.19	0.19	0.19	0.28	1.78	0.01	679	0.03	0.01
1400 < kW ≤ 2000	2004-2006	9.20	0.19	0.18	0.28	1.80	0.01	679	0.03	0.01
Tier 2 Engines										
37 < kW ≤ 600	2007-2012	5.96	0.15	0.15	0.25	0.93	0.01	679	0.03	0.01
600 < kW ≤ 1000	2007-2011	6.10	0.14	0.13	0.22	0.90	0.01	679	0.03	0.01
1000 < kW ≤ 1400	2007-2011	6.10	0.14	0.13	0.22	0.90	0.01	679	0.03	0.01
1400 < kW ≤ 2000	2007-2011	6.10	0.14	0.13	0.22	0.90	0.01	679	0.03	0.01
Tier 3 Engines										
37 < kW ≤ 600	2013+	4.58	0.08	0.08	0.13	0.93	0.01	679	0.03	0.01
600 < kW ≤ 1000	2014-2017	4.82	0.08	0.08	0.12	0.90	0.01	679	0.03	0.01
1000 < kW ≤ 1400	2013-2015	4.88	0.08	0.08	0.12	0.90	0.01	679	0.03	0.01
Tier 4 Engines										
600 < kW ≤ 1000	2018+	1.30	0.03	0.03	0.04	0.90	0.01	679	0.03	0.01
1000 < kW ≤ 1400	2017+	1.30	0.03	0.03	0.04	0.90	0.01	679	0.03	0.01
1400 < kW ≤ 2000	2016+	1.30	0.03	0.03	0.04	0.90	0.01	679	0.03	0.01

Engine load factors represent the average load of an engine or the percentage of rated engine power that is used during the engine's normal operation. Table 4.5 summarizes the average engine load factors that were used in this inventory for the harbor craft vessel types for their propulsion and auxiliary engines. The load factors are consistent with the latest EPA Ports EI Guidance document.

Table 4.5: Commercial Harbor Craft Load Factors

Harbor Craft Type	Propulsion Engine	Auxiliary Engine
Crew and supply	0.45	0.43
Ferry and excursion	0.42	0.43
Government	0.45	0.43
Pilot boat	0.51	0.43
Tugboat	0.50	0.43
Towboat and pushboat	0.68	0.43
Work boat	0.45	0.43

4.4 Commercial Harbor Craft Emission Estimates

Table 4.6 presents the PHA and non-PHA emissions for commercial harbor craft by vessel type. Tugboats and towboats have the highest emissions compared to other vessel types due to quantity and time spent in the area. Table 4.7 presents the PHA emissions by terminal for harbor craft.

Table 4.6: PHA and Non-PHA Commercial Harbor Craft Emissions

Entity	Vessel Type	NO_x	PM_{10}	$PM_{2.5}$	VOC	CO	SO_x	CO_2e
		tons	tons	tons	tons	tons	tons	tonnes
PHA	Crew and supply	5	0.1	0.1	0.2	1.0	0.0	463
PHA	Ferry and excursion	3	0.1	0.1	0.1	0.6	0.0	314
PHA	Gov/Pilot/Misc/Workboat	2	0.1	0.1	0.1	0.4	0.0	206
PHA	Tugboat	275	6.8	6.6	6.4	64.3	0.2	22,503
PHA	Towboat and pushboat	211	4.9	4.7	5.0	46.8	0.2	16,319
PHA		**496**	**11.9**	**11.6**	**11.8**	**113.1**	**0.4**	**39,805**
Non-PHA	Crew and supply	81	2.3	2.2	2.4	18.4	0.1	8,256
Non-PHA	Ferry and excursion	34	0.6	0.6	0.8	6.1	0.0	1,946
Non-PHA	Gov/Pilot/Misc/Workboat	210	5.2	5.0	7.6	48.1	0.2	22,540
Non-PHA	Tugboat	2,099	47.9	46.5	48.6	472.0	1.6	163,582
Non-PHA	Towboat and pushboat	1,392	32.1	31.1	33.5	302.4	1.1	106,120
Non-PHA		**3,816**	**88.1**	**85.4**	**92.9**	**847.0**	**3.0**	**302,443**
Total		**4,312**	**100**	**97**	**105**	**960**	**3**	**342,249**
Percent PHA		**12%**	**12%**	**12%**	**11%**	**12%**	**12%**	**12%**

Table 4.7: PHA Commercial Harbor Craft Emissions by Terminal

Terminal	NO_x	PM_{10}	$PM_{2.5}$	VOC	CO	SO_x	CO_2e
	tons	tons	tons	tons	tons	tons	tonnes
Bayport Terminal	127	3	3	3	29	0	10,163
Barbours Cut Terminal	103	2	2	2	24	0	8,218
Turning Basin	90	2	2	2	20	0	7,161
CARE Terminal	43	1	1	1	10	0	3,406
Woodhouse	24	1	1	1	6	0	1,951
Manchester Wharves	23	1	1	1	5	0	1,841
Jacintoport Terminal	20	0	0	0	5	0	1,595
Southside Wharves	20	0	0	0	5	0	1,588
Bulk Materials Handling	19	0	0	0	4	0	1,491
Sims Bayou	9	0	0	0	2	0	754
Industrial Park East	8	0	0	0	2	0	653
Total	**486**	**12**	**11**	**11**	**111**	**0**	**38,822**

Figures 4.3 and 4.4 show the distribution of NO_x emissions by commercial harbor craft type for PHA- and for the Houston Ship Channel (non-PHA), respectively. Other includes ferry, excursion, crew and supply vessels, government, pilot, miscellaneous and workboats.

Figure 4.3: 2019 PHA Distribution of NO_x Emissions by Commercial Harbor Craft

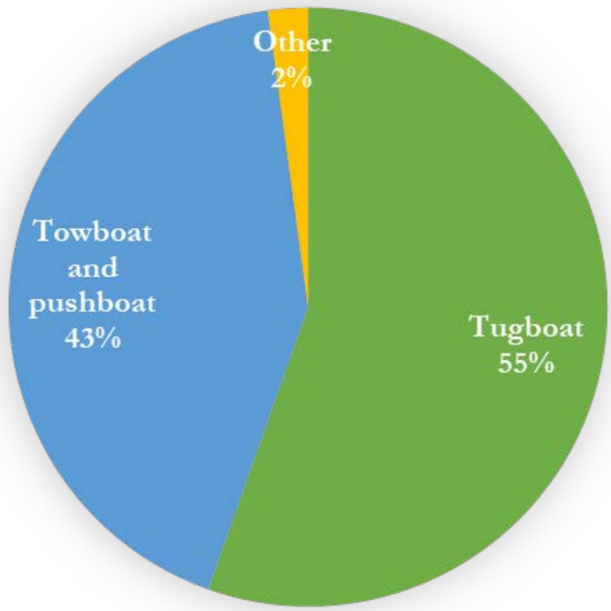
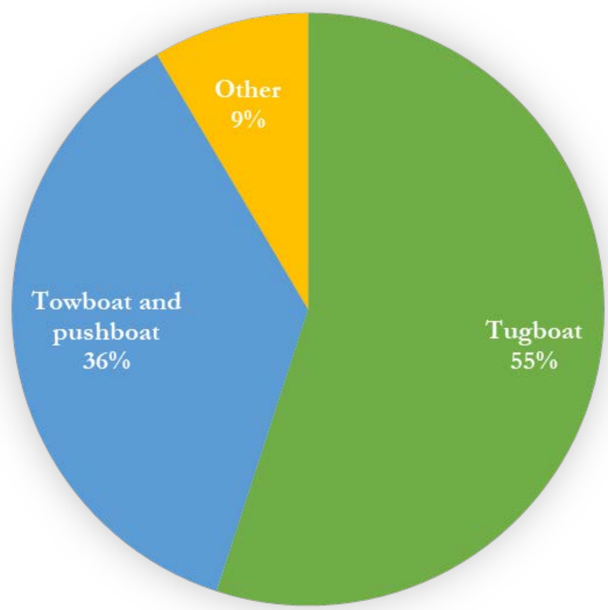
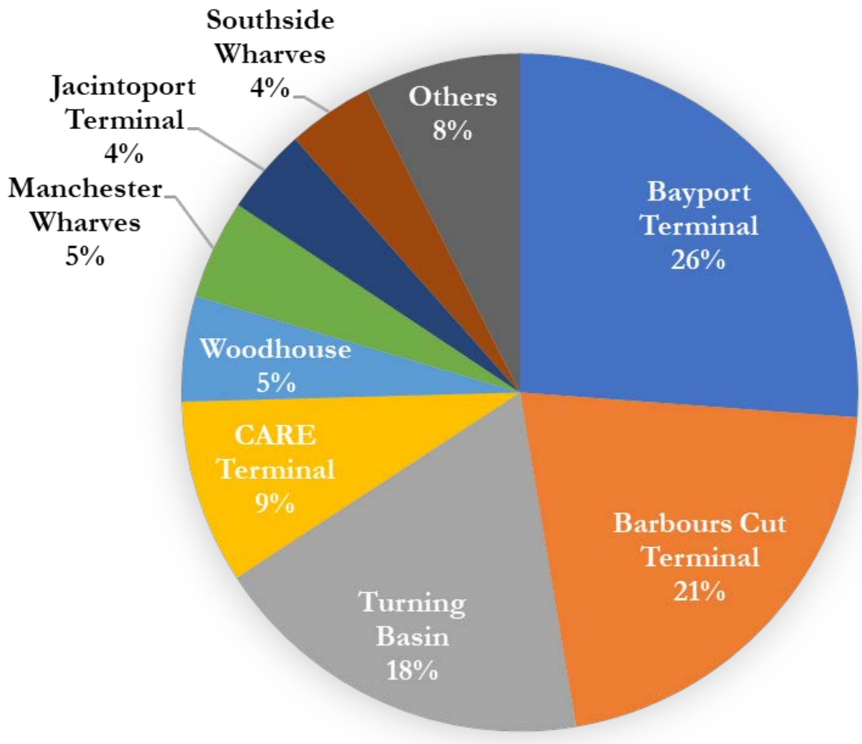


Figure 4.4: 2019 Houston Ship Channel Distribution of NO_x Emissions by Commercial Harbor Craft



Figures 4.5 shows the distribution of NO_x emissions by commercial harbor craft type for PHA terminals only. Others include Bulk Material Handling, Sims Bayou and Industrial Park.

Figure 4.5: 2019 PHA Commercial Harbor Craft Distribution of NO_x Emissions by Terminal



SECTION 5
CARGO HANDLING EQUIPMENT

This section presents emission estimates for the cargo handling equipment source category and is organized into the following subsections: source description (5.1), data and information acquisition (5.2), emissions estimation methodology (5.3), and the cargo handling equipment emission estimates (5.4).

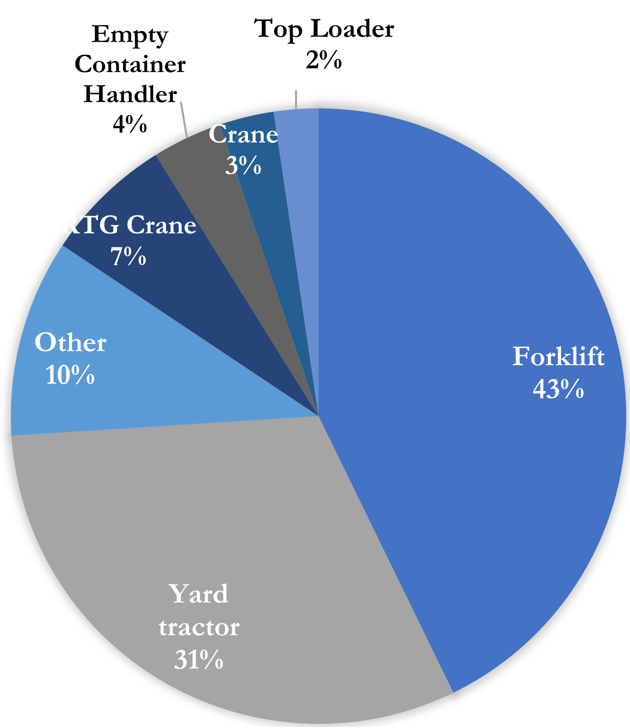
5.1 Source Description

Emissions from the following types of diesel-fueled cargo handling equipment (CHE) were quantified for PHA facilities only which include public facilities that operate tenant equipment and/or PHA owned equipment:

- Backhoe
- Crane
- Dozer
- Forklift
- Front end loader
- Generator
- Grader
- Light Tower
- Manlift
- Telehandler
- Tractor
- Top loader
- Yard tractor
- Reach stacker
- Railcar mover
- Skid steer loader
- Sweeper
- Truck
- Rubber tired gantry (RTG) crane
- Ship to shore (STS) cranes

Figure 5.1 presents the distribution of the 1,330 pieces of cargo handling equipment by type inventoried for PHA in 2019. Most of the equipment are forklifts (43%) and yard tractors (31%). Other equipment in Figure 5.1 includes: ship to shore cranes, manlift, tractor, reach stacker, sweeper, dozer, light tower, wheel loader, truck (fuel and water), excavator, front end loader, telehandler, railcar mover, backhoe, skid steer loader, generator, and grader.

Figure 5.1: 2019 Distribution of Cargo Handling Equipment by Type



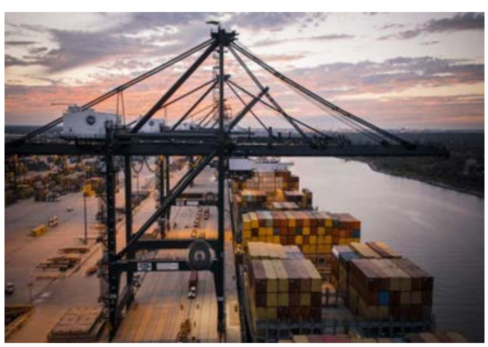
Figures 5.2-5.5 are photos of some of the equipment types that operate at the terminals.

Figure 5.2: Photo of Forklift

Figure 5.3: Photo of RTG Crane

Figure 5.4: Photo of Yard Tractor

Figure 5.5: Photo of Ship to Shore Crane (Wharf Crane)



5.2 Data and Information Acquisition

Table 5.1 summarizes the characteristics of the cargo handling equipment operating at PHA terminals in 2019, include PHA-owned and operated equipment and equipment owned by the tenants and stevedores. The terminals and stevedores provided their equipment fleet along with hours of use. Averages of the model year, horsepower, or operating hours are used as default values when equipment specific data is not available.

Table 5.1: 2019 Equipment Characteristics

Equipment	Count	Model Year Average	Horsepower Average	Annual Hours Average
Backhoe	3	2011	81	241
Crane	38	1988	213	574
Dozer	9	2011	460	1,207
Forklift	569	2005	108	367
Front End Loader	5	2007	112	409
Generator	1	2008	157	50
Grader	1	2008	176	100
Light Tower	9	2008	14	115
Manlift	13	2005	69	546
Sweeper	11	2010	69	72
Telehandler	5	2010	157	1,206
Top Loader	31	2005	261	1,775
Tractor	12	2014	44	77
Wheel Loader	9	2001	270	544
Yard tractor	415	2011	185	1,628
Truck	7	2003	370	383
STS Crane (electric)	27	na	na	na
Reach Stacker	12	2009	355	1,166
Railcar mover	5	2006	216	205
Excavator	6	2011	365	910
Empty Container Handler	49	2010	210	2,138
Skid Steer Loader	3	2019	77	478
RTG Crane	85	2008	682	3,232
RTG Crane (Hybrid)	5	2011	140	1,700
Total	**1,330**			

Figures 5.6 and 5.7 summarize the distribution of diesel cargo handling equipment's engines by off-road standards[13] (Tier 0, 1, 2, 3, 4 interim, and 4 final) based on model year and horsepower range. In addition to the diesel equipment, the inventory includes 27 propane forklifts and 29 electric wharf cranes. The unknown is for equipment that did not provide horsepower and/or model year. Once defaults were incorporated, the emissions were estimated accordingly.

