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## Discussion paper

# Can an Emission Trading Scheme really reduce CO<sub>2</sub> emissions in the short term? Evidence from a maritime fleet composition and deployment model

BY

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# Can an Emission Trading Scheme really reduce CO<sub>2</sub> emissions in the short term? Evidence from a maritime fleet composition and deployment model

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## **Abstract**

Global warming has become one of the most popular topics on this planet in the past decades, since it is the challenge that needs the efforts from the whole mankind. Maritime transportation, which carries more than 90% of the global trade, plays a critical role in the contribution of green house gases (GHGs) emission. Unfortunately, the GHGs emitted by the global fleet still falls outside the emission reduction scheme established by the Kyoto Protocol. Alternative solutions are therefore strongly desired. Several market-based measures are proposed and submitted to IMO for discussion and evaluation. In this paper, we choose to focus on one of these measures, namely Maritime Emissions Trading Scheme (METS). An optimization model integrating the classical fleet composition and deployment problem with the application of ETS (global or regional) is proposed. This model is used as a tool to study the actual impact of METS on fleet operation and corresponding CO<sub>2</sub> emission. The results of the computational study suggest that in the short term the implementation of METS may not guarantee further emission reduction in certain scenarios. However, in other scenarios with low bunker price, high allowance cost or global METS coverage, a more significant CO<sub>2</sub> decrease in the short term can be expected.

## **1 Introduction**

Global warming has become a major issue in the past decades, particularly since it is a challenge needing global solutions. The emission of greenhouse gasses (GHGs) is the main reason for global warming, and one of the major sources of GHG emissions is transportation. Maritime transportation, which carries more than 90% of the global trade (ICS, 2017), plays a critical role. Although the CO<sub>2</sub> emission per tonne-km for shipping is only around 30% of that of road transport, maritime transport still accounts for 15% of the global transport CO<sub>2</sub> emissions (Goldsworthy, 2010) and 2.6% the global anthropogenic CO<sub>2</sub> emission (IMO, 2014). Furthermore, according to Buhaug (2009), the GHG emissions from ships are expected to increase by 150 - 250% in the next few decades if the world trade continuously increases without a proper measure for mitigation.

Recently, the voice for implementing a market-based measure (MBM) in the shipping sector has become strong. An MBM addresses the negative externalities of a market, such as pollution, through market mechanisms. Different from command-and-control measures (e.g., legislations), a MBM offers economic incentives rather than fixed rules to achieve a more cost-effective and sustainable pollution control (Miola et al., 2011). In terms of shipping, an MBM can help to internalise the external costs of the fleet emission by making the ship owner or operator pay for the CO<sub>2</sub> emitted from their ships, which finally creates an incentive for them to cut the emissions (Psaraftis, 2012).

Although seven MBM proposals have been submitted to the IMO for discussion and evaluation, it seems that only two of them, namely the Emissions Trading Scheme (ETS) and the GHG Fund, are favoured and widely studied in the literature (Shi, 2016). The ETS is a type of cap-and-trade system. In such a system, first a legally binding limit on total emissions (cap) during a certain period is set by the authority. Then the equivalent amount of emission allowances are issued by the administration and assigned to or purchased by different concerned parties. In the system, participants can choose to submit the allowance for their own emissions or trade with other players for cash based on the market price of the allowance. However, if all the issued allowances are consumed, no more emissions will be allowed due to the legal limit. Such a market-based cap-and-trade system will help achieve the emission reduction target with certainty as well as minimal costs. However, the uncertainty of the allowance price may cause problems, for example cost volatility and investment risks for the participants. The application of an ETS can be either global or regional. On the other hand, the GHG Fund proposal can be considered as a bunker levy scheme. In such a scheme, a fixed levy will be collected by the authority from the ship owners or operators based on their fuel consumption and the money raised will eventually enter the GHG Fund and finance future CO<sub>2</sub> emission reduction projects. Compared to the ETS approach, the bunker levy scheme guarantees the CO<sub>2</sub> price and therefore brings less volatility and risk to the shipping industry. However, the reduction of CO<sub>2</sub> emissions remains uncertain under such a scheme. In this paper, we choose to focus on the Maritime Emission Trading Scheme (METS) option (Kågeson, 2008) as the potential MBM for emission reduction in maritime transportation.

In general, the expected emission reduction brought by the MBM (METS in this paper) can be divided into long term and short term effects. In the long term, the market-based scheme offers strong incentives for the shipping companies to invest more in technological change and innovation, which can help them significantly reduce their vessel's CO<sub>2</sub> emissions and save money (IMO, 2011). Normally, such emission reduction will not occur immediately due to the difficulties of technological breakthroughs. Hence, such reduction effects are expected in the long term. On the other hand, the amount of CO<sub>2</sub> emitted from a ship is proportional to its fuel consumption which is positively correlated to the ship's sailing speed. In the short term, therefore, the shipping companies may also slow down their ships in order to reduce the fuel consumption, and thus reduce the emissions and the corresponding METS allowance costs.

However, the fuel consumption and corresponding CO<sub>2</sub> emissions of a ship depend not only on its sailing speed but also on its sailing route. Moreover, the price of CO<sub>2</sub> allowance is just one of many factors that will affect a ship's sailing speed and route. Other factors, such as fuel price and charter rate, can impact these operational decisions as well. Therefore, whether or to what extent a METS can cut the CO<sub>2</sub> emissions of a ship, based on its daily operations in the short term, remains unclear and should be examined. Therefore, in this paper we propose an optimization model integrating the fleet composition and deployment problem with the application of METS (global or regional). Note that the main purpose of this study is not to develop a practical model for direct application. In the computational study, however, we use this model as a tool to test and observe the actual impacts of METS on short term emission reduction in different scenarios. Other variables, including fuel price and charter rate, are also

investigated. We believe that through this study, a better understanding of METS (especially its ability to decrease CO<sub>2</sub> emissions in the short term) can be reached, which may help policy makers to make a more informed decisions in the future.

The rest of the paper is organized as follows. A comprehensive literature review is made in Section 2. The description of the problem and research assumptions are given in Section 3, while in Section 4, the mathematical formulation of the optimization model is presented. Section 5 introduces the test case and the relevant settings. In Section 6, the results of the computational study and the corresponding insights are shown and explained. Finally, we conclude this paper in Section 7.

## 2 Literature review

The maritime fleet composition and deployment are two classical problems which have been intensively studied in the literature of operations research in maritime transportation. The maritime fleet composition decisions affects the size and mix of the fleet in a shipping company, while the fleet deployment aims to find the optimal match between available transport capacity and freight demand. The readers can find more comprehensive information about these two types of problem in the surveys conducted by Wang and Meng (2017) and Pantuso et al. (2014). Wang et al. (2017) develop a stochastic programming model that integrates the fleet composition and deployment problem. Wang et al. (2017) develop a stochastic programming model that integrates the fleet composition and deployment problem. In this paper, we further extend the model by involving the environmental policy into consideration.

Regarding CO<sub>2</sub> emission in shipping, unfortunately, the industry still falls outside the scheme of GHG emissions reduction established by the Kyoto Protocol. Alternative solutions are therefore strongly desired. The Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) has made its efforts. Two new measures, namely Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP), were adopted in the MARPOL Annex VI and came in to force in 2013 (IMO, 2013). The former (EEDI) is a non-prescriptive but performance-based mechanism which puts mandatory technical requirement on the ship design so that the required energy efficiency level can be attained. Meanwhile, the latter (SEEMP) builds a scheme to improve the energy efficiency of shipping from an operational perspective. Nevertheless, Shi (2016) argues that the technical approach may have difficulty to achieve breakthroughs in a short time while the operational measure can bring negative impacts (e.g. longer supply chain lead time) on international seaborne trade. Hence, by using EEDI and SEEMP alone may not achieve absolute emission reduction from shipping and a market-based measure (MBM) should be adopted to complete the whole mechanism.

Lately, the discussion of the METS starts to earn more and more attention. Nevertheless, the studies dealing with this issue are limited in the literature. Psaraftis (2012) and Psaraftis (2016) comprehensively review all the potential MBMs (including the METS) proposed to the IMO and analyse their pros and cons. Meanwhile, Kågeson (2007) and Kågeson (2008) discuss the most basic details of the METS proposal, such as cap setting, allowance allocation and use of revenues. Luo (2013) evaluates the impact of adopting an open METS on various perspectives, for instance world trade pattern, net exporting countries and market concentration in the shipping industry. Miola et al. (2011) discuss the possibility of including the shipping sector in the existing EU ETS and compare this proposal with other alternatives, such as bunker levy scheme and Maritime Sector Crediting Mechanism (MSCM). Shi (2016) examines whether it is the right timing to adopt ETS in shipping now and suggests his own revised MBM proposal based on the existing solutions. Koesler et al. (2015) conduct a case study involving ship operators to assess the organizational and operational implications of the METS on shipping

companies. The results of this study show that shipping companies are optimistic about the potential performance of METS. [Franc and Sutto \(2014\)](#) explore the impacts of a cap-and-trade system on liner companies and European ports. Substantial and differentiated effects in different scenarios are found in this study. [Wang et al. \(2015\)](#) compare the applications of METS in an open and in a maritime only environment. The paper shows that the sailing speed of vessels will decrease in both cases, while challenges for specific shipping sectors vary from scenario to scenario. [Gritsenko \(2017\)](#) carries out a qualitative research discussing the suitable geographical scope of METS. [Hermeling et al. \(2015\)](#) conduct an analysis of including shipping in the current EU ETS from both economic and legal considerations. They argue that such an attempt may run into a dilemma where it is difficult to achieve a cost efficient emission reduction and comply with the existing international law simultaneously.

