MarineTraffic

Just In Time Arrival

Emissions reduction potential in global container shipping

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Table of Contents

Acronyms and abbreviations

AIS	Automatic Identification System
CO_2	Carbon Dioxide
FC	Fuel Consumption
GHG	Greenhouse Gas
GIA	Global Industry Alliance
GPS	Global Positioning System
IMO	International Maritime Organization
JIT	Just In Time
LNG	Liquefied Natural Gas
Low Carbon GIA	Global Industry Alliance to Support Low Carbon Shipping
LSHFO	Low Sulphur Heavy Fuel Oil
MDO	Marine Distillate Oil
ME	Main Engine
MEPC	Marine Environment Protection Committee
MT	Metric Tonnes (1,000 kg)
NM	Nautical Mile
PBP	Pilot Boarding Place
SFC	Specific Fuel Consumption
TEU	Twenty-foot Equivalent Unit

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Executive summary

The concept of Just in Time (JIT) Arrival of ships allows for ships to optimise their speed during the voyage in order to arrive at the Pilot Boarding Place (PBP) when the availability of berth, fairway and nautical services is ensured. Therefore, since JIT Arrival allows the ship to adjust and optimise its speed during the voyage, it has been identified as a feasible opportunity to reduce GHG emissions from ships and support the goals of the Initial IMO GHG Strategy.[1]

This study calculated the potential fuel consumption and CO_2 emission reduction from the effective implementation of JIT for the container shipping sector. Using AIS data, all containership voyages in 2019 were reconstructed and three JIT Scenarios were applied, in which speed was adjusted to minimise fuel consumption and still arrive in time (1) from Pilot Boarding Place to Pilot Boarding Place (JIT PBP-PBP), (2) over the last 24 hrs of the voyage to Pilot Boarding Place (JIT 24), and (3) over the last 12 hrs of the voyage to Pilot Boarding Place (JIT 12).

Results in this study demonstrate that operational changes to industry practices, to effectively implement JIT can result in significant fuel consumption and thus CO_2 emission savings.

The analysis based on the observed baseline dataset calculated that the total fuel consumed was 43.97 million metric tonnes (MT), with a mean fuel consumption on a per voyage basis of 129.56 MT. Calculations in this study show potential fuel consumption savings across the 339,390 voyages considered in all three scenarios (JIT PBP-PBP, JIT 24, and JIT 12).

	JIT PBP-PBP	**JIT 24**	**JIT 12**
Total CO_2 saving[2] (MT)	19.39 million	8.08 million	5.80 million
Total fuel consumption saving (MT)	6.23 million	2.59 million	1.86 million
Mean fuel consumption saving, on per voyage basis compared to baseline	14.16%	5.90%	4.23%

Scenario JIT PBP-PBP offers the greatest opportunity for fuel consumption savings followed by JIT 24, and by JIT 12. This is expected as the optimisation from PBP-PBP would offer the maximum amount of time to optimise the voyage. The greater the time a voyage can be optimised, the greater the fuel consumption savings potential. In other words, the earlier the ship can optimise its speed, the greater the savings can be achieved. However, the results also show that optimisation in the last 12 hours can already have a substantial saving potential, and hence be a good time horizon to start optimisation.

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[1] Resolution MEPC.304(72)

[2] Assuming all vessels operate on LSHFO.

From an operational perspective, it is virtually impossible to optimise a voyage from PBP to PBP as delays at the destination port are not often known at the time the ship departs its origin port. Even in the JIT 24 and JIT 12 scenarios, the savings calculated are theoretical because not all delays are known 24 hr before arrival or 12 hr before arrival, for the simple fact that these delays are experienced after this point and are not planned or expected by anyone until that moment. Whilst this study has only considered three scenarios from this theoretical perspective, the trend is clear that the earlier the ship can take action to optimise speed, the greater the fuel consumption savings potential.

The analysis has shown that 50% of potential fuel savings could be achieved through focusing on a comparatively small subset of the total voyages (8.51% of voyages in JIT PBP-PBP, 6.55% in JIT 24, and 3.18% in JIT 12) (See Figure 9). These voyages are potential candidates for first movers under a JIT arrival program. Further work could study these voyages in greater detail in order to target this small percentage of voyages with potentially big returns.

Whilst the results in this study demonstrate significant savings through the implementation of JIT in the container sector, much needs to be done in order to realise such potential. Collaboration between shipping lines, ports and terminals, to enhance the exchange of data and information required for the ship to optimise its voyage is critical to properly implementing JIT Arrivals.

Introduction and purpose

IMO, in April 2018, adopted resolution MEPC.304(72) on the Initial IMO Strategy on reduction of GHG emissions from ships, setting out a vision to reduce GHG emissions from international shipping and phase them out as soon as possible in this century.

It is recognized that the goals of the Strategy will only be achieved through a combination of measures: operational, technical, as well as the use of alternative low-carbon and zero-carbon fuels. Furthermore, there is increasing awareness of the important role of ports in the wider supply chain and the action that ports can take to facilitate the reduction of GHG emissions from shipping. This has been recognized through the adoption of resolution MEPC.323(74), in May 2019, which encourages voluntary cooperation between the port and shipping sectors to contribute to reducing GHG emissions from ships. The resolution also invites IMO Member States to facilitate, among others, actions that support the industry's collective efforts to improve quality and availability of data and develop necessary global digital data standards that would allow reliable and efficient data exchange between ship and shore as well as enhanced slot allocation policies thereby optimising voyages and port calls and facilitating Just In Time (JIT) Arrival of ships.

The concept of JIT Arrival of ships allows for ships to optimise their speed during the voyage in order to arrive at the Pilot Boarding Place (PBP) when the availability of berth, fairway and nautical services is ensured. Therefore, since JIT Arrival allows the ship to adjust and optimise its speed during the voyage, it has been identified as a feasible opportunity to reduce GHG emissions from ships and support the goals of the Initial IMO GHG Strategy.

The objective of this study is to calculate the potential fuel consumption and CO_2 emission reduction from the effective implementation of JIT for the container shipping sector. Since from 2020 onwards, maritime transport has been heavily impacted by the COVID-19 pandemic, 2019 was used as the reference year. This study considered three JIT Scenarios, in which speed was adjusted to minimise fuel consumption (1) from PBP to PBP, (2) over the last 24 hrs of the voyage, and (3) over the last 12 hrs of the voyage.

This study focuses on the container shipping sector, as container ships have no contractual barriers to adjust speed during the voyage and is therefore considered to be a good starting point for implementation of JIT. More information on barriers and potential solutions for JIT implementation can be found in the Low Carbon GIA JIT Guide.[3] It is envisaged that other sectors will be analysed in more detail in the future to increase understanding of the potential fuel consumption and emission reduction through the implementation of JIT for the rest of the global fleet.

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[3] https://greenvoyage2050.imo.org/wp-content/uploads/2021/01/GIA-just-in-time-hires.pdf

Methodology

Data preparation and cleaning

As an initial step, all containerships (5,131 containerships) with recorded AIS positions in 2019 were extracted from the MarineTraffic database. AIS data includes, among others, positional coordinates, speed over ground (in knots), timestamps, heading and draught information.

AIS is very effective in tracking vessels sailing close to shore (continuous positional updates) where reception from terrestrial means is supported. For remote areas, open seas and areas of no coastal coverage, the system relies on satellite tracking where the data availability is more sparse. Hourly positions were sampled to avoid skewing the output with near-shore data points causing overfitting. For discussion of potential uncertainties related to AIS data, further information can be found in Annex I.

For the purpose of this study, all vessels with recorded activity via the AIS during 2019 were considered regardless of their current status at the time of writing this study. This includes vessels that might no longer be in service in 2022 to ensure data integrity over the reference year (2019).