[13] *EPA, Nonroad Compression-Ignition Engines- Exhaust Emission Standards, June 2004*

Figure 5.6: 2019 Diesel Equipment Tier Count Distribution

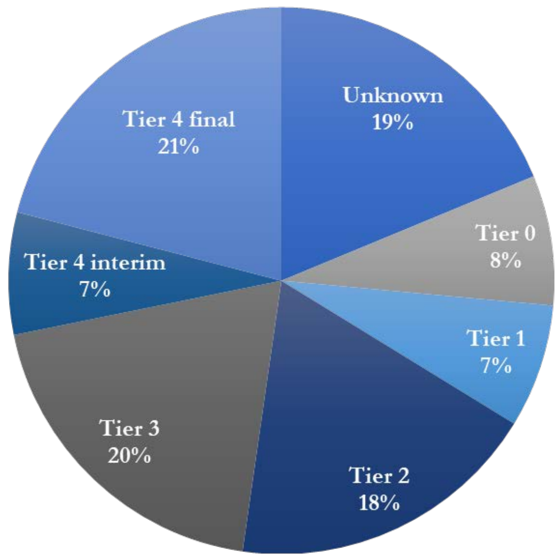
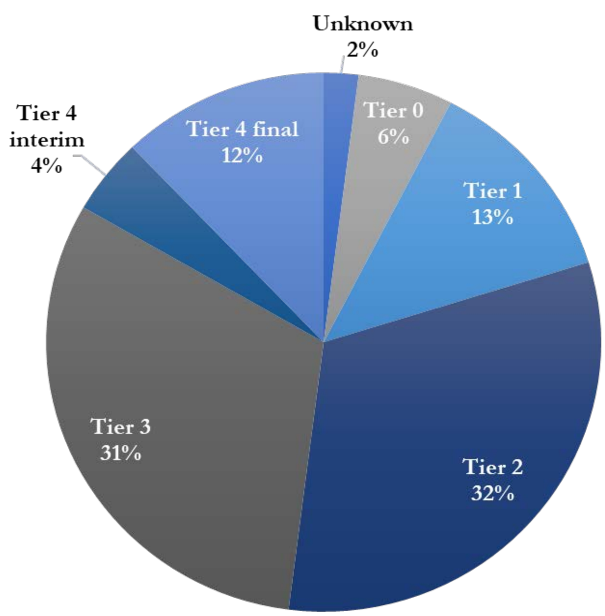


Figure 5.7: 2019 PHA-owned and Operated Diesel Equipment Tier Count Distribution



In 2019, for both the tenant and PHA-operated equipment (Figure 5.6), almost half of the diesel equipment had Tier 3 or Tier 4 engines, the newest and cleanest engines. For PHA-operated equipment only (Figure 5.7), 45% of the diesel equipment had Tier 3 or newer engines.

5.3 Emission Estimation Methodology

Emissions were estimated using the MOVES3 emission estimating model[14] which is designed to accommodate a wide range of off-road equipment types and recognize a defined list of equipment designations. The pieces of terminal equipment identified at the terminals were categorized into the most closely corresponding MOVES3 equipment type. Table 5.2 presents equipment types by Source Classification Code (SCC), load factor, and MOVES3/NONROAD category common name.

Table 5.2: MOVES/NONROAD Engine Source Categories

Equipment Type	SCC	Load Factor	NONROAD Category
Backhoe, loader	2270002066	0.21	Tractors/Loaders/Backhoes
Bulldozer	2270003040	0.43	General industrial equipment
Crane	2270002045	0.43	Cranes
Empty container handler	2270003040	0.43	General industrial equipment
Excavator	2270002036	0.59	Excavators
Forklift, diesel	2270003020	0.59	Forklifts
Manlift	2270003010	0.21	Aerial lifts
Rail pusher	2270003040	0.43	General industrial equipment
RTG cranes	2270003050	0.21	Other material handling equipment
Water and fuel truck	2270002051	0.59	Off-highway trucks
Portable light set	2270002027	0.43	Signal board / light plant
Skid-steer loader	2270002072	0.21	Skid-steer loader
Sweeper	2270003030	0.43	Sweeper / scrubber
Reach stacker	2270003040	0.43	General industrial equipment
Top handler	2270003040	0.43	General industrial equipment
Tractor	2270002075	0.59	Off-highway tractor
Yard tractor	2270003070	0.39	Terminal tractor

[14] *EPA MOVES, www.epa.gov/otaq/models/moves/*

The general form of the equation used for estimating CHE emissions is:

Equation 5.1

$$\mathbf{E = Power \times Activity \times LF \times EF \times CF \times Fuel\ Adjustment}$$

Where:

E = emissions, grams or tons/year
Power = rated power of the engine, hp or kW
Activity = equipment's engine activity, hr/year
LF = load factor (ratio of average load used during normal operations as compared to full load at maximum rated horsepower, it is an estimate of the average percentage of an engine's rated power output that is required to perform its operating tasks), dimensionless
EF = emission factor, grams of pollutant per unit of work, g/hp-hr or g/kW-hr
CF = control factor to reflect changes in emissions due to installation of emission reduction technologies or use of certified on-road engine instead of off-road engine not originally reflected in the emission factors.
Fuel Adjustment = Fuel Adjustments are used if the EF used is based on fuel that is different than the actual fuel used.

Equipment specific power and activity was obtained through surveys. Defaults were used if the power or activity information was missing. For each calendar year, the MOVES3 model has the option to output emission factors in grams/hp-hr by calendar year for each of the MOVES3 equipment types by horsepower groups and model year. The model year groups are aligned with EPA's nonroad equipment emissions standards. MOVES3 emission factors reflect the actual ULSD fuel used in 2019. The estimates of CHE emissions from each piece of equipment are based on its model year, horsepower rating, annual hours of operation, and equipment-specific load factor assumptions.

The load factors by NONROAD category as used by MOVES3 are listed in Table 5.2. Except for yard hustlers, load factors for all other equipment were obtained from MOVES3. For yard hustlers (also known as yard tractors), a load factor of 0.39 is used based on a 2008 study[15] prepared for the Port of Los Angeles and Port of Long Beach by Starcrest Consulting Group, LLC. This load factor is the most current and appropriate load factor representing diesel yard hustlers at ports. MOVES3 use a load factor of 0.59 for yard hustlers based on a 1997 study prepared for the EPA.[16]

MOVES3 was run for calendar year (CY) 2019 with default conditions to obtain emission factors in grams/hp-hr. A control factor was applied to equipment identified as being equipped with on-road engines. The MOVES3 EFs are based on ULSD fuel, the NO_x was adjusted to take into account the TxLED fuel (6% reduction).

[15] *Ports of Los Angeles and Long Beach, San Pedro Bay Ports Yard Tractor Load Factor Study, December 2008.*
[16] *EPA, Evaluation of Power Systems Research (PSR) Nonroad Population Data Base, 1997.*

5.4 Cargo Handling Equipment Emission Estimates

Tables 5.3 and 5.4 present the estimated cargo handling equipment emissions. Rubber tired gantry (RTG) cranes have the highest emissions, followed by yard tractors and forklifts.

Table 5.3: Total PHA Cargo Handling Equipment Emissions by Equipment Type

Equipment	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
RTG crane	142.6	9.1	8.8	14.8	80.0	0.1	24,972
Yard tractor	90.6	10.0	9.7	10.0	43.8	0.1	26,018
Forklift	58.6	5.6	5.5	9.0	26.0	0.0	7,394
Top Handler	24.2	1.3	1.2	1.8	6.8	0.0	3,414
Empty Container Handle	22.2	1.1	1.1	1.6	4.6	0.0	5,073
Crane	15.4	0.7	0.7	0.6	1.2	0.0	1,013
Reach Stacker	5.1	0.2	0.2	0.3	1.4	0.0	1,146
Bulldozer	3.7	0.1	0.1	0.2	0.9	0.0	1,325
Truck	2.6	0.2	0.2	0.4	1.5	0.0	257
Excavator	1.5	0.1	0.1	0.1	0.7	0.0	716
Loader	1.0	0.1	0.1	0.1	0.6	0.0	185
Manlift	0.7	0.1	0.1	0.2	0.8	0.0	78
Hybrid RTG	0.6	0.0	0.0	0.1	0.2	0.0	158
Telehandler	0.4	0.0	0.0	0.0	0.1	0.0	258
Rail Pusher	0.4	0.0	0.0	0.0	0.1	0.0	51
Sweeper	0.1	0.0	0.0	0.0	0.0	0.0	15
Tractor	0.1	0.0	0.0	0.0	0.0	0.0	10
Backhoe	0.0	0.0	0.0	0.0	0.0	0.0	9
Skid Steer Loader	0.0	0.0	0.0	0.0	0.0	0.0	17
Grader	0.0	0.0	0.0	0.0	0.0	0.0	6
Light Tower	0.0	0.0	0.0	0.0	0.0	0.0	4
Generator	0.0	0.0	0.0	0.0	0.0	0.0	2
Total	**370.0**	**28.8**	**27.9**	**39.2**	**168.9**	**0.3**	**72,121**

Figure 5.8 shows that 68% of the NO_x emissions are emitted by the older Tier 0-Tier 2 diesel engines.

Figure 5.8: 2019 PHA Diesel CHE NO_x Emissions by Tier

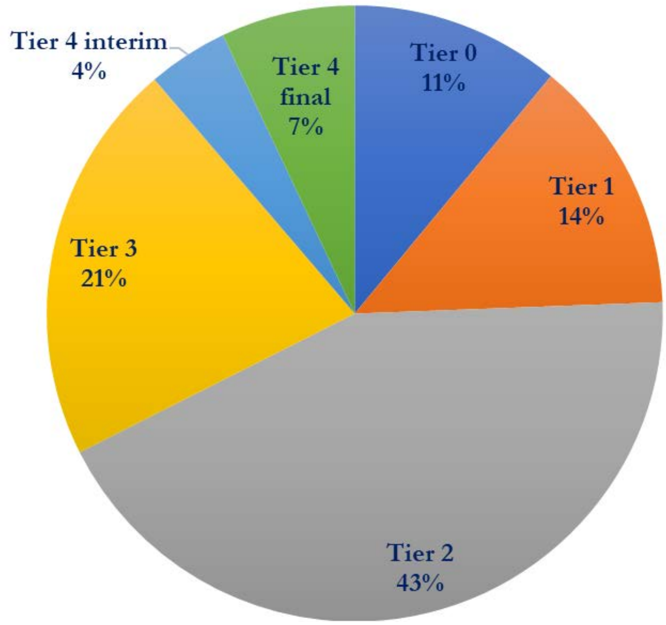


Figure 5.9 shows that 57% of the $PM_{2.5}$ emissions are emitted by the older Tier 0-Tier 2 diesel engines.

Figure 5.9: 2019 PHA Diesel CHE $PM_{2.5}$ Emissions by Tier

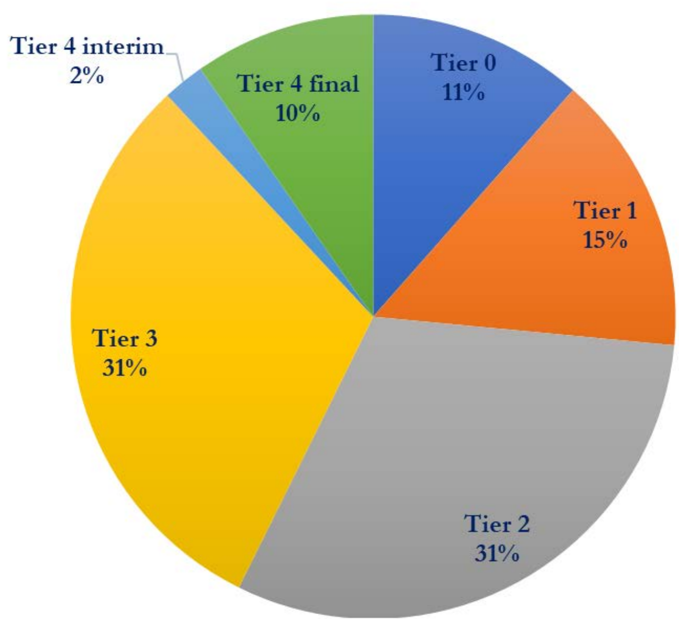


Table 5.4 presents the CHE emissions by terminal. In 2019, Barbours Cut and Bayport Terminals had the highest CHE emissions for total PHA. Care Terminal is not included since the stevedore/operator from 2019 is no longer there. Total CHE emissions may be underestimated by 2%. Care Terminal will be included in future inventories with the equipment from latest terminal operator.

Table 5.4: Total PHA Cargo Handling Equipment Emissions by Terminal

Terminal	Unit Count	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
Barbours Cut Terminal	399	168.0	12.5	12.2	17.3	85.6	0.1	26,669
Bayport Terminal	301	95.4	7.9	7.7	8.9	48.7	0.1	29,453
Turning Basin	379	60.4	5.1	5.0	9.0	19.1	0.0	6,970
Jacintoport Terminal	161	34.4	2.5	2.4	3.2	11.6	0.0	5,888
Bulk Materials Handling	27	5.1	0.2	0.2	0.3	1.6	0.0	1,902
Industrial Park East	35	4.7	0.4	0.4	0.4	1.8	0.0	630
Southside Wharves	4	0.8	0.0	0.0	0.1	0.2	0.0	107
Manchester Wharves	10	0.7	0.0	0.0	0.0	0.1	0.0	179
Sims Bayou	5	0.3	0.0	0.0	0.0	0.1	0.0	284
PTRA	9	0.2	0.0	0.0	0.0	0.0	0.0	39
Total	**1,330**	**370.0**	**28.8**	**27.9**	**39.2**	**168.9**	**0.3**	**72,121**

In 2019, roughly 42-59% percent of the emissions were from Port operated equipment although the equipment counts accounts for only 17%. This is due to equipment being used the most at the container terminals (see Table 5.1, higher hours are for RTG cranes, container handler, yard tractor and top loader). Table 5.5 provides the summary for PHA operated and tenant operated CHE, while Table 5.6 shows the port operated equipment emissions by terminal.

Table 5.5: Port Operated and Tenant Operated Cargo Handling Equipment Emissions

Association	Units	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
PHA Operated	229	182	12	12	19	100	0	30,284
PHA Tenant Operated	1,101	188	16	16	21	68	0	41,837
Total	**1,330**	**370**	**29**	**28**	**39**	**169**	**0**	**72,121**
PHA Operated %	**17%**	**49%**	**43%**	**43%**	**47%**	**59%**	**44%**	**42%**

Table 5.6: Port Operated Cargo Handling Equipment Emissions by Terminal

Terminal	Units	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
Barbours Cut -PHA operated	125	121.8	8.3	8.0	12.4	66.9	0.06	15,896
Bayport - PHA operated	96	60.5	4.2	4.0	6.2	33.5	0.05	14,347
Turning Basin - PHA operated	8	0.2	0.0	0.0	0.0	0.1	0.00	41
Total	**229**	**182.4**	**12.5**	**12.1**	**18.6**	**100.5**	**0.12**	**30,284**

SECTION 6
RAILROAD LOCOMOTIVES

This section presents emission estimates for the railroad locomotives emission source category and is organized into the following subsections: emission source description (6.1), data and information acquisition (6.2), emissions estimation methodology (6.3), and the locomotive emission estimates (6.4).

6.1 Source Description

Locomotive operations typically consist of line haul and switching or yard activity. Line haul refers to the movement of cargo over long distances (e.g., cross-country) and occurs within a port, marine terminal, or rail yard as the initiation or termination of a line haul trip, as cargo is either picked up for transport to destinations across the country or is dropped off for shipment overseas. Switching generally refers to the assembling and disassembling of trains, sorting of the railcars of inbound cargo trains into contiguous "fragments" for delivery to recipients and the short distance hauling of rail cargo within a port or rail yard.

Locomotives used for line haul operations are typically powered by diesel engines of over 4,000 horsepower, while switching locomotive engines are smaller, typically producing 1,200 to 3,000 horsepower. Older line haul locomotives have often been converted to switch duty as newer line haul locomotives with more horsepower become available. Locomotive engines are operated in a series of discrete power steps called notches which range from positions one through eight. This differs from the finely adjustable throttle controls used in automobiles and most powered equipment. Many locomotives also have a setting called dynamic braking, which is a means of slowing the locomotive using the drive system.