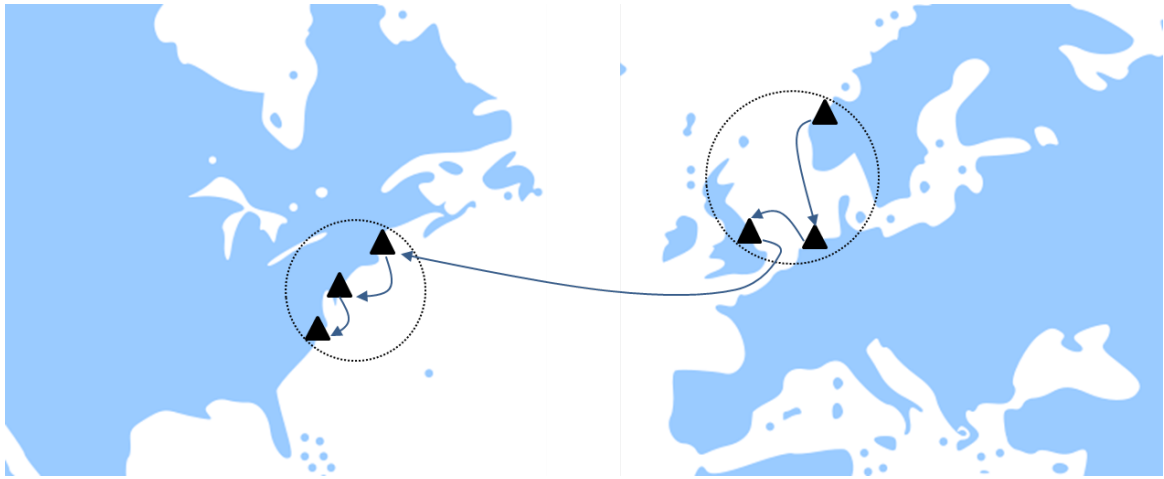
Obviously, the advantage and disadvantage of applying METS are properly discussed according to the literature review. To the best of our knowledge, however, no previous paper has quantitatively examined the emission reduction performance of a global or regional METS together with the consideration of other determining factors, for instance fuel price and charter rate. As mentioned in the previous section that these determining factors also affects a fleet's operation and hence its CO<sub>2</sub> emission in the short term. Any analysis without seeing the whole picture and ignoring these determining factors can lead to a wrong estimation of METS on its capability of emission reduction in the short term.

### 3 Problem description and assumptions

In the traditional maritime fleet composition and deployment problem, a shipping company needs to make a plan so that its fleet is optimally utilized to fulfil the shippers' demands in the next planning horizon. The demands from the customers normally consist of two parts, the fixed contracts which are mandatory and the spot cargoes which are optional. In order to meet the specific volume and frequency requirements or these demands, the shipping company has to first ensure enough ships and cargo capacity available. Hence they need to decide the number and type of ships to time-charter in from the spot market. In the mean time the company also has to think about how to deploy and operate these ships on hand so that the demands of the consignors are fulfilled in a timely and cost efficient manner.

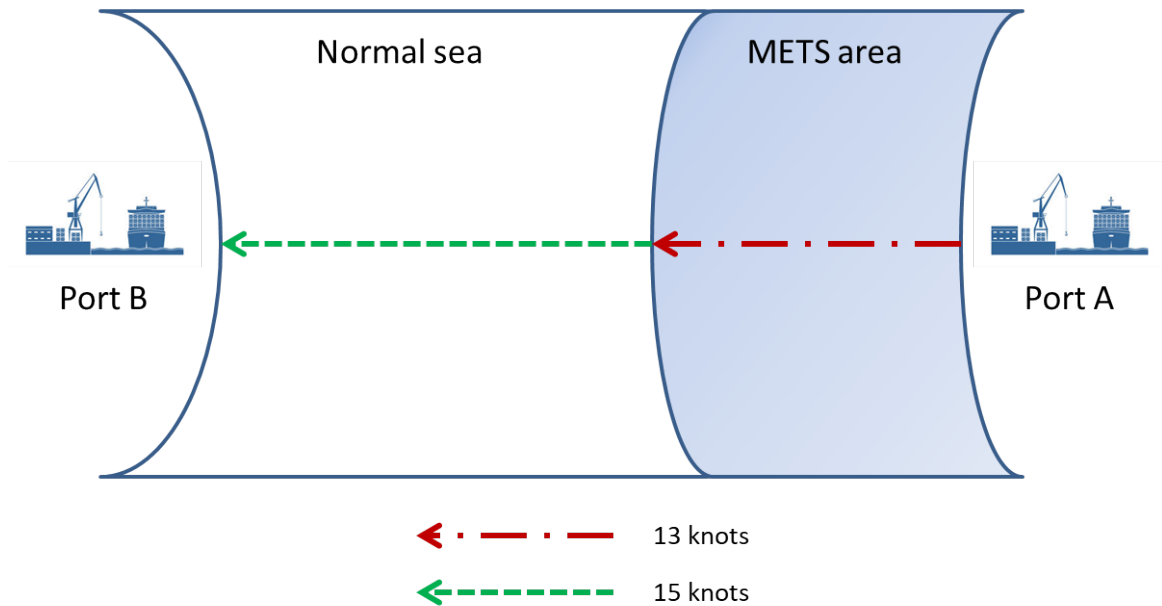
In this paper, the concept of *trade lanes* between geographical areas is introduced. The trade lanes are considered as the carrier of a highly abstracted demand of freight transportation. Such high level abstraction can also be found in the literature, e.g., [Pantuso et al. \(2016\)](#) and [Wang et al. \(2017\)](#). In a trade lane, ships pick up different cargoes from a number of adjacent loading ports located in the same geographical area, then transport these cargoes to another geographical area and finally unload the cargoes at the corresponding destination ports. An example trade lane from Western Europe to the East Coast of US can be found in [Figure 1](#). In this example, cargoes from three loading ports in Western Europe are collected first, then transported cross the Atlantic Ocean and finally delivered at the unloading points in America. If the demands served by the trade lane are contractual, specific frequency requirement (e.g., once every month) may need to be fulfilled. Furthermore, the type of ship that can serve the trade lane may also be restricted if there is a cargo compatibility issue, typically in bulk or tanker sector.

Besides these classical settings in the maritime fleet composition and deployment problem, some additional new decisions need to be made by the shipping company due to the implementation of METS. First, the company has to decide the amount of emission allowance they want to buy so that the CO<sub>2</sub> emission of its fleet can be covered. Moreover, if the METS is regional, the operation cost inside the regulated areas will be higher than the cost outside due to the extra allowance cost for the METS regions. Such cost difference offers the shipping company



**Figure 1:** An example of trade lane from Western Europe to the East Coast of US

an incentive to differentiate its vessel's speed in- and outside the METS regions. For instance, in Figure 2 the ship can choose to slow down inside METS areas so as to emit less CO<sub>2</sub> and consume less allowances, which helps to save money. However, the sailing speed outside METS areas may increase so that the total travelling time or transport capacity can still be guaranteed. In general, the total cost can be minimized through such speed differentiation strategy. Hence, rather than one universal speed, the shipping company now needs to make two separate speed decisions for a single voyage which crosses the border of the METS areas. Similar applications of speed differentiation can also be found in the cases of the Emission Control Area in e.g., [Fagerholt et al. \(2015\)](#), [Gu and Wallace \(2017\)](#) and [Gu et al. \(2018b\)](#).



**Figure 2:** An example of speed differentiation

The shipping company's aim is to minimize its total cost from both tactical and operational levels. On the tactical level, owing to the consideration of the METS, the fixed cost in this new fleet composition and deployment problem consists of the chartering expenses and the allowance procurement fees. The chartering strategy offers adequate number of ship and cargo capacity, while the purchasing of allowance, on the other hand, ensures the emission of the fleet during operation complies with the regulation of METS. However, if there is an excess transport capacity in the existing fleet of the shipping company or a surplus of unused allowance,

the company can charter out the redundant vessel and sell the unneeded allowance on the spot market for profit. On the operational level, the variable cost (mainly fuel consumption) is affected by the decisions of routing, ship deployment and sailing speed. These decisions make sure that the fleet and its corresponding transport capacity are fully utilized to fulfil the frequency and volume requirement of the demand with CO<sub>2</sub> emission less than the amount of allowance bought. Different from the traditional fleet composition and deployment problem, this extended version of the problem captures the three dimensional trade-off among chartering cost, bunker cost and allowance cost.