The data was then filtered to remove AIS records which did not have complete and reliable information on Capacity (TEU), resulting in 5,050 vessels. A dataset of all recorded voyages of these 5,050 vessels during 2019 was reconstructed using positional AIS data together with geofenced areas of anchorage areas and port area limits of global ports, which have been identified from MarineTraffic databases.

Each voyage has a voyage start point and a voyage end point defined as below:

> **Voyage start point:** The vessel starts picking up speed over 5 knots and has exited the geofenced port area of origin.
>
> **Voyage end point:** The vessel has entered the geofenced port area at destination.

Both speed and geopositional criteria need to be met to be considered as a voyage start or end point. For the purpose of this study, the voyage start point and end point as defined, correspond to the pilot boarding place at the departure and arrival ports, respectively.

The reconstruction of voyages resulted in a **raw dataset** of 455,906 unique voyages (from 5,050 vessels). Approximately 65% of these voyages were longer than 24 hrs.

The initial raw dataset of voyages and positions was cleaned to remove data gaps, reduce noise, control uncertainties, and prepare the baseline dataset, in line with the following reasoning.

Table 1: Data cleaning and processing

Removal of potentially erroneous AIS positional readings and basic voyages consistency checks	Remove positions where coordinates did not match geospatial parameters (GPS misreadings, inconsistent distances) or showing sailing speeds above 26 knots as highly likely to be erroneous since this speed is outside of the normal operating range for containerships, as reported by industry experts. Where positions were removed, gaps were filled through interpolation between valid positional data. Furthermore, voyages with fewer than 2 observed positions overall were removed since they would not consist of a voyage.
Identification and marking of positions through canals	Many canals may have speed limits, and as a result ships may go at slow speeds when transiting a canal. These AIS positions were flagged as being a canal passage, in order to distinguish it from a manoeuvring state.
Removal of voyages under 6 hours	These voyages were considered too short to be optimised and were excluded.
Removal of voyages above 30 days	These voyages were considered unscheduled/unplanned and unusual in real operations. Including these voyages could have had a disproportionate influence on the results.
Removal of voyages with an observed overall waiting/manoeuvring time over 240 hrs (10 days)	These waiting times were considered substantial and likely associated with systemic issues falling outside of normal operation cycles.

The resulting **baseline dataset** consisted of 339,390 voyages. An overview of the raw and the baseline datasets can be found in Table 2.

Table 2: Overview of number of voyages, vessels, ports and port pairs in each dataset

Datasets	Voyages	Vessels	Ports	Port Pairs
Raw dataset	455,906	5,050	1,226	10,839
Baseline dataset	339,390	4,946	1,158	9,539

Metadata was added to each hourly AIS position to indicate the state of the vessel (underway, waiting, manoeuvring), to assess voyage optimisation potential, in consideration of the JIT scenarios, as per the definitions below:

- **Underway:** the vessel sails outside geofenced Anchorage and Port areas with a speed over 5 knots.
- **Waiting:** the vessel enters and stays within the geofenced Anchorage area of the Destination port at a speed below 5 knots.
- **Manoeuvring:** the vessel moves outside port-related geofenced areas with a speed below 5 knots.
- **Waiting time** is calculated by the difference in timestamps between the entering and exiting of the geofenced Anchorage area.
- **Manoeuvring time** is calculated based on the cluster of consecutive positions that are marked as Manoeuvring (Last Manoeuvring Position - First Manoeuvring Position = Manoeuvring Time) on a per voyage basis.

Calculating fuel consumption and emissions

Figure 1: Construction of voyages from origin port to destination port. Source: MarineTraffic collection.

The speed (u_i) of a vessel was calculated between each pair of consecutive positions, one hour apart (e.g. position i, and i-1, see Figure 1). The speed calculated between those positional pairs is the average speed between these two points and is assumed to be constant for the relevant time period, in this case, an hour. Furthermore, every position also holds information regarding the total distance travelled from the start and end of the voyage (d_i), used to identify waiting and manoeuvring modes, the timestamp (T_i) that the position was captured, and other information used for quality assurance purposes and voyage analysis.

Based on the calculated speed at each hourly interval and the draught (t), which is assumed constant for the voyage and considered the last reported draught prior to arrival at the port of destination, the fuel consumption (FC_i) (for main engine, auxiliary engines and boilers) was determined by utilising fuel consumption data provided by two large container shipping companies. The total fuel consumption data (main engine, auxiliary engines and boilers) was tabulated by speed, and draught and segmented per container vessel size bins used in the Fourth IMO GHG Study. Each bin size consisted of real data from both owned and chartered vessels with varying efficiencies, as efficiency depends on design, class age, energy saving devices fitted, maintenance and operation of the vessel. In total, data from 590 ships was taken into consideration, and averaged by speed and draught to produce the fuel consumption curves found in Figure 11 in Annex I. Since this data is from observed operations, it takes into account fuel consumption while sailing in different sea states.

To calculate the total fuel consumption for each voyage, the fuel consumption at each positional point was aggregated for all positions of a particular voyage. CO_2 emissions were then calculated assuming that all ships operate on LSHFO (CO_2 emission factor of 3.114g CO_2/g LSHFO).

Using the baseline dataset of 339,390 voyages, the fuel consumption was calculated for each voyage and the mean and total fuel consumption and CO2 emissions are shown below.

Table 3: Baseline: Mean and Total FC and CO_2 emissions, on a per voyage basis

TEU Class	**IMO Bin**	**No. of Vessels**	**No. of Voyages**	**Mean voyage duration (days)**	**Mean FC (MT)**	**Total FC (1,000 MT)**	**Mean CO_2 (MT)**	**Total CO_2 (1,000 MT)**
0-999	**1**	794	76,271	1.74	**30.42**	**2,320.46**	**94.74**	**7,225.92**
1000-1999	**2**	1,155	90,388	2.19	**49.68**	**4,490.04**	**154.69**	**13,981.98**
2000-2999	**3**	641	42,283	2.82	**85.93**	**3,633.29**	**267.58**	**11,314.06**
3000-4999	**4**	805	47,309	3.65	**170.21**	**8,052.36**	**530.03**	**25,075.05**
5000-7999	**5**	570	34,469	3.56	**221.27**	**7,626.96**	**689.04**	**23,750.35**
8000-11999	**6**	587	31,394	4.02	**304.95**	**9,573.66**	**949.62**	**29,812.37**
12000-14499	**7**	230	10,200	4.64	**478.45**	**4,880.15**	**1,489.88**	**1,5196.8**
14500-19999	**8**	113	5,279	4.48	**440.62**	**2,326.02**	**1,372.08**	**7,243.22**
20000+	**9**	51	1,797	4.88	**595.45**	**1,070.02**	**1,854.23**	**3,332.05**
TOTAL		4,946	339,390		**129.56**	**43,972.97**	**403.46**	**136,931.82**

Just In Time Scenarios

The following three scenarios were considered:

Scenario JIT PBP-PBP – the voyage is fully optimised from PBP to PBP.

Scenario JIT 24 – the voyage is optimised over the last 24 hrs of the voyage to PBP.

Scenario JIT 12 – the voyage is optimised over the last 12 hrs of the voyage to PBP.

Each of these scenarios utilized the same baseline dataset of 339,390 voyages, after data processing and cleaning, and the optimisation of speed is explained below.

According to the data, some vessels were already in a waiting/manoeuvring state close to the destination port 24 or 12 hours before the vessel could enter the port. As these vessels already arrived (close) to the port and do not have to sail any (significant) distance anymore, these voyages do not benefit from JIT in the JIT 24 and JIT 12 scenarios. These voyages were not removed in order to have a consistent baseline set to enable comparison across the three scenarios. In the PBP-PBP scenario all vessels can have optimisation potential as the scenario is not related to a timeframe.