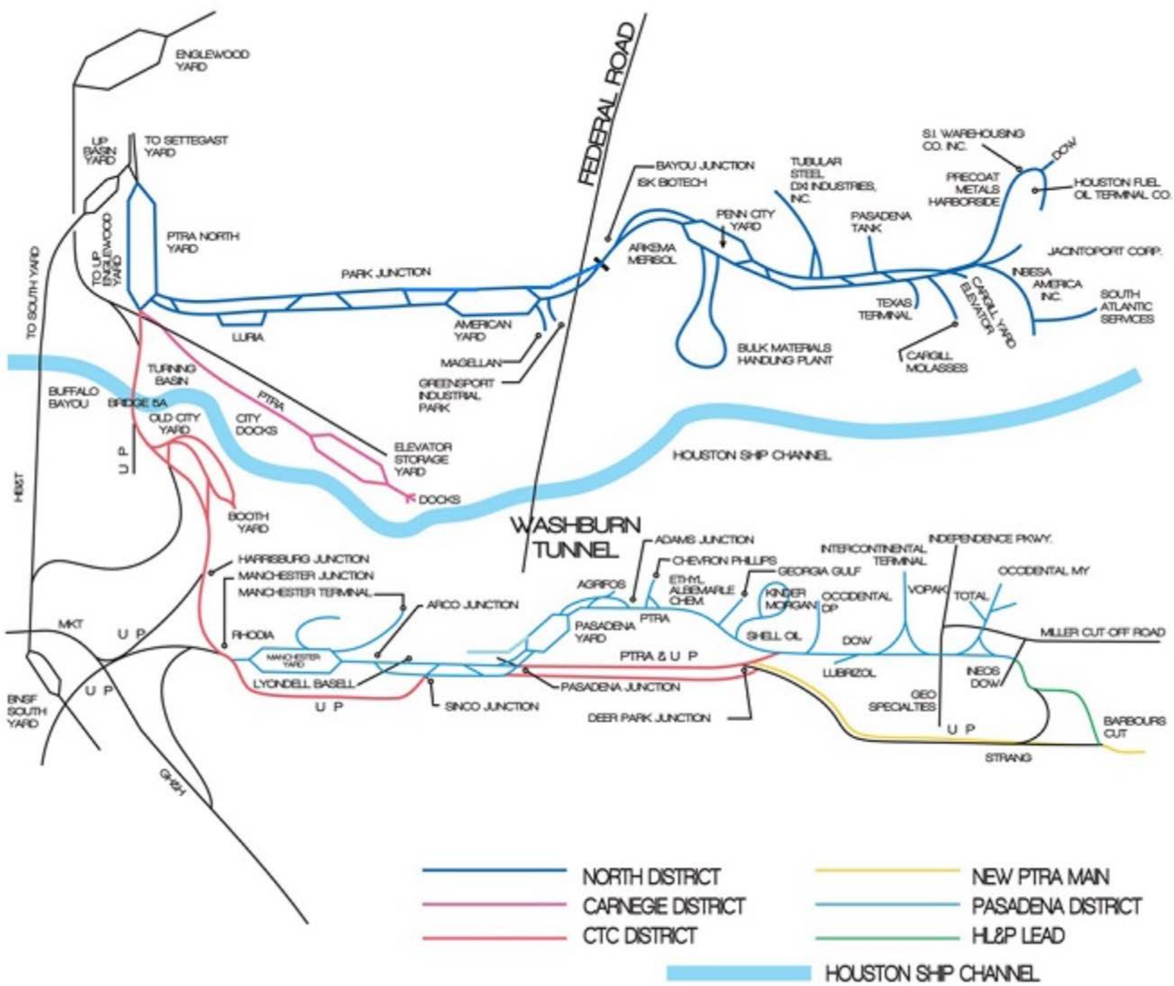
Locomotive operations included in this inventory are switching and rail yard activities of the Port Terminal Railroad Association (PTRA), and line haul activities of the Class 1 railroads Union Pacific (UP), Burlington Northern Santa Fe (BNSF), and Kansas City Southern (KCS) within the HGB nonattainment area counties.

Formed in 1924, PTRA is currently an association of the three Class 1 railroads listed above, the Port of Houston Authority, and Houston Belt & Terminal Railway Co. The association serves as an interchange between the many terminals and other facilities along the Houston Ship Channel and the Class 1 railroads that move cargo to other parts of the country. The railroad serves a total of 226 public and private customers along both sides of the Ship Channel, primarily moving railcars along a total of 154 miles of track between terminals and nearby rail yards where they are picked up by one of the Class 1 railroads for further transport. They also perform storage and switching services at seven rail yards in the vicinity.[17] In 2019 PTRA moved almost 600,000 railcars between terminals and interchange locations.[18]

[17] *www.ptra.com*
[18] *Information provided by PTRA in support of this study*

Figure 6.1 provides an illustration of the area and tracks served by PTRA.[17]

Figure 6.1: PTRA Area Map



The emissions inventory includes locomotive operations associated with Port-related cargo take place at many locations near the Port, including the following PTRA rail yards:

- North Yard – East of Wayside Drive between Market Street and Clinton Drive
- Storage Yard – south of Clinton Drive east of Wayside
- Penn City Yard – north side of the Houston Ship Channel south of Jacintoport Blvd. and west of the Beltway 8 Sam Houston Tollway
- Manchester Yard – intersection of the east loop of 610 and Manchester Street
- Pasadena Yard – east of the Washburn Tunnel, north of Red Bluff on the south side of the Houston Ship Channel.

In addition, Port terminals that have rail connections include the following:

- Bulk Materials Handling Plant – PTRA
- Care Terminal – PTRA
- Jacintoport – PTRA
- Public Elevator No. 2 – UP
- Turning Basin Northside – PTRA
- Jacob Stern & Sons – PTRA
- Empire Terminal – UP
- Old Manchester Terminal – BNSF, KCS, UP
- Sims Terminal – PTRA
- Richardson Steel Terminal – UP

The emissions inventory also includes line haul operations conducted by the Class 1 railroads arriving or departing a PTRA rail yard or Port terminal within the 8-county HGB area.

6.2 Data and Information Acquisition

PTRA provided information on 24 switching locomotives that operate at least some of the time on the PHA railyards. The information provided includes the model, year of manufacture, horsepower, and engine tier level of each locomotive. In addition, PTRA provided an estimate of the number of locomotives that typically operate on the PHA terminals, the daily and annual operating hours, and average fuel consumption rate of each locomotive. Three other facilities also provided information on a total of seven additional switching locomotives operated at their locations, including model, year of manufacture, horsepower, engine tier level, and annual hours of operation.

For line haul operations, PHA and PTRA provided throughput information in the form of total railcar counts for each line haul railroad and, separately, loaded railcar counts by commodity. In addition to this information, one of the Class 1 railroads provided detailed information on the movement of cargo within the eight-county nonattainment area. However, it is not possible to determine the Port-related component of this information, so it was not suitable for use in developing emission estimates.

Further information was obtained from annual reports submitted by the Class 1 railroads to the Surface Transportation Board, a Federal agency that oversees the nation's freight rail system.[19] These annual reports, known as R-1 reports, include operating information such as fuel consumption, train-miles of travel, and ton-miles of freight movements.[20] While not location-specific, the information can be used to develop operating profiles such as the average weights of trains, railcars, and locomotives, average fuel consumption per mile of travel, and average number of railcars per train. These profiles can be developed for each Class 1 railroad and as averages representing a group of railroads. Table 6.1 illustrates the information derived from the 2019 R-1 reports from UP, BNSF, and KCS.

[19] *www.prod.stb.gov/about-stb/*
[20] *www.prod.stb.gov/reports-data/economic-data/annual-report-financial-data/*

Table 6.1: Locomotive and Train Characteristics from 2019 R-1 Reports

Characteristic		UP		BNSF		KCS		Averages
Gross ton-miles per gallon of fuel		960	0	878	0	984	0	913
Gallons per thousand GTM		1.041	0.000	1.138	0.000	1.016	0.000	1.095
Gross tons per train	Unit Trains	9,919	0	9,712	0	8,262	0	9,715
	Way Trains	2,237	0	2,207	0	2,491	0	2,239
	Through Trains	6,891	0	5,948	0	7,177	0	6,404
	All trains	7,258	0	7,179	0	7,133	0	7,209
Locomotives per train	Unit Trains	3.2	0.0	3.4	0.0	2.8	0.0	3.3
	Way Trains	2.0	0.0	2.3	0.0	2.2	0.0	2.2
	Through Trains	3.1	0.0	3.3	0.0	2.5	0.0	3.2
	All trains	3.1	0.0	3.3	0.0	2.6	0.0	3.2
Gross tons per railcar	Unit Trains	83.7	0.0	90.2	0.0	91.5	0.0	88.2
	Way Trains	77.5	0.0	94.2	0.0	79.7	0.0	84.1
	Through Trains	88.9	0.0	108.6	0.0	82.1	0.0	97.3
	All trains	87.1	0.0	98.4	0.0	86.0	0.0	93.1
Average cars per train	Unit Trains	118.5	0.0	107.7	0.0	90.3	0.0	110.1
	Way Trains	28.9	0.0	23.4	0.0	31.3	0.0	26.6
	Through Trains	77.5	0.0	54.8	0.0	87.5	0.0	65.8
	All trains	83.4	0.0	72.9	0.0	82.9	0.0	77.4

6.3 Emission Estimation Methodology

The following provides a description of the methods used to estimate emissions from switching and line haul locomotives operating within the inventory area.

While EPA's MOVES3 model, as described in a preceding section, was used for estimating emissions from non-road equipment such as CHE, the model does not estimate emissions from locomotives. Therefore, estimates of emissions from switching and line haul locomotives are based on estimates of the horsepower-hours of work performed by locomotives operating in the inventory domain and on emission factors published by EPA.[21] The switching locomotive calculations estimate horsepower-hours worked by each locomotive based on fuel consumption in gallons per year, and combine the horsepower-hour estimates with emission factors in terms of grams of emissions per horsepower-hour (g/hp-hr). Fuel usage is converted to horsepower-hours using conversion factors that equate horsepower-hours to gallons of fuel (hp-hr/gal), which represent a property known as brake-specific fuel consumption (BSFC):

Equation 6.1

$$\textbf{Annual work in hphr per year} = \frac{\textbf{gallons}}{\textbf{year}} \times \frac{\textbf{hphr}}{\textbf{gallon}}$$

The calculation of emissions from horsepower-hours uses the following equation.

Equation 6.2

$$\mathbf{E} = \frac{\textbf{Annual work} \times \textbf{EF}}{(\mathbf{453.59\ g/lb \times 2,000\ lb/ton})}$$

Where:

E = emissions, tons per year
Annual work = annual work, hp-hrs/yr
EF = emission factor, grams pollutant per horsepower-hour
(453.59 g/lb x 2,000 lb/ton = tons per year conversion factor

The BSFC value used for the switching locomotive calculations was 15.2 hp-hr/gal, while the value used for the line haul locomotive calculations was 20.8 hp-hr/gal, both from the cited 2009 EPA document.

Table 6.2 summarizes the estimated fuel consumption and horsepower-hours attributed to the switching locomotives operated by PTRA and by three terminals that operate switching locomotives on a limited basis within their facilities. The locomotive operators reported annual operating hours and PTRA reported an average fuel consumption rate of 7 gallons per hour. Cumulative fuel consumption of locomotives in each tier level was calculated by multiplying the hours operated by the fuel consumption rate and horsepower-hours were calculated using equation 6.1 above.

Table 6.2: Estimated Switching Locomotive Hours, Fuel Consumption, & Horsepower-hours

Tier Level	Hours	Fuel gallons	Horsepower -hours
Pre-tier	7,700	53,900	819,280
Tier 0	40,970	286,790	4,359,208
Totals	**48,670**	**340,690**	**5,178,488**

[21] *EPA, Emission Factors for Locomotives, EPA-420-F-09-025, Office of Transportation and Air Quality, April 2009 and U.S. Inventory of Greenhouse Gas Emissions and Sinks: 1990-2019, April 2021.*

Table 6.3 presents an annual picture of locomotive and train activity based on the data from the Port and PTRA on railcar movements, the information derived from the R-1 reports presented above in Table 6.1, and the BSCF calculation presented in equation 6.1 above. The R-1 information includes fuel consumption rate in gallons per thousand gross ton-miles, average number of railcars and locomotives per train, and average weight of railcars and trains. These values allow calculation of total gross tons which, combined with the estimated distance traveled within the inventory domain, allow the estimation of total gross ton-miles. From this, fuel consumption and horsepower-hours are calculated.

Table 6.3: Estimated Line Haul Train Parameters, Fuel Consumption, & Horsepower-hours

Characteristic / Parameter	UP	BNSF	KCS	Avg / total
Miles in Area	77	79	78	78
Railcars	304,001	240,509	27,321	571,831
Trains	3,647	3,298	330	7,275
Locomotives	11,165	10,881	841	22,887
Gross tons, railcars	26,469,697	23,677,347	2,350,689	52,497,733
Gross tons, locomotives	2,344,737	2,284,909	176,579	4,806,226
Gross tons, totals	28,814,434	25,962,256	2,527,269	57,303,959
Gross ton-miles	2,218,711,433	2,051,018,220	197,126,973	4,466,856,626
gals /1,000 gross ton-mile	1.041	1.138	1.016	1.095
Gallons fuel	2,309,679	2,334,059	200,281	4,844,018
Horsepower-hours	**48,041,315**	**48,548,422**	**4,165,845**	**100,755,581**

The EPA emission factors for line haul locomotives cover particulate matter, NO_x, CO, and hydrocarbon (HC) emissions, published as g/gal factors and converted to g/hp-hr using the BSFC value for line haul noted above, while the emission factors for switching locomotives from the same source are published directly as g/hphr. SO_x emission factors have been developed to reflect the use of 15 ppm ULSD using a simplified mass balance approach. This approach assumes that all the sulfur in the fuel is converted to SO_2 and emitted during the combustion process. While the mass balance approach calculates SO_2 specifically, it is a reasonable approximation of SO_x. The following example shows the calculation of the SO_x emission factor for switching locomotives. The calculation for line haul locomotives is identical except for the use of the line haul BSFC value.

Equation 6.3

$$\frac{\mathbf{15\ g\ S}}{\mathbf{1,000,000\ g\ fuel}} \times \frac{\mathbf{3,200\ g\ fuel}}{\mathbf{gal\ fuel}} \times \frac{\mathbf{2\ g\ SO_2}}{\mathbf{g\ S}} \times \frac{\mathbf{gal\ fuel}}{\mathbf{15.2\ hp\ hr}} = \mathbf{0.006\ g\ SO_2/hphr}$$

In this calculation, 15 ppm S is written as 15 g S per million g of fuel. The value of 15.2 hp-hr/gallon of fuel is the average BSFC noted in EPA's technical literature on locomotive emission factors (EPA, 2009). Two grams of SO_2 is emitted for each gram of sulfur in the fuel because the atomic weight of sulfur is 32 while the molecular weight of SO_2 is 64, meaning that the mass of SO_2 is two times that of sulfur.

Greenhouse gas emission factors from EPA references[22] have been used to estimate emissions of the greenhouse gases CO_2, CH_4, and N_2O from locomotives. Additionally, all particulate matter emissions are assumed to be PM_{10}. $PM_{2.5}$ emissions have been estimated as 97% of PM_{10} emissions to be consistent with the $PM_{2.5}$ ratio used by MOVES in estimating $PM_{2.5}$ emissions from other types of nonroad engines.

[22] *EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019, April 2021.*

Table 6.4 lists the emission factors, as g/hphr, used in calculating line haul and switching emissions. The line haul emission factors are composites representing the nation-wide fleet of locomotives in 2019 as estimated by EPA. Because line haul locomotives operate over large parts of the country (for example, UP operates in 23 states) and individual locomotives are generally not dedicated to a particular area, the use of a wide area composite is appropriate for estimating emissions from locomotives that operated within the inventory domain. Railroads have historically been reluctant to provide detailed lists of locomotives operating in any particular area given their wide range of operations, so the EPA composites are the best readily available information.