Due to the consideration of METS in this study, the following assumptions about the details of this scheme need to be made first.

- We assume that the allowance for CO<sub>2</sub> emission needs to be bought through auctioning in the scheme. Other options, such as grandfathering based on historic data or grandfathering based on benchmark, are found impractical for the shipping industry due to its volatility and complexity (Kågeson, 2007, 2008; Miola et al., 2011). The market situation in the shipping industry is very volatile. Hence the historical data of fuel consumption or emission in a recession period is not reliable as the basis for the cap setting in the booming years. On the other hand, the enormous number of ship types and sizes also bring significant challenges in the design of a fair benchmark.
- According to the literature, a cap-and-trade scheme can be either an open or a close system (Kågeson, 2007, 2008; Koesler et al., 2015; Wang et al., 2015). The former allows the companies in the system to trade with other sectors, while the latter requires the trade of allowance to be restricted inside this cap-and-trade scheme. The disadvantage of a close system is that the cap of CO<sub>2</sub> emission for the whole sector needs to be set cautiously or even generously (Kågeson, 2008). According to Kågeson (2007), the shipping sector is expected to become a net-buyer of allowances due to the relatively high abatement cost in this industry. Hence, without an emergency exit available in the system, a too tight cap may lead to a skyrocketing allowance price when the availability of allowance is low on the market (Psaraftis, 2012). However, too much “mercy” in the cap setting process may also bring negative effects to the original intention, emission reduction, of the cap-and-trade scheme. Therefore, we assume the METS in this paper to be an open system in which the shipping companies can trade with other sectors, e.g., electricity generation, that have a lower marginal CO<sub>2</sub> abatement cost (Wang et al., 2015; Koesler et al., 2015). Furthermore, an open system with a larger volume of allowance in the pool can lead to a more transparent and stable system (Kågeson, 2008).
- In a global setting of METS, it is easy to understand that all emissions of a vessel need to be covered by the equivalent amount of allowances. In a regional METS, nevertheless, the scope of a vessel’s emission liability is controversial. Some studies suggest that the ship is responsible for the entire emission during the whole voyage between two ports as long as one of them is located inside the METS areas (Franc and Sutto, 2014; Kågeson, 2008). Such route-based approach used to be adopted by the aviation sector in the early stage when it was included in the EU ETS. However, this approach failed due to massive complaints and boycotts from the non-EU countries because these countries questioned the legitimacy of EU to charge the emissions outside its territorial airspace (Meleo et al., 2016; Li et al., 2016; Scheelhaase et al., 2018). Moreover, the route-based approach may be easily evaded in the shipping sector as long as a transshipment is arranged at a hub outside but near the METS area (Kågeson, 2007; Franc and Sutto, 2014). Therefore, we assume a geographical area-based approach proposed in Hermeling et al. (2015) and Miola et al. (2011) to calculate the liability of ship’s emission for the regional METS in

this study. In this approach, the shipping company only needs to submit the allowances for the CO<sub>2</sub> of its fleet emitted inside the territorial waters and the exclusive economic zone (EEZ) of the regulating authorities. Such approach seems to be more reasonable and feasible for a regional METS.

## 4 Mathematical model

In this section, we present the mathematical model for the fleet composition and deployment problem with METS. Section 4.1 introduces the modelling approaches and relevant assumptions. The mathematical formulation of the model is presented in Section 4.2

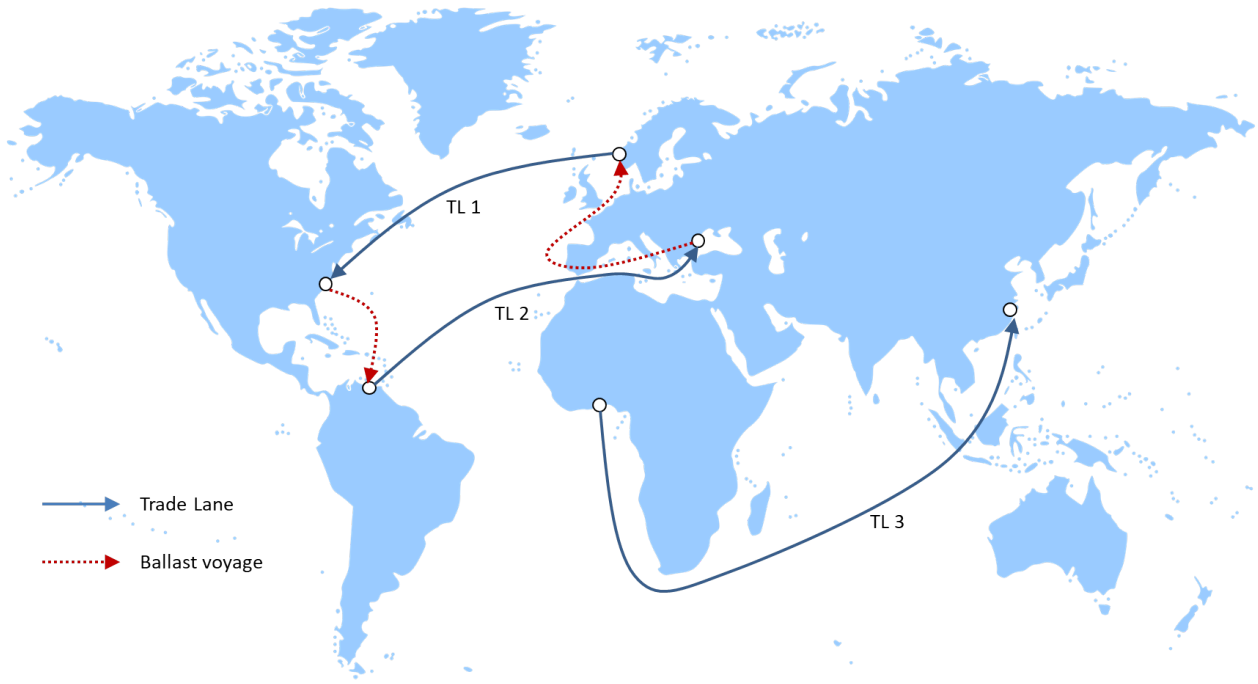
### 4.1 Model development

The optimization model proposed in this paper is a deterministic model. Therefore, the tactical decisions including chartering strategy and allowance procurement plan are made immediately in the beginning of the planning horizon. Simultaneously, the corresponding operational decisions during the planning horizon, such as route choice, vessel allocation and sailing speed, are also determined to support the tactical decision-making. In Section 3, we mentioned that highly a abstracted demand based on trade lane is used. Every freight contract is associated with one corresponding trade lane that covers the loading and unloading areas in this contract. One trade lane may have several associated freight contracts and each of these contracts represents the aggregated demand compatible with the same type of ship from the same origin area to the same destination area.

In order to serve all the demands, the shipping company needs to make the routing and fleet deployment decisions based on their own ships and the chartering plan. Due to the abstraction of the demand, the routing and fleet deployment decisions are also kept at an aggregated level. For the routing decisions, we use the concept of *loop* defined in Pantuso et al. (2016) and Wang et al. (2017). According to the definition, a loop means a round trip involving one or several trade lanes which begin and finish in the same geographical area. In the case of multiple trade lanes, ballast sailing may be performed so as to connect two consecutive trade lanes, if the destination port of one trade lane is different from the loading port of the subsequent trade lane. In Figure 3, a simple example of several trade lanes and the potential loops derived from these trade lanes are illustrated. The solid arrows in Figure 3a shows the trade lanes, TL 1, TL 2 and TL 3, while the dotted arrows represent the ballast sailings that connect two consecutive trade lanes. TL 1, TL 2 and the ballast voyage together constitute the example loop in the Figure 3a. Hence, if a ship is assigned to this example loop, it firstly sails TL 1 from Northern Europe to the East Coast of US. Then the ship takes the ballast voyage to the North Coast of South America and performs TL 2 which ends at Southern Europe. Finally, the ship returns the origin of TL 1 and finishes the loop. Figure 3b further illustrates this example loop with bold arrows as well as all other potential loops that can be generated in the three trade lanes case. Please note that a loop consists of a single trade lane needs to have a ballast sailing back to the origin area of this trade lane after unloading at the destination, which is represented by the dotted line pointing back to itself in Figure 3b. With all potential loops constructed based on the trade lanes, the fleet will then be deployed. The available vessels and their corresponding transport capacity will be assigned to different loops so that the demand of all trade lanes can be met.

