Waterside Air Emission Inventory for the Port of Brisbane 2007/8

Final Report

May 2009

prepared by

AMCsearch LTD
WAY AHEAD !

AMC
AUSTRALIAN MARITIME COLLEGE

ABBREVIATIONS

General

AFOC	Actual fuel oil consumption (tonnes/h)
AMC	Australian Maritime College
AMCS	AMC Search Ltd
ARB	Air Resources Board California
AS	Actual vessel speed
Aux	Auxiliary engine
BAC	Brisbane Airport Corporation
BMP	Brisbane Marine Pilots
DCC	Australian Government Department of Climate Change
DG	Diesel generator
DWT	Deadweight tonnage
EPA	Environmental Protection Agency
GT	Gas turbine
GWP	Global warming potential
HHV	Higher heating value
HSD	High speed diesel engine
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardization
LF	Load factor
LHV	Lower heating value
LPG	Liquefied petroleum gas
MCR	Maximum continuous rating
MDO	Marine diesel oil (heavy distillate)
MGO	Marine gas oil (lighter distillate)
MSD	Medium speed diesel engine
MSQ	Maritime Safety Queensland
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
NGA	National Greenhouse Accounts
NPI	National Pollutant Inventory
OGV	Ocean going vessel
Pax	Passengers
PB	Port of Brisbane

PBC Port of Brisbane Corporation

PLA Port of Los Angeles

ppm Parts per million

RO Residual fuel oil (Heavy fuel oil, Intermediate fuel oil)

Ro-Ro Roll on roll off vessel

SFOC Specific fuel oil consumption (g/kWh)

SS Service speed

SSD Slow speed diesel engine

ST Steam turbine

TEU Twenty foot equivalent units

ULSD Ultra low sulphur diesel

Emissions

CO_2 Carbon Dioxide

CO_2e Equivalent to CO_2

CH_4 Methane

CO Carbon Monoxide

HC Hydrocarbons

NMVOC Non-methane volatile organic compounds

PM Particulate matter

PM_{10} Particulate matter less than 10 microns

$PM_{2.5}$ Particulate matter less than 2.5 microns

ROG Reactive organic gases

SO_2 Sulphur dioxide

NOx Oxides of nitrogen

N_2O Nitrous oxide

VOC Volatile organic compounds

Locations in the port

EB Entrance Beacons

FI Fisherman Islands

HAM Hamilton Berths

PBG Pilot Boarding Ground at Point Cartwright

QCL Queensland Cement Ltd Wharf

STS Transfer Anchorage

CONTENTS

Figures

Tables

ACKNOWLEDGEMENTS

This project would not have been possible without the considerable assistance given by a number of people. In particular, the following provided invaluable assistance:

Organisation	Name	Position	Assistance provided
Brisbane Marine Pilots	Steve Easton	Pilot	General assistance and advice during pilotage
	Chris Kline	General Manager	Provision of information on pilotage, berths, distances, and assistance to arrange trip on piloted port transit
Carnival Corporate Shipbuilding Southampton	Stephen Payne	Vice President Chief Naval Architect	Provision of information on cruise ships
Inchcape Shipping Services	Andreas Kaech	Cruise Operations Controller, Queensland	Provision of information on cruise ships
	Daniel Van Vliet	Port Manager	Provision of information on cruise ships
PB Towage	Tony Cousins	Chief Executive	Provision of information on tugs, and arrangements to visit tugs
	Evan Milne	Port Manager Brisbane	Provision of information on tugs, and arrangements to visit tugs
Port of Brisbane Corporation	Daniel Blackmore	Analyst - Trade & Economic	Provision of information on vessel movements, and on vessel types
	Arie Geelhoed	Senior Manager, Reclamation and Land Development	Provision of information on dredge *Amity*
	Sue Koreman	Sustainable Business Manager	PBC project leader Considerable assistance with provision of PBC information, and guidance on how to obtain information from other stakeholders
	Peter Nella	Senior Manager, Dredging and Channels	Provision of information on dredge *Brisbane* and a number of small PBC workboats

Organisation	Name	Position	Assistance provided
Maritime Safety Queensland	Stephen Geck	A/MVTM Brisbane Port Control	Assistance with obtaining information on vessel movements
	Deb Willmington	Maritime Officer VTM & Technology Unit	Provision of information on vessel movements
Royal Australian Navy	Steve Cole	RAN Environmental Manager	Provision of information on fuels used by RAN
	Glenn Green	Engineer Officer HMAS KANIMBLA	Provision of information on fuels used by RAN
	Tony Vine	Commanding Officer, Navy Headquarters, Tasmania	Provision of information on fuels used by RAN
Svitzer	Chris Barnes	Port Manager	Provision of information on Svitzer tugs
NDA	Jeff Garner	Training and Applications Development Consultant	Database programming

Authors

Laurie Goldsworthy, Research Leader (Marine Engines), Australian Maritime College, University of Tasmania

Martin Renilson, Director, Port Development Unit, Australian Maritime College, University of Tasmania

EXECUTIVE SUMMARY

Introduction

In order to develop a baseline from which to create and implement emission reduction strategies and track performance over time, the Port of Brisbane Corporation (PBC) commissioned AMC Search Ltd to conduct an inventory of air emissions from waterside activities at the port.

The scope of the project was to produce an inventory of waterside emissions and fuel consumption for the defined port limits of the Port of Brisbane (PB) for the 2007/8 financial year. The inventory includes air quality and greenhouse gas emissions for vessels related to port operations only, including ocean going vessels, tugs, pilot boats, and dredges etc.

Methodology

It was necessary to obtain information on all Ocean Going Vessel (OGV) movements within the port waters during this period. It was also necessary to obtain, or make assumptions on, the size and type of machinery for these vessels, and the appropriate load factors. Data gaps were filled where possible through liaison with PBC, Brisbane Marine Pilots, Maritime Safety Queensland and tug and dredge operators. Where necessary, broader assumptions based on vessel type and size were used where no suitable information was available.

Five different operating modes were identified: transit; manoeuvring; hotelling; anchorage; and repositioning. Each visit was defined as involving a number of movements, each movement comprising one of these operating modes.

For the transit movement, average speeds were calculated using the known distance between the pilot boarding ground and the entrance beacons. From this, average power loadings were obtained for the main engines by comparing the actual average speed with the vessel’s service speed. The total time was also used to obtain the contribution from the auxiliary engines. For each manoeuvring movement the individual times at the entrance beacons and the berth were used, together with the distances from the entrance beacons to the relevant berth, to give the average power loading.

To facilitate the inventory, PBC had conducted a survey of 121 ships visiting the port for a 3 month period and the results from this were used where appropriate. Further data were obtained for cruise ships from Carnival and Inchcape Shipping Services and various other data sources. Additional data on naval vessels were obtained from various sources.

An emissions model was developed to calculate fuel consumption, air quality and greenhouse gas emissions for the OGVs, from these inputs. This program could be used readily for updating the inventory.

The emissions from tugs, dredges and other workboats were calculated in the same program using information provided by PBC and the tug companies. Calculations were based on the supplied fuel consumption data.

Estimates were made of the upper and lower bounds on the reported totals, and of the potential for improvement in the accuracy of the inventory.

Results

During the year a total of 824 unique OGVs visited the port, and there were a total of 2,548 individual visits. The total time in port spent by container ships was greater than any other type. This was reflected in the fact that there were 1,060 visits by container ships during the year. The next most common vessel type to visit the port was tankers, with 473 visits. Total numbers of OGV visits by vessel type are shown in Figure ES.1.

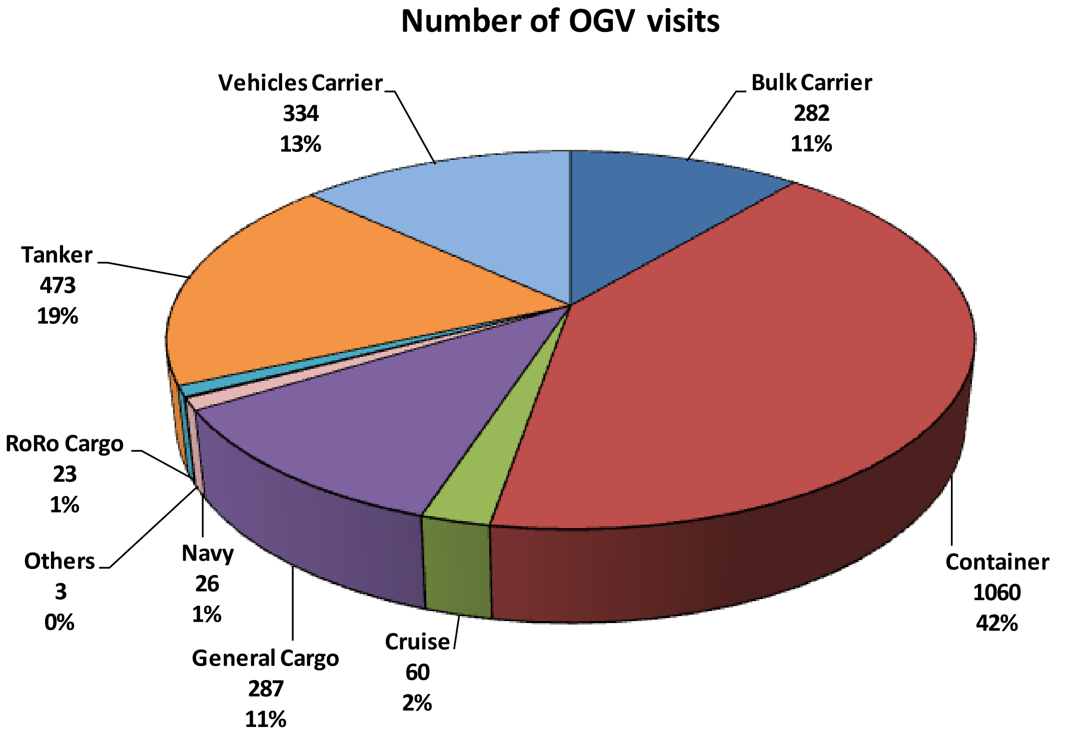


Figure ES.1 Number of OGV visits by vessel type

Average activity hours for OGV, by vessel type and operating mode, are presented in Figure ES.2. The length of time spent hotelling dominated the times for each vessel type in the port. Bulk carriers spent the greatest time in port on average, followed by tankers and general cargo ships. Tankers and general cargo ships spent a significant amount of time at anchorage on average.

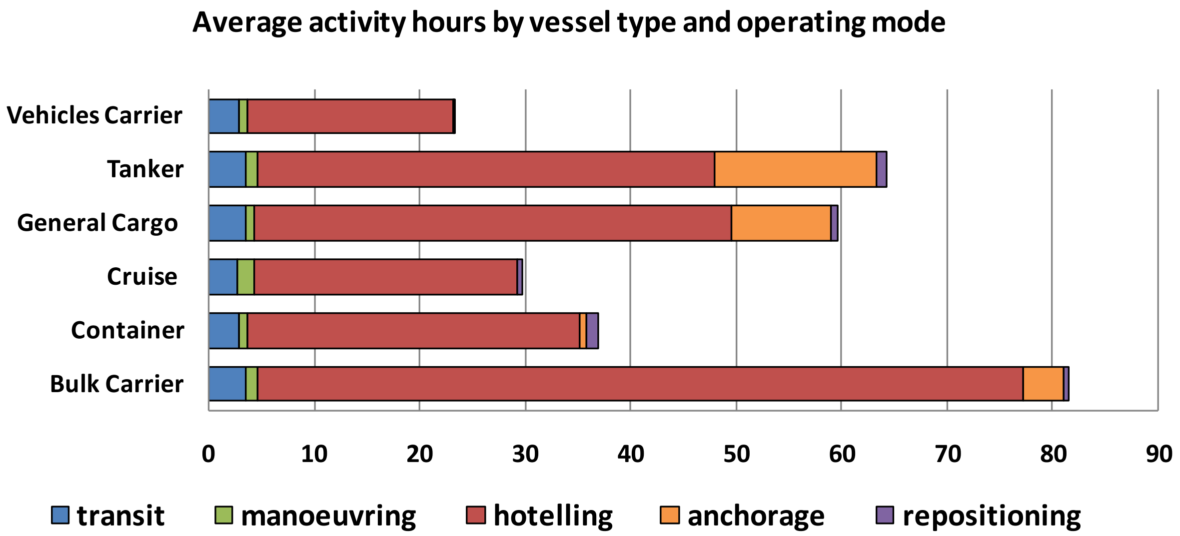


Figure ES.2 Average OGV activity hours by vessel type and operating mode

Total fuel consumption and emissions for all vessels for the inventory period are shown in Table ES.1.

Table ES.1 Total all vessels fuel consumption and primary air quality and greenhouse emissions – all values in tonnes

Machinery Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	total greenhouse gases CO_2e
OGV	45,995	2,845	230.5	119.4	266.7	258.9	2,262	143,866
Dredge	9,197	505.1	45.7	19.5	32.5	31.6	199.4	29,255
Tug	1,943	79.0	8.0	2.9	2.2	2.1	0.04	6,316
Total	**57,135**	**3,429**	**284.2**	**141.8**	**301.4**	**292.7**	**2,461**	**179,437**

OGVs accounted for about 81% of the fuel consumption and emissions during the year, dredges about 16% and tugs about 3%.

In the inventory period, the contract dredge *Volvox Asia* was used for capital works for PBC and the Brisbane Airport Corporation (BAC). The *Volvox Asia* consumed more than twice as much fuel and produced more than twice the emissions of the PBC dredges *Brisbane* and *Amity*, which are used for routine channel maintenance and some capital works.

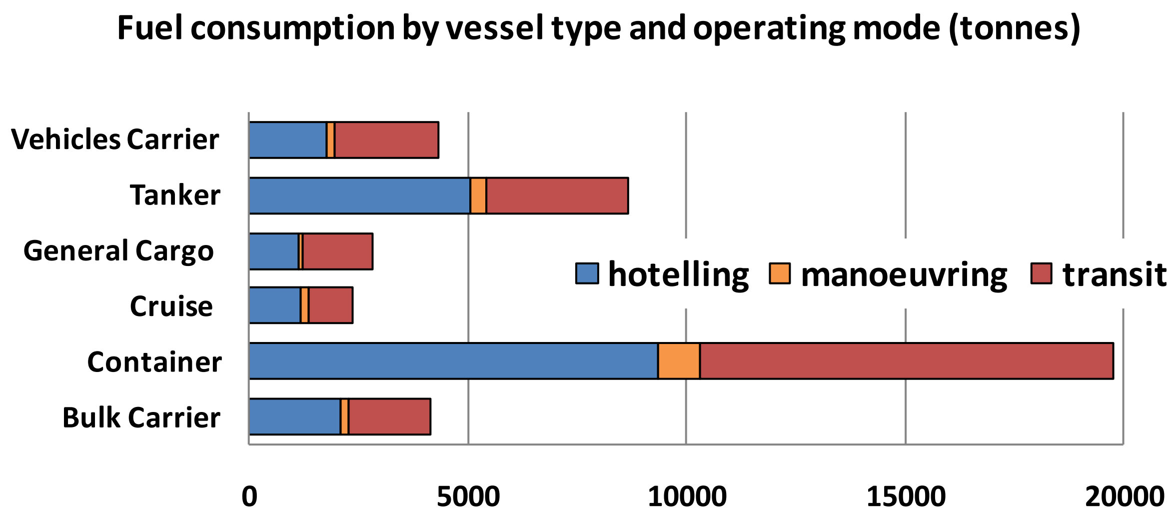
Total greenhouse gases are composed of CO_2, CH_4 and N_2O. When expressed as CO_2 equivalent, CH_4 represented 0.1% of total greenhouse gas emissions for the inventory year and N_2O represented 0.8% of total greenhouse gas emissions for the inventory year.

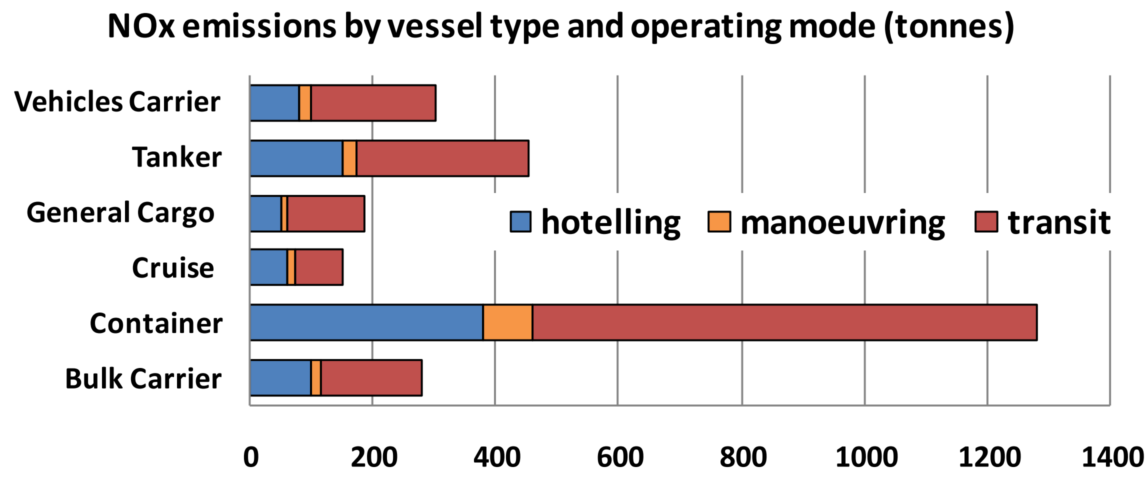
Total OGV fuel consumption, NOx and PM_{10} emissions by vessel type and operating mode for hotelling, manoeuvring and transit are presented in Figure ES.3.

Of the OGV fuel used during the year, almost half of this was in hotelling (47%), with about 43% in transit. All other operating modes (repositioning, anchorage, and manoeuvring) only accounted for about 10% of the total fuel consumed by OGVs.

Nearly 60% of the NOx emitted by OGVs was during transit, with approximately a further 30% being emitted during hotelling. The other operating modes together only accounted for about 10% of the NOx emitted by OGVs.

Container ships consumed the most fuel and produced the most emissions, followed by tankers. Tanker fuel consumption during hotelling was relatively high due to the use of inefficient steam turbines to drive cargo pumps. However, the quantities of tanker emissions were not in proportion to their fuel consumption, because the fuel was consumed in boilers which produce significantly lower emissions per mass of fuel burned than diesel engines. This is inherent in the different nature of the combustion processes in the two types of machinery.





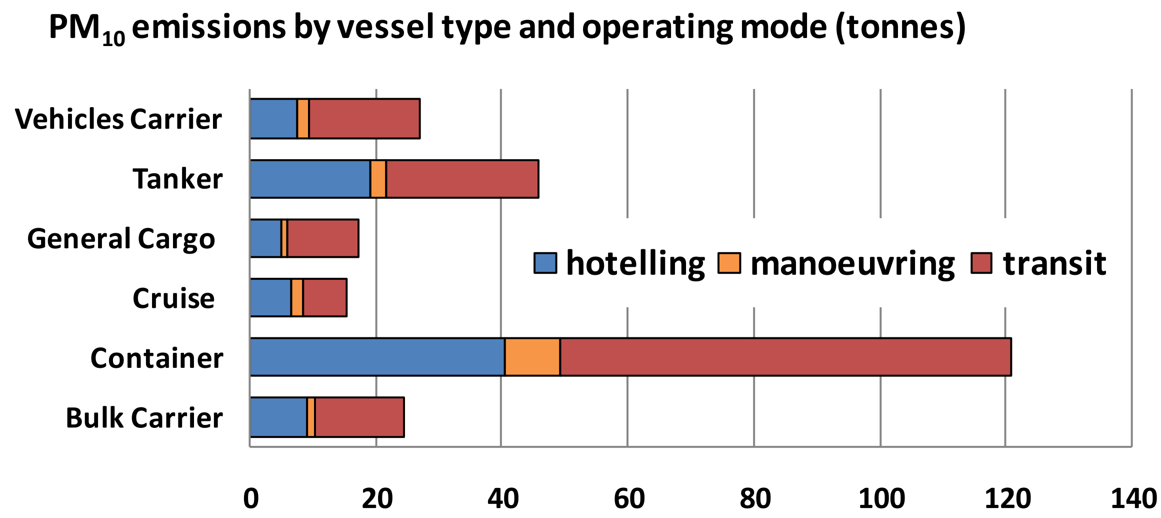


Figure ES.3 Total OGV fuel consumption, NOx and PM_{10} emissions by vessel type and operating mode.

Reducing emissions due to hotelling

Reductions in emissions while hotelling may be achieved by changing fuel type or by providing electricity to the vessel from shore to displace the running of onboard auxiliary generators (cold ironing).

The effect of these measures on the base case for OGVs was modelled. The results assume 100% uptake of the measure by all OGVs and, for cold ironing, exclude emissions attributed to generating the electricity from land-based sources.

The modelling of 100% uptake suggests that use of low sulphur distillate may reduce particulates and SO_2 by 70% and 96% respectively if adopted by all OGVs. The modelled reduction in particulates from cold ironing would be similar because the onboard boilers would still be operating, and using RO in the majority. For the same reason, the modelled effect of cold ironing on SO_2 would not be as great as the low sulphur distillate option.

Confidence ranges and improvements for future emissions inventories

Improved outcomes for future inventories could be achieved with more accurate information on the actual boiler and auxiliary engine power while hotelling. Therefore it was recommended that further surveying be conducted in the future, preferably by visiting vessels while berthed and interviewing the chief engineers. It was estimated that the confidence ranges for estimated total fuel consumption and greenhouse gas emissions in PB for the inventory year could be improved from ±20% to ±10% if the surveying was thorough. Confidence ranges for air quality emissions totals could be improved from ±30% to ±20%.

In-situ measurements of vessel emissions while hotelling could result in a further reduction in the air quality emissions totals confidence ranges to ±15%.

1. INTRODUCTION

1.1 General

Trade through the Port of Brisbane (PB) has grown dramatically over the last 10 years. As traffic increases, so do the greenhouse gas emissions and air pollution. In order to develop a baseline from which to create and implement emission reduction strategies and track performance over time, the Port of Brisbane Corporation (PBC) commissioned AMC Search Ltd (AMCS) to conduct an inventory of air emissions from waterside activities at the port.

1.2 Scope

The scope of the project was to produce an inventory of waterside emissions and fuel consumption for the defined port limits of the PB for the 2007/8 financial year.

The inventory includes air quality and greenhouse gas emissions for vessels related to port operations only, including ocean going vessels (OGVs), tugs, pilot boats, and dredges etc. Vessels such as yachts and fishing boats, not associated with the operations of the port, are excluded.

The inventory covers activities of all these vessels in the defined port limits for the PB, bounded by the pilot station at Point Cartwright, East to Morton Island, and up the Brisbane River as far as Breakfast Creek.

Typical OGVs that visit the PB include: container ships; bulk carriers; tankers; Ro-Ro cargo ships; general cargo ships; vehicles carriers; cruise ships and naval vessels. Refrigerated ships are not identified as a separate category as refrigerated goods are transported by container ships in refrigerated containers.

By far the majority of these ships are powered by single low speed diesel engines, as is the normal practice for such vessels. Most also have a number of medium speed auxiliary engines for providing power for hotelling, operation of the bow thrusters, and/or cargo handling equipment.

Many of the cruise ships have diesel/electric propulsion, where the diesel engines provide electric power for both propulsion and hotel loads.

Tankers make use of steam driven boilers to pump cargo and ballast.

The two PBC dredges that operate in the port waters are the *Brisbane* and the *Amity*. In addition, during the 2007/08 financial year the *Volvox Asia* was used to conduct dredging operations for capital works for PBC and BAC. Information on fuel usage and engine type was provided for the dredges by PBC.

Two tug companies operate at PB: PB Towage, and Svitzer. Information on fuel usage and engine types was provided by these companies, and this was used together with assumed operating profiles to obtain emissions.

The inventory is aligned with detailed inventories such as have been conducted in a number of ports in the USA, to the extent possible within the limitations of time and data availability. Air emissions inventoried included: particulate matter (PM_{10} and $PM_{2.5}$); oxides of nitrogen; hydrocarbons; sulphur dioxide; and carbon monoxide. Greenhouse gasses are reported in equivalent tonnes of carbon dioxide.

1.3 Machinery Types

1.3.1 Main engines

The most common type of main engine for OGVs is the slow speed two stroke diesel. This is large and heavy, and operates at revolutions suitable for directly driving the ship's propeller, negating the need for a gearbox, with associated losses. It is very efficient, but as it is necessary to stop the engine and start it in reverse to give astern thrust it makes manoeuvring in port difficult, unless the ship is fitted with a controllable pitch propeller.

The other common type of main engine is the medium speed four stroke diesel. This is smaller and lighter than the slow speed equivalent for the same power. As it operates at higher revolutions it requires a reduction gearbox between the engine and the propeller. Again, it is necessary to start the engine in reverse to give astern thrust.

Some ships use diesel/electric propulsion where the diesel engine is used to generate electrical power, which drives an electric motor which in turn drives the propeller. This gives quick control of propeller rpm, particularly important for manoeuvring. Such a propulsion system can also be used to generate electrical power for other purposes such as hotelling, bow thrusters and cargo handling.

A small number of ships use gas turbines as their main propulsion engine. Gas turbines are much lighter than diesels for the equivalent power, however they generally have higher fuel consumption. Navy vessels often use a combination propulsion system with large gas turbines for high speed sprint, and either smaller gas turbines, or more usually, medium speed diesels for low speed cruise. Some cruise ships use gas turbines to generate electrical power for either propulsion or hotel load.

A very small number of naval ships visiting the port during the inventory period used steam turbines for their main propulsion. In addition, one nuclear submarine visited the port. The nuclear propulsion plant generates steam, which in turn drives a steam turbine, directly connected to the single propeller.

1.3.2 Auxiliary engines

Most ships have auxiliary engines to provide electricity for hotel load and other purposes. These are normally medium speed diesels.

Generally a number of medium speed diesels will be installed, rather than one large one, allowing for redundancy, and to ensure that when minimal power is required the engine is not operating at low load, which would not be very efficient.

1.3.3 Boilers

Boilers are required to supply hot water and for heating the residual fuel oil used by the main engines, as otherwise it is too viscous to be used. In addition, larger tankers (over about 80,000 dwt) use boilers to drive steam driven cargo and ballast pumps, and also for heating the cargo oil.

When the main engine is running a boiler can be driven using the waste heat from the main engine exhaust. However, when in port an oil fired auxiliary boiler is required.

All air quality emissions from boilers are lower than from diesel engines for the same mass of fuel burnt.

1.4 Ship Types

OGVs that used PB during the inventory period were categorised as follows: bulk carrier; container ship; cruise ship; general cargo; navy; Ro-Ro cargo; tanker; and vehicles carrier.

1.4.1 Bulk carriers

Bulk carriers are designed to carry cargo, such as cement, coal, iron ore, sugar and woodchips, in bulk. The cargo is loaded and unloaded using either grabs or conveyor belts. They are categorised by the deadweight (dwt) that they can carry, with large bulk carriers being up to 400,000 dwt, although such large bulk carriers are very limited in what ports they can visit, and they are not able to visit PB. The average size of bulk carrier visiting PB during the inventory period was about 45,000 dwt.

They typically operate in a loaded condition on one leg of a voyage, and in ballast on the return journey. Often bulk carriers are draught restricted depending on the port they operate into. When in ballast they are typically trimmed by the stern and have draughts which are far less than when in the full load condition. Care needs to be taken when loading and unloading them to avoid overstressing the hull girder, and consequently a loading/ballasting sequence needs to be adhered to.

Bulk carriers usually are propelled using a direct drive slow speed diesel engine connected to a single fixed pitch propeller. In addition, they have separate auxiliary engines to supply power for hotelling and cargo handling (when fitted with their own cargo cranes).

Typical service speeds for bulk carriers are in the range of around 15 knots.

A typical bulk carrier is illustrated in Figure 1.1.

Figure 1.1 Bulk Carrier (courtesy of Gwyn Mason)

1.4.2 Container ships

Container ships are designed to carry cargo in a number of standard containers, either 20 foot or 40 foot long. These are stored in specially designed guides under the deck, and stacked on the hatch covers four or five high. They are categorised by the number of equivalent twenty foot containers (TEUs) that they can carry. The largest container ships are capable of carrying over 15,000 TEUs, although these ships would be too large to visit PB. The largest container ship to visit PB in the inventory year was 5,089 TEU.

Container ships are able to carry a wide range of cargo, and typically have very short turnaround times in port. Containers are loaded and unloaded using specially designed cranes. Although some container ships have their own cranes, most rely on dock side cranes. Most container vessels are configured to also carry a number of refrigerated containers.

A new class of container ship has been developed recently which is not fitted with hatch covers. This permits quicker loading and unloading, and hence even shorter turnaround times.

Container ships generally operate close to full load condition, depending on the available water depth at the ports that they are visiting. Because of the height of the containers stacked on deck, stability can be an issue, and care needs to be taken when loading them.

Container ships are generally propelled by direct drive slow speed diesel engines connected to a single fixed pitch propeller, however many smaller container ships have controllable pitch propellers, which make manoeuvring in port easier. Also, most container ships have one or more bow thrusters, again to make manoeuvring in port easier. They have separate medium speed diesel auxiliary engines to supply power for hotelling, bow thrusters, cargo handling (when fitted with their own cargo cranes) and refrigerated containers.

Typical service speeds for container ships are in the range of 20 – 25 knots, although the recent increases in fuel costs have meant that a number of these are operating in ‘slow steaming’ mode to save fuel.

A typical container ship is illustrated in Figure 1.2.

Figure 1.2 Container Ship

1.4.3 Cruise ships

Cruise ships are designed to carry paying passengers, and to provide considerable comfort on board, with appropriate amenities. Large cruise ships can carry over 4,000 passengers, as well as over 1,000 crew. Consequently the hotel load for such vessels can be substantial.

They regularly call at ports, and so considerable effort is made in their design to enable them to be as manoeuvrable as possible. Most are twin screw and are fitted with one or more sets of thrusters (bow and stern). The more recent ones are propelled using azimuthing thrusters, which combined with bow thrusters makes them very manoeuvrable indeed.

Although older cruise ships use twin medium speed diesel engines connected to twin controllable pitch propellers, more modern ones make use of diesel/electric propulsion, where the medium speed diesel engines provide the power for both propulsion and hotel load. In some cases additional power is generated using gas turbines.

Cruise ships typically have speeds around 20 knots.

A typical cruise ship is illustrated in Figure 1.3.

Figure 1.3 Cruise Ship (courtesy of Gwyn Mason)

1.4.4 General cargo ships

General cargo ships carry a diverse range of cargos in a range of formats. Some can also carry containers. They are categorised by the deadweight that they can carry.

General cargo ships are generally propelled by direct drive diesel engines connected to a single fixed pitch propeller, however some smaller ones may have controllable pitch propellers, which make manoeuvring in port easier. About half of the general cargo ships that called at the port during the inventory period used slow speed diesels for their main propulsion, with the other half using medium speed diesels.

They have separate medium speed diesel auxiliary engines to supply power for hotelling, bow thrusters and cargo handling.

General cargo ships typically have speeds in the range of around 15 knots.

A typical general cargo ship is illustrated in Figure 1.4.

Figure 1.4 General Cargo Ship (courtesy of Gwyn Mason)

1.4.5 Navy ships

A range of different naval ships, from small patrol boats to a large aircraft carrier visited the port in the inventory period. In addition, a nuclear powered submarine visited the port during the inventory period.

Naval ships can be powered by: medium speed diesels; gas turbines; steam turbines, or nuclear propulsion. They have a range of displacements and speeds. As carrying capacity is not a main feature of naval vessels they are not generally categorised by deadweight. Consequently, displacement is used as a measure of ship size in this report for naval vessels, rather than deadweight.

1.4.6 Ro-Ro cargo ships

Ro-Ro cargo ships are designed to load and unload cargo on wheeled trailers using a loading ramp. Often such cargo is loaded in containers on trailers, but it can comprise of other types of cargo on trailers. Lane length can be used to categorise such vessels, but the carrying capacity is measured using deadweight, as with other cargo vessels.

Ro-Ro cargo vessels are fitted with a ramp to permit the cargo on trailers to be loaded and unloaded. These need to be aligned with suitable dockside facilities.