The switching emission factors are listed by emission tier levels, which reflect the level of emission control based on the year of manufacture. The oldest locomotives, manufactured before 1973, are termed "uncontrolled" because no emission control standards were applied to them, while Tier 0 applies to locomotives manufactured between 1973 and 2001 with a basic level of emission control. These tier levels account for the switchers operated by PTRA and the other facilities operating switchers, although stricter standards will apply when these locomotives are rebuilt.

Table 6.4: Emission Factors for Locomotives, g/hp-hr

Activity / Tier Level	NO_x	VOC	CO	SO_2	PM_{10}	PM_{25}	CO_2	N_2O	CH_4
			g/hphr						
Line haul									
2019 composite	4.95	0.19	1.28	0.01	0.12	0.12	490	0.012	0.038
Switching									
Uncontrolled	17.4	1.01	1.83	0.006	0.44	0.43	670	0.017	0.052
Tier 0	12.6	1.01	1.83	0.006	0.44	0.43	670	0.017	0.052

6.4 Locomotive Emission Estimates

The estimated line haul and switching emissions are presented in Table 6.2. The NO_x emissions were adjusted to account for the use of TxLED fuel (6.2% reduction). The nature of the activity, fuel consumption, and cargo data underlying the estimates has not allowed more precise geographical allocation of line haul or switching emissions.

Table 6.5: Estimated Emissions from Locomotives

Activity	NO_x	PM_{10}	PM_{25}	VOC	CO	SO_2	CO_2e
			tons				**tonnes**
Line haul	515.3	13.3	13.3	20.8	142.2	0.6	49,826
Switching	71.4	2.5	2.5	5.8	10.4	0.0	3,503
Totals	**586.8**	**15.9**	**15.8**	**26.6**	**152.6**	**0.6**	**53,329**

SECTION 7
HEAVY-DUTY VEHICLES

This section presents emission estimates for the heavy-duty vehicles (HDV) emission source category and is organized into the following subsections: emission source description (7.1), data and information acquisition (7.2), emission estimation methodology (7.3), and the heavy-duty vehicles emission estimates (7.4).

7.1 Source Description

Heavy-duty trucks move cargo to and from the terminals and facilities that serve as the bridge between land and sea transportation. They are primarily driven on the public roads near the port and on highways within the inventory domain as they arrive from or depart to locations outside the domain. The vehicles are usually not under the direct control of the ports, the terminals, or the shippers who use the terminals, but are usually either owner-operated or are components of a carrier fleet. The most common configuration of HDVs in maritime freight service is the articulated tractor-trailer (truck and semi-trailer) having five axles, including the trailer axles. Common trailer types in the study area include container trailers built to accommodate standard-sized cargo containers, as well as tankers, boxes, and flatbeds.

Figure 7.1: Typical Heavy-duty Trucks

Most truck trips associated with the Port (approximately 80%) are made by container trucks that almost exclusively service two terminals, Barbours Cut Container Terminal (BCCT) and Bayport Container Terminal (BCT). The approximately 20% of trips made by non-container trucks are to and from other PHA cargo facilities. The PHA facilities for which truck trips were identified are listed below. Their locations are illustrated in Figure 1.1 of Section 1 of this report.

- Barbours Cut Container Terminal
- Bayport Container Terminal, including:
  - Bayport Auto Terminal
- Bulk Materials Handling Plant
- Care Terminal
- Jacintoport Terminal
- Woodhouse, including:
  - Richardson Steel
  - Public Elevator #2
  - Ardent Mills
- Turning Basin Terminal gates:
  - Industrial Park East
  - Cargo Bay Rd
  - Southside 18
  - Jacob Stern & Sons
  - Manchester Terminal

7.2 Data and Information Acquisition

HDV emission estimates are based on the number of miles traveled by the trucks within the inventory domain, which is a function of the number of trips made to and from the Port's terminals and facilities and the distance traveled within the domain on each trip. The other major variable that contributes to the emission estimates is the distribution of model years of the trucks making the trips, since emission standards result in newer trucks emitting lower levels of some pollutants than earlier model year trucks.

Information on the number of truck trips associated with the Port's container terminals was obtained from the Port's gate data system that provides detailed information on trucks entering and leaving the Bayport and Barbours Cut container terminals. In addition to a count of trucks, the data includes model year information that allowed the development of a model year distribution that was used to develop fleet-specific emission factors.

The number of truck trips associated with three major Turning Basin Terminal gates (Cargo Bay Road, Southside Gate 18, and Industrial Park East) was obtained from a truck count survey conducted at the three gates during November 2019. The month's total was annualized by first dividing the total number of days of data (30) to obtain the daily average. Then the daily average was multiplied by the total number of days in 2019 (365) since every day of the week showed some level of truck activity and November was said to be a "typical" month in terms of truck activity in 2019.

Information on truck trips associated with other tenant and PHA facilities was obtained by contacting each facility directly and requesting information on whether their operations included truck traffic and, if so, how many truck visits they had during 2019. Truck visits were estimated for facilities that declined to provide specific numbers by extrapolating from annual cargo throughput information provided by the Port, or from the percentage of trips in 2013. Table 7.1 lists the reported or estimated number of truck trips associated with each terminal or facility, and the source or method used to arrive at the number of trips.

Table 7.1: Estimated Truck Trip Counts and Data Sources

Facility	Trucks 2019	Data Source or Estimate Method
Barbours Cut Container Terminal	781,477	PHA Gate Data System
Bayport Container Terminal	1,548,084	PHA Gate Data System
Bayport Auto Terminal	9,500	Estimate from throughput
Bulk Materials Handling Plant	24,100	Estimate from 2013 %
Care	28,000	Estimate from 2013 %
Jacintoport	115,900	Estimate from 2013 %
Woodhouse		
Richardson Steel Terminal	54	Reported by facility
The Andersons (Grain Elev. No. 2)	8,714	Reported by facility
Ardent Mills (flour mill)	5,000	Reported by facility
Turning Basin Terminal		
Industrial Park East (IPE)	44,754	Extrapolated from 2019 survey
Cargo Bay Rd (TBT gate)	243,820	Extrapolated from 2019 survey
Southside 18 (TBT gate)	11,662	Extrapolated from 2019 survey
Jacob Stern and Sons	6,547	Reported by facility
Manchester	34,541	Estimate from 2013 %
Totals - container trucks	2,329,561	
Totals - non-container trucks	532,592	
Totals	**2,862,153**	

The average on-road distance traveled on each trip has been estimated using road travel distances from a truck mobility study conducted by the Texas Department of Transportation, Houston Division in 2020. The study includes the percentages of truck trips throughout the inventory area (and to the area boundary) that travel from and to four Port terminal areas: Barbours Cut, Bayport, Jacintoport, and Turning Basin. The study presented the results of two different surveys which were averaged for this inventory. To calculate average trip distances for this inventory, the distances between the Port terminal areas and various zones within the inventory area (and to the area boundary) were estimated and weighted average trip distances were calculated for each Port terminal area.

Figure 7.2 illustrates the distribution area and the zones covered by the trip data, while Table 7.2 presents the percentage (fraction) of trips between each terminal area and each zone covered by the trip data, and the distances between each terminal area and each zone. The fractions are the average of the two surveys underlying the truck mobility survey. The weighted average trip distance shown on the last row of each distance column in the table is the weighted average for that terminal area calculated by multiplying and summing each fraction/distance pair for all the listed locations. Total vehicle miles traveled (VMT) were calculated by multiplying each terminal area's trip total by the corresponding weighted average trip distance. This method resulted in a total of approximately 114 million VMT within the inventory area.

Figure 7.2: Example Truck Trip Percentage Distribution

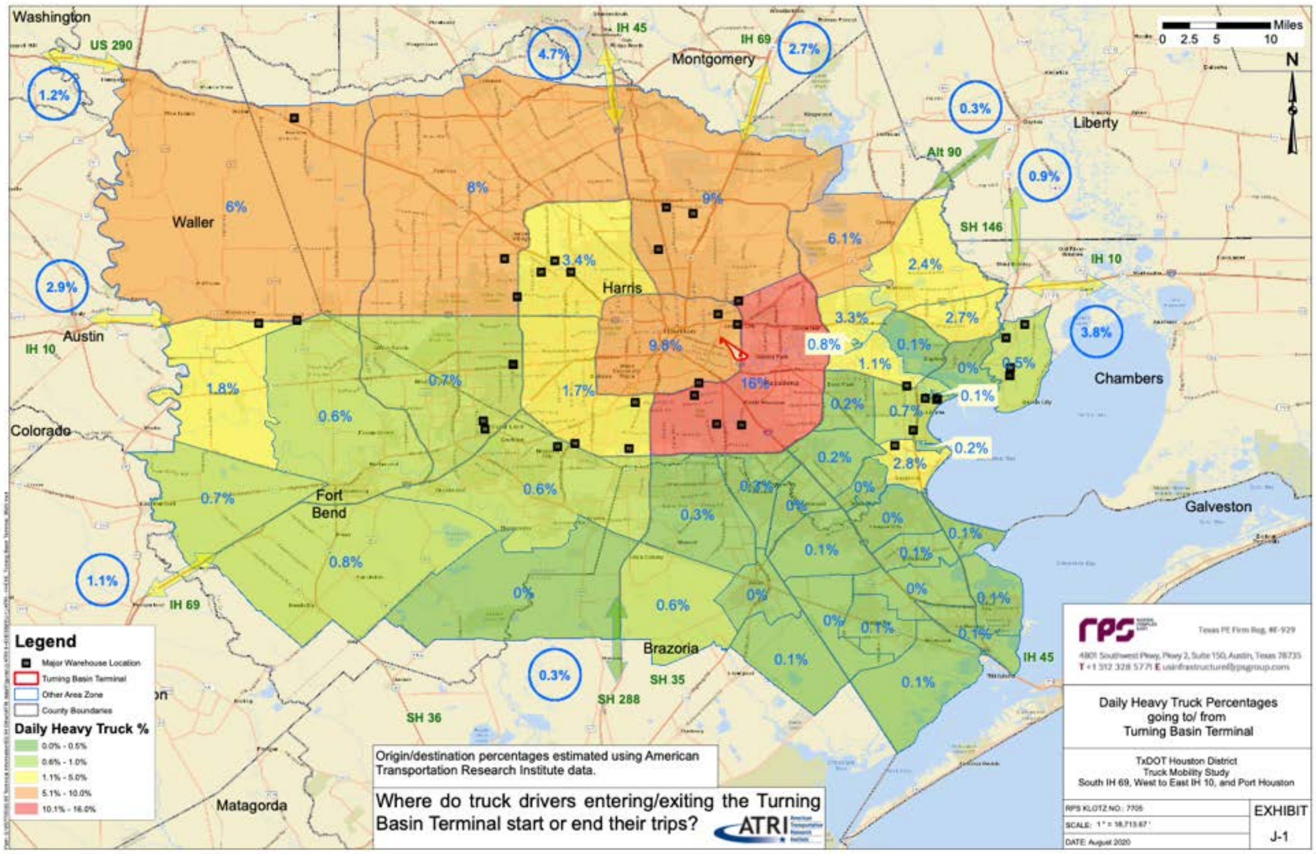


Table 7.2: Distribution of Truck Trips and Trip Distance, miles

	Fraction of trucks from each terminal area				One-way miles			
Origin/destination (Terminal:)	Turning Basin	Jacintoport	Barbours Cut	Bayport	Turning Basin	Jacintoport	Barbours Cut	Bayport
Terminals:								
Turning Basin Terminal		0.004	0.001	0.001		13	19	25
Jacintoport	0.005		0.003	0.003	13		19	22
Barbours Cut	0.001	0.008		0.058	19	19		7
Bayport	0.002	0.008	0.043		25	22	7	
Map zones:								
Inside 610 Loop	0.117	0.070	0.042	0.038	10	17	26	31
Pasadena	0.206	0.104	0.109	0.122	9	12	14	20
NE of Pasadena (Crosby)	0.059	0.095	0.010	0.013	21	18	22	27
N of 610 Loop (Humble)	0.077	0.039	0.020	0.032	23	25	36	41
NW of 610 Loop (290 to Jersey Village)	0.030	0.013	0.004	0.007	26	32	43	49
NW of 610 Loop (Cypress)	0.055	0.016	0.006	0.007	36	42	53	59
NW of 610 Loop (290 to Hempstead)	0.041	0.009	0.006	0.006	62	67	78	84
Channelview	0.037	0.357	0.069	0.074	12	5	17	22
Highlands	0.017	0.025	0.007	0.008	19	12	15	21
S of Highlands	0.027	0.014	0.059	0.066	20	12	14	20
Pasadena east	0.011	0.031	0.041	0.050	12	12	14	20
Baytown west	0.001	0.002	0.018	0.020	20	16	8	12
Baytown east	0.000	0.009	0.015	0.019	22	18	8	12
Deer Park	0.002	0.003	0.006	0.005	13	11	9	15
La Porte	0.010	0.073	0.350	0.239	20	20	3	5
Seabrook	0.024	0.014	0.031	0.065	26	26	9	5
Beach City	0.004	0.006	0.045	0.053	30	29	15	20
Other map zones (SE)	0.025	0.009	0.021	0.022	30	34	31	24
Other map zones (SW)	0.050	0.017	0.026	0.019	36	53	55	51
Out of map area								
East on I-10	0.038	0.016	0.010	0.014	58	48	47	53
North on 146	0.005	0.006	0.030	0.034	69	66	67	72
NE on Alt 90	0.003	0.003	0.000	0.000	62	57	60	65
NE on I-69	0.039	0.017	0.005	0.005	48	52	70	79
North on I-45	0.064	0.018	0.007	0.009	63	70	81	86
NW on 290	0.009	0.002	0.001	0.002	67	72	83	88
West on I-10	0.027	0.009	0.005	0.003	53	60	69	75
SW on I-69	0.008	0.004	0.005	0.003	56	63	70	75
South on 288	0.007	0.002	0.004	0.004	56	68	70	65
Total	1.000	1.000	1.000	1.000				
Average one-way miles per trip					**28**	**18**	**16**	**21**

Another component of travel distance is the distance traveled while the trucks are within the terminal or facility boundaries. Part of the data collection process was asking facility operators how far, on average, trucks travel while within the facility boundaries. Other on-terminal distances were estimated by evaluating gate-to-gate distances using online measuring tools such as "Google Earth."[23]

[23] *www.google.com/earth/*

In addition to VMT, another component of truck operations that results in emissions is idling in place, such as when waiting to unload or load cargo. The emission factors for on-road travel include idling that is incidental to routine driving but idling for longer periods is not included. Truck engines can idle at low speed when waiting in line, for example, or at a higher speed when idling for extended periods and the engine power is needed to run heating or cooling for driver safety or comfort. Emissions have been estimated for low-speed idling at the facilities to account for wait times on loading and unloading. While facility operators were asked for estimates of on-terminal idling times as part of the data collection effort, the amount of on-site idling is difficult to determine since few, if any, locations monitor or record duration of idling or wait times. A time estimate of 40 minutes of idling time per truck visit has been included in the estimates for locations whose operators did not provide an estimate. The time estimate of 40 minutes was based on the average idling times reported for terminals, other than container terminals, in three recent port-related emissions inventories,[24] and on a study published by the Oak Ridge National Laboratory[25] that reported the most common range of idling times for heavy-duty trucks, excluding overnight idling, is in the 15- to 60-minute range.

As noted above, the distribution of model years of the trucks is important to the development of emission estimates. The 2019 gate moves data for the Bayport and Barbours Cut container terminals provided model year information on the trucks calling at those terminals from which the distribution of model years was developed. Truck calls to and from these terminals accounted for 81% of truck calls counted in the inventory. The distribution of model years for the remaining "non-container" terminals was developed from the container terminal distribution by evaluating the 2013 distributions of container and non-container trucks and applying adjustment factors to the 2019 container truck model year fractions to approximate the likely distribution of model years of non-container trucks in 2019. The resulting distributions of container and non-container trucks are illustrated in Figure 7.3. In this figure the newest model year is to the left with trucks of progressively older model years displayed to the right.