Another important factor considered in the fleet deployment decisions is the sailing speed of the ships. Speed optimization is critical for the problem since it affects the travelling time and fuel consumption. The former impacts the number of ships needed to meet the demand

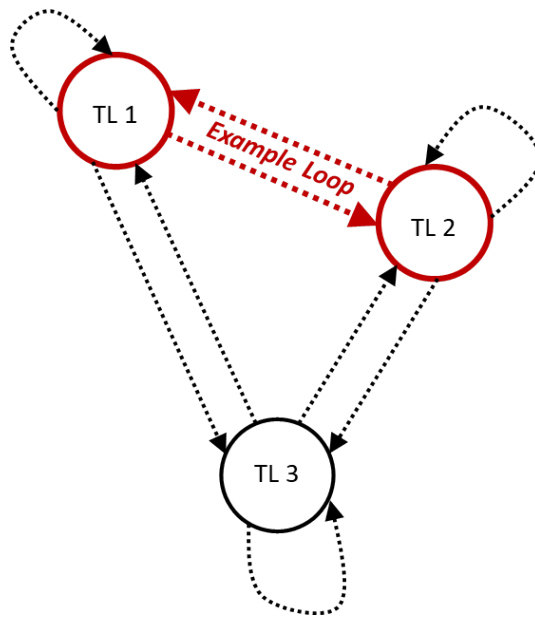




Trade Lanes: TL 1, TL 2, TL 3

Example Loop: TL 1 → TL 2

(a) Example loop



(b) Potential loops for three trade lanes

**Figure 3:** Example of three trade lanes and possible loops

and hence the chartering cost, while the latter decides the fuel cost. Moreover, another important outcome depending on sailing speed is the CO<sub>2</sub> emission of the ship which influences the allowance cost due to the existence of METS in this paper. It is widely recognized that the fuel consumption per time unit of a ship is approximately proportional to the third power of its sailing speed (Ronen, 1982; Psaraftis and Kontovas, 2013). Nevertheless, shipping companies usually only have the fuel consumption data of their ships for a few discrete speed points, which also applies for the case in this paper. Hence, an alternative approach, called piecewise linearisation, adopted from (Andersson et al., 2015) is used here to handle the non-linearity of the function of speed and fuel consumption. For example, if we want to estimate the fuel consump-

tion rate of a particular speed  $v^*$  which can be represented by a linear combination of speed  $v_1$  and  $v_2$  (see Figure 4), then the same linear combination can also be used in the estimation of the corresponding fuel consumption rate  $F_{est}^*$ . Please note that such approximation normally leads to an overestimation, but the gap is normally negligible as long as enough discrete speed points are adopted (see Andersson et al. (2015) for detailed explanations). Furthermore, this approach is also used in this study to properly estimate the relationship between (a) sailing time and speed as well as (b) CO<sub>2</sub> emission and speed.

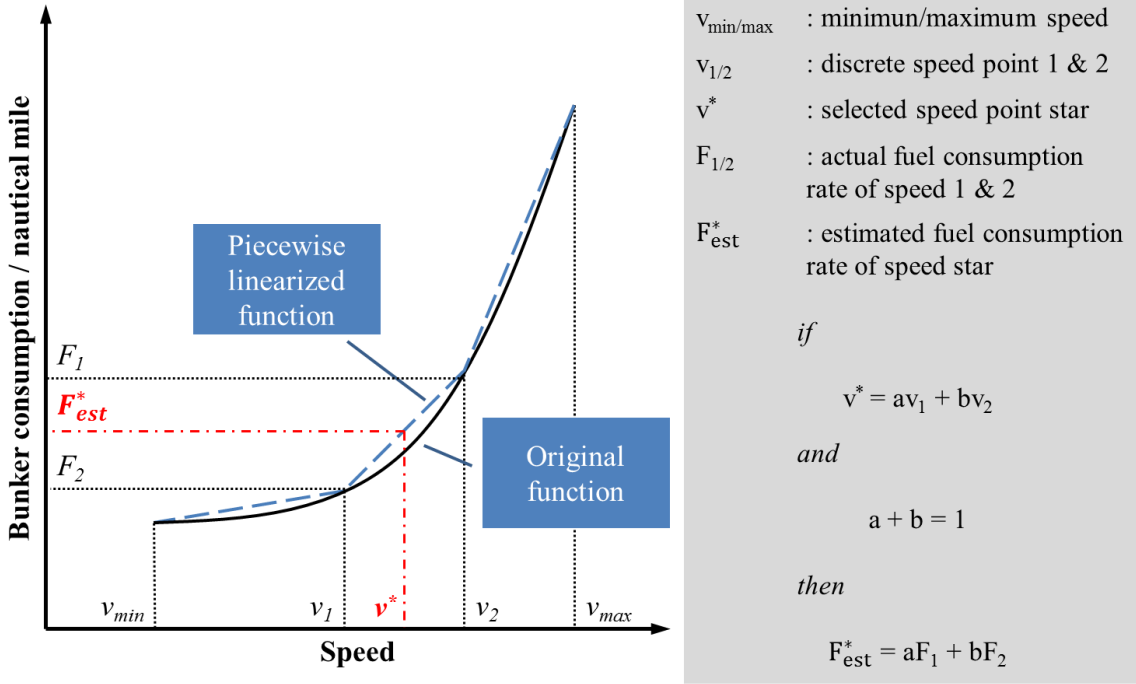
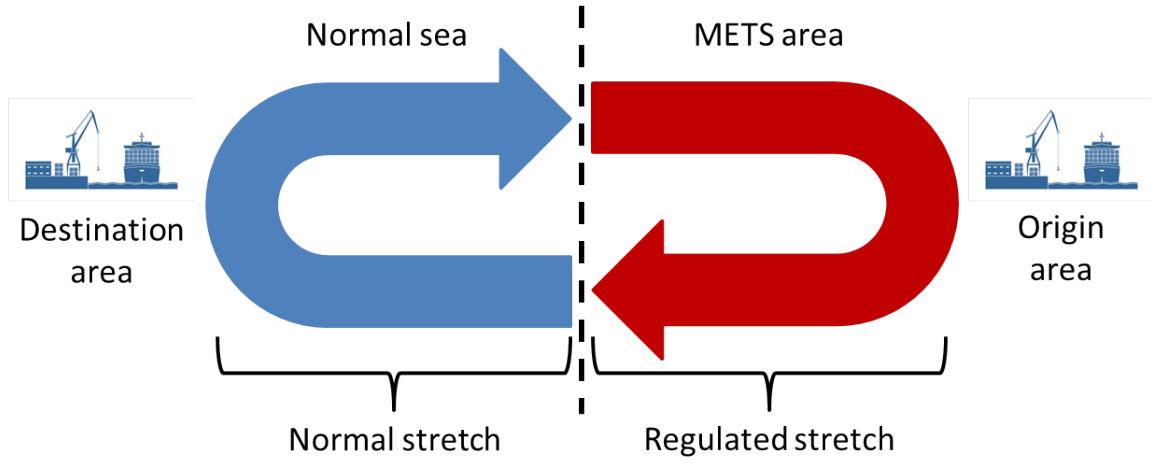


Figure 4: Piecewise linearisation of fuel consumption (Gu et al., 2018a)

Lastly, in the case of a regional METS, the sailing speed inside the METS area can be different from the speed outside. In order to achieve such speed differentiation in the decision-making process, we consider a loop crossing the regulated region as two separated stretches in the model, see Figure 5. Two groups of speed related decision variables are assigned to each stretch of the loop and different speed may be applied on different stretches. However, the interdependency between these two groups of variables, such as the consistency in the total number of round trips sailed on both stretches with different speed, need to be guaranteed with specific constraints which is further explained in the next section. In general, the model balances among the travelling time (chartering cost), fuel consumption (bunker cost) and emission (allowance cost) to decide the most economic speed on each stretch. Please note that in the case of a loop involving only METS area or normal sea, i.e., a global METS or a business as usual (no METS) scenario, only one stretch will be observed.

## 4.2 Mathematical formulation

The mathematical formulation of the fleet composition and deployment problem with METS and its notation are shown as follows.