Like container ships Ro-Ro ships usually have very quick turnaround times in port.

Ro-Ro cargo vessels usually use a single slow speed diesel engine directly driving a single propeller. Often one or more bow thrusters are fitted to make manoeuvring in port easier. They have separate medium speed diesel auxiliary engines to supply power for hotelling, and bow thrusters.

Typical service speeds for Ro-Ro cargo ships are in the range of 20 knots.

A typical Ro-Ro cargo ship is illustrated in Figure 1.5.

Figure 1.5 Ro-Ro Cargo Ship

1.4.7 Tankers

Tankers are designed for carrying liquid cargo in bulk. Within the general category of tanker there are a range of specialisations including: crude oil carriers; oil product carriers; products carriers; and gas carriers. Tankers are categorised by the deadweight that they can carry, with large crude oil carriers having deadweights over 500,000 dwt. Because of their deep draughts these large tankers cannot use many ports, and do not use the PB. The size of the average tanker visiting PB is about 50,000 dwt.

Tankers unload their liquid cargo using on board cargo pumps. For the larger vessels these are steam driven pumps, with the steam provided by boilers, whereas for smaller tankers the pumps can be hydraulically driven. These pumps are also required for discharging ballast, when taking on cargo.

They normally operate in a loaded condition on one leg of their journey and on ballast on the return journey. When in ballast they are typically trimmed by the stern and have draughts which are much less than in full load.

Tankers usually are propelled using a direct drive slow speed diesel engine connected directly to a single fixed pitch propeller. They have separate auxiliary engines to supply power for hotelling, and boilers to keep their cargo oil heated and to provide steam for the cargo pumps (if they are steam driven).

The typical service speed for tankers is around 15 knots.

A small LPG carrier is illustrated in Figure 1.6.

A typical tanker is illustrated in Figure 1.7.

Figure 1.6 Small LPG Carrier

Figure 1.7 Tanker (courtesy of Gwyn Mason)

1.4.8 Vehicles carrier

Vehicle carriers are purpose built to carry cars as cargo. They have a number of decks spaced to optimise their ability to carry cars, together with ramps for loading and unloading. As cars are not very dense, a vehicle carrier has a very large superstructure, to give the large enclosed volume required for the number of cars that it can carry in its deadweight.

Vehicle carriers are usually propelled by a diesel engine directly coupled to a single propeller, with auxiliary diesels to provide power for hotel load.

A typical vehicle carrier is illustrated in Figure 1.8.

Figure 1.8 Vehicle Carrier

1.5 Dredges

Dredges are specially designed vessels for dredging the channels, either to maintain a required depth (maintenance dredging) or to increase the depth for the purposes of port expansion (development dredging).

There are a variety of different techniques used for dredging including: suction; trailing suction; cutter suction; bucket; and grab.

The *Amity* and the *Brisbane* are both owned by PBC. The Amity is a cutter suction dredger and is used for developing berths and associated reclamation at the river mouth, whereas the *Brisbane* is a trailing suction hopper dredger used for maintenance and development dredging.

The *Volvox Asia* is an ocean going trailing suction dredge owned by the Dutch dredging contractor Van Oord. It is used as required at a number of different ports around the world. The *Volvox Asia* was used for capital works in PB during the inventory period.

The *Volvox Asia* uses a medium speed diesel as main propulsion and high speed diesels for auxiliaries, whereas the *Amity* and the *Brisbane* only use high speed diesel engines.

PBC dredge *Brisbane* is illustrated in Figure 1.9.

Figure 1.9 PBC dredge *Brisbane*

1.6 Tugs

Shiphandling tugs are designed for handling OGVs when they are in port. Tugs are necessary as many OGVs are not capable of being manoeuvred at low speed into and out of berths. They also provide a safety role, as they are available as back up if problems occur with either the OGV bow thrusters or main engines. Many tugs are also fitted with firefighting capabilities for use in the event of a fire.

Modern shiphandling tugs are normally equipped with twin screw azimuthing propulsion. The propellers can either be located forward (tractor) or aft (reverse tractor). Generally, tractor tugs operate over the stern, whereas reverse tractor tugs operate over the bow.

Although some tugs are fitted with vertical axis propulsion (Voith Schneider) most in Australia have azimthing Z drive propulsion. All the tugs at BP are reverse tractor using azimuthing propulsion – often referred to as: Azimuthing Stern Drive (ASD) tugs.

The main propulsion engines on the tugs in PB are either medium speed, or high speed diesels operating on ULSD.

A typical modern tug is illustrated in Figure 1.10.

Figure 1.10 Tug

1.7 Fuels

Ships primarily use low cost residual fuel oil (RO), which is based on the residues from the crude oil refining process. It is sometimes called heavy fuel oil. This fuel needs to be heated to make it fluid enough for introduction to the engines and boilers. RO is dark coloured and opaque and has a characteristic smell. The sulphur content is generally high, around 2.5%, as the sulphur in the crude oil tends to concentrate in the refinery residues.

Distillates are also used to some extent. They are extracted from crude oil by various distillation processes. They do not need to be heated and are generally clear and light coloured. Sulphur content is generally lower than RO, around 0.5%. Marine Diesel Oil (MDO) is the heaviest of the distillates, followed by Marine Gas Oil (MGO). MDO and MGO are not generally available in Australia and are carried into Australia by the ships which use them. MDO and MGO are often used to fuel the auxiliary diesel engines, which may not be designed to operate on RO. Ultra Low Sulphur Diesel (ULSD) is the distillate produced for land based diesel powered transport in Australia. It has negligible sulphur content and is used domestically, instead of MDO or MGO. The PBC dredges, tugs and Australian naval vessels generally use ULSD.

RO results in higher emissions of sulphur and particulate matter from engines and boilers than distillates.

1.8 Data sources

Ship movement data were obtained from both the PBC and Maritime Safety Queensland (MSQ) records. These were compared, and merged to develop a single database of movements which could be interrogated to give the required information.

Information on ship and engine characteristics were obtained for the ships identified in the movement data using the Lloyd's Seaweb database[1]. In addition, use was made of the results of a survey conducted by PBC of 121 ships visiting the port during the inventory period, and further data were obtained for cruise ships and for naval vessels.

Data gaps have been filled where possible through liaison with PBC, Brisbane Marine Pilots (BMP), Maritime Safety Queensland (MSQ) and tug and dredge operators. Where necessary, broader assumptions based on vessel type and size were used where no suitable information was available.

Information on fuel usage and engine type was provided for the dredges by PBC and for the tugs by PB Towage and Svitzer.

1.9 Emissions

An overview of the emissions estimation methodology is given in the body of the report, with a detailed description, including all data sources and assumptions, in the appendices.

The report includes information on vessel characteristics and movements for those vessels that visited PB during the year, together with detailed information on the following by vessel type and operating mode:

- mass of primary air quality emissions:
  - Oxides of Nitrogen (NOx),
  - Carbon Monoxide (CO),
  - Hydrocarbons (HC),
  - Particulate Matter (PM_{10}, $PM_{2.5}$),
  - Sulphur Dioxide (SO_2);
- mass of greenhouse gas emissions as CO_2 equivalents:

- Carbon Dioxide (CO_2),
- Methane (CH_4),
- Nitrous Oxide (N_2O);

- fuel consumption; and
- mass of fugitive Volatile Organic Compounds (VOC).

Air quality emissions are important for their effect on air quality in areas close to the source. Greenhouse gas emissions are important for their direct contribution to global warming. They do not significantly affect local air quality. CH_4 emissions are the component of total HC emissions which contribute directly to global warming. The air quality emissions also make a small indirect contribution to global warming.

2. METHODOLOGY

2.1 Introduction

The purpose of this inventory is to quantify the air pollution and greenhouse gas emissions attributed to ships utilising the port for the base year 2007/2008. This information was categorised by: vessel type; emissions; and mode of operation (transit, manoeuvring, hotelling, anchorage, or repositioning).

To do this it was necessary to obtain information on all Ocean Going Vessel (OGV) movements within the port waters during this period. An overview of the process of obtaining this information is given in section 2.2, and a detailed description is given in Appendix A.

It was also necessary to obtain, or make assumptions on, the size and type of machinery (main and auxiliary) for these vessels, and the appropriate load factors.

From these inputs, the relevant air quality and greenhouse gas emissions were calculated. An overview of the calculation methodology is given in section 2.3, and a detailed description is given in Appendix B.

Figure 2.1 is a schematic of the process.

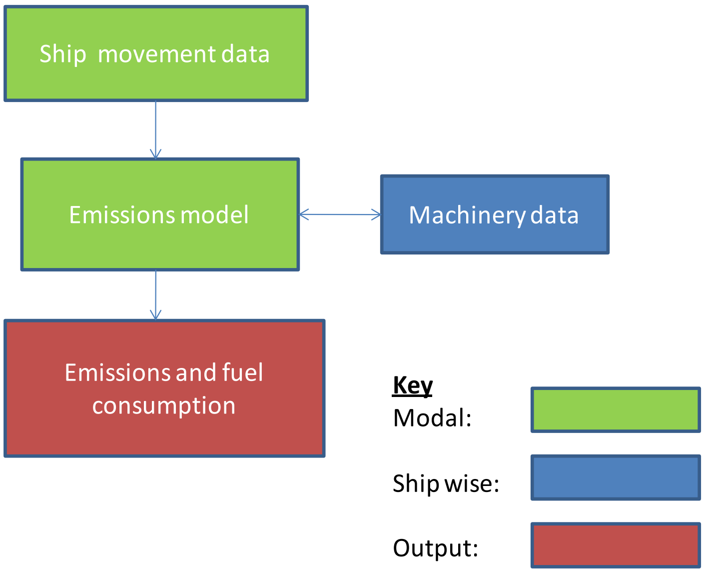


Figure 2.1 Schematic of methodology

The emissions from tugs, dredges and other workboats were obtained separately using information provided by the tug companies and PBC.

To assist with the information gathering two team members visited Brisbane for a week in early January 2009. The opportunity to visit tugs and a ship during manoeuvring was taken. Discussions were held with staff at: PBC; BMP; PB Towage; Svitzer; and MSQ.

2.2 Ocean Going Vessel Movements

2.2.1 Introduction

Each ship enters the port precincts at the Pilot Boarding Ground (PBG), Point Cartwright, as shown in Figure 2.2. It then transits across the bay until it reaches the entrance beacons (EB) near the river mouth. From there the ships proceed at reduced speed to one of a number of berths. Tugs assist the berthing operations, as required. The ships remain at berth while loading or discharging cargo and then manoeuvre away from the berth, with the assistance of tugs as required, and then proceed out through the EB and on to the PBG.

Ships also occasionally are required to anchor in the anchorage area outside the river.

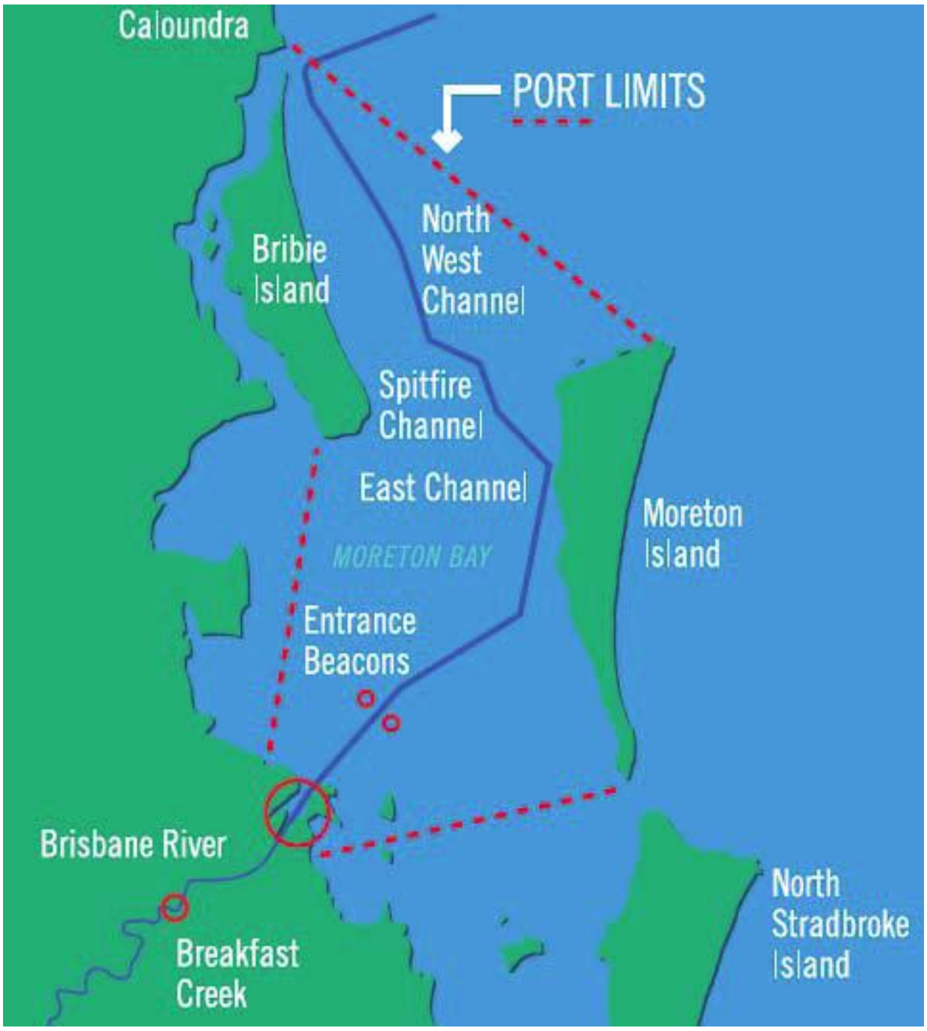


Figure 2.2 Chart of port waters (courtesy of PBC)

2.2.2 Operating modes

Five different operating modes were identified: transit; manoeuvring; hotelling; anchorage; and repositioning. Each visit was defined as involving a number of movements, normally comprising: an inbound transit movement; an inbound manoeuvring movement; a hotelling 'movement'; an outbound manoeuvring movement; and an outbound transit movement. In addition, for some vessels a visit also involved one or more anchorage 'movements' and/or one or more re-positioning movements.

Transit

Transit was defined as being between the PBG at Point Cartwright, and the EB.

Manoeuvring

Manoeuvring was defined as occurring between the EB and the allocated berth. This is the closest data point to the actual berths and it was observed that between the berth and the EB the main engines are in a low load operating mode. Between the PBG at Point Cartwright and the EB ships move at speeds close to service speed.

Hotelling

Hotelling was defined as being when the ship is alongside a defined berth. Times at anchorage were not included in this category.

Anchorage

Anchorage was defined as when ships are anchored, usually in the anchorage outside the river. The auxiliary engines will be running to provide hotel power only – there will be no cargo operations. This mode is distinguished from the 'hotelling' mode as it is not possible to provide shore power to vessels at anchor.

Repositioning

Repositioning is defined as when a ship is moved from one location to another during a visit.

2.2.3 Calculations

Times were obtained from the movement records at the PBG, the EB and the berth for each individual movement for every visit.

For the transit movement, average speeds were calculated using the known distance between the PBG and the EB. From this, average power loadings were obtained for the main engine by comparing the actual average speed with the vessel's service speed. The total time was also used to obtain the contribution from the auxiliary engines.

Issues such as: speed variation on the transit; the effect of displacement; and the additional power required due to shallow water, wind and waves were not allowed for. These factors may need to be considered if a further, much more detailed, study is to be undertaken.

For each manoeuvring movement the individual times at the EB and the berth were used, together with the distances from the EB to the relevant berth, to give the average power loading. The distances used for each berth are given in Table A.1 in Appendix A, where more detailed information is given regarding the calculation of the manoeuvring data.

For a small number of the movement records the times at the way points were inconsistent. For example, often times just after midnight were given the previous day's date. These were generally very obvious and were altered manually. There were also a small number of movements where the times were not thought to be realistic, and for these cases the transit time was amended manually to limit it to between two and four hours.

2.3 Emissions and Fuel Consumption

2.3.1 Ocean Going Vessels

A Microsoft Access database program was developed to handle the data associated with the OGVs.

The PBC ship movement data were input into the database program and established as one part of the database.

For the ships identified in the movement data, PBC provided detailed information on ship and engine characteristics using Lloyd's Seaweb database[1][1]. These data were read into the database program and interrogated for all the relevant information for the ships listed in the PBC and MSQ movement data files.

The results of the PBC survey were established as another element of the database. These data were compared with the corresponding data from the Lloyd's database, and a report generated on the correspondence. Where relevant, the PBC survey data were substituted for the corresponding Lloyd's data.

The PBC survey data were analysed for values such as fuel type and average fuel sulphur content for ships visiting PBC, which were used for ships where actual values were not available.

Tables of emissions factors, default fuel consumption and load by vessel type and mode, *etc* were entered and interrogated by the database program where required. If specific values were not available for a given vessel, the database program substituted default values.

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[1] superscript numbers indicate the reference number in the Reference section

Finally, the emissions and fuel consumption were calculated and each calculated value remained linked to the mode and vessel identification and thus to all the other vessel characteristics. This enabled sorting of outputs according to the reporting requirements.

Sample calculations were made by hand to verify the database program calculations.

Additional detail is given in Appendix B.

2.3.2 Dredges

For the dredges, which consisted of the PBC dredges and a contract dredge, data were obtained for the inventory period from PBC. These included total hours of operation and total fuel consumption, as well as main and auxiliary engine type and size, and fuel type for each dredge.

The load factor and Specific Fuel Oil Consumption (SFOC) during dredging operations was estimated by liaison with PBC. Dredges are designed to operate at high load factors in all phases of operation, so full load SFOC and emissions factors were used.

Emissions were calculated directly from the given fuel consumption. See Appendix B for further details.

2.3.3 Tugs

For each ship call there may be tugs used for either the arrival, the departure, or both. Tugs may also be used for movements within the port.

The actual power usage for each tug movement differs depending on: vessel size; vessel type; whether the vessel is fitted with a bow thruster; the number of tugs being used; and the environmental conditions at the time. It was therefore decided that a more accurate estimate of the emissions from the tugs during the year would be obtained using total fuel usage, which was provided by the tug companies on a commercial in confidence basis.

Data for the actual machinery used on the tugs was also provided by the tug companies.

Emissions of CO_2 and SO_2 were calculated from the total fuel consumed, the type of fuel and the sulphur content. However, the emissions of NOx, PM, HC and CO may depend on engine load factor in the three tug modes (tug idling, transit, towing). The estimation of typical load cycles was not possible, so overall load factors were applied. These were calculated from supplied actual fuel consumption rate and full load fuel consumption rate, on a monthly basis for each individual tug.

Further details of the methods used, and the assumptions are provided in Appendix B.

2.3.4 Other Vessels

Other vessels include pilot boats and port workboats. These were not included as their contributions to total port precinct fuel consumption and emissions were negligible.

2.4 Vessel Survey

To facilitate the inventory, PBC conducted a survey of ships visiting the port from June to August 2008, partially outside the inventory period. Questionnaires were handed to each ship by the BMP. Data on 121 unique vessels were obtained. Further data were obtained for cruise ships from Carnival and Inchcape Shipping Services and various other data sources. Additional data on naval vessels were obtained from various sources. The results are analysed in Appendix C.

2.5 Assumptions and Limitations

The inventory was based on detailed information on individual ship movements and characteristics. Not all details were available and assumptions were needed.

2.5.1 Movement Data

In general the movement data were clear for each vessel visit, so only a small amount of data adjustment was required.

2.5.2 Main Engine Load Factor

The estimation of main engine load factor during transit was straightforward and fairly precise, as it was based on the propeller law relationship between ship speed and engine power.

2.5.3 Auxiliary Engine Power

There is uncertainty as to the power produced by the auxiliary engines in the various operating modes. Considerable use was made of default values published in US studies, where actual values were not available in the survey data.

2.5.4 Fuel Type and Sulphur Content

Reasonable information on fuel type and sulphur content was obtained from the PBC survey data. This allowed the setting of representative average fuel sulphur contents by mode. Unless survey data on a specific vessel indicated otherwise, the fuel type was assumed to be RO in the main engine and boiler, but with port average sulphur content. The auxiliary engine default fuel was a modelled as a hybrid of RO and MGO/MDO.

2.5.5 Boilers

Boiler powers are probably the least well defined of all the default data. For tankers visiting the PB, extra information from a number of sources was used to benchmark actual tanker boiler fuel consumption, given that the tanker boiler fuel consumption and emissions represent a significant proportion of the port total.

It was assumed that boilers were used while hotelling and at anchorage only, but tanker boilers were only used at full power at berth when pumping cargo or ballast. It was assumed that tanker cargo was heated by waste heat boilers on the main engine exhaust before entering the port and so did not require significant additional fuel consumption.

2.5.6 Specific Fuel Oil Consumption

Manufacturer data tends to underestimate actual full load SFOC. Generally, published default values of SFOC by engine type and fuel type were used. The effect of engine load on SFOC was not considered, due to the lack of data and given that low load operation occurs primarily during manoeuvring, which represents a small proportion of the total fuel consumption and emissions.

2.5.7 Emissions Indices

The set of emissions indices used in the present study are aligned with the latest US studies. Some uncertainty remains as the effect of engine design, age and state of maintenance.

2.5.8 Survey

The PBC vessel survey was a valuable source of port specific information and it is recommended that further surveying be done in the future.

2.5.9 Uncertainties

The uncertainties in the reported totals are analysed in Section 4.

Further details on assumptions are given in Appendix B.

3 RESULTS

3.1 Ocean Going Vessel Characteristics

3.1.1 Unique Vessels

The total number of unique OGV that visited PB in 2007/08 was 824.

3.1.2 Average characteristics

Average OGV characteristics by vessel type (based on the number of unique vessels, not weighted by number of visits) are presented in Table 3.1. Also presented are the number of unique vessels and the total number of visits under each vessel type.

Table 3.1 OGV Vessel Characteristics

Vessel type	Twenty foot equivalent units (TEU)	Unique vessels	Visits	Ave year built	Average deadweight (tonnes)	Average service speed (knots)	Average main engine power (kW)	Average auxiliary engine power (kW)
Bulk Carrier		157	282	1999	45,093	14	7,729	1,540
Container 1000	<1000	10	121	1992	12,991	17	7,455	1,180
Container 2000	1000 - 2000	46	277	2001	22,490	20	14,608	2,616
Container 3000	2000 - 3000	90	413	1998	35,949	22	23,137	4,316
Container 4000	3000 - 4000	20	101	2000	45,871	23	30,480	4,848
Container 5000	4000 - 5000	25	147	2004	52,558	25	42,158	8,171
Container 6000	5000 - 6000	1	1	2007	68,235	24	41,130	7,342
All Container		**192**	**1,060**	**1999**	**34,893**	**21**	**23,612**	**4,267**
Cruise		17	60	1993	6,140	21	33,218	**9,366
General Cargo		96	287	1995	18,028	15	6,567	1,107
Navy		24	26	1991	*11,518	22	16,230	2,678
Other***		3	3	1986	3,715	13	3,949	425
Ro-Ro Cargo		10	23	1999	21,665	21	16,927	3,935
Tanker		169	473	2002	54,367	15	9,013	1,452
Vehicles Carrier		156	334	1996	18,045	19	13,017	2,898
All OGV		**824**	**2,548**	**1998**	**34,131**	**18**	**13,408**	**2,647**

* For naval vessels, the average displacement is used in this column.

** For cruise ships 9 of the 17 visitors were diesel/electric. For these diesel/electric vessels, main engines are run in port to generate ship electricity, rather than using separate auxiliary generators. In such cases, the auxiliary power represents the proportion of main engine power available for hotel load.

***"Other" included an Offshore tug/supply ship, a Research ship and a Heavy load carrier

The numbers of OGV visits by vessel type are illustrated in Figure 3.1 as percentages. Container ships were the most frequent ship type, followed by tankers then vehicle carriers. Container ships in the 2000 to 3000 TEU range (Container 3000) were the most frequent visitors of all the container ships.

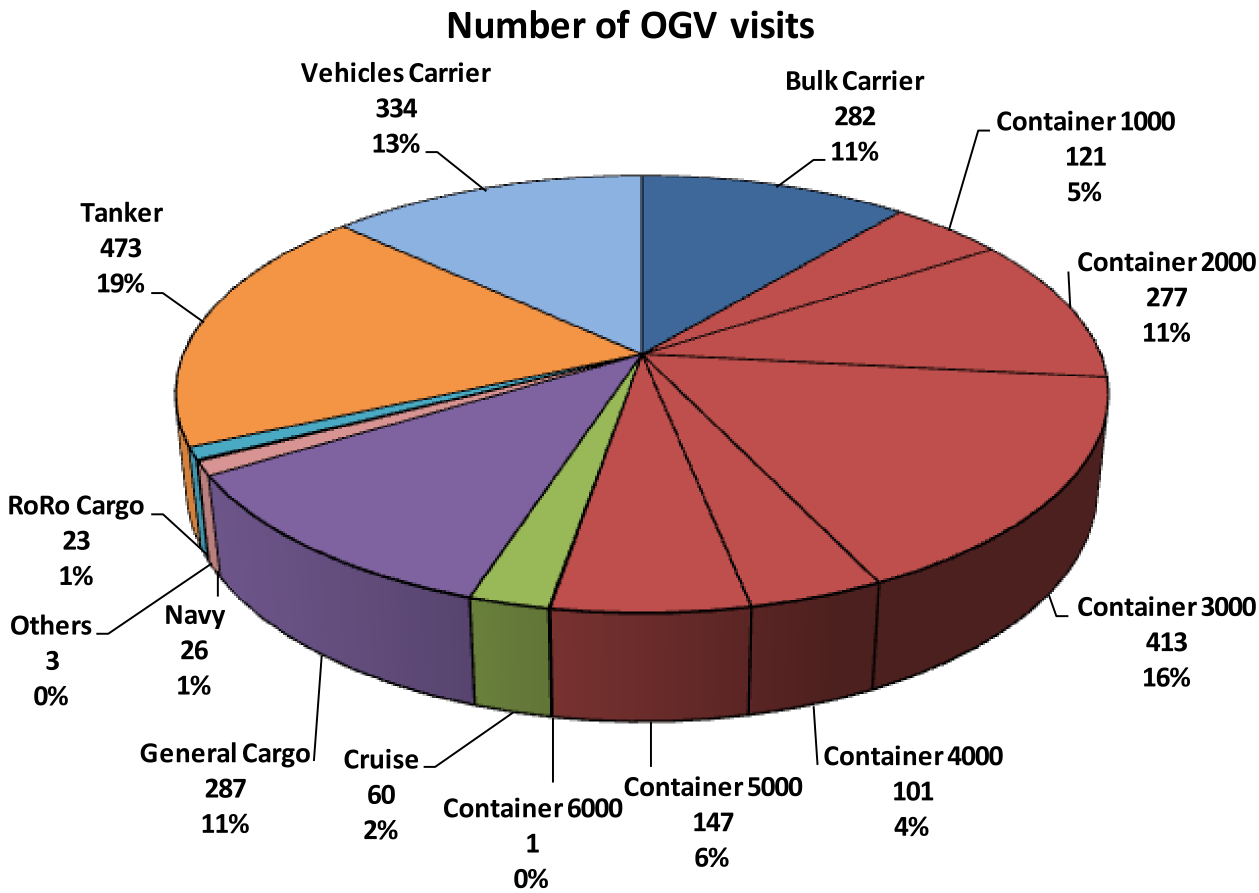


Figure 3.1 Number of OGV visits by vessel type

For all OGV, the number of visits by deadweight range are presented in Table 3.2.

Table 3.2 Number of OGV visits by deadweight range

Deadweight tonnes	Visits
0 - 20,000	952
20,000 - 40,000	902
40,000 - 60,000	491
60,000 - 80,000	32
80,000 - 100,000	48
100,000 - 120,000	111
120,000 - 140,000	9
140,000 - 160,000	3

No figures were available for deadweight of naval vessels, so the 24 naval vessels are included in the 0 – 20,000 deadweight range.

3.2 Ocean Going Vessel Activity

3.2.1 Activity Hours and Load Factors

Total and average activity hours over the inventory year for OGV, by vessel type and operating mode, are illustrated in Figure 3.2 and Table 3.3. The averages are by visit. Average engine load factors weighted according to the number of visits are also presented in Table 3.3.

As can be seen from Figure 3.2, the length of time spent hotelling dominated the times for each vessel type in the port. The greatest total time spent in the port was by container ships, with the next greatest being tankers, however the type of vessel that spent longest, on average, was the bulk carrier. Cruise ships spent the least amount of total time in the port. Tankers spent a significant amount of time at anchorage.

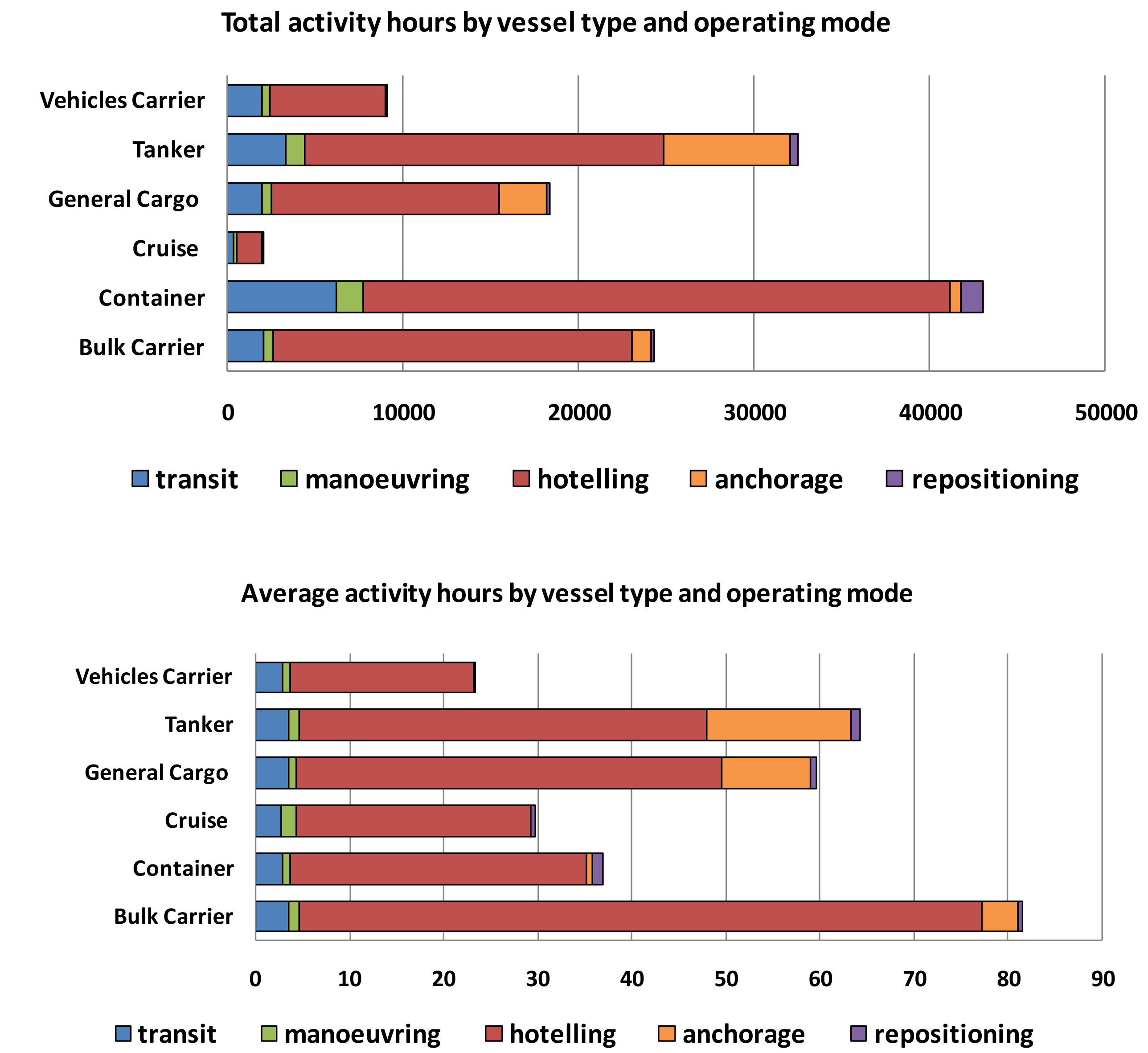


Figure 3.2 OGV total and average activity hours by vessel type and operating mode

Table 3.3 OGV total and average activity hours per visit by vessel type and operating mode, plus average engine load factors

				Load factors	
Vessel type	**Operating mode**	**Total activity hours**	**Average activity hours**	**Auxiliary engine**	**Main engine**
Bulk Carrier	Anchorage	1,083	3.8	0.22	
	Manoeuvring	622	1.1	0.45	0.12
	Transit	2,021	3.6	0.17	0.67
	Hotelling	20,429	72.4	0.22	
	Repositioning	150	0.5	0.45	0.01
Container Ship	Anchorage	609	0.6	0.18	
	Manoeuvring	1,472	0.7	0.50	0.04
	Transit	6,243	2.9	0.13	0.45
	Hotelling	33,472	31.6	0.18	
	Repositioning	1,220	1.2	0.50	0.00
Cruise Ship	Manoeuvring	191	1.6	0.31	0.06
	Transit	332	2.8	0.31	0.60
	Hotelling	1,490	24.8	0.31	
General Cargo	Anchorage	2,698	9.4	0.22	
	Manoeuvring	533	0.9	0.45	0.11
	Transit	1,975	3.4	0.17	0.72
	Hotelling	12,981	45.2	0.22	
	Repositioning	160	0.6	0.45	0.03
Navy	Anchorage	63	2.4	0.22	
	Manoeuvring	52	1.0	0.45	0.10
	Transit	136	2.6	0.17	0.40
	Hotelling	5,518	212.2	0.22	
	Repositioning	5	0.2	0.45	0.00
Other	Anchorage	17	5.5	0.22	
	Manoeuvring	8	1.3	0.45	0.14
	Transit	21	3.6	0.17	0.66
	Hotelling	710	236.5	0.22	
	Repositioning	10	3.2	0.45	
Ro-Ro Cargo	Manoeuvring	32	0.7	0.45	0.05
	Transit	129	2.8	0.15	0.61
	Hotelling	565	24.6	0.30	
	Repositioning	2	0.1	0.45	0.00
Tanker	Anchorage	7,253	15.3	0.26	
	Manoeuvring	1,067	1.1	0.33	0.13
	Transit	3,306	3.5	0.24	0.72
	Hotelling	20,468	43.3	0.26	
	Repositioning	473	1.0	0.33	0.00
Vehicles Carrier	Anchorage	7	0.0	0.26	
	Manoeuvring	473	0.7	0.45	0.05
	Transit	1,943	2.9	0.15	0.56
	Hotelling	6,551	19.6	0.26	
	Repositioning	56	0.2	0.45	0.00

The main engine is not used during hotelling or anchorage, except for diesel/electric ships, where main engines may be used to generate auxiliary power. The only diesel/electric ships were cruise ships.