Furthermore, for those voyages which were less than the respective timeframe (24/12 hrs), these voyages were fully optimised from PBP to PBP. Figure 2 illustrates the consideration of voyages of different lengths under the various scenarios. The use of the same baseline dataset allows for direct comparisons across the three scenarios.

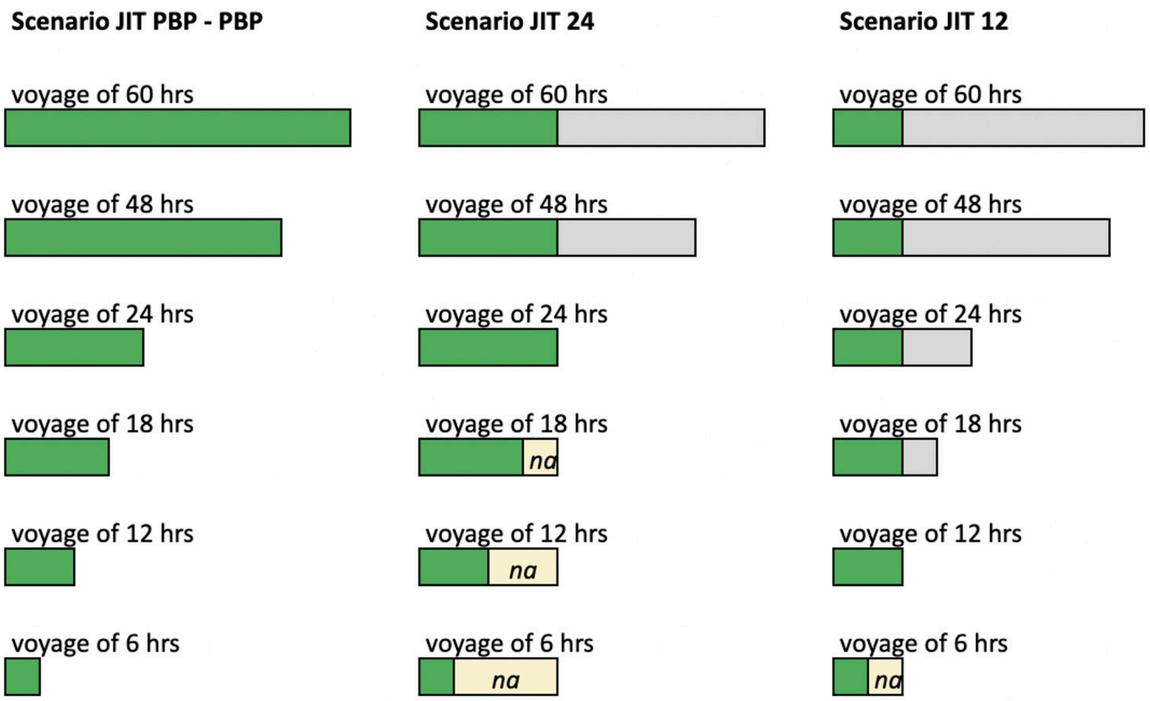


Figure 2: Consideration of different voyage lengths under each JIT scenario (green indicates optimisation timeframe)

This study aims to understand the impact of JIT arrival of vessels, in which the voyage speed is adjusted to minimise overall fuel consumption and emissions and still arrive on time. This study is based on observed historical data, therefore to “still arrive in time” means that the overall observed duration of the voyage (i.e. the total time taken for each voyage from PBP to PBP, as observed) is unchanged.

To explain “**JIT speed**”, an example of a vessel sailing from Felixstowe (UK) to Bremerhaven (GER), a voyage of 300 nautical miles (NM) is used. In the actual situation the voyage had a duration of 21 hours. The vessel sailed 15 hours at 20 knots and then anchored for 6 hours. To calculate the JIT speed of this voyage, two numbers must be defined: **the minimum speed of this voyage to arrive Just In Time** and **the most economical speed** of the vessel.

To calculate the minimum speed for this voyage, a constant optimal speed is assumed. As the voyage is 300 NM and the total duration of the voyage is 21 hours, the minimum speed the vessel can sail and still arrive in time is 300/21= 14.3 knots.

The most economical speed of the vessel is defined as the most fuel-efficient speed on a per nautical mile basis. This speed is derived from the provided fuel tables, based on vessel size bin and draught. For this voyage the most economical speed is 10 knots.

Sailing the most economical speed of 10 knots is not an option as the vessel will arrive too late. There are only 21 hours available, but the vessel needs 30 hours to arrive. So, the most optimal way to sail this voyage from Felixstowe to Bremerhaven is by sailing 21 hours at 14.3 knots.

Figure 3: Understanding JIT speed (minimal speed to arrive in time)

Another vessel within the same size bin and draught has 35 hours available to sail the same voyage. The most economical speed is still 10 knots, while the minimum speed to still arrive in time has changed to 300/35= 8.6 knots.

So JIT speed is the most economical speed for this voyage. That can be explained as the consumption per mile is lower at 10 knots compared to 8.6 knots. The most optimal way to sail this voyage from Felixstowe to Bremerhaven is by sailing 30 hours at 10 knots and anchor for 5 hours.

Figure 4: Understanding JIT speed (most economical speed)

JIT speed is the speed at which the ship could travel to minimise total fuel for a particular voyage and is dependent on the minimum speed to arrive Just In Time, and the most economical speed. Arriving Just In Time will not necessarily eliminate waiting or manoeuvring time.

Results

Results take into account three different voyage scenarios:

Scenario JIT PBP-PBP – the voyage is fully optimised from PBP to PBP.

Scenario JIT 24 – the voyage is optimised over the last 24 hrs of the voyage to PBP.

Scenario JIT 12 – the voyage is optimised over the last 12 hrs of the voyage to PBP.

For each of the scenarios, fuel consumption and CO_2 savings were calculated (the same dataset was used, consisting of 339,390 voyages).

Scenario JIT PBP-PBP – Optimisation from PBP to PBP

In this scenario, all 339,390 voyages in the dataset were optimised from PBP to PBP, irrespective of voyage length.

Table 4: Scenario JIT PBP-PBP: Fuel consumption and CO_2 emissions savings, mean values on a per voyage basis.