**Figure 5:** Two stretches of a loop in the regional METS scenario

### Sets

$\mathcal{V}, \mathcal{C}$  Set of ship types and contracts

$\mathcal{N}, \mathcal{R}$  Set of of trade lanes and loops

$\mathcal{E}_v$  Set of speed alternatives for ship type  $v$

$\mathcal{R}_v \subseteq \mathcal{R}$  Set of loops that can be sailed by ship type  $v$

$\mathcal{R}_{iv} \subseteq \mathcal{R}$  Set of loops serving Trade Lane  $i$  and compatible with ship type  $v$

$\mathcal{C}_i^{TR} \subseteq \mathcal{C}$  set of contracts serviced by Trade Lane  $i$

$\mathcal{V}_i \subseteq \mathcal{V}$  Set of ship types that can sail Trade Lane  $i$

## Parameters

$N_v$	No. of ships of type $v$ owned by the shipping company
$M_v$	No. of available service days for a ship of type $v$ owned by the shipping company
$Q_v$	Volume of ship type $v$
$T_{vre}^{ETS}$	Time for ship type $v$ to complete the METS stretch of a round trip on Loop $r$ with speed $e$
$T_{vre}^N$	Time for ship type $v$ to complete the normal stretch of a round trip on Loop $r$ with speed $e$
$F_c$	Frequency requirement of contract $c$
$D_c$	Demand of contract $c$
$C_{vre}^{ETS}$	Cost for ship type $v$ to complete the METS stretch of a round trip on Loop $r$ with speed $e$
$C_{vre}^N$	Cost for ship type $v$ to complete the normal stretch of a round trip on Loop $r$ with speed $e$
$C_v^{In}$	Daily charter-in rate for a ship of type $v$
$R_v^{Out}$	Daily charter-out revenue for a ship of type $v$ (lower than $C_v^{In}$ )
$R_i^{SP}$	Freight rate for a unit of spot cargo on Trade Lane $i$
$D_i^{SP}$	Demand of spot cargo on Trade Lane $i$
$E_{vre}^{ETS}$	CO <sub>2</sub> emitted from ship type $v$ to complete the METS stretch of a round trip on Loop $r$ with speed $e$
$C^A$	Cost of the METS allowance for a ton of CO <sub>2</sub>

## Decision variables

$w_v$	No. of days that ship of type $v$ is chartered in
$z_v$	No. of days that ship of type $v$ is chartered out
$x_{vre}^{ETS}$	No. of times sailed by a ship of type $v$ on the METS stretch of Loop $r$ with speed alternative $e$
$x_{vre}^N$	No. of times sailed by a ship of type $v$ on the normal stretch of Loop $r$ with speed alternative $e$
$q_{ivc}$	Volume carried by ship type $v$ for contract $c$ on Trade Lane $i$
$q_{iv}^{SP}$	Volume of spot cargo carried by ship type $v$ on Trade Lane $i$
$y^{ETS}$	Amount of METS allowance bought in

## Objective function

$$\begin{aligned}
\min \quad & \sum_{v \in \mathcal{V}} C_v^{In} w_v - \sum_{v \in \mathcal{V}} R_v^{Out} z_v - \sum_{i \in \mathcal{N}} \sum_{v \in \mathcal{V}} R_i^{SP} q_{iv}^{SP} \\
& + \sum_{v \in \mathcal{V}} \sum_{r \in \mathcal{R}_v} \sum_{e \in \mathcal{E}_v} (C_{vre}^{ETS} x_{vre}^{ETS} + C_{vre}^N x_{vre}^N) + C^A y^{ETS}
\end{aligned} \tag{1}$$

Subject to

$$\sum_{r \in \mathcal{R}_v} \sum_{e \in \mathcal{E}_v} (T_{vre}^{ETS} x_{vre}^{ETS} + T_{vre}^N x_{vre}^N) + z_v = M_v N_v + w_v \quad v \in \mathcal{V} \quad (2)$$

$$\sum_{e \in \mathcal{E}_v} x_{vre}^{ETS} = \sum_{e \in \mathcal{E}_v} x_{vre}^N \quad v \in \mathcal{V}, r \in \mathcal{R}_v \quad (3)$$

$$\sum_{v \in \mathcal{V}_i} \sum_{r \in \mathcal{R}_{iv}} \sum_{e \in \mathcal{E}_v} x_{vre}^{ETS} \geq F_c \quad i \in \mathcal{N}, c \in \mathcal{C}_i^{\mathcal{TR}} \quad (4)$$

$$\sum_{v \in \mathcal{V}_i} q_{ivc} = D_c \quad i \in \mathcal{N}, c \in \mathcal{C}_i^{\mathcal{TR}} \quad (5)$$

$$\sum_{r \in \mathcal{R}_{iv}} \sum_{e \in \mathcal{E}_v} Q_v x_{vre}^{ETS} \geq \sum_{c \in \mathcal{C}_i^{\mathcal{TR}}} q_{ivc} + q_{iv}^{SP} \quad i \in \mathcal{N}, v \in \mathcal{V}_i \quad (6)$$

$$\sum_{v \in \mathcal{V}_i} q_{iv}^{SP} \leq D_i^{SP} \quad i \in \mathcal{N} \quad (7)$$

$$\sum_{v \in \mathcal{V}} \sum_{r \in \mathcal{R}_v} \sum_{e \in \mathcal{E}_v} E_{vre}^{ETS} x_{vre}^{ETS} = y^{ETS} \quad (8)$$

$$w_v, z_v \geq 0 \quad v \in \mathcal{V} \quad (9)$$

$$x_{vre}^{ETS}, x_{vre}^N \geq 0 \quad v \in \mathcal{V}, r \in \mathcal{R}_v, e \in \mathcal{E}_v \quad (10)$$

$$q_{ivc} \geq 0 \quad i \in \mathcal{N}, v \in \mathcal{V}_i, c \in \mathcal{C}_i^{\mathcal{TR}} \quad (11)$$

$$q_{iv}^{SP} \geq 0 \quad i \in \mathcal{N}, v \in \mathcal{V}_i \quad (12)$$

$$y^{ETS} \geq 0 \quad (13)$$

The objective function (1) minimizes the total cost including the ship chartering cost, fleet operation cost and the emission allowance cost. Furthermore, the revenue of chartering out surplus ships and carrying spot cargo are also considered as negative costs in the objective function. Constraints (2) keep the balance between the transport capacity available and the capacity needed for each type of vessel. The available capacity consists of the self-owned fleet and the ships chartered in, while the needed capacity covers the demand for freight transport and the possible chartering out. Constraints (3) make sure that for a each ship type  $v$  and Loop  $r$ , the corresponding number of times sailed on the METS stretch and the normal stretch must be the same. Constraints (4) - (5) guarantee that the contractual demands, including both frequency and volume requirements, are fulfilled with enough transport capacity. Constraints (6) state that the total cargo volume offered by ship type  $v$  on Trade Lane  $i$  should be sufficiently large to carry the contractual and spot demands on Trade Lane  $i$  assigned to ship type  $v$ . Constraints (7) restrict the total amount of spot cargo can be picked up. Constraint (8) enforces METS requirement that the emission generated during the fleet operation in side METS areas must be covered by the allowance bought. Constraints (9) - (13) define the domains of the decision variables. Please note that the fleet deployment variables ( $x_{vre}^{ETS}$  and  $x_{vre}^N$ ) are allowed to be continuous in this paper. The fractional part of the solution means a round trip to be finished in the future planning period.

## 5 Test case

In this study we consider a shipping company which offers transportation service of chemical liquid bulk among different geographical areas. We assume that there are two types of chemical tanker owned by this shipping company while these two types of ship are also available on the spot market for chartering. The basic information of these two types of tanker are collected through the statistics of a peer group analysis made by Clarkson (2018b). The detailed data are listed in Table 1. Moreover, we assume that the shipping company in the case owns four type 1 tankers and one type 2 tanker. All owned vessels in the fleet have 250 days available per year for freight transportation.

**Table 1:** Basic information of two types of chemical tanker

	Type 1	Type 2
<b>Deadweight tonnage</b>	49503	10239
<b>Cargo Capacity (cu.m.)</b>	45127	10921
<b>Draft</b>	12.96	8.05
<b>Speed - Low/Medium/High (Knots)</b>	12.5/14.4/15.5	12.5/14.4/15.5
<b>Fuel Consumption - Low/Medium/High (Tonne/Nautical mile)</b>	0.084/0.091/0.101	0.042/0.054/0.058
<b>No. of vessel owned</b>	4	1

For the demand perspective, we assume the shipping company needs to serve three trade lanes with corresponding long term contracts, see Figure 6. In Trade Lane 1, the vessel travels from Northern Europe to East Coast of North America. The contract served by Trade Lane 2 requires the cargo to be picked up at the South-east Coast of U.S. and delivered at West Coast of Africa. The last trade lane in the case starts at the Persian Gulf and finishes at Southern Europe. Other detailed contractual terms for each trade lane, such as frequency and freight volume, can be found in Table 2. In a real world case, there might be several loading or unloading ports in a specific trade lane. However, we use one origin and destination port representing all demands and deliveries in the same geographical area for simplicity purpose. Moreover, we exclude the consideration of spot cargo in this test case because spot freight market in the chemical shipping industry is quite limited due to the restriction from both demand and supply side. Different from other shipping sectors, the specialized tankers compatible for the cargo on the spot market are not always available with short notice. More importantly, the main goal of this study is to examine the impact of METS on fleet’s CO<sub>2</sub> emission during operation rather than direct application. Therefore, we believe such simplification will not affect the original purpose of the test.