It is assumed that the boiler is not used during transit, as the waste heat boiler running from the main engine exhaust will fulfill any heating requirements.

Load factors

Load factors represent the fraction of total power that is actually in use at any one time. Actual main engine and auxiliary engine powers are calculated by multiplying the full load power by the load factor. Main engine load factor during transit ranges from 0.45 for container ships to 0.72 for tankers and general cargo ships. This is because all ships transit at approximately the same speed, which is closer to the service speed for tankers and general cargo ships, than it is to the service speed of container ships. Container ships have the ability to go much faster, so their engines are operating at a much lower load factor in transit in the PB waters.

Auxiliary engine load factors primarily represent the default load factors found in Table B.3, Appendix B, except where actual load factors were available from survey data.

Actual boiler loads are used directly so boiler load factors are not relevant and thus are not shown in Table 3.3.

3.2.2 Number of Movements

Total OGV movements by vessel type and operating mode are presented in Table 3.4. From this table a pattern of the behaviour of each vessel type at the port can be deduced. For example, because there were many more hotelling movements than transit/manoeuvring movements for the bulk carriers and the tankers this implies that they were often repositioned between berths, and/or to anchorage.

The total number of movements for each vessel type does not agree with the total of the individual movements for that vessel type. This was due to some inconsistencies in the original data but it was considered that the material effect on the overall result was insignificant.

Table 3.4 Total OGV movements

Vessel type	TEU	Total Movements	Anchorage	Arrive Manoeuvring	Arrive Transit	Depart Manoeuvring	Depart Transit	Hotelling	Repositioning
Bulk Carrier		1,609	25	278	282	262	285	401	76
Container 1000	<1000	635	7	123	121	123	121	132	8
Container 2000	1000 - 2000	1,449	7	276	277	271	277	308	33
Container 3000	2000 - 3000	2,170	4	413	413	408	417	463	52
Container 4000	3000 - 4000	530	0	101	101	99	101	117	11
Container 5000	4000 - 5000	760	0	147	147	146	148	153	19
Container 6000	5000 - 6000	5	0	1	1	1	1	1	0
Cruise		306	0	60	60	60	60	63	3
General Cargo		1,652	37	291	287	293	292	383	69
Navy		134	5	24	26	14	24	37	4
Other OGV		41	1	3	3	3	3	22	6
Ro-Ro Cargo		120	0	22	23	23	23	28	1
Tanker		2,828	128	447	473	467	471	620	222
Vehicles Carrier		1,704	1	333	334	332	334	351	19
Totals		**13,943**	**215**	**2,519**	**2,548**	**2,502**	**2,557**	**3,079**	**523**

3.3 Emissions and Fuel Consumption

3.3.1 By Vessel Type

Totals by Vessel Type

Total fuel consumption, primary air quality and greenhouse emissions by vessel type for all vessels are presented in Figure 3.3 and Table 3.5.

Air quality emissions (NOx, CO, HC, PM, SO_2) are important for their effect on air quality in areas close to the source. Greenhouse gas emissions (CO_2, CH_4, N_2O) are important for their direct contribution to global warming. They do not significantly affect local air quality. CH_4 emissions are the component of total HC emissions which contribute directly to global warming.

The vessel types in Figure 3.3 are ordered according to fuel consumption. Container ships consumed most fuel and produced most emissions, followed by tankers and dredges. In the inventory period, the contract dredge *Volvox Asia* was used for capital works. The *Volvox Asia* was used for capital works for PBC and BAC and consumed more than twice as much fuel and produced more than twice the emissions of the PBC dredges *Brisbane* and *Amity* (see Section 3.4)

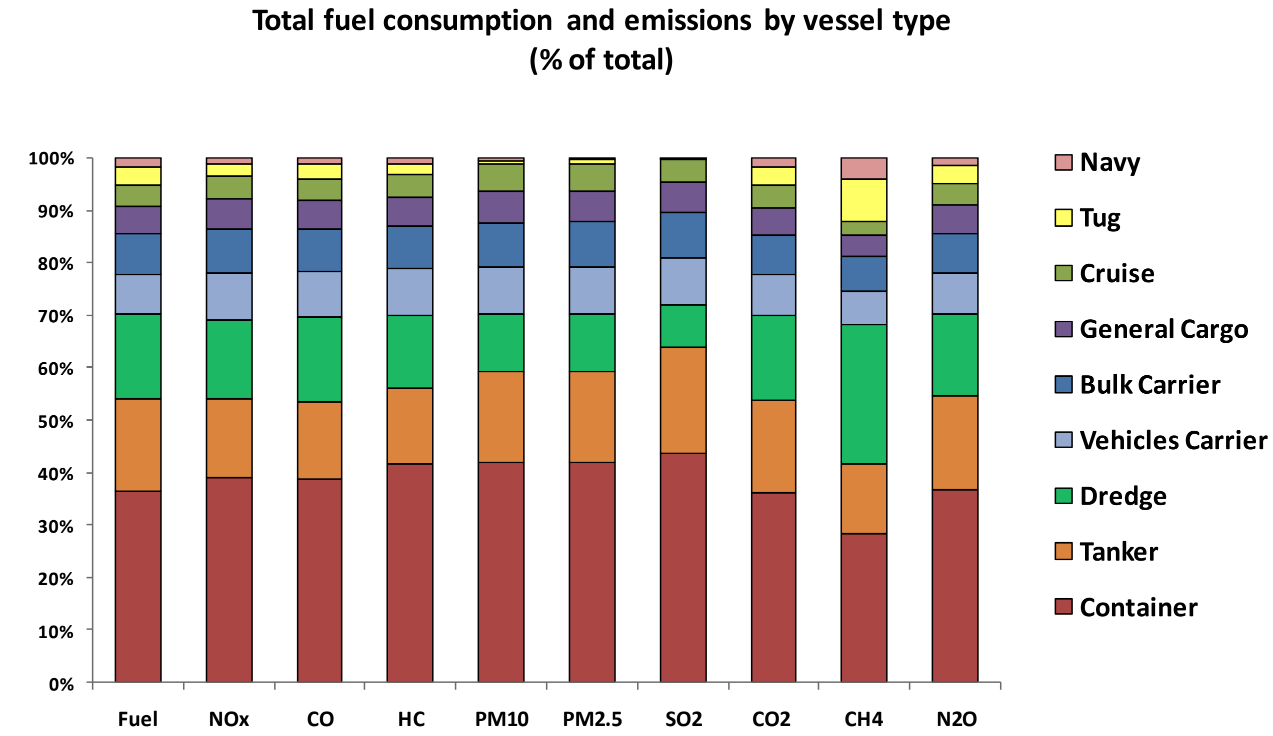


Figure 3.3 Total fuel consumption, primary air quality and greenhouse emissions by vessel type for all vessels

The contract dredge *Volvox Asia* used RO and MGD/MDO. The tugs, naval vessels and the PBC dredges *Brisbane* and *Amity* used only ULSD, so their SO_2 emissions were negligible and their PM emissions were relatively low. PM emissions from distillate fuel (MGO/MDO and ULSD) are lower than from RO.

Values for the greenhouse gases (CO_2, CH_4 and N_2O) are calculated using the Australian Government Department of Climate Change[2] (DCC) factors.

The dredge, tug and navy CH_4 emissions were relatively high because the DCC[2] emissions factor for CH_4 for MGO/MDO and ULSD is higher than for RO. However, the effect of increased CH_4 emissions on total CO_2 equivalent greenhouse gas emissions was negligible.

Table 3.5 All vessels total fuel consumption, primary air quality and greenhouse emissions by vessel type – all values in tonnes

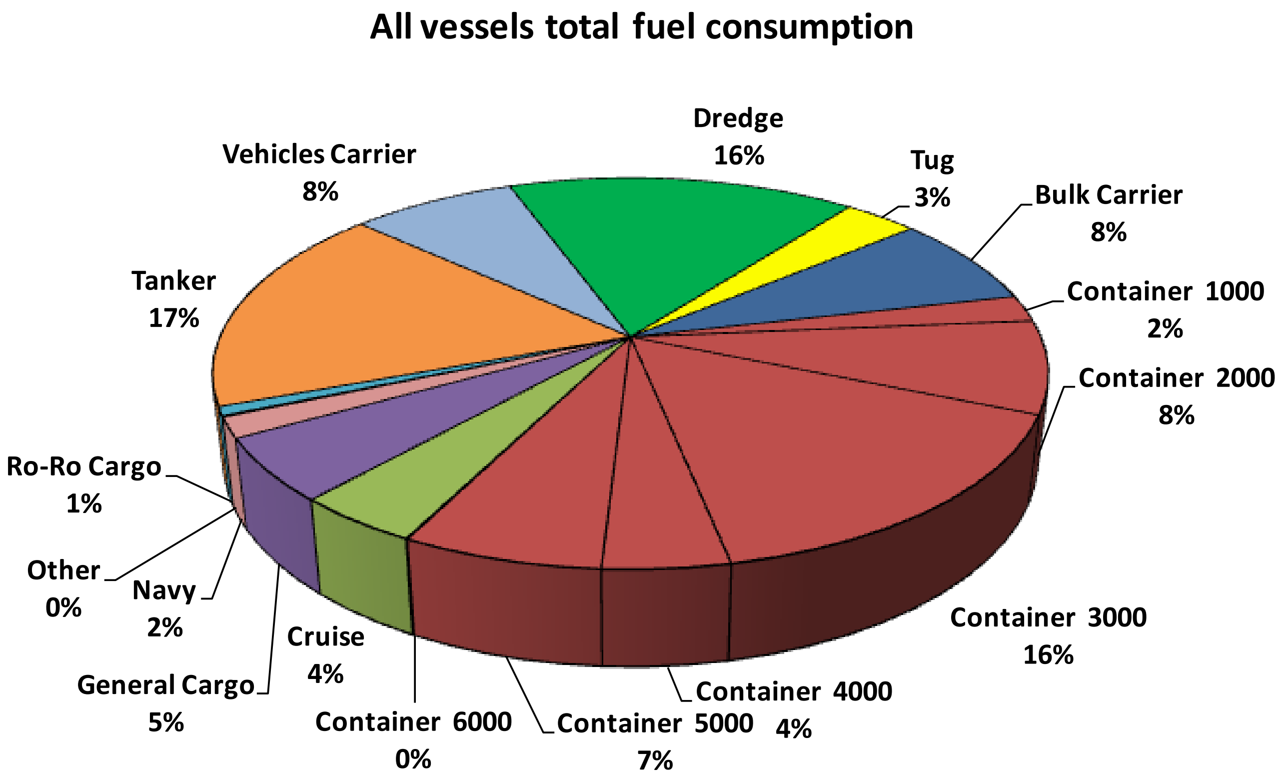
Vessel Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Bulk Carrier	4,305	289.3	22.9	11.3	25.3	24.6	208.3	13,329	14.8	107.8
Container 1000	1,253	67.3	5.4	2.8	6.5	6.3	58.9	3,878	4.3	31.4
Container 2000	4,381	263.5	21.5	11.2	25.7	25.0	229.7	13,568	12.8	110.9
Container 3000	8,856	575.6	47.1	25.2	53.1	51.6	449.3	27,426	28.2	223.0
Container 4000	2,362	151.9	12.5	6.8	14.4	14.0	125.4	7,316	7.2	59.6
Container 5000	3,744	262.9	22.3	12.3	25.3	24.6	197.9	11,597	10.9	94.8
Container 6000	28	2.0	0.2	0.1	0.2	0.2	1.4	86	0.1	0.7
Container total	**20,624**	**1,323**	**108.9**	**58.4**	**125.1**	**121.5**	**1,063**	**63,872**	**63.5**	**520.4**
Cruise	2,368	150.5	12.0	6.0	15.4	14.9	113.6	7,338	6.0	60.4
General Cargo	2,975	191.4	15.2	7.7	17.8	17.3	142.8	9,213	9.3	75.0
Navy	959	38.7	3.2	1.7	1.5	1.2	0.0	3,085	8.9	22.3
Other	61	2.5	0.2	0.1	0.3	0.3	3.0	187	0.2	1.5
Ro-Ro Cargo	411	30.9	2.5	1.3	2.8	2.7	17.7	1,273	1.2	10.4
Tanker	9,924	514.7	41.3	20.4	51.6	50.1	497.4	30,735	30.4	250.5
Vehicles Carrier	4,368	304.0	24.4	12.7	27.0	26.2	216.1	13,527	14.3	109.8
OGV total	**45,995**	**2,845**	**230.5**	**119.4**	**266.7**	**258.9**	**2,262**	**142,560**	**148.6**	**1,158**
Dredge	9,197	505.1	45.7	19.5	32.5	31.6	199.4	28,974	59.4	221.2
Tug	1,943	79.0	8.0	2.9	2.2	2.1	0.0	6,253	18.1	45.2
All Vessels	**57,135**	**3,429**	**284.2**	**141.8**	**301.4**	**292.7**	**2,461**	**177,787**	**226.2**	**1,424**

*CH_4 and N_2O in tonnes CO_2 equivalent

Note that the CH_4 values are expressed as CO_2 equivalent throughout, so the actual CH_4 emissions are 21 times smaller than the values shown in the tables. The actual CH_4 emissions must be less than the total HC emissions as CH_4 is just one component of total hydrocarbons from combustion of fuel. Similarly, actual N_2O emissions are 310 times smaller than the CO_2 equivalent values shown in the tables.

Fuel consumption and NOx emissions of all vessels are plotted in Figure 3.4, with the container totals shown by size subcategory. The 3000 TEU group (2000 – 3000 TEU) being the most frequent visitors of the container ships dominated the container ship fuel consumption and emissions.

Fuel consumption and NOx are plotted in Figure 3.4. The levels of all emissions accord with fuel consumption levels, but boilers produce much less NOx emissions for a given mass of fuel burnt than diesel engines. This is inherent in the different nature of the combustion process in these two types of machinery. Thus, along with fuel consumption, NOx emissions are plotted, to highlight this difference. Further, NOx emissions are of considerable importance for their impact on local air quality, and are difficult to control. Boilers generally produce lower levels of all the air quality emisisons than diesel engines, for a given amount of fuel burnt.



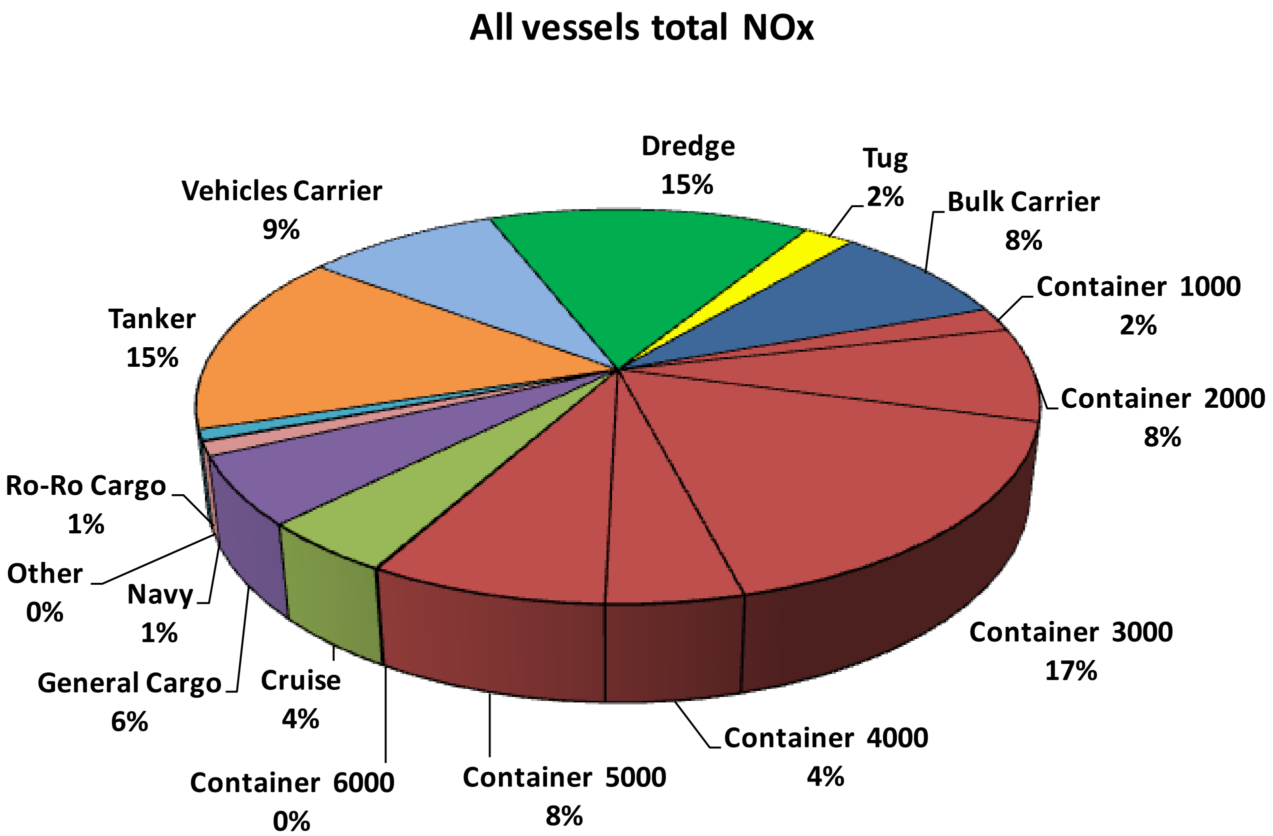


Figure 3.4 Total fuel consumption and NOx emissions for all vessels, with the container ship totals shown by TEU subcategory

Averages by Vessel Type

Average OGV fuel consumption and primary air quality and greenhouse emissions per visit by vessel type are shown in Figure 3.5 and Table 3.6. The vessel types in Figure 3.5 are ordered according to average fuel consumption.

On average, cruise ships and naval vessels consumed the most fuel per visit. Cruise ships produced the most air quality emissions per visit.

Naval averages were high because they spent on average 212 hours hotelling per visit. Naval CH_4 emissions were relatively high because they operated on ULSD and the DCC emissions factor for ULSD is higher than for RO. However, CH_4 emissions represent only 0.1% of total greenhouse gas emissions, as can be seen in Table 3.5.

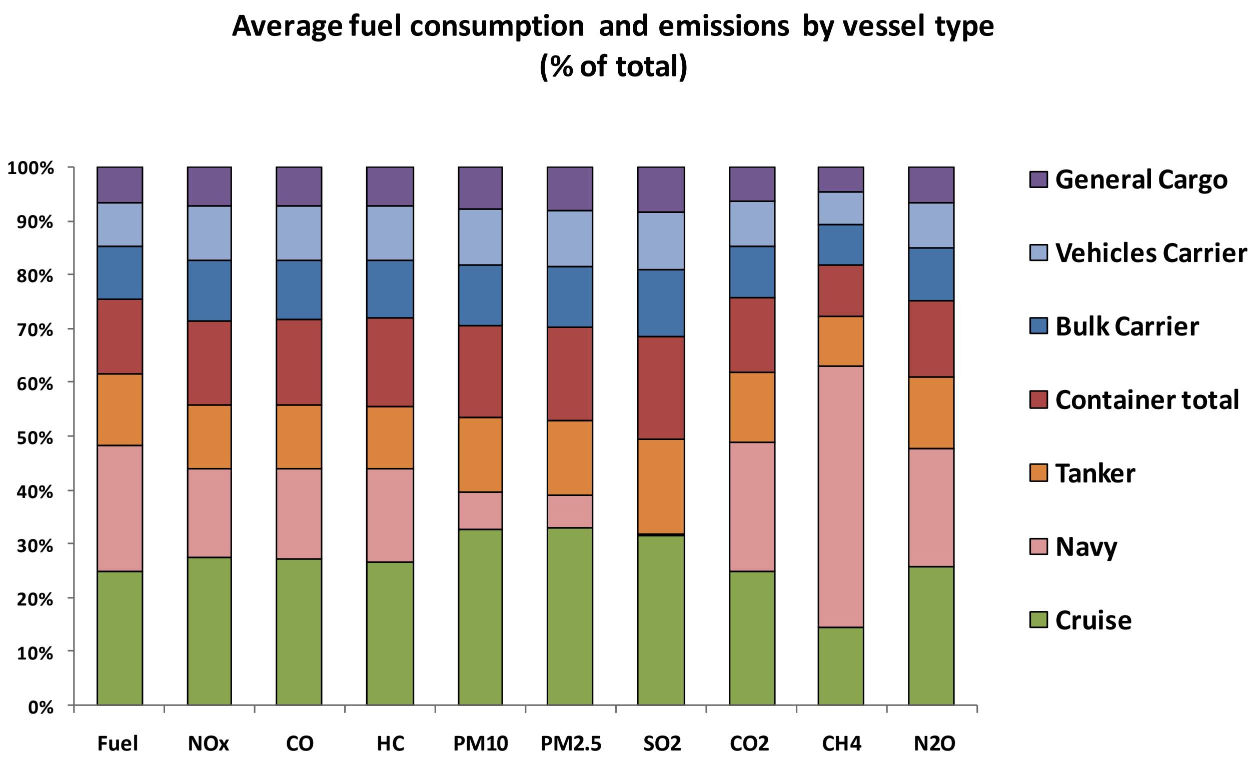


Figure 3.5 Average OGV fuel consumption and primary air quality and greenhouse emissions per visit by vessel type

Table 3.6 Average OGV fuel consumption and primary air quality and greenhouse emissions by vessel type – all values in tonnes

Vessel Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*	visits
Bulk Carrier	15.27	1.026	0.081	0.040	0.090	0.087	0.739	47.3	0.053	0.382	282
Container 1000	10.35	0.556	0.045	0.023	0.053	0.052	0.487	32.1	0.036	0.259	121
Container 2000	15.81	0.951	0.078	0.041	0.093	0.090	0.829	49.0	0.046	0.400	277
Container 3000	21.44	1.394	0.114	0.061	0.129	0.125	1.088	66.4	0.068	0.540	413
Container 4000	23.39	1.504	0.124	0.067	0.142	0.138	1.241	72.4	0.071	0.591	101
Container 5000	25.47	1.788	0.152	0.084	0.172	0.167	1.346	78.9	0.074	0.645	147
Container 6000	27.83	1.998	0.165	0.090	0.183	0.178	1.424	86.2	0.086	0.702	1
Container overall	**21.96**	**1.409**	**0.116**	**0.062**	**0.133**	**0.129**	**1.132**	**68.0**	**0.068**	**0.554**	**939**
Cruise	39.47	2.508	0.199	0.100	0.256	0.249	1.893	122.3	0.101	1.007	60
General Cargo	10.37	0.667	0.053	0.027	0.062	0.060	0.498	32.1	0.033	0.261	287
Navy	36.87	1.488	0.122	0.065	0.056	0.045	0.001	118.7	0.343	0.857	26
Other	20.17	0.849	0.068	0.034	0.096	0.093	0.998	62.5	0.061	0.510	3
Ro-Ro Cargo	17.87	1.342	0.108	0.054	0.122	0.119	0.767	55.4	0.053	0.452	23
Tanker	20.98	1.088	0.087	0.043	0.109	0.106	1.052	65.0	0.064	0.530	473
Vehicles Carrier	13.08	0.910	0.073	0.038	0.081	0.078	0.647	40.5	0.043	0.329	334
OGV overall	**18.05**	**1.117**	**0.090**	**0.047**	**0.105**	**0.102**	**0.888**	**55.9**	**0.058**	**0.455**	**2548**

*CH_4 and N_2O in tonnes CO_2 equivalent

3.3.2 By Machinery Type

Table 3.7 and Figure 3.6 show total fuel consumption and primary air quality and greenhouse emissions by machinery type for all vessels.

Table 3.7 Total all vessels fuel consumption and primary air quality and greenhouse emissions by machinery type – all values in tonnes

Machinery Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
OGV auxiliary engine	16,996	1,101	83.5	36.1	92.3	89.3	776	52,661	70.1	420.4
OGV boiler	10,266	71	6.7	3.7	25.8	25.1	481	31,844	29.7	260.4
OGV main engine	18,733	1,674	140.2	79.7	148.6	144.5	1,004	58,054	48.8	477.3
Total OGV	**45,995**	**2,845**	**230.5**	**119.4**	**266.7**	**258.9**	**2,262**	**142,560**	**148.6**	**1,158**
Dredge engine	9,197	505	45.7	19.5	32.5	31.6	199	28,974	59.4	221.2
Tug engine	1,943	79	8.0	2.9	2.2	2.1	0	6,253	18.1	45.2
Total	**57,135**	**3,429**	**284.2**	**141.8**	**301.4**	**292.7**	**2,461**	**177,787**	**226.2**	**1,424**

*CH_4 and N_2O in tonnes CO_2 equivalent

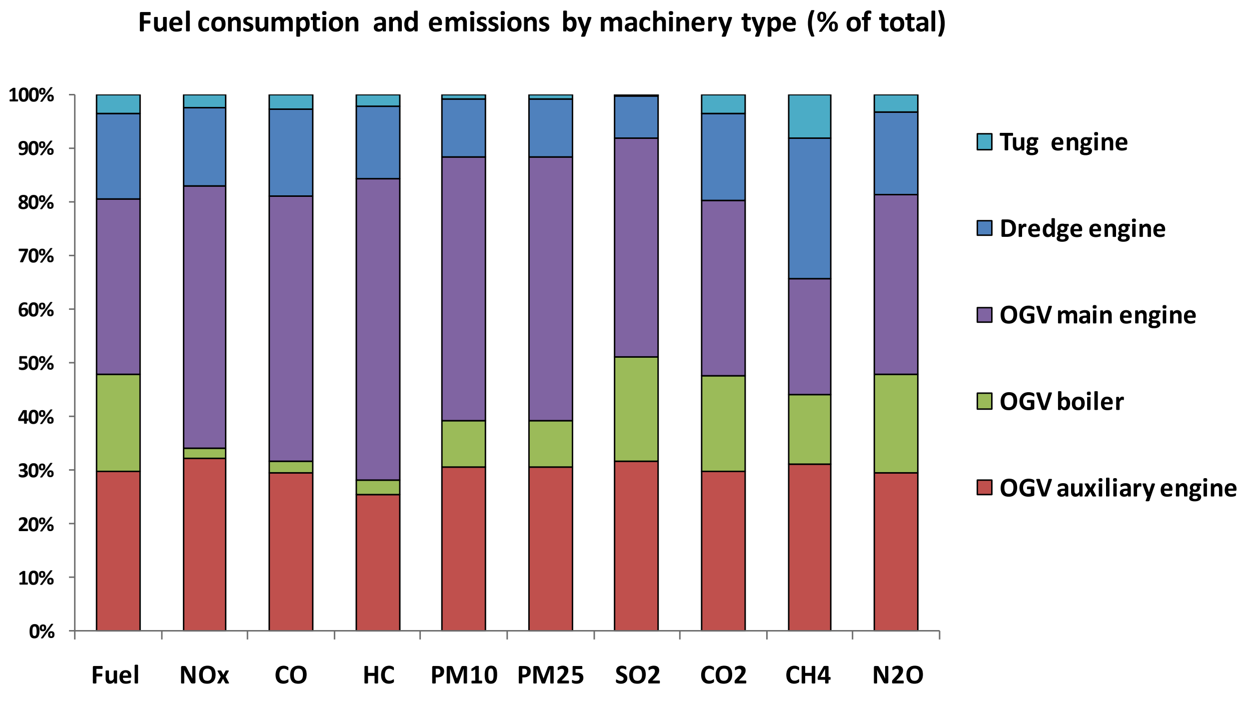


Figure 3.6 Total all vessels fuel consumption and primary air quality and greenhouse emissions by machinery type

Proportions of greenhouse gas emissions (CO_2, CH_4 and N_2O) generally align with fuel consumption across all machinery types, because these emissions depend primarily on mass of fuel consumed. The greenhouse gas emissions are calculated using DCC[2] guidelines, which give a lower CH_4 factor for RO than for distillates. The tugs use ULSD exclusively and the dredges use a high proportion of ULSD and MGO, so they show higher proportions of CH_4 than other greenhouse gases. However, the percentage contribution of CH_4 to total CO_2 equivalent greenhouse gas emissions is small.

OGV boilers use a significant proportion of the total fuel, but produce a much lower proportion of NOx emissions because boilers produce less NOx per mass of fuel burned than diesel engines. Similarly for CO and HC.

3.3.3 OGV by Operating mode

Total OGV fuel consumption and primary air quality and greenhouse emissions by operating mode are given in Table 3.8 and Figure 3.7. The greatest fuel consumption and greenhouse gas emissions occurred during hotelling, while the greatest air quality emissions occurred during transit. This difference is due to the use of oil fired boilers while hotelling, which produce less air quality emissions per mass of fuel burnt than diesel engines, apart from SO_2, which is directly related to the mass of fuel burnt and the fuel sulphur content.