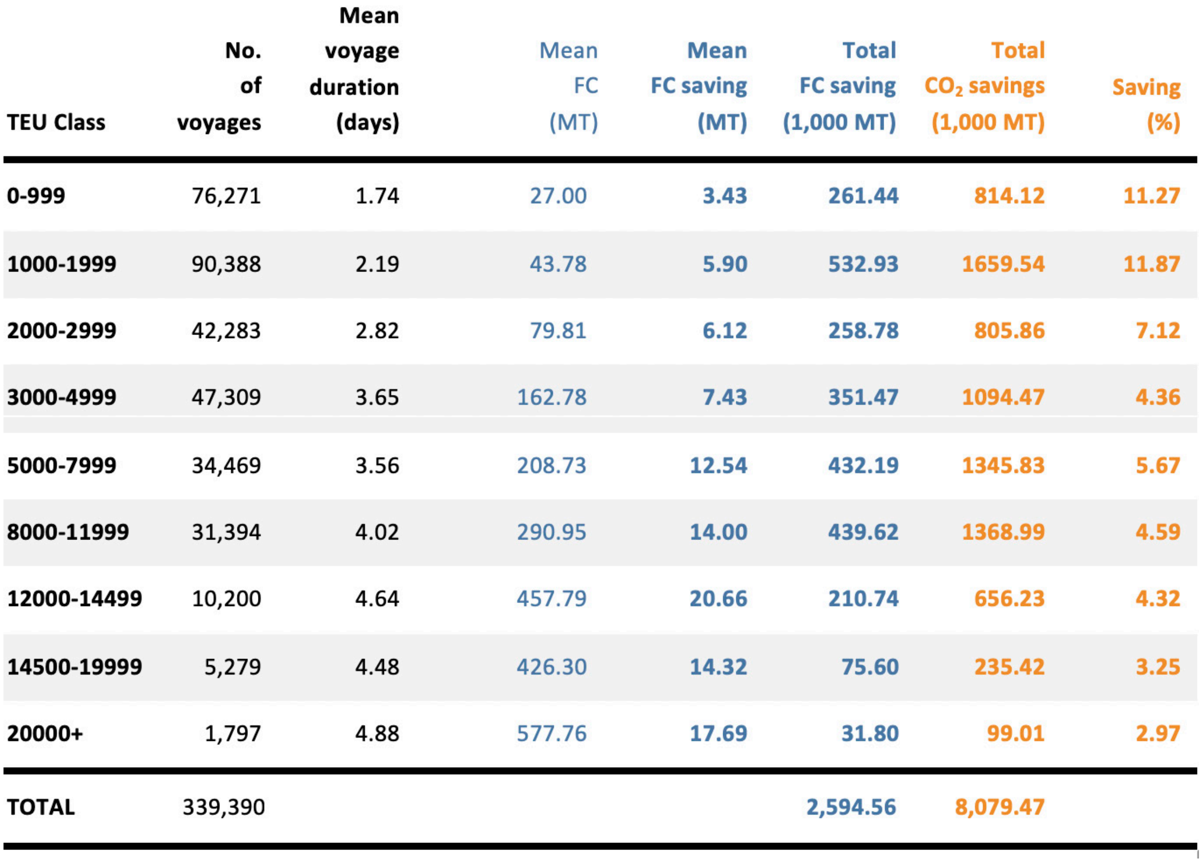
TEU Class	No. of voyages	Mean voyage duration (days)	Mean FC (MT)	Mean FC saving (MT)	Total FC saving (1,000 MT)	Total CO_2 savings (1,000 MT)	Saving (%)
0-999	76,271	1.74	23.84	**6.58**	**502.22**	**1,563.90**	**21.64**
1000-1999	90,388	2.19	37.76	**11.91**	**1,076.61**	**3,352.55**	**23.98**
2000-2999	42,283	2.82	70.56	**15.37**	**649.77**	**2,023.40**	**17.88**
3000-4999	47,309	3.65	149.66	**20.55**	**972.31**	**3,027.78**	**12.07**
5000-7999	34,469	3.56	189.33	**31.94**	**1,101.10**	**3,428.82**	**14.44**
8000-11999	31,394	4.02	268.46	**36.49**	**1,145.51**	**3,567.11**	**11.97**
12000-14499	10,200	4.64	429.99	**48.46**	**494.25**	**1,539.10**	**10.13**
14500-19999	5,279	4.48	402.40	**38.22**	**201.75**	**628.26**	**8.67**
20000+	1,797	4.88	549.38	**46.07**	**82.79**	**257.81**	**7.74**
TOTAL	339,390				**6,226.31**	**19,388.73**	

Scenario JIT 24 – Optimisation over the last 24 hrs of the voyage

In this scenario, out of the total of 339,390 voyages:

146,230	were able to be optimised over the complete last 24 hrs of the voyage.
38,498	were not able to be optimised over the last 24 hrs of the voyage, because the ship had already entered a waiting/manoeuvring state. For these voyages, the optimisation potential would be zero.
154,662	had a duration of less than 24 hrs. These voyages were optimised for the full duration of the voyage (from PBP to PBP). For further details see Figure 2.

Table 5: Scenario JIT 24: Fuel consumption and CO_2 emissions savings, mean values on a per voyage basis.



TEU Class	**No. of voyages**	**Mean voyage duration (days)**	Mean FC (MT)	**Mean FC saving (MT)**	**Total FC saving (1,000 MT)**	**Total CO_2 savings (1,000 MT)**	**Saving (%)**
0-999	76,271	1.74	27.00	**3.43**	**261.44**	**814.12**	**11.27**
1000-1999	90,388	2.19	43.78	**5.90**	**532.93**	**1659.54**	**11.87**
2000-2999	42,283	2.82	79.81	**6.12**	**258.78**	**805.86**	**7.12**
3000-4999	47,309	3.65	162.78	**7.43**	**351.47**	**1094.47**	**4.36**
5000-7999	34,469	3.56	208.73	**12.54**	**432.19**	**1345.83**	**5.67**
8000-11999	31,394	4.02	290.95	**14.00**	**439.62**	**1368.99**	**4.59**
12000-14499	10,200	4.64	457.79	**20.66**	**210.74**	**656.23**	**4.32**
14500-19999	5,279	4.48	426.30	**14.32**	**75.60**	**235.42**	**3.25**
20000+	1,797	4.88	577.76	**17.69**	**31.80**	**99.01**	**2.97**
TOTAL	339,390				**2,594.56**	**8,079.47**	

Scenario JIT 12 – Optimisation over the last 12 hrs of the voyage

In this scenario, out of the total of 339,390 voyages:

178,094	were able to be optimised over the complete last 12 hrs of the voyage.
68,522	were not able to be optimised over the last 12 hrs of the voyage, because the ship had already entered a waiting/manoeuvring state. For these voyages, the optimisation potential would be zero.
92,774	had a duration of less than 12 hrs. These voyages were optimised for the full duration of the voyage (from PBP to PBP). For further details see Figure 2.

Table 6: Scenario JIT 12: Fuel consumption and CO_2 emissions savings, mean values on a per voyage basis

TEU Class	No. of voyages	Mean voyage duration (days)	Mean FC (MT)	Mean FC saving (MT)	Total FC saving (1,000 MT)	Total CO_2 savings (1,000 MT)	Saving (%)
0-999	76,271	1.74	28.16	**2.27**	**172.77**	**538.00**	**7.45**
1000-1999	90,388	2.19	45.62	**4.06**	**366.90**	**1,142.52**	**8.17**
2000-2999	42,283	2.82	81.71	**4.21**	**178.21**	**554.95**	**4.90**
3000-4999	47,309	3.65	164.89	**5.32**	**251.46**	**783.04**	**3.12**
5000-7999	34,469	3.56	212.35	**8.92**	**307.53**	**957.64**	**4.03**
8000-11999	31,394	4.02	294.26	**10.69**	**335.62**	**1,045.13**	**3.51**
12000-14499	10,200	4.64	462.40	**16.05**	**163.69**	**509.72**	**3.35**
14500-19999	5,279	4.48	429.53	**11.09**	**58.55**	**182.32**	**2.52**
20000+	1,797	4.88	580.25	**15.20**	**27.32**	**85.07**	**2.55**
TOTAL	339,390				**1,862.04**	**5,798.38**	

Comparison across Scenarios JIT PBP to PBP, JIT 24 and JIT 12

The speed adjusted PBP to PBP voyage JIT scenario offers the greatest opportunity for fuel savings, and associated CO_2 emission reductions. In total, the PBP to PBP JIT scenario has the potential to reduce fuel consumption by up to 6.23 million tonnes, corresponding to CO_2 emission reductions of 19.39 million tonnes (assuming LSHFO fuels).

The JIT 24 scenario has the potential to reduce total fuel consumption by up to 2.59 million metric tonnes, with corresponding CO_2 reductions of up to 8.08 million metric tonnes. Last, the JIT 12 scenario would lead to a reduction in fuel consumption of up to 1.86 million metric tonnes, and CO_2 reductions of up to 5.80 million metric tonnes (see Figure 5).