The 2013 distributions were determined by surveys of container and non-container trucks, and the 2013 container truck distribution is very similar to the 2019 distribution that was determined from the 2019 gate moves data, with the obvious exception of newer trucks being present in the 2019 distribution, and lower fractions of older trucks. Figure 7.4 compares the 2019 and 2013 container truck model year distributions. This similarity provides a measure of confidence that the 2013 model year surveys were robust and supports the assumption that the 2019 non-container truck model year distribution was similar to the analogous 2013 distribution, with the same relative shift toward newer trucks as seen in the container truck distributions. This assumption was the basis for the estimated 2019 non-container truck model year distribution as shown in Figure 7.3

[24] *Port of Los Angeles, 2019 Inventory of Air Emissions, 2020.*
www.portoflosangeles.org/environment/studies_reports.asp
Port of Long Beach, 2019 Air Emissions Inventory, 2020
www.polb.com/environment/air/emissions.asp
Port Authority of New York & New Jersey, 2019 Multi-Facility Emissions Inventory, 2021
www.panynj.gov/about/port-initiatives.html

[25] *Oak Ridge National Laboratory, Class-8 Heavy Truck Duty Cycle Project Final Report, Dec. 2008. ORNL/TM-2008/122. www.cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008-122.pdf*

Figure 7.3: 2019 Model Year Distributions

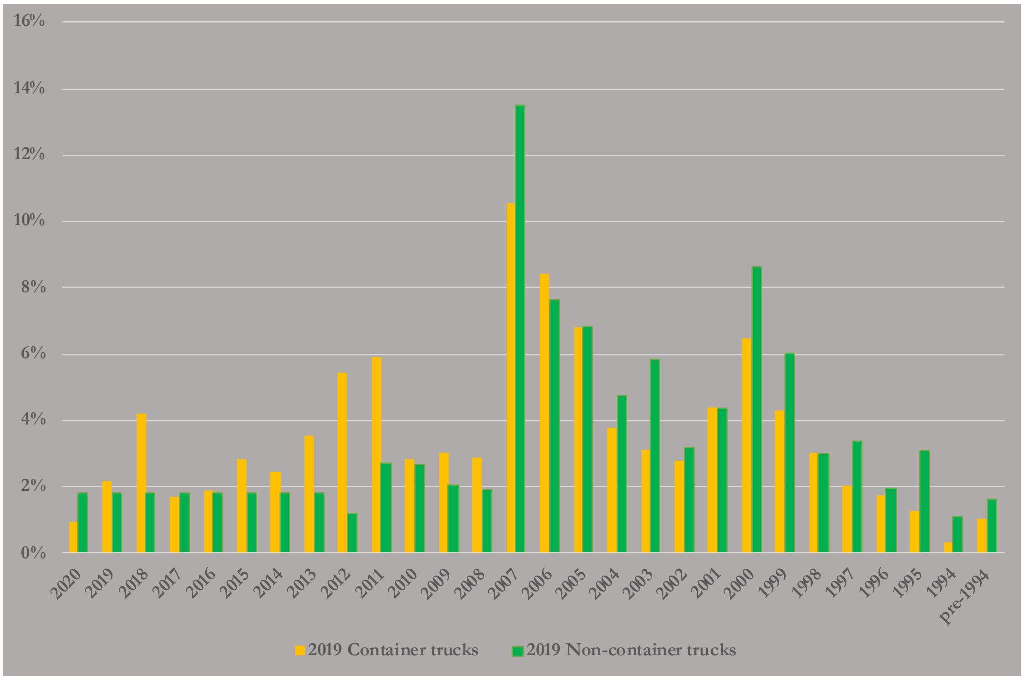
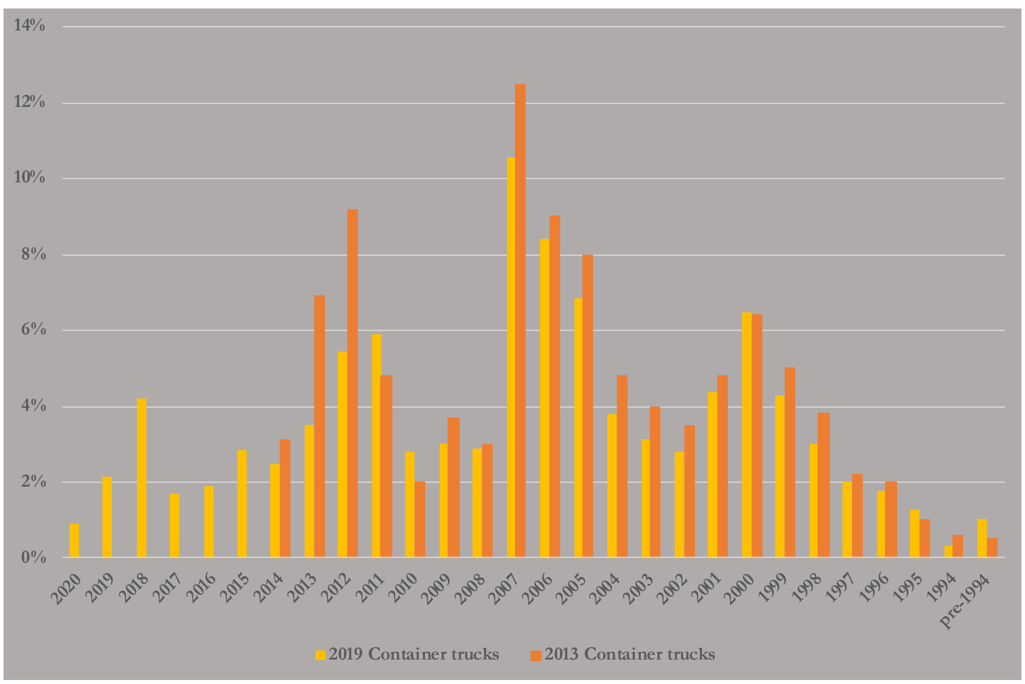


Figure 7.4: Comparison of 2019 and 2013 Container Truck Model Year Distributions



7.3 Emission Estimation Methodology

In general, emissions from HDVs are estimated using the general equation.

Equation 7.1

$$\mathbf{E} = \mathbf{EF} \times \mathbf{A}$$

Where:

E = mass of emissions per defined period (such as a year)
EF = emission factor (mass per unit of distance or time)
A = activity (distance driven, or time at idle, during the defined period)

Emissions are estimated by multiplying the emission factor by the miles driven or the hours of idling time. The units of distance in this inventory are miles, the idling units are hours, and the emission factors are expressed as grams of emissions per mile of travel (g/mile) or grams of emissions per hour of idling (g/hr). Annual emissions are expressed in short tons for the criteria pollutants and metric tons (tonnes) for greenhouse gases.

The emission factors have been developed using the EPA model MOVES3, which estimates emissions and emission factors for on-road vehicles of all types, including HDVs. The MOVES3 model is EPA's latest iteration in a series of on-road vehicle emission estimating models. The model can be run in such a way as to produce emission estimates for each model year of the specified vehicle types in a given state/county combination, and the estimated total number of miles driven in the county. These model outputs are used to calculate g/mile and g/hr emission factors by dividing total grams of emissions by total miles traveled or by total hours of idling.

The resulting emission factors are applicable to individual model years. Composite emission factors are calculated by multiplying and summing each model year's emission factor for a given pollutant by the fraction of that model year in the model year distribution. The composite emission factors are also in units of g/mile and g/hr and are used to estimate on-terminal and on-road driving emissions and on-terminal idling emissions.

The MOVES3 model was run in two modes for Harris County, Texas. For on-road travel within the inventory domain, the model was run in default scale, producing annual emissions and mileage for each road type, vehicle type, and model year, using the model's own data related to average road speeds. The model was run for truck type 61, "combination short-haul," using diesel fuel, for road types "urban restricted access" and "urban unrestricted access." For on-terminal travel and idling, the model was run in project scale, defining 15-mph and idling links at a one-hour time scale. The model's design dictates that idling emissions are estimated for single hours rather than a one-year period, so the model was run for a January morning hour and a July afternoon hour to cover the range of typical temperature conditions, and the results of the two runs were averaged to estimate average hourly low-speed driving emissions and idling emissions. The project-scale model was run for truck type 61, "combination short-haul," using diesel fuel. Table 7.3 summarizes the model parameters used to develop the emission factors, as summarized above.

Table 7.3: MOVES3 Model Parameters

Parameter / pollutant	Values used in model runs*			
Geographic bounds	Harris County, TX			
Time scale for on-road	Annual, 2019			
Time scale for on-terminal	Two one-hour periods, 8:00 am in January averaged with 5:00 pm in July			
Vehicle type	Combination short-haul truck			
Fuel type	Diesel			
Road types for on-road	Urban restricted access and urban unrestricted access			
Road type for on-terminal	Urban unrestricted access			
Pollutants and processes	Running exhaust	Crankcase running	Start exhaust	Crankcase start
Total gaseous hydrocarbons	X	X	X	X
Non-methane hydrocarbons	X	X	X	X
Non-methane organic gases	X	X	X	X
Total organic gases	X	X	X	X
Volatile organic compounds	X	X	X	X
CH_4	X	X	X	X
CO	X	X	X	X
NO_x	X	X	X	X
N_2O	X	X	X	X
Primary exhaust PM_{25}	X	X	X	X
Primary exhaust PM_{25} species	X	X	X	X
Primary exhaust PM_{10} total	X	X	X	X
SO_2	X	X	X	X
Total energy consumption	X	---	X	---
Atmospheric CO_2	X	---	X	---

* "X" adjacent to pollutant name indicates included in model run

Table 7.4 lists the emission factors developed from the model output files that have been used to estimate emissions.

Table 7.4: Emission Factors for HDVs, grams/mile and grams/hour

	NO_x	PM_{10}	PM_{25}	VOC	CO	SO_2	CO_2	N_2O	CH_4
Container trucks									
On-road (g/mi)	9.5	0.41	0.38	0.5	3.2	0.006	1,766	0.024	0.002
On-terminal (g/mi)	14.6	0.81	0.75	1.1	6.0	0.009	2,465	0.059	0.006
On-terminal idling (g/hr)	68.2	4.79	4.41	9.0	25.0	0.027	7,899	0.355	0.083
Non-container trucks									
On-road (g/mi)	11.3	0.52	0.48	0.7	3.5	0.006	1,765	0.022	0.002
On-terminal (g/mi)	16.5	1.02	0.94	1.4	6.5	0.009	2,478	0.052	0.006
On-terminal idling (g/hr)	76.9	5.89	5.41	10.9	26.9	0.027	7,835	0.321	0.083

7.4 Heavy-duty Vehicles Emission Estimates

The estimated emissions from on-road travel throughout the inventory domain, and on-terminal slow-speed driving and idling, are presented in Tables 7.5 through 7.8. Table 7.5 presents a summary of all emissions. The NO_x emissions have been adjusted to account for the use of TxLED fuel (6% reduction).

Table 7.5: Estimated Emissions from HDVs, tons and tonnes

Activity Location	NO_x	PM_{10}	PM_{25}	VOC	CO	SO_2	CO_2e
	tons	tons	tons	tons	tons	tons	tonnes
On-terminal (driving and idling)	198	13.5	12.4	22.3	81.9	0.1	27,092
On-road within inventory domain	1,196	56.0	51.5	73.9	416.4	0.8	206,775
Totals	**1,395**	**69.5**	**64.0**	**96.2**	**498.2**	**0.9**	**233,867**

Table 7.6 present the on-terminal emissions by facility.

Table 7.6: Estimated On-Terminal Emissions from HDVs, tons and tonnes

Facility	NO_x	PM_{10}	PM_{25}	VOC	CO	SO_2	CO_2e
	tons	tons	tons	tons	tons	tons	tonnes
Barbours Cut Container Terminal	48.4	3.3	3.0	5.4	20.1	0.03	6,697
Bayport Container Terminal	118.5	8.0	7.3	13.3	49.2	0.06	16,428
Bayport Auto Terminal	1.3	0.1	0.1	0.2	0.5	0.00	141
Bulk Materials Handling Plant	1.2	0.1	0.1	0.1	0.5	0.00	148
Care	1.1	0.1	0.1	0.1	0.4	0.00	130
Jacintoport	4.4	0.3	0.3	0.6	1.7	0.00	485
Woodhouse							
Richardson Steel Terminal	0.0	0.0	0.0	0.0	0.0	0.00	0
The Andersons (Grain Elev. No.2)	1.8	0.1	0.1	0.3	0.7	0.00	190
Ardent Mills (flour mill)	0.0	0.0	0.0	0.0	0.0	0.00	6
Turning Basin Terminal							
Industrial Park East (IPE)	2.2	0.2	0.1	0.3	0.9	0.00	274
Cargo Bay Rd (TBT gate)	17.0	1.2	1.1	1.7	7.0	0.01	2,326
Southside 18 (TBT gate)	0.5	0.0	0.0	0.1	0.2	0.00	66
Jacob Stern and Sons	0.1	0.0	0.0	0.0	0.0	0.00	6
Manchester	1.6	0.1	0.1	0.2	0.6	0.00	195
Totals	**198.3**	**13.5**	**12.4**	**22.3**	**81.9**	**0.10**	**27,092**

Table 7.7. presents the on-terminal driving emissions by terminal.

Table 7.7: Estimated On-Terminal Driving Emissions from HDVs, tons and tonnes

Facility	NO_x tons	PM_{10} tons	PM_{25} tons	VOC tons	CO tons	SO_2 tons	CO_2e tonnes
Barbours Cut Container Terminal	23.6	1.4	1.3	2.0	10.4	0.01	3,881
Bayport Container Terminal	58.5	3.5	3.2	4.9	25.8	0.04	9,610
Bayport Auto Terminal	0.2	0.0	0.0	0.0	0.1	0.00	36
Bulk Materials Handling Plant	0.6	0.0	0.0	0.1	0.3	0.00	90
Care	0.4	0.0	0.0	0.0	0.2	0.00	52
Jacintoport	1.0	0.1	0.1	0.1	0.4	0.00	145
Woodhouse							
Richardson Steel Terminal	0.0	0.0	0.0	0.0	0.0	0.00	0
The Andersons (Grain Elev. No.2)	0.1	0.0	0.0	0.0	0.1	0.00	22
Ardent Mills (flour mill)	0.0	0.0	0.0	0.0	0.0	0.00	6
Turning Basin Terminal							
Industrial Park East (IPE)	1.1	0.1	0.1	0.1	0.5	0.00	168
Cargo Bay Rd (TBT gate)	13.5	0.9	0.8	1.2	5.7	0.01	1,977
Southside 18 (TBT gate)	0.2	0.0	0.0	0.0	0.1	0.00	36
Jacob Stern and Sons	0.0	0.0	0.0	0.0	0.0	0.00	2
Manchester	0.7	0.0	0.0	0.1	0.3	0.00	108
Totals - driving	**100.1**	**6.1**	**5.6**	**8.4**	**43.8**	**0.06**	**16,133**

Table 7.8 presents the idling emissions by terminal.

Table 7.8: Estimated On-Terminal Idling Emissions from HDVs, tons and tonnes

	Idling emissions						
Facility	**NO_x**	**PM_{10}**	**PM_{25}**	**VOC**	**CO**	**SO_2**	**CO_2e**
	tons	**tons**	**tons**	**tons**	**tons**	**tons**	**tonnes**
Barbours Cut Container Terminal	24.8	1.9	1.7	3.5	9.7	0.01	2,816
Bayport Container Terminal	60.1	4.5	4.1	8.4	23.5	0.03	6,818
Bayport Auto Terminal	1.1	0.1	0.1	0.2	0.4	0.00	106
Bulk Materials Handling Plant	0.6	0.0	0.0	0.1	0.2	0.00	57
Care	0.8	0.1	0.1	0.1	0.3	0.00	78
Jacintoport	3.4	0.3	0.3	0.5	1.3	0.00	340
Woodhouse							
Richardson Steel Terminal	0.0	0.0	0.0	0.0	0.0	0.00	0
The Andersons (Grain Elev. No.2)	1.7	0.1	0.1	0.3	0.6	0.00	168
Ardent Mills (flour mill)	0.0	0.0	0.0	0.0	0.0	0.00	0
Turning Basin Terminal							
Industrial Park East (IPE)	1.1	0.1	0.1	0.2	0.4	0.00	107
Cargo Bay Rd (TBT gate)	3.5	0.3	0.3	0.5	1.3	0.00	348
Southside 18 (TBT gate)	0.3	0.0	0.0	0.0	0.1	0.00	30
Jacob Stern and Sons	0.0	0.0	0.0	0.0	0.0	0.00	5
Manchester	0.9	0.1	0.1	0.1	0.3	0.00	88
Totals - idling	**98.1**	**7.4**	**6.8**	**13.9**	**38.1**	**0.04**	**10,959**

SECTION 8
COMPARISON OF 2019 AND 2013 EMISSION ESTIMATES

This section provides a comparison of the PHA emission estimates for 2019 and 2013 by source category. Calculation methodologies changed for most of the emission source category due to new EPA Ports Emissions Inventory Guidance published September 2020 and the updated EPA emissions model, MOVES3, which is used for nonroad equipment and trucks.