Table 3.8 Total OGV fuel consumption and primary air quality and greenhouse emissions by operating mode – all values in tonnes

Mode	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Anchorage	1,537	70.9	5.5	2.4	6.8	6.6	70.1	4,759	5.8	38.3
Manoeuvring	2,139	163.6	18.6	17.1	17.3	16.8	100.7	6,626	7.3	53.6
Transit	19,846	1,696.7	135.7	68.4	148.2	144.0	1,054.2	61,500	53.6	504.7
Hotelling	21,562	866.0	67.0	29.7	89.8	87.0	992.2	66,854	78.6	538.8
Repositioning	911	47.8	3.8	1.8	4.6	4.4	44.3	2,820	3.3	22.7

*CH_4 and N_2O in tonnes CO_2 equivalent

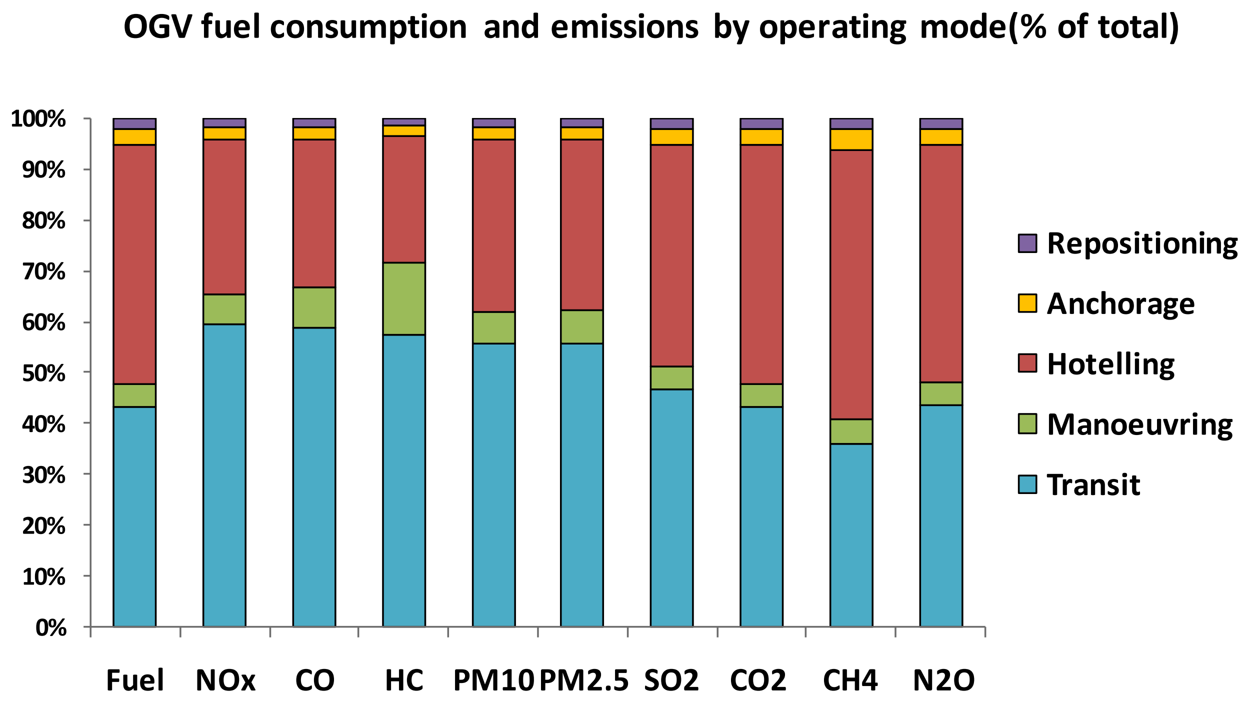


Figure 3.7 Total OGV fuel consumption and primary air quality and greenhouse emissions by operating mode

Fuel consumption and NOx emissions are further illustrated in Figure 3.8. As can be seen, almost half the total OGV fuel consumption occurred while hotelling (47%), while about 43% occurred during transiting. Manoeuvring, repositioning and anchorage combined accounted for only 10% of the total OGV fuel consumption. Manoeuvring, repositioning and anchorage combined also only accounted for 10% of the OGV NOx, with the transit mode accounting for nearly 60% and the hotelling mode about 30%. Boiler fuel consumption accounted for a greater proportion of fuel consumption during hotelling than during transit, and boilers produce less NOx and particulates per tonne of fuel consumed than diesel engines.

As the fuel consumption and NOx for the dredges and tugs combined was less than 20% of the total, this means that the fuel consumption and NOx at PB were dominated by the OGV hotelling and transit operating modes.

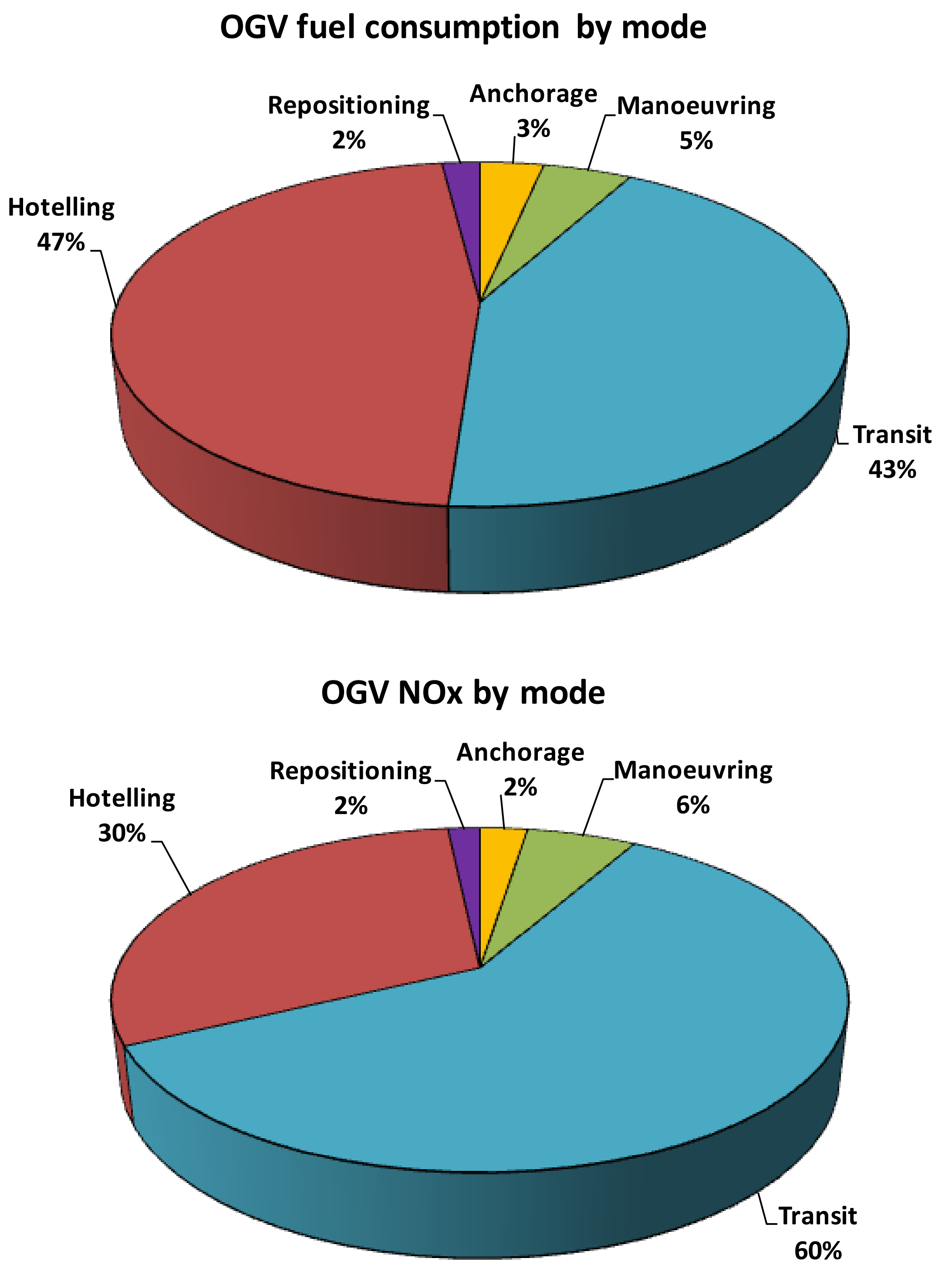


Figure 3.8 OGV fuel consumption and NOx emissions by operating mode

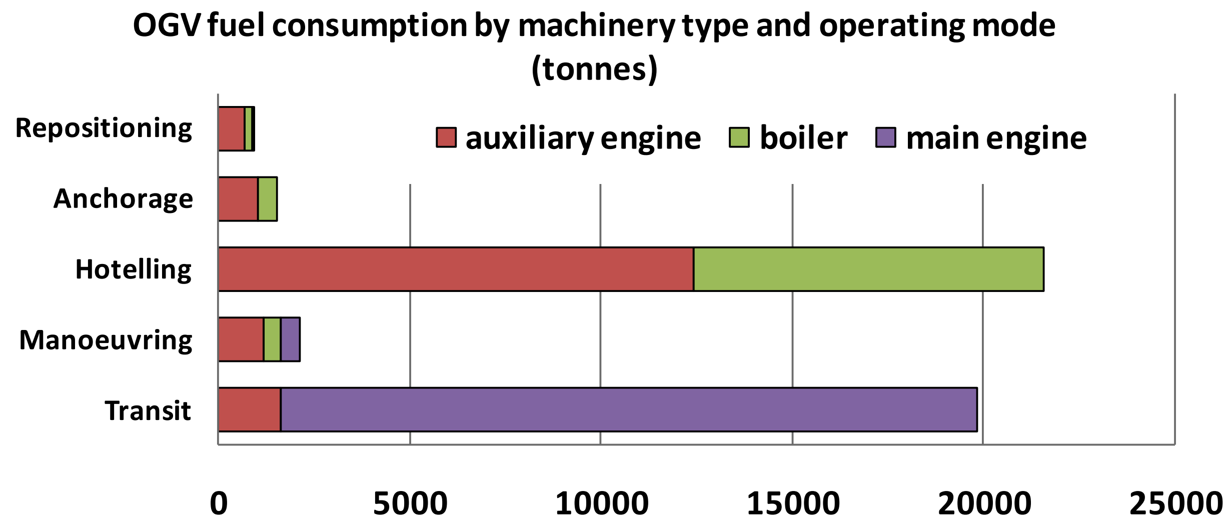
3.3.4 OGV by Machinery Type and Operating Mode

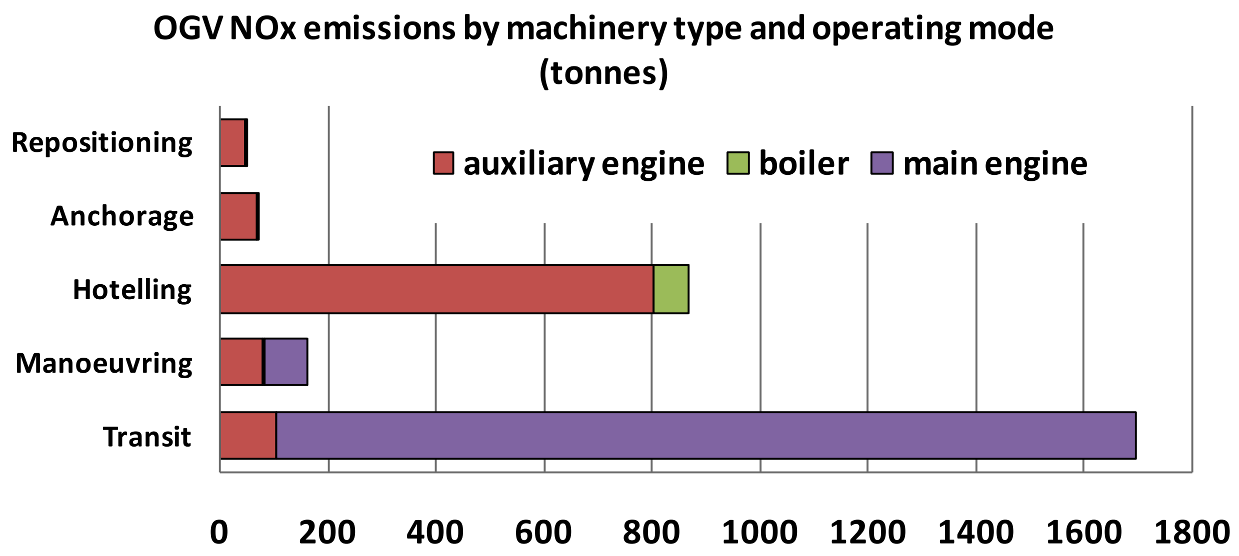
Total OGV fuel consumption and primary air quality and greenhouse emissions by machinery type and operating mode are presented in detail in Table D.1, Appendix D. A selection of the data is plotted in Figure 3.9, which shows fuel consumption and NOx emissions by machinery type and operating mode.

The main engine accounted for the majority of fuel consumption during transit. The boilers and auxiliary engines consumed similar amounts of fuel during hotelling.

The greenhouse gas emissions are directly related to the fuel consumption, regardless of the machinery type. NOx emissions are significantly lower from boilers than diesel engines. PM_{10} (and $PM_{2.5}$) emissions are also lower from boilers than diesel engines, but not to the same extent as NOx emissions. SO_2 emissions are directly related to the mass of fuel burnt and the fuel sulphur content, regardless of the machinery type.

Note that for diesel/electric ships the main propulsion engine is also used to generate power for hotelling. For these ships the proportion of power used for hotelling was determined, and the emissions due to this were included in the auxiliary engine category, rather than the main engine category.





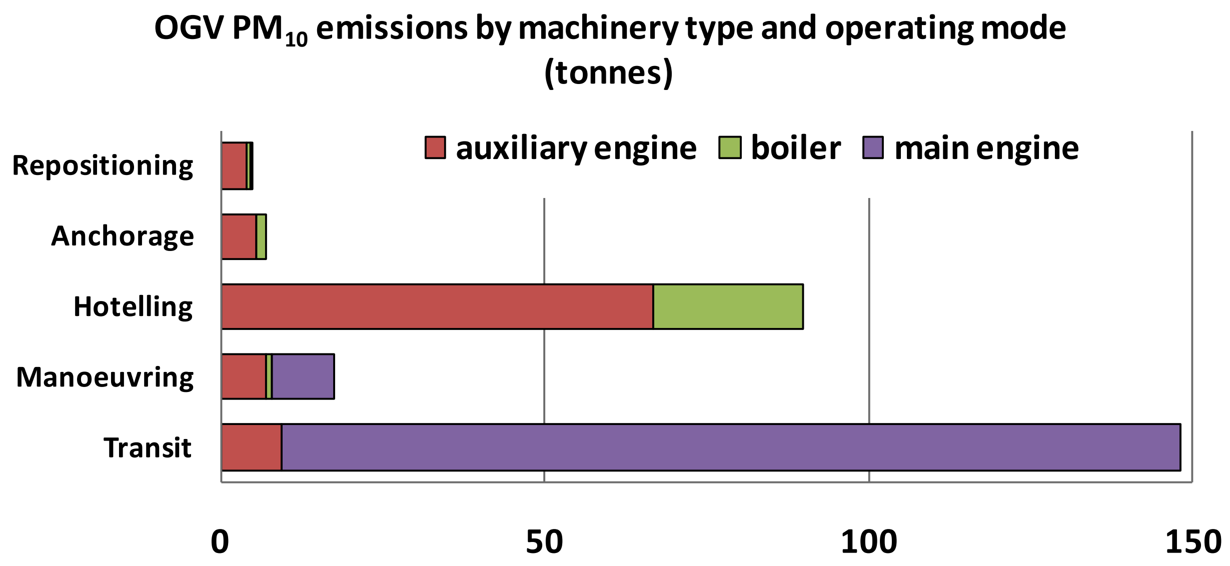


Figure 3.9 OGV fuel consumption, NOx and PM_{10} emissions by machinery type and operating mode

3.3.5 OGV by Vessel Type and Machinery Type

Total OGV fuel consumption and primary air quality and greenhouse emissions by vessel type and machinery type are presented in Table D.2, Appendix D and a selection is plotted in Figure 3.10 below.

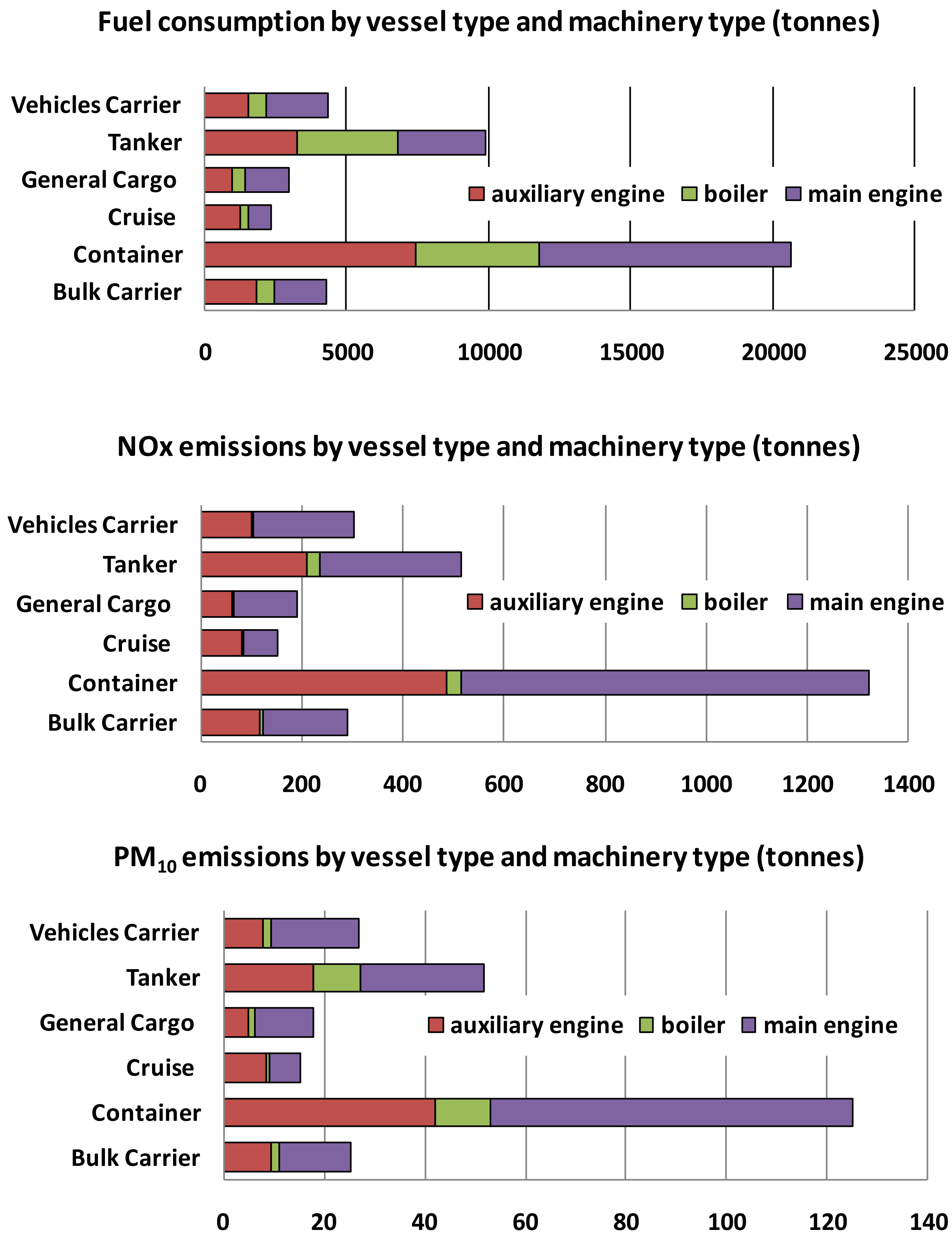
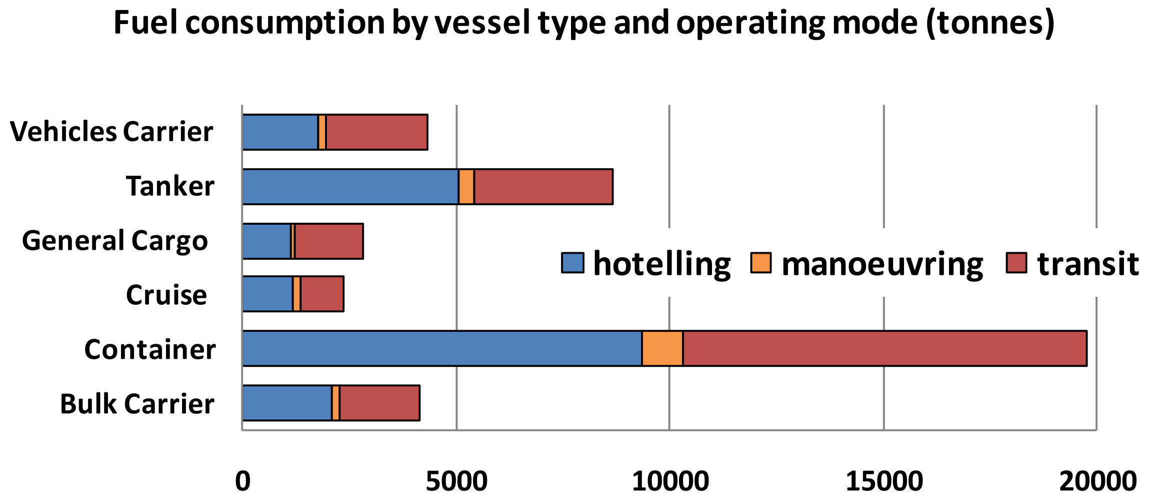
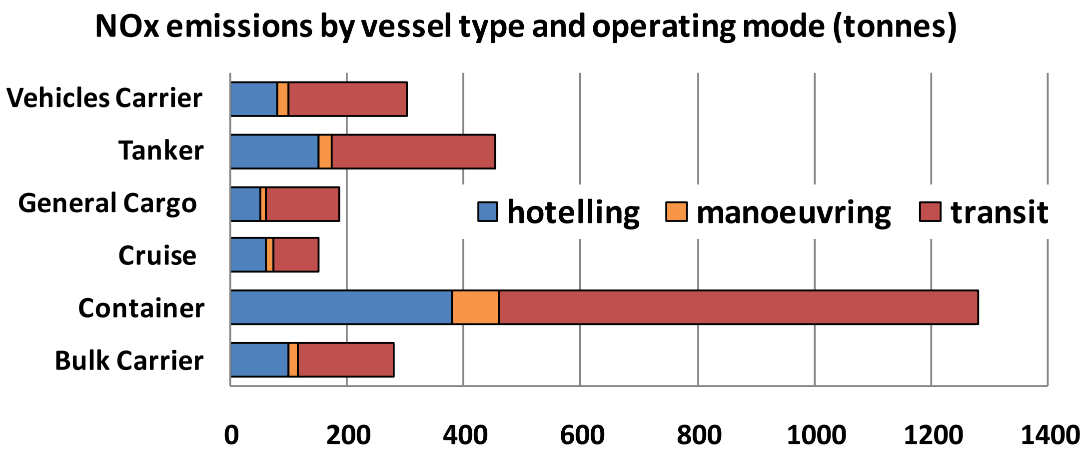


Figure 3.10 Total OGV fuel consumption, NOx and PM_{10} emissions by vessel type and machinery type

3.3.6 OGV by Vessel Type and Operating Mode

Total OGV fuel consumption and primary air quality and greenhouse emissions by vessel type and operating mode are presented in Table D.3, Appendix D and a selection is plotted in Figure 3.11 below. For simplicity, only transit, manoeuvring and hotelling are shown. Anchorage and repositioning are excluded from Figure 3.11 because their contribution to the totals are relatively minor.





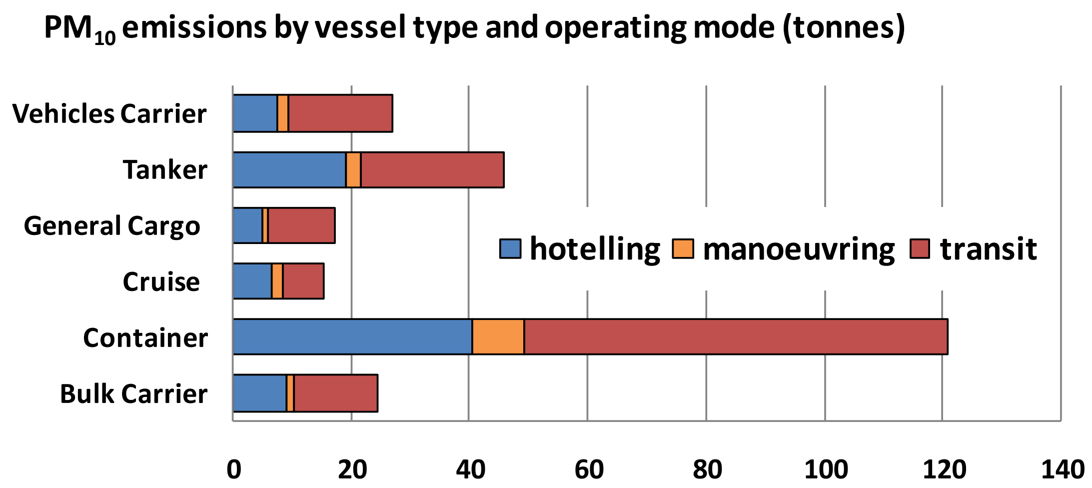


Figure 3.11 Total OGV fuel consumption, NOx and PM_{10} emissions by vessel type and operating mode

3.3.7 OGV by Fuel Type

Totals by Fuel Type for all Operating Modes

Total OGV fuel consumption, air quality and greenhouse emissions by fuel type are shown in Table 3.9. The dominant fuel type used by OGVs was RO. Cruise ships used RO exclusively. The vessel survey showed that 25% of OGV auxiliary engines in the port used MGO or MDO and 75% RO.

PM emissions are higher from RO than from the distillates (MGO/MDO and ULSD), mainly due to the higher sulphur content but also due to the nature of the fuel.

In the OGV group, only the naval vessels used ULSD.

Table 3.9 Total OGV fuel consumption, air quality and greenhouse emissions by fuel type – all values in tonnes

Fuel Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
MGO/MDO	3,917	240.4	19.1	9.3	6.7	6.2	47.6	12,059	34.85	87.1
RO	41,119	2,566	208.2	108.4	258.6	251.7	2,214.0	127,416	104.87	1,049
ULSD	959	38.7	3.2	1.7	1.5	1.2	0.0	3,085	8.92	22.3
Totals	**45,995**	**2,845**	**230.5**	**119.4**	**266.7**	**259.1**	**2,262**	**142,560**	**148.6**	**1,158**

*CH_4 and N_2O in tonnes CO_2 equivalent

Where fuel type was not specified in the survey data RO was used, apart from the auxiliary engines. Approximately 25% of auxiliary engines operated on MGO/MDO, because their design may not allow the use of RO. To model the distribution of fuel types used in auxiliary engines, a hybrid fuel model was used which consisted of 25% MGO/MDO and 75% RO. The hybrid fuel model used aggregated emissions and fuel consumption factors proportioned according to the proportions of MGO/MDO and RO. To arrive at the figures in Table 3.9, the calculated hybrid fuel type totals were disaggregated and distributed to the appropriate real fuel type. This disaggregation took into account the different SFOC and emissions factors for the different fuels.

Sulphur content was assigned to RO and the hybrid fuel type according to average values determined from the vessel surveys. Sulphur contents used for cruise ships were 2.7% for all machinery types and operating modes. For OGV other than cruise ships, sulphur content of 2.7% was used for main engines in transit and 2.4% for all other machinery types and operating modes, because some auxiliary machinery operate on MGO/MDO.

More results by fuel type are presented in the next section for hotelling.

3.3.8 OGV Hotelling

Totals by Vessel Type while Hotelling

Total OGV fuel consumption, air quality and greenhouse emissions by vessel type while hotelling are shown in Table 3.10.

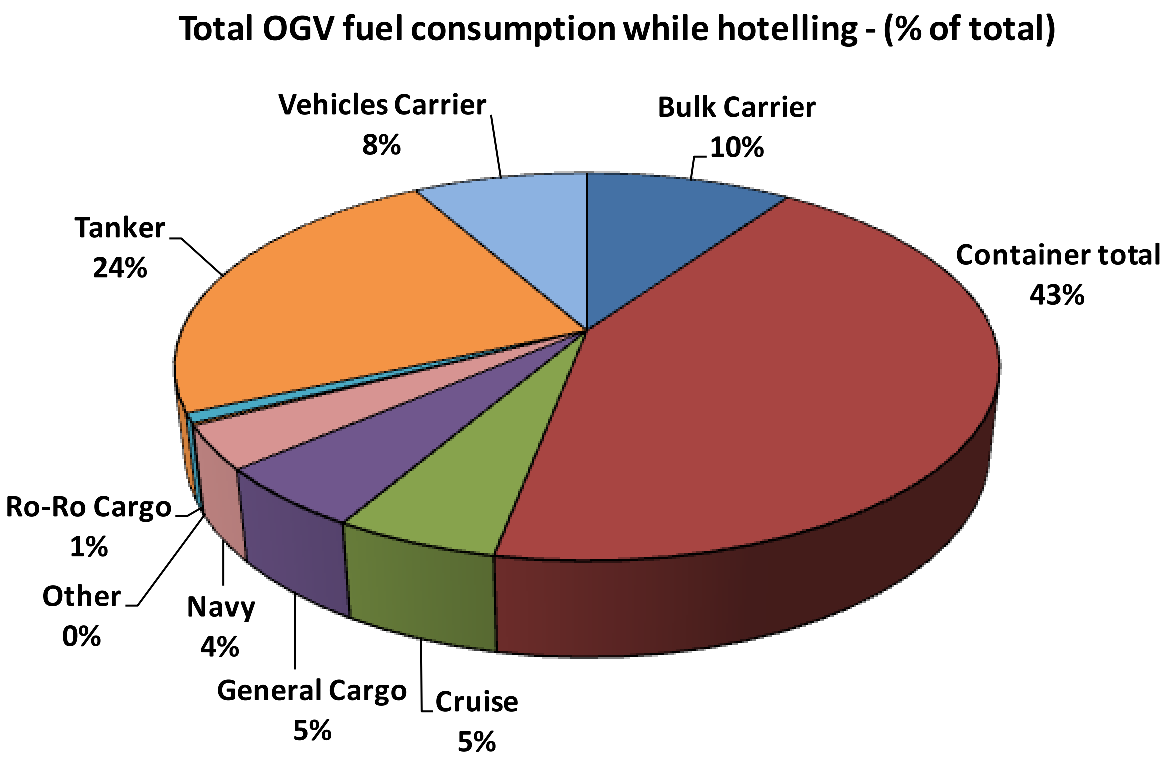
In total, container ships consume most fuel and produce most emissions during hotelling, followed by tankers. Tanker fuel consumption was relatively high due to the amount of boiler fuel consumed to provide steam for the cargo pumps. However, the proportion of NOx , CO, HC and PM emissions from tankers was less significant because boilers produce less of these emissions per mass of fuel burnt than do diesel engines.

Table 3.10 Total OGV primary air quality and greenhouse emissions plus fuel consumption while hotelling by vessel type – all values in tonnes

PoB Category	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Bulk Carrier	2,087	99.3	7.6	3.4	9.0	8.7	92.1	6,457	8.5	51.6
Container 1000	1,228	51.9	4.0	1.8	5.5	5.3	62.3	3,803	4.1	30.8
Container 2000	3,922	165.4	12.8	5.6	16.9	16.4	187.8	12,141	14.0	98.0
Container 3000	10.6	0.5	0.0	0.0	0.0	0.0	0.5	33	0.0	0.3
Container 4000	576.4	13.6	1.1	0.5	1.7	1.7	23.7	1,783	2.4	14.2
Container 5000	2,048	71.1	5.5	2.5	8.3	8.1	102.5	6,342	6.5	51.6
Container 6000	1,556	77.5	5.9	2.5	8.0	7.8	80.0	4,820	4.9	39.2
Container total	**9,341**	**379.9**	**29.3**	**12.9**	**40.5**	**39.3**	**456.9**	**28,922**	**32.0**	**234.1**
Cruise	1,169	61.0	4.6	1.9	6.7	6.5	55.5	3,623	3.0	29.8
General Cargo	1,131	50.5	3.9	1.7	5.0	4.8	51.9	3,500	4.2	28.2
Navy	784.1	31.1	2.5	1.2	0.9	0.9	0.0	2,523	7.3	18.2
Other	41.6	1.2	0.1	0.0	0.2	0.2	2.0	129	0.1	1.0
Ro-Ro Cargo	172.0	10.3	0.8	0.3	1.0	0.9	6.9	533	0.6	4.3
Tanker	5,069	151.0	11.9	5.4	19.0	18.4	246.5	15,699	16.0	127.7
Vehicles Carrier	1,767	81.5	6.3	2.8	7.6	7.3	80.4	5,470	7.0	43.8
Totals	**21,652**	**866.0**	**67.0**	**29.7**	**89.8**	**87.0**	**992.2**	**66,854**	**78.6**	**538.8**

*CH_4 and N_2O in tonnes CO_2 equivalent

Total OGV fuel consumption and NOx while hotelling are illustrated in Figure 3.12. Greenhouse gas and SO_2 emissions and directly related to the mass of fuel burnt. Air quality emissions depend also on the machinery type and the plot of NOx emissions compared with the plot of fuel consumption illustrates these differences. Tanker fuel consumption is a much higher proportion of total fuel consumption than tanker NOx is of total NOx, because much of the tanker fuel during hotelling is consumed in boilers, which produce lower NOx emissions than diesel engines for a given mass of fuel.