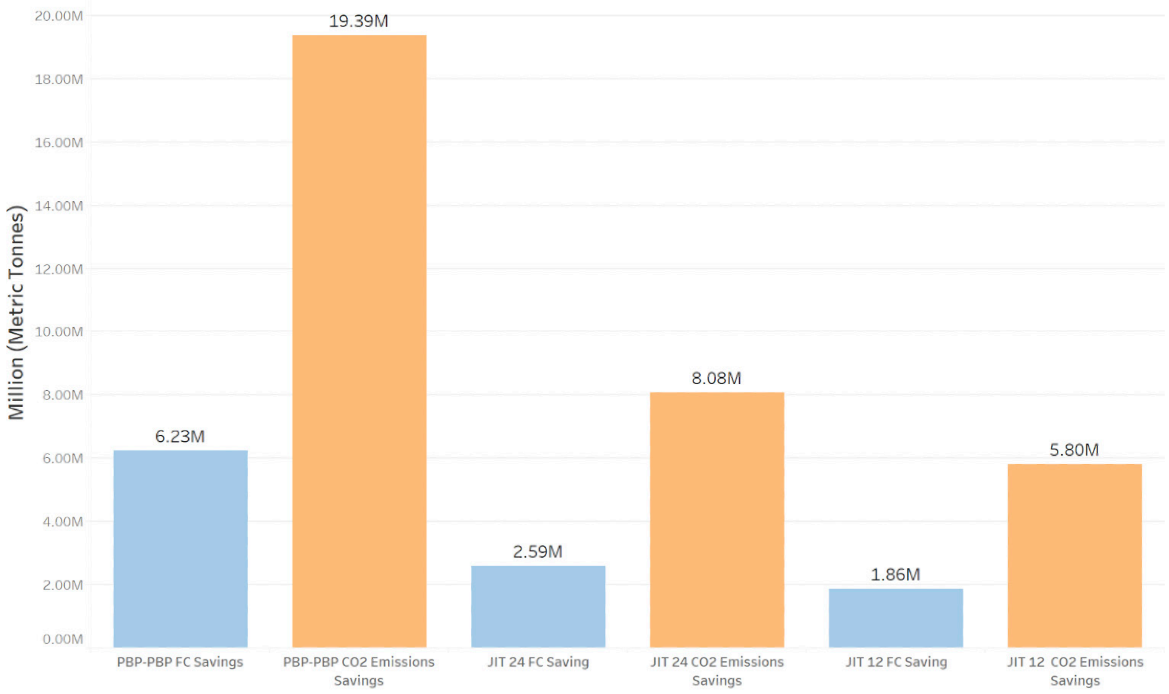


Figure 5: Total FC and CO_2 savings across three scenarios

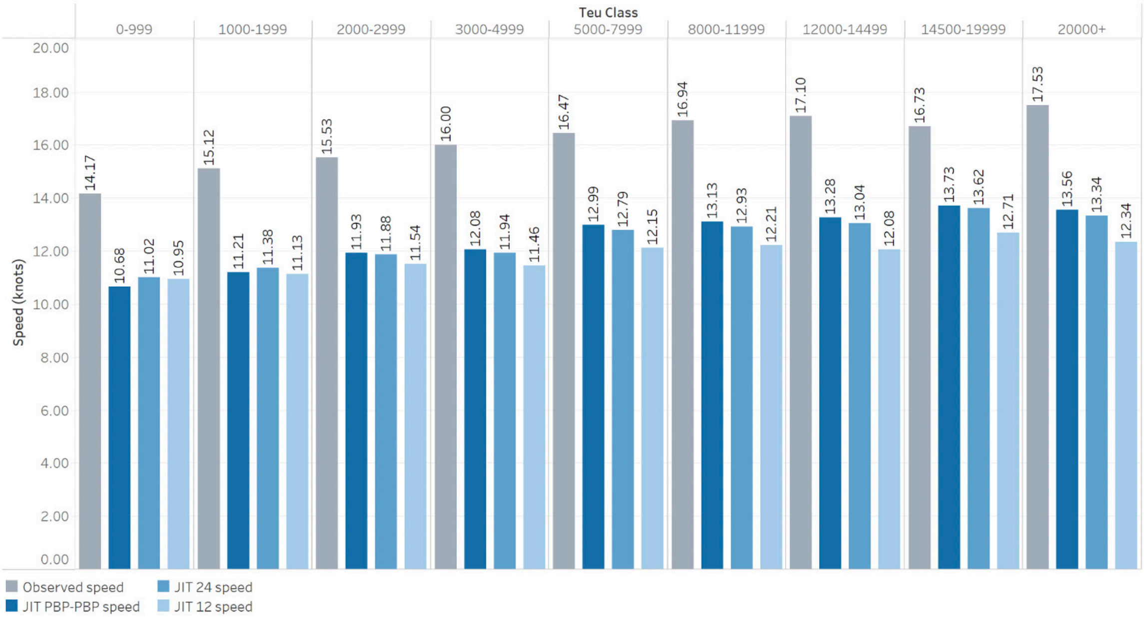


Figure 6: Observed speed vs. JIT speed across scenarios

Figure 6 shows the average speed per voyage as observed from the data, per TEU class and the corresponding calculated average speed to arrive JIT across the three scenarios. As the TEU class size increases, so does the observed speed, as to be expected with larger ships generally sailing at higher speeds than smaller ships. Across the three scenarios, the variation in JIT speed does not change dramatically (ranging from approximately 10 to 14 knots) across the scenarios which suggests that irrespective of the scenario, the calculated speed across the three scenarios is 3-4 knots lower than the observed speed. This means, the speed of vessels could be reduced and still arrive in time.

Figure 7 (overleaf) shows the mean fuel consumption on a per voyage basis, and the calculated potential fuel consumption savings across the three scenarios. The figure shows that as the TEU class size increases, the mean fuel consumption per voyage also increases (blue bars). This is to be expected not only due to the larger ship size but also that these ships usually travel on longer voyages and therefore fuel consumption will be higher. As fuel consumption in JIT 24 and JIT 12 are only optimised for the last 24 and 12 hours, the fuel consumption is higher in these scenarios.

When considering absolute fuel consumption reduction potential in MT, the general trend indicates that on a per voyage basis, the larger the vessel, the greater the fuel consumption saving.

The figure also shows that the greatest savings (white bars) are to be achieved through optimisation from PBP-PBP which is expected, as this provides the maximum length of voyage to optimise speed. In the JIT 24 and JIT 12 Scenarios fuel consumption savings can also be realised, and the trend demonstrates that the greater the time horizon to optimise, the greater the fuel consumption savings, and as a result greater emission reduction. It would appear that the difference in savings between the JIT 24 and JIT 12 scenarios are not huge, which suggests that JIT 12 would already be a good starting point to realise some of the potential fuel consumption savings.