**Table 2:** Trade Lanes and Contracts

	<i>Trade Lane 1</i>	<i>Trade Lane 2</i>	<i>Trade Lane 3</i>
<b>Origin port</b>	Mongstad	Houston	Ras Tanura
<b>Destination port</b>	Saint John	Luanda	Rijeka
<b>Frequency</b>	12 visits per year	12 visits per year	10 visits per year
<b>Total freight demand (1000 cu.m.)</b>	490	450	95

Different loop options are then formed as input for the computational study. As mentioned in Section 4.1, each potential loop covers one or several trade lanes. Figure 7 shows an example



**Figure 6:** Three trade lanes in the case

of the loop serving both Trade Lane 2 and Trade Lane 3. The ballast sailing connecting these two trade lanes are marked as dotted arrows in the figure. The detailed data of travelling distance for each loop is measured through Google Map. The amount of CO<sub>2</sub> emitted from the ship on a loop with certain speed equals the product of sailing distance (nautical mile), fuel consumption rate (tonne/nautical mile) and CO<sub>2</sub> emission factor (tonne/tonne fuel). The emission factor applied in this case is  $3.021$  (Psaraftis and Kontovas, 2009).

## 6 Computational Study

In this section, different settings of the tests and the corresponding results of the computational study are given. Section 6.1 introduces different scenarios applied in the tests. Then the observations of the tests and the insights gained through comparison among different scenarios are presented in Section 6.2.

### 6.1 Tested Scenarios

As mentioned in Section 1, the main purpose of this study is to examine the actual impact of METS on short term emission reduction when other relevant factors, such as charter rate, are considered. Therefore, different scenarios for these determinants are assumed in the computational study and the corresponding results of these tests are compared to identify the real impact of different determinants on CO<sub>2</sub> emission. The considered determinants include the charter rates of the vessels, the price of emission allowance, bunker price and the geographical scope of METS.

First, for charter rate, we introduce three scenarios for tests. When the freight market is booming, the charter rate of the vessel is usually high due to the high demand for transportation. But when the economy is in recession, the total supply of ships may exceed the demand on the market. Therefore, if the shipping company has surplus capacity, it normally has to (a) accept



**Figure 7:** Loop for Trade Lane 2 & 3

the minimum charter rate which equals the mandatory cost for running the ship, (b) lay up the vessel or (c) send the vessel for demolition. In the latter two case, the value of a surplus vessel is almost 0. Therefore, the expected earning for charter-out in the bad market can be very low. The charter rates under different scenarios applied in the tests are assumed based on the historical data observed in [Clarkson \(2018a\)](#). Note that, the actual value of a surplus vessel during the recession should be much lower than the recorded charter rate in the historical data due to the unrecorded lay-up or demolition cases. With that thought in mind, we further adjusted the average charter-out rate in the low scenario, which should better represent the situation in the real world.

Second, we also assume two different situations, namely high and low, for the price of emission allowance issued by the METS. Since there is no real world data for the allowance price of METS, we have to make reasonable assumption based on the price of allowance traded in EU ETS. Similarly, a high and low bunker price are also adopted in the tests. Since we have assumed an open system for the METS in Section 3, we consider no correlations between the allowance price and the other two factors. Furthermore, the type of chartering applied in this paper is time charter. Hence, the charter rate is also independent from the bunker price. The detailed information for the tested scenarios of charter rate, allowance price and fuel price are listed in Table 3.

Last, for the geographical scope of METS, three possible scenarios are assumed, namely global METS, regional METS and business-as-usual. In a global METS, the entire voyage of the vessel are regulated and emission allowance needs to be submitted for the total CO<sub>2</sub> emission. For the regional METS in this study, we assume the regulation is only implemented in EU and U.S. As already assumed in Section 3, the EEZ of the regulating country or authority



**Table 3:** Scenarios for charter rate, allowance price and bunker price (USD)

Scenario	<i>High</i>	<i>Normal</i>	<i>Low</i>
<b>Charter-in rate per day (type 1/2)</b>	22000/15000	11000/8000	5000/4000
<b>Charter-out rate per day (type 1/2)</b>	22000/15000	11000/8000	2000/1500
<b>Allowance price per tonne CO<sub>2</sub></b>	65	<i>n/a</i>	10
<b>Bunker price per tonne</b>	600	<i>n/a</i>	200

is accepted as the territory of the regional METS, see Figure 8. Hence, the shipping company is only liable for the emissions of its fleet inside the regulated areas in the regional METS scenario. In the business-as-usual scenario, no METS is introduced and therefore no allowance is required for any emission of the ship.

**Figure 8:** The geographical scope of the regional METS

## 6.2 Main Results

In this section, we present the main results of the computational study in all scenario combinations. In the following analysis, we compare the results obtained under different METS settings (e.g. geographical scope and allowance cost) with the benchmark case (business-as-usual), while other two factors, namely bunker price and charter rate, remain fixed during the comparison. The purpose of such tests is to clearly observe the real emission reduction impact of METS under the optimal plan for fleet composition and deployment when other determinants are also considered. We also compare the results with same METS settings but different bunker price or charter rate, so as to find out how these two factors influence the CO<sub>2</sub> reduction performance of METS. A brief summary of the findings will be offered in the end of this section.

We first consider a low bunker price scenario in the test and run the model with different combinations of all other parameters. The results are shown in Table 4. The numbers in the table represents the total amount of CO<sub>2</sub> emitted by the ships in the optimal fleet composition and deployment solution of a specific scenario. Meanwhile, the percentages listed in the parentheses show the volume change of emission comparing to the benchmark scenario. A negative percentage refers to a emission reduction in that scenario, while a positive ratio means an increase.

**Table 4:** Result summary in the low bunker price scenario

CO <sub>2</sub> Tonne (% of change)	Business-as-usual (Benchmark)	Regional METS		Global METS	
		<i>Low allowance cost</i>	<i>High allowance cost</i>	<i>Low allowance cost</i>	<i>High allowance cost</i>
<i>Low charter rate</i>	66288.2 (n/a)	66291.5 (0.0%)	73195.4 (10.4%)	66288.2 (0.0%)	66288.2 (0.0%)
<i>Normal charter rate</i>	79043.6 (n/a)	77076.8 (-2.5%)	77076.8 (-2.5%)	72693 (-8.0%)	72693 (-8.0%)
<i>High charter rate</i>	79043.6 (n/a)	79040.1 (0.0%)	79040.1 (0.0%)	79043.6 (0.0%)	79043.6 (0.0%)

**Scenario: low bunker price, normal charter rate**

In this subsection, a low bunker price and normal charter rate is assumed in the tested scenarios. Based on the results in Table 4, we can find that when the freight market is in a normal situation, the application of METS will lead to a decrease of CO<sub>2</sub> emission. Moreover, such reduction effect in the global METS case is much stronger than the regional setting. The underlying reasons for these observations can be found in the following paragraphs.

In the business-as-usual case, Loop 1, 2, 3 and 6 are adopted in the solutions. The former three loops cover Trade Lane 1, 2 and 3 correspondingly while the latter serves both Trade Lane 1 and 2. According to the optimal solutions listed in Table 5, ships of type 1 sails Loop 1 and Loop 6 for 0.31 and 11.69 times respectively, while ships of type 2 completes 0.31 and 10 round trips on Loop 2 and Loop 3. A high speed is adopted during the voyages on all loops and the surplus capacity (447 days) are chartered out for profit.

**Table 5:** Solutions summary in the business-as-usual case with normal charter rate and low bunker price

	No. of round trips Vessel Type 1	Speed - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed - knots Vessel Type 2
Loop 1 (TL1)	0.31	15.5	0	0
Loop 2 (TL2)	0	0	0.31	15.5
Loop 3 (TL3)	0	0	10	15.5
Loop 6 (TL1 & TL2)	11.69	15.5	0	0
	Vessel Type 1		Vessel Type 2	
Chartered days in/out (+/-)	-447		0	

But if a regional METS is included in the consideration, the emission from the fleet start to decrease. In the solution summary of this scenario offered in Table 6, we can find that the loop decisions are almost the same comparing to the decisions in the business-as-usual case. But a lower speed is adopted on the METS stretches of Loop 1 and 6 by the ships of type 1. Such operational change is triggered by the additional allowance cost due to the implementation of the regional METS. In order to adapt to the new regulation and simultaneously minimize the total cost, the ship choose to decrease its sailing speed inside the METS areas so that less emission is generated and thus less allowances need to be purchased. In return, nevertheless, more transport capacity is occupied since the total sailing time to finish the same loop becomes longer. Therefore, the chartered out days of the surplus ships decline.