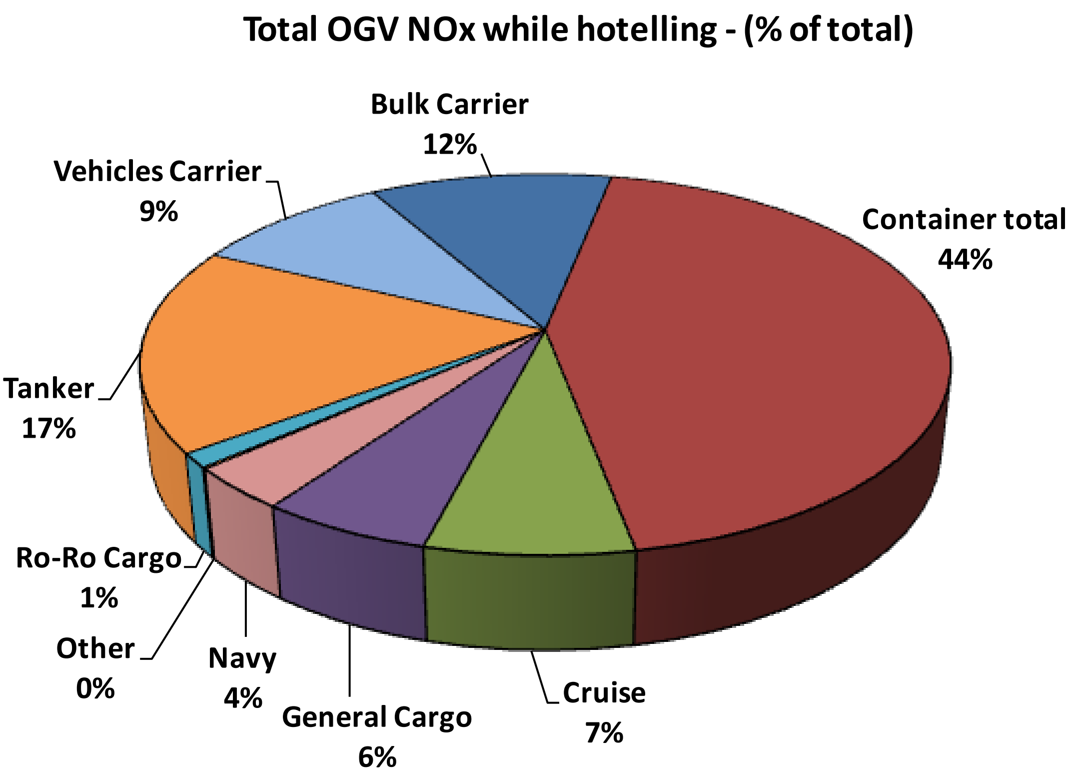


Figure 3.12 Total OGV fuel consumption and NOx emissions while hotelling – percent of total

Totals by Fuel Type while Hotelling

Total OGV fuel consumption, air quality and greenhouse emissions by fuel type while hotelling are shown in Table 3.11. RO dominates the fuel type.

Table 3.11 Total OGV fuel consumption, air quality and greenhouse emissions by fuel type while hotelling – all values in tonnes

Fuel Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
MGO/MDO	2,888	174.2	13.81	6.54	4.85	4.47	34.5	8,890	25.70	64.24
RO	17,890	660.7	50.65	21.93	84.01	81.80	957.7	55,441	45.63	456.30
ULSD	784	31.1	2.51	1.20	0.93	0.86	0.0	2,523	7.29	18.23
Totals	**21,562**	**866.0**	**67.0**	**29.7**	**89.8**	**87.1**	**992**	**66,854**	**78.6**	**538.8**

*CH_4 and N_2O in tonnes CO_2 equivalent

Totals by Vessel Type, Machinery Type and Fuel Type while Hotelling

Total fuel consumption and emissions by vessel type, machinery type and fuel type while hotelling are presented in Table D.4, Appendix D. RO dominates the fuel type. The biggest fuel consumptions were for RO from the container auxiliary engines, container boilers then tanker boilers.

No boilers are shown using MGO/MDO because the PBC survey data showed that less than 10% of boilers were operated on MGO/MDO. In contrast, around 25% of auxiliary engines operated on RO according to the PBC survey, so the hybrid fuel type was used to model auxiliary engines, as explained in Appendix B.1.3. The results were disaggregated as explained in Section 3.3.7.

No averages by fuel type could be obtained because the fuel type was known for only a few vessels and machinery types, these being the vessels in the PBC survey which had valid responses for fuel type. The limited data set did not allow the calculation of meaningful averages by fuel type.

Figure 3.13 30% of OGV NOx emissions and 34% of OGV particulate emissions are emitted during hotelling

3.3.9 Modelled Effect of Changing Fuel Type or Use of Cold Ironing on OGV Hotelling Emissions

Reductions in emissions while hotelling may be achieved by changing fuel type or by cold ironing. Cold ironing is the practice of providing electricity to the vessel from shore to displace the running of onboard auxiliary generators.

The effect of these measures on the base case for OGVs was modelled. If, for all OGVs while hotelling, distillate of low sulphur content was used or cold ironing was implemented, fuel consumption, air quality and greenhouse emissions would reduce to the values shown in Table 3.12. The percentage changes are shown in Figure 3.14.

For the purposes of modelling 100% uptake of the measure by all OGVs was assumed. For cold ironing, emissions attributed to generating the electricity from land-based sources was excluded.

Table 3.12 Total OGV fuel consumption, air quality and greenhouse emissions while hotelling if all vessels used distillate of the indicated type and sulphur content, or cold ironing was implemented on all vessels - tonnes and % change compared with base case

Fuel Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2e*
base case (tonnes)	21562	866	67	30	90	87	992	67472
MGO 0.1% (tonnes)	21135	830	67	32	27	25	42	65742
% change on base case	-2	-4	0	8	-70	-71	-96	-3
ULSD (tonnes)	21039	830	67	32	25	23	0.4	68383
% change on base case	-2	-4	0	8	-72	-74	-100	1
Cold ironing (tonnes)	9153	63	6	3	23	22	429	28653
% change on base case	-58	-93	-91	-89	-74	-74	-57	-58

*sum of CO_2, CH_4 and N_2O, where CH_4 and N_2O are expressed as CO_2equivalent

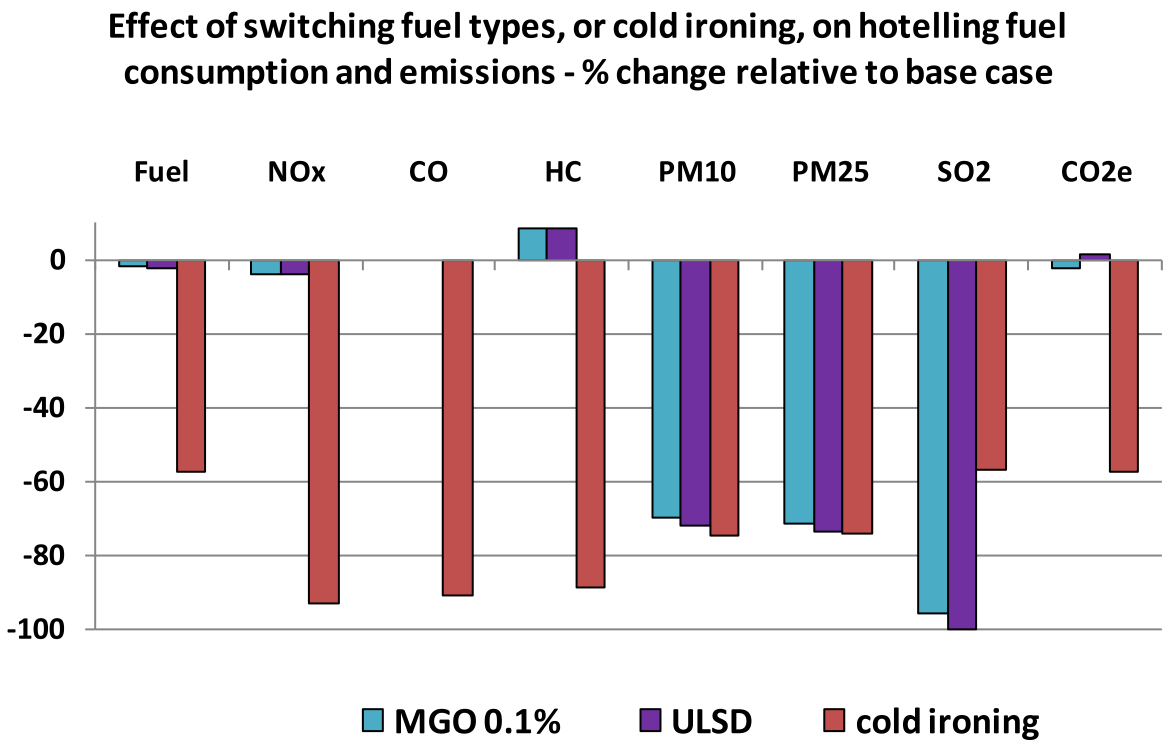


Figure 3.14 Modelled effect of use of low sulphur distillate, or cold ironing, on total OGV fuel consumption, air quality and greenhouse emissions while hotelling

The modelling suggests that use of low sulphur distillate (MGO, 0.1% sulphur) may reduce particulates and SO_2 by 70% and 96% respectively if adopted by all OGVs. The modelled reduction in particulates from cold ironing would be similar because the onboard boilers would still be operating, and using RO in the majority. For the same reason, the modelled effect of cold ironing on SO_2 would not be as great as the low sulphur distillate option. The modelled results for fuel use, NOx , CO, HC and PM attributed to cold ironing shows significant reductions, although the net effect with generating the shore-based electricity is not included in this analysis.

3.3.10 OGV by Vessel Age

Total OGV fuel consumption, air quality and greenhouse emissions by vessel age are shown in Table 3.13. The values represent the totals for all vessels within the given age class.

Table 3.13 Total OGV fuel consumption, air quality and greenhouse emissions by vessel age

Age	Year	Visits	Return Visits	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
0	2008	30	1	1,189	64.8	5.2	2.5	6.3	6.1	59.9	3,681	4.0	29.8
1	2007	274	3	5,726	346.5	28.6	14.9	33.8	32.8	299.9	17,733	17.4	144.6
2	2006	217	3	3,892	233.7	19.3	10.0	22.8	22.2	209.1	12,054	11.7	98.4
3	2005	184	3	3,245	204.1	17.0	9.0	19.7	19.1	164.3	10,051	9.7	82.0
4	2004	115	2	2,478	146.4	11.9	6.0	14.1	13.7	126.5	7,675	7.7	62.5
5	2003	106	2	2,623	144.2	11.8	6.0	14.4	14.0	139.2	8,129	7.9	66.3
6	2002	149	4	2,768	192.6	16.3	8.9	18.4	17.9	146.2	8,575	8.0	70.1
7	2001	79	3	1,310	88.9	7.4	3.9	8.3	8.0	61.9	4,063	4.1	33.1
8	2000	144	4	2,729	164.0	13.3	6.7	15.9	15.4	135.8	8,452	8.4	68.9
9	1999	79	2	1,075	67.9	5.4	2.8	6.2	6.1	45.3	3,329	3.3	27.1
10	1998	123	3	1,989	123.4	9.7	5.0	11.3	11.0	98.5	6,163	6.4	50.1
11	1997	51	2	891	59.6	4.7	2.4	5.5	5.3	46.3	2,761	2.6	22.5
12	1996	71	3	1,024	67.8	5.3	2.8	6.0	5.8	50.6	3,170	3.3	25.7
13	1995	90	3	1,447	88.4	7.0	3.6	8.1	7.9	67.9	4,483	5.2	36.2
14	1994	62	3	1,103	70.2	5.6	3.0	6.3	6.1	52.2	3,426	3.8	27.7
15	1993	20	2	694	39.0	3.1	1.5	3.9	3.8	36.0	2,149	2.0	17.6
16	1992	56	3	968	55.3	4.4	2.2	5.0	4.9	43.0	3,014	3.6	24.3
17	1991	91	5	1,015	65.5	5.2	2.7	5.9	5.7	48.9	3,151	3.3	25.6
18	1990	82	6	912	48.1	3.8	1.9	4.8	4.7	43.4	2,826	2.7	23.1
19	1989	37	19	476	25.0	2.0	1.0	2.5	2.4	23.8	1,475	1.4	12.0
20	1988	30	4	543	38.0	3.0	1.7	3.5	3.4	28.3	1,681	1.6	13.8
21	1987	42	3	465	33.2	2.6	1.4	3.0	2.9	23.9	1,441	1.4	11.8
22	1986	61	5	1,392	89.6	7.2	3.7	7.8	7.6	46.2	4,347	5.7	34.8
23	1985	24	2	238	16.5	1.3	0.7	1.5	1.5	12.1	738	0.7	6.0
24	1984	36	3	735	47.9	3.8	1.9	3.7	3.6	27.9	2,273	3.4	18.0
25	1983	36	3	462	27.8	2.2	1.2	2.6	2.5	22.7	1,432	1.5	11.6
26	1982	35	3	460	29.8	2.3	1.1	2.7	2.6	23.2	1,425	1.4	11.6
27	1981	46	5	1,034	65.8	5.2	2.7	6.0	5.8	50.3	3,201	3.3	26.0
28	1980	35	5	476	31.6	2.6	1.4	2.9	2.9	24.2	1,473	1.5	12.0
29	1979	18	3	379	24.4	2.0	1.1	1.7	1.7	11.6	1,172	2.0	9.2
30	1978	63	9	903	64.1	5.0	2.5	5.6	5.4	45.7	2,797	2.9	22.7
31	1977	12	6	179	12.7	1.0	0.5	1.1	1.1	9.0	554	0.6	4.5
32	1976	15	8	331	22.0	1.8	1.0	2.0	1.9	16.7	1,024	1.0	8.3
35	1973	5	3	39	2.1	0.2	0.1	0.2	0.2	2.1	122	0.1	1.0
36	1972	12	4	395	25.4	2.2	1.3	1.7	1.7	11.8	1,220	2.2	9.5
37	1971	5	5	144	9.4	0.8	0.4	0.9	0.8	7.2	445	0.5	3.6
41	1967	1	1	44	1.6	0.1	0.1	0.1	0.1	0.0	141	0.4	1.0
47	1961	1	1	19	0.9	0.1	0.0	0.0	0.0	0.0	62	0.2	0.4

*CH_4 and N_2O in tonnes CO_2 equivalent

Data were not available on the ages of 11 visiting vessels.

The number of visits and the number of return visits on average within each age class are also shown in Table 3.13. The average return visits data were obtained by dividing the total visits by the number of unique vessels for each age class.

Fuel consumption by year of build is shown in Figure 3.15. The totals were higher for the newer vessels because the numbers of visits were higher.

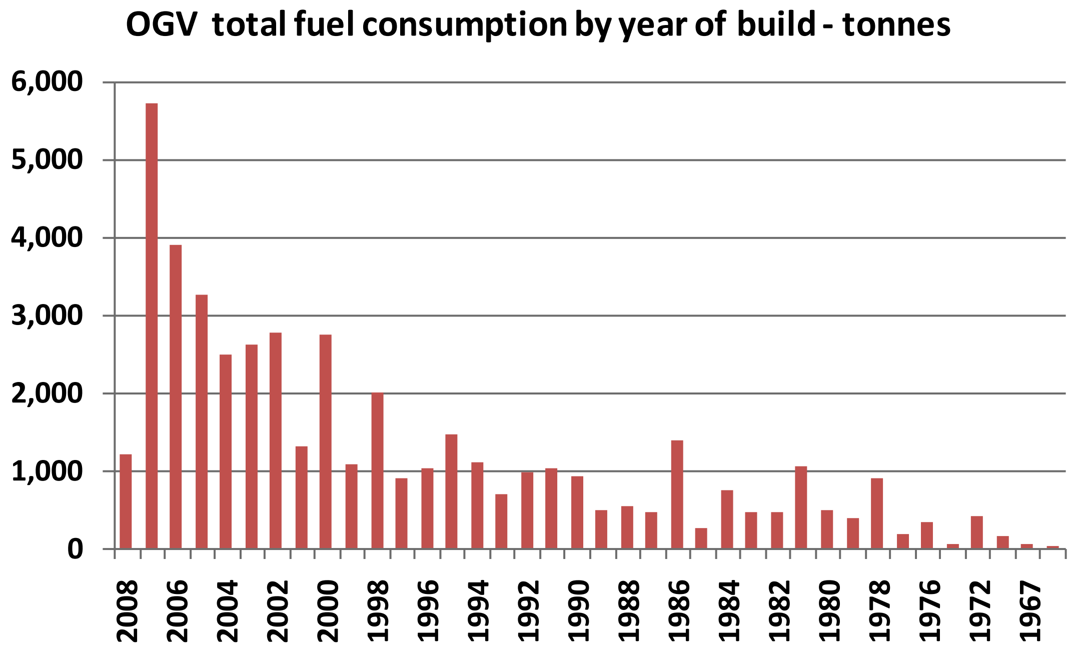


Figure 3.15 OGV total fuel consumption by year of build

There was no clear trend in the fuel consumption and emissions by age when averaged by the number of visits.

3.4 Dredges

Dredge characteristics and fuel consumption and emissions are shown in Tables 3.14 and 3.15.

In the inventory period, the contract dredge *Volvox Asia* was used for capital works for PBC and BAC. As can be seen, the *Volvox Asia* consumed more than twice as much fuel and produced more than twice the emissions of the PBC dredges *Brisbane* and *Amity*, which are used for routine channel maintenance and some capital works.

The *Volvox Asia* is powered by a combination of two medium speed diesels (MSD) and four high speed diesels (HSD). The MSD operated on RO, while the HSD operated on MGO. *Brisbane* and *Amity* are powered by HSD using ULSD.

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Table 3.14 Dredge fuel and engine details

Name	Total engine power (kW)	Fuel usage tonne	Fuel Sulphur%	Engine type	Fuel type
Volvox Asia	17,280	3,793.6	2.5	MSD	RO
Volvox Asia	6,780	1,207.1	0.4	HSD	MGO
Brisbane	3,148	3,106.5	0.001	HSD	ULSD
Amity	3,700	1,090.0	0.001	HSD	ULSD

Table 3.15 Dredge fuel consumption and primary air quality and greenhouse gas emissions in tonnes

Name	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Volvox Asia	5,000.8	309.7	25.7	12.4	28.4	27.6	199.3	14,673.5	19.5	117.2
Brisbane	3,106.5	155.3	15.7	5.7	4.3	4.1	0.062	9,996.1	28.9	72.2
Amity	1,090.0	54.5	5.5	2.0	1.5	1.4	0.022	3,507.4	10.1	25.3
Totals	9,197.3	519.5	46.9	20.1	34.2	33.2	199.4	28,177.0	58.5	214.7

*CH_4 and N_2O in tonnes CO_2 equivalent

SO_2 emissions from *Amity* and *Brisbane* are low because they operate on ULSD.

Dredge fuel consumption and emissions are compared with OGV totals in Sections 3.3.1 and 3.3.2.

The dredge fuel consumption and emissions represented about 15% of the totals for all vessels. The *Volvox Asia's* fuel consumption represented about 54% of the totals for the dredges. However, the *Volvox Asia's* NOx emissions represented about 60% of the total dredge NOx emissions, because MSD produce higher NOx than HSD for the same mass of fuel burnt.

3.5 Tugs

Tug characteristics and total fuel consumption and emissions are shown in Tables 3.16 and 3.17. Some tugs are powered by MSD and some by HSD. All operated on ULSD fuel.

Table 3.16 Tug fuel and engine details

Name	Company	Year	Total engine power (kW)	Engine type	Fuel type
Austral	Svitzer	1986	3,600	HSD	ULSD
Bulimba	Svitzer	1979	3,700	MSD	ULSD
Colmslie	Svitzer	2007	4,200	HSD	ULSD
Cook	PB	1994	6,413	MSD	ULSD
Gibson	PB	1994	6,413	MSD	ULSD
Karoo	Svitzer	1991	2,133	HSD	ULSD
Newstead	Svitzer	2007	4,200	HSD	ULSD
Wyambi	Svitzer	1977	3,720	MSD	ULSD

Tug total fuel consumption and emissions are shown in Tables 3.17. SO_2 emissions from tugs were low because they operated on ULSD. Tug fuel consumption and emissions are compared with OGV totals in Sections 3.3.1 and 3.3.2. Tug fuel consumption represented about 3% of the total for all vessels, while tug NOx emissions represented about 2% of the totals for all vessels.

Table 3.17 Tug fuel consumption and primary air quality and greenhouse gas emissions in tonnes

	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Totals	1,943.2	78.99	7.971	2.899	2.174	2.102	0.039	6,252.9	18.07	55.61

*CH_4 and N_2O in tonnes CO_2 equivalent

Figure 3.16 Emissions from tugs account for about 2% of total emissions

3.6 Comparison of IPCC and DCC Greenhouse Emissions

As detailed in Appendix B, the DCC[2] recommends a different set of factors from the IPCC[3]. International greenhouse gas emissions from shipping will probably be calculated by the IPCC factors, domestic by the DCC factors.

The ratios of emissions calculated by the two different methods are given in Table 3.18. The CO_2 values align closely. The main differences are in the CH_4 emissions, where the IPCC factor for MGO/MDO and ULSD is similar to that for RO. The DCC set uses a lower factor for RO. Tugs and naval vessels use ULSD and this fuel yields lower CH_4 using the IPCC factors. Dredges used a mixture of RO, MGO/MDO and ULSD.

However, when the CH_4 and N_2O values are aggregated with CO_2 as CO_2 equivalent values, the differences between DCC and IPCC become negligible.

Table 3.18 Ratio of primary greenhouse gas emissions calculated using two different sets of factors – IPCC[3] and DCC[2]

	IPCC/DCC ratios		
Vessel Type	**CO_2**	**CH_4**	**N_2O**
Bulk Carrier	1.01	1.74	1.01
Container	1.01	1.94	1.00
Cruise	1.01	2.33	0.98
General Cargo	1.01	1.91	1.00
Navy	0.99	0.68	1.15
Other	1.01	1.98	1.00
Ro-Ro Cargo	1.01	2.01	1.00
Tanker	1.01	1.95	1.00
Vehicles Carrier	1.01	1.83	1.00
OGV total	1.01	1.85	1.00
Dredge	1.00	0.95	1.08
Tug	0.99	0.68	1.15
All vessels	**1.01**	**1.52**	**1.02**

3.7 Fugitive Emissions

Fugitive emissions are defined as being: '.. *emissions not released through a vent or stack'*.[4] '*Fugitive sector emissions in 2005 represented 5.5 per cent of the Australian total, and at 32.3 Mt CO2-e were 10.9 per cent higher than 1990 emissions of 29.1 Mt CO2-e.'*[5]

The primary source of fugitive emissions from vessels in the PB is from the tankers. These emissions consist of hydrocarbon vapours (VOC) which are expelled from the cargo tanks while they are being filled with cargo. The Australian Government's emission estimation technique manual for maritime operations[4] sources a table from the US EPA[6] , which gives VOC emissions factors for petroleum carrying marine vessels. This is reproduced as Table 3.19.

Table 3.19 Fugitive VOC emission factors from US EPA[6]

Petroleum Liquid	Ship/Ocean Vessel Loading (Pounds VOC per 1,000 gallons transferred)	Barge Loading (Pounds VOC per 1,000 gallons transferred)	Ballasting (Pounds VOC per 1,000 gallons ballasted)	Transit (Pounds VOC per week per 1,000 gallons transported)
Crude Oil	0.61	1	1.1	1.3
Gasoline	1.8	3.4	0.8	2.7
Jet Naphtha/Other	0.5	1.2	na	0.005
Distillate Oil/Kerosene	0.005	0.012	na	3×10^{-5}
Residual Oil	4×10^{-5}	9×10^{-5}	na	

It is assumed that none of the tankers visiting the PB during the inventory would have dual ballast/cargo oil tanks, and hence there will be no fugitive emissions caused by ballasting operations.

As can be seen from Table 3.19, the type of cargo used will have a significant influence on the fugitive VOC emissions. Assuming an average value of 0.6, and based on a total fuel loaded at the PB during the year of 1,280,656 tonnes, this results in fugitive VOC emissions of approximately 120 tonnes during the year. This value is just slightly less than the estimated total HC emissions from combustion in all vessels of 142.5 tonnes during the inventory period.

Further investigation would identify the specific products loaded in PB and appropriate emissions factors for overall VOC and significant individual hydrocarbon species.

The discharge of crude oil and oil products into tanks on-shore (8,747,397 tonnes) would result in significant quantities of vapour discharge from those storage tanks. Those emissions are not included in the waterside inventory.

In addition to the tankers there will be some fugitive VOC emissions from the other ships, including bunkering, however this will probably be an order of magnitude less than that from the tanker operations. There will also be some leakage of refrigerants from ship refrigeration systems, but these were not estimated and will not affect local air quality.

In addition to the fugitive emissions from liquids, there will also be fugitive emissions from the loading and unloading of dry bulk cargos, however this is outside the scope of the present study.

3.8 Benchmarking

The overall calculated emissions and fuel consumption were benchmarked against other port inventories, by adjusting for average vessel power and hotelling times. The comparisons were favourable leading to increased confidence in the data calculated for the present inventory.

4. Upper and Lower Bounds and Recommendations for Future Inventories

In order to obtain the upper and lower bounds for the overall result, calculations were undertaken by combining estimated confidence ranges on engine and boiler powers, emissions factors, times spent in operating modes and power profiles.

For total fuel consumption and CO_2 equivalent greenhouse gas emissions in the inventory period, a confidence range of around ±20% of the reported values was estimated. The greatest contributions to the uncertainties were from boiler and auxiliary engine power and fuel consumption at berth. For air quality emissions totals the confidence range was estimated at ±30% on the reported values. Uncertainties in the emissions factors add to the uncertainties in actual power usage.

Improved outcomes of future inventories could be achieved with more accurate information on the actual boiler and auxiliary engine power and fuel consumption while hotelling as well as on main engine power and fuel consumption in transit. The survey administered by PBC was very useful and provided valuable data, but the number of vessels which responded was limited and some of the information provided was not consistent. Therefore it is recommended that further surveying be done in the future, by visiting vessels while berthed and interviewing the chief engineers. It was estimated that the confidence ranges for estimated total fuel consumption and CO_2 equivalent greenhouse gas emissions in PB could be reduced to ±10% if the surveying was thorough. Confidence ranges for air quality emissions totals could be improved to ±20%.

An improved understanding of the emissions factors for all machinery types, particularly boilers could improve the accuracy of the inventory. The latest published data from US studies were used in the present study. However there is still some uncertainty due to effects which are difficult to quantify such as the effect of engine design, age and maintenance. More confidence in the emissions factors could be achieved by conducting physical measurements of emissions. In-situ measurements made of vessel emissions while hotelling, along with the extensive surveying program, could result in a further reduction in the confidence ranges for air quality emissions totals while hotelling to ±10% of the reported values. The potential for reduction in uncertainty in total air quality emissions totals is limited because measurements during transit would be difficult, so only measurements on ships at berth would be practicable. Thus, the uncertainty in total air quality emissions are estimated to reduce to ±15% with both measurements and surveying at berth.

Further refinement of the calculation of the load factors for the main engines during transit is possible but not straightforward. This may incorporate allowances for load condition, weather, and additional drag due to restricted under-keel clearance. This could result in a reduction in the uncertainty in total fuel consumption and emissions by approximately 1 percentage point.

Thus, the primary recommendation from the present study regarding methods to improve the confidence in the estimates is that future inventories utilise a thorough program of vessel visits at berth, where each chief engineer is interviewed by a person with a marine engineering background, to complete a questionnaire covering details of fuel type, fuel usage and actual power output of main engines, auxiliary engines and boilers in the different operating modes.

5. CONCLUDING REMARKS

This report provides a detailed inventory of waterside emission for the PB for the financial year 2007/2008, using data obtained from a wide variety of sources, including from a range of stakeholders.

The 824 unique OGVs that made a total of 2,548 individual visits to the port account for around 80% of the waterside fuel consumption and emissions during the year.

In those instances where actual data were not available, assumptions were made based on a combination of benchmarking with published data and the professional knowledge of the authors.

A more rigorous inventory would be possible where more factual data were available on actual engine and boiler powers and fuel consumption. This could be achieved by interviewing the chief engineers of the ships when alongside. Estimates were made of the uncertainties and the potential impact of improved surveying. Better understanding of emissions factors could further reduce the uncertainties.

The numerical model developed during this project to calculate the data would be readily modified to accept additional data obtained from any further studies, and to facilitate compilation of new inventories.

The overall calculated emissions and fuel consumption were benchmarked against other port inventories, by adjusting for average vessel power and hotelling times. The comparisons were favourable leading to increased confidence in the data calculated for the present inventory.

This report suggests further investigation into ways in which emissions at the PB might be reduced. Hotelling accounts for around 30% of the air quality emissions from OGVs. The modelling suggests that cold ironing and the use of low sulphur distillate during hotelling could reduce waterside emissions significantly, assuming 100% uptake. These would not be easy options to implement, and each presents its own challenges and difficulties.

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Appendix A

Appendix A

Movement Data

As discussed in Section 2.2, OGVs normally enter the port precinct at the Pilot Boarding Grounds (PBG), transit to the Entrance Beacons (EB), and then on up the river to the allocated berth. The times recorded at the PBG and the EB were used to calculate the average load factor during the transit based on an assumed distance of 44.8 nautical miles for the journey. Whilst this is the distance required for the deep draught ships, the pilots reported that they generally use this channel for lighter ships too.

The distances from the EB to the various berths were obtained from a chart of the river, and are reproduced in Table A.1. For 'berths' which are not further up river than the EB distances to PBG are also given.

The berth locations are illustrated in Figure A.1.

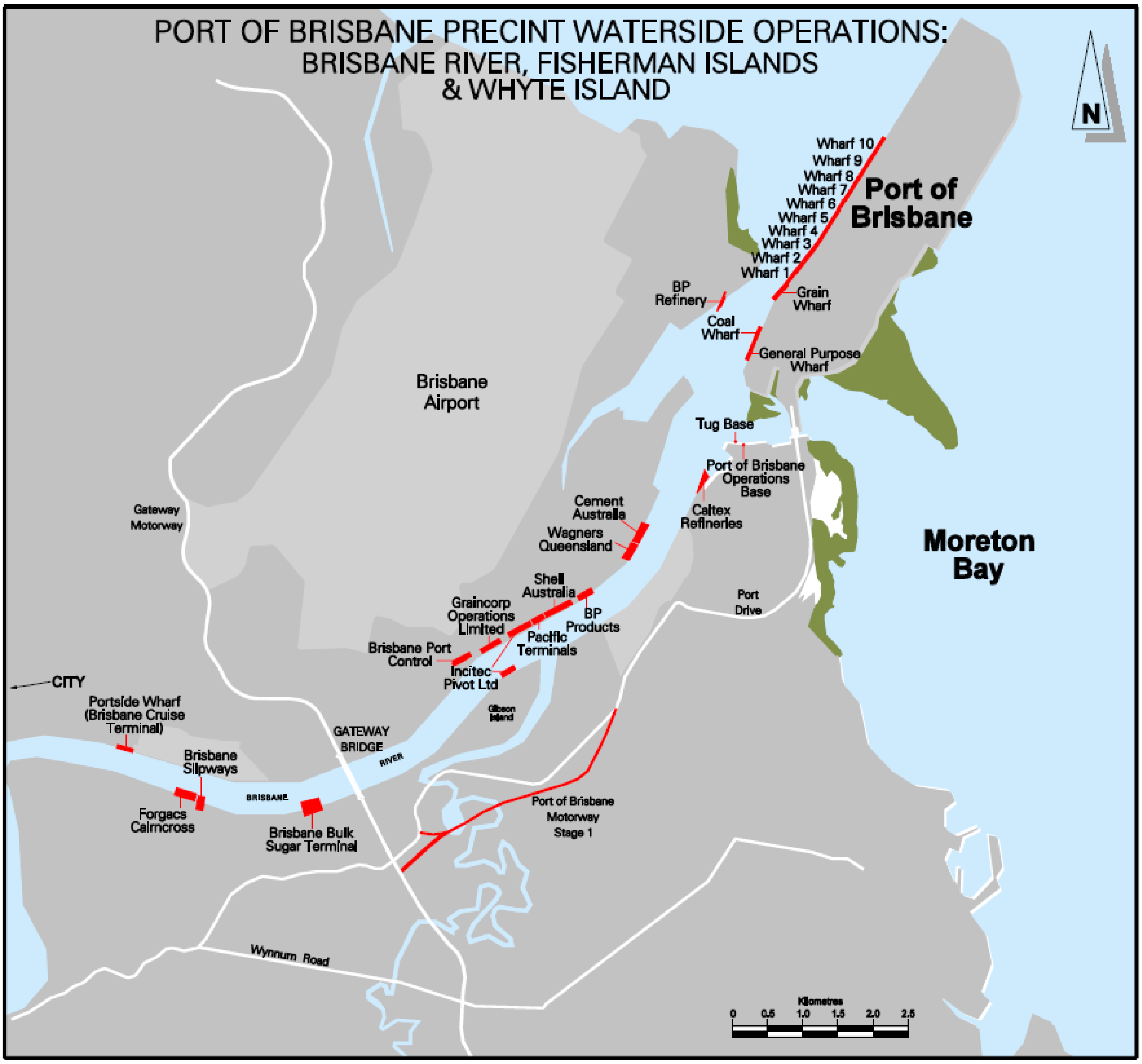

Figure A.1 Map of Port of Brisbane berth locations (courtesy of PBC).