Table 7: Mean FC of the baseline and reduction potential (%) across scenarios, on a per voyage basis

		Observed values (Baseline)		**JIT PBP-PBP**	**JIT 24**	**JIT 12**
TEU Class	**No. of voyages**	Mean FC (MT)	CO_2 (MT)	Reduction (%)	Reduction (%)	Reduction (%)
0-999	76,271	30.42	94.74	21.64	11.27	7.45
1000-1999	90,388	49.68	154.69	23.98	11.87	8.17
2000-2999	42,283	85.93	267.58	17.88	7.12	4.90
3000-4999	47,309	170.21	530.03	12.07	4.36	3.12
5000-7999	34,469	221.27	689.04	14.44	5.67	4.03
8000-11999	31,394	304.95	949.62	11.97	4.59	3.51
12000-14499	10,200	478.45	1,489.88	10.13	4.32	3.35
14500-19999	5,279	440.62	1,372.08	8.67	3.25	2.52
20000+	1,797	595.45	1,854.23	7.74	2.97	2.55
AVERAGE		129.56	403.46	**14.16**	**5.90**	**4.23**

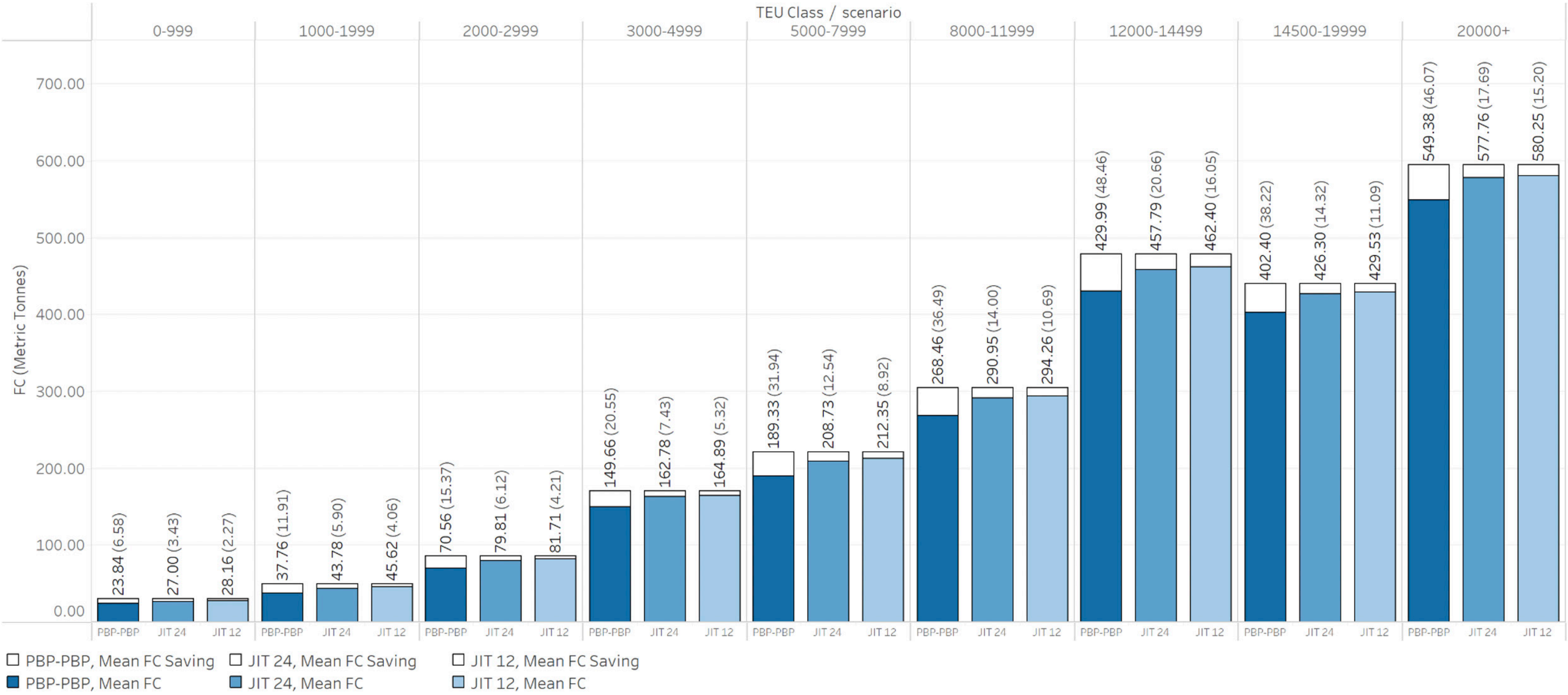


Figure 7: Mean FC and FC savings (in parenthesis) across scenarios

From the baseline dataset, the number of voyages per class size in general decreases the larger the class size. This is expected as the largest vessels usually undertake the longest voyages (of which there are fewer). There are a high number of voyages for class size 1000-1999 TEU ships, and this is likely due to the high number of shortsea voyages, and voyages of feederships which operate shorter but more frequent voyages.

When considering the three scenarios per class size, the voyages of the smaller class vessels (below 3000 TEU) have greater fuel consumption reduction potential in all three scenarios in % terms of fuel consumed over the whole voyage. The reason may be that these smaller class vessels may get less priority over larger mainliner vessels, and as such would have longer waiting times.

Table 8: Total FC and CO_2 *savings across scenarios*

TEU Class	JIT PBP-PBP Total FC savings (1,000 MT)	JIT 24 Total FC savings (1,000 MT)	JIT 12 Total FC savings (1,000 MT)	JIT PBP-PBP Total CO_2 savings (1,000 MT)	JIT 24 Total CO_2 savings (1,000 MT)	JIT 12 Total CO_2 savings (1,000 MT)
0-999	502.22	261.44	172.77	1,563.90	814.12	538.00
1000-1999	1,076.61	532.93	366.90	3,352.55	1,659.54	1,142.52
2000-2999	649.77	258.78	178.21	2,023.40	805.86	554.95
3000-4999	972.31	351.47	251.46	3,027.78	1,094.47	783.04
5000-7999	1,101.10	432.19	307.53	3,428.82	1,345.83	957.64
8000-11999	1,145.51	439.62	335.62	3,567.11	1,368.99	1,045.13
12000-14499	494.25	210.74	163.69	1,539.10	656.23	509.72
14500-19999	201.75	75.60	58.55	628.26	235.42	182.32
20000+	82.79	31.80	27.32	257.81	99.01	85.07
TOTAL	6,226.31	2,594.56	1,862.04	19,388.73	8,079.47	5,798.38

Figure 8 (overleaf) validates that across the scenarios, optimisation from PBP-PBP will result in the greatest fuel consumption savings. Furthermore, it indicates that while total fuel consumption from vessel sizes 3000-11,999 TEU are highest in absolute terms, it is the vessels of sizes 1,000-1,999 TEU, and 3,000-11,999 TEU which overall, have the greatest fuel consumption saving potential, indicated by the white bars. However, as fuel consumption in this Figure is not expressed in % terms, it is heavily influenced by the number of vessels and voyages per scenario.