In the case of a global METS, the emission of CO<sub>2</sub> is further reduced. The shipping company decides to utilize more of its surplus transport capacity, rather than charter them out for profit, and slow down its operation on the Loop 1 and 6 during the entire voyage, so as to minimize its consumption of emission allowances, see Table 7. Note that the composition and deployment

**Table 6:** Solutions summary in the regional METS case with normal charter rate and low bunker price

	No. of round trips Vessel Type 1	Speed (normal stretch) - knots Vessel Type 1	Speed (METS stretch) - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed (normal stretch) - knots Vessel Type 2	Speed (METS stretch) - knots Vessel Type 2
Loop 1 (TL1)	0.32	15.5	14.4	0	0	0
Loop 2 (TL2)	0	0	0	0.32	15.5	15.5
Loop 3 (TL3)	0	0	0	10	15.5	15.5
Loop 6 (TL1 & TL2)	11.68	15.5	14.4	0	0	0
	Vessel Type 1			Vessel Type 2		
Chartered days in/out (+/-)	-434			0		

decisions are indifferent in the scenarios with same METS scope but different allowance cost. The reason is that the difference between a high and low allowance cost here is not large enough to motivate the vessel to deviate from its current loop choices or further slow down its navigation for allowance saving purpose which needs more transport capacity and leads to a higher charter-in cost or lower charter-out revenue.

**Table 7:** Solutions summary in the global METS case with normal charter rate and low bunker price

	No. of round trips Vessel Type 1	Speed - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed - knots Vessel Type 2
Loop 1 (TL1)	0.31	14.4	0	0
Loop 2 (TL2)	0	0	0.31	15.5
Loop 3 (TL3)	0	0	10	15.5
Loop 6 (TL1 & TL2)	11.69	14.4	0	0
	Vessel Type 1		Vessel Type 2	
Chartered days in/out (+/-)	-405		0	

### Scenario: low bunker price, high charter rate

However, if we assume a booming freight market (high charter rate) with still a low bunker price, the effect of METS on emission reduction witnessed in the previous tests disappears, see Table 4. The high charter rate offers significant incentives for the fleet to speed up so that it can use as less transport capacity as possible to finish the job, which minimizes its demand for costly chartering in or maximizes its possibility of profitable chartering out. Therefore, in spite of the extra allowance cost, the introduction of the METS, both regional and global, is not sufficient to make the fleet composition and deployment decisions more environmental friendly. The optimal solutions show that a high speed is adopted in all scenarios in the high charter rate case. The composition and deployment decisions in the high charter rate scenarios are identical with the solutions listed in Table 5.

### Scenario: low bunker price, low charter rate

Similar results are also observed when the market is in a recession (low charter rate). The enforcement of the METS does not lead to any emission reduction in this case. But comparing

to the cause just discussed in the high charter rate scenario, the reason for the observation here is actually the opposite. In the business-as-usual case with market recession, the optimal solutions choose to fulfil all contractual demands with Loop 3 and 6 only and slow down its operation considerably while more transport capacity is involved, see Table 8. When the charter rate is low, the value of the surplus vessels or the cost of supplementing the insufficiency of transport capacity become low as well. This means it is more cost efficient for the shipping company to fully utilize its own idle ships or take advantage of the cheap resources on the chartering market so as to reduce the sailing speed during the operation for bunker saving purpose, although such slow steaming strategy requires more vessels which leads to a decrease/increase in the profit/cost of chartering out/in. Since a minimum speed has already been applied in the business-as-usual scenario, the additional cost of METS allowance can not push the speed to an even lower level, which therefore stops further emission reduction in other METS scenarios.

**Table 8:** Solutions summary in the business-as-usual case with low charter rate and bunker price

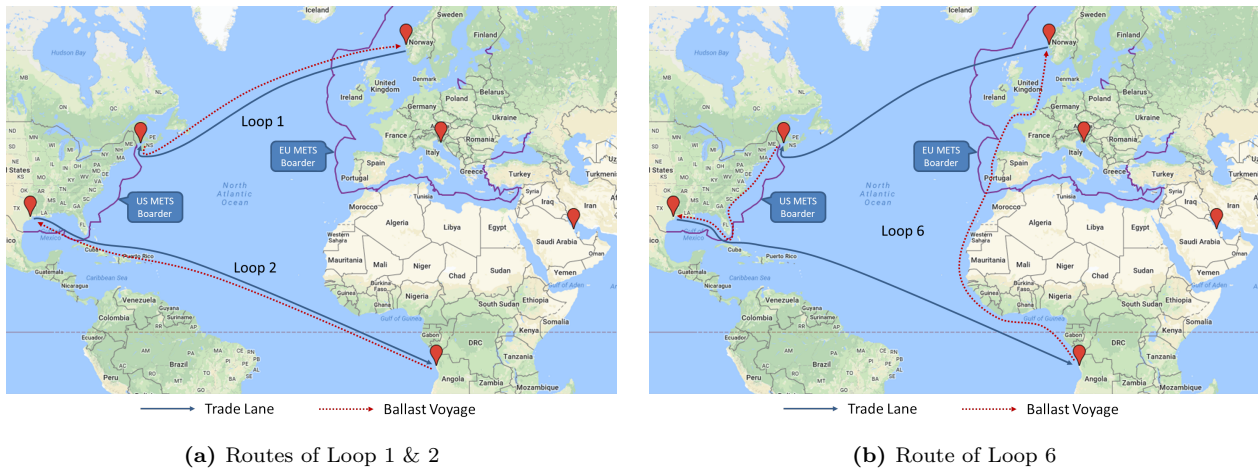
	No. of round trips Vessel Type 1	Speed - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed - knots Vessel Type 2
Loop 3 (TL3)	1.55	12.5	8.45	12.5
Loop 6 (TL1 & TL2)	12	12.5	0	0
	Vessel Type 1		Vessel Type 2	
Chartered days in/out (+/-)	-256		0	

Surprisingly, in the scenario with high allowance cost and regional METS, an increase of CO<sub>2</sub> emission is observed. The optimal solution in Table 9 suggests the shipping company to use the loop options with minimum sailings in the METS areas so that the effect of high allowance cost can be minimized. Hence comparing to the solutions in the business-as-usual case in Table 8, the new plan here abandons Loop 6 (more METS involvement) while uses Loop 1 and Loop 2 (less METS involvement) to serve Trade Lane 1 and Trade Lane 2 separately, see Figure 9. Unfortunately, the total travelling distance of Loop 1 and Loop 2 is longer than that of Loop 6, which leads to the total emission increase (although decrease inside METS areas) observed in Table 4. The longer voyage also causes an increased fuel consumption (higher bunker cost) and vessel demand (higher chartering cost). Nevertheless, the saving on the allowance side still exceeds these cost increases since the bunker price and charter rate are both low in this scenario.

**Table 9:** Solutions summary in the regional METS case with low allowance cost, charter rate and bunker price

	No. of round trips Vessel Type 1	Speed (normal stretch) - knots Vessel Type 1	Speed (METS stretch) - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed (normal stretch) - knots Vessel Type 2	Speed (METS stretch) - knots Vessel Type 2
Loop 1 (TL1)	12	12.5	12.5	0	0	0
Loop 2 (TL2)	12	12.5	12.5	0	0	0
Loop 3 (TL3)	0.06	12.5	12.5	9.94	15.5	12.5
	Vessel Type 1			Vessel Type 2		
Chartered days in/out (+/-)	-231			0		

Now we change the setting of bunker price from low to high and repeat the tests again with all other assumptions. The results under different scenarios in the high bunker price cases are summarized in Table 10. We observe a similar pattern which is also witnessed in the low



**Figure 9:** Different METS coverage of Loop 1, 2 & 6

bunker price case in Table 4. The emission reduction caused by the implementation of METS is only experienced in the scenarios with a normal charter rate. Moreover, a higher allowance cost facilitates more emission reduction, while a global geographical scope of the regulation also encourage the ships to emit less. However, comparing to the benchmark, no further emission reduction is observed in the high and low charter rate scenarios after introducing either regional or global METS. .

**Table 10:** Result summary in the high bunker price scenario

CO <sub>2</sub> Tonne (% of change)	Business-as-usual (Benchmark)	Regional METS		Global METS	
		<i>Low</i> <i>allowance cost</i>	<i>High</i> <i>allowance cost</i>	<i>Low</i> <i>allowance cost</i>	<i>High</i> <i>allowance cost</i>
<i>Low charter rate</i>	66288.2 (n/a)	66291.5 (0.0%)	66291.5 (0.0%)	66288.2 (0.0%)	66288.2 (0.0%)
<i>Normal charter rate</i>	72693 (n/a)	72108.4 ( <b>-0.8%</b> )	70772.6 ( <b>-2.6%</b> )	72109.8 ( <b>-0.8%</b> )	67983.9 ( <b>-6.5%</b> )
<i>High charter rate</i>	72693 (n/a)	72690.6 (0.0%)	72690.6 (0.0%)	72693 (0.0%)	72693 (0.0%)

### Scenario: high bunker price, normal charter rate

Firstly, a *high* bunker price and *normal* charter rate is assumed in this subsection. Table 11 shows the detailed optimal composition and deployment decisions in the business-as-usual case with high bunker price and normal freight market. Comparing to the results observed in Table 5 (low bunker price, normal charter rate), we can find that in this scenario the ships on Loop 1 and 6 start slow steaming due to the higher bunker price. Certainly, more transport capacity is used as well, which leads to less chartering out.