Table A.1 Summary of distances to berths

Berth	Distance from EB nautical miles	Distance from PBG nautical miles
BP Products	7.6	
BP Tanker Berth	5.4	
Brisbane Cruise Terminal	12.4	
Brisbane Roads Anchorage	2	43
Brisbane Ship Lifts (Hemmant)	8.3	
Bulimba Navy Wharf	13.5	
Bulk Sugar	11	
Cairncross Breasting	12.4	
Cairncross Dry Dock	11.8	
Cairncross No 1	11.7	
Cairncross No 2	11.7	
Cairncross No 3	11.7	
Cairncross No 4	11.7	
Cairncross Slip	12.4	
Caltex Products	6.7	
FI Caltex Tanker Berth	6.7	
FI Coal Barge Wharf	5.5	
FI Export Coal Wharf	5.5	
FI Grain Berth	5.1	
FI Swing Basin	5.4	
Fisherman Islands No 1	4.2	
Fisherman Islands No 2	4.2	
Fisherman Islands No 3	4.2	
Fisherman Islands No 4	4.2	
Fisherman Islands No 5	4.2	
Fisherman Islands No 6	4.2	
Fisherman Islands No 7	4.2	
Fisherman Islands No 8	4.2	
Fisherman Islands No 9	4.2	
Hamilton Cold Stores	12.4	
Hamilton No 1	12.4	
Hamilton No 2	12.4	
Hamilton No 3	12.4	
Hamilton No 4	12.4	
Incitec North	8.8	
Incitec South	8.8	
Maritime No 1	11.5	
Maritime No 2	11.5	
Maritime No 3	11.5	
Maritime No 4	11.5	
Mobil Oil	11	
Pacific Terminals	8.5	
Pinkenba 1/2	8.8	
Pinkenba No 1	8.9	
Pinkenba No 2	8.8	
Pinkenba QT	8.7	
Point Cartwright	44.8	

Berth	Distance from EB nautical miles	Distance from PBG nautical miles
QCL	7.3	
Shark Spit	9	36
Shell Products	8.3	
Spit Fire	16	30
STS Transfer 1 Anch	4	41
STS Transfer 2 Anch	4	41
Tangalooma	11	35
Tug Base	6.6	
Whyte Island Base	6.7	
Yule Roads Anchorage	16	30
Pelican Banks	5.7	
Entrance Beacon	0	44.8

The MSQ data were compared and merged with PBC data. "Change of berth" movements were identified from the PBC data. The PBC data did not identify times at the EB.

For each ship visit, the following were calculated:

- time from PBG to EB, then the average **arrival transit** speed using distances given in Table A.1
- time from EB to berth, then the average **arrival manoeuvring** speed using distances given in Table A.1
- time(s) from berth to berth, then the average **repositioning** speed using distances given in Table A.1
- time(s) at berth, to give total **hotelling** time
- time from berth to EB, then average **departure manoeuvring** speed using distances given in Table A.1
- time from EB to PBG, then the average **departure transit** speed using distances given in Table A.1

About 50 vessels in the movement data had IMO/Lloyd's numbers that did not match. All but 19 of these were identified by their names and included in the analysis.

A total of 824 unique identified OGVs visited PB during the survey period. These are categorised by MSQ, US EPA and PBC in slightly different ways. Table A.2 summarises the different category types.

Table A.2 Different categories for OGVs

MSQ ship type	US EPA ship type	PBC Category
Vehicles carrier	Auto Carrier	Vehicles Carrier
Bulk carrier	Bulk Carrier	Bulk Carrier
Cement carrier	Bulk Carrier	Bulk Carrier
Ore carrier	Bulk Carrier	Bulk Carrier
Self-unloading bulk cargo	Bulk Carrier	Bulk Carrier
Wood-chip carrier	Bulk Carrier	Bulk Carrier
Container ship	Container Ship	Container Ship
Container Ship (fully cellular)	Container Ship	Container Ship
General cargo/container ship	Container Ship	Container Ship
Passenger	Cruise Ship	Cruise Ship
General cargo	General Cargo	General Cargo Ship
Livestock carrier	General Cargo	General Cargo Ship
Open hatch cargo ship	General Cargo	General Cargo Ship
Passenger/ Ro-Ro cargo	Ro-Ro	Ro-Ro Cargo Ship
Ro-Ro cargo	Ro-Ro	Ro-Ro Cargo Ship
Ro-Ro Cargo/vehicles carrier	Ro-Ro	Ro-Ro Cargo Ship
Liquefied gas tanker	Tanker	Tanker
Tanker	Tanker	Tanker
Chemical/Products Tanker	Tanker	Tanker
Training ship	Miscellaneous	Others
Tug	Miscellaneous	Others
Research	Miscellaneous	Others
Barge carrier	Miscellaneous	Others
Dredge	Miscellaneous	Others
Heavy load carrier, semi-sub	Miscellaneous	Others
Offshore Tug/Supply Ship	Miscellaneous	Others
Naval	Miscellaneous	Navy
Patrol ship (naval)	Miscellaneous	Navy
Naval Ro-Ro tank landing troopship	Miscellaneous	Navy

Appendix B

Appendix B
Fuel Consumption and Emissions Factors and Calculation Details

B.1 Power, Load Factor, Fuels and Fuel Consumption

B.1.1 Introduction

For each vessel, for both main engines and auxiliaries, data were assembled for maximum rated power, full load specific fuel oil consumption rate (SFOC, g/kWh), full load vessel speed, engine type, fuel type (RO, MDO, MGO), engine age and fuel sulphur content. The Lloyd's Seaweb data[1] for each vessel yielded maximum rated power, service speed and engine type. EPA[7] recommends the use of the Lloyd's data as accurate estimations of ship maximum propulsion power and speed.

PBC conducted a survey of OGV visiting PB, covering some 121 vessels. Further data were collected for the cruise ships from a number of sources including Inchcape Shipping Services and Carnival, to extend the survey data.

The Lloyd's data were compared with the data from the PBC's OGV survey. No significant discrepancies between the two data sources were found.

The emissions during hotelling are significant, as has been found in other port inventories. Surveying of vessels while in port would yield more accurate data on fuel type for main and auxiliary engines, auxiliary and boiler installed power, and auxiliary and boiler load factors. PBC advised that this level of accuracy was not sought for this inventory. These data could be obtained at a later stage to update the inventory and it is recommended that this be done in future.

B.1.2 Engine Power and Load Factors

Main engines

All vessels were assigned a value for rated main engine power from either the Lloyd's Seaweb data, the PBC survey data, the cruise ship survey data, or from other sources specific to each vessel. Default powers by vessel type and size were not used because the characteristics of vessels can vary from port to port. Load factor for main engines is calculated using the propeller law relationship:

$LF = (AS/SS)^3$

where LF = load factor
AS = actual vessel speed
SS = service speed

Actual engine power at a given load was found by multiplying engine power at service speed by the load factor. Service speed was taken from the Lloyd's Seaweb data. An average service speed was calculated by vessel type and used where the Seaweb data did not give service speed for a particular vessel.

The engine maximum power is not used at ship service speed (normal cruise speed). Starcrest[8] reduced rated power by a factor of 0.8 for normal cruise. Environ[9] used a factor of 0.823. The present study used 0.85. Thus, all rated engine powers were multiplied by 0.85 to derive the engine power at service speed. The choice of the adjustment factor affects the calculated emissions. For variation of the factor over the range 0.8 to 0.9, the main engine fuel consumption and emissions change by ± 6% about the values at 0.85. Total fuel consumption and emissions for all vessels change by ±2.5% about the values at 0.85.

The main engine load factor during manoeuvring may not be directly related to the vessel speed, due to the highly transient nature of the engine power demand. Starcrest used 2% engine load during docking. However, in the absence of more detailed data, the main engine load factor during manoeuvring was calculated in the same way as during transit. This resulted in reasonable values as can be seen in Table 3.3.

A number of cruise ships are diesel/electric powered, so that they do not have auxiliary generators separate from the main engines. A proportion of the total engine power was assigned as propulsion power and the remainder as auxiliary power. Where the power of the electric propulsion motors was available for diesel/electric ships, the main engine power was taken as the electric propulsion power divided by an assumed conversion efficiency of 90%. The remainder was assigned as auxiliary power. Where the power of the electric propulsion motors was not available, 60% of the main engine power was assigned as propulsion power and the remainder as auxiliary power. This is the value for the most frequent visitor of the direct drive cruise ships.

Auxiliary Engines

Installed Power

Auxiliary engine installed powers were taken from the PBC survey data or cruise ship survey data where available. Otherwise, they were derived by multiplying main engine power by default ratios of auxiliary engine power to main engine power. These ratios were primarily taken from Table 2.4 in EPA's Methodologies and Best Practices[7], which lists the ratio of auxiliary power to propulsion power for eight different ship types.

For diesel/electric cruise ships, actual effective auxiliary power was used where actual power ratio was not available, as explained under main engines above and in Appendix C. A default ratio of 0.4 was used in the present study for cruise ships, being the ratio for the most frequent visitor. EPA[7] used 0.278 as the ratio of cruise ship auxiliary engine power to main engine power. Starcrest[8] did not provide any values for cruise ship auxiliary engine power or load factor defaults and treated each cruise ship individually. ARB[10] considered all cruise ships to be diesel/electric with all engine power assigned as auxiliary engine power, then applied a low value of auxiliary engine load factor while hotelling.

From the PBC survey, it was possible to define a representative ratio of 0.21 for container ships, as described in Appendix C, which was used as the default.

The various sources are compared in Table B.1

Table B.1 Comparison of auxiliary power ratios from a number of sources

Vessel type	Auxiliary power ratio			
	Starcrest[8]*	ARB[10]**	EPA[7]	AMC
Bulk Carrier	0.248	0.315	0.222	0.222
Container Ship	0.211-0.216	0.219	0.220	0.21
Cruise Ship	na	na	0.278	0.4
General Cargo	0.216	0.237	0.191	0.191
Navy	na	na	na	0.2
Others	0.177	na	na	0.2
Reefer	0.395	0.325	0.406	0.406
Ro-Ro	0.144	0.214	0.259	0.259
Tanker	0.306	0.179	0.211	0.211
Vehicles Carrier	0.248	0.259	0.266	0.266

*The Starcrest values were calculated from Starcrest[8] Tables 2.11 and 2.13 which give default powers.

**The ARB values were calculated from ARB[10] Table II-4 which gives powers averaged from a number of sources

Load Factor

Auxiliary engine load factor was taken from the cruise ship survey data where available, otherwise from Table 2.7 in EPA[7], which lists the load factor for 8 different ship types. This table is similar to Table II-5 in ARB[10]. There were insufficient valid responses in the PBC survey data to warrant use of the load factors.

Auxiliary load factors while hotelling from a number of sources are compared in Table B.2. The hotelling values are the most important because that is when the majority of the auxiliary engine fuel consumption occurs. The auxiliary load factor for cruise ships while hotelling used here is higher than the value of 0.16 found in ARB[10], but ARB considered all cruise ships to be diesel/electric with all engine power assigned as auxiliary engine power. For instance, ARB[10] used 0.80 as auxiliary load factor during transit for cruise ships. The cruise ship survey for the PB (see Section C.2.2) yielded a well defined hotelling load factor of 0.32 for the most frequent visitor, which is the value used in the present study.

The product of auxiliary power ratio and load factor determines actual auxiliary power for a given main engine power. For the values chosen for the present study, this product equals 0.13. For EPA's values, with a relatively high load factor of 0.64, the product equals 0.18. The ARB value of 0.16 for load factor while hotelling, assuming all engines are effectively auxiliaries, can be compared directly with the product of auxiliary power ratio and auxiliary load factor. Thus, the ratio of actual auxiliary power to installed main engine power used in the present study is slightly lower than EPA and ARB values (0.13 against 0.18 and 0.16). However, the chosen values were determined from actual survey data from the PBC and are reflective of the age/type/size profiles for the vessels visiting PB.

Table B.2 Comparison of auxiliary load factors while hotelling from a number of sources

Vessel type	Auxiliary load factor hotelling			
	Starcrest[8]	ARB[10]	EPA[7]	AMC
Bulk Carrier	0.10	0.10	0.22	0.22
Container Ship	0.15-0.22	0.18	0.17	0.18
Cruise Ship	na	0.16	0.64	0.32
General Cargo	0.22	0.22	0.22	0.22
Navy	na	na	na	0.22
Others	0.22	na	0.22	0.22
Reefer	0.32	0.32	0.34	0.32
Ro-Ro	0.26	0.26	0.30	0.3
Tanker	0.26	0.26	0.67	0.26
Vehicles Carrier	0.26	0.26	0.24	0.26

Over the full range of vessel types and operating modes, the EPA, ARB and Starcrest load factors generally correspond, apart from the exceptions already mentioned.

Table B.3 shows auxiliary power ratio and load factors used in the present study.

Table B.3 Default auxiliary engine to main engine power ratios and auxiliary engine load factors

Vessel type	Auxiliary power ratio	Auxiliary load factor		
		Transit	Manoeuvre	Hotel
Bulk Carrier	0.222	0.17	0.45	0.22
Container Ship	0.21	0.13	0.5	0.18
Cruise Ship	0.40	0.32	0.32	0.32
General Cargo	0.191	0.17	0.45	0.22
Navy	0.2	0.17	0.45	0.22
Others	0.2	0.17	0.45	0.22
Reefer	0.406	0.15	0.45	0.32
Ro-Ro	0.259	0.15	0.45	0.3
Tanker	0.211	0.24	0.33	0.26
Vehicles Carrier	0.266	0.15	0.45	0.26

Ro-Ro and Vehicles Carrier load factors are significantly larger during hotelling than transit. This allows for the use of ventilation fans during loading/unloading.

Boilers

Many ships use auxiliary boilers to maintain RO at the required viscosity and for hot water. While the main engines are operating, an economiser on the main engine exhaust will generally be used to provide this heating.

Actual boiler powers were used rather than multiplying rated power by load factor. Where data were not available from the extended PBC survey, default boiler powers were taken from the PLA study by Starcrest[8] Table 2.14. These were obtained by a vessel boarding program and are the most detailed values available. The values used are shown in Table B.4.

Table B.4 Default actual boiler powers (kW) from Starcrest[8]

vessel type	Starcrest boiler power defaults (kW)		
	Transit	**Manoeuvre**	**Hotel**
Bulk Carrier	0	109	109
Container Ship	0	506	506
Cruise Ship	0	1000	1000
General Cargo	0	106	106
Navy	0	200	200
Others	0	106	106
Reefer	0	464	464
Ro-Ro	0	109	109
Tanker	0	371	3000
Vehicles Carrier	0	371	371

The values shown were calculated by Starcrest from vessel survey program data, which were obtained as actual boiler fuel consumption rates. Starcrest then converted the fuel consumption rates to kW (energy content of steam) by assuming an SFOC for boilers of 305g/kWh, which is a typical SFOC for a steam turbine power plant. This value is not realistic when applied to a boiler in isolation. For a boiler operating on RO at 80% boiler efficiency, the SFOC can be calculated at 112.5g/kWh. However, to use the Starcrest power values correctly, it was necessary to use their SFOC to ensure that the correct fuel consumption rate was recovered. (Starcrest also converted boiler emission factors from g/kg fuel to g/kWh using the same SFOC, so using Starcrest's SFOC was necessary to recover the correct boiler emissions factors.)

The rate of pumping is strongly determined by the on-shore facility's capacity to receive, so a large tanker may pump at a similar rate to a smaller tanker.

Table B.5 shows the default boiler powers used by ARB[10], compared with main and auxiliary installed power averages. The boiler powers were used as actual power (ie load factor = 1) and the boiler SFOC was 305 g/kWh. By comparison with Table B.4 it can be seen that ARB used lower boiler power values than Starcrest used, even though ARB claims to have obtained the values from Starcrest's survey.

Table B.5 Default actual boiler powers used by ARB[10], along with main and auxiliary engine installed power averages

Vessel type	ARB power averages (kW)		
	Main engine	Aux engine	Boiler
Bulk Carrier	7,803	2,459	82
Container Ship	37,265	8,156	380
Cruise Ship	0	44,042	750
General Cargo	7580	1799	99
Navy	na	na	na
Others	na	na	na
Reefer	11,091	3,605	348
Ro-Ro	12,181	2,605	82
Tanker	13,034	2,339	1,593
Vehicles Carrier	11,593	2,999	278

For consistency with the use of ARB[10] emissions indices, ARB boiler powers were used for manoeuvring and hotelling. For tankers manoeuvring, the Starcrest manoeuvring value of 371kW was used as tankers are not discharging cargo while manoeuvring. The ARB[10] cruise ship boiler power is close to the value from the cruise ship survey (Appendix C). Starcrest's 3000kW for tanker boiler power gave excessive fuel consumption.

Tankers use steam turbines to drive pumps for discharging cargo and pumping out ballast water while loading cargo. The steam turbines are simple and not highly efficient. Relatively low temperature and pressure steam are used for safety and convenience. The amount of fuel consumed by tanker boilers to create the steam is uncertain. There is considerable uncertainty as to the correct value of boiler power for tankers.

Using reasonable boiler pressure, boiler efficiency, turbine efficiency, pump efficiency and pump discharge pressure it was calculated that around 0.35 kg of boiler fuel is required to move 1 tonne of cargo. Survey data from 4 tankers visiting PB show a range of 0.18 to 0.35 kg boiler fuel per tonne of oil unloaded at the port. Anecdotal evidence from a number of sources not associated with PB indicated values in the range 0.25 to 1.0 kg boiler fuel per tonne of oil unloaded.

An International Maritime Organisation expert working group[11] suggested that for tankers of DWT less than 80,000 tonnes, the cargo pumps might be hydraulically driven. The power would be provided by the auxiliary engines rather than the boiler, and the amount of fuel required to power the hydraulically driven pumps for a given quantity of cargo transferred would be considerably less due to the greater efficiency of this method. Of the 447 tanker visits to PB in the inventory period, 132 were from tankers of DWT greater than 80,000 tonnes. It is not known how much oil was delivered by the various tanker size ranges, but it is reasonable to assume that the biggest tankers would deliver the greatest proportion of oil. Some fuel would also be used to maintain cargo temperature. It is reasonable to assume that the mass of boiler fuel consumed per tonne of oil delivered would be less than the values suggested by the anecdotal evidence, because some of the oil would be delivered by smaller tankers using hydraulically driven pumps. The smaller tankers would still use some boiler steam to maintain cargo temperature while in port. The total oil imported into PB for the inventory year was 8.747 million tonnes.

Thus, in the absence of comprehensive data on the actual usage of steam driven pumps in PB during the inventory period, it was assumed that only tankers of DWT greater than 80,000 tonnes used steam driven pumps, that smaller tankers used hydraulically driven pumps and that the power to drive the hydraulically driven pumps was supplied by auxiliary engines, and that this auxiliary engine power was accounted for by the default values of installed auxiliary engine power and load factor. The boiler power while hotelling for the tankers less than 80,000 DWT was taken as the manoeuvring value of 371 kW. The boiler power while hotelling for tankers greater than 80,000 DWT was taken as the ARB[10] value of 1593 kW and the total time spent pumping cargo was limited to 30 hours per vessel visit. Thus, calculated total tanker boiler fuel consumption while hotelling for the inventory year was 3,065 tonnes. This is equivalent to an overall value of about 0.35 kg of boiler fuel consumed per tonne of oil delivered to PB in the inventory year, which is consistent with calculated pumping power and survey data.

Incinerators

It was assumed that incinerators are not used in port.

Dredges

Dredge calculations were based on fuel consumption figures supplied by PBC, with no corrections for load factor given that the dredges are designed to operate at around 70% load in all phases of operation. Thus, engine power was not used.

Tugs

Tug engine power was obtained for each tug from tug owners' data and engine makers' specifications. Tug fuel usage and operating hours were supplied by tug owners on a monthly basis. Using monthly figures facilitated checking for erroneous data. The load factors were calculated as the ratio of the given fuel consumption and the full power fuel consumption. Manufacturers' specified fuel consumption at full load was used where possible. Where unavailable, the full power fuel consumption was calculated from specified full load power and assumed full load SFOC.

B.1.3 Fuels and fuel sulphur content

Fuels were either RO, MDO, MGO or ULSD. Table B.6 compares typical ranges of key attributes of the fuels.

Table B.6 Typical ranges of values of density, sulphur content and heating value for marine fuels

Fuel type	Density kg/litre	Sulphur content % by mass	Heating Value LHV MJ/kg	Source	Appearance
RO	0.92 to 0.98	2.0 to 3.5	40.0 to 41.0	refinery residue	dark, opaque
MGO/MDO	0.89 to 0.9	0.1 to 1.5	42.0 to 43.0	distillate	clear, bright
ULSD	0.83 to 0.835	0.001	43.0 to 43.5		

For auxiliary engines it was found from the PBC survey data that a significant proportion, approximately 25%, operated on MGO/MDO in port rather than RO. To cater for this, a hybrid set of emissions factors, SFOC and Lower Heating Value (LHV) was used for auxiliary engines while hotelling. These are composed of 75% of the RO values plus 25% of the MGO/MDO values.

Global RO sulphur content is on average around 2.4% by mass. Most OGVs use RO in their main engines and auxiliaries. Some may carry MDO or MGO from international bunkering for use in auxiliaries. MDO and MGO are distillates but sulphur content can be as high as 1.5% for MGO and 2.0% for MDO under ISO 8217:2005[12]. Typically sulphur content of MGO and MDO is lower than these values. MGO and MDO are not generally available in Australia, and any fuel purchased as MDO or MGO is assumed to be automotive diesel (ULSD) with sulphur content 10ppm by mass (0.001%).

Fuel sulphur content was taken either from the known value for a specific vessel or as an average for the operating mode, from PBC's survey data. During transit, the average from the PBC survey data was 2.7% sulphur by mass. During manoeuvring and at berth, this average was 2.4%. The reason for lower average fuel sulphur content during manoeuvring and at berth is that some ships switch from RO to MDO or MGO, while some use these fuels in their auxiliary engines at all times. Cruise ships generally operate exclusively on RO.

Where the required data for fuel type were not available from the PBC's OGV survey or the Lloyd's data, then it was be assumed that all engines use RO, but with sulphur content equivalent to the survey averages.

Where actual fuel sulphur content was not available from the cruise ship survey data, the average for the cruise ships of 2.8% sulphur by mass was used.

Naval vessels use a special fuel, made to the F76 specification. The specification mandates maximum sulphur content of 1%. The Australian Navy advised that when they source their fuel in Australia, the sulphur content is 0.001%, the same as ULSD. Thus, it was assumed that naval vessels use ULSD.

Tugs used ULSD and dredges *Amity* and *Brisbane* used ULSD. Dredge *Volvox Asia* used RO and MGO. It is possible that *Volvox Asia* also used some ULSD while working in Brisbane, if it needed to take on board more fuel than it brought with it. However, this was not determined.

B.1.4 Specific Fuel Consumption

Main engines

Specific fuel oil consumption (SFOC) gives the engine’s fuel consumption rate for a given power output. The Lloyd’s Seaweb data[1] did not give SFOC. The PBC survey data gave SFOC, but the values were generally the manufacturer’s specifications, which were obtained under ideal conditions and using distillate rather than RO. The PBC survey data values were corrected for fuel type using the ratio of LHV for RO to LHV for distillate, or 40.4/43.0.

Where SFOC was not available from the PBC survey data, published default values, taken from Entec[13] and ARB[10], are shown in Table B.7.

Table B.7 Specific fuel consumption(g/kWh) for OGV main engines using residual oil

Engine	SFOC g/kWh
Slow Speed Diesel (SSD)	195
Medium Speed Diesel (MSD)	213
Steam Turbine (ST)	290

At part load, in the absence of other data, the SFOC at full load was used. Further refinement would modify SFOC for engine load. For example Table 2.9 in Entec[13] gives SFOC while manoeuvring for all engine and fuel types. However, the small proportion of fuel consumed during manoeuvring did not warrant the extra complication of applying a different SFOC.

For any naval vessels using a gas turbine as the main engine, SFOC of 290 g/kWh was used.

Auxiliary engines

Where SFOC was not available from the PBC survey data, published default values were taken from Entec[13] and ARB[10] as shown in Table B.8.

Table B.8 Specific fuel consumption (g/kWh) for auxiliary engines from Entec[13]

Engine	Fuel	SFOC g/kWh
MSD	RO	227
MSD	MDO	217
MSD	MGO	217
HSD	MGO/MDO	218

At part load, full load SFOC consumption was used, because a number of generators are installed on each ship and large changes in demand are catered for by switching engines in or out, so any individual engine generally won't be operated at low load.

Dredges

Full load SFOC was obtained from Table B.8 according to engine type. *Volvox Asia* has two MSD using RO and four HSD using MGO. *Brisbane* and *Amity* are powered by HSD using ULSD. Full load SFOC was used as actual SFOC.

Tugs

Some tugs used MSD and others use HSD. Actual fuel usage and engine hours were supplied for each tug. Actual SFOC was obtained by dividing actual fuel rate by actual engine power. Load factor was calculated as the ratio of actual fuel consumption rate to full load fuel consumption rate. Some manufacturer data for full load fuel consumption rate gave unreasonably low values for full load SFOC, in which case full load fuel consumption was calculated using full load power and default values of full load SFOC. Default SFOC for tug HSD was set at 217 g/kWh and for tug MSD on ULSD at 210 g/kWh. The tugs operate on ULSD so the SFOC can be expected to be lower than if operating on RO or MGO/MDO.

B.2 Emissions Factors

B.2.1 Air Quality

Main engines

Factors used in previous studies into the primary air quality emissions factors for ocean going vessels are given in Table B.9.

Table B.9 Primary air quality emissions factors for OGV main engines using RO g/kWh

Engine	NOx	CO	HC	PM_{10}	$PM_{2.5}$
SSD	18.1[7-10]	1.40[7-9] 1.38[10]	0.60[7-9] 0.69[10]	1.08[7] 1.50[8-10]	0.99[7] 1.46[10] 1.2[8]
MSD	14.0[7-10]	1.10[7-10]	0.50[7-9] 0.57[10]	1.14[7] 1.50[8-10]	1.10[7] 1.46[10] 1.2[8]
ST	2.1[7-9]	0.20[7-9]	0.10[7-9]	1.55[7] 1.50[9] 0.8[8]	0.66[7] 0.6[8]

$PM_{2.5}$ is taken as a percentage of PM_{10}, and the factor varies with fuel type. EPA[7] claims to have used a factor of 0.92 for SSD and MSD, but the EPB[7] published value for MSD uses a factor of 0.96. Entec[13] does not give PM factors for main engines at sea. The ARB[10] PM factors are the most recent and are the same as those recommended by Environ[9] and EPA[7], so they were used. It is likely that the differences in the PM factors are within the range of uncertainty.

The ARB[10] factors for HC are for the ROG (NMVOC) component of total HC, but are larger than the factors used by Starcrest[8], Environ[9] or EPA[7].

For vessels built in or after 2000 and thus complying with IMO Marpol Annex VI[14] "Tier 1", reduced factors for NOx emissions from diesel propulsion engines were used as suggested by Starcrest[8] (17.0 g/kWh SSD, 13.0 g/kWh MSD). NOx emissions from OGV main engines were reduced for such vessels by applying an age reduction factor of 0.939 (17/18.1) for SSD and 0.929 (13/14) for MSD. These reduction factors were derived from Tables 2.6 and 2.7 in Starcrest[8].

Emissions factors for NOx, CO and HC were adjusted for loads below 20% using Table 2.9 in EPA's Methodologies[7]. Environ[9] used a different table (Table 2.10) for emissions factor adjustment for PM10 and PM2.5, which is claimed to be based on more relevant data from California Air Resources Board (ARB). However, ARB[10] uses a table (Table II-7) for main engine emission factors during manoeuvre, rather than applying a low load multiplier. Table 2.9 in EPA's Methodologies[7] was used for NOx, CO, HC and PM, as reproduced in Table B.10. The low load adjustment mainly occurs during manoeuvring and the total amount of emissions during manoeuvre is a small proportion of the total, so the precision of the emissions factors does not need to be high. The main engine load factor during manoeuvre was calculated from the time and distance between the EB and berth. This gave reasonable values during manoeuvring. The auxiliary engine emission factors do not need to be adjusted for engine load, because the availability of multiple engines allows shutdown of any engine if its load factor becomes low.

Table B.10 Emissions index adjustment by engine load factor

	adjustment factors				
Engine load %	**NOx**	**CO**	**HC**	**PM_{10}**	**$PM_{2.5}$**
1	4.63	10.0	31.62	9.82	9.82
2	4.63	10.0	31.62	5.60	5.60
3	2.92	6.67	17.21	4.03	4.03
4	2.21	5.0	11.18	3.19	3.19
5	1.83	4.00	8.00	2.66	2.66
6	1.60	3.33	6.09	2.29	2.29
7	1.45	2.86	4.83	2.02	2.02
8	1.35	2.5	3.95	1.82	1.82
9	1.27	2.22	3.31	1.65	1.65
10	1.22	2.0	2.83	1.52	1.52
11	1.17	1.82	2.45	1.40	1.40
12	1.14	1.67	2.15	1.31	1.31
13	1.11	1.54	1.91	1.22	1.22
14	1.08	1.43	1.71	1.15	1.15
15	1.06	1.33	1.54	1.09	1.09
16	1.05	1.25	1.40	1.03	1.03
17	1.03	1.18	1.28	1	1
18	1.02	1.11	1.17	1	1
19	1.01	1.05	1.08	1	1
20	1	1	1	1	1

SO_2 emission factors were calculated according to local fuel sulphur content, rather than using the emissions factors used in the US studies. All the sulphur in the fuel can be assumed to have oxidised. Thus, SO_2 emissions are directly related to the mass of fuel burnt and the fuel sulphur content. A sulphur emissions factor was be calculated directly from the fuel sulphur content and SFOC:

(g SO_2)/kWh = (kg S)/(kg fuel) x (g fuel)/kWh

In this way, the mass emissions are sensitive to the SFOC and the local fuel sulphur content.

Auxiliary engines

Table B.11 shows primary air quality emissions factors for OGV auxiliary engines.