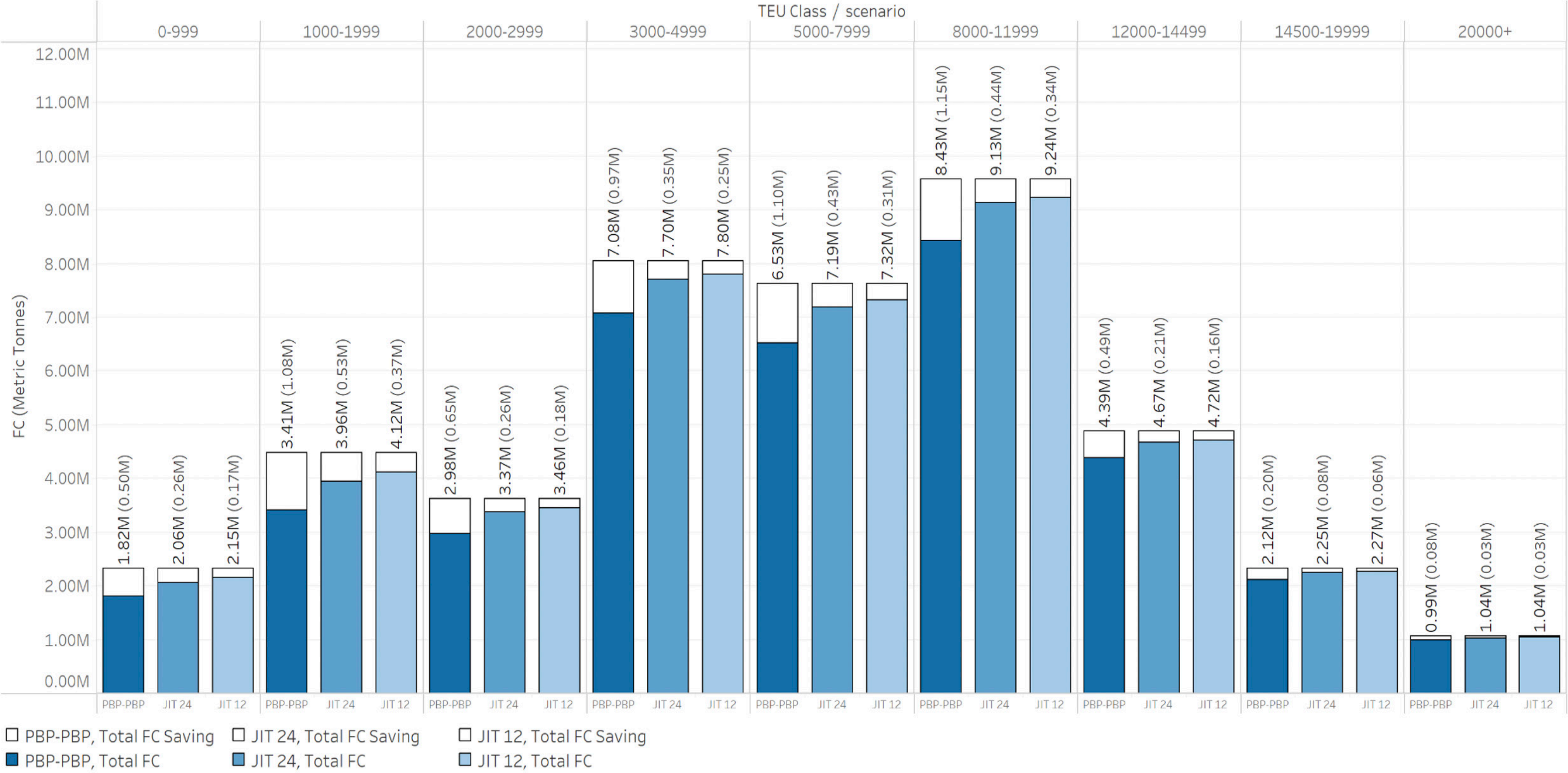


Figure 8: Total FC and savings across scenarios, on a per voyage basis.

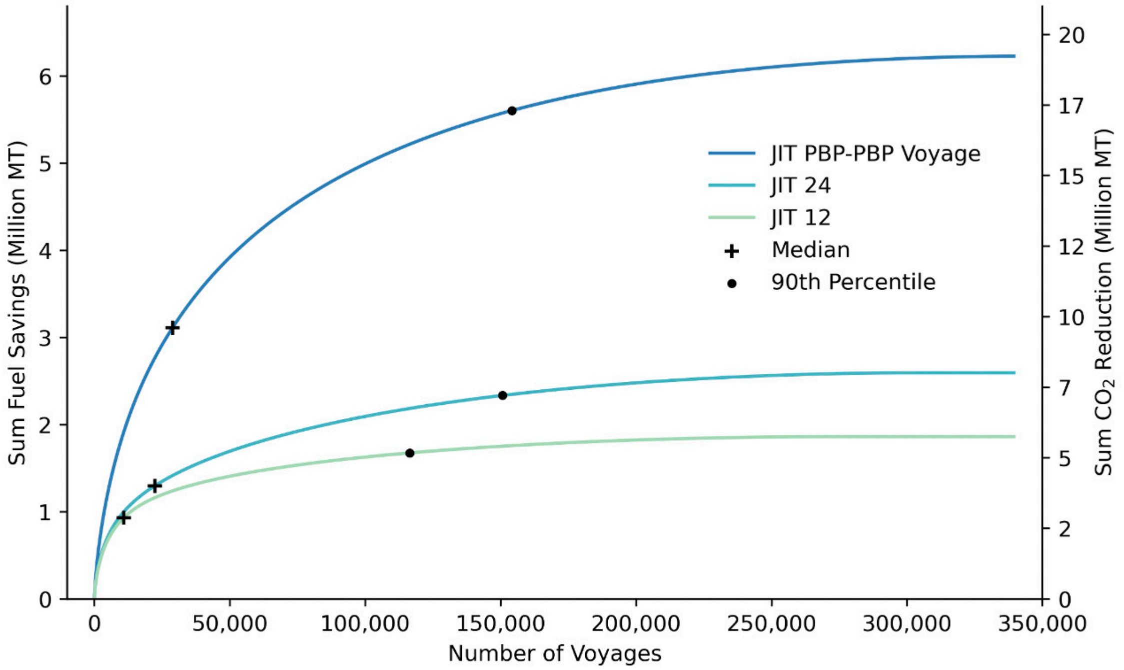


Figure 9: Cumulative fuel savings and CO_2 emission reductions grouped by voyage across scenarios

The cumulative sum of fuel savings for each of the three JIT scenarios is shown in Figure 9. The three curves illustrate the total fuel savings (left axis) and CO2 abatement (right axis) for each JIT scenario. These curves also show that a comparatively small number of voyages account for half of all fuel and CO2 savings. For the scenario JIT PBP-PBP, half of all savings could be achieved through optimisation of 8.51% of the total number of voyages. These voyages were completed by 3,941 vessels, with a mean voyage duration of 8.94 days and an average distance of 2,940 NM. 22.2% of these voyages were undertaken by vessels in IMO Bin 6 (8000-11999 TEU), 20.6% in Bin 5 (5000-7999 TEU), and 16.6% in Bin 4 (3000-4999 TEU). The one hundred voyages with the greatest fuel savings and emission reductions have a mean duration of 16.09 days (median = 19.48 days).

For the JIT 24 scenario, half of all savings could be achieved through the optimisation of 6.55% of the total number of voyages. These voyages were completed by 3,930 unique vessels, with a mean voyage duration of 5.46 days and average distance of 1,736 NM. Among these voyages, 21.8% were by vessels in IMO Bin 2 (1000-1999 TEU), 17.9% in Bin 5 and 17.4% in Bin 6.

For the JIT 12 scenario, half of all savings could be achieved through the optimisation of 3.18% of the total number of voyages. These voyages were completed by 3,151 vessels with a mean voyage duration of 6.99 days and a distance of 2,186 NM. Among these voyages 21.0% were by vessels in IMO Bin 2, 17.3% in Bin 5, and 17.2% in Bin 6.

Given that a small percentage of voyages account for half of all fuel and CO_2 savings, these results represent an important area for further study, which may include detailed analysis of ports, port pairs, geography and routing, and vessels.

Conclusions and next steps

Results in this study demonstrate that operational changes to industry practices, to effectively implement JIT can result in mean fuel consumption and CO_2 emission savings of up to 14.2%, depending on the scenario.

The analysis based on the observed baseline dataset calculated that the total fuel consumed was 43.972 million MT, with a mean fuel consumption on a per voyage basis of 129.56 MT. In percentage terms, calculations in this study show potential fuel consumption savings across the 339,390 voyages considered in all three scenarios (JIT PBP-PBP, JIT 24, and JIT 12).

Scenario JIT PBP-PBP offers the greatest opportunity for fuel consumption savings followed by JIT 24, and then JIT 12. This is expected as the optimisation from PBP-PBP would offer the maximum amount of time to optimise the voyage. The greater the time a voyage can be optimised, the greater the fuel consumption savings potential. In other words, the earlier the ship can optimise its speed, the greater the savings can be achieved. However, the results also show that optimisation in the last 12 hours can already have a substantial saving potential, and hence be a good time horizon to start optimisation.