If a regional METS with low allowance cost is implemented, the optimal solutions propose a simpler deployment plan and further speed reduction on the METS stretch of Loop 3, see Table 12. However, the speeds on Loop 6 and normal stretch of the Loop 3 remain unchanged. Furthermore, the sailing on the METS stretch of Loop 3 (see Figure 10) is just a small part of the entire voyage including all other used loops (approximately 5% based on travelling distance). Hence, the further speed reduction on the METS stretch of Loop 3 here has very limited impact on the total emission. Therefore, a merely 0.8% reduction of CO<sub>2</sub> is observed in Table 10. Similar situation also happens in the scenario with a global METS and low allowance cost. Although the global coverage of METS forces the ships to slow down on the entire voyage on Loop 3, the low allowance cost can only lead to a relatively slight speed reduction, see Table 13, which again has minor impact on the total emission.

**Table 11:** Solutions summary in the business-as-usual case with normal charter rate and high bunker price

	No. of round trips Vessel Type 1	Speed - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed - knots Vessel Type 2
Loop 1 (TL1)	0.31	14.4	0	0
Loop 2 (TL2)	0	0	0.31	15.5
Loop 3 (TL3)	0	0	10	15.5
Loop 6 (TL1 & TL2)	11.69	14.4	0	0
	Vessel Type 1		Vessel Type 2	
Chartered days in/out (+/-)	-405		0	

**Table 12:** Solutions summary in the regional METS case with low allowance cost, normal charter rate and high bunker price

	No. of round trips Vessel Type 1	Speed (normal stretch) - knots Vessel Type 1	Speed (METS stretch) - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed (normal stretch) - knots Vessel Type 2	Speed (METS stretch) - knots Vessel Type 2
Loop 3 (TL3)	0	0	0	10	15.5	12.8
Loop 6 (TL1 & TL2)	12	14.4	14.4	0	0	0
	Vessel Type 1			Vessel Type 2		
Chartered days in/out (+/-)	-394			0		

Comparing to the results observed in the previous paragraph with low allowance cost scenarios, the emission decreases significantly in the scenarios with higher allowance cost, see Table 10. The reason for the lower emission is that the sailing speed of the vessel further declined due to the higher cost of CO<sub>2</sub> allowance. In the setting of a regional METS, the vessels start slow steaming not only on the METS stretch of Loop 3, as already mentioned in Table 12, but also on the METS part of Loop 6, see Table 14. Moreover, unlike the METS stretch of Loop 3, the regulated voyage of Loop 6 accounts for a much more considerable percentage in the total travelling distance, see Figure 9b. Therefore, the speed reduction on the METS stretch of Loop 6 brings a substantial impact on the total emission. Similar observation of such upgraded slow steaming is also found in the global METS case, see Table 15. A minimum speed is adopted during the entire trip on Loop 6, which leads to a most dramatic CO<sub>2</sub> reduction in the tests in this study.

### Scenario: high bunker price, high/low charter rate

However, for the scenarios with high bunker price but low or high charter rate, the implementation of the METS, regardless regional or global, leads to no further emission reduction comparing to the situation in the business-as-usual case, see Table 10. The reason for such observation here is actually the same as the one explained in the previous paragraphs for the scenarios with low bunker price and low or high charter rate. In a booming freight market or a recession, the high or low charter rate plays the dominant role which influences the fleet's composition and deployment decisions.

In the business-as-usual case with high charter rate, the model suggests the same optimal solution (with limited slow steaming) as the one obtained in the benchmark case with normal charter rate, see Table 11. With METS, a further slow steaming can help to save more allowance



— Normal Stretch      - - - - - METS Stretch

Figure 10: The normal and METS stretches on loop 3

and fuel costs, but the total travelling time becomes longer, which leads to an increased need for transport capacity. When the charter rate is high, the additional savings brought by the further speed reduction can not compensate the increased charter-in cost (or decreased charter-out revenue) for more vessels. Hence, no further slow steaming is triggered and the introduction of the METS in the booming freight market scenario does not contribute additional emission reduction comparing to the benchmark.

In a market recession, the low charter rate has already motivated the fleet to slow down to its minimum speed in the business-as-usual case in order to fully utilize the cheap vessel resources on the spot market or the idle capacity in its own fleet which is not very profitable for chartering out at that time. Therefore, no matter a high or low extra allowance cost can not bring any more reduction on this minimum speed (same as the solutions in Table 8), which leaves an unaffected CO<sub>2</sub> emission even though the METS is implemented.

### Low bunker price v.s. high bunker price

The last insight of the computational study can be obtained from the comparison between the results with low bunker price (Table 4) and the results with high fuel cost (Table 10). Based on the comparison we find that a high bunker price can substantially undermine the capability of METS on short term emission reduction through fleet's operation. The reason for this observation is that a high fuel cost has already initiated the slow steaming of the ships, which leaves limited room for the METS to trigger further speed reduction. Therefore, the emission reduction in the high bunker price scenarios brought by the METS also becomes

**Table 13:** Solutions summary in the global METS case with low allowance cost, normal charter rate and high bunker price

	No. of round trips Vessel Type 1	Speed - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed - knots Vessel Type 2
Loop 3 (TL3)	0	0	10	14.8
Loop 6 (TL1 & TL2)	12	14.4	0	0
	Vessel Type 1		Vessel Type 2	
Chartered days in/out (+/-)	-394		0	

**Table 14:** Solutions summary in the regional METS case with high allowance cost, normal charter rate and high bunker price

	No. of round trips Vessel Type 1	Speed (normal stretch) - knots Vessel Type 1	Speed (METS stretch) - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed (normal stretch) - knots Vessel Type 2	Speed (METS stretch) - knots Vessel Type 2
Loop 3 (TL3)	0.1	14.4	12.5	9.9	15.5	12.5
Loop 6 (TL1 & TL2)	12	14.4	12.5	0	0	0
	Vessel Type 1			Vessel Type 2		
Chartered days in/out (+/-)	-364			0		

limited.

To briefly summarize, the findings obtained from this computational study include the following points. First, the introduction of METS may not lead to further short term emission reduction in certain situations. Second, a larger geographical scope and higher allowance cost bring positive impact on the emission reduction performance of METS. Last, high bunker price significantly undermines the capability of METS on short term emission reduction.

## 7 Conclusion

The Maritime Emission Trading Scheme is one of the most popular market-based measures that has the potential to be implemented in the shipping industry for CO<sub>2</sub> emission control purpose. The advantage and disadvantage of METS are widely discussed by researchers in the literature. The impact of the METS on emission reduction is normally divided into two categories. First, it is commonly agreed that the adoption of the MBM, such as METS, can bring strong incentives for the industry to invest in new technology which can lead to long term emission reduction. Moreover, it is also believed that due to the extra allowance cost the application of METS can also force the shipping company to adjust its fleet's operation, for example slow steaming, and hence achieve emission reduction in the short term as well. However, besides the allowance cost, other factors including bunker price and charter rate will also affect the operational behaviour of the vessels. Hence, whether the enforcement of the METS can still lead to emission reduction should remain in doubt when other mentioned variables are simultaneously considered. Nevertheless, the previous studies in the literature seems to ignore this question and take the emission reduction effect of METS in short term for granted. Therefore, the authors of this study try to fill this gap in the literature and examine the actual capability of METS in short term emission reduction with a more comprehensive setting.

In this paper, we have proposed an optimization model integrating the fleet composition



**Table 15:** Solutions summary in the global METS case with high allowance cost, normal charter rate and high bunker price

	No. of round trips Vessel Type 1	Speed - knots Vessel Type 1	No. of round trips Vessel Type 2	Speed - knots Vessel Type 2
Loop 3 (TL3)	0	0	10	14.8
Loop 6 (TL1 & TL2)	12	12.5	0	0
	Vessel Type 1		Vessel Type 2	
Chartered days in/out (+/-)	-302		0	

and deployment problem with the METS which may be implemented in the future. A computational study is performed with a case of chemical tanker company. Different scenarios constructed consist of all factors affecting the fleet’s CO<sub>2</sub> emission are tested in the study and the corresponding emission level in the optimal solution of each scenario is observed and compared. The results show three main insights which are believed to be valuable reference for the policy markers in the future. First, the implementation of METS will not guarantee a short term emission reduction. Other factors, for example charter rate, may have the overwhelming influencing power on the fleet’s operational decisions in certain situations, while the impact of the METS becomes minor. In certain special case, such as the scenario with low bunker price, low charter rate, regional METS and high allowance cost, the application of METS can even increase the fleet’s CO<sub>2</sub> emission. Second, if the scenario allows the METS to have substantial effect on the fleet’s operation, for example with a normal freight market, then a high allowance cost or a global coverage of the scheme may have the best performance in emission reduction. Last, a stronger impact of the MEST on CO<sub>2</sub> emission is expected in a low bunker price scenario.

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