Table B.11 Primary air quality emissions factors for OGV auxiliary engines g/kWh

Engine	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$
MSD	RO	14.70[7-10]	1.10[7-10]	0.40[7-9] 0.46[10]	1.14[7] 1.50[8-10]	1.10[7] 1.2[8] 1.46[10]
MSD	MDO	13.90[7-10]	1.10[7-10]	0.40[7-9] 0.52[10]	0.75[7] 0.38[9,10] 0.3[8]	0.28[7] 0.2[8] 0.35[10]
MSD	MGO	13.90[7-10]	1.10[7-10]	0.40[7-9] 0.52[10]	0.42[7] 0.38[9] 0.3[8] 0.25[10]	0.23[7] 0.2[8] 0.35[10]
HSD	MGO/MDO	10.9[13]	1.10[13]	0.40[13]	0.30[13]	0.29

There is general agreement in the literature on emission factors for NOx and CO, but a spread of factors for HC and PM. The most recent values from ARB[10] were used.

As with the main engines, SO_2 emission factors were calculated according to local fuel sulphur content, rather than using the emissions factors used in the US studies.

HSD values are included here even though it is unlikely that OGVs will use HSD for auxiliaries. These values were used for tug and dredge HSD.

Boilers

It was assumed that all boilers operated on RO. Emissions factors for boilers from a number of sources are compared in Table B.12. The most recent figures available were from ARB[10] (2008) and Agrawal et al[15] (2008). The results from Agrawal et al[15] are probably the most recent measurements and were done on a tanker boiler at high power, typical of a tanker boiler in use in port to supply steam turbine driven pumps.

Table B.12 Auxiliary boiler emissions factors using RO

	ARB[10]	Entec[13] Table 2.8	ARB[10] /0.305	Entec[13] Table 2.8 /0.305	Entec[13] Table C.7	EPA[7]	Agrawal et al[15]	NPI[16]	EPA AP42[16]	ARB[10] @112.5g/ kWh
units	**g/kWh**	**g/kWh**	**kg/t**	**kg/t**	**kg/t**	**kg/t**	**kg/t**	**kg/t**	**kg/t**	**g/kWh**
NOx	2.1	2.1	6.89	6.89	6.98	12.3	9.24 ±0.09	7.32	6.70	0.77
CO	0.2		0.66		0.43	4.6		0.67	0.61	0.07
HC	0.11	0.1	0.36	0.33	0.09	0.38		0.04	0.16	0.04
PM_{10}	0.8		2.62		2.5	1.3	2.78 ±0.26	0.054	1.4	0.29
$PM_{2.5}$	0.78		2.56			1.04		0.033		0.29
SFOC g/kWh	305	305	305	305						112.5
Source	Starcrest /Entec	steam turbine main engine at sea	Starcrest/Entec	steam turbine main engine at sea	steam turbine main engine cruise	not sourced!	direct measure tanker boiler	station-ary boiler	industrial boiler	

The ARB[10] factors are given as g/kWh, which is the rate of production of emissions divided by the rate of energy supplied to the feedwater to convert it to steam. The Agrawal et al factors are given in kg/tonne fuel, or kg of emissions produced per tonne of fuel supplied to the boiler. The ARB[10] factors were converted to kg/tonne as shown in Table B.12. To do this, boiler SFOC of 30 g/kWh was assumed because ARB[10] used values from Entec[13] for a steam turbine power plant, where SFOC represents the fuel flow rate divided by the turbine power output.

Similarly, Starcrest[8] converted measured boiler fuel consumption rates to kW (energy taken up by the steam) by assuming an SFOC for boilers of 305 g/kWh, which is a typical SFOC for a steam turbine power plant. This value is not realistic when applied to a boiler in isolation. For a boiler operating at 80% boiler efficiency on RO, the SFOC is 112.5g/kWh. ARB also listed boiler powers in kW with boiler SFOC of 305 g/kWh.

Emissions factors for boilers were also sourced from EPA[7](ship boilers), NPI[16] (stationary boilers), and EPA[16,17] (stationary boilers).

There is considerable variation in the factors. NOx factors vary from 6.7 to 12.3kg/tonne. PM_{10} factors vary from 0.054 to 2.62 kg/tonne. However, some of the lower values are for stationary land based boilers and necessary design differences may lead to the discrepancies.

For consistency with the most recent US inventories, the ARB[10] factors were used. The NOx factor is less than the most recent measurements of Agarwal et al[15], but the PM_{10} factor is similar.

B.2.2 Summary of air quality emissions factors and SFOC for all engines and boilers

Table B.13 gives a summary of the air quality emissions factors and SFOC used in the present study for all engines and boilers

Table B.13 Air quality emissions factors and SFOC for all engines and boilers used in present study

				Air quality emissions factors and specific fuel consumption g/kWh					
Machinery Type	**Engine type**	**Engine stroke**	**Fuel type**	**NOx**	**CO**	**HC**	**PM_{10}**	**$PM_{2.5}$**	**SFOC**
OGVMain	SSD	2	RO	18.1	1.38	0.69	1.5	1.46	195
OGVMain	SSD	2	MDO	17	1.1	0.78	0.38	0.35	190
OGVMain	SSD	2	MGO	17	1.1	0.78	0.38	0.35	190
OGVMain	MSD	4	RO	14	1.1	0.57	1.5	1.46	213
OGVMain	MSD	4	MDO	13.2	1.1	0.65	0.38	0.35	213
OGVMain	MSD	4	MGO	13.2	1.1	0.65	0.38	0.35	213
OGVMain	MSD	4	ULSD	13.2	1.1	0.65	0.38	0.35	210
OGVAux	MSD	4	RO	14.7	1.1	0.46	1.5	1.46	227
OGVAux	MSD	4	MDO	13.9	1.1	0.52	0.38	0.35	217
OGVAux	MSD	4	MGO	13.9	1.1	0.52	0.38	0.35	217
OGVAux	MSD	4	ULSD	13.9	1.1	0.52	0.38	0.35	215
OGVAux	HSD	4	MDO	10.9	1.1	0.4	0.3	0.29	218
OGVAux	HSD	4	MGO	10.9	1.1	0.4	0.3	0.29	218
OGVAux	HSD	4	ULSD	10.9	1.1	0.4	0.3	0.29	217
OGVBoiler			RO	2.1	0.2	0.11	0.8	0.78	305*
OGVBoiler			MDO	2	0.2	0.11	0.2	0.19	305*
OGVBoiler			MGO	2	0.2	0.11	0.13	0.12	305*
OGVBoiler			ULSD	2	0.2	0.11	0.13	0.12	305*
OGVMain	ST		MGO	2.1	0.2	0.1	1.65	0.66	290
OGVMain	GT		MGO	5.7	0.2	0.1	0.25	0.25	290
OGVMain	ST		ULSD	2.1	0.2	0.1	1.65	0.66	290
OGVMain	GT		ULSD	5.7	0.2	0.1	0.25	0.25	290

*Starcrest[8] converted measured boiler fuel consumption rates to kW (energy content of steam) by assuming an SFOC for boilers of 305 g/kWh, which is a typical SFOC for a steam turbine power plant. This value is not realistic when applied to a boiler in isolation. For a boiler operating at 80% boiler efficiency, the SFOC is 112.5g/kWh. However, to use the Starcrest power values correctly, it was necessary to use the Starcrest SFOC to ensure that the correct fuel consumption rate was recovered.

For auxiliary engines it was found from the PBC survey data that a significant proportion, approximately 25%, operated on MGO/MDO in port rather than RO. To cater for this, a hybrid set of emissions factors SFOC and LHV was used for auxiliary engines while hotelling. These are composed of 75% of the RO values plus 25% of the MGO/MDO values.

B.2.3 Greenhouse Gas Emissions Factors

The primary greenhouse gas emissions are:

CO_2 – the main source of greenhouse gases from shipping

CH_4 (methane) – a powerful greenhouse gas with a global warming potential (GWP) 21 times CO_2[2].

N_2O (nitrous oxide) – a powerful greenhouse gas with a GWP 310 times CO_2[2].

The DCC 2008 Workbook on National Greenhouse Accounts (NGA) Factors, November 2008[2], gives greenhouse emission factors. The DCC emissions factors for the primary greenhouse gases are shown in Table B.14.

Table B.14 DCC[2] Greenhouse Gas Emission Factors

	Emission factors kg CO_2e/TJ		
Fuel type	**CO_2**	**CH_4**	**N_2O**
RO	72,900	60	600
MGO/MDO	69,200	200	500
ULSD	69,200	200	500

There is evidence that the amount N_2O produced by engines burning residual fuel (RO) with high sulphur content[18-20] is significantly higher than for low sulphur fuels, but DCC does not differentiate significantly between RO and distillate (MGO/MDO and ULSD).

The DCC factors are configured to use the Higher Heating Value (HHV) of the fuel. DCC defines fuel energy values on a volumetric basis for diesel oil and fuel oil. Fuel density values were applied to the volumetric HHV to give mass based values of HHV. This was necessary because fuel mass is the primary output from the vessel activity calculations, based on SFOC and engine energy output. Fuel density values are not given by DCC, so typical values were applied to yield reasonable values of HHV on a mass basis. The volumetric HHV of MGO/MDO was taken as the value for industrial diesel fuel in the 2006 DCC methodology manual[21] because no value was given in the DCC 2008 workbook[2]. If the volumetric HHV for ULSD is divided by the density of MGO/MDO, it yields a mass based HHV which is too low (see Table 2.7 Borman and Ragland[22] and Table 5.5, Petchers[23], taking MGO/MDO to be midway between No. 2 fuel oil and No. 3 fuel oil.) DCC fuel energy is presented in Table B.15.

Table B.15 DCC Fuel Energy Content: Conversion from GJ/kL to MJ/kg

DCC fuel type	Marine fuel type	HHV GJ/kL	Density kg/litre	HHV MJ/kg
Fuel oil	RO	39.7	0.935	42.5
Diesel oil	MGO/MDO	39.2	0.89	44.5
Diesel oil	ULSD	38.6	0.83	46.5

The IPCC[3] uses a fuel mass based approach for LHV. The IPCC emissions factors for the primary greenhouse gases are shown in Table B.16.

Table B.16 IPCC Greenhouse Gas Emissions Factors and their confidence limits for all engines in kg/TJ (from IPCC 2006[3] Tables 3.5.2 and 3.5.3)

	Emission factors kg /TJ		
Fuel	**CO_2**	**CH_4**	**N_2O**
RO	77,400 (75,500 to 74,800)	7 (±50%)	2 (+140% -40%)
MGO/MDO	74,100 (72,600 to 78,800)	7 (±50%)*	2 (+140% -40%)*

*IPCC does not give guidance on the values for CH_4 and N_2O for MGO/MDO, so the values for RO were used, in spite of the evidence that low sulphur fuels yield lower N_2O than RO in the marine context.

IPCC fuel energy values are shown in Table B.17

Table B.17 IPCC Fuel Energy MJ/kg (Table 1.2 IPCC[3])

Fuel type	LHV MJ/kg
RO	40.4
Gas Oil/Diesel Oil	43.0

IPCC recommend the use of LHV based on local fuel values. A value of 43.0 was used in the present study[24].

The two sets of factors and fuel energy values were brought to the same fuel energy basis. The IPCC factors for CH_4 and N_2O were adjusted for their GWP by factors of 21 and 310 respectively to align them with the DCC factors as CO_2 equivalents. The differences in emissions factors are apparent in Table B.18.

Table B.18 Comparison of IPCC and DCC emission factors and fuel energy contents

		kgCO_2e/(TJ fuel energy)			MJ/(kg fuel)	MJ/(kg fuel)
Fuel type	**Source**	**CO_2**	**CH_4**	**N_2O**	**LHV**	**HHV**
RO	IPCC	77,400	147	620	40.4	
	DCC	72,900	60	600		42.5
MGO/MDO	IPCC	74,100	147	620	43.0	
	DCC	69,200	200	500		44.5
ULSD	IPCC	74,100	147	620	43.4	
	DCC	69,200	200	500		46.5

CO_2 emissions are directly related to the mass of fuel burnt. CO_2 emissions factors were stored as kg/TJ (where the denominator is the energy content of the fuel burnt) and converted to g/kWh using the SFOC. In this way, the mass emissions are sensitive to the SFOC, which can be load sensitive.

CH_4 and N_2O emissions calculations followed the same method as used for CO_2.

For auxiliary engines it was found from the PBC survey data that a significant proportion, approximately 25%, operated on MGO/MDO in port rather than RO. To cater for this, a hybrid set of emissions factors was used for auxiliary engines while hotelling. These were composed of 75% of the RO values plus 25% of the MGO/MDO values.

B.3 Database Program Calculation Details

This section describes the calculation procedures of the database program, in abbreviated form.

Arrival transit and departure transit use the same ship transit characteristics data.

Arrival manoeuvring, departure manoeuvring and repositioning use the same ship manoeuvring characteristics data.

Anchorage uses the same characteristic data as hotelling, except for the tankers, where boiler power is set at the manoeuvring value (Table B.4) because the tankers would not be discharging cargo while at anchorage.

In the following descriptions of the database program procedures, actual variable names are shown in bold type and the names of the various data sources are shown in italic type.

B.3.1 OGV Main Engine Emissions and Fuel Consumption Calculations

Figure B.1 shows the calculation procedure for an OGV main engine. Ship movement data are provided by the ship movement model. The load factor is calculated from the actual vessel speed during transit. During hotelling, the main engine is unlikely to be used unless it is a diesel/electric propulsion system, in which case a main engine may be used for generating hotel or cargo operations power.

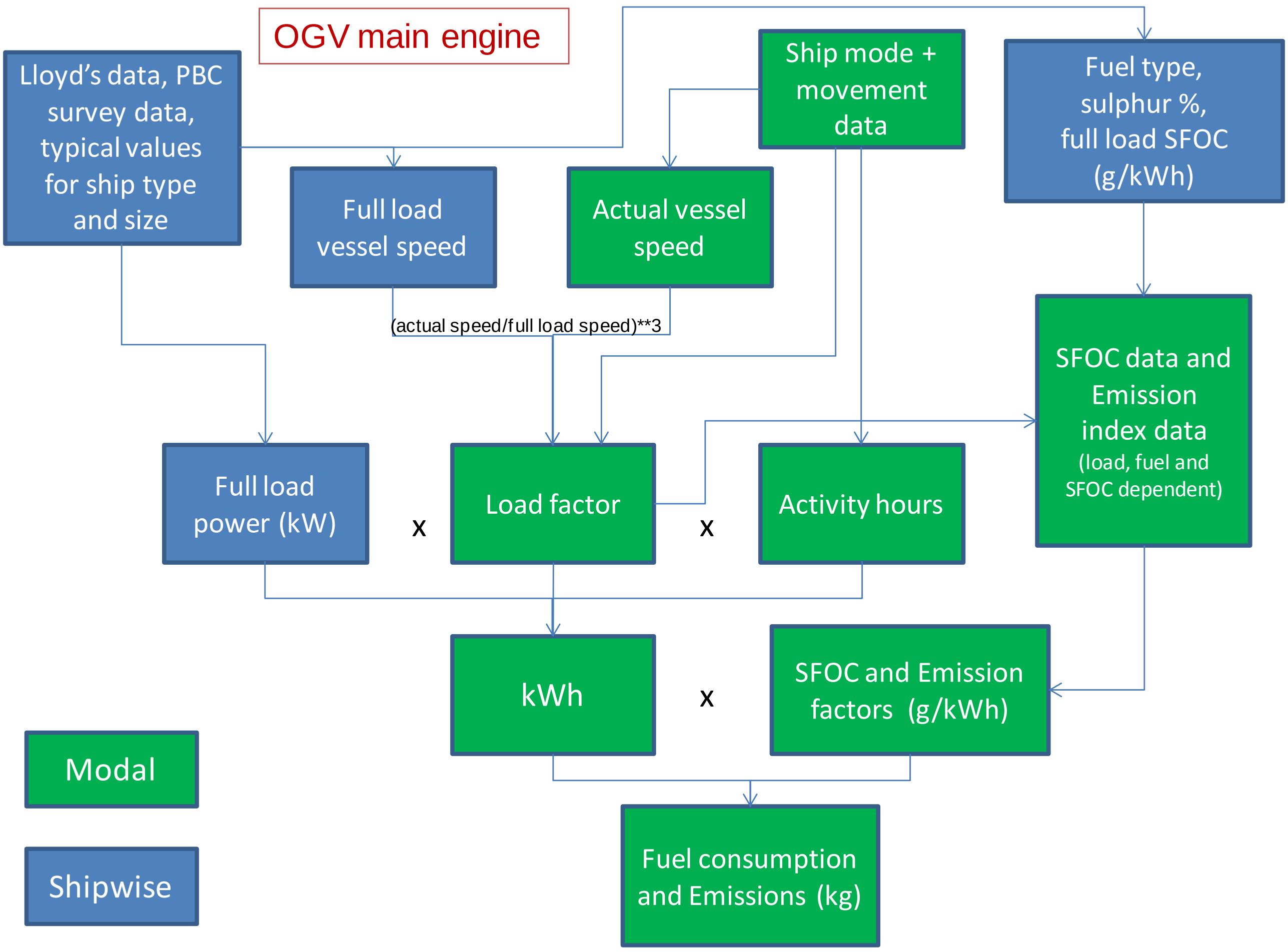

Figure B.1 Calculation of fuel consumption and emissions for an OGV main engine(s)

Data specific to each movement are referred to as "modal" data. Ship characteristic data are referred to as "shipwise" data.

Calculation of kWh and SFOC

Full load vessel speed: *Seaweb data*, **Service_Speed** (if unavailable from *Seaweb data*, use default values created from *Seaweb data* by **Seaweb ship type**)

Full load power: *Seaweb data*, **Total_Power_kW**. Multiplied by a correction factor of 0.85, correction factor accessible for later modification.

Actual vessel speed: for each movement within a visit, from movement data

Activity hours: for each movement within a visit, from movement data

Load Factor = (Actual vessel speed /Full load vessel speed)**3

Manoeuvring Load Factor: use Actual Vessel Speed in the formula above

Fuel type: from Port of Brisbane Emissions Survey,

transit - main engine fuel type during transit % (or if unavailable assume RO)

manoeuvring and repositioning - main engine fuel type during manoeuvring % (or if unavailable assume RO)

Sulphur %: from *Port of Brisbane Emissions Survey*,

transit **- main engine sulphur content during transit %** (or if unavailable assume 2.7%)

manoeuvring and repositioning - **main engine sulphur content during manoeuvring %** (or if unavailable assume 2.4%)

for cruise ships, for all modes, use *Cruise Ship Survey* fuel sulphur % (or if unavailable assume 2.7%)

Full load SFOC: from *Port of Brisbane Emissions Survey* main engine SFOC g/kWh (if unavailable, source data from Table B.13, using **Engine_Stroke_Type** from *Seaweb Ship data*)

SFOC data: uses full load SFOC at all loads

Having calculated load factor and activity hours, engine energy output in kWh is calculated:

kWh = full load power x load factor x activity hours

Calculate emissions and fuel consumption:

Emissions index data:

NOx, CO, HC, PM_{10}, $PM_{2.5}$: Table B.13, using **Engine_Stroke_Type** from *Seaweb Ship data* and fuel type and sulphur % from above

SO_2: sulphur % x SFOC / 100 (use SFOC data from above)

Greenhouse emissions (CO_2, CH_4,N_2O) are calculated using two different sets of factors, IPCC and DCC. Thus there will be IPCC CO2 and DCC CO_2, etc. The factors given in Table B.18 are converted to the same units as the other emissions (g/kWh).

CO_2: (g CO_2)/ kWh = (g CO_2)/GJ x GJ/(g fuel) x (g fuel)/kWh

(g CO_2)/GJ from Table B.18, using fuel type from above

GJ/(g fuel) = LHV from Table B.18, using fuel type from above

(g fuel)/kWh = SFOC from above

CH_4, N_2O: as for CO_2

Adjustment of Emissions Indices for NOx, CO, HC, PM_{10}, $PM_{2.5}$ for Load Factor:

Emissions indices multiplied by the adjustment factors in Table B.10, according to Load Factor

Further adjustment of Emissions Indices for NOx, CO, HC, PM_{10}, $PM_{2.5}$ for vessel age:

Emissions indices multiplied by the adjustment factors according to vessel age, given as **Year** in *Seaweb Ship data*

Having calculated kWh, emissions indices and SFOC, mass of fuel used and mass of each emission are calculated:

mass of fuel(kg) = SFOC x kWh / 1000

mass of emission (kg) = emissions index x kWh / 1000

B.3.2 OGV Auxiliary Engine Emissions and Fuel Consumption Calculations

Figure B.2 shows the calculation procedure for an auxiliary engine. Full load power, load factor, SFOC and fuel type are obtained from survey data or default tables. The ship movement data give the time spent in the various modes and inform the selection of the load factor.

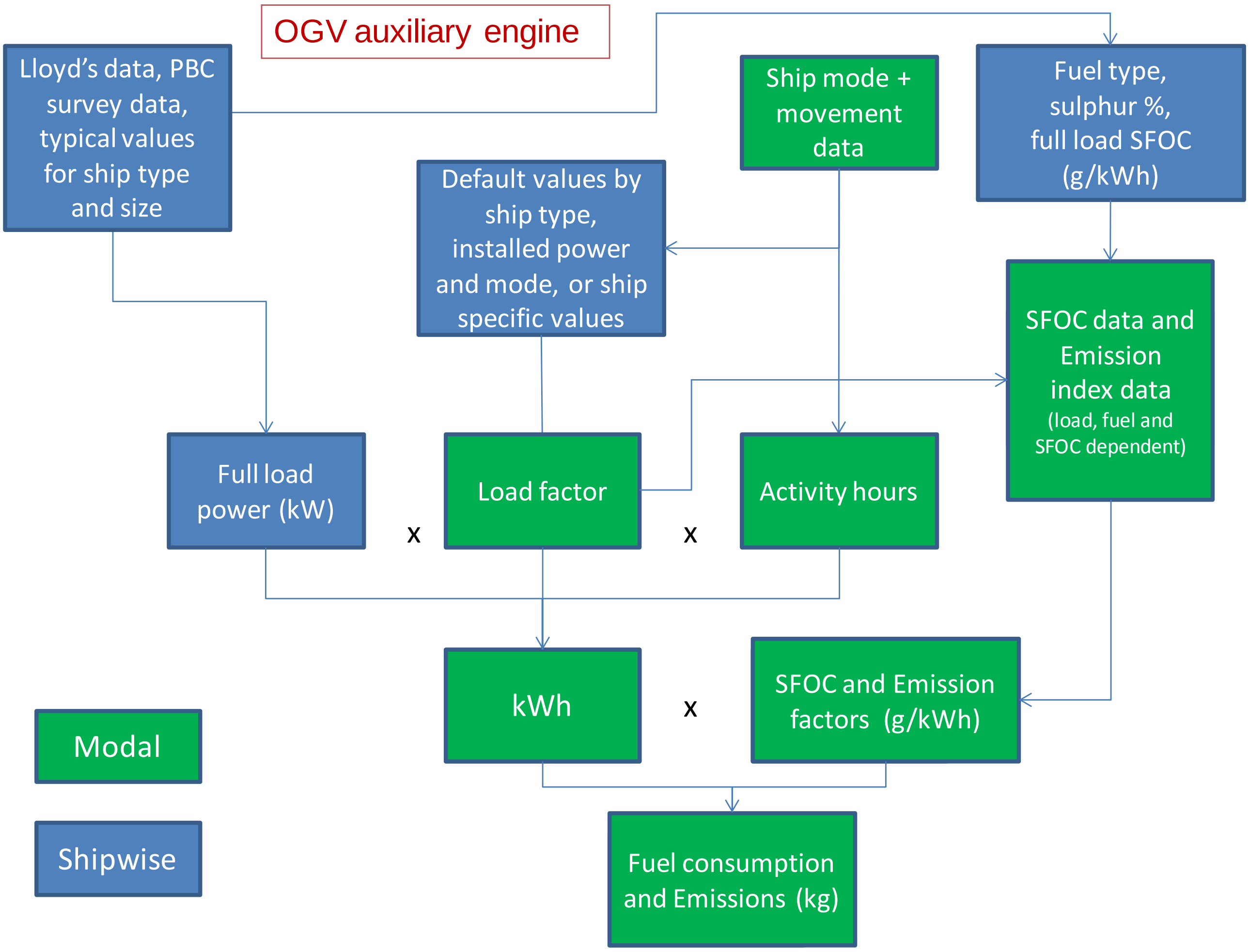

Figure B.2 Calculation of fuel consumption and emissions for OGV auxiliary engines

Calculate kWh and SFOC

Activity hours: for each movement within a visit, from movement data

Full load power:

first try *Port of Brisbane Emissions Survey* **total auxiliary power kW** and *Cruise Ship Survey* **effective auxiliary power kW** if not available from the above, use **auxiliary power ratio** from Table B.3 by **MSQ ship type**, multiply **auxiliary power ratio** by main engine **full load power kW**

flag if unavailable from any of the above

Load factor:

for cruise ships, *Cruise Ship Survey* auxiliary load factor if available

otherwise, Table B.3 by **MSQ ship type** and by mode

Fuel type:

for all modes from *Port of Brisbane Emissions Survey*,- **auxiliary fuel type** (or if unavailable assume RO)

Sulphur %:

for all modes from *Port of Brisbane Emissions Survey* - **auxiliary fuel sulphur %** (or if unavailable assume 2.3%)

for cruise ships, for all modes, use *Cruise Ship Survey* **fuel sulphur %** (or if unavailable assume 2.7%)

Full load SFOC:

from *Port of Brisbane Emissions Survey* **auxiliary SFOC g/kWh** and *Cruise Ship Survey* **auxiliary SFOC kW** (if unavailable, source data from Table B.13, assuming all engine type MSD)

SFOC data: use full load SFOC at all loads

Having calculated load factor and activity hours, engine energy output in kWh is calculated:

kWh = full load power x load factor x activity hours

Calculate emissions and fuel consumption:

As for OGV main engine but without adjusting emissions factors for load.

B.3.3 Auxiliary Boilers

Figure B.3 shows the calculation procedure for an OGV boiler.

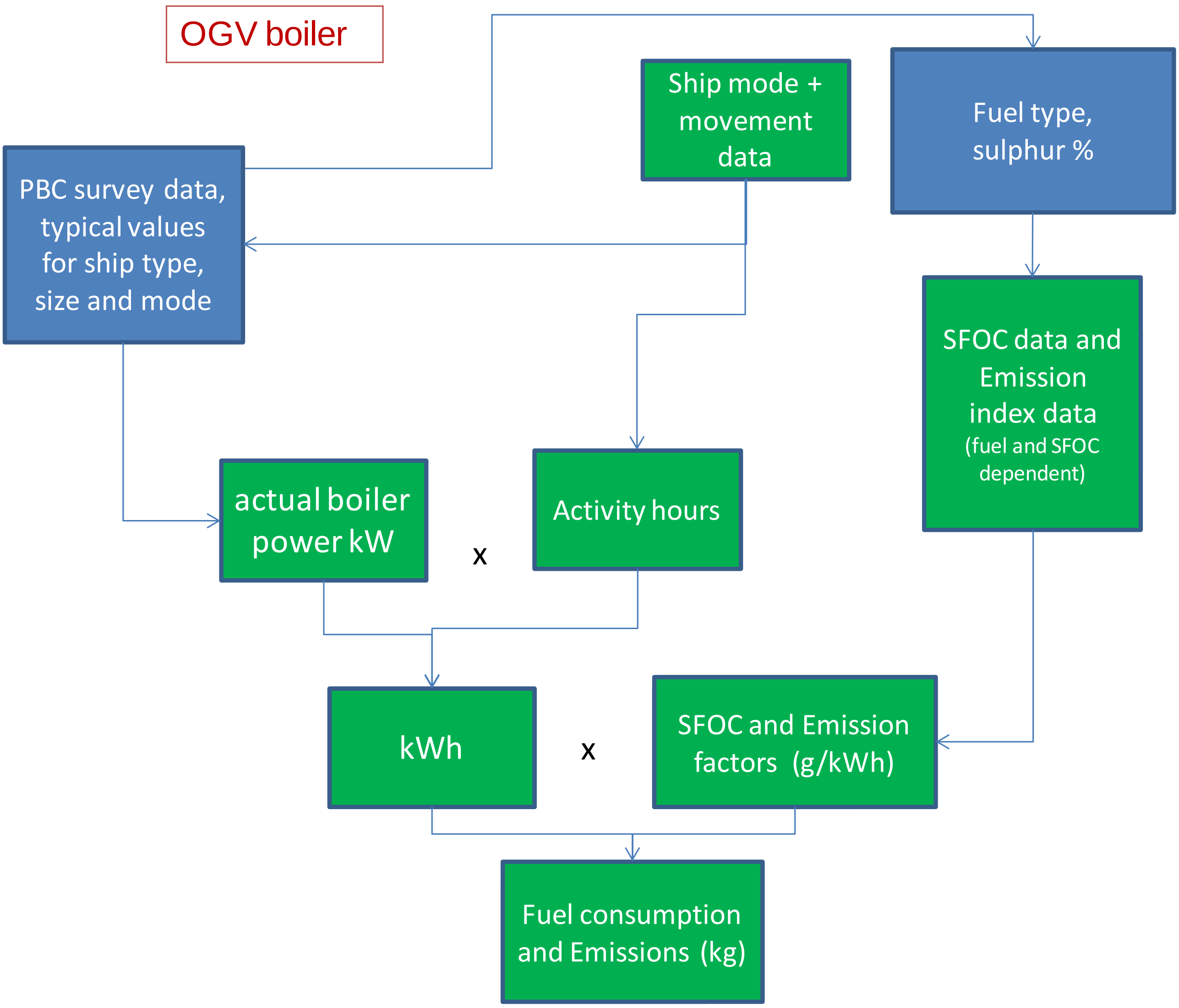

Figure B.3 Calculation procedure for an OGV boiler.

Calculate kWh and SFOC

Activity hours: for each movement within a visit, from movement data

Actual boiler power:

> for transit and manoeuvring, use **boiler power kW** from Table B.4 by **MSQ ship type**
>
> for hotelling, first try *Port of Brisbane Emissions Survey* **boiler usage at berth kW** and *Cruise Ship Survey* **boiler usage at berth kW** (if not available, use **boiler power kW** from Table B.4 by **MSQ ship type**)
>
> flag if unavailable from any of the above

Load factor = 1 as using actual power

Fuel type:

for all modes from *Port of Brisbane Emissions Survey*- **boiler fuel type** (or if unavailable assume RO)

Sulphur %:

for all modes from *Port of Brisbane Emissions Survey* - **boiler fuel sulphur %** (or if unavailable assume 2.3%)

for cruise ships, for all modes, use *Cruise Ship Survey*- **fuel sulphur %** (or if unavailable assume 2.7%)

SFOC:

use 305 g/kWh for all modes

Having found boiler power and activity hours, boiler energy output in kWh is calculated:

kWh = actual boiler power x activity hours

Calculate emissions and fuel consumption:

As for OGV main engine but without adjusting emissions factors for load.

B.3.4 Dredges

Calculations are based on given fuel consumption, with no corrections for load factor given that the dredges are designed to operate at around 70% load in all phases of operation.

The *Volvox Asia* has two types of engine, MSD operating on RO and HSD operating on MGO. So two sets of calculations are done for the *Volvox Asia*, one set for each engine type. For the *Amity* and the *Brisbane*, only one engine type is considered.

For NOx, CO, HC, PM_{10} and $PM_{2.5}$

mass of emission (kg) = emissions index (g/kWh) x tonnes fuel x1000 / SFOC

emission indices from Table B.13 using fuel type and engine type

tonnes of fuel from *dredge data summary*

SFOC from Table B.13 using fuel type and engine type

For SO_2

mass of emission (kg) = sulphur % x tonnes fuel x 2000

sulphur % from *dredge data summary* by fuel type

For CO_2, CH_4, N_2O (IPCC and DCC)

mass of emission (kg) = emissions factor (g/GJ) x LHV (GJ/g) x tonnes fuel x 1000

emissions factors (g/GJ) from Table B.17 by fuel type

LHV (GJ/g) from Table B.17 by fuel type

Total fuel consumption is sourced directly from *dredge data summary*

Table B.19 Dredge data summary

IMO	Name	Total fuel usage tonne	Fuel Sulphur%	Engine type	Fuel type
9174737	*Volvox Asia*	3793.62	2.5	MSD	RO
9174737	*Volvox Asia*	1207.14	0.4	HSD	MGO
	Amity	1090.00	0.001	HSD	ULSD
9204623	*Brisbane*	3106.5	0.001	HSD	ULSD

B.3.5 Tugs

Tugs use a simpler approach than OGVs, using use supplied monthly fuel consumption and engine hours to calculate load factors. Figure B.4 outlines the calculation procedure.