From an operational perspective, it is virtually impossible to optimise a voyage from PBP to PBP as delays at the destination port are not often known at the time the ship departs its origin port. Even in the JIT 24 and JIT 12 scenarios, the savings calculated are theoretical because not all delays are known 24 or 12 hours before arrival, for the simple fact that these delays are experienced after this point and are not planned or expected by anyone until that moment. Whilst this study has only considered three scenarios from this theoretical perspective, and the fuel consumption data utilised may not be representative of the global container fleet, the trend is clear that the earlier the ship can take action to optimise speed, the greater the fuel consumption savings potential.

As the TEU class size increases, so does the observed speed, as to be expected with larger ships generally sailing at higher speeds than smaller ships. The adjusted JIT speed does not change dramatically (ranging from approximately 10 to 14 knots) across the scenarios which suggests that irrespective of the scenario, the calculated speed across the three scenarios is 3-4 knots lower than the observed speed. This means speed of vessels could be reduced and still arrive in time (Figure 6).

From the baseline dataset, the number of voyages per class size in general decreases the larger the class size. This is expected as the largest vessels usually undertake the longest voyages (of which there are fewer). However, there are a substantially high number of voyages for class size 1000-1999 TEU ships, and this is likely due to the high number of shortsea voyages, and voyages of feederships which operate shorter but more frequent voyages (Table 7).

When considering the three scenarios per class size, the voyages of the smaller class vessels (below 3,000 TEU) have greater fuel consumption reduction potential in all three scenarios in % terms of fuel consumed over the whole voyage (Table 7).

When considering absolute fuel consumption reduction potential in MT, the general trend indicates that on a per voyage basis, the larger the vessel, the greater the fuel consumption saving (Figure 7).

When considering total fuel consumption savings in absolute terms, the analysis shows that vessels of sizes 1,000-1,999 TEU, and 3,000-11,999 TEU have the greatest total fuel consumption saving potential (Figure 8).

The analysis further shows that 50% of potential savings could be achieved through focusing on a comparatively small subset of voyages (8.51% of voyages in JIT PBP-PBP, 6.55% in JIT 24, and 3.18% in JIT 12). Further work could study these voyages in greater detail in order to target this small percentage of voyages with potentially big returns (Figure 9).

Further studies could be undertaken on a regional or on a per fleet characteristics basis (class, ownership, chartered/non-chartered vessels, among others), to provide further insight into where implementation of JIT could yield the most significant savings. Given that dry and wet bulk make up a significant proportion of the maritime shipping fleet, it is recommended that further studies be undertaken to explore the potential of JIT in those segments.

Whilst the results in this study demonstrate significant savings through the implementation of JIT in the container sector, much needs to be done in order to realize such potential. This includes, and most importantly, the collaboration between shipping lines, ports and terminals, to enhance the exchange of data and information required for the ship to optimise its voyage.

Annex I – Uncertainties

AIS data

AIS was originally conceived as a navigational aid for ship monitoring and collision avoidance at sea. According to regulation 19.2 of the International Convention for the Safety of Life at Sea (SOLAS), an AIS transceiver shall be equipped in every sea-going ship larger than 300 gross tonnes and every passenger vessel irrespective of size. AIS infrastructure enables the transmission and collection of static and voyage-related information in addition to dynamic information transmitted at higher rates depending on navigational status (3 min when anchored) and vessel speed (~2-10 seconds depending on speed). This allows the view of detailed insights on the past and present state of maritime traffic together with predicting future behaviour. Also, a substantial reduction in uncertainties when analysing the operational states of ships, engines and many other operational aspects such as efficiencies and inefficiencies based on times spent at sea, at the port and at berth through relevant analytics.

Limitations of the AIS as a system exist, including the following:

- **Temporal gaps** particularly in the open seas and away from coastal areas covered by terrestrial infrastructure, as well as in high-traffic areas where information transmitted by VHF can lead to message collisions and jamming in terms of satellite reception (due to wider footprint and AIS protocol specifics). The impact of temporal gaps can be major or minor depending on coverage. In this study, where minor gaps have been identified in the data, interpolation has been done to address them.
- **Erroneous information** (poor data quality or incomplete information) as a result of human error where data fields are required to be completed by the vessel's crew (e.g. draught, reported ETA, destination). Since draught is used to determine fuel consumption, inaccuracies in draught information could lead to greater uncertainty in the resulting calculations.

Fuel consumption data

Fuel consumption can be impacted by many factors including, but not limited to:

- time schedule and engine loads
- abatement technologies
- sea states (currents, waves, ice conditions, wind)
- freight load and displacement of a ship
- shallow waters and squat phenomena

The fuel consumption tables used in this study are representative of the total fuel consumption (ME + AEB) of the 590 vessels in the fleets of two large shipping companies provided for this project. Uncertainty may arise where the fuel systems and physical characteristics of the vessels in the fleets provided do not align with the fleet at large. The data provided for this project are for a range of vessels, with varying propulsion and efficiency systems, ages, sizes, and hull configurations, and so represent the range of vessel configurations observed in the fleet. Figure 11 below provides the aggregated fuel consumption data, and Figure 12 shows the distribution of vessel counts, by IMO bin, used to generate the fuel consumption curves.

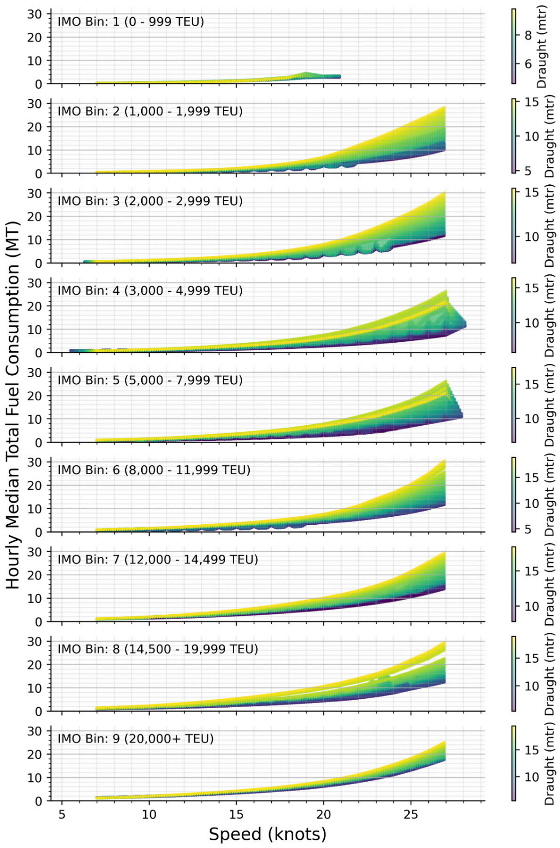


Figure 11: Fuel consumption per speed, draught and TEU size class from the fuel consumption tables

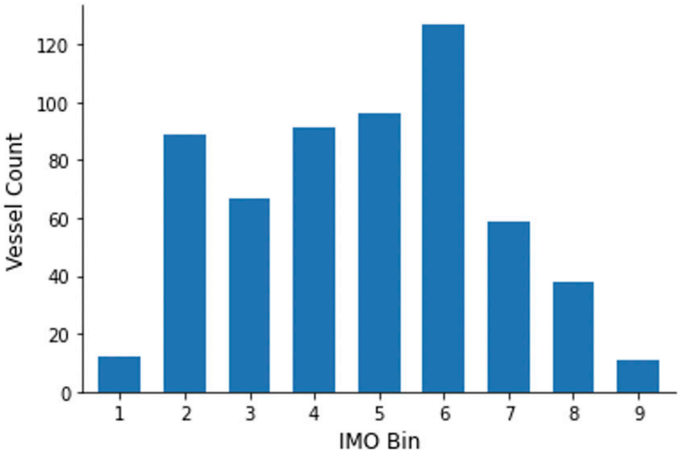


Figure 12: Number of vessels, by IMO bin, used to calculate the fuel consumption curves