Other reasons for emission changes are based on various factors including activity and operational differences, fleet turnover, different fleet mix, methodology changes, compliance with regulations, efficiency, and implementation of emission reduction strategies. This section will explain those changes at a high level for each source category.

Whenever possible, the 2013 emissions were re-estimated using the latest methodology or otherwise adjusted to account for the changes for a more meaningful comparison that reduces the effect of methodology differences and enables a high-level discussion of the changes in emissions due to activity changes and emission reduction strategies that occurred. The following 2013 emissions were adjusted to take into account some of the latest methodologies and therefore are not the same as those published in the 2013 report:

- Commercial harbor craft
- Locomotives (switching emissions)
- Heavy-duty vehicles

The 2013 emissions for OGV and CHE were left as they were in the 2013 report, except for the GHG emissions which were converted from short tons to metric tons.

8.1 PHA Emissions Comparison

Table 8.1 provides a comparison of cargo volumes in short tons and container throughput for PHA terminals only. Compared to 2013, cargo volumes were higher by 8% and container throughput in TEU was 53% higher in 2019. The significantly increased container throughput in 2019 since 2013 is due to facility improvements at PHA's Bayport and Barbours Cut Terminals, such as increasing container yard capacity, new post-Panamax ship to shore cranes and wharf expansions.

Table 8.1: PHA Cargo Volumes Comparison

Year	Cargo (short tons)	Containers TEU
2019	48,240,858	2,990,175
2013	44,756,323	1,952,122
Change	**8%**	**53%**

Table 8.2 presents the total net change in PHA emissions for all source categories in 2019 compared to 2013. Despite the 53% TEU throughput increase for PHA, the PHA emissions were lower for all pollutants. The emission changes for each source category are discussed in sections 8.3 to 8.7.

Table 8.2: PHA Emissions Comparison, tons, metric tons and %

Year	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019	6,967	195	182	306	1,281	173	658,256
2013	8,145	511	477	472	1,666	2,666	833,215
Change	**-1,178**	**-316**	**-295**	**-167**	**-385**	**-2,492**	**-174,960**
Change (%)	**-14%**	**-62%**	**-62%**	**-35%**	**-23%**	**-93%**	**-21%**

8.2 Non-PHA Emissions Comparison

The OGV and commercial harbor vessels emissions for non-PHA entities in the Houston Ship Channel are included in Table 8.3 emissions. The 2013 OGV emissions included are as listed in the 2013 report. Commercial harbor craft vessels emissions are adjusted to take into account the 2019 methodology.

Table 8.3: 2013-2019 Non-PHA Emissions Comparison by Source Category

	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019							
Ocean-going vessels	7,939	172	159	247	716	448	678,387
Commerical harbor vessels	3,816	88	85	93	847	3	302,443
Total	**11,755**	**261**	**244**	**340**	**1,563**	**451**	**980,831**
2013							
Ocean-going vessels	4,054	288	264	172	409	2,586	388,594
Commerical harbor vessels	4,138	93	90	106	755	3	285,602
Total	**8,192**	**381**	**354**	**278**	**1,164**	**2,589**	**674,195**
Change between 2013 and 2019 (percent)							
Ocean-going vessels	96%	-40%	-40%	44%	75%	-83%	75%
Commerical harbor craft	-8%	-6%	-5%	-13%	12%	5%	6%
Total	**44%**	**-32%**	**-31%**	**22%**	**34%**	**-83%**	**45%**

Although the 2013 OGV emissions were not re-estimated to take into account the various methodology and other changes, there were major activity impacts to non-PHA emissions in 2019 that are noted below when comparing the 2019 OGV emissions to 2013:

- The non-PHA terminals saw increased vessel activity including a 27% increase in OGV calls which increased OGV emissions overall and 6% increase in tugboat/towboat movements[26].
- At the end of 2015, a 40-year ban on exporting oil was lifted allowing the export of U.S. oil to be exported to foreign destinations and increasing liquid bulk activity in the U.S. Gulf Coast.
- For the Houston Ship Channel, tankers are the predominant vessel calling (80%) and tankers have high auxiliary boiler loads at berth while discharging. The high tanker boiler load at berth increased emissions.
- The use of lower sulfur fuel (0.1% sulfur) to comply with the North American ECA in 2019 instead of the 1% sulfur fuel used in 2013 significantly lowered the PM and SO_x emissions. The reduction in NO_x emissions for OGV due to the fuel switch was only 6% and was outweighed by the tanker boiler load increase and overall increased activity.
- In 2019, there were 33 vessels with Tier III propulsion engines that called non-PHA entities, including 31 tankers, one bulk vessel and one ATB. NO_x emissions from Tier III vessels are 75% lower than from Tier II vessels when operating at or above 25% main engine load.
- For commercial harbor craft, the CO, SO_x and GHG emissions increased due to increased activity, but all other emissions are lower due to fleet turnover and newer engines in 2019 as compared to 2013.

8.3 Ocean-going Vessels

Table 8.4 provides a comparison for PHA OGV emissions. The PHA OGV emissions are lower in 2019 as compared to 2013.

Table 8.4: PHA OGV Emissions Comparison

Year	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019	4,120	69	63	132	348	171	259,134
2013	4,683	302	278	213	488	2,663	401,053
Change, 2019-2013	**-12%**	**-77%**	**-77%**	**-38%**	**-29%**	**-94%**	**-35%**

[26] *Source: Greater Houston Port Bureau Annual Report for 2019 and 2013.*

Major highlights for PHA that impacted PHA OGV emissions in 2019 as compared to 2013:

- The overall vessel calls decreased slightly (3%) for PHA terminals in 2019 as compared to 2013, despite an increase in TEU throughput. The overall decrease in vessel calls is due to a container terminal tenant leaving in 2015 and larger containerships visiting in 2019, resulting in more containers per call. The reduced number of vessel calls resulted in lower OGV emissions.
- The use of lower sulfur fuel (0.1% sulfur) to comply with the North American ECA in 2019 instead of the 1% sulfur fuel used in 2013 lowered the PM and SO_x emissions.
- In 2019, there were four tankers with Tier III propulsion engines that called PHA terminals. NO_x emissions from Tier III vessels are 75% lower than from Tier II vessels when operating at or above 25% main engine load.

8.4 Commercial Harbor Craft

The total harbor craft emissions for 2013 were recalculated using the latest 2019 emission factors and load factors included in the EPA Ports EI Guidance document. Table 8.5 shows the total (PHA and Non-PHA) harbor craft emissions comparison for 2019 and 2013. The NO_x, PM and VOC emissions are lower due to newer vessels in 2019 as compared to 2013. The CO, SO_x and CO_2e emissions increased due to increased activity in 2019, and because those pollutants are not generally affected by the new emission standards that can lower emissions for NO_x, PM and VOC. All harbor craft used ULSD in 2019 and 2013, therefore there was no decrease in SO_x emissions. As discussed in section 4, most commercial harbor craft emissions (88%) are non-PHA related.

Table 8.5: 2013-2019 Total PHA and non-PHA Commercial Harbor Craft Emissions Comparison

Year	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019	4,312	100	97	105	960	3.4	342,249
2013	4,498	104	101	114	858	3.1	306,978
Change, 2019-2013	**-4%**	**-4%**	**-4%**	**-8%**	**12%**	**11%**	**11%**

The PHA comparison for harbor craft presented in Table 8.6 is not a true comparison as the 2013 PHA harbor craft emissions were not re-estimated. The 2013 emissions listed in Table 8.7 are as published in 2013 GMEI and not with the latest methodology.

Table 8.6: 2013-2019 PHA Commercial Harbor Craft Emissions Comparison

Year	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019	496	12	12	12	113	0.4	39,805
2013	360	11	11	8	103	0.2	21,376
Change, 2019-2013	**38%**	**8%**	**5%**	**47%**	**10%**	**99%**	**86%**

8.5 Cargo Handling Equipment

Table 8.7 shows the total cargo handling equipment emissions comparison. The emissions are lower for all pollutants in 2019 due to fleet turnover.

Table 8.7: 2013-2019 Total CHE Emissions Comparison, tons, metric tons and %

	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019	370	29	28	39	169	0.3	72,121
2013	1,315	97	94	101	437	1.0	133,821
Change	**-945**	**-68**	**-66**	**-62**	**-268**	**-1**	**-61,700**
Change (%)	**-72%**	**-70%**	**-70%**	**-61%**	**-61%**	**-74%**	**-46%**

Table 8.8 shows the diesel equipment count only (i.e., no propane or electric equipment included), with defaults included so there is no unknown Tier. It shows that there was fleet turnover since 2013. In 2019, there are equipment with the newer Tier 4 interim and final engines which have significantly lower emissions than the Tier 0-2 engines.

Table 8.8: 2013-2019 Diesel Equipment Engine Standard Comparison

	2019	2013
Tier 0	9%	16%
Tier 1	11%	23%
Tier 2	27%	33%
Tier 3	21%	24%
Tier 4 interim	8%	3%
Tier 4 final	24%	0%

Table 8.9 shows the Port owned and operated cargo handling equipment emissions comparison. The Port operated CHE emissions are lower for NO_x and SO_x, but higher for PM, VOC, CO and CO_2e emissions due to combined effect of increased activity, fleet turnover and methodological changes.

In 2019, there were more units than in 2013 mainly due to the expansion at Bayport Terminal. The equipment was used more in 2019 than 2013 due to the increase in TEU throughput at both Barbours Cut and Bayport terminals and also resulted in the emissions increase.

Table 8.9: 2013-2019 PHA Operated CHE Emissions Comparison, tons, metric tons and %

	Units Count	NO_x tons	PM_{10} tons	$PM_{2.5}$ tons	VOC tons	CO tons	SO_x tons	CO_2e tonnes
2019	229	182	12	12	19	100	0.1	30,284
2013	172	218	11	10	12	68.6	0.2	21,946
Change	**57**	**-36**	**2**	**2**	**7**	**32**	**-0.1**	**8,338**
Change (%)	**33%**	**-16%**	**18%**	**17%**	**54%**	**46%**	**-42%**	**38%**

8.6 Railroad Locomotives

Table 8.10 shows the line haul rail locomotive activity in million gross ton miles (MGTM) of cargo moved in 2013 and 2019 which shows a 14% increase in 2019 as compared to 2013.

Table 8.10: 2013-2019 Rail Locomotive Activity, MGTM

Emissions year	Million GTM
2019 activity	4,467
2013 activity	3,923
Difference	544
% change	**14%**

The line haul locomotive emissions in 2013 were not recalculated since there was no methodology change from 2013 to 2019 for locomotives. Switching emissions in 2013 were under-estimated due to misinterpretation of activity data during preparation of the prior inventory. Therefore 2013 emissions were re-estimated for a better comparison to 2019. Table 8.11 shows the emission comparison for locomotives. Overall, locomotive emissions decreased for NO_x, PM and VOC in 2019. Emissions increased for CO, SO_2 and CO_2e in 2019 as compared to 2013.

Table 8.11: 2013-2019 Locomotives Emissions Comparison, tons, metric tons and %

Year	NO_x tons	PM_{10} tons	PM_{25} tons	VOC tons	CO tons	SO_2 tons	CO_2e tonnes
2019	587	16	16	27	153	0.6	53,329
2013	640	22	21	36	127	0.4	44,533
Change, 2019-2013	**-8%**	**-28%**	**-26%**	**-27%**	**20%**	**33%**	**20%**

8.7 Heavy-duty Vehicles

Table 8.12 compares the heavy-duty vehicles count and vehicle miles traveled for 2013 and 2019. In 2019, the truck calls increased by 33% and vehicle miles traveled increased by 9%. The increase is due to the increase in throughput for PHA and the region.

Table 8.12: 2013-2019 HDV Count and Vehicle Miles Traveled

Emissions year	Truck Calls	Vehicle Miles Traveled
2019 activity	2,803,871.3	114,371,214.6
2013 activity	2,104,769.0	104,754,234.0
Difference	699,102	9,616,981
% change	**33%**	**9%**

The HDV emissions for 2013 were recalculated to account for the change in EPA models since MOVES3 is the latest model and produces different estimates compared with the model used in 2013 (MOVES2010). Table 8.13 shows the emissions comparison for heavy-duty vehicles. The 2019 heavy-duty vehicle emissions decreased for PM, VOC and CO, while the 2019 emissions increased for NO_x, SO_2 and CO_2e. The newer fleet may account for the decreases in emissions of PM, VOCs, and CO. The increase in tuck calls and VMT account for the increase in emissions for the other pollutants.

Table 8.13: 2013-2019 HDV Emissions Comparison, tons, metric tons and %

Year	NO_x tons	PM_{10} tons	PM_{25} tons	VOC tons	CO tons	SO_2 tons	CO_2e tonnes
2019	1,395	70	64	96	498	1	233,867
2013	1,147	79	73	114	510	1	232,432
Change	**248**	**-10**	**-9**	**-18**	**-12**	**0**	**1,434**
Change (%)	**22%**	**-12%**	**-12%**	**-16%**	**-2%**	**2%**	**1%**

SECTION 9
CONCLUSION AND RECOMMENDATIONS

Between 2013 and 2019, Port Houston saw significant growth in cargo volume. For PHA facilities alone, cargo throughput increased by 8% in short tons and 53% in container TEU throughput over the period. Despite the increase in cargo volume, overall emissions of all pollutants were lower for PHA terminals, primarily due to fleet turnover and the use of lower sulfur content fuel by ocean-going vessels in 2019 as compared to 2013.

With respect to total emissions from PHA and non-PHA sources, NO_x and CO_2e emissions increased in 2019 due to the increased vessel activity in the Houston Ship Channel.

Looking Ahead

Looking into the future, the PHA and Houston Ship Channel facilities will continue to grow as reflected in vessel activity and throughput during 2020 and the first half of 2021. With this growth and increased activity, we expect NO_x and CO_2e emissions to increase in the future as compared to 2019. We also expect to continue to see larger vessels, specifically tankers and containerships, call PHA and the Houston Ship Channel. Depending on vessel type and future fleet mix, the ocean-going vessels' emissions may decrease overall due to fewer vessel calls as a result of the larger vessels or they may increase due to higher operating loads for engines and boilers on larger tankers. Whether there is an increase or decrease will depend on the future vessel fleet mix, which is difficult to predict.

Although activity may continue to increase in the future for most emission source categories, some of the emission increases may be offset by fleet turnover. However, if the rate of growth continues at the present rate, activity increases may overshadow emission reductions achieved through fleet turnover and the effect of present emission reduction initiatives.

Recommendations

Since Port Houston is still expanding, a future emissions inventory is recommended in approximately three to five years. The ocean-going vessel inventory is especially crucial to understand the changes in activity counts, vessel movements and types of tankers that call the Port. The other emission source categories are also important as operations may change, causing effects that are hard to predict. The Port is encouraged to include in the scope a more robust emissions comparison by recalculating the activity from the most recent emissions inventory with the latest methodology changes in order to make a more detailed comparison, as opposed to evaluating changes at a high level. This will ensure that the emission reduction strategies the Port has undertaken over the recent years are adequately taken into consideration in the emissions comparison.