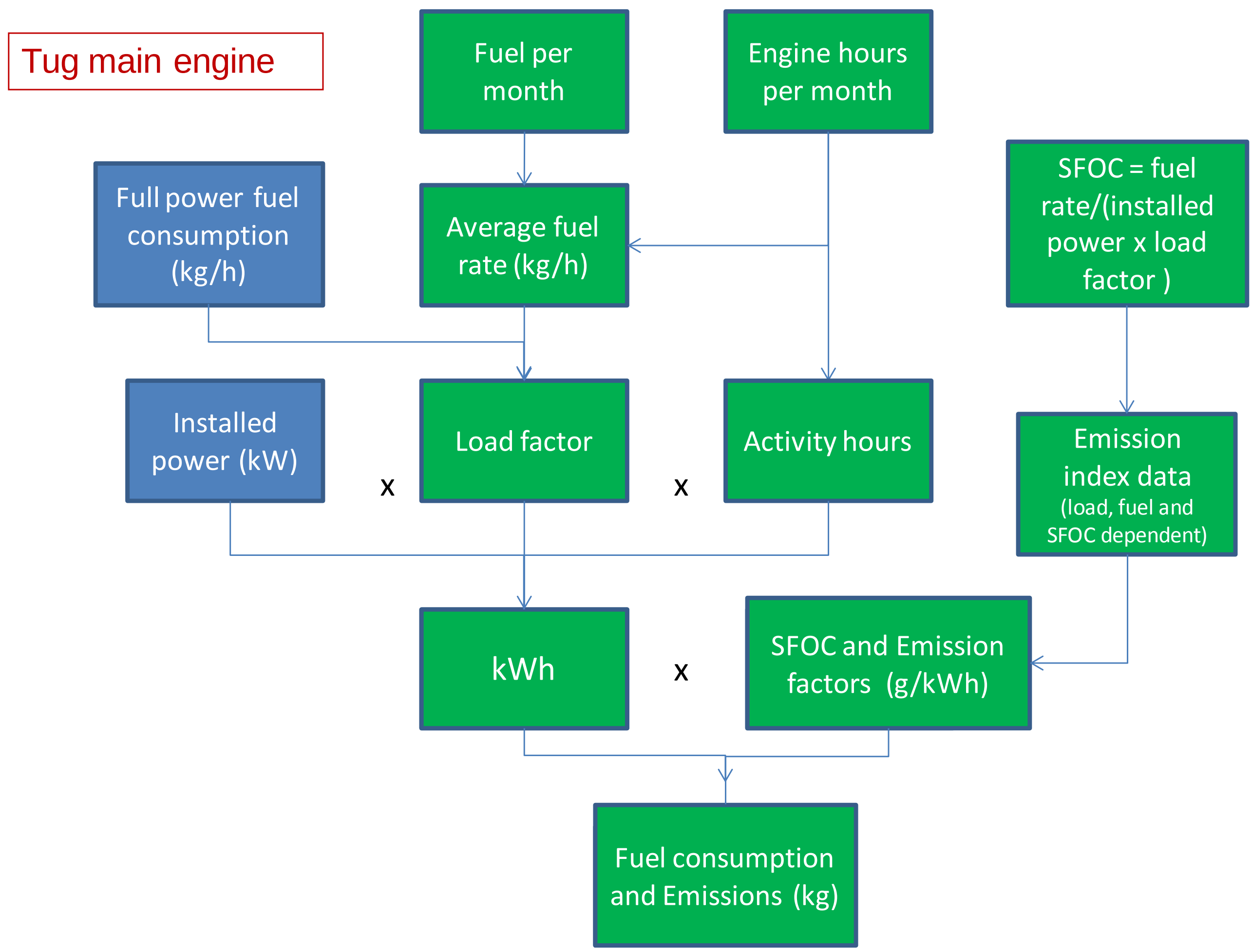

Figure B.4 Calculation procedure for a working tug.

Calculate kWh and SFOC

Full power fuel consumption and installed power: **full power fuel consumption l/h** and **total engine power kW** from tug specifications in *tug combined data*

Activity hours: for each month, **tug engine hours** from monthly tug fuel use and engine hours data file

Average fuel rate: for each month, litres of fuel per month divided by engine hours

Load factor: for each month, average fuel rate divided by full power fuel consumption

Fuel type: ULSD

Sulphur %: 0.001

SFOC: fuel rate/(installed power x load factor)

fuel rate in g/hour = 1000 x average fuel rate / fuel density

Having calculated load factor and activity hours, engine energy output in kWh is calculated:

kWh = full load power x load factor x activity hours

Calculate emissions and fuel consumption:

As for OGV main engine but without adjusting emissions factors for load.

B.4 Assumptions and Limitations

The inventory was based on detailed information on individual ship movements and characteristics. Not all details were available and assumptions were needed.

Movement Data

In general the movement data were clear for each vessel visit, so only a small amount of data adjustment was required, for instance by revising some date and time recordings and by limiting transit times and tanker berth times to reasonable bounds.

Main Engine Load Factor

The estimation of main engine load factor during transit was straightforward and fairly precise, as it was based on the propeller law relationship between ship speed and engine power. The estimation of main engine power at service speed and thus fuel consumption and emissions from the main engine could have an uncertainty of ±6%, as discussed in Appendix B.1.2. The load factors during transit were high enough to avoid the need to adjust emissions indices for low load.

For manoeuvring it was assumed that a single manoeuvring load factor could be calculated directly from the average vessel speed from the EB to berth. This yielded reasonable values of load factor (see Table 3.3). The main effect of load factor was on the adjustment to the emissions indices. This adjustment was based on default tables used in US inventories, and the certainty of the values in the tables is unknown. Future work could improve the estimation of the effect of engine load on SFOC and emissions indices, and the estimation of representative engine loads during manoeuvring, but the total manoeuvring fuel consumption and emissions are small compared with transit and hotelling.

Auxiliary Engine Power

The estimation of auxiliary engine power was not straightforward, as published data on ship characteristics contain little information on installed auxiliary engine power. Further, there is uncertainty as to the power produced by the auxiliary engines in the various modes. Some data were available from the PBC survey, but not enough to draw general conclusions about installed and actual power by vessel type and by mode, except for the cruise ships. Thus, considerable use was made of default values published in US studies, where actual values were not available in the survey data. The default data give a ratio of installed auxiliary power to main engine power by vessel type, and load factors by vessel type and mode. Some adjustments were made to these published data according to the specific data obtained on cruise ships visiting PB.

Fuel Type and Sulphur Content

Reasonable information on fuel type and sulphur content was obtained from the PBC survey data. This allowed the setting of representative average fuel sulphur contents by mode. Not enough data were available to differentiate fuel type by vessel type or mode. However, enough data were available from the vessel survey to allow the definition a hybrid fuel type for the purpose of modelling auxiliary engines, which allowed for 25% of auxiliary engines to operate on distillate, Marine Diesel Oil/Marine Gas Oil (MGO/MDO). The trend in shipping is to use Residual Oil (RO) wherever possible, except in a few auxiliary engines which are not set up to run on RO. Cruise ships generally use RO. (This trend may change in the future given the current emphasis on reducing fuel sulphur content.) Thus, unless survey data on a specific vessel indicated otherwise, the fuel type was assumed to be RO in the main engine and boiler, but with port average sulphur content. The auxiliary engine default fuel was a hybrid of RO and MGO/MDO, as discussed in Appendix B.1.3.

Boilers

Boiler installed power and actual power by vessel type and by mode were difficult to obtain, as with auxiliary engines. Where specific data were not available from the PBC survey, published default tables from

US studies were used. The tables give actual boiler power by vessel type and by mode. Scrutiny of the US studies showed that boiler powers are probably the least well defined of all the default data. For tankers visiting the PB, extra information from a number of sources was used to benchmark actual tanker boiler fuel consumption, given that the tanker boiler fuel consumption and emissions represent a significant proportion of the port total.

It was assumed that boilers were used while hotelling and at anchorage only, but tanker boilers were only used at full power at berth when pumping cargo or ballast. It was assumed that tanker cargo was heated by waste heat boilers on the main engine exhaust before entering the port and so did not require significant additional fuel consumption.

It was assumed that incinerators were not used within the port limits.

Specific Fuel Oil Consumption

Manufacturer data tends to underestimate actual full load SFOC. Generally, published default values of SFOC by engine type and fuel type were used. These values could carry an uncertainty of ±10%. The effect of engine load on SFOC was not considered, due to the lack of data and given that low load operation occurs primarily during manoeuvring, which represents a small proportion of the total fuel consumption and emissions. The best way to check SFOC would be to acquire accurate values of fuel usage from vessel surveys in the future.

Emissions Indices

Default emissions indices come with a degree of uncertainty. Considerable effort was made to compare indices from a number of sources and to check original data sources for currently used defaults (see Appendix B.2). The set of indices used in the present study generally represent the latest data and are aligned with the latest US studies. For NOx and CO from diesel engines, there is general agreement on emissions factors in the literature. For HC and PM from diesel engines the range of published values is about ±12% on the mean. For boilers, some recent measurements indicate the NOx factor could be 50% higher than the accepted value. There is reasonable agreement in the literature on the emission factor for marine boiler PM.

The Intergovernmental Panel on Climate Change[3] (IPCC) estimates the uncertainties associated with emissions factors for CO_2 at ±6%, CH_4 at ±50% and N_2O at +140% -40%. However, the impact on CO_2 equivalent greenhouse gas emissions of the uncertainties in CH4 and N2O emissions would be minimal, because CH_4 and N_2O only contribute 1% of the total.

The emissions factors are based on published data which do not necessarily allow for the effect of the design or state of maintenance of engines and boilers on particulate emissions. These effects could be significant.

Appendix C

Appendix C Vessel Surveys

C.1 Port of Brisbane Survey

To facilitate the inventory, PBC conducted a survey of ships visiting the port in a 3 month period. Questionnaires were handed to each ship by the pilots. Data on 121 unique vessels were obtained. Table C.1 shows the distribution of ship types from completed surveys.

Table C.1 PBC survey ship types

Vessel type	number
Bulk	20
Container	55
Cruise	0
General cargo	4
Ro-Ro	2
Tanker LPG	1
Tanker coastal products	1
Tanker chemical	4
Tanker oil/chemical	2
Tanker oil	9
Vehicle carrier	20
Other	3
	121

C.1.1 Fuels

Table C.2 summarises the fuel type and sulphur content data from the survey. The responses on fuel type are occasionally ambiguous, but generally auxiliary engines use about 80% RO in all modes, boilers about 90% in all modes, main engines 100% in transit and 85% while manoeuvring.

Table C.2 fuel type and sulphur content data from the survey.

Machinery type	Mode	Average sulphur %	Fuel type instances				% RO
			RO	MDO	MGO	ULSD	
Main engine	transit	2.7	121	0	0	0	100
	manoeuvring	2.4	104	6	12	0	85
Auxiliary engine	transit	2.3	109	7	14	1	82
	manoeuvring	2.3	91	13	16	1	75
	hotelling	2.3	91	13	16	1	75
Auxiliary boiler	manoeuvring	2.5	108	4	9	0	89
	hotelling	2.5	108	4	9	0	89

There is no clear trend as to type and age of vessels which use MGO/MDO. Some allowance could be made for the proportion of engines and boilers not given in the survey data which might use MGO/MDO rather than RO. The proportion of total emissions from auxiliary engines during transit and manoeuvring, and main engines during manoeuvring is small. The most important effect of fuel type would be for auxiliary engines during hotelling. Allowance was made for the 25% which use MGO/MDO rather than RO while hotelling. Of all the emissions factors, the PM factors are the most sensitive to fuel type.

Average MGO sulphur content was 0.48%. Average MDO sulphur content was 0.63%. Average sulphur content of all fuels is shown in Table C.2.

C.1.2 Auxiliary power

The average ratios of auxiliary engine power to main engine power calculated from the survey results are presented in Table C.3. There were sufficient response from container ships to obtain a useful average, which happens to correspond to the default value from US studies (Table B.1). The vehicles carrier value is also very similar to the US defaults.

Table C.3 Average ratio of auxiliary engine power to main engine power from the survey results

Vessel type	Average ratio	Valid responses
Bulk	0.18	3
Container	0.21	17
General cargo	0.14	1
Tanker	0.24	2
Vehicles carrier	0.28	4

Vehicle carriers use a significant amount of auxiliary power to drive ventilation systems to clear vehicle exhaust during loading and unloading.

For auxiliary engine load factor while hotelling there were only 4 valid responses: bulk 0.19; container 0.15, 0.4; vehicles carrier 0.19. Thus, default tables were used for auxiliary load factor for OGV other than cruise ships for which there were valid data in the cruise ship survey (see Section C.2).

Only one non-ambiguous response for boiler fuel usage in port was obtained, at 5.5 tonnes/day for a container ship of 3596 TEU. This is equivalent to a boiler power of 2037kW at 80% boiler efficiency, which reduces to 751kW when reduced to the same basis as ARB and Starcrest, which is around twice the default value given in Table B.5. However, due to the limited amount of data, the default value was used.

C.2 Cruise Ship Survey

No cruise ships responded to the initial PBC survey. Additional data were collected, two being actual ship survey data collected with the assistance of Inchcape Shipping Services. Further data were collected from Carnival and from e-ships, an internet based service which gave the necessary information on whether the cruise ships were diesel/electric drive.

C.2.1 Fuels

Only two cruise ships gave fuel data and both indicated that they used RO exclusively. The average sulphur content was 2.8%.

C.2.2 Auxiliary Power

A summary of the cruise ship survey data is given in Table C.4. As explained in Section B.1.2, a number of cruise ships are diesel/electric powered, so that they do not have auxiliary generators separate from the main engines. Main engines are used to generate hotelling power in port. In the present study, a proportion of the total engine power was assigned as propulsion power and the remainder as auxiliary power. Where the power of the electric propulsion motors was available for diesel/electric ships, the main engine power was taken as the electric propulsion power divided by an assumed conversion efficiency of 90%. The remainder was assigned as auxiliary power. Where the power of the electric propulsion motors was not available, 60% of the main engine power was assigned as propulsion power and the remainder as auxiliary power. This is consistent with the average power ratio for the previously mentioned vessels.

Table C.4 Cruise ship survey data summary

Number of visits	pax	d/e?	Main engine power kW	Effective main engine power kW	Aux/main power ratio	Effective installed auxiliary power kW	Actual auxiliary power kW	Aux load factor	Actual boiler power at berth kW*
21	1896		23,510	23,510	0.403	9,474	3,000	0.32	1,852
16	1411		19,566	19,566	na	na	na	na	na
5	2342	y	46,800	31,111	0.504	17,326	3,440	0.2	926
4	916		13,112	13,112					
2	777	y	39,832	28,451	0.400	11,381			
1	1878	y	56,000	44,444	0.260	13,895			3,956
1	1629	y	34,560	26,667	0.296	9,297			
1	388		15,600	15,600	0.601	9,375			
1									
1	540		9,708	9,708					
1	1804		39,750	39,750	0.445	17,680			
1	1100	y	52,200	37,286					
1	930		11,424	11,424					
1	812		17,400	17,400					
1	2416	y	50,400	36,000					
1	3078	y	60,700	44,444	0.366	18,595			
1	3500	y	63,360	39,111	0.620	26,307			
0		y	21,600	15,429	0.400	6,171			2,044

* boiler power calculated from given fuel consumptions using 80% boiler efficiency (112.5g/kWh) – reduce by a factor of 0.369 to compare with ARB and Starcrest boiler powers.

Average auxiliary to main power ratio is 0.42 for the two non-diesel/electric vessels with known auxiliary power and 0.44 for an expanded vessels set which also includes the five diesel/electric vessels for which the electric propulsion motor power is known and when the electric conversion efficiency for the main drive is assumed to be 90%. These values are slightly higher than the default values from US studies, so the survey value for the most frequent visitor of 0.4 (0.403) was used.

C.2.3 Boiler Power

Using the boiler power data from Table C.4, average boiler power from the survey is calculated as 2,194 kW, using 80% boiler efficiency (SFOC 112.5 g/kWh). When reduced to the same basis as ARB and Starcrest this becomes 809 kW which compares well with the ARB and Starcrest values for cruise ship boiler power at berth of 1,000 kW and 750 kW respectively.

Appendix D

Appendix D Detailed OGV Results Tables

D.1 OGV by Operating Mode and Machinery Type

Total OGV fuel consumption and primary air quality and greenhouse emissions by movement and machinery type are given in Table D.1. The main fuel usage and production of emissions occurred from the main engines during transit, the auxiliary engines during hotelling and the boilers during hotelling. Boilers during hotelling consumed significant fuel but did not produce the most air quality emissions because boiler emissions per tonne of fuel are less than diesel engine emissions on the same basis. The boiler fuel usage during hotelling was dominated by the tankers, as can be seen in Table D.2.

Table D.1 Total OGV fuel consumption and primary air quality and greenhouse emissions by movement and machinery type – all values in tonnes

Operating mode	Machinery Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Anchorage	auxiliary engine	1,045	67.5	5.1	2.2	5.5	5.4	48.7	3,234	4.4	25.7
Anchorage	boiler	492	3.4	0.3	0.2	1.3	1.2	21.5	1,526	1.3	12.5
Manoeuvring	auxiliary engine	1,215	78.9	6.0	2.6	6.8	6.6	55.9	3,761	4.7	30.2
Manoeuvring	boiler	411	2.8	0.3	0.1	1.1	1.0	20.1	1,275	1.1	10.5
Manoeuvring	main engine	513	81.8	12.3	14.4	9.4	9.2	24.7	1,590	1.5	13.0
Transit	auxiliary engine	1,632	106.0	8.0	3.5	9.2	8.9	74.6	5,053	6.3	40.5
Transit	main engine	18,214	1,590.7	127.7	65.0	139.0	135.1	979.5	56,447	47.3	464.2
Hotelling	auxiliary engine	12,409	803.2	61.0	26.4	66.9	64.7	563.1	38,460	51.9	306.7
Hotelling	boiler	9,153	62.9	6.0	3.3	22.9	22.3	429.1	28,394	26.7	232.1
Repositioning	auxiliary engine	696	45.1	3.4	1.5	3.9	3.7	33.8	2,154	2.7	17.3
Repositioning	boiler	210	1.4	0.1	0.1	0.5	0.5	10.3	650	0.5	5.3
Repositioning	main engine	5	1.2	0.2	0.3	0.2	0.2	0.2	17	0.0	0.1
OGV total		**45,995**	**2,845**	**230.5**	**119.4**	**266.7**	**258.9**	**2,262**	**142,560**	**148.6**	**1,158**

*CH_4 and N_2O in tonnes CO_2 equivalent

The main engine is not used during hotelling or anchorage, except for diesel/electric ships, where main engines may be used to generate auxiliary power. In the present study, the diesel electric ships were treated as direct drive, with a portion of the total engine power assigned to propulsion and the remainder assigned to auxiliary power. It was assumed that the boiler was not used during transit, as the waste heat boiler running from the main engine exhaust would fulfill any heating requirements.

D.2 OGV by Vessel Type and Machinery Type

Table D.2 Total OGV fuel consumption and primary air quality and greenhouse emissions by vessel type and machinery type – all values in tonnes

Vessel Type	Machinery Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Bulk Carrier	auxiliary engine	1,836	117.4	8.9	3.9	9.3	9.0	79.2	5,679	8.4	45
Bulk Carrier	boiler	644	4.4	0.4	0.2	1.6	1.6	30.6	1,994	1.8	16
Bulk Carrier	main engine	1,826	167.4	13.5	7.1	14.4	14.0	98.5	5,656	4.7	47
Container Ship	auxiliary engine	7,446	485.6	36.8	15.8	42.1	40.8	365.5	23,047	28.9	185
Container Ship	boiler	4,314	29.6	2.8	1.6	11.0	10.7	210.6	13,361	12.0	109
Container Ship	main engine	8,864	807.8	69.3	41.0	72.0	70.0	486.5	27,463	22.6	226
Cruise Ship	auxiliary engine	1,286	81.5	6.1	2.5	8.3	8.1	55.1	3,984	3.3	33
Cruise Ship	boiler	270	1.9	0.2	0.1	0.7	0.7	14.6	835	0.7	7
Cruise Ship	main engine	813	67.1	5.7	3.4	6.3	6.2	43.9	2,519	2.1	21
General Cargo Ship	auxiliary engine	953	61.6	4.7	2.0	5.0	4.8	43.4	2,948	4.1	23
General Cargo Ship	boiler	493	3.4	0.3	0.2	1.3	1.3	21.8	1,527	1.3	13
General Cargo Ship	main engine	1,529	126.4	10.2	5.5	11.6	11.2	77.7	4,739	3.9	39
Navy	auxiliary engine	479	31.0	2.5	1.2	0.8	0.8	0.0	1,542	4.5	11
Navy	boiler	344	2.3	0.2	0.1	0.1	0.1	0.0	1,107	3.2	8
Navy	main engine	136	5.5	0.5	0.4	0.5	0.3	0.0	436	1.3	3
Others	auxiliary engine	18	1.2	0.1	0.0	0.1	0.1	0.9	57	0.1	0
Others	boiler	26	0.2	0.0	0.0	0.1	0.1	1.3	81	0.1	1
Others	main engine	16	1.2	0.1	0.1	0.1	0.1	0.9	50	0.0	0
Ro-Ro Cargo Ship	auxiliary engine	188	12.2	0.9	0.4	1.1	1.1	7.6	583	0.7	5
Ro-Ro Cargo Ship	boiler	15	0.1	0.0	0.0	0.0	0.0	0.6	46	0.0	0
Ro-Ro Cargo Ship	main engine	208	18.6	1.6	0.9	1.7	1.6	9.4	643	0.5	5
Tanker	auxiliary engine	3,251	210.7	16.0	6.9	17.7	17.1	155.7	10,062	13.3	80
Tanker	boiler	3,548	24.4	2.3	1.3	9.3	9.1	172.6	10,993	9.0	90
Tanker	main engine	3,124	279.6	23.0	12.2	24.6	23.9	169.2	9,680	8.0	80
Vehicles Carrier	auxiliary engine	1,538	99.6	7.6	3.3	7.8	7.6	68.7	4,759	7.0	38
Vehicles Carrier	boiler	613	4.2	0.4	0.2	1.6	1.5	29.0	1,900	1.6	16
Vehicles Carrier	main engine	2,217	200.1	16.4	9.1	17.6	17.1	118.4	6,868	5.7	57

*CH_4 and N_2O in tonnes CO_2 equivalent

D.3 OGV by Vessel Type and Operating Mode

Table D.3 OGV total fuel consumption and primary air quality and greenhouse emissions by vessel type and operating mode – all values in tonnes

Vessel Type	Operating Mode	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Bulk Carrier	Anchorage	131.8	6.9	0.5	0.2	0.6	0.6	6.1	408	0.5	3.3
Bulk Carrier	Hotelling	2,086.5	99.3	7.6	3.4	9.0	8.7	92.1	6,457	8.5	51.6
Bulk Carrier	Manoeuvring	191.2	15.3	1.6	1.1	1.4	1.4	8.7	592	0.7	4.8
Bulk Carrier	Repositioning	30.1	1.9	0.2	0.1	0.2	0.2	1.4	93	0.1	0.7
Bulk Carrier	Transit	1,865.5	165.8	13.0	6.5	14.1	13.7	100.1	5,779	5.0	47.5
Container	Anchorage	132.0	4.4	0.3	0.2	0.5	0.5	6.1	409	0.5	3.3
Container	Hotelling	9,341.3	379.9	29.3	12.9	40.5	39.3	456.9	28,922	32.0	234.1
Container	Manoeuvring	985.4	81.5	9.6	10.0	8.8	8.6	49.0	3,051	3.4	24.7
Container	Repositioning	716.7	38.4	3.0	1.3	3.6	3.5	35.4	2,219	2.6	17.9
Container	Transit	9,448.2	818.8	66.7	34.0	71.6	69.7	515.3	29,271	25.0	240.5
Cruise	Hotelling	1,169.2	61.0	4.6	1.9	6.7	6.5	55.5	3,623	3.0	29.8
Cruise	Manoeuvring	209.4	14.1	1.5	1.2	1.7	1.6	8.8	649	0.5	5.3
Cruise	Repositioning	1.4	0.1	0.0	0.0	0.0	0.0	0.1	4	0.0	0.0
Cruise	Transit	988.4	75.3	5.8	2.8	7.0	6.8	49.3	3,062	2.5	25.2
General Cargo	Anchorage	137.3	4.2	0.3	0.2	0.5	0.4	5.0	425	0.5	3.4
General Cargo	Hotelling	1,130.5	50.5	3.9	1.7	5.0	4.8	51.9	3,500	4.2	28.2
General Cargo	Manoeuvring	122.7	9.4	1.0	0.8	0.9	0.9	5.6	380	0.4	3.1
General Cargo	Repositioning	26.5	1.6	0.2	0.1	0.2	0.2	1.2	82	0.1	0.7
General Cargo	Transit	1,558.0	125.7	9.8	4.9	11.3	11.0	79.1	4,827	4.1	39.7
Navy	Anchorage	7.6	0.3	0.0	0.0	0.0	0.0	0.0	24	0.1	0.2
Navy	Hotelling	784.1	31.1	2.5	1.2	0.9	0.9	0.0	2,523	7.3	18.2
Navy	Manoeuvring	20.7	1.3	0.1	0.1	0.0	0.0	0.0	67	0.2	0.5
Navy	Repositioning	3.2	0.2	0.0	0.0	0.0	0.0	0.0	10	0.0	0.1
Navy	Transit	143.1	5.8	0.5	0.3	0.5	0.3	0.0	461	1.3	3.3
Other	Anchorage	0.3	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0	0.0
Other	Hotelling	41.6	1.2	0.1	0.0	0.2	0.2	2.0	129	0.1	1.0
Other	Manoeuvring	2.4	0.2	0.0	0.0	0.0	0.0	0.1	8	0.0	0.1
Other	Repositioning	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1	0.0	0.0
Other	Transit	15.9	1.1	0.1	0.0	0.1	0.1	0.9	49	0.0	0.4

Table D.3 continued

Vessel Type	Operating Mode	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Ro-Ro Cargo	Hotelling	172.0	10.3	0.8	0.3	1.0	0.9	6.9	533	0.6	4.3
Ro-Ro Cargo	Manoeuvring	17.7	1.5	0.2	0.2	0.2	0.2	0.7	55	0.1	0.4
Ro-Ro Cargo	Repositioning	0.6	0.0	0.0	0.0	0.0	0.0	0.0	2	0.0	0.0
Ro-Ro Cargo	Transit	220.8	19.0	1.5	0.8	1.7	1.6	9.9	684	0.6	5.6
Tanker	Anchorage	1,126.3	55.0	4.2	1.8	5.2	5.1	52.9	3,487	4.2	28.1
Tanker	Hotelling	5,069.1	151.0	11.9	5.4	19.0	18.4	246.5	15,699	16.0	127.7
Tanker	Manoeuvring	373.9	23.8	2.6	1.9	2.5	2.4	17.9	1,158	1.2	9.4
Tanker	Repositioning	113.0	4.5	0.4	0.2	0.5	0.5	5.4	350	0.4	2.8
Tanker	Transit	3,241.5	280.4	22.3	11.1	24.4	23.7	174.8	10,042	8.7	82.4
Vehicles Carrier	Anchorage	1.9	0.1	0.0	0.0	0.0	0.0	0.1	6	0.0	0.0
Vehicles Carrier	Hotelling	1,767.4	81.5	6.3	2.8	7.6	7.3	80.4	5,470	7.0	43.8
Vehicles Carrier	Manoeuvring	215.7	16.7	1.9	1.8	1.7	1.7	9.9	667	0.8	5.4
Vehicles Carrier	Repositioning	19.1	1.0	0.1	0.0	0.1	0.1	0.8	59	0.1	0.5
Vehicles Carrier	Transit	2,364.4	204.7	16.1	8.0	17.6	17.1	124.9	7,325	6.4	60.1
OGV Total		**45,995**	**2,845**	**230.5**	**119.4**	**266.7**	**258.9**	**2,262**	**142,560**	**148.6**	**1,158**

*CH_4 and N_2O in tonnes CO_2 equivalent

D.4 OGV Totals by Vessel Type, Machinery Type and Fuel Type while Hotelling

Table D.4 OGV total fuel consumption and primary air quality and greenhouse emissions by vessel type, machinery type and fuel type while hotelling – all values in tonnes

Vessel Type	Machinery Type	Fuel Type	Fuel	NOx	CO	HC	PM_{10}	$PM_{2.5}$	SO_2	CO_2	CH_4*	N_2O*
Bulk Carrier	auxiliary engine	MGO/MDO	477.9	29.67	2.35	1.11	0.81	0.75	4.08	1,471.3	4.25	10.63
Bulk Carrier	auxiliary engine	RO	1,011.4	65.52	4.90	2.05	6.69	6.51	59.63	3,135.4	2.58	25.81
Bulk Carrier	boiler	RO	597.3	4.11	0.39	0.22	1.52	1.49	28.37	1,850.1	1.66	15.16
Container	auxiliary engine	MGO/MDO	1,148.8	73.79	5.84	2.76	2.02	1.86	14.86	3,536.7	10.22	25.55
Container	auxiliary engine	RO	4,262.5	279.11	20.89	8.73	28.48	27.72	250.07	13,211.8	10.87	108.74
Container	boiler	RO	3,930.0	27.01	2.58	1.42	10.03	9.78	191.98	12,173.6	10.92	99.76
Cruise	auxiliary engine	RO	943.8	59.45	4.45	1.86	6.07	5.90	43.30	2,924.2	2.41	24.07
Cruise	boiler	RO	225.4	1.55	0.15	0.08	0.59	0.58	12.17	698.4	0.57	5.75
General Cargo	auxiliary engine	MGO/MDO	197.1	12.65	1.00	0.47	0.35	0.32	2.43	606.9	1.75	4.38
General Cargo	auxiliary engine	RO	543.0	35.21	2.63	1.10	3.59	3.50	31.77	1,683.4	1.39	13.86
General Cargo	boiler	RO	390.4	2.69	0.26	0.14	1.02	0.99	17.71	1,209.4	1.02	9.94
Navy	auxiliary engine	ULSD	447.5	28.93	2.29	1.08	0.79	0.73	0.01	1,440.1	4.16	10.41
Navy	boiler	ULSD	336.6	2.21	0.22	0.12	0.14	0.13	0.01	1,083.1	3.13	7.83
Others	auxiliary engine	MGO/MDO	4.0	0.26	0.02	0.01	0.01	0.01	0.05	12.3	0.04	0.09
Others	auxiliary engine	RO	12.5	0.81	0.06	0.03	0.08	0.08	0.74	38.8	0.03	0.32
Others	boiler	RO	25.1	0.17	0.02	0.01	0.07	0.06	1.21	77.8	0.06	0.64
Ro-Ro Cargo	auxiliary engine	MGO/MDO	22.3	1.43	0.11	0.05	0.04	0.04	0.30	68.7	0.20	0.50
Ro-Ro Cargo	auxiliary engine	RO	135.6	8.78	0.66	0.27	0.90	0.87	6.06	420.2	0.35	3.46
Ro-Ro Cargo	boiler	RO	14.1	0.10	0.01	0.01	0.04	0.04	0.59	43.8	0.04	0.36
Tanker	auxiliary engine	MGO/MDO	481.1	30.84	2.44	1.15	0.84	0.78	6.31	1,480.9	4.28	10.70
Tanker	auxiliary engine	RO	1,522.2	99.09	7.41	3.10	10.11	9.84	89.90	4,719.0	3.88	38.84
Tanker	boiler	RO	3,065.9	21.11	2.01	1.11	8.04	7.84	150.25	9,498.8	7.82	78.18
Vehicles Carrier	auxiliary engine	MGO/MDO	378.4	24.37	1.93	0.91	0.67	0.61	5.23	1,164.9	3.37	8.42
Vehicles Carrier	auxiliary engine	RO	821.1	53.26	3.99	1.67	5.43	5.29	48.35	2,545.3	2.09	20.95
Vehicles Carrier	boiler	RO	568.0	3.91	0.37	0.20	1.47	1.43	26.86	1,759.5	1.52	14.45

*CH_4 and N_2O in tonnes CO_2 equivalent