Emissions from harbor craft, specifically towboats and tugboats, will continue to increase as the engines get older until a significant amount of turnover occurs. A program to encourage engine repower or fleet turnover would hasten this process. In California, the Carl Moyer marine diesel engine repower program has been successful in replacing old engines with newer cleaner engines by providing funds to successful applicants. In Texas, although there are incentive programs such as the Texas Emissions Reduction Plan (TERP), towboats are mostly ineligible due to the TERP requirement that equipment or engines must be guaranteed to operate mainly in non-attainment areas. Other grant opportunities include the EPA Diesel Emission Reduction Act (DERA) which can only be applied through a public entity such as a port authority. In other words, a vessel owner would not be able to apply directly to EPA for a DERA grant. For this federal grant program to be of value, Port Houston or another public entity must be willing to manage the grant funding for the EPA and work with the vessel operators. In 2021, the Port did apply to EPA DERA on behalf of a local tugboat company and was successfully awarded $2.5 million towards vessel repower for two existing tugboats. Based on this recent award and past successes, the Port should continue to offer grant application support and encourage local private companies to apply for grants and continue modernizing their fleets. Another emission reduction strategy is for local tug companies to provide shore power at their berths or shut auxiliary engines off while at berth for those vessels that work full time in the region.

For CHE, it is recommended that the Port and its stevedores continue to replace equipment with newer Tier 4 engines and purchase or retrofit equipment with hybrid technology, when possible. Recently, the Port has purchased hybrid RTG cranes which will result in lower emissions from the CHE source category in future inventories. The 2020 and 2021 acquisitions of hybrid RTG cranes were not included in the 2019 emissions for this inventory.

Line haul locomotive emissions may lower with fleet turnover in the future, although activity increases may overshadow any emission reductions achieved through fleet turnover. Advancements in emission standards for trucks have come earlier than for locomotives. This means that current truck fleet emissions may provide lower transportation emissions than rail transport by the current line haul locomotive fleet, but this will vary greatly by pollutant and careful analysis would be required to establish which mode is “cleaner” and by which pollutants. In addition, ports typically have little to no ability or leverage to influence the locomotive fleet mix of the Class 1 railroads, which make up most of the locomotive emissions in the port setting. The locomotives operated locally by PTRA and other entities were originally manufactured before significant locomotive emission standards came into effect (they are Tier 0 or pre-Tier 0). While their emissions contribute a minority (7%-22%) of total locomotive emissions in the inventory, they represent the possibility of notable emission reductions using readily available replacement locomotives.

HDV emission reductions due to fleet turnover can be accelerated by active measures such as incentive programs to encourage replacement of older trucks and progressive restrictions on the oldest model years that are authorized to operate on Port terminals. If successful, these types of measures can result in fairly rapid emission reductions.

APPENDIX A: Propulsion Engines Low Load Emission Factor Adjustments

Propulsion Engines Low Load Emission Factor Adjustments
In general terms, diesel-cycle engines are not as efficient when operated at low loads compared with higher load operation. An EPA study[27] prepared by Energy and Environmental Analysis, Inc. (EEAI) established a formula for calculating emission factors for low engine load conditions such as those encountered during harbor maneuvering and when traveling slowly at sea (e.g. in the reduced speed zone) This formula was later used and described in a study conducted for the EPA by ENVIRON.[28] While mass emissions in pounds per hour tend to go down as vessel speeds and engine loads decrease, the emission factors in g/kW-hr increase.

Equation A.1 is the equation developed by EEAI to generate emission factors for the range of load factors from 2% to 20% for each pollutant:
Equation A.1

$$\mathbf{y} = \mathbf{a}\,(\mathbf{fractional\ load})^{-\mathbf{x}} + \mathbf{b}$$

Where:

y = emissions, g/kW-hr
a = coefficient, dimensionless
b = intercept, dimensionless
x = exponent, dimensionless
fractional load = propulsion engine load factor (2% - 20%), derived from the Propeller Law, percent

Table A.1 presents the variables for equation A.1.

Table A.1: Low-Load Emission Factor Regression Equation Variables for Non-MAN Propulsion Engines

Pollutant	Exponent (x)	Intercept (b)	Coefficient (a)
PM	1.5	0.2551	0.0059
NO_x	1.5	10.4496	0.1255
CO	1.0	0.1548	0.8378
HC	1.5	0.3859	0.0667

The base emission factors used in the development of the low-load regression equation are not the currently accepted emission factors for OGV propulsion engines. Therefore, Starcrest developed low-load adjustment (LLA) multipliers by dividing the emission factors for each load increment between 2% and 20% by the emission factor at 20% load. These LLA multipliers are listed in Table A.2. In keeping with the Port's emission estimating practice of assuming a minimum propulsion engine load of 2%, the table of LLA factors does not include values for 1% load. During emission estimation, the LLA factors are multiplied by the latest emission factors for 2-stroke (slow speed) non-MAN diesel propulsion engines, adjusted for fuel differences between the actual fuel and the fuel used when the emission factors were developed. Adjustments to N_2O and CH_4 emission factors are made based on the NO_x and HC low load adjustments, respectively. The LLA adjustments are applied only to engine loads less than 20%. Low load emission factor adjustments do not apply to steamships or ships having gas turbines because the EPA study referenced above only observed an increase in emissions from diesel engines.

[27] *EPA, Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data, February 2000*
[28] *EPA, Commercial Marine Inventory Development, July 2002*

Table A.2: Low Load Adjustment Multipliers for Emission Factors for Non-MAN Propulsion Engines[29]

Load	PM	NO_x	SO_2	CO	VOC	CO_2	N_2O	CH_4
2%	7.29	4.63	3.30	9.68	21.18	3.28	4.63	21.18
3%	4.33	2.92	2.45	6.46	11.68	2.44	2.92	11.68
4%	3.09	2.21	2.02	4.86	7.71	2.01	2.21	7.71
5%	2.44	1.83	1.77	3.89	5.61	1.76	1.83	5.61
6%	2.04	1.60	1.60	3.25	4.35	1.59	1.60	4.35
7%	1.79	1.45	1.47	2.79	3.52	1.47	1.45	3.52
8%	1.61	1.35	1.38	2.45	2.95	1.38	1.35	2.95
9%	1.48	1.27	1.31	2.18	2.52	1.31	1.27	2.52
10%	1.38	1.22	1.26	1.96	2.18	1.25	1.22	2.18
11%	1.30	1.17	1.21	1.79	1.96	1.21	1.17	1.96
12%	1.24	1.14	1.17	1.64	1.76	1.17	1.14	1.76
13%	1.19	1.11	1.14	1.52	1.60	1.14	1.11	1.60
14%	1.15	1.08	1.11	1.41	1.47	1.11	1.08	1.47
15%	1.11	1.06	1.09	1.32	1.36	1.08	1.06	1.36
16%	1.08	1.05	1.06	1.24	1.26	1.06	1.05	1.26
17%	1.06	1.03	1.05	1.17	1.18	1.04	1.03	1.18
18%	1.04	1.02	1.03	1.11	1.11	1.03	1.02	1.11
19%	1.02	1.01	1.01	1.05	1.05	1.01	1.01	1.05
20%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The low load emission factor is calculated for each pollutant using Equation A.2.
Equation A.2

$$\mathbf{EF} = \mathbf{Adjusted\ EF} \times \mathbf{LLA}$$

Where:

EF = calculated low load emission factor, expressed in terms of g/kW-hr
Adjusted EF = fuel adjusted emission factor for 2-stroke diesel propulsion engines, g/kW-hr
LLA = low load adjustment multiplier, dimensionless

[29] *The LLA multipliers for N_2O and CH_4 are based on NO_x and HC, respectively.*

The emissions from MAN 2-stroke propulsion (main) engines were adjusted as a function of engine load using test data from the San Pedro Bay Ports' (SPBP) MAN Slide Valve Low-Load Emissions Test Final Report (Slide Valve Test) completed under the SPBP Technology Advancement Program (TAP) in conjunction with MAN and Mitsui. The following enhancements are incorporated into the emissions estimates for applicable propulsion engines based on the findings of the study.

- Emission factor adjustment (EFA) is applied to pollutants for which test results were significantly different in magnitude than the base emission factors used in the inventory. A slide valve EFA (EFA_{SV}) is applied only to vessels equipped with slide valves (SV), which include 2004 or newer MAN 2-stroke engines and vessels identified in the VBP data as having slide valves. A conventional nozzle (C3) EFA (EFA_{C3}) is used for all other MAN 2-stroke engines, which are typically older than 2004 vessels. EFAs were developed by compositing the test data into the E3 duty cycle load weighting and comparing them to the E3-based EFs used in the inventories. The following EFAs are used:

  a. NO_x: $EFA_{SV} = 1.0$ $EFA_{C3} = 1.0$
  b. PM: $EFA_{SV} = 1.0$ $EFA_{C3} = 1.0$
  c. THC: $EFA_{SV} = 0.43$ $EFA_{C3} = 1.0$
  d. CO: $EFA_{SV} = 0.59$ $EFA_{C3} = 0.44$
  e. CO_2: $EFA_{SV} = 1.0$ $EFA_{C3} = 1.0$

- Load adjustment factors (LAF) are calculated and applied to the EF x EFA across all loads (0% to 100%). The LAF is pollutant based and valve specific (SV or C3), using the same criteria as stated above for EFA. The adjusted equation for estimating OGV MAN propulsion engine emissions is:

Equation A.3

$$\mathbf{Ei} = \mathbf{Energy} \times \mathbf{EF} \times \mathbf{EFA} \times \mathbf{LAFi} \times \mathbf{FCF} \times \mathbf{CF}$$

Where,

Ei = Emission by load i, g
Energy = Energy demand by mode, kW-hr
EF = default emission factor (E3 duty cycle by pollutant or GHG), g/kW-hr
EFA = emission factor adjustment by pollutant or GHG, dimensionless
LAF_i = test-based EF_i (by valve type and pollutant or GHG) at load i / test-based composite EF (E3 duty cycle), dimensionless
FCF = fuel correction factor by pollutant or GHG, dimensionless
CF = control factor (by pollutant or GHG) for any emission reduction program, dimensionless

Tables A.3 and A.4 present the LAFs used across the entire engine load range.

Table A.3: Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Slide Valves

Load	PM	$PM_{2.5}$	DPM	NO_x	SO_x	CO	HC	CO_2	N_2O	CH_4
1%	0.36	0.36	0.36	1.90	1.10	0.12	1.36	1.10	1.90	1.36
2%	0.37	0.37	0.37	1.86	1.10	0.12	1.32	1.10	1.86	1.32
3%	0.38	0.38	0.38	1.82	1.09	0.12	1.28	1.09	1.82	1.28
4%	0.38	0.38	0.38	1.78	1.09	0.12	1.24	1.09	1.78	1.24
5%	0.39	0.39	0.39	1.74	1.09	0.12	1.20	1.09	1.74	1.20
6%	0.40	0.40	0.40	1.70	1.08	0.12	1.17	1.08	1.70	1.17
7%	0.41	0.41	0.41	1.67	1.08	0.12	1.14	1.08	1.67	1.14
8%	0.41	0.41	0.41	1.63	1.08	0.12	1.11	1.08	1.63	1.11
9%	0.42	0.42	0.42	1.60	1.07	0.12	1.08	1.07	1.60	1.08
10%	0.43	0.43	0.43	1.57	1.07	0.12	1.05	1.07	1.57	1.05
11%	0.44	0.44	0.44	1.53	1.07	0.26	1.02	1.07	1.53	1.02
12%	0.45	0.45	0.45	1.50	1.07	0.39	0.99	1.07	1.50	0.99
13%	0.45	0.45	0.45	1.47	1.06	0.52	0.97	1.06	1.47	0.97
14%	0.46	0.46	0.46	1.45	1.06	0.64	0.94	1.06	1.45	0.94
15%	0.47	0.47	0.47	1.42	1.06	0.75	0.92	1.06	1.42	0.92
16%	0.48	0.48	0.48	1.39	1.06	0.85	0.90	1.06	1.39	0.90
17%	0.49	0.49	0.49	1.37	1.05	0.95	0.88	1.05	1.37	0.88
18%	0.49	0.49	0.49	1.34	1.05	1.04	0.86	1.05	1.34	0.86
19%	0.50	0.50	0.50	1.32	1.05	1.12	0.84	1.05	1.32	0.84
20%	0.51	0.51	0.51	1.30	1.05	1.20	0.82	1.05	1.30	0.82
21%	0.52	0.52	0.52	1.28	1.04	1.27	0.81	1.04	1.28	0.81
22%	0.53	0.53	0.53	1.26	1.04	1.34	0.79	1.04	1.26	0.79
23%	0.54	0.54	0.54	1.24	1.04	1.40	0.78	1.04	1.24	0.78
24%	0.54	0.54	0.54	1.22	1.04	1.46	0.76	1.04	1.22	0.76
25%	0.55	0.55	0.55	1.20	1.03	1.51	0.75	1.03	1.20	0.75

Table A.3 (continued): Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Slide Valves

Load	PM	$PM_{2.5}$	DPM	NO_x	SO_x	CO	HC	CO_2	N_2O	CH_4
26%	0.56	0.56	0.56	1.19	1.03	1.55	0.74	1.03	1.19	0.74
27%	0.57	0.57	0.57	1.17	1.03	1.59	0.73	1.03	1.17	0.73
28%	0.58	0.58	0.58	1.16	1.03	1.63	0.72	1.03	1.16	0.72
29%	0.59	0.59	0.59	1.14	1.03	1.66	0.71	1.03	1.14	0.71
30%	0.60	0.60	0.60	1.13	1.02	1.68	0.70	1.02	1.13	0.70
31%	0.60	0.60	0.60	1.12	1.02	1.70	0.70	1.02	1.12	0.70
32%	0.61	0.61	0.61	1.10	1.02	1.72	0.69	1.02	1.10	0.69
33%	0.62	0.62	0.62	1.09	1.02	1.74	0.69	1.02	1.09	0.69
34%	0.63	0.63	0.63	1.08	1.02	1.75	0.68	1.02	1.08	0.68
35%	0.64	0.64	0.64	1.07	1.02	1.75	0.68	1.02	1.07	0.68
36%	0.65	0.65	0.65	1.06	1.01	1.75	0.68	1.01	1.06	0.68
37%	0.66	0.66	0.66	1.05	1.01	1.75	0.67	1.01	1.05	0.67
38%	0.67	0.67	0.67	1.05	1.01	1.75	0.67	1.01	1.05	0.67
39%	0.68	0.68	0.68	1.04	1.01	1.74	0.67	1.01	1.04	0.67
40%	0.69	0.69	0.69	1.03	1.01	1.73	0.67	1.01	1.03	0.67
41%	0.70	0.70	0.70	1.03	1.01	1.72	0.67	1.01	1.03	0.67
42%	0.70	0.70	0.70	1.02	1.01	1.71	0.68	1.01	1.02	0.68
43%	0.71	0.71	0.71	1.02	1.01	1.69	0.68	1.01	1.02	0.68
44%	0.72	0.72	0.72	1.01	1.00	1.67	0.68	1.00	1.01	0.68
45%	0.73	0.73	0.73	1.01	1.00	1.65	0.69	1.00	1.01	0.69
46%	0.74	0.74	0.74	1.00	1.00	1.62	0.69	1.00	1.00	0.69
47%	0.75	0.75	0.75	1.00	1.00	1.60	0.70	1.00	1.00	0.70
48%	0.76	0.76	0.76	1.00	1.00	1.57	0.70	1.00	1.00	0.70
49%	0.77	0.77	0.77	0.99	1.00	1.54	0.71	1.00	0.99	0.71
50%	0.78	0.78	0.78	0.99	1.00	1.51	0.71	1.00	0.99	0.71

Table A.3 (continued): Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Slide Valves

Load	PM	$PM_{2.5}$	DPM	NO_x	SO_x	CO	HC	CO_2	N_2O	CH_4
51%	0.79	0.79	0.79	0.99	1.00	1.48	0.72	1.00	0.99	0.72
52%	0.80	0.80	0.80	0.99	1.00	1.45	0.73	1.00	0.99	0.73
53%	0.81	0.81	0.81	0.99	1.00	1.41	0.74	1.00	0.99	0.74
54%	0.82	0.82	0.82	0.99	1.00	1.38	0.75	1.00	0.99	0.75
55%	0.83	0.83	0.83	0.98	0.99	1.35	0.75	0.99	0.98	0.75
56%	0.84	0.84	0.84	0.98	0.99	1.31	0.76	0.99	0.98	0.76
57%	0.85	0.85	0.85	0.98	0.99	1.27	0.77	0.99	0.98	0.77
58%	0.86	0.86	0.86	0.98	0.99	1.24	0.78	0.99	0.98	0.78
59%	0.87	0.87	0.87	0.98	0.99	1.20	0.80	0.99	0.98	0.80
60%	0.88	0.88	0.88	0.98	0.99	1.16	0.81	0.99	0.98	0.81
61%	0.89	0.89	0.89	0.98	0.99	1.13	0.82	0.99	0.98	0.82
62%	0.90	0.90	0.90	0.98	0.99	1.09	0.83	0.99	0.98	0.83
63%	0.91	0.91	0.91	0.99	0.99	1.06	0.84	0.99	0.99	0.84
64%	0.92	0.92	0.92	0.99	0.99	1.02	0.85	0.99	0.99	0.85
65%	0.93	0.93	0.93	0.99	0.99	0.98	0.87	0.99	0.99	0.87
66%	0.94	0.94	0.94	0.99	0.99	0.95	0.88	0.99	0.99	0.88
67%	0.95	0.95	0.95	0.99	0.99	0.92	0.89	0.99	0.99	0.89
68%	0.97	0.97	0.97	0.99	0.99	0.88	0.91	0.99	0.99	0.91
69%	0.98	0.98	0.98	0.99	0.99	0.85	0.92	0.99	0.99	0.92
70%	0.99	0.99	0.99	0.99	0.99	0.82	0.93	0.99	0.99	0.93
71%	1.00	1.00	1.00	0.99	0.99	0.79	0.95	0.99	0.99	0.95
72%	1.01	1.01	1.01	0.99	0.99	0.76	0.96	0.99	0.99	0.96
73%	1.02	1.02	1.02	0.99	0.99	0.74	0.98	0.99	0.99	0.98
74%	1.03	1.03	1.03	0.99	0.99	0.71	0.99	0.99	0.99	0.99
75%	1.04	1.04	1.04	0.99	0.99	0.69	1.00	0.99	0.99	1.00

Table A.3 (continued): Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Slide Valves

Load	PM	$PM_{2.5}$	DPM	NO_x	SO_x	CO	HC	CO_2	N_2O	CH_4
76%	1.05	1.05	1.05	0.99	0.99	0.66	1.02	0.99	0.99	1.02
77%	1.06	1.06	1.06	0.99	0.99	0.64	1.03	0.99	0.99	1.03
78%	1.07	1.07	1.07	0.99	0.99	0.63	1.05	0.99	0.99	1.05
79%	1.09	1.09	1.09	0.99	0.99	0.61	1.06	0.99	0.99	1.06
80%	1.10	1.10	1.10	0.99	0.99	0.60	1.08	0.99	0.99	1.08
81%	1.11	1.11	1.11	0.99	0.99	0.58	1.09	0.99	0.99	1.09
82%	1.12	1.12	1.12	0.99	0.99	0.57	1.10	0.99	0.99	1.10
83%	1.13	1.13	1.13	0.98	0.99	0.57	1.12	0.99	0.98	1.12
84%	1.14	1.14	1.14	0.98	0.99	0.56	1.13	0.99	0.98	1.13
85%	1.15	1.15	1.15	0.98	0.99	0.56	1.15	0.99	0.98	1.15
86%	1.16	1.16	1.16	0.98	0.99	0.56	1.16	0.99	0.98	1.16
87%	1.18	1.18	1.18	0.97	0.99	0.56	1.18	0.99	0.97	1.18
88%	1.19	1.19	1.19	0.97	0.99	0.57	1.19	0.99	0.97	1.19
89%	1.20	1.20	1.20	0.96	0.99	0.58	1.20	0.99	0.96	1.20
90%	1.21	1.21	1.21	0.96	0.99	0.59	1.22	0.99	0.96	1.22
91%	1.22	1.22	1.22	0.95	1.00	0.61	1.23	1.00	0.95	1.23
92%	1.23	1.23	1.23	0.95	1.00	0.63	1.24	1.00	0.95	1.24
93%	1.25	1.25	1.25	0.94	1.00	0.65	1.25	1.00	0.94	1.25
94%	1.26	1.26	1.26	0.93	1.00	0.67	1.27	1.00	0.93	1.27
95%	1.27	1.27	1.27	0.93	1.00	0.70	1.28	1.00	0.93	1.28
96%	1.28	1.28	1.28	0.92	1.00	0.73	1.29	1.00	0.92	1.29
97%	1.29	1.29	1.29	0.91	1.00	0.77	1.30	1.00	0.91	1.30
98%	1.31	1.31	1.31	0.90	1.00	0.81	1.31	1.00	0.90	1.31
99%	1.32	1.32	1.32	0.89	1.00	0.85	1.32	1.00	0.89	1.32
100%	1.33	1.33	1.33	0.88	1.00	0.90	1.34	1.00	0.88	1.34

Table A.4: Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Conventional Valves

Load	PM	$PM_{2.5}$	DPM	NO_x	SO_x	CO	HC	CO_2	N_2O	CH_4
1%	0.84	0.84	0.84	1.91	1.10	1.38	2.53	1.10	1.91	2.53
2%	0.83	0.83	0.83	1.86	1.10	1.36	2.45	1.10	1.86	2.45
3%	0.83	0.83	0.83	1.82	1.09	1.34	2.37	1.09	1.82	2.37
4%	0.82	0.82	0.82	1.77	1.09	1.33	2.30	1.09	1.77	2.30
5%	0.82	0.82	0.82	1.72	1.09	1.31	2.23	1.09	1.72	2.23
6%	0.81	0.81	0.81	1.68	1.08	1.29	2.16	1.08	1.68	2.16
7%	0.81	0.81	0.81	1.64	1.08	1.28	2.10	1.08	1.64	2.10
8%	0.80	0.80	0.80	1.60	1.08	1.26	2.03	1.08	1.60	2.03
9%	0.80	0.80	0.80	1.56	1.07	1.25	1.97	1.07	1.56	1.97
10%	0.79	0.79	0.79	1.52	1.07	1.24	1.91	1.07	1.52	1.91
11%	0.79	0.79	0.79	1.49	1.07	1.22	1.86	1.07	1.49	1.86
12%	0.78	0.78	0.78	1.45	1.07	1.21	1.80	1.07	1.45	1.80
13%	0.78	0.78	0.78	1.42	1.06	1.20	1.75	1.06	1.42	1.75
14%	0.78	0.78	0.78	1.39	1.06	1.19	1.70	1.06	1.39	1.70
15%	0.77	0.77	0.77	1.36	1.06	1.18	1.65	1.06	1.36	1.65
16%	0.77	0.77	0.77	1.33	1.06	1.17	1.61	1.06	1.33	1.61
17%	0.77	0.77	0.77	1.30	1.05	1.16	1.56	1.05	1.30	1.56
18%	0.77	0.77	0.77	1.28	1.05	1.15	1.52	1.05	1.28	1.52
19%	0.76	0.76	0.76	1.25	1.05	1.14	1.48	1.05	1.25	1.48
20%	0.76	0.76	0.76	1.23	1.05	1.13	1.44	1.05	1.23	1.44
21%	0.76	0.76	0.76	1.20	1.04	1.13	1.41	1.04	1.20	1.41
22%	0.76	0.76	0.76	1.18	1.04	1.12	1.37	1.04	1.18	1.37
23%	0.76	0.76	0.76	1.16	1.04	1.11	1.34	1.04	1.16	1.34
24%	0.75	0.75	0.75	1.14	1.04	1.10	1.31	1.04	1.14	1.31
25%	0.75	0.75	0.75	1.12	1.03	1.10	1.28	1.03	1.12	1.28

Table A.4 (continued): Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Conventional Valves

Load	PM	$PM_{2.5}$	DPM	NO_x	SO_x	CO	HC	CO_2	N_2O	CH_4
26%	0.75	0.75	0.75	1.11	1.03	1.09	1.25	1.03	1.11	1.25
27%	0.75	0.75	0.75	1.09	1.03	1.08	1.22	1.03	1.09	1.22
28%	0.75	0.75	0.75	1.07	1.03	1.08	1.20	1.03	1.07	1.20
29%	0.75	0.75	0.75	1.06	1.03	1.07	1.17	1.03	1.06	1.17
30%	0.75	0.75	0.75	1.05	1.02	1.07	1.15	1.02	1.05	1.15
31%	0.75	0.75	0.75	1.03	1.02	1.06	1.13	1.02	1.03	1.13
32%	0.75	0.75	0.75	1.02	1.02	1.06	1.11	1.02	1.02	1.11
33%	0.75	0.75	0.75	1.01	1.02	1.05	1.09	1.02	1.01	1.09
34%	0.75	0.75	0.75	1.00	1.02	1.05	1.08	1.02	1.00	1.08
35%	0.76	0.76	0.76	0.99	1.02	1.04	1.06	1.02	0.99	1.06
36%	0.76	0.76	0.76	0.98	1.01	1.04	1.05	1.01	0.98	1.05
37%	0.76	0.76	0.76	0.98	1.01	1.03	1.04	1.01	0.98	1.04
38%	0.76	0.76	0.76	0.97	1.01	1.03	1.02	1.01	0.97	1.02
39%	0.76	0.76	0.76	0.96	1.01	1.02	1.01	1.01	0.96	1.01
40%	0.76	0.76	0.76	0.96	1.01	1.02	1.00	1.01	0.96	1.00
41%	0.77	0.77	0.77	0.95	1.01	1.01	0.99	1.01	0.95	0.99
42%	0.77	0.77	0.77	0.95	1.01	1.01	0.99	1.01	0.95	0.99
43%	0.77	0.77	0.77	0.94	1.01	1.01	0.98	1.01	0.94	0.98
44%	0.78	0.78	0.78	0.94	1.00	1.00	0.97	1.00	0.94	0.97
45%	0.78	0.78	0.78	0.94	1.00	1.00	0.97	1.00	0.94	0.97
46%	0.78	0.78	0.78	0.94	1.00	0.99	0.96	1.00	0.94	0.96
47%	0.79	0.79	0.79	0.94	1.00	0.99	0.96	1.00	0.94	0.96
48%	0.79	0.79	0.79	0.93	1.00	0.98	0.96	1.00	0.93	0.96
49%	0.79	0.79	0.79	0.93	1.00	0.98	0.96	1.00	0.93	0.96
50%	0.80	0.80	0.80	0.93	1.00	0.98	0.96	1.00	0.93	0.96

Table A.4 (continued): Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Conventional Valves

Load	PM	$PM_{2.5}$	DPM	NO_x	SO_x	CO	HC	CO_2	N_2O	CH_4
51%	0.80	0.80	0.80	0.94	1.00	0.97	0.95	1.00	0.94	0.95
52%	0.81	0.81	0.81	0.94	1.00	0.97	0.95	1.00	0.94	0.95
53%	0.81	0.81	0.81	0.94	1.00	0.96	0.95	1.00	0.94	0.95
54%	0.82	0.82	0.82	0.94	1.00	0.96	0.95	1.00	0.94	0.95
55%	0.82	0.82	0.82	0.94	0.99	0.96	0.96	0.99	0.94	0.96
56%	0.83	0.83	0.83	0.94	0.99	0.95	0.96	0.99	0.94	0.96
57%	0.84	0.84	0.84	0.95	0.99	0.95	0.96	0.99	0.95	0.96
58%	0.84	0.84	0.84	0.95	0.99	0.95	0.96	0.99	0.95	0.96
59%	0.85	0.85	0.85	0.95	0.99	0.94	0.96	0.99	0.95	0.96
60%	0.86	0.86	0.86	0.95	0.99	0.94	0.97	0.99	0.95	0.97
61%	0.86	0.86	0.86	0.96	0.99	0.93	0.97	0.99	0.96	0.97
62%	0.87	0.87	0.87	0.96	0.99	0.93	0.97	0.99	0.96	0.97
63%	0.88	0.88	0.88	0.96	0.99	0.93	0.98	0.99	0.96	0.98
64%	0.89	0.89	0.89	0.97	0.99	0.93	0.98	0.99	0.97	0.98
65%	0.89	0.89	0.89	0.97	0.99	0.92	0.98	0.99	0.97	0.98
66%	0.90	0.90	0.90	0.98	0.99	0.92	0.99	0.99	0.98	0.99
67%	0.91	0.91	0.91	0.98	0.99	0.92	0.99	0.99	0.98	0.99
68%	0.92	0.92	0.92	0.98	0.99	0.91	0.99	0.99	0.98	0.99
69%	0.93	0.93	0.93	0.99	0.99	0.91	1.00	0.99	0.99	1.00
70%	0.94	0.94	0.94	0.99	0.99	0.91	1.00	0.99	0.99	1.00
71%	0.94	0.94	0.94	0.99	0.99	0.91	1.00	0.99	0.99	1.00
72%	0.95	0.95	0.95	1.00	0.99	0.91	1.01	0.99	1.00	1.01
73%	0.96	0.96	0.96	1.00	0.99	0.91	1.01	0.99	1.00	1.01
74%	0.97	0.97	0.97	1.00	0.99	0.91	1.01	0.99	1.00	1.01
75%	0.98	0.98	0.98	1.01	0.99	0.90	1.01	0.99	1.01	1.01

Table A.4 (continued): Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Conventional Valves

Load	PM	$PM_{2.5}$	DPM	NO_x	SO_x	CO	HC	CO_2	N_2O	CH_4
76%	0.99	0.99	0.99	1.01	0.99	0.90	1.01	0.99	1.01	1.01
77%	1.00	1.00	1.00	1.01	0.99	0.90	1.01	0.99	1.01	1.01
78%	1.01	1.01	1.01	1.01	0.99	0.91	1.01	0.99	1.01	1.01
79%	1.03	1.03	1.03	1.02	0.99	0.91	1.01	0.99	1.02	1.01
80%	1.04	1.04	1.04	1.02	0.99	0.91	1.01	0.99	1.02	1.01
81%	1.05	1.05	1.05	1.02	0.99	0.91	1.01	0.99	1.02	1.01
82%	1.06	1.06	1.06	1.02	0.99	0.91	1.01	0.99	1.02	1.01
83%	1.07	1.07	1.07	1.02	0.99	0.92	1.01	0.99	1.02	1.01
84%	1.08	1.08	1.08	1.02	0.99	0.92	1.00	0.99	1.02	1.00
85%	1.10	1.10	1.10	1.02	0.99	0.92	1.00	0.99	1.02	1.00
86%	1.11	1.11	1.11	1.02	0.99	0.93	0.99	0.99	1.02	0.99
87%	1.12	1.12	1.12	1.02	0.99	0.93	0.99	0.99	1.02	0.99
88%	1.13	1.13	1.13	1.02	0.99	0.94	0.98	0.99	1.02	0.98
89%	1.15	1.15	1.15	1.01	0.99	0.95	0.97	0.99	1.01	0.97
90%	1.16	1.16	1.16	1.01	0.99	0.95	0.97	0.99	1.01	0.97
91%	1.17	1.17	1.17	1.01	1.00	0.96	0.96	1.00	1.01	0.96
92%	1.19	1.19	1.19	1.00	1.00	0.97	0.94	1.00	1.00	0.94
93%	1.20	1.20	1.20	1.00	1.00	0.98	0.93	1.00	1.00	0.93
94%	1.22	1.22	1.22	0.99	1.00	0.99	0.92	1.00	0.99	0.92
95%	1.23	1.23	1.23	0.99	1.00	1.01	0.91	1.00	0.99	0.91
96%	1.24	1.24	1.24	0.98	1.00	1.02	0.89	1.00	0.98	0.89
97%	1.26	1.26	1.26	0.97	1.00	1.03	0.87	1.00	0.97	0.87
98%	1.28	1.28	1.28	0.97	1.00	1.05	0.86	1.00	0.97	0.86
99%	1.29	1.29	1.29	0.96	1.00	1.07	0.84	1.00	0.96	0.84
100%	1.31	1.31	1.31	0.95	1.00	1.08	0.82	1.00	0.95	